ngvla

Next Generation Very Large Array

SYSTEM REFERENCE DESIGN

Volume 1: System Design

Preface

The ngVLA Science Book describes the frontiers of discovery enabled by a next-generation centimeter-wavelength interferometer with unprecedented sensitivity and angular resolution. Realizing such a facility will require a substantial financial investment, and the commitment of these funds comes with a responsibility upon the project to fulfill this vision within funding and time constraints. At this stage of the project, it is incumbent upon us to develop our facility concept to a degree where the investment required and the associated risks can be understood by both decision makers and the project team.

This three-volume compendium describes the ngVLA Reference Design. The reference design is a low-technical-risk, costed concept that supports the key science goals for the facility, and forms the technical and cost basis of the ngVLA Astro2020 Decadal Survey proposal. The compendium includes a total of 55 technical documents and represents the work of more than 54 engineers and scientists contributing to the project. While led by the project team at the National Radio Astronomy Observatory, the author list includes many collaborators from the US and international radio astronomy community who have contributed their expertise to the project. Many more have contributed to the definition of the science case and science requirements, or contributed through critical review.

This technical compendium describes the system from end to end, and provides a snapshot of the technical development of the facility concept as of August, 2019. As the first technical baseline, it has gaps and minor inconsistencies that will be addressed in advance of the system conceptual design review, but it presents the clear and substantive progress that has been made in defining a realizable ngVLA facility concept.

What is most important at this juncture is to have a viable concept for each subsystem that supports the overall system and science requirements, enabling robust performance and cost estimates, and a technical baseline for future trade studies. Alternate concepts that improve performance to key parameters or reduce cost can, and will, be revisited as part of the conceptual design activities.

The volume of this compendium is indicative of the effort invested and the technical maturation of the project. It is only through the documentation of our ideas that we identify the inconsistencies and gaps in our thinking, and the act of writing forces us to make multiple small decisions that sharpen our concepts and produce a realizable design. The development of this reference design gives us confidence in our performance and cost estimates, the technical readiness of the design, and our ability to achieve the transformational science described in the ngVLA Science Book.

With the realization of this technical concept, the ngVLA will uniquely tackle a broad range of high-priority scientific questions in modern astronomy, physics, chemistry, and biology, dramatically extending the scientific frontiers that are within reach of existing facilities. In doing so, the ngVLA will transform our understanding of planet formation, the initial conditions for life, galaxy formation and evolution, and the physics of black holes, and will ultimately advance humanity's understanding of the cosmos and our place within it.

Robert J. Selina
ngVLA Project Engineer
August, 2019

For more information and updates, please see the digital version of this book that is available on the ngVLA website.

Use the QR Code above, or visit us at ***https://ngvla.nrao.edu/page/projdoc***.

Volume I

Preface

R. Selina

Part I: System Reference Design

System Reference Design

020.10.20.00.00-0001-REP-B

R. Selina, E. Murphy, M. McKinnon, A. Beasley, J. Allison, S. Bhatnagar, B. Butler, C. Carilli, L. Ball, B. Clark, V. Cosper, V. Dhawan, D. Dunbar, S. Dunbar, S. Durand, G. Cole, P. Demorest, A. Erickson, E. Ford, D. Gerrard, W. Grammer, C. Hales, J. Hibbard, R. Hiriart, T. Hunter, J. Jackson, A. Kepley, B. Kent, J. Kern, W. Koski, C. Langley, P. Lopez, B. Mason, M. Morgan, O. Ojeda, P. Perley, U. Rao, M. Romero, V. Rosero, W. Shillue, L. Sjouwerman, S. Sturgis, N. Towne, R. Treacy, D. Urbain, A. Walter and J. Wrobel

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020.10.15.00.00-0001-REQ-A

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Legacy Science Program

020.10.05.00.00-0004-PLA-A

E. Murphy

Reference Observing Program

020.10.15.05.10-0001-REP-A

J. Wrobel

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020.10.05.00.00-0002-PLA-B

E. Ford, G. Cole, L. Ball, B. Butler, B. Clark, S. Durand, A. Erickson, J. Hibbard, A. Kepley, J. Kern, W. Koski, M. McKinnon, E. Murphy, P. Perley, R. Selina, L. Sjouwerman, J. Thunborg, R. Treacy, and J. Wrobel

Assembly, Integration, and Verification (AIV) Concept

020.10.05.00.00-0005-PLA-A

C. Langley, J. Kern, S. Durand, E. Ford, R. Hiriart, J. Effland, M. Shannon, R. Long, V. Dhawan, R. Selina, T. Hunter, D. Dunbar, and J. Bolyard

Commissioning and Science Validation (CSV) Concept

020.10.05.00.00-0006-PLA-A

T. Hunter, W. Brisken, B. Butler, B. Clark, V. Dhawan, J. Hibbard, R. Hiriart, J. Kern, E. Murphy, R. Selina, and J. Wrobel

Preliminary Stakeholder Requirements

020.10.15.01.00-0001-REQ-A

L. Zuckerberg, R. Treacy, R. Selina, and R. Hiriart

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J. Bolyard

Part III: L1 System Requirements & Architecture

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R. Selina

System Environmental Specifications
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R. Selina

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020.10.15.10.00-0002-REQ-A
R. Selina and C. Simon

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020.10.20.00.00-0002-DWG-A
R. Selina

Antenna Electronics Front End Enclosure Block Diagram
020.30.00.00.00-0002-BLK-A
J. Jackson and R. Selina

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020.22.00.00.00-0001-REQ-A
C. Hales

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C. Carilli, V. Rosero, A. Erickson, and E. Murphy

Array Configuration: Reference Design Description
020.23.00.00.00-0002-DSN-A
C. Carilli, V. Rosero, A. Erickson, B. Mason, and E. Murphy

System Reference Design

020.10.20.00.00-0001-REP-B-SYSTEM_REFERENCE_DESIGN

Status: **RELEASED**

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APPROVALS (Name and Signature)		**ORGANIZATION**	**DATE**
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M. McKinnon, Project Director	Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 16:37:56 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-25

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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2017-02-21	Selina	All	First draft of outline.
02	2017-07-28	Selina	6, 7	Updated to match latest PBS.
03	2017-08-25	Selina	7	Reduced scope of some PBS elements. Added SBA.
04	2017-09-20	Selina	6	Incorporating feedback from M. Rupen.
05	2018-05-23	Selina	All	Updating to better reflect referenced document structure and latest WBS.
06	2018-06-20	Selina, Ford	1, 5	Updated Ops Concept section with introduction material by Ford et. al. Removed assumptions and constraints section. Other minor edits.
07	2018-07-22	Selina	Cover, 1.1, 1.2, 8	Updated author list. Updated document numbers in AD/RD tables. Other minor edits.
08	2018-09-27	Selina	All	Added LBA. Updates to text and figures throughout in preparation for October internal RDR. Pulled Sci Case summary (redundant). Sync'd with Ref Design chapter of Sci Book.
09	2018-10-01	Selina	6.1, 6.2, 6.5	Text clarifications, corrections to imaging sensitivity.
10	2019-01-03	Selina	All	Addressed RIDs from internal review. Significant edits throughout document.
11	2019-03-05	Selina, Lear	All	Updated System Architecture section. Removed up-scope/descope section. Edits for consistency with ngVLA documentation standards and templates.
A	2019-05-20	Lear	All	Prepared document for approvals & release (v.A).
A.1	2019-05-31	Selina	All	Updated to reflect TAC, PS feedback. Corrections throughout, and significant extension of the Computing and Software System subsections.
A.2	2019-07-24	McKinnon, Selina	All	Minor edits throughout. Updated data rates in Section 7.9.
B	2019-07-25	Lear	All	Prepared PDF for signatures and release (v.B).

Table of Contents

1 Introduction

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The ngVLA will be a synthesis radio telescope composed of approximately 244 reflector antennas each of 18 meters diameter, and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

The facility will operate as a proposal-driven instrument with Principal Investigator (PI)-led proposals determining the science program. Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products; automated pipelines will calibrate raw data and create higher-level data products (typically image cubes). Data and quality assured data products will be available through an Observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

The array's signal processing center will be located at the Very Large Array site on the Plains of San Agustin, New Mexico. The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Array operations will be conducted from both the VLA site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will likely be located in a metropolitan area and will serve as the base for science operations and support staff, software operations, and related administration. Research and development activities will be split among these centers as appropriate.

1.1 Purpose of this Document

This document provides an overview of the ngVLA Reference Design. The reference design details a low-technical-risk, costed concept that supports key science goals and forms the technical and cost basis of the ngVLA Astro2020 Decadal Survey proposal.

As the ngVLA is presently in the development stage, it is too early to complete a full conceptual design down-select of all major subsystems. The reference design is one plausible implementation that supports the instrument requirements and provides a baseline for evaluating the cost realism and technical risk associated with the ngVLA. The project is pursuing technology development activities in parallel with this design, with the goal of maturing leading-edge technologies to an appropriate technical readiness before a conceptual design down-select. These development efforts are intended to exploit opportunities to reduce cost or improve performance as the design effort progresses.

This document presents the overall system architecture as well as supporting concepts for major system elements such as the antenna, receiving electronics, and central signal processor. The traceability from the requirements to the reference design is captured in the system-level Requirements Verification Traceability Matrix (RVTM) [AD07] and the allocation matrices are incorporated in the System Architecture model [AD09].

This document is the highest-level document in the reference design package. Supporting pieces of the reference design are listed here to give a full overview of the proposed and costed design while also identifying key supporting design materials relevant to specific system elements.

1.2 Applicable Documents

The following documents are applicable to this design report and are incorporated by reference. In the event of conflict, the applicable document supersedes the content of this report.

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD03	System Requirements	020.10.15.10.00-0003-SPE
AD04	Environmental Specification	020.10.15.10.00-0001-SPE
AD05	System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD06	Requirements Management Plan	020.10.15.00.00-0001-PLA
AD07	Requirements Traceability Verification Matrix	020.10.15.00.00-0002-REQ
AD08	Operations Concept	020.10.05.00.00-0002-PLA
AD09	System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD10	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK
AD11	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK
AD12	Product Breakdown Structure	020.10.10.05.00-0001-LIS
AD13	Array Configuration: Preliminary Requirements	020.23.00.00.00-0001-REQ
AD14	Array Configuration: Reference Design Description	020.23.00.00.00-0002-DSN
AD15	Calibration Strategy & Requirements	020.22.00.00.00-0001-REQ
AD17	ngVLA Antenna: Preliminary Technical Specifications	020.25.00.00.00-0001-SPE
AD18	ngVLA Antenna: Optical Reference Design	020.25.01.00.00-0001-REP
AD19	ngVLA Antenna: Reference Design	101-0000-001-PDD-001
AD20	Short Baseline Array Antenna: Preliminary Technical Specifications	020.47.05.00.00-0001-SPE
AD21	Short Baseline Array Antenna: Reference Design	102-0000-001-CDD-001
AD22	Front End: Preliminary Requirements	020.30.03.01.00-0001-REQ
AD23	Front End: Reference Design	020.30.03.01.00-0003-DSN
AD24	Cryogenic System: Preliminary Requirements	020.30.10.00.00-0001-REQ
AD25	Cryogenic System: Reference Design	020.30.10.00.00-0002-DSN
AD26	Integrated Receiver Digitizer: Preliminary Requirements	020.30.15.00.00-0001-REQ
AD27	Integrated Receiver Digitizer: Reference Design	020.30.15.00.00-0002-DSN
AD28	Digital Back End & Data Transmission System: Preliminary Requirements	020.30.25.00.00-0001-REQ
AD29	Digital Back End & Data Transmission System: Reference Design	020.30.25.00.00-0002-DSN
AD30	DC Power Supply System: Preliminary Requirements	020.30.50.00.00-0001-REQ
AD31	DC Power Supply System: Reference Design	020.30.50.00.00-0002-DSN
AD32	Bins, Modules & Racks: Preliminary Requirements	020.30.55.00.00-0001-REQ
AD33	Bins, Modules & Racks: Reference Design	020.30.55.00.00-0002-DSN
AD34	Environmental Control: Preliminary Requirements	020.30.60.00.00-0001-REQ
AD35	Environmental Control: Reference Design	020.30.60.00.00-0002-DSN
AD36	LO Reference and Timing: Preliminary Requirements	020.35.00.00.00-0001-SPE
AD37	LO Reference and Timing: Reference Design	020.35.00.00.00-0002-DSN
AD38	Central Signal Processor: Preliminary Requirements	020.40.00.00.00-0001-SPE
AD39	Central Signal Processor: Reference Design	020.40.00.00.00-0002-DSN
AD40	Independent Phase Cal System: Preliminary Requirements	020.45.00.00.00-0001-REQ

Ref. No.	Document Title	Rev/Doc. No.
AD41	Independent Phase Cal System: Reference Design	020.45.00.00.00-0002-DSN
AD42	Computing & Software Systems: Preliminary Requirements	020.50.00.00.01-0001-REQ
AD43	Computing & Software Systems: Reference Design Architecture	020.50.00.00.01-0002-REP
AD44	Monitor & Control System: Reference Design Concept	020.50.25.00.00-0002-DSN
AD45	Monitor & Control System: Preliminary Requirements	020.50.25.00.00-0001-REQ
AD46	Monitor & Control System: Hardware Technical Requirements	020.30.45.00.00-0002-REQ
AD47	Buildings & Array Infrastructure Reference Design Study	020.60.00.00.01-0002-REP
AD48	Integrated Construction Cost Estimate	020.05.15.05.00-0004-BUD
AD49	Integrated Operations Cost Estimate	020.05.15.05.00-0007-BUD
AD50	ngVLA Lexicon and Acronyms	020.10.10.10.00-0005-LIS
AD51	Trident Correlator-Beamformer Preliminary Design Specification	TR-DS-000001
AD52	Assembly, Integration, & Verification (AIV) Concept	020.10.05.00.00-0006-PLA
AD53	Commissioning & Science Validation (CSV) Concept	020.10.05.00.00-0006-PLA
AD54	Long Haul Fiber Workgroup Preliminary Report	020.60.00.00.00-0002-REP

1.3 Reference Documents

The following documents provide additional material or supporting context.

Ref. No.	Document Title	Rev/Doc. No.
RD01	Summary of the Science Use Case Analysis	ngVLA Memo No. 18
RD02	Key Science Goals for the ngVLA	ngVLA Memo No. 19
RD03	ngVLA Science Book	Astronomical Society of the Pacific, Monograph Vol. 7, 2018
RD04	Interferometry & Synthesis in Radio Astronomy	Thomson, Moran, Swenson, 2nd Edition
RD05	Science Ready Data Products System Concept	530-SRDP-014-MGMT
RD06	Science Ready Data Products System Architecture	(In Prep.)
RD07	ngVLA Cost Model Memo	020.05.15.00.00-0004-REP
RD08	ngVLA Cost Model Spreadsheet	020.05.15.00.00-0005-REP
RD09	Reference Design Development & Performance Estimates	ngVLA Memo No. 17
RD10	More on Synthesized Beams and Sensitivity	ngVLA Memo No. 16
RD11	Possible Configurations for the ngVLA	ngVLA Memo No. 03
RD12	SKA Design Studies Technical Memo 107	Lal, D., Lobanov, A., Jimenez-Monferrer, S., SKA Design Studies Technical Memo 107, 2011
RD13	Fast Switching Phase Calibration at 3mm at the VLA site	ngVLA Memo No. 1
RD14	Calibration Strategies for the Next Generation VLA	ngVLA Memo No. 2
RD15	An RFI Survey at the Site of the Long Wavelength Demonstration Array (LWDA)	Stewart, K. P. et al., BAAS 37, 1389, 2005
RD16	The ngVLA Short Baseline Array	ngVLA Memo No. 43

Ref. No.	Document Title	Rev/Doc. No.
RD17	Getting the Big Picture: Design Considerations for a ngVLA Short Spacing Array	Mason, B. et al., American Astronomical Soc., 2018
RD18	SKA-1 System Baseline Design	SKA Doc No. SKA-TEL-SKO-DD-001
RD19	Imaging Capabilities: Protoplanetary Disks Comparison	ngVLA Memo No. 11
RD20	The Strength of the Core	ngVLA Memo No. 12
RD21	Short Spacing Considerations for the ngVLA	ngVLA Memo No. 14
RD22	Resolution & Sensitivity of ngVLA-RevB	ngVLA Memo No. 47
RD23	The Concept of a Reference Array for the ngVLA	ngVLA Memo No. 4
RD24	Considerations for a Water Vapor Radiometer System	ngVLA Memo No. 10
RD25	Polarization Calibration with Linearly Polarized Feeds	ngVLA Memo No. 45
RD26	Technical Study: Offset Gregorian Antenna	ngVLA Memo No. 26
RD27	Exploration of Suitable Mounts for a 15m Offset Antenna Next Generation Very Large Array NRC 15m Mount	ngVLA Memo No. 25
RD28	Various Suitable Mounts for an 18m Antenna	ngVLA Memo No. 27
RD29	Advanced Cryocoolers for the Next Generation VLA	ngVLA Memo No. 24
RD30	Short Baseline Array: Reference Design Description	ngVLA Memo No. 43
RD31	RFI Flagging Algorithms	(ngVLA Memo #TBD)
RD32	Imaging Algorithms	(ngVLA Memo #TBD)
RD33	Computing System Sizing	(ngVLA Memo #TBD)
RD34	Legacy Science Program	020.10.05.00.00-0004-PLA
RD35	ngVLA Front End Thermal Study Analysis Report	Calisto REP/1406/4366
RD36	An Integrated Receiver Concept for the ngVLA	ngVLA Memo No. 29
RD37	TM's View of the Mid.CBF Frequency Slice Approach.	Rupen, M. 2017
RD38	Precipitable Water at the VLA: 1990–1998	VLA Scientific Memo 176
RD39	Phase Fluctuations at the VLA Derived from One Year of Site Testing	VLA Test Memo 222
RD40	An RFI Survey at the Site of the Long Wavelength Demonstration Array (LWDA)	Stewart, K. P. et al. BAAS 37, 1389, 2005
RD41	A Preliminary Survey of Radio-Frequency Interference Over the US in Aqua AMSR-E Data	Li et al. *IEEE TGRS*, *42*, 380, 2004
RD42	Subarray Processing for Projection-based RFI Mitigation in Radio Astronomical Interferometers	Burnett, M et al. *AJ*, *155*, id.146, 2018
RD43	The Very Large Array	Thomson, A. R. et al. *ApJSS*, *44*, 151, 1980
RD44	Snapshot UV Coverage of the ngVLA: An Alternate Configuration	ngVLA Memo No. 49
RD45	A Dedicated Pulsar Timing Array Telescope	ngVLA Memo No. 34
RD46	Next Generation Low Band Observatory: A Community Study Exploring Low Frequency Options for ngVLA	ngVLA Memo No. 20
RD47	Taperability Study for the ngVLA and Performance Estimates	ngVLA Memo No. 55
RD48	System-level Cost Comparison of Offset and Symmetric Optics	ngVLA Antenna Memo No. 1
RD49	System-level Evaluation of Aperture Size	ngVLA Antenna Memo No. 2

2 Science Requirements

The ngVLA Science Requirements appear in [AD01], Science Requirements, 020.10.15.00.00-0001-REQ. Additional supporting material that led to definition of these science requirements appears in [RD01–03]:

- Summary of the Science Use Case Analysis, ngVLA Memo No. 18
- Key Science Goals for the ngVLA, ngVLA Memo No. 19
- ngVLA Science Book, ASP Monograph Vol. 7, 2018

To develop the facility science case, the project solicited science use cases from the user community. Eighty science use cases compiled from more than 200 authors were submitted to the Science Working Groups (SWGs). The Science Advisory Council (SAC) ranked use cases based on scientific merit, degree of development, feasibility, and other relevant metrics. The five Key Science Goals (KSGs) of the ngVLA emerged from this ranking process [RD02]. The KSGs were chosen to satisfy three criteria:

- Each addresses an important, unanswered question in astrophysics that has broad scientific and societal implications.
- Progress in each area is uniquely addressed by the capabilities of the ngVLA.
- Each exhibits key synergies and complementarity with science goals being pursued by existing or planned facilities in the 2025 and beyond time frame.

The Key Science Goals and all other science use cases were parameterized and analyzed [RD01] to determine the ngVLA Science Requirements. While this aspect of the requirements definition is top-down and mission-driven, some judicious adjustment of the requirements is still appropriate. A primary science requirement for the ngVLA is to be flexible enough to support the breadth of scientific investigations that its creative scientist-users will propose over the instrument's decades-long lifetime. The requirements have therefore been adjusted to provide a balanced, flexible, and coherent complement of capabilities. The requirements that drive the design are encapsulated in [AD01] and summarized below.

Frequency Coverage: The ngVLA should be able to observe in all atmospheric windows between 1.2 and 116 GHz. These frequency limits are bracketed by spectral line emission from HI and CO respectively.

Continuum Sensitivity: A continuum sensitivity of better than 0.07 μJy/bm at 30 GHz and 0.5 μJy/bm 100 GHz is required for studying protoplanetary disks (KSG1). This requires a combination of large collecting area and wide system bandwidth. VLB continuum sensitivity of better than 0.23 μJy/bm at 10 GHz is required to detect gravitational wave (GW) events at a distance of 200 Mpc.

Line Sensitivity: A line sensitivity of 30 μJy/bm/km/s for frequencies between 10 and 50 GHz is simultaneously required to support both astrochemistry studies and deep/blind spectral line surveys. A line sensitivity of 1–750 mK at 5"–0.1" angular resolution and 1–5 km/s spectral resolution between 70 and 116 GHz is required to simultaneously support detailed studies of CO and variations in gas density across the local universe. The spectral line cases push the system design towards quantum-limited noise performance at the expense of bandwidth above 10 GHz.

Angular Resolution: A synthesized beam having a FWHM better than 5 mas with uniform weights is required at both 30 and 100 GHz, while meeting the continuum sensitivity targets. VLB angular resolution of 0.6 mas at 10 GHz is required to measure the proper motions of GW events at a distance of 200 Mpc.

Largest Recoverable Scale: Angular scales of >20" x (100 GHz/n) must be recovered at frequencies *n* <100 GHz. A more stringent desire is accurate flux recovery on arcminute scales at all frequencies. These scales approach the primary beam size of an 18 m dish, so both shorter baselines and a total power capability are necessary to completely fill in the central hole in the *(u, v)*-plane.

Surface Brightness Sensitivity: The array shall provide high-surface brightness sensitivity over the full range of angular scales recoverable with the instrument. This leads to a centrally condensed distribution of antennas.

Brightness Dynamic Range: The system brightness dynamic range shall be better than 50 dB for deep field studies. This requirement pushes several systematic requirements including antenna pointing, and electronic gain and phase stability.

Survey Speed: The array shall be able to map a ~7 square degree region to a depth of ~1 μJy/bm at 2.5 GHz and a 10 square degree region to a depth of ~10 μJy/bm at 28 GHz within a 10-hour epoch to localize transient phenomena identified with other instruments. Holding collecting area and receiver noise constant, this favors smaller apertures.

Beamforming for Pulsar Search, Pulsar Timing, and VLBI: The array shall support no less than ten beams spread over one to ten subarrays that are transmitted, over the full available bandwidth, to a pulsar search engine or pulsar timing engine. The pulsar search and timing engine must be integral to the baseline design. VLBI recording of a single element, or phased array output, requires at least three beams.

Science Ready Data Products: The primary data product delivered to users shall be calibrated images and cubes. Uncalibrated ("raw") visibilities shall be archived to permit reprocessing. Producing these higher-level data products requires standardization of initial system modes/configurations (e.g., limited tuning options) and repeatability/predictability from the analog system to reduce calibration overheads.

3 System Requirements

The ngVLA system requirements, the flow-down process, and supporting analysis can be found in [AD03–06]. Figure 1 shows the relationship of these documents within the requirements hierarchy.

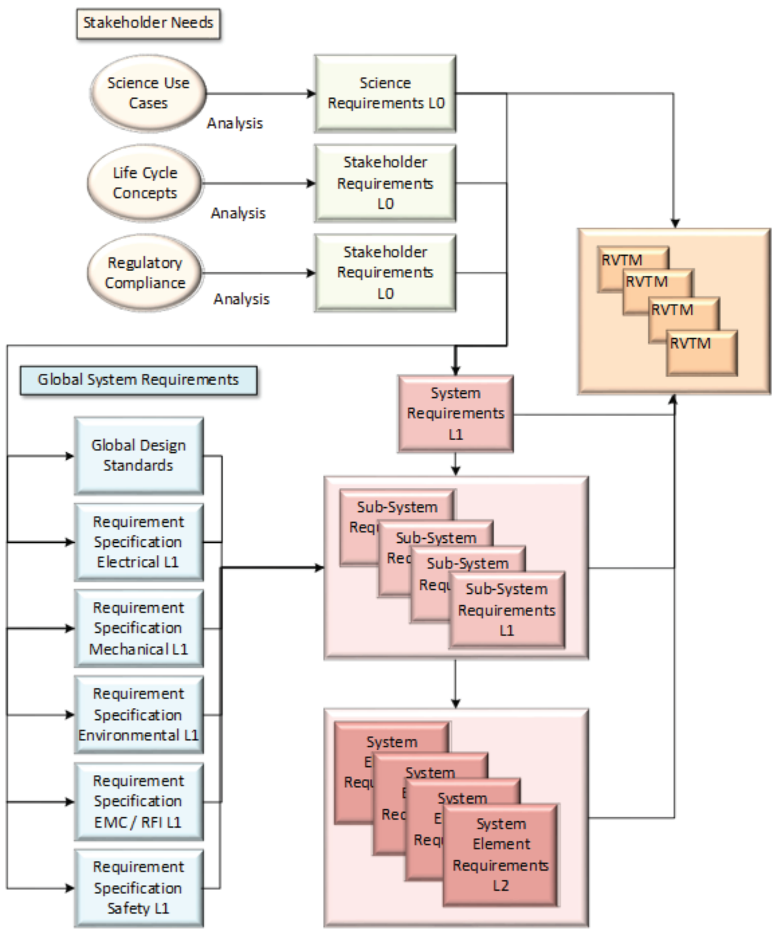

Figure 1 - Relationship between L0 science requirements, L1 system requirements, and associated specifications. [AD06]

The system requirements [AD03] support the science requirements [AD01] as well as other stakeholder requirements [AD02] elicited through the development of lifecycle concepts and other identified programmatic or regulatory requirements. The Requirements Traceability Verification Matrix [AD07] captures the traceability from science use cases to science requirements to system requirements.

The lifecycle concepts describe the project approach to design, assembly, integration, verification, scientific commissioning, operations, maintenance, and disposal. Requirements are identified within each concept and captured in the stakeholder requirements. The Operations and Maintenance Concepts drive the design, dictating operation efficiencies to reduce total lifecycle cost. This flow-down also reflects the needs established in the Assembly, Integration, and Verification (AIV) and Commissioning and Science Validation (CSV) concepts.

In addition to the main System Requirements document, a set of global design standards capture other key specifications. These provide common references for requirements and guidance on the environmental conditions present at the site and within other defined areas, RFI and EMC requirements, and design specifications to address electrical standards, mechanical standards, and the safety of both equipment and personnel.

The main requirements document identifies 179 system requirements, not including the global design standards. To provide some indication of significance, Table 1 shows the Measures of Performance (MOPs) identified as the most important for overall system effectiveness.

Parameter	Req. #	Value	Traceability
Effective Area/ T_{sys} Ratio	SYS1001	The effective area/T_{sys} ratio of the system shall meet or exceed values given in Figure 2 (below) while operating in the precision environment conditions defined in 020.10.15.10.00-0001-SPE [AD04] and assuming 1 mm of PWV. This requirement must be met over 80% of the bandwidth of any given receiver (i.e. band edges are exempted).	SCI0100, SCI0102, SCI0106
Distribution and Weighting of Visibilities	SYS1308	The system shall achieve a Gaussian distribution via weighting, with the quadratic mean of the weights greater than 0.5 over the full range of scales that correspond to 100 m to 420 km baselines on an 8 hr observation about the meridian. The quadratic mean of the weights shall also be better than 0.05 at scales corresponding to 8600 km baselines.	SCI0100, SCI0102, SCI0103, SCI0108, SCI0118
Calibration Efficiency	SYS1061	Overheads for system calibration shall be minimized, with a goal of 90% of time spent on source for Standard Observing Modes.	SCI0100, SCI0102, SCI0106, STK1403, STK0704
Instantaneous Field of View	SYS1101	The system instantaneous FOV (FWHM), when scaled by center frequency, shall be larger than 2 arcmin at 28 GHz.	SCI0106, SCI104
Shortest Baseline	SYS1302	The shortest baselines between antennas shall be shorter than 22 m, with a goal of 10 m.	SCI0104
Longest Baseline	SYS1301	The longest baseline between antennas in the main array shall be greater than 420 km with extended baselines (VLB) out to 8600 km.	SCI0103, SCI0118

Table 1 - System-level measures of performance (MOPs).

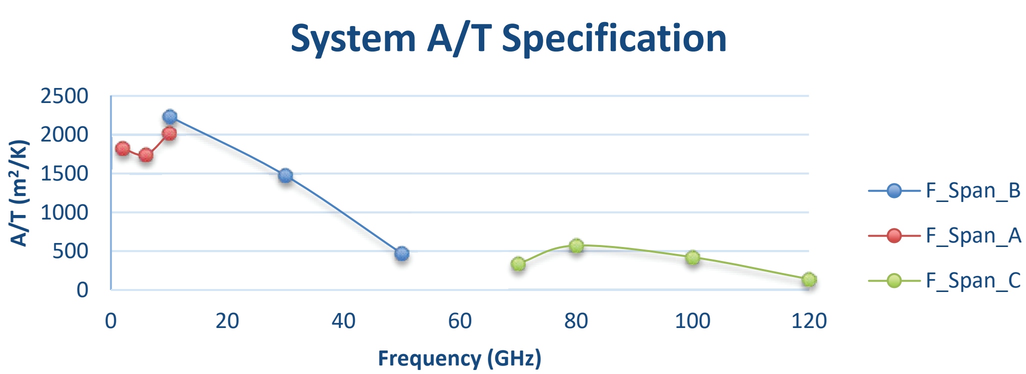

Figure 2 - System A/T specification in m²/K. (SYS1001)

4 Lifecycle Concepts

4.1 Operations Concept

The operations and maintenance concept for the facility can be found in [AD08], ngVLA Operations Concept, 020.10.05.00.00-0002-PLA. The facility will operate as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Regular (likely annual) calls will solicit observing proposals, which will be peer reviewed and assigned a rank based on scientific merit and technical feasibility. Trained staff will incorporate the approved observations into dynamically scheduled blocks based on environmental conditions and array status, and in accordance with the user's scientific requirements.

Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products (SRDPs) [RD05]; automated pipelines will calibrate raw data and create higher-level data products (typically image cubes). Data and quality assured data products will be made available through an Observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

The delivery of quality assured SRDPs and provision of standard observing strategies will enable the Observatory to, first, support a broad community of scientific users that extends considerably wider than radio interferometry experts, and, second, facilitate multi-wavelength and multi-messenger astronomy. Innovative, non-standard observations not accessible through the standard modes will also be supported where the scientific goals are of sufficient merit.

Three primary centers will support the operation and maintenance of the array. A Maintenance Center will be located near the array core, where field technicians will provide day-to-day maintenance support for the antennas and associated array systems. An Array Operations and Repair Center will be located in Socorro, NM, and staff based there will repair failed system elements, provide system diagnostics and engineering support, and operate and supervise the array. A Science Operations Center and Data Center will likely be located in a large metropolitan area and will be the base for science operations and support staff, software operations, and related administration. Research and development activities will be split among these centers as appropriate. Technicians responsible for maintaining remote long-baseline antennas may be based at additional small service depots (Remote Support Stations).

This Operations Concept further informs ngVLA operational requirements through a subsequent Operations Plan, a Transition Plan, and a Development Plan. The Operations Plan will fully describe the operational model to be employed following ngVLA construction, while the Transition Plan will cover the transition from VLA operations to ngVLA operations. The Development Plan will describe the research and development activities necessary to advance the ngVLA's technical and user support capabilities after construction has ended and operations has begun.

4.2 Assembly, Integration, and Verification (AIV) Concept

The ngVLA AIV concept is detailed in [AD52], ngVLA Assembly, Integration, and Verification Concept, 020.10.05.00.00-0005-PLA. It describes the production and construction concept for work package deliverables, degree of verification, and point of delivery. It then elaborates assembly of these deliverables into integrated systems and verification to the system requirements. The AIV concept describes these steps qualitatively, identifying likely resources and supporting infrastructure to achieve these goals.

The AIV concept imposes requirements on systems packaging, element deployment schedule, and ancillary equipment or processes required for component or subsystem verification. These requirements and their impacts are reflected in the stakeholder requirements, with subsequent flow down to the system requirements and this reference design. The overall ngVLA construction concept has work packages delivering qualified subsystems or sub-assemblies to the AIV team, the AIV team assembling these into integrated and verified systems, and handing over these verified systems to the Commissioning and Science Validation (CSV) team for progressive commissioning of capabilities. Construction ends with the hand-over of a commissioned telescope to Operations. The final AIV milestone, where capabilities transfer to CSV, is stable computer-controlled fringes on a calibrator source. These hand-offs are expected to be incremental, with a goal of completing the construction phase by 2035 (ten years for all construction activities; see Figure 3).

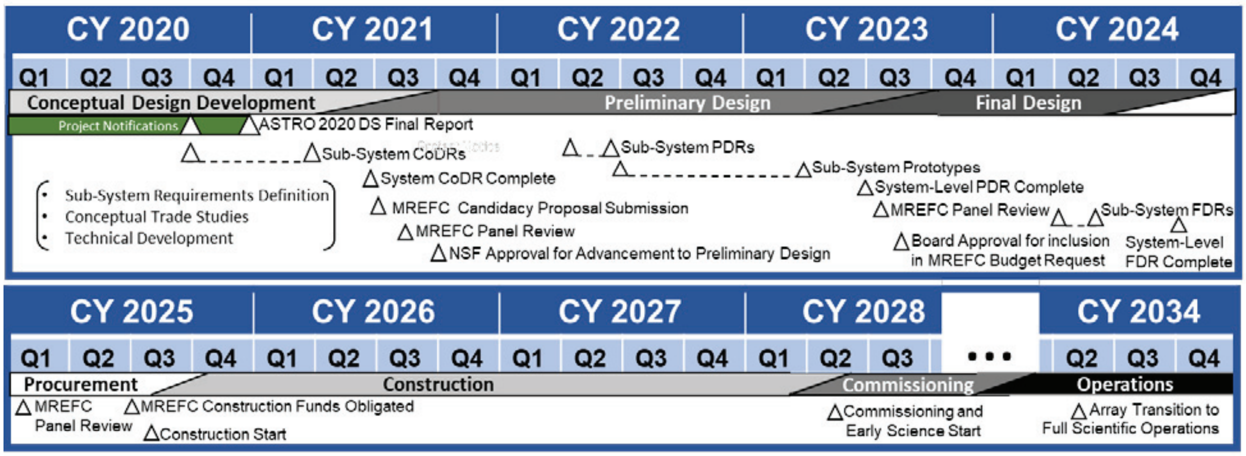

Figure 3 - Preliminary roadmap through design (conceptual, preliminary, final) to construction and operations. Major milestones are shown, such-as sub-system and system-level reviews, and interactions with the NSF MREFC process.

The technical AIV concept relies on line replaceable units (LRUs) that are verified independently before integration into more complex subsystems. LRUs and their sub-assemblies will generally be built to specification on contract. The ngVLA project team will act as system integrator. Subsystem architectures are scalable where required, ensuring that they can be deployed and tested incrementally, consistent with the overall AIV plan.

4.3 Commissioning and Science Validation (CSV) Concept

The ngVLA CSV concept is detailed in [AD53], ngVLA Commissioning and Science Validation Concept, 020.10.05.00.00-0006-PLA. The split between AIV and CSV is based on team specialization. AIV aims to deliver subsystems to specification and an integrated system with demonstrated core functionality. CSV assumes these verified components, performs additional integrated testing to validate the deliverables, and develops operational processes that enable observing modes for users.

The CSV concept defines a set of early commissioning milestones that show a progressive system integration and provide incremental observing capabilities. Example milestones include phase closure, long-baseline fringe tracking, short-baseline manual imaging, long-baseline manual imaging, full-beam and full-bandwidth modes, automated instrumental calibration, and automated imaging. CSV ends upon achievement of all capabilities required to meet the Science Requirements and Operations Concept and facility handover to Operations. The general exit criterion is data acquisition for any delivered mode using a standard scheduling block (SB) created using the Proposal Submission Tool (PST) and post-processed by the automated system.

The requirements imposed by the CSV concept and their indirect impacts, are reflected in the stakeholder requirements, with subsequent flow down to the system requirements and this reference design.

5 System Architecture

The ngVLA System Architecture is described in [AD09–12]:

- ngVLA System-Level Architecture Model, 020.10.20.00.00-0002-DWG
- Antenna Electronics Front End Enclosure Block Diagram, 020.30.00.00.00-0002-BLK
- Antenna Electronics Pedestal Enclosure Block Diagram, 020.30.00.00.00-0003-BLK
- ngVLA Product Breakdown Structure, 020.10.10.05.00-0001-LIS

The system-level architecture model is implemented in the Systems Modeling Language (SysML) and provides a logical decomposition of the system, leading to a physical implementation of the logical architecture that is consistent with the Product Breakdown Structure (PBS) [AD12] of the ngVLA Reference Design. When combined with the Requirements Verification Traceability Matrix [AD07], this provides upward traceability from the Reference Design to the logical architectural model, to L1 System Requirements, and to L0 Science and Stakeholder requirements as shown in Figure 4.

The system architecture aims to be

- loosely coupled, with high cohesion within subsystems, to enable parallel development with clean interfaces;
- flexible, scalable, and extensible to adjust to evolving performance requirements and programmatic constraints; and
- maintainable over the instrument's lifetime.

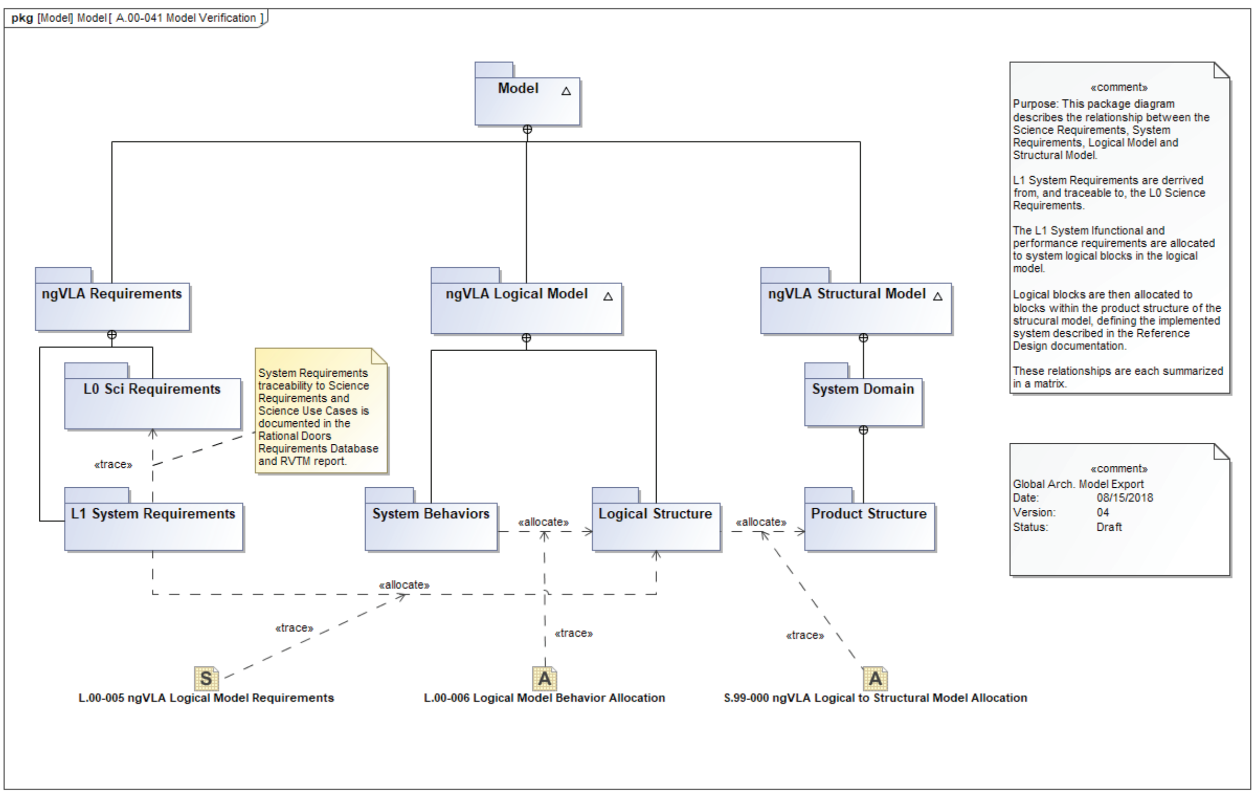

Figure 4 - System architecture model hierarchy and verification strategy. Traceabilty from L0 Science Requirements to L1 System Requirements is captured in the RVTM [AD07]. Requirements and functional behaviors are allocated to blocks in the logical model, and summarized in a Satisfy and Allocate matrix. The logical elements of the architecture are then traced to system elements of the Reference Design, captured as the structural model.

For an overview of the system architecture, Figure 5 provides a high-level view of the system starting with the submission of a proposal by a Principal Investigator (PI) using the Proposal Management System, and ending with the PI accessing their science ready data products through the Data Archive System.

Proposals progress through a Time Allocation Committee and technical review, are built into suitable observations with quality control (QC) checks, and are processed by a scheduling tool within the Online Control and Monitoring sub-system. An array supervisor configures the various array elements (the antennas and associated electronic sub-systems), central reference distribution system, and the central signal processor, executes the observation, and stages the low-level data for archiving. The Offline post-processing systems access this low-level data from the archive and prepare the high-level user data products which are stored in the same archive.

The architecture will continue to be developed and elaborated through the project's conceptual design phase. Alternative physical architectures that satisfy the logical architecture will be explored as part of the conceptual design trade-studies.

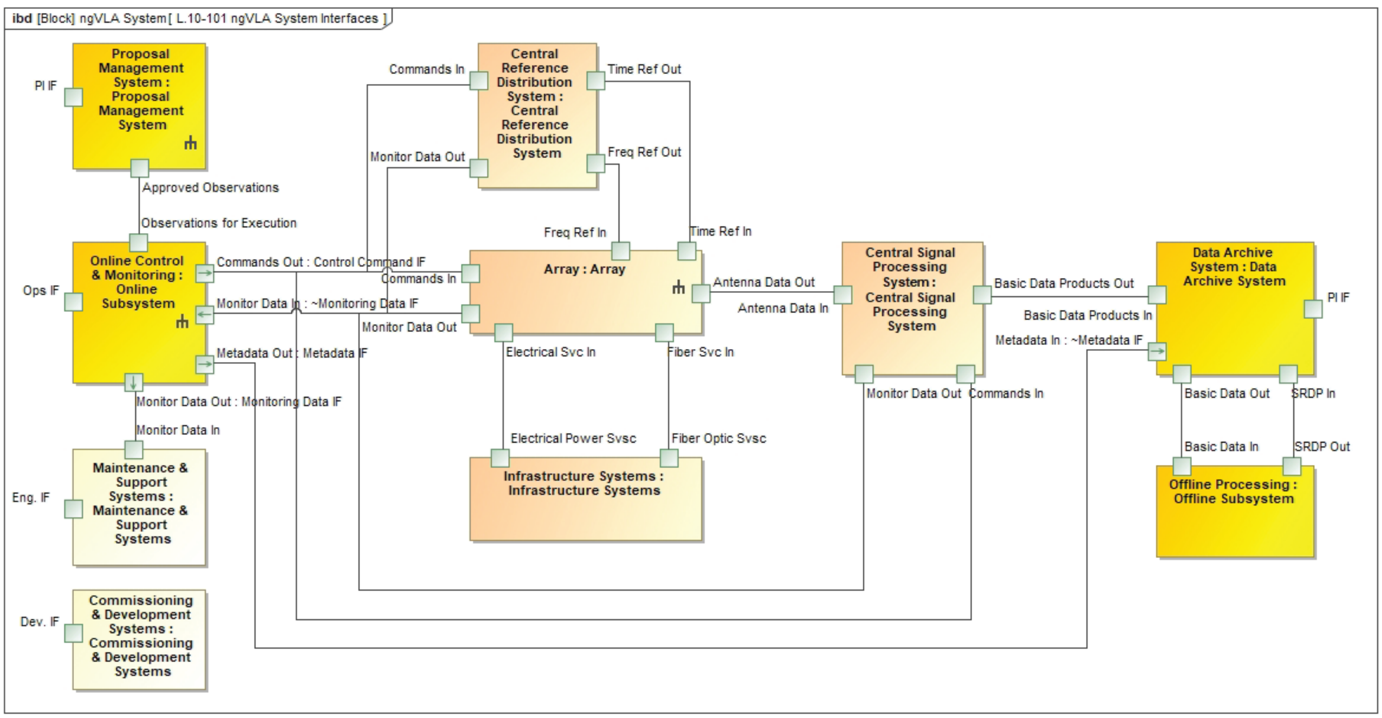

Figure 5 – The high-level ngVLA System Architecture. All deliverables within the facility are sub-components of the identified 10 systems, with major interfaces (IFs) to principal investigators, operations, and engineering shown. [AD09]

6 System Overview

This section provides a system-level overview of the reference design and describes the facility concept, its projected performance, and data products delivered to users. Major subsystem concepts follow in Section 7.

6.1 Overview

The ngVLA is planned as an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of three array components:

- A main array of 214 18-meter reflector antennas, operating in a phased or interferometric mode, will sample a wide range of scales from tens of meters to 1000 km. A dense core and spiral arms provide high surface brightness sensitivity, with mid-baseline stations enhancing angular resolution.
- A short baseline array (SBA) of 19 6-meter reflector antennas will capture a portion of the larger angular scales undetected by the main array. The SBA may be combined with four 18 m (main array) antennas used in total power mode to completely fill in the central hole in the (*u,v*)-plane left by the 6 m dishes.
- A long baseline array (LBA) will add 30 18-meter reflector antennas in ten clusters providing continental-scale baselines (B_{MAX} ~8860 km). The LBA will sample a broad range of scales for standalone sub-array use as well as for integrated operation with the main array.

In total, the ngVLA will have approximately ten times the sensitivity of the VLA and ALMA, continental-scale baselines providing sub-milliarcsecond-resolution, and a dense core on km-scales for high surface brightness sensitivity. Such an array bridges the gap between ALMA, a superb sub-millimeter array, and the future SKA1, optimized for longer wavelengths.

The array's dense core and signal processing center will be located at the Very Large Array site on the Plains of San Agustin, New Mexico. The high desert plains of the southwest US, at over 2000 m elevation, provide excellent observing conditions for the frequencies under consideration, including reasonable phase stability and opacity at 3 mm wavelength over a substantial fraction of the year.

The main array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will likely be located in a large metropolitan area and will be the base for science operations and support staff, software operations and related administration. Research and development activities will be split among these centers as appropriate.

The facility will be operated as a proposal-driven instrument. The fundamental data products for ngVLA users will be science-ready data products (images and cubes) generated using calibration and imaging pipelines created and maintained by the project. Archiving both pipeline products and "raw" visibilities and calibration tables will retain the option of future re-processing and archival science projects.

6.2 Reference Array Performance

Table 2 summarizes the array's predicted performance, updated from those originally documented in [RD09].

Receiver Band	B1	B2	B3	B4	B5	B6	Notes
Center Frequency, f	**2.4 GHz**	**8 GHz**	**16 GHz**	**27 GHz**	**41 GHz**	**93 GHz**	
Band lower frequency [GHz]	1.2	3.5	12.3	20.5	30.5	70.0	a
Band upper frequency [GHz]	3.5	12.3	20.5	34.0	50.5	116.0	a
Field of view FWHM [arcmin]	24.4	7.3	3.6	2.2	1.4	0.6	b
Aperture efficiency	0.77	0.76	0.87	0.85	0.81	0.58	b, e
Effective Area, A_{eff} x 10^3 [m^2]	47.8	47.1	53.8	56.2	50.4	36.0	b, e
System temp, t_{sys} [K]	25	27	28	35	56	103	a, e
Max inst. bandwidth [GHz]	2.3	8.8	8.2	13.5	20.0	20.0	a
Sampler resolution [bits]	8	8	8	8	8	4	
Antenna sefd [Jy]	372.3	419.1	372.1	485.1	809.0	2080.5	a, b
Resolution of max. baseline [mas]	2.91	0.87	0.44	0.26	0.17	0.07	c
Continuum rms, 1 hr [μJy/beam]	0.38	0.22	0.20	0.21	0.28	0.73	d, e
Line width, 10 km/s [kHz]	80.1	266.9	533.7	900.6	1367.6	3102.1	
Line rms, 1 hr, 10 km/s [μJy/beam]	65.0	40.1	25.2	25.2	34.2	58.3	d, e

(a) Six-band "baseline" receiver configuration.
(b) Reference design concept of 244 18 m aperture antennas. Unblocked aperture with 160 um surface.
(c) Rev. C 2018 Configuration. Resolution in EW axis.
(d) Point source sensitivity using natural weights, dual pol, and all baselines.
(e) Averaged over the band. Assumes 1 mm PWV for Band 6, 6 mm PWV for others; 45 deg elev. on sky for all.

Table 2 - ngVLA key performance metrics.

The continuum and line rms values in Table 2 are for point source sensitivity with a naturally weighted beam. Imaging sensitivity is estimated based on [RD22, RD47] and provided as a function of angular resolution in Table 3. The table is by necessity a simplification. The imaging sensitivity will vary from these reported values depending on the quality of the (sculpted) synthesized beam (defined as the ratio of the power in the main beam attenuation pattern to the power in the entire beam attenuation pattern as a function of the FWHM of the synthesized beam [AD01]) required to support the science use case.

The brightness sensitivity of an array is critically dependent on the array configuration. The ngVLA has the competing desires of both good point source sensitivity at full resolution, and good surface brightness sensitivity on scales similar to the primary beam size. Different array configurations that might provide a reasonable compromise through judicious weighting of the visibilities for a given application have been explored [RD11] (see [RD12] for similar studies for the SKA). It is important to recognize the fact that for any given observation, from full resolution imaging of small fields, to imaging structure on scales approaching that of the primary beam, some compromise must be accepted to enable a practical and flexible general-purpose facility.

Receiver Band	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**
Center Frequency, f	**2.4 GHz**	**8 GHz**	**16 GHz**	**27 GHz**	**41 GHz**	**93 GHz**
Resolution [mas]	**1000**					
Continuum rms, 1 hr, Robust [μJy/beam]	0.52	0.34	0.35	0.39	0.59	2.24
Line rms 1 hr, 10 km/s Robust [μJy/beam]	88.9	61.1	43.3	47.9	70.9	179.6
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	0.110	6.4E-3	1.7E-3	0.7E-3	0.4E-3	0.3E-3
T_B rms line, 1 hr, 10 km/s, Robust [K]	18.76	1.16	0.21	0.08	0.05	0.03
Resolution [mas]	**100**					
Continuum rms, 1 hr, Robust [μJy/beam]	0.50	0.30	0.27	0.28	0.40	1.14
Line rms 1 hr, 10 km/s Robust [μJy/beam]	85.0	53.6	33.6	34.8	48.4	91.3
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	10.58	0.56	0.13	0.05	0.03	0.02
T_B rms line, 1 hr, 10 km/s, Robust [K]	1794.1	101.9	15.9	5.8	3.5	1.3
Resolution [mas]	**10**					
Continuum rms, 1 hr, Robust [μJy/beam]	0.41	0.27	0.26	0.27	0.38	0.97
Line rms 1 hr, 10 km/s Robust [μJy/beam]	69.9	48.3	32.4	33.2	46.3	77.7
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	870.6	50.51	12.42	4.53	2.77	1.36
T_B rms line, 1 hr, 10 km/s, Robust [K]	1.5E5	9173	1540	555	335	109
Resolution [mas]	**1**					
Continuum rms, 1 hr, Robust [μJy/beam]	-	20.87	0.31	0.21	0.29	0.90
Line rms 1 hr, 10 km/s Robust [μJy/beam]	-	3789.8	38.2	25.7	34.7	72.0
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	-	4.5E5	1466	350	207	126
T_B rms line, 1 hr, 10 km/s, Robust [K]	-	7.2E7	1.8E5	4.3E4	2.5E4	1.0E4
Continuum rms, 1 hr, Robust [μJy/beam]	-	-	-	-	-	20.96
Line rms 1 hr, 10 km/s Robust [μJy/beam]	-	-	-	-	-	1683.2
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	-	-	-	-	-	2.9E5
T_B rms line, 1 hr, 10 km/s, Robust [K]	-	-	-	-	-	2.0E7

Table 3 - Projected imaging sensitivity as a function of angular resolution. All values at center frequency.

Imaging sensitivity will be dependent on the required resolution and imaging fidelity. Figure 6 and Figure 7 show the effects of adjusting imaging weights to vary the resolution and quality of the point spread function (PSF). These figures are based on a four-hour simulation at 30 GHz using the 244 antenna array configuration (Main Array and Long Baseline Array combined), for a source at +24° Declination observed during transit. The reported beam size is the geometric mean of the major and minor axes full width at half maximum (FWHM) of the synthesized beam as parameterized by Gaussian fitting in the CASA 'tclean' task. [RD47]

The centrally condensed antenna distribution leads to a naturally weighted beam that is not well characterized by a Gaussian function. Specific science applications may need to adjust the (*u,v*)-weighting and image parameters to sculpt a synthesized beam that is adequate for the particular science goal being considered. The results in Figure 6 and Figure 7 should be considered representative of the possibilities, and optimizing sensitivity vs. resolution will be a major area of investigation during telescope development.

To account for the change in sensitivity due to use of imaging weights (relative to the naturally weighted rms (σ_{NA}), an efficiency factor η_{weight} is adopted such that the expected image rms after weighting is $\eta_{weight} * \sigma_{NA}$. The sensitivity calculations in Table 3 include η_{weight}, estimated using the blue and red data series in Figure 6 scaled by frequency.

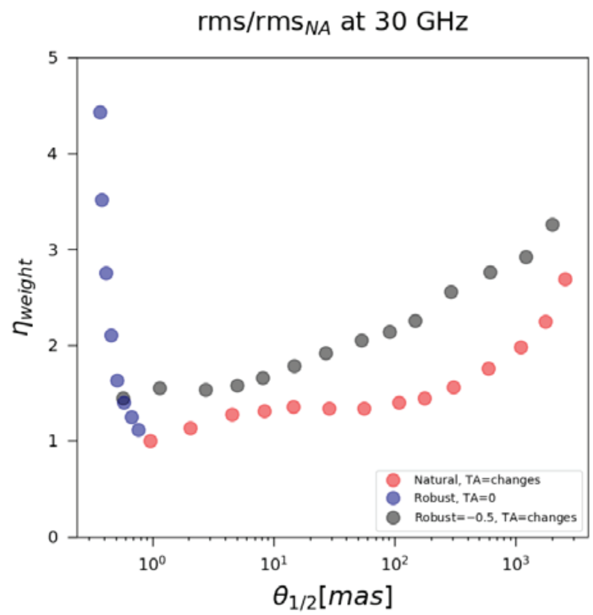

Figure 6 - Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz. The noise has been scaled relative to that of the naturally weighted image (σ_{NA}). The red symbols correspond to use of a (*u,v*) taper and natural weights, and the blue symbols to Briggs robust weighting without a taper. The gray symbols are for Briggs robust = –0.5 and a varying (*u,v*) taper, which has a large effect on beam quality (see Figure 7). [RD47]

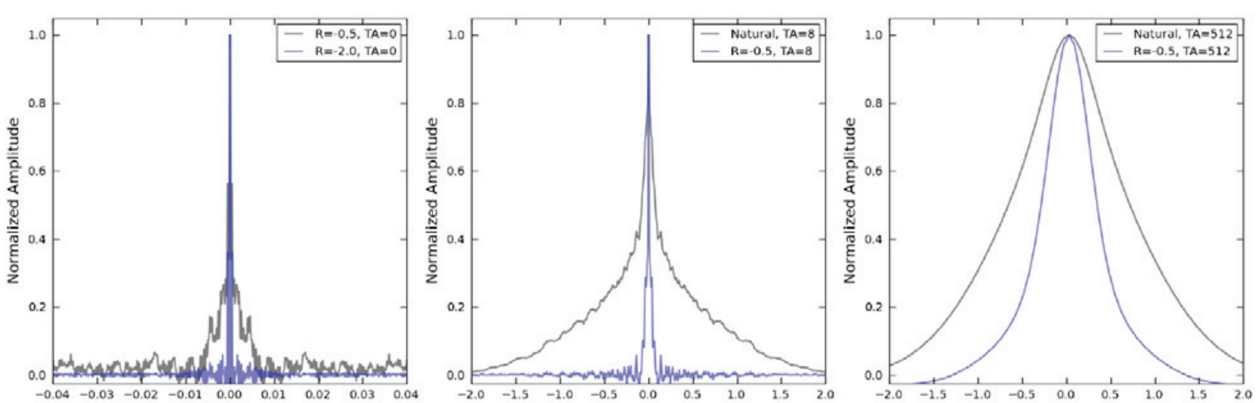

Figure 7 - Simulated 30 GHz PSFs over a range of resolutions show the effect of different imaging weights (TA: (*u,v*) taper in mas, R: Briggs robust parameter). The PSFs are a selection of the data presented in Figure 6: left panel (blue circles), central and right panels (gray and red circles). These illustrate how combinations of robustness and tapering allow for a beam of much higher quality at the expense of sensitivity. [RD47]

6.3 New Parameter Space

With an order of magnitude improvement in sensitivity and resolution compared to existing and planned facilities, the ngVLA opens up new parameter space ripe for discovery. Furthermore, the system capabilities will yield transformational advances in areas of astrophysics that are also highly synergistic with the science goals of next-generation ground-based optical/infrared (OIR) and NASA missions.

Figure 8 shows a slice through the parameter space, angular resolution versus frequency, covered by the ngVLA along with other existing and planned facilities that are expected in the 2030s at all wavelengths. The maximum baselines of the ngVLA imply an angular resolution of better than 0.5mas at 1cm.

Coupled with the high sensitivity of the array, this angular resolution provides a unique window into the formation of terrestrial planets in Solar systems like our own by providing AU-scale resolution at the distance of the nearest active star-forming regions.

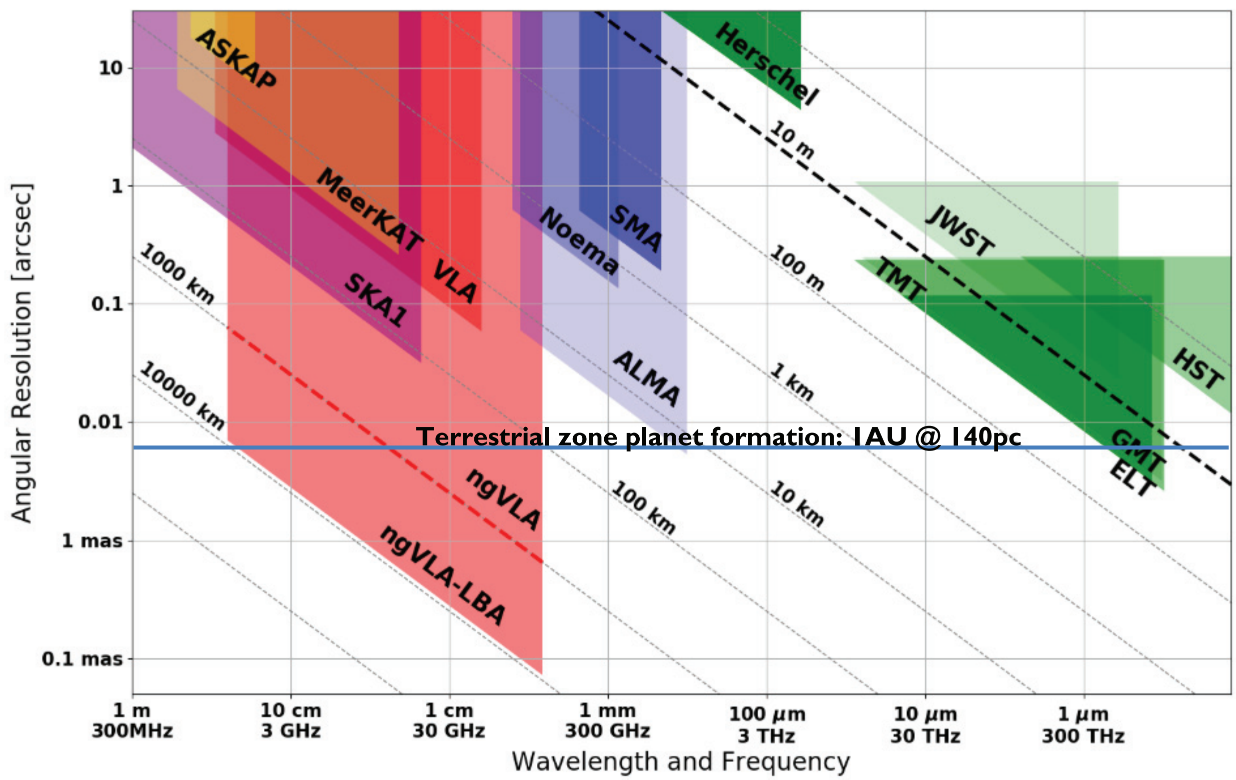

Figure 8 - Spatial resolution versus frequency set by ngVLA maximum baselines as compared to that of other existing and planned facilities.

Figure 9 shows a second slice through parameter space: effective collecting area versus frequency. A linear-linear plot highlights the parameter space opened by the ngVLA. Note that the SKA-1 will extend to below 100 MHz while ALMA extends up to almost a THz.

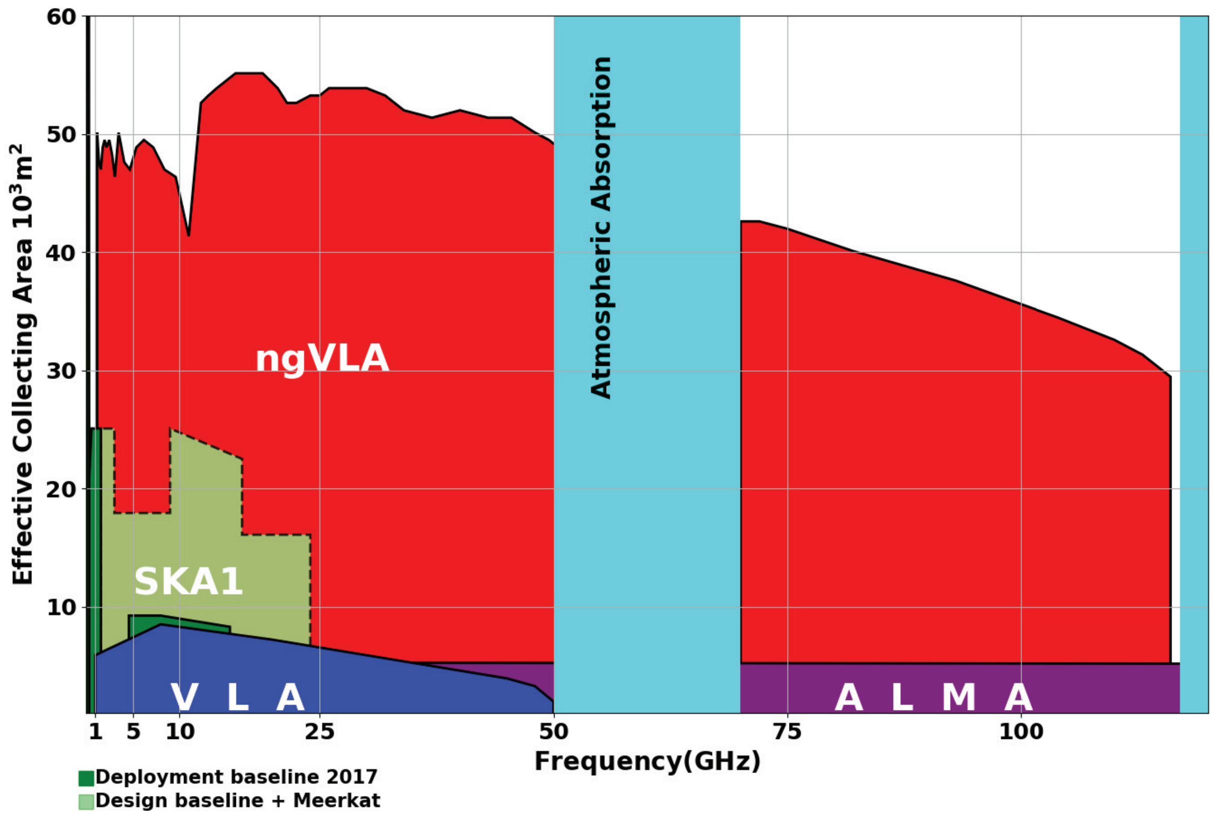

Figure 9 - Effective collecting area versus frequency for ngVLA as compared to that for other existing or planned facilities. Note that lower and higher frequencies are not shown (e.g., SKA-1 will extend to below 100 MHz and ALMA extends up to about a THz). Both the SKA-1 deployment baseline (dark green) and design baseline (light green) are shown, inclusive of the MeerKAT array. [RD18]

Other relevant aspects of telescope phase space include field of view, mapping speed, surface brightness sensitivity, bandwidth, system temperature, dynamic range, etc. However, here we have presented the two principle and simplest design goals, namely, maximum spatial resolution and total effective collecting area (as a reasonable proxy for system sensitivity).

6.4 Data Products

The standard method of delivery of scientific data from ngVLA to PIs will be automatically generated and quality assured Science Ready Data Products. ngVLA data rates will be high enough to make data reduction at a PI's home institution challenging, but low enough that real-time processing of the visibilities (à la SKA) is not required [RD33].)

The Observatory will provide sufficient computing resources for the data processing associated with normal operations using standard modes and capabilities (including delivery of Science Ready Data Products to PIs) as well as reasonable reprocessing by PIs and a broader community of users of archival (public) data.

Delivery of a fully commissioned standard observing mode or capability will include an operational SRDP pipeline before it is offered for regular use through PI-led proposals.

The definition and delivery of ngVLA data products will be informed by NRAO's development of Science Ready Data Products via the ALMA data pipeline and the efforts already underway to extend this approach to the VLA [RD05, RD06]. Standard and optimized data products are anticipated to meet both the needs of the original PI for ngVLA observations, and the scientific goals of subsequent users of publicly available data from the Data Archive. Raw visibilities, calibration tables and SRDPs will all be stored and made available through the Data Archive, as will some classes of user-generated data products where they can be suitably quality assured.

Large and Legacy [RD34] scale projects will need to identify data processing requirements and resources, and may require additional computing resources to be made available from non-Observatory sources in order to be scheduled. Large and Legacy projects will likely not be offered until well after the start of science operations, but are incorporated into the operations plan.

The Observatory will provide separate software packages to the user community for processing ngVLA visibilities and for data analysis. Both packages will be executable on Observatory computer resources and on non-Observatory computers, though the visibility processing software is likely to be aimed primarily at use only by domain experts.

6.5 Site Selection

The VLA site on the Plains of San Agustin was originally chosen as the location for the array because of its desirable properties: relatively flat, undeveloped (to minimize RFI) yet not too remote (for accessibility), at low latitude (for sky coverage), and at high elevation (to minimize atmospheric effects) [RD43]. These properties still hold true, and motivate examination of the VLA site as the center of the ngVLA.

Furthermore, with extensive existing infrastructure, the VLA site leverages an already existing system of power, fiber, and buildings, which will reduce cost. The three main environmental or atmospheric quantities that may affect data, and what is known about them at the VLA site, are discussed in the following sections.

6.5.1 RFI

The VLA site is remote enough that Radio Frequency Interference (RFI) is not a debilitating problem, so it will be possible to observe at the lower frequencies of the ngVLA [RD40]. Furthermore, the ngVLA will benefit from advanced studies of RFI detection and excision that are currently ongoing [RD42]. The degree of RFI characterization of the site reduces the risk in site selection, and leveraging existing infrastructure could create significant cost savings for both the construction and operation of the array.

Given the large extent of ngVLA (B_{MAX} ~8860 km), it is clear that the antennas located outside the plains will experience different RFI environments than that at the site. However, there are locations which are relatively free of locally generated RFI (downward RFI from orbiting satellites is ubiquitous and nearly site-independent), and the US southwest has many such locations [RD41].

6.5.2 Atmospheric Phase Stability

Analysis of data from the VLA site atmospheric phase monitor shows that fast switching phase calibration at 3 mm should be viable for most of the year with a 30-second total calibration cycle time [RD13]. This analysis was based on one year of atmospheric phase monitoring at the VLA site [RD39]. A much longer time base of these values is now available. Figure 10 shows median values of the rms phase on the 300 m E-W baseline of the atmospheric phase monitor from 1995 through 2017, plotted as a function of UTC hour and month.

It is easy to see that these fluctuations are small for much of the time, and only become greater than 10° (rms @11.7 GHz, over 10 minutes) in the summer during daytime. Little information is available on phase fluctuations at locations outside the plains; this is a topic to be studied to determine the ability to use the remote sites at the highest frequencies of ngVLA.

Note that there should also be a 25 mJy calibrator source within 2° in 98% of observed fields, ensuring short slews. Such a calibrator is adequate to ensure that the residual rms phase noise due to the signal-to-noise ratio on the phase calibrator is much less than that due to the troposphere, even for a 30s cycle time with only 3s on the calibrator each visit [RD13]. The project is also investigating radiometric phase correction techniques as part of the ngVLA project to increase the total phase calibration cycle time.

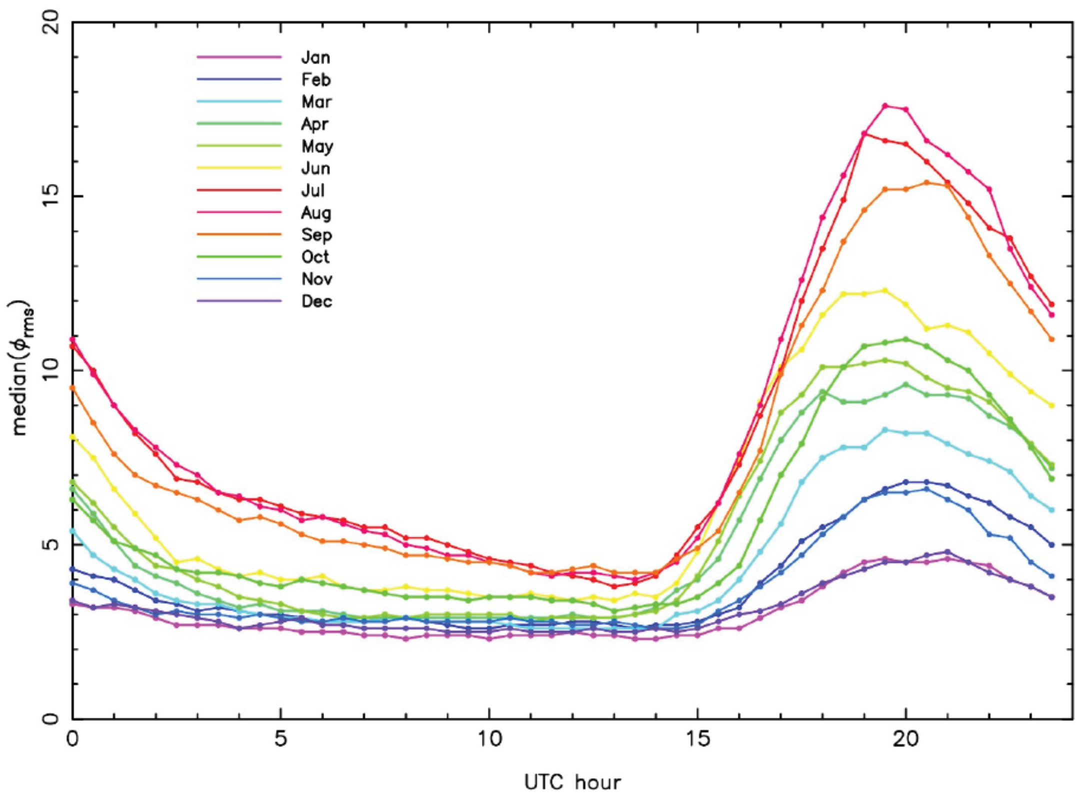

Figure 10 - The median rms phase measured with the atmospheric phase monitor at the VLA (300 m E-W baseline, 11.7 GHz beacon), from 1995 to 2017. Measurements are calculated over a ten-minute period after subtracting any linear trend. Different months are plotted as different colors, as shown in the legend.

6.5.3 Atmospheric Opacity

While at centimeter wavelengths atmospheric opacity is a relatively minor issue compared to phase stability, it becomes a much bigger issue at millimeter wavelengths. Similar to the atmospheric phase stability data, there is a long-time baseline of surface weather data at the VLA site. This can be used to estimate the atmospheric Precipitable Water Vapor (PWV), which is the main contributor to the fluctuating part of atmospheric opacity [RD38].

Figure 11 shows this value for the years 2010 through 2017. In winter months, the median over all hours is around 3 mm, and over the entire year the median over all hours is 5.4 mm. Vertical opacity for 5.4 mm PWV at 90 GHz is less than 7%, so opacity should not be a major problem for ngVLA.

As with RFI and phase stability, there is little information on atmospheric opacity at other locations, though it is almost always clear that higher sites have less opacity. The project does have access to surface weather data, and to radiosonde launch data (twice per day) from NOAA for some tens of sites across the southwest US, which will be the subject of a future study to determine opacity properties across the extent of ngVLA.

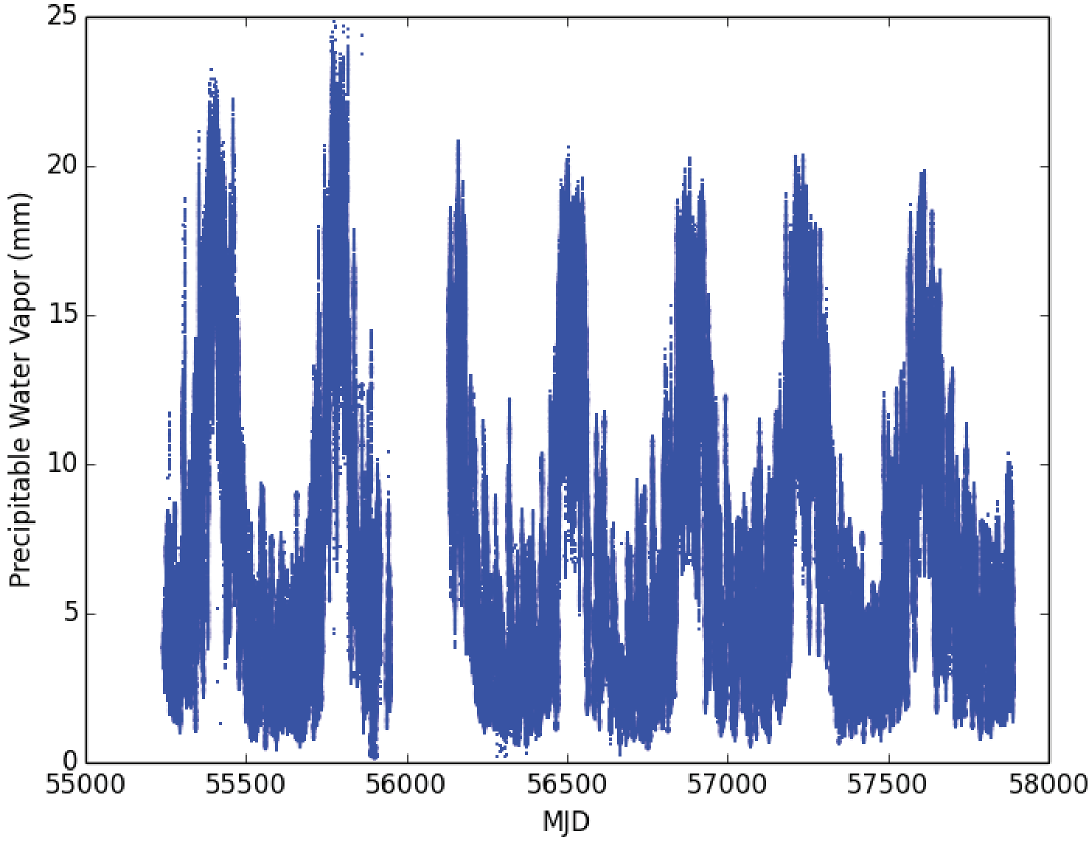

Figure 11 - PWV at the VLA site, estimated using surface weather measurements, from 2010 to 2017. Note that a PWV of 6 mm produces an opacity of less than 7% at 90 GHz.

6.5.4 Final Site Selection

Because of the quality of the site for both low- and high-frequency observing, and the existing infrastructure, ngVLA is centered near the current VLA. The southwest US and northern Mexico are sparsely populated and the antennas within 1000 km of the VLA are sited to select remote, radio quiet, and dry sites, while still considering the logistics of site access, electrical infrastructure, and fiber optic network topology. The long baseline array sites were selected to minimize site impact and leverage shared infrastructure of other existing observatories, so sites operated by the VLBA or other observatories are preferred. Note that the VLA site was used for acceptance testing of the original ALMA antennas, including observations up to 230 GHz, and the experience was that the VLA site at 2124 m elevation is a high-quality 90 GHz site—comparable to the Plateau de Bure site in overall performance [RD04].

7 Reference Design

7.1 Array Configuration

The Reference Array Configuration for the facility can be found in the following documents [AD13–14]:

- ngVLA Array Configuration Requirements, 020.23.00.00.00-0001-REQ
- ngVLA Array Configuration Reference Design, 020.23.00.00.00-0002-DSN

Additional supporting material that led to the selected reference design can be found in the following documents [RD10–11, 16, 19–22]:

- Possible Configurations for the ngVLA, ngVLA Memo No. 3
- Imaging Capabilities: Protoplanetary Disks Comparison, ngVLA Memo No. 11
- The Strength of the Core, ngVLA Memo No. 12
- Short Spacing Considerations for the ngVLA, ngVLA Memo No. 14
- More on Synthesized Beams and Sensitivity, ngVLA Memo No. 16
- ngVLA Short Baseline Array Configuration, ngVLA Memo No. 43
- Resolution & Sensitivity of ngVLA-RevB, ngVLA Memo No. 47

The ngVLA array design includes three main subarrays: a main interferometric array (MA), a short baseline array (SBA), and a long-baseline array (LBA), providing a wide range of angular scales. The main array configuration will consist of 214 18-meter antennas at the approximate locations shown in Figure 12.

The array collecting area is distributed to provide high surface brightness sensitivity on a range of angular scales spanning from approximately 1000 to 10 mas (see Table 4). In practice, this means a core with a large fraction of the collecting area in a randomized distribution to provide high snapshot imaging fidelity, and arms extending asymmetrically out to ~1000 km baselines, filling out the *(u, v)*-plane with Earth rotation and frequency synthesis.

Radius	Collecting Area Fraction	No. of 18m Antennas
0 km < R < 1.3 km	44%	94
1.3 km < R < 36 km	35%	74
36 km < R < 1000 km	21%	46

Table 4 - Radial distribution of collecting area in the main array (MA).

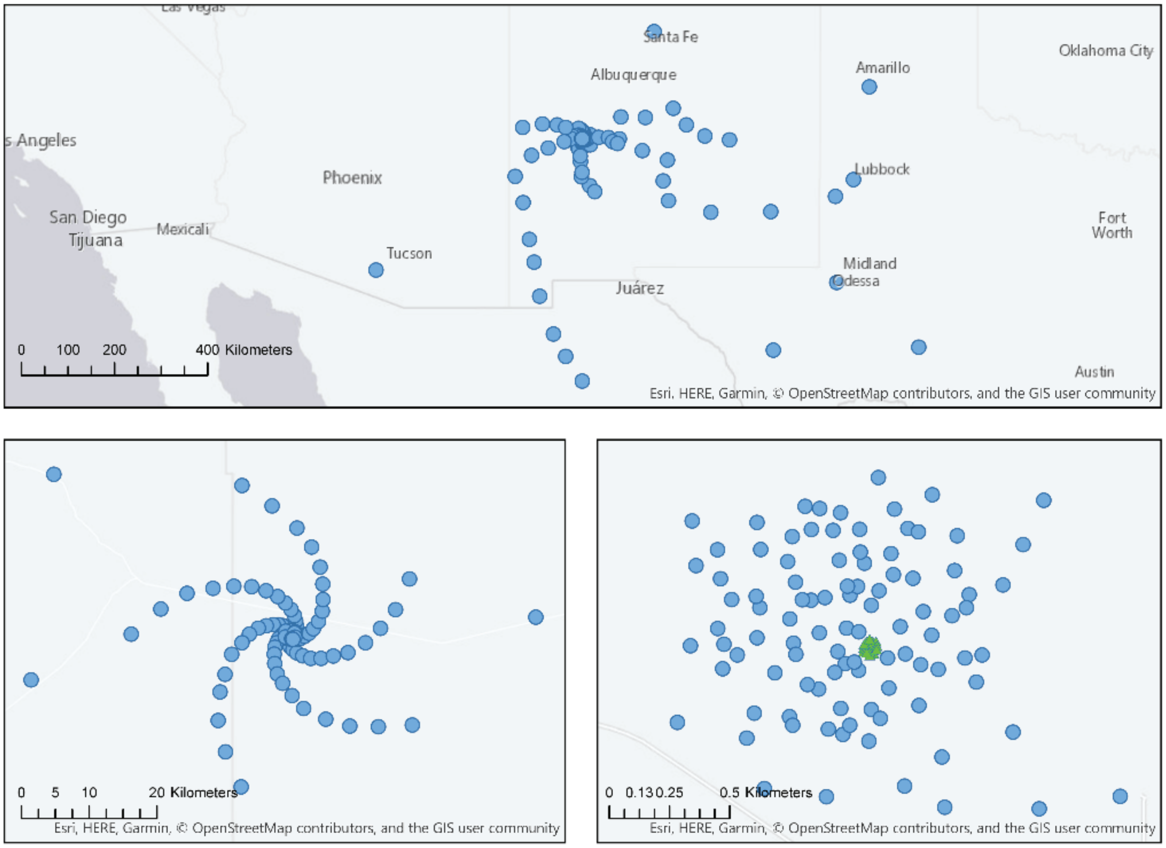

Figure 12 - Top: ngVLA Main Array Configuration Rev. B (Spiral-214). The antenna positions are still notional, but are representative for performance quantification and cost estimation. Bottom left: Zoom view of the Plains of San Agustin. Bottom right: Zoom view of the compact core. SBA antennas are shown in green.

The array configuration is practical, accounting for logistical limitations such as topography and utility availability. Investigations are underway to improve the imaging sensitivity and fidelity while accounting for additional limitations such as local RFI sources and land management/availability.

The configuration will be a primary area for investigation in the coming years. Investigations into different Briggs weighting schemes for specific science applications have been performed [RD10], and the current configuration provides a reasonable compromise and baseline for further iteration.

The design has been extended from the main interferometric array to include a long baseline array, a short spacing array, and total power dishes. This is necessary after a review of the key science goals, as these are dependent on the recovery of both small-scale structure requiring continental-scale baselines (KSG5) and large-scale structure that approaches the size of the antenna primary beam (KSG3).

An auxiliary short baseline array (SBA) of 19 reflector antennas of 6m aperture will be sensitive to a portion of the larger angular scales undetected by the main array. The SBA will provide antenna spacings from 11 m to 60 m, providing comparable surface brightness sensitivity to the main array, in equal observing time, when the main array is *(u, v)*-tapered to the natural resolution of the SBA. This allows for commensal observing, and more importantly, full cross-correlation and cross-calibration of the SBA and main array. The array distribution is semi-randomized to improve the point spread function [RD16]. The SBA will be combined with four 18m (main-array) antennas used in total power (TP) mode to completely fill the central hole in the *(u, v)* plane left by the 6m dishes. It is a design goal to share the mount design of the 18m interferometric array antennas and the TP antennas, but this will require further study.

The long baseline array (Figure 13) consists of 30 18-meter antennas at ten sites. The LBA provides continental scale (B_{MAX} = 8860 km) baselines while also providing scales from 100 m to 1000 km within the subarray. This will enable the LBA to function effectively as a stand-alone array or as an integrated part of the main array.

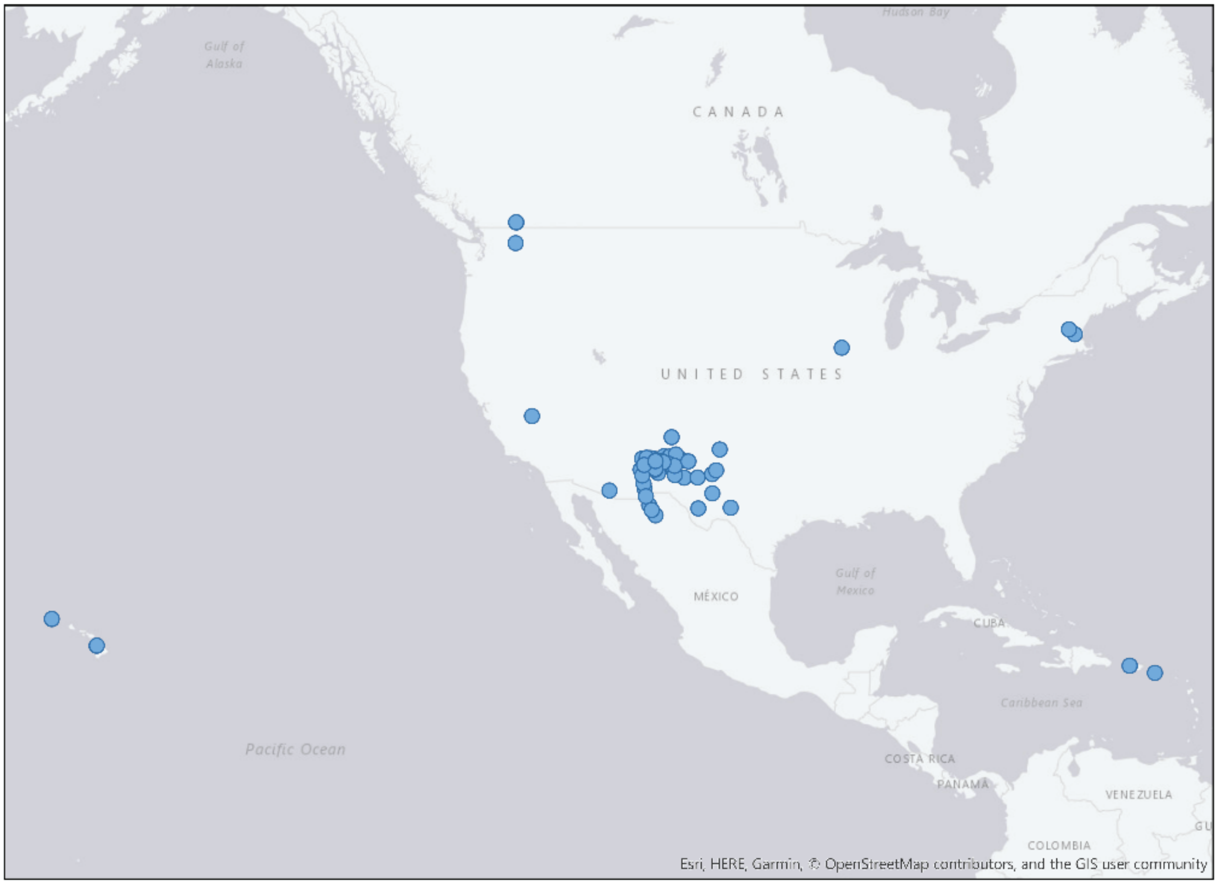

Figure 13 - View of Main Array and Long Baseline Array stations. Multiple antennas are located at each LBA site.

The notional sites of the LBA are summarized in Table 5. The ngVLA array configuration elements are summarized in Table 6.

Antenna Quantity	Location	Possible Site
3	Arecibo, Puerto Rico	Arecibo Observatory
3	St. Croix, US Virgin Islands	VLBA Site
3	Kauai, HI	Kokee Park Geophysical Observatory
3	Hawaii, HI	New Site
2	Hancock, NH	VLBA Site
3	Westford, MA	Haystack Observatory
2	Brewster, WA	VLBA Site
3	Penticton, BC, Canada	Dominion Radio Astrophysical Observatory
4	North Liberty, IA	VLBA Site
4	Owens Valley, CA	Owens Valley Radio Observatory

Table 5 - Possible antenna sites and cluster configurations of the ngVLA Long Baseline Array.

Array Element	Aperture Diameter	Quantity	B_{MIN}	B_{MAX}	F_{MIN}	F_{MAX}
Long Baseline Array	18m	30	100 m	8860 km	1.2 GHz	116 GHz[1]
Main Array	18m	214	30 m	1005 km	1.2 GHz	116 GHz[1]
Short Baseline Array	6m	19	11 m	56 m	1.2 GHz	116 GHz
Total Power/Single Dish[2]	18m	4	-	-	1.2 GHz	116 GHz

Table 6 - Elements within the ngVLA configuration.

7.2 *Array Calibration*

The current array calibration strategy can be found in [AD15], Preliminary Calibration Strategy and Requirements, 020.22.00.00.00-0001-REQ.

Supporting analysis leading up to this strategy can be found in documents [RD13, 14, 23–25]:

- Fast Switching Calibration at the ngVLA Site, ngVLA Memo No. 1
- Calibration Strategies for the ngVLA, ngVLA Memo No. 2
- The Concept of a Reference Array for the ngVLA, ngVLA Memo No. 4
- Considerations for a Water Vapor Radiometer System, ngVLA Memo No. 10
- Polarization Calibration with Linearly Polarized Feeds, ngVLA Memo No. 45

The ngVLA calibration strategy is being developed early in the design so that it may guide the design of the hardware, software, and computing elements. The science requirement to deliver high-level Science Ready Data Products (SRDP) can only be supported with robust and automated system and atmospheric calibration. The size and complexity of the calibration and imaging pipeline requires that the system design be responsive to its needs, and it should drive the design where possible.

A secondary concern is the efficiency of the calibration process. Algorithms used must be suitable for parallel processing, antennas must not require much individual attention, and minimal human intervention should be required. The calibration overheads applied will vary with the science requirements of a given observation, and less rigorous (and computationally or time efficient) calibration approaches will be applied when possible. In general, a set of normal calibration strategies will be applicable to the automatically generated SRDPs, with more advanced strategies reserved for cases where the greatest possible accuracy is required.

The Operations Concept [AD08] calls for guaranteed time on source to each observer, with calibration overheads being the responsibility of the facility. This enables reuse of calibration observations for adjacent observations when their requirements are sufficiently similar, further improving observation efficiency. The general calibration strategies under consideration for SRDP production with the reference design are summarized below.

Fast Atmospheric Phase Calibration: Rapid atmospheric phase fluctuations will be mitigated by a combination of relative water vapor radiometry (WVR) and antenna switching cycles to astronomical phase calibrators. The switching cycle time will depend on empirical validation of the strategy, but is expected to be necessary on one to ten minute scales. The antenna is designed to both house the WVR and enable fast switching cycles. The later calls for moving 4° on sky and to settle within the pointing specification within 10 seconds of time for elevation angles <70° [AD17].

[1] May not extend to 116 GHz at all sites. Sites below 1000 m elevation to operate up to 50 GHz.
[2] Included in 214-element main array total.

Slow Atmospheric & Electronic Phase Calibration: Slow atmospheric and electronic phase calibration will be achieved by traditional approaches, with astronomical phase calibrator observations bracketing all observations. Several astronomical calibrators may be used to map the slow varying terms, including ionospheric fluctuations.

Amplitude Calibration: An extensive grid of sources will be required for phase and amplitude calibration. A list of known astronomical amplitude calibrators will be used to correct for system gain fluctuations within and between observations taken over an extended period of time. The large range of baselines present on the ngVLA means that it cannot be assumed that the source is unresolved at all scales, and the calibrators themselves must be imaged before use in the calibration process. The calibration pipeline will maintain a history of recent solutions to enable look-up of prior values.

Bandpass Calibration: At a minimum, the system would first correct for digital effects, given the predictable bandpass ripple from FIR filters. The number of setups in the analog portions of the system will be limited, so typical calibration can correct for analog bandpass effects based on historical lookup tables that are updated as the configuration of the system changes (when an antenna is serviced). When required, bandpass calibration observations can also calibrate the sideband rejection of the quadrature mixers.

Polarization Calibration: The use of linear feeds will require polarization calibration for most observations. Feeds may be placed at different (but known) position angles in the various antennas, so a single observation of a point source can solve simultaneously for the polarization leakage terms and the source polarization. Calibration for polarization as a function of position within the antenna beam will be assumed to be time invariant and corrected based on look-up tables.

Relative Flux Calibration: This calibration is used to tie together observations of a source taken over an extended period. The system will model atmospheric opacity based on barometric pressure and temperature monitored at the array core and each outlying station. A temperature stabilized noise diode will provide a flux reference, and when combined with corrections for modeled atmospheric opacity, a constant ratio in power from the switched noise calibrator and the source is assumed. Alternatively, an astronomical flux calibrator may be used.

7.3 Antennas

The requirements and supporting reference design of the antennas are described in the following documents [AD17–21]:

- ngVLA Antenna: Preliminary Technical Specifications, 020.25.00.00.00-0001-SPE
- ngVLA Antenna: Optical Reference Design, 020.25.01.00.00-0001-REP
- ngVLA Antenna: Reference Design, 101-0000-001-PDD-001
- ngVLA Short Baseline Array Antenna: Preliminary Technical Specifications, 020.47.05.00.00-0001-SPE
- ngVLA Short Baseline Array Antenna: Reference Design, 102-0000-001-CDD-001

Supporting analysis leading up to this design can be found in the following documents [RD16, 26–28,48,49]:

- ngVLA Technical Study Offset Gregorian Antenna, ngVLA Memo No. 26
- Exploration of Suitable Mounts for a 15m Offset Antenna, ngVLA Memo No. 25
- Various Suitable Mounts for an 18m Antenna, ngVLA Memo No. 27
- The ngVLA Short Baseline Array, ngVLA Memo No. 43
- System-level Cost Comparison of Offset and Symmetric Optics, ngVLA Antenna Memo No. 1
- System-level Evaluation of Aperture Size, ngVLA Antenna Memo No. 2

As described in Section 7.1, the reference design includes an 18-meter aperture antenna in the main array and long baseline array, and a 6-meter aperture antenna in the short baseline array.

The antenna concept strikes a balance between competing science and the programmatic targets for lifecycle cost. Sensitivity goals will be met by the total effective collecting area of the array. The reference design includes 244 antennas of 18m aperture (MA and LBA) and 19 antennas of 6m aperture (SBA), both using an offset Gregorian optical design [AD18].

The optimization for operations and construction cost suggests that a smaller number of larger apertures (~20–22m) is preferable to larger numbers of small apertures. Survey speed requirements push the opposite direction, and a compromise value of 18m diameter is adopted for the reference design [RD49].

The inclusion of frequencies down to 1.2 GHz when combined with the operational cost targets significantly constrain the optical configuration. The use of feeds with wide illumination angles decreases their size such that they can be mounted within shared cryostats. This choice constrains the secondary angle of illumination to a degree that only Gregorian optical designs are practical. However, with a science priority of high imaging dynamic range in the 10–50 GHz frequency range, an offset Gregorian is near optimal. System-level cost analysis also suggest this choice is optimal [RD48]. The unblocked aperture will minimize scattering, spillover and sidelobe pickup. Maintenance requirements favor antenna optical configurations where the feed support arm is on the "low side" of the reflector.

The design aims for Ruze performance to 116 GHz, with a surface accuracy of 160 μm rms (λ/16 @116 GHz) for the primary and subreflector combined under precision environmental conditions. The antenna optics are optimized for performance above 5 GHz with some degradation in performance accepted at the lowest frequencies due to diffraction, in exchange for more stiffness in the feed arm to improve pointing performance.

Since the ngVLA is envisioned as a general purpose, proposal-driven, pointed instrument (rather than a dedicated survey telescope), the optics will be shaped to optimize the illumination pattern of single pixel feeds, increasing antenna gain while minimizing spillover.

High pointing accuracy will also be necessary to provide the required system imaging dynamic range. With an unblocked aperture, variations in the antenna gain pattern are expected to be dominated by pointing errors. Preliminary requirements are for absolute pointing accuracy of 18 arc-seconds rms, with referenced pointing of 3 arc-seconds rms, during the most favorable environmental conditions [AD17].

The mechanical and servo design is a typical altitude-azimuth design. Initial studies suggest pedestal designs are expected to have lower lifecycle cost while meeting pointing specifications. The antenna mechanical and servo design will need to be optimized for rapid acceleration and a fast settling time, in order to manage the switching overhead associated with short slews.

The project has pursued a costed conceptual design to specifications for the 18-meter antenna with General Dynamics Mission Systems (GDMS). A parallel study (to the same requirements) into a composite design concept with the National Research Council of Canada (NRC) was also commissioned. Two designs were pursued given the prominence of the antenna in the total construction budget. Both estimates are included as basis for the system construction cost estimate, while the NRC design has been used to define subsystem interfaces and is provided for design context.

The short baseline array 6m aperture design shares the majority of its specifications with the main antenna, including the interfaces with the front end equipment such that feeds, receivers and other antenna electronics are interchangeable between the two arrays. The design employs a composite reflector and backup structure on a steel pedestal mount. The mount includes space to house the digital electronics, power supplies and servo system (Figure 14).

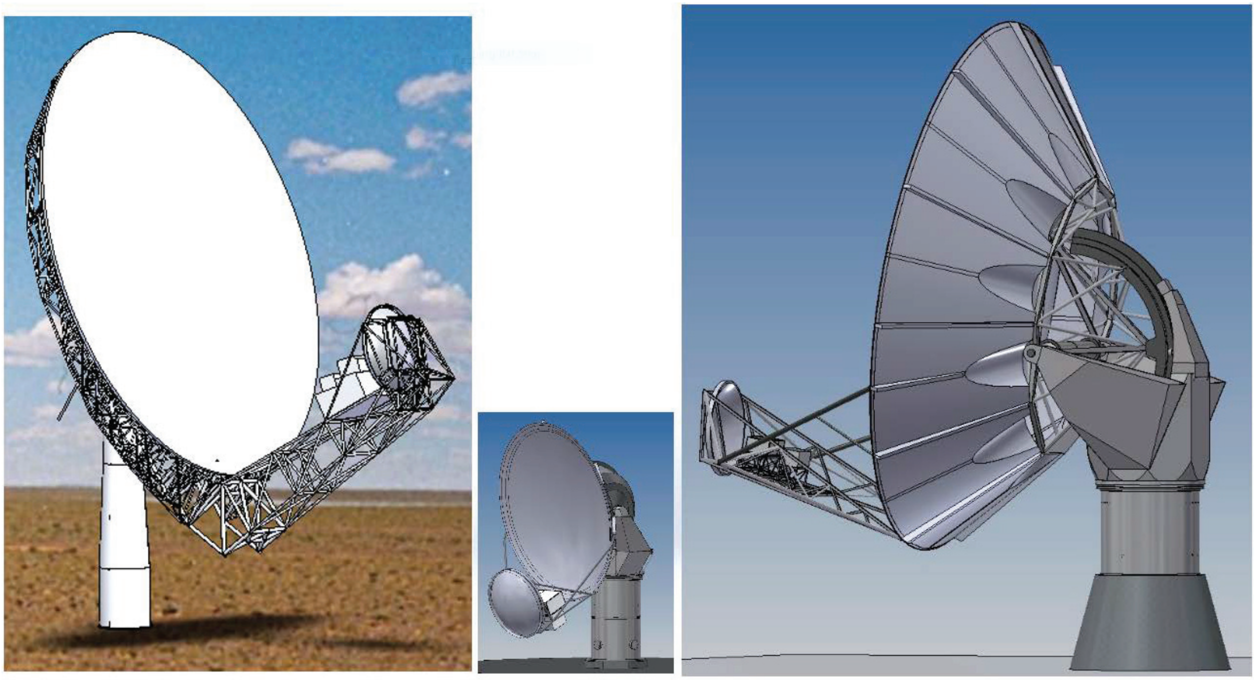

Figure 14 - Left: ngVLA 18-meter antenna design concept prepared by GDMS. Right: 18m antenna concept prepared by NRC. Center: 6m short spacing array antenna concept prepared by NRC.

7.4 Antenna Electronics

7.4.1 Front End

The Front End system requirements and supporting reference design are described in the following documents [AD22–23]:

- ngVLA Front End: Preliminary Technical Specifications, 020.30.03.01.00-0001-REQ
- ngVLA Front End: Reference Design, 020.30.03.01.00-0003-DSN

The ngVLA will provide continuous frequency coverage from 1.2–50.5 GHz and 70–116 GHz in multiple bands. Receivers will be cryogenically cooled, with the receiver cryostats designed to integrate multiple receiver bands to the extent possible. Limiting the number of cryostats will reduce both maintenance and electrical power costs.

The total number of bands required strongly depends on their fractional bandwidths: maximizing bandwidths will reduce the number of cryostats, with a possible penalty in sensitivity. Feeds for all receiver bands are cooled and fully contained within the cryostat(s).

The reference design receiver configuration consists of the low-frequency receiver (1.2–3.5 GHz) in one cryostat, and five receivers spanning from 3.5 to 116 GHz in a second cryostat. Bands 1 and 2 employ wideband feed horns and LNAs, each covering L+S bands and C+X bands (Table 7). Quad-ridged feed horns (QRFHs) are used, having dual coaxial outputs.

Due to improved optical performance (improving illumination efficiency and reducing T_{SPILL}), cooled feeds, and the simplified RF design sensing linear polarization, the T_{SYS} is lower than current VLA L, S bands and comparable for C and X bands (Figure 15). Overall aperture efficiency and T_{SYS} are slightly degraded from optimal due to the wider bandwidths spanned but permit a compact package that can be affordably constructed and operated.

Band #	f_L GHz	f_M GHz	f_H GHz	BW GHZ	Aperture Eff., η_A			Spillover, K			T_{RX}, K			T_{SYS}, K		
					@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H
1	1.2	2.4	3.5	2.3	0.80	0.79	0.74	12.8	10.1	4.0	9.9	10.3	13.8	27.1	24.9	22.4
2	3.5	7.9	12.3	8.8	0.80	0.78	0.76	12.8	7.0	3.9	13.4	15.4	14.4	30.8	27.1	23.6
3	12.3	16.4	20.5	8.2	0.84	0.87	0.86	4.1	4.1	4.1	13.9	16.9	18.6	23.3	27.3	36.3
4	20.5	27.3	34	13.5	0.83	0.86	0.83	4.1	4.1	4.1	15.4	16.2	19.5	33.1	32.4	36.0
5	30.5	40.5	50.5	20	0.81	0.82	0.78	4.1	4.1	4.1	19.1	20.4	26.5	34.0	41.0	101
6	70	903	116	46	0.68	0.61	0.48	4.1	4.1	4.1	50.6	49.0	72.6	123	68	189

(*) Assumes 1 mm PWV for band 6, 6 mm PWV for others; 45 deg elev. on sky for all.

Table 7 - Key parameters of the baseline receiver configuration.

The four high-frequency bands (12.3–116 GHz) employ waveguide-bandwidth (~1.67:1) axially corrugated feed horns (ACFHs) and LNAs for optimum aperture efficiency and noise performance. The axially corrugated feed horns with circular waveguide output ensure uniform illumination over frequency, with minimum spillover and resistive loss.

Figure 15 and Figure 16 show system temperature and sensitivity projections for all six bands over the entire 263-antenna array.

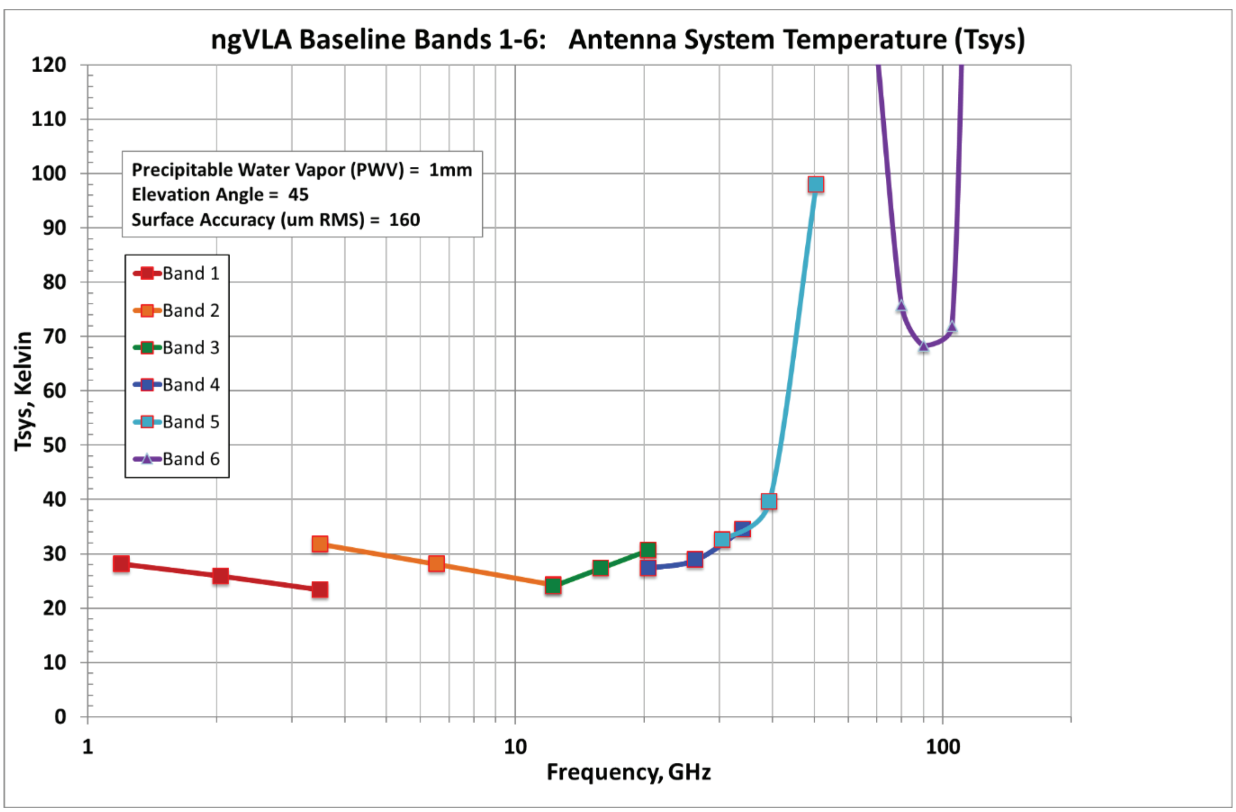

Figure 15 - System temperature for the ngVLA 6-band receiver configuration.

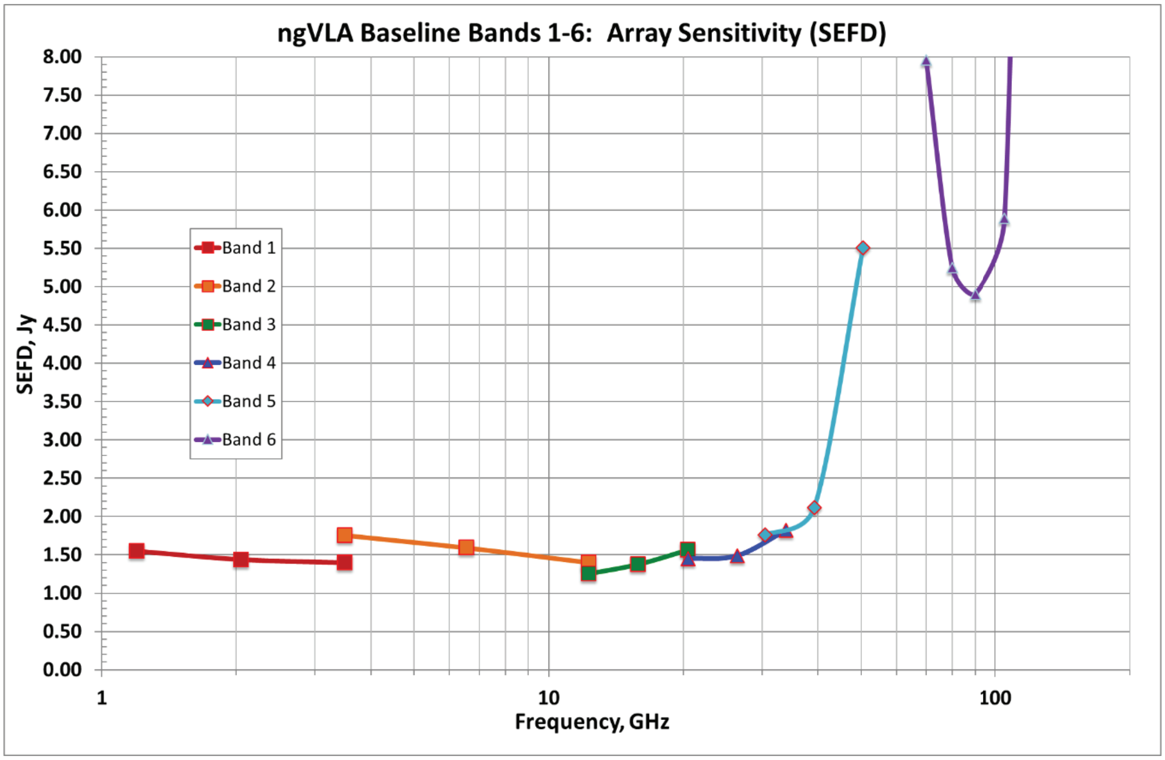

Figure 16 - System SEFD for the full 263 element array (244 @ 18 m, 19 @ 6 m).

7.4.2 Cryogenic System

The requirements and supporting reference design of the cryogenic system are described in [AD24–25]:

- ngVLA Cryogenic System: Preliminary Technical Specifications, 020.30.10.00.00-0001-REQ
- ngVLA Cryogenic System: Reference Design, 020.30.10.00.00-0002-DSN

Supporting analysis leading up to this design can be found in [RD29], Advanced Cryocoolers for Next Generation VLA, ngVLA Memo No. 24.

The performance requirements for the cryogenics are driven by the Front End concept [AD23] and by maintenance and power requirements established for the project [AD02, AD03]. It has been emphasized that for the ngVLA project to be successful, the annual operation cost shall not exceed the current VLA and VLBA budget by more than a factor of three. This is quite challenging considering that the project is aiming for nine times the number of antennas.

To meet the programmatic requirements, the number of cryostats per antenna has been reduced to two (housing six receivers total), reducing the preventative maintenance effort, corrective maintenance effort, and power consumption per antenna (see Figure 17). Various cryogenic cycles and refrigerator concepts were explored and a two-stage Gifford-McMahon design was selected for the reference design. While other cooling cycles (such as the Sterling cycle) look attractive, the GM system was selected based on a preliminary thermal analysis of the loads for each Dewar [RD35]. Projected thermal lift required on the first and second stages for each Dewar is comparable to that of the well-characterized CTI350 GM Refrigerator, and too large for a Sterling cycle system that expels waste heat in the Dewar vicinity.

The reference design employs two Trillium 350CS GM refrigerators and a single Sumitomo FA-40 compressor. Both the refrigerators and compressor are equipped with variable frequency drives (VFDs) for adjustable cooling capacity. Having the capability to adjust the cooling power allows us to match supply and demand in order to minimize the power consumption and lengthen the preventive maintenance cycle by reducing the wear on the refrigerator seals, which are proportional to the operating speed.

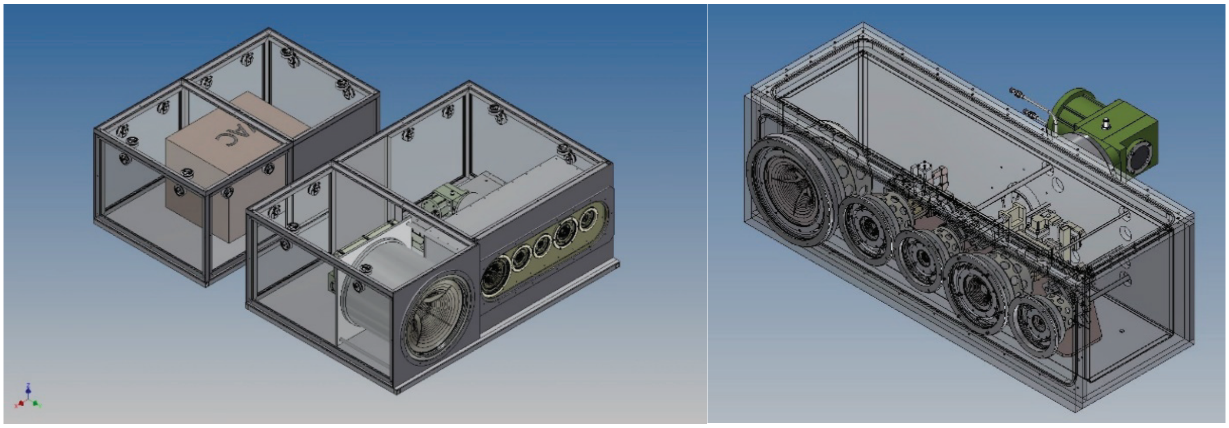

Figure 17 - Left: Front End component packaging at the secondary antenna focus. Band selection and focus are achieved with a dual-axis translation stage. Integrated receiver packages are located in close proximity to cryostats, minimizing the analog signal path length (Section 7.4.3). Right: Bands 2-6 are housed within a single cryostat.

The cryogenic system design also includes the vacuum roughing pumps required to cool the refrigerators from room temperature. Due to the feedback loops required to effectively control the VFD system, the design is integrated with both the Front End and the Monitor and Control system. The major elements of the cryogenic system and their interfaces are summarized in Figure 18.

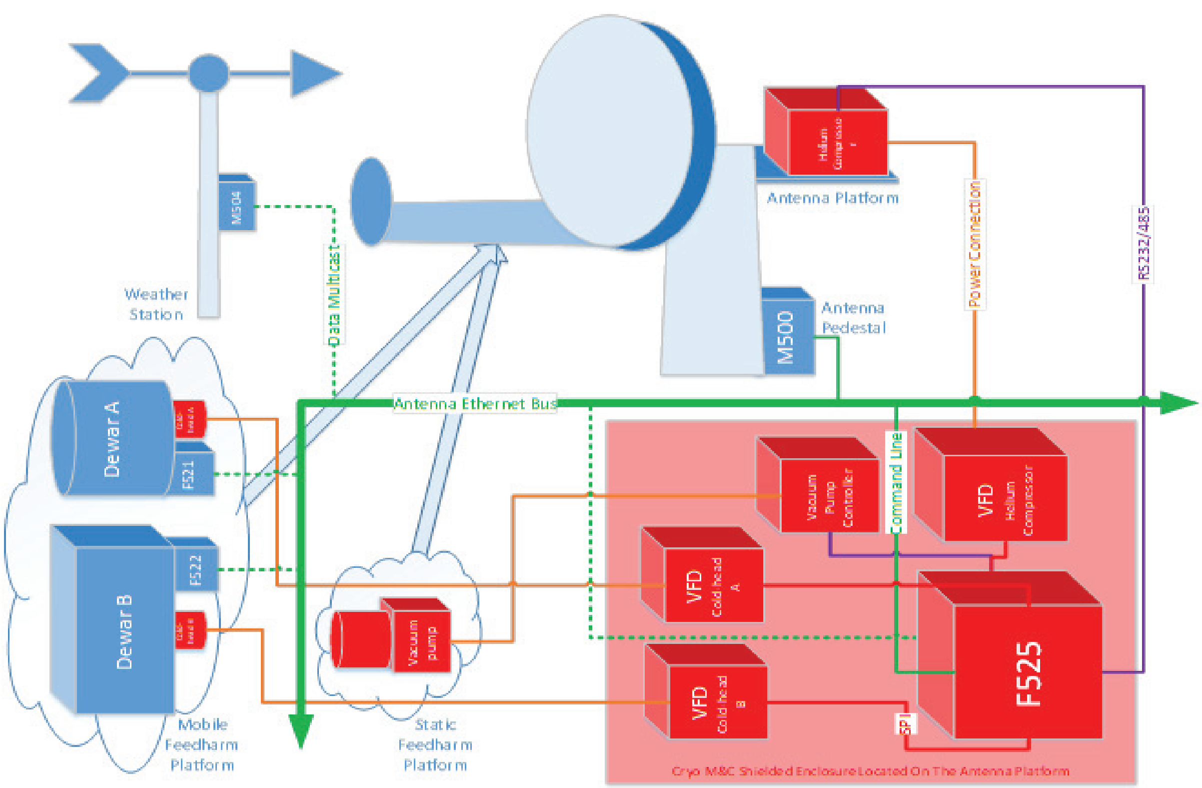

Figure 18 - Cryogenic system interfaces within the antenna. Cryogenic components are shown in red, with interfacing components in blue [AD25].

7.4.3 Integrated Down Converters, Digitizers, and Serializers

The requirements and supporting reference design of the integrated downconverter digitizer system are described in the following documents [AD26–27]:

- Integrated Receiver Digitizer: Preliminary Technical Specifications, 020.30.15.00.00-0001-REQ
- Integrated Receiver Digitizer: Reference Design, 020.30.15.00.00-0002-DSN

Supporting analysis leading up to this design can be found in [RD36], An Integrated Receiver Concept for the ngVLA, ngVLA Memo No. 29.

The role of the Integrated Receiver and Digitizer (IRD) packages [AD27] is to further amplify signals provided by the cryogenic front end, downconvert them where necessary, digitize them, and deliver the resultant data streams by optical fiber to a moderately remote collection point from the focal plane (but possibly still inside the antenna base). Here they can be time-stamped and launched onto a more conventional network for transmission back to the array correlator and central processing facility. Hooks are needed to provide for synchronization of local oscillators (LOs) and sample clocks, power leveling, command and control, health and performance monitoring, and diagnostics for troubleshooting in the event of component failure.

This subsystem consists of direct-sampled and sideband-separating modules for all telescope bands, which include warm amplification, filtering, power leveling, analog-to-digital conversion, and fiber-optic transmission, as well as external splitters and combiners as needed to feed them from the cryogenic signal paths. Cryogenic systems and thermal transitions, as well as front-end cabling, waveguide runs, and fiber-optic signal paths outside the IRD modules themselves are outside the scope of this work package, though interfaces must be considered.

The frequency plan for the reference design is shown in Figure 19. [AD27]. The IRD modules are located adjacent to the cryostats on the antenna feed arm, as shown in Figure 17.

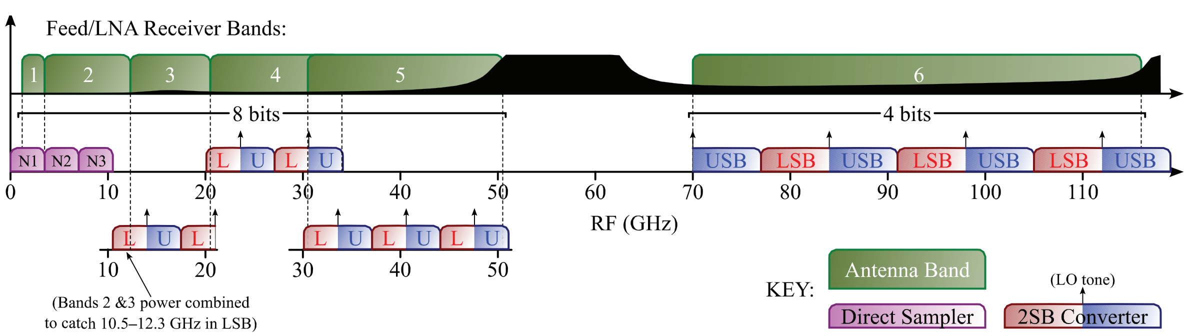

Figure 19 - Present sampling concept employing integrated receiver technology for both direct and dual sideband converter/samplers. Nyquist zones 1 through 3 are direct sampled single-sideband at 8 bits. From 10 GHz to 50 GHz the system uses single-stage down conversion to baseband and IQ sampling at 8 bits; 4-bit quantization is used above 70 GHz due to the reduced risk of persistent RFI at these frequencies.

The design of the ngVLA IRD modules evolved from an internal research program (the Integrated Receiver Development program), which has been perfecting the techniques used in their construction for more than a decade. The original program aimed to leverage the advantages of modern electronic integration and digital signal processing, to digitize as closely to the antenna feed-point as possible without comprising the ultimate performance, and to re-optimize legacy receiver architectures in light of these new techniques and in anticipation of future telescope facilities such as the ngVLA.

Integration and digital signal processing (DSP) are deemed complementary in this program, in that the latter provides for greater signal fidelity and precision in concert with detailed calibrations compared to purely analog techniques, while the former guarantees the long-term stability and uniformity of those calibrations. This resulted also in compact, low-power, field-replaceable receiver units which were a perfect fit for ngVLA's maintenance and operability requirements.

7.4.4 Digital Back End (DBE) and Data Transmission System Interface

The requirements and supporting reference design of the digital back end and data transmission system are described in the following documents [AD28–29]:

- DBE & DTS: Preliminary Technical Specifications, 020.30.25.00.00-0001-REQ
- DBE & DTS: Reference Design, 020.30.25.00.00-0002-DSN

The ngVLA digital back end (DBE) is responsible for two critical functions. First, it must ingest the unformatted data stream from the integrated receiver digitizer and align it with a known timing reference. Second, it must perform bandwidth selection and provide data at the correct bitrate and format for transmission to the correlator/beam-former. The first task will be performed in a custom sampler interface block, and the second by down-converting the sampled data, requantizing the incoming data stream, and reframing it for further network transmission. Internal block diagrams of the DBE can be found in [AD28].

The functionality required for bandwidth selection overlaps with a number of single-dish corrections required at the input to the central signal processor (CSP) and results in some duplication of capability. In future iterations of the design, the input of the correlator and the DBE/DTS system may share common designs to reduce redundant capabilities and cost. However, the design presented here ensures that all required functionality is inherent in the design while using well-developed cost analogs to substantiate the system cost estimate.

The data transmissions system interface relies on commercial 100 GbE interfaces, providing up to 320 Gbps per antenna to the correlator over multiple data streams. The data transmission system is further described in Section 7.6.

7.4.5 DC Power Supply System

The requirements and supporting reference design of the DC power supply system are described in the following documents [AD30–31]:

- DC Power Supply System: Preliminary Technical Specifications, 020.30.50.00.00-0001-REQ
- DC Power Supply System: Reference Design, 020.30.50.00.00-0002-DSN

The DC power supply system provides central conversion from AC to DC, with battery backup, and common service voltages for local regulation at each module. This architecture enables centralized control and monitoring of the power supply system for sequential turn on/off and other management features that support the operations and maintenance concept.

The DC Power Supply System (specifically, the P500) receives 208V three-phase AC @17A and converts it to –48V DC. Lithium batteries will be used as a backup source for the 48V in the event the AC supply is lost. A battery charger will be used to charge the batteries when AC is available.

The batteries and battery charger will be located in the pedestal area of each antenna. The 48V is then fed into three power supply modules (P501, P502, and P503) that convert the 48V to +32.5V, ±17.5V, +15.5V, ±7.5V, ±5.5V, and +3.8V depending on the module.

Each power supply module has internal monitor and control (M&C) and temperature sensors so they can be shut down for over-current or over-temperature conditions. The P500 also directly powers the fire alarm, Ethernet switch, Digital Back End (DBE), and Data Transmission System (DTS).

The P501 power supply module powers the Front End (FE) Low Noise Amplifier (LNA) noise diodes and bias voltages for Bands 1–6. The P501 also powers the Local Oscillator (LO) Reference Sample Clock Generator and LO A–K Generator modules and the Integrated Downconverter/Digitizers (IRD) for Bands 1–6. The P501 will be located next to the IRDs in the Front End Enclosure.

The P502 power supply module powers the LO Clock Receiver module, two Band 4 IRDs, the Water Vapor Radiometer (WVR) antenna amplifier, and cooling system. The P502 will be located in the WVR Enclosure. The P503 is used to power the LO Reference Receiver Generator and Distribution module and the four Monitor Control Modules located in the pedestal area of each ngVLA antenna. A block diagram of these connections is shown in Figure 20.

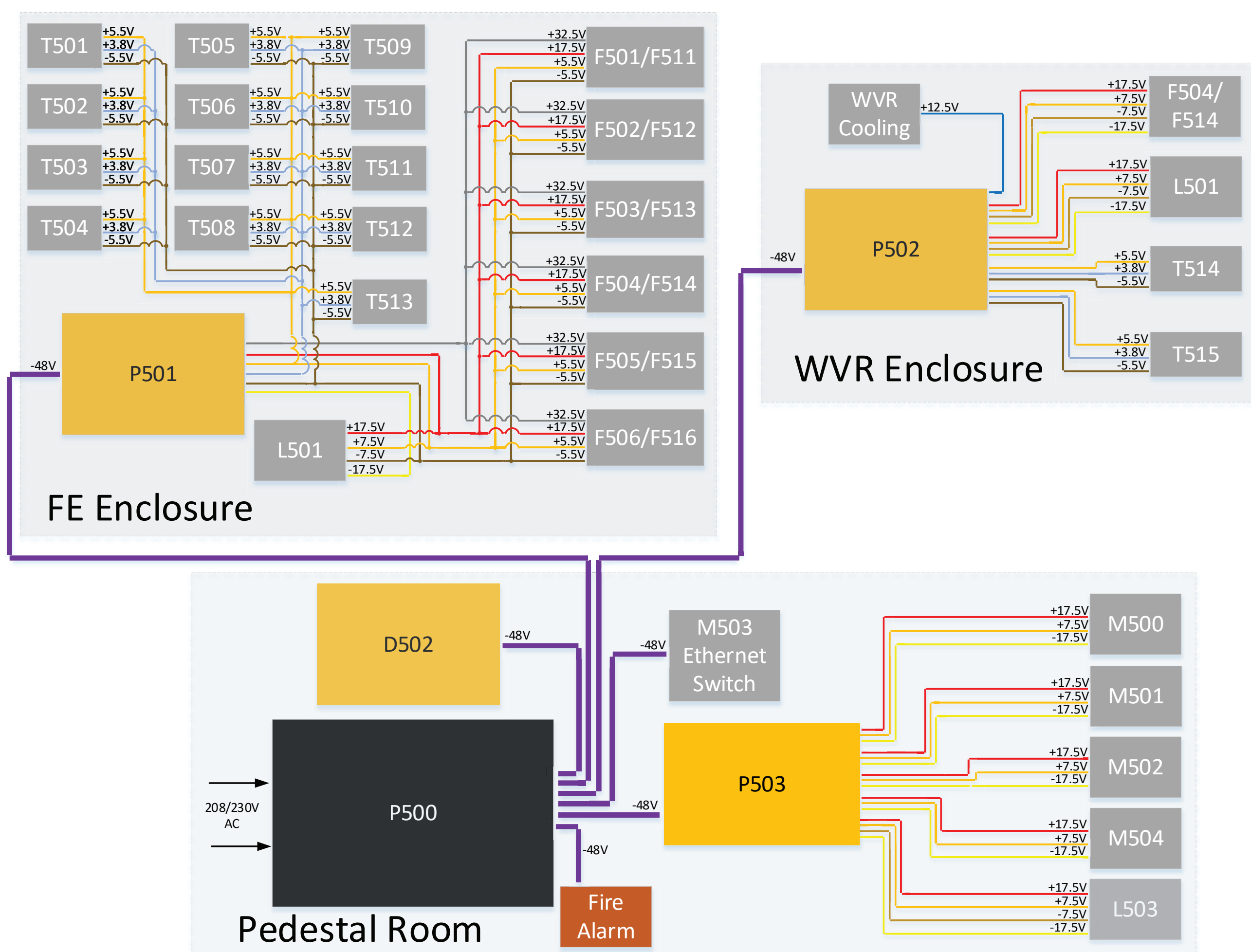

Figure 20 - Block diagram of the DC power supply system.

7.4.6 Bins, Modules and Racks

The requirements and supporting reference design for the antenna electronics packaging (Bins, Modules & Racks) are described in the following documents [AD32–33]:

- Bins, Modules, and Racks: Preliminary Technical Specifications, 020.30.55.00.00-0001-REQ
- Bins, Modules, and Racks: Reference Design, 020.30.55.00.00-0002-DSN

The Bins, Modules, and Racks subsystem consists of individual modules (LRUs) housed in several bins all inside an EIA standard electronics rack located in the pedestal room of the antenna. The work package also includes a number of modules and bins in locations other than the electronics rack and other than the pedestal room. Its key function is to house the LRUs that make up the antenna electronics in standardized housing, and make assembly and maintenance of the antenna electronics as simple as possible while providing adequate RFI shielding.

The proposed modules for this subsystem are the Advanced RFI Containment System (ARCS) modules recently developed by NRAO. Three primary ARCS module types are designated as series 100, 200, and 300 (Figure 21 shows the 100 and 300 series). The 100 series modules consist of two high-tolerance machined pieces of aluminum that fit together like a clamshell leaving a cavity in the middle for electronics. The 200 series modules consist of three pieces and allow for dual internal cavities that are independently RFI shielded. The 300 series modules are also three-piece modules but with individually removable side panels that allow access to the internal electronics from either side of the module. Optional finned side panels act as a heatsink for internal electronics. All module types have double gasket seams around the edge using specialized RFI gaskets and a series of compression latches that compress the gasket and ensure that a high level of RFI shielding is achieved. All modules will have guide blocks that help guide the module into the bin as well as a front panel used to secure the module in the bin via four captive thumbscrews.

The bins provide a convenient and reliable method of organizing groups of modules near one another. The standard bin is six rack units tall by 508 mm (20") deep and is designed for a standard EIA-310 (19") rack, but bins can be configured for any rack height, width, or depth.

The racks will be very similar to the ALMA Back End racks, as they have proved to be high quality RFI-shielded racks. The racks provide a high level of RFI shielding using a combination of a welded steel external shell, RFI gaskets, and an RFI absorbing foam. The rack has multiple I/O panel location options to run any power and signals in or out of the rack, and honeycomb filters on the top and bottom to allow air flow to pass through the rack for cooling without impacting the RFI shielding level.

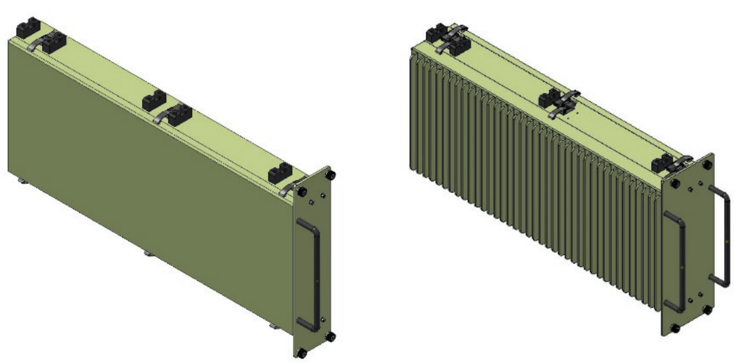

Figure 21 - Series 100 (left) and 300 (right, with heatsink) ARCS Module housings employed in the reference design.

7.4.7 Environmental Control

The requirements and supporting reference design for the environmental control system are described in the following documents [AD34–35]:

- Environmental Control: Preliminary Technical Specifications, 020.30.60.00.00-0001-REQ
- Environmental Control: Reference Design, 020.30.60.00.00-0002-DSN

The antenna electronics are located in various places around the antenna (Figure 22). Primary locations include but are not limited to the electronics rack in the pedestal room, the Front End enclosure on the feed arm, the WVR enclosure near the base of the feed arm, and the compressor platform/enclosure at the top rear of the pedestal. Environmental control of the antenna electronics consists of temperature control of all electronics in these locations as well as protection from water, dust, animals, or other environmental hazards.

The primary temperature control system consists of a cold liquid loop, possibly glycol, which runs from the compressor at the top rear of the pedestal to the WVR module and the front end enclosure. A local tubed liquid cold plate consists of an aluminum block that components may be directly mounted to cool the front end, the WVR, and components in the compressor enclosure. The pedestal room electronics rack will be forced air cooled with a separate commercial closed-loop heat exchanger and a blower (i.e. a split HVAC unit) to force cold air through the rack from bottom to top.

Protection from water, dust, animals, and other environmental hazards will be accomplished with custom sealed enclosures for the Front End, WVR, and compressor enclosure, and an EIA electronics rack in the pedestal room.

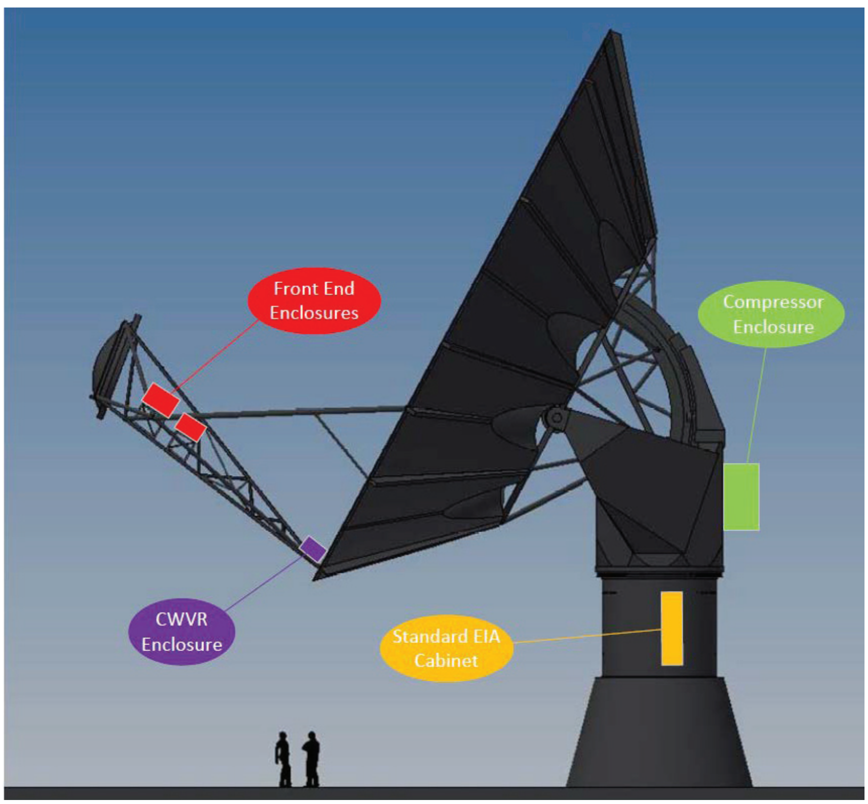

Figure 22 - Location of the thermally regulated enclosures and environmental control system hardware. The NRC 18m antenna is shown as reference.

7.5 Time and Frequency Reference Signal Generation and Distribution

The requirements and supporting reference design for the time and frequency reference generation and distribution system are described in the following documents [AD36–37]:

- LO Reference and Timing: Preliminary Technical Specifications, 020.35.00.00.00-0001-SPE
- LO Reference and Timing: Reference Design, 020.35.00.00.00-0002-DSN

In these documents, the antenna time and frequency system is treated as part of an integrated ngVLA-wide time and frequency distribution system, with [AD36–37] documenting the requirements and reference design from the generation of references to the delivery of synchronized time and frequency systems to both the correlator and antenna electronics modules.

The LO Reference and Timing work element is responsible for supplying accurate and reliable local oscillator, sampler clock, and timing references to the antenna stations and the central signal processor. The block diagram shown in Figure 23 illustrates the major functional blocks of the LO reference and timing for antennas within 300 km of the array center. The references are generated and synchronized in the central building, and a frequency reference and timing signal are provided to the central signal processor. The references are then distributed with all necessary amplification, buffering, splitting, etc., and the required signals are transmitted to each antenna.

For the reference design, the following assumptions are made:

- Central LO Reference and Timing are assumed to be in the same central building as the CSP.
- Only LO reference and timing functions are shown. The data backhaul is expected to have a similar arrangement on separate fibers in a shared bundle or duct. Power and monitor and control functions are not shown.
- Connection to each antenna station is shown as bidirectional, which indicates that a bidirectional connection is required in order to accomplish the phase synchronization and absolute timing.
- A single repeater station is shown, but additional repeater stations will be needed for signal regeneration or amplification outside the Plains of San Agustin.
- The transmission medium is assumed to be optical fiber. However, the most distant antennas in the main array and the antennas in the long baseline array will need an independent central timing reference.

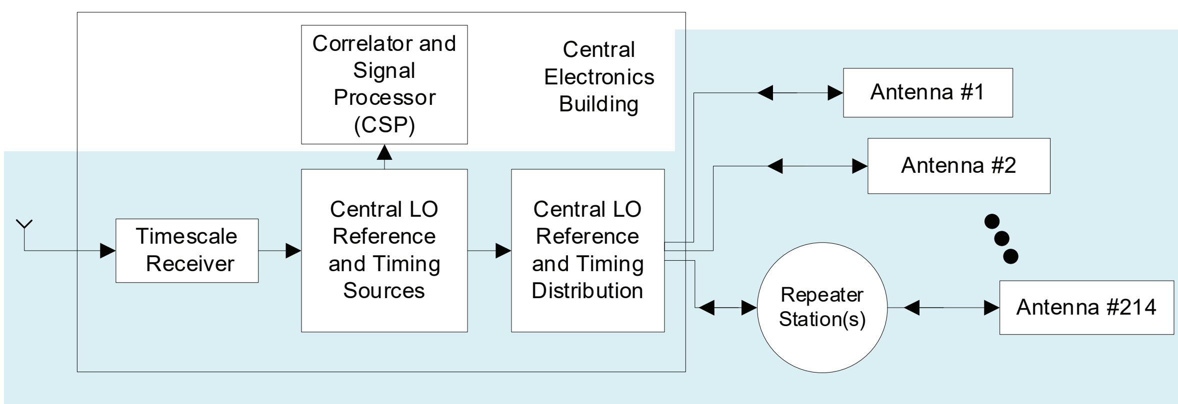

Figure 23 - Block diagram of main array LO Reference and Timing system parts (shaded in blue).

Antennas further than 300 km from the array center will follow a VLBI model with their own primary frequency and time references, using a local active hydrogen maser and GPS receiver. This approach is proven in the VLBA and reduces the risk of distributing a coherent reference over the extent of the array, and is also consistent with the DTS concept proposed in Section 7.6.

Further development in the conceptual design phase would aim to provide coherent references to all antennas in the main array, if the fiber optic infrastructure can support the frequency reference distribution requirements. The reference design calls for the distribution of a single high-frequency reference tone to each antenna, to which is added

- one PPS encoded for digital backend timing, and

- a small (antenna-dependent) frequency offset for minimization of digitizer self-interference and coherent out-of-band interference.

At each antenna the reference is also looped back to the central building where the measured round-trip phase is used to actively correct the transmission so that the LO signal to each antenna is coherent. (A new development concept is being investigated that removes this active correction, allowing incoherent LOs at each antenna with the equiphase correction applied to the front end of the correlator.)

At the antenna, LO signals are needed for each downconverter (IRD) module. These are developed by multiplication of the 7 GHz, with offset phase-locking using integer subharmonics of the 7 GHz. These offsets allow some flexibility of the LO tuning to allow optimum band coverage and to fill in the zero-IF hole associated with the digitized sidebands.

7.6 Data Transmission System

The requirements and supporting reference design for the DTS are described in the following documents [AD28–29, 54]:

- DBE & DTS: Preliminary Technical Specifications, 020.30.25.00.00-0001-REQ
- DBE & DTS: Reference Design, 020.30.25.00.00-0002-DSN
- Long Haul Fiber Workgroup Preliminary Report, 020.60.00.00.00-0002-REP

The Data Transmission System (Figure 24) provides connectivity from the antennas to the correlator. Monitor and control connectivity is also provided, but the associated data rates are immaterial compared to the digitized bandwidth of the Front End.

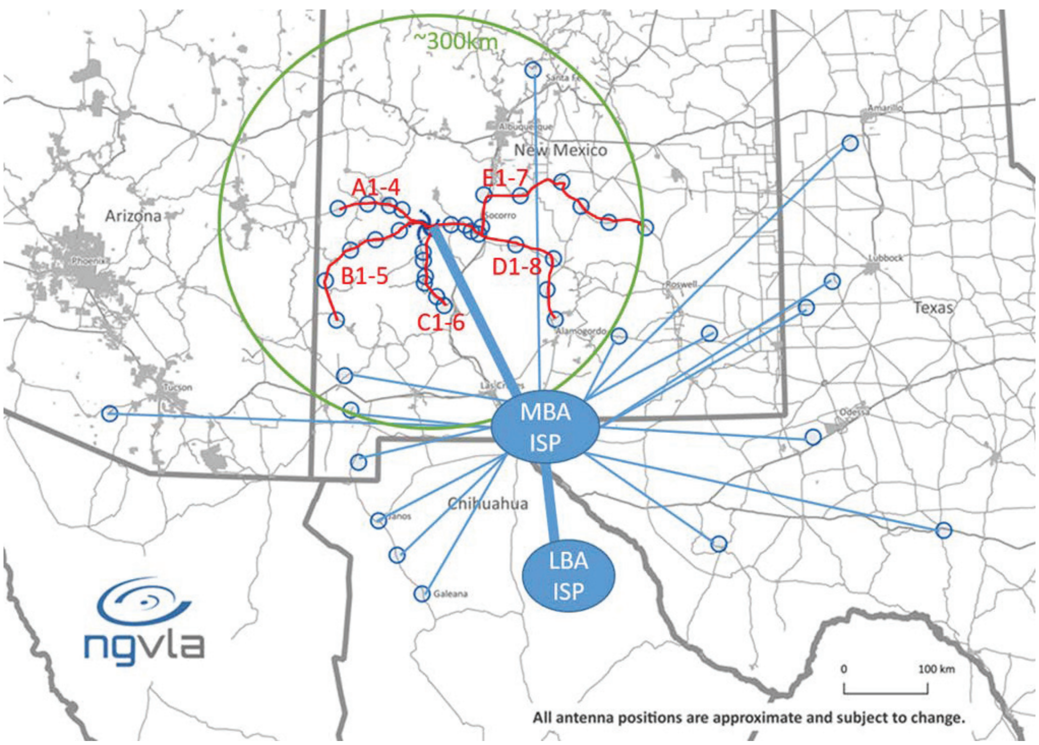

Figure 24 - Data transmission network topology. Antennas within the core and spiral arms are direct point-to-point connections over ngVLA operated fiber. Mid-baseline stations within ~300km are connected over dedicated fiber links with repeater infrastructure hosed at each antenna station. Service points are noted on five trunks (A-E). Mid-baseline stations outside the ~300 km radius, and all long-baseline stations, rely on leased bandwidth provided by network operators.

Each antenna transmits 320 Gbps to the correlator. The data transmission system relies on three topologies depending on the antenna location:

- 187 antennas are within the Plains of San Agustin and within a 40 km fiber span that can be direct point-to-point, with no intervening hardware between the DBE/DTS at the antenna and the CSP input.
- An additional 30 stations are within a 300 km radius where the project can procure or lay dark fiber and enable controlled point-to-point links with repeaters and erbium-doped fiber amplifiers (EDFAs).
- The remaining 16 mid-baseline and 30 long-baseline antennas (Figure 25) are too remote to rely on controlled links so will instead rely on shared bandwidth over commercial networks.

The extent of the array and the use of commercial packet switched networks will introduce a significant variation in latency between antennas (of order 250 ms). The correlator includes the requisite functionality to buffer the incoming data streams from each antenna and correctly sequence the packetized and formatted data for all three topologies. The required network infrastructure at the central site is comparable to what ISPs provide to small metropolitan areas and can be procured off-the-shelf today (at significant cost). Technology cycles over the project design phase are expected to make the selected DTS concept affordable for both construction and operation. Should this assumption not be realized, the bandwidth at the 46 remote antennas could be throttled at the DBE to fit within cost constraints.

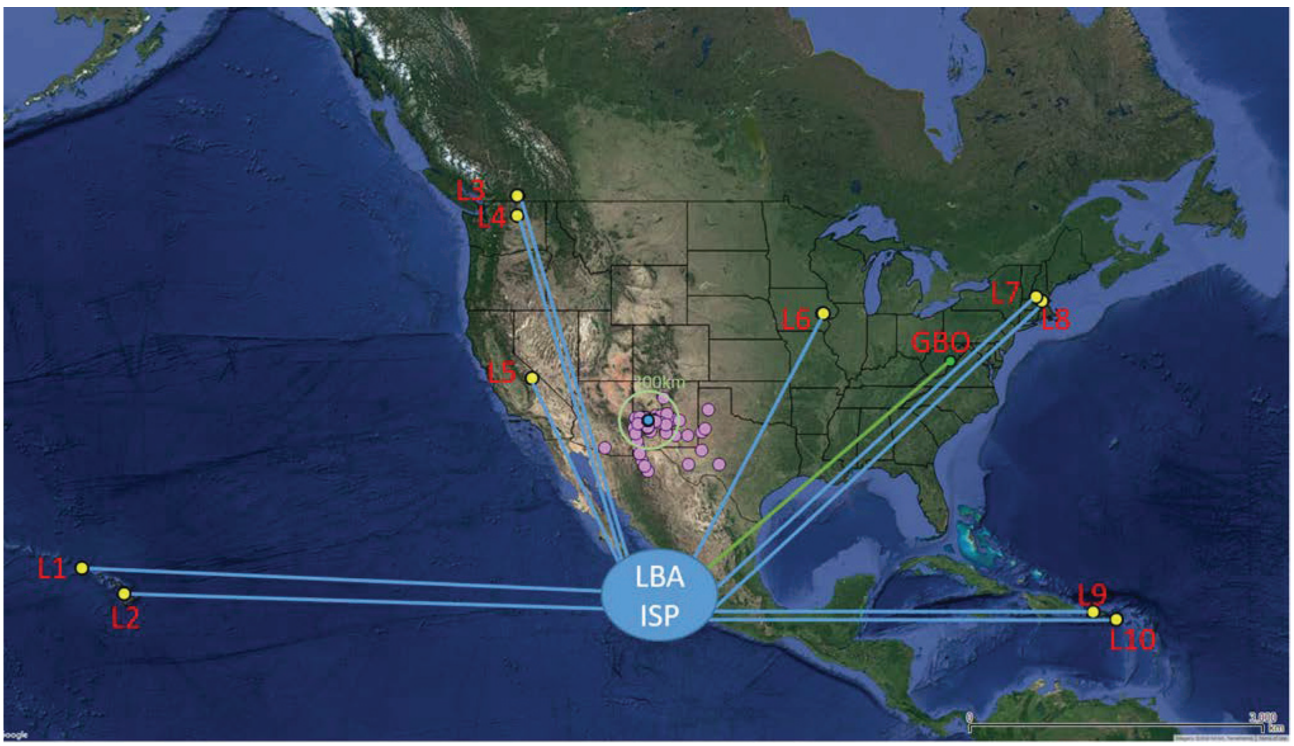

Figure 25 - ngVLA LBA ISP data links. LBA sites are shown in yellow and the GBO site is in green. The ngVLA core and main array are in blue and purple, respectively. A total of 30 antennas are included in the LBA configuration (see Section 7.1) and share links from the ten sites.

7.7 Central Signal Processor

The requirements and supporting reference design of the central signal processor are described in the following documents [AD38–39, 51]:

- Central Signal Processor: Preliminary Technical Specifications, 020.40.00.00.00-0001-SPE
- Central Signal Processor: Reference Design, 020.40.00.00.00-0002-DSN
- Trident Correlator-Beamformer Preliminary Design Specification, TR-DS-000001

The Central Signal Processor (CSP) ingests the voltage streams recorded and packetized by the antennas and transmitted via the data transmission system, and produces a number of low-level data products to be ingested by the archive. Among its many functionalities, the CSP is responsible for

- compensating the large transmission delays from the remote stations,
- tracking the delay and phase differences between antennas,
- flagging the spectral channels corrupted with RFI at a pre-correlation stage,
- selecting the spectral window of interest within the digitized and transmitted bandwidth,
- offsetting the different frequency standards used by the remote stations, and
- achieving the desired spectral resolution.

In addition to synthesis imaging, the CSP will support other capabilities required of modern telescopes to enable VLBI and time-domain science. The functional capabilities of the CSP include full-polarization auto- and cross-correlation computation, and beamforming capabilities for pulsar timing, pulsar/transient search, and VLBI recording.

The CSP data products will vary by operation mode. The most common will be raw/uncalibrated visibilities, recorded in a common data model. The CSP will include all necessary back end infrastructure to average visibilities and package them for the archive, where they will be recorded to disk in a standard format. Calibration of these data products will be carried out through asynchronous data post-processing pipelines.

The CSP will support multiple sub-arrays operating simultaneously and fully independent from each other. Two key system requirements are the degree of commensality supported within a sub-array and the desired capabilities for sub-arrays operating simultaneously. At a minimum, the CSP will be able to compute auto- and cross-correlation products within a sub-array, as well as simultaneous cross-correlation and either pulsar timing, pulsar search, or VLBI capabilities for different sub-arrays.

Enabling correlation and beamforming products simultaneously within a sub-array is also under evaluation. Such a mode would reduce beamformer calibration overheads and provide for localization/imaging concurrent with time-domain observations. The degree of commensality is expected to be a cost/complexity driver in the system and will be optimized on a best-value basis.

The CSP is split into two systems: a correlator-beamformer (CBF) and a pulsar engine. The pulsar engine is reconfigurable to support both pulsar timing and pulsar search. The ngVLA correlator-beamformer [AD51] will use an FX architecture and process an instantaneous bandwidth of up to 20 GHz per polarization.

The CBF Frequency Slice Architecture (FSA) developed by NRC Canada for the SKA Phase 1 mid-frequency telescope in South Africa is well suited to ngVLA demands and is adopted for the reference design. The project has entered into a nondisclosure agreement (NDA) with NRC to share relevant design documentation and to collaborate on the CBF design.

This frequency slice architecture will scale to the additional ngVLA apertures, bandwidth, and commensal mode requirements. Adopting this architecture could significantly reduce the non-recurring engineering costs during the design phase, while additional improvements in electrical efficiency can be expected from one additional FPGA manufacturing process improvement cycle due to ngVLA's later construction start date as compared to SKA Phase 1.

Key performance requirements for the correlator are summarized in Table 8.

Requirement Description	Specification
Number of Connected Antennas	263 total
Maximum Baseline Length	10,000 km
Maximum Instantaneous Bandwidth	20 GHz per polarization
Maximum Number of Channels	≥750,000 channels
Highest Frequency Resolution	400 Hz, corresponding to 0.1 km/s resolution at 1.2 GHz.
Pulsar Search Beamforming	≥10 beams ≥60 km diameter sub-array, 1" coverage
Pulsar Timing Beamforming	≥5 independent sub-arrays ≥1 beam per subarray

Table 8 - Correlator-beamformer key specifications.

7.8 Independent Phase Calibration System

The requirements and supporting reference design of the independent phase calibration system are described in the following documents [AD40–41]:

- Independent Phase Cal. System: Preliminary Technical Specifications, 020.45.00.00.00-0001-REQ
- Independent Phase Cal. System: Reference Design, 020.45.00.00.00-0002-DSN

Supporting analysis leading up to this design can be found in the following documents [RD13, 14, 23–25]:

- Fast Switching Calibration at the ngVLA Site, ngVLA Memo No. 1
- Calibration Strategies for the ngVLA, ngVLA Memo No. 2
- The Concept of A Reference Array for the ngVLA, ngVLA Memo No. 4
- Considerations for a Water Vapor Radiometer System, ngVLA Memo No. 10

Early studies on the phase calibration required to correct for atmospheric disturbances [RD13] suggested relatively fast phase correction would be required, with correction cycle times of order 30 seconds. Correcting for the atmospheric phase with astronomical observations of phase calibrators (high SNR sources) would then require a fast slewing antenna, and a significant portion of observing time would be spent observing the calibrator or slewing between the calibrator and science target.

To improve observational efficiency (time on science target), the system architecture uses an independent phase calibration system. For the reference design, this system will use water vapor radiometry (WVR). The WVR system constantly observes an atmospheric water vapor emission line centered at 22 GHz to calculate the column density of water vapor in the WVR beam (the primary contributor to atmospheric phase perturbations). Before the observation, a calibrator is observed (as in switching) to establish an absolute phase offset between antennas while the estimated WVR column density is noted.

Monitoring changes in the water vapor column density throughout an observation permits applying phase change estimates to the science data. Periodically—but with a much larger interval than that of fast switching—the calibrator can be re-observed to reestablish absolute phase offset. The WVR (shown as a block diagram in Figure 26) consists of a 1.2 meter antenna mounted to the main feed arm. The fixed WVR beam is aligned parallel to the main antenna beam. The WVR antenna architecture is offset prime focus. The feed, receivers, digitizers, and support electronics are located in a module mounted to the main feed arm at the offset focal point. A mounting plate connected to the antenna's liquid cooling system provides a heat reservoir.

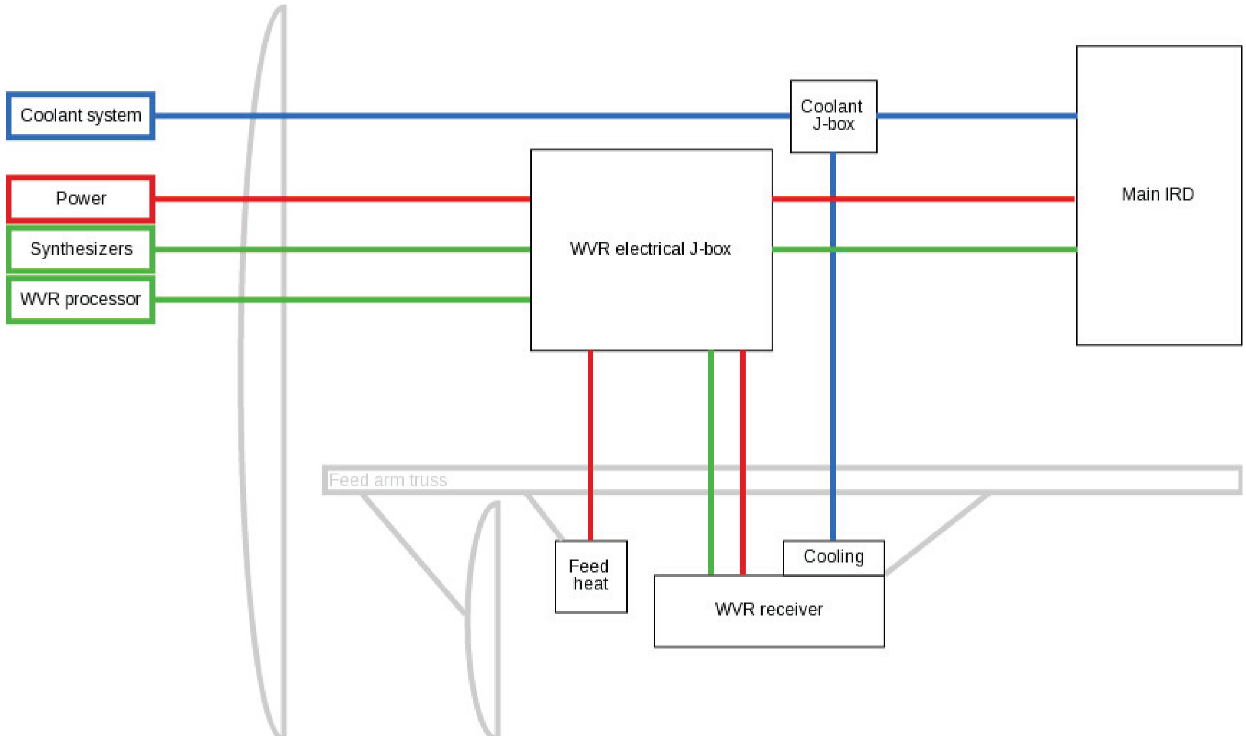

Figure 26 - WVR system block diagram and interfaces.

The receiver and digitizer electronics are thermally stabilized using Peltier heat pumps. A band from 18–32 GHz is digitized in the receiver module and digital data is streamed via fiber to the WVR processor in the pedestal room. Low-data-rate output is emitted into the M&C data stream so corrections can be applied in post-processing.

7.9 Computing and Software System

The requirements and supporting reference design architecture of the online and offline computing and software systems are described in the following documents [AD42–43]:

- Computing & Software Systems: Preliminary Technical Specifications, 020.50.00.00.01-0001-REQ
- Computing & Software Systems: Reference Design Architecture, 020.50.00.00.01-0002-REP

Supporting analysis leading up to this design can be found in the following documents [RD31–33]:

- RFI Flagging Algorithms, ngVLA Memo #TBD
- Imaging Algorithms, ngVLA Memo #TBD
- Computing System Sizing, ngVLA Memo #TBD

The ngVLA software architecture (see Figure 27) will leverage NRAO's existing algorithm development in reducing VLA and ALMA data and the CASA software infrastructure. The array will have a progressive series of data products suitable to different user groups. The data products may also change based on how well supported a mode is: common modes should have higher-level data products that add value to the user, while clearly not all permutations can benefit from such a degree of automation.

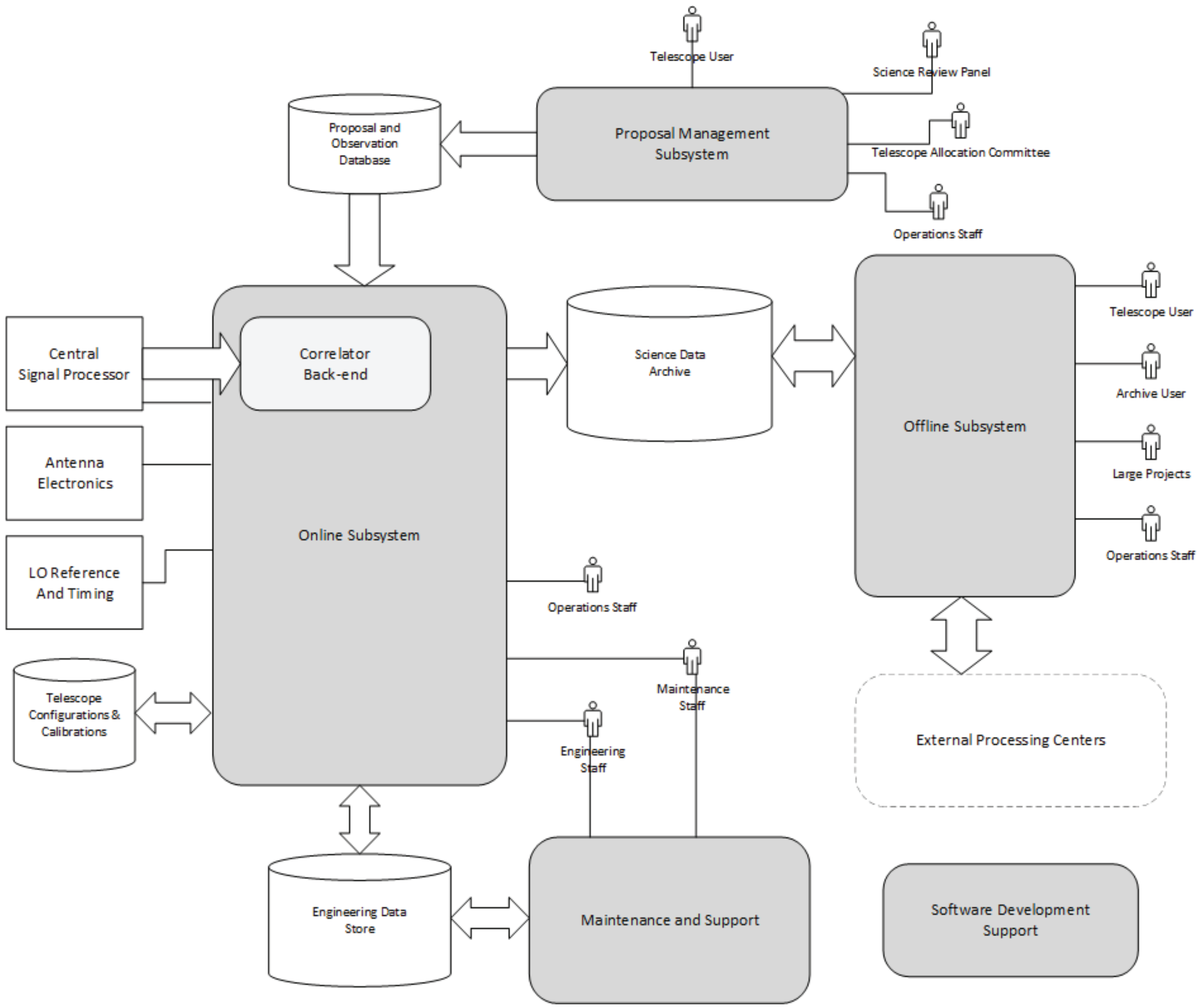

Figure 27 - General Computing and Software architecture, with major subsystems shown as gray boxes. Also shown are interfaces and dataflows between the subsystems, data stores, main actors, and other external system elements. [AD43]

As with the VLA, the fundamental data product that will be archived are uncalibrated visibilities. The online software system will also produce flags to be applied to the visibilities that would identify known system problems such as antennas being late on source, or the presence of RFI.

Automated post-processing pipelines will calibrate the raw data and create higher-level data products (typically image cubes) that will be delivered to users via the central archive. Calibration tables that compensate for large-scale instrumental and atmospheric effects in phase, gain, and bandpass shapes will be provided. Data analysis tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

The VLA and ALMA Science Ready Data Products project is an ngVLA pathfinder to identify common high-level data products to be delivered to the Principal Investigator and the data archive to facilitate data reuse. This will also enable the facility to support a broader user base, possibly catering to astronomers who are not intimately aware of the nuances of radio interferometry and thereby facilitating multi-wavelength science.

7.9.1 Proposal Management System

The Proposal Management Subsystem consists of the same system that currently handles the NRAO proposal process, extended to accommodate ngVLA requirements. This system is expected to be modernized and improved before the ngVLA construction phase begins. Although its architecture may change as a result of these improvements, at the present time its modules include:

Proposal Submission Tool (PST): This web application permits principal investigators to submit an observing proposal for any NRAO research facility: VLA, VLBA, or GBT. This application will be extended to support ngVLA. This application also supports the proposal evaluation process, allowing members of the Science Review Panel to score the proposals.

Proposal Handling Tool (PHT): This Web application supports the time allocation process. It facilitates the process of ranking and assigning time for each accepted proposal, taking into account its observing requirements, the available telescope time, predicted weather patterns, etc.

Proposal Builder Tool (PBT): This utility generates Scheduling Blocks from the Proposal.

Observation Preparation Tool (OPT): This web application allows users to manage Scheduling Blocks and associated structures prior to the execution of their observation.

These applications require several modifications for ngVLA. These include changes necessary for SRDP, such as the introduction of the observing modes that are supported for automated imaging and the generation of observable Scheduling Blocks (currently the PBT creates only a skeleton Scheduling Block, which needs to be edited by the user to make it observable).

7.9.2 Online Subsystem

The Online Subsystem is responsible for the near-real-time operation of the telescope and includes the following modules:

Scheduling: This module reads the set of scheduling blocks to be observed from the Proposal and Observation Database and constructs an observation schedule based on current weather conditions and short time prediction. The observation schedule defines a program of sub-arrays and their corresponding queues of scheduling blocks.

Observation: The Observation module exposes interfaces to create and destroy sub-arrays, and execute observations on them. This module implements the supported observing modes, which represent different ways to use telescope hardware to perform observations. The execution of an observation results in several commands sent to the telescope hardware, which trigger parallel and sequential operations that are coordinated by the Observation module. This module sends metadata to the Metadata Capture component as the observation proceeds.

Control: This module uses software components to control telescope hardware elements, organized into different hierarchies for Antenna Electronics, Local Oscillator, and Timing equipment.

Correlator: Correlator module components control the Central Signal Processor.

Correlator Back End: The Correlator Back End receives visibility data from correlator hardware and performs a series of post-correlation operations before saving the files in their final format. It also receives, formats, and saves pulsar search and timing data.

Metadata Capture: This module receives data from multiple sources and integrates it all in a series of tables that are saved along with the visibility data.

Telescope Configuration: This module provides interfaces for other components to query telescope configuration and calibration data.

Calibration: This module reads the visibility data saved during calibration scans and computes several calibration tables. These are saved along with other observation metadata tables, and in some cases are applied on the telescope instrumentation.

Quick-Look: This module computes observation quality assurance information and provides interfaces to present this data to the Astronomer on Duty and the Operators.

Monitoring: This module provides several components that collect monitoring data from hardware controller and supervisor components, and archives the data into the Engineering Database. This module also contains interfaces to query and present results from this database.

7.9.3 Monitor and Control System

The Monitor and Control (M&C) system is a sub-component of the Online System, but given its importance it is summarized here. The overall concept, requirements, and supporting reference design for the Monitor and Control system are described in the following documents [AD44–46]:

- Monitor & Control System: Reference Design Concept, 020.50.25.00.00-0002-DSN
- Monitor & Control System: Preliminary Requirements, 020.50.25.00.00-0001-REQ
- Monitor & Control System: Hardware Reference Design, 020.30.45.00.00-0002-REQ

The M&C system leverages NRAO experience with both the VLA and ALMA M&C systems. It is designed for high reliability, maintainability, and usability to decrease operational and maintenance costs. In general, the ngVLA M&C concept is guided by two principles:

- the system should be composed of autonomous and decoupled components, controlling smart devices, and
- it should be organized hierarchically, preserving the knowledge of a connected system.

Following these considerations, the ngVLA M&C system will be structured in five layers, as Figure 28 shows.

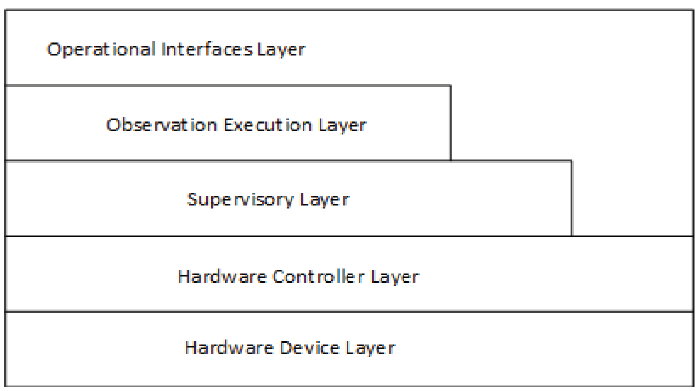

Figure 28 - ngVLA Monitor and Control architecture layers. [AD44]

The bottom Hardware Device layer represents the hardware devices that compose the telescope. The electronics devices will be packaged as Line Replacement Units, identified by a unique serial number. The Hardware Controller layer corresponds to controller boards (analogous to MIB boards in the VLA or AMBSI boards for ALMA), which provide a standardized Ethernet interface to its connected hardware devices. They translate Ethernet messages to the low-level interfaces used by hardware devices: SPI, I2C, and GPIO. This layer also includes the CSP Local Control System and other central electronic systems (e.g., local oscillator and timing). In this case, the Hardware Controller will not necessarily use controller boards but could consist of computers that implement the same interface.

Each LRU is controlled by a single controller board, which can be queried for the corresponding serial numbers. The system automatically discovers the serial numbers of each LRU and keeps track of their corresponding type and the system slots where they have been installed. This is necessary to associate data streams with specific hardware devices. The Supervisor should be able to detect when an LRU has been replaced and reconfigure itself, detecting and propagating the new serial numbers.

The Supervisory Layer provides higher-level system functions, integrating one or more controller boards. For example, the Antenna Supervisor would accept a high-level command to tune the Front End, which could then be translated into several commands sent to the controller boards involved in this operation. The Supervisory Layer incorporates logic to react to events detected in the lower layers, and supports maintenance operations without requiring interactions with a centralized control. The Supervisory Layer supports both reliability, by detecting and reacting to faults before they become failures, and maintainability, by providing smart interfaces for error reporting, diagnostics, and maintenance operations.

Each LRU should be autonomous and come up in an operational state after power up. The initial initialization routine will be executed by the Controller boards, and will include the connection to the network. Each LRU has a defined type, which identifies its function in the system, and a role, which identifies where it is installed in the system. As an example, each antenna has two LRUs of the IF processor type, each connected to receive different polarizations. As soon as the LRU reaches the operational state, it will send a multicast message containing identifying information such as its serial number(s), type, role, and status. This message will be received by the Supervisor, which will configure itself accordingly. The initialization routine should also include a built-in diagnostic, which could also be invoked on demand.

The Observation Execution layer orchestrates the execution of astronomical observations, following the operations defined in the telescope observing modes. This is the layer that supports the allocation of antenna sets into sub-arrays and implements the required observing modes.

The Operational Interfaces Layer incorporates user interfaces in the operator consoles. The components belonging to this layer interact not only with the Observation Execution layer, but with the Supervisory and Hardware Controller layers as well. The ability to bypass layers is important to support effective troubleshooting. Usually, the lower layers are accessed by means of console applications (a.k.a. administrative or service ports).

Regarding allocation of real-time requirements, the system architecture is divided into hard real-time requirements and soft real-time requirements, the distinction residing on how critical it is if a task misses its defined deadlines. Any deadline that cannot be missed without placing humans and/or equipment in danger should be regarded as a hard deadline and implemented in the Controller or Device layers. The Supervisory and above layers will deal only with soft deadlines, where missing them will result in most cases in an interval of flagged science data. In general, LRUs (i.e. hardware devices and their controllers) should be designed so they deal with any safety critical condition on their own, without requiring the participation of higher-level functions in the M&C system.

Integral in this architecture is the use of a database to manage the current and past system configurations, tracking which hardware devices (identified by S/N) were installed in the system at any given time. Tracking this information is fundamental for the application of automated diagnostics and preventive maintenance algorithms. It will also facilitate developing tools that facilitate the task of gathering all the necessary information needed to troubleshoot problems effectively.

7.9.4 Offline Subsystem

The Offline Subsystem is responsible for all the telescope functions that occur after the observation raw data has been stored in the Science Archive. These functions include the generation of derived data products (images, catalogs), support for quality assurance activities, and interfaces for searching, visualizing, and retrieving raw data and derived products. Table 9 shows the telescope expected data rates. These figures are large enough to make it unlikely that end users have in-house computational resources to calibrate and image the raw data locally. The ngVLA system will be integrated with the Science Ready Data Products (SRDP) project, a general NRAO initiative originated with the goal of creating the necessary infrastructure and interfaces for the generation and distribution of science-ready calibrated datasets, images, and catalogs for current and future NRAO telescopes. The ngVLA Offline subsystem will be integrated into the SRDP architecture, extending it to supply additional computational and storage resources, and data analysis pipelines. The size of the expected datasets makes necessary the development of large-scale parallelization algorithms for calibration and imaging.

This section discusses only aspects of the SRDP project that affect the ngVLA architecture. See [RD05] for additional information about SRDP.

Science Case	Use Fraction	Vis Per Hour	Data Rate	Storage Rate
KSG1 Driving Cont. Band 6 e.g. Taurus disk	8%	73.19 GVis	0.081 GB/s	0.21 PB/Month
KSG1 Driving Cont. Band 4 e.g. Taurus disk	4%	216.28 GVis	0.240 GB/s	0.63 PB/Month
KSG2 Driving Line Band 5 e.g. Sgr. B2(N)	4%	97241.83 GVis	108.05 GB/s	284.14 PB/Month
KSG2 Driving Line Band 4 e.g. Sgr. B2(N)	1%	72129.85 GVis	80.15 GB/s	210.76 PB/Month
KSG2 Driving Line Band 3 e.g. Sgr. B2(N)	1%	119342.01 GVis	132.60 GB/s	348.72 PB/Month
KSG3 Driving Line Band 5 e.g. COSMOS	4%	5985.35 GVis	6.650 GB/s	17.49 PB/Month
KSG3 Driving Line Band 4 e.g. COSMOS	1%	2996.82 GVis	3.330 GB/s	8.76 PB/Month
KSG3 Driving Line Band 3 e.g. COSMOS	1%	3030.45 GVis	3.367 GB/s	8.85 PB/Month
KSG3 Driving Line Band 6 e.g. Spiderweb galaxy	2%	11.16 GVis	0.012 GB/s	0.03 PB/Month
KSG3 Driving Line Band 5 e.g. Spiderweb galaxy	1%	11.16 GVis	0.012 GB/s	0.03 PB/Month
KSG3 Driving Line Band 4 e.g. Spiderweb galaxy	1%	5.58 GVis	0.006 GB/s	0.02 PB/Month
KSG3 Driving Line Band 6 e.g. Virgo Cluster	7%	3232.05 GVis	3.591 GB/s	9.44 PB/Month
KSG3 Driving Line Band 1 e.g. M81 Group	10%	149.48 GVis	0.166 GB/s	0.44 PB/Month
KSG3 Driving Line Band 1 e.g. M81 Group	12%	4.66 GVis	0.005 GB/s	0.01 PB/Month
KSG5 Driving Cont. Band 1 OTF Find LIGO event	7%	7347.53 GVis	8.164 GB/s	21.47 PB/Month
KSG5 Driving Cont. Band 4 OTF Find LISA event	7%	1090.82 GVis	1.212 GB/s	3.19 PB/Month
KSG5+4 Driving Cont. Band 2 OTF Find BHs + Possible Pulsars	8%	2034.17 GVis	2.260 GB/s	5.94 PB/Month
KSG5 Driving Cont. Band 3 Gw170817@200Mpc	23%	4.18 GVis	0.005 GB/s	0.01 PB/Month
Avg.:		6714.55 GVis	7.461 GB/s	19.62 PB/Month

Table 9 - Expected data rates, from key science use cases. It is assumed that full polarization is required, and visibilities are stored in half precision (2 bytes/number), with no baseline dependent averaging.

The Offline Subsystem is divided into the following modules:

Science Archive: This is the final repository for all data products. It consists of a metadata database, a file storage system, and services constructed around them. This system will be provided by the SRDP project, although it will be extended to accommodate additional ngVLA requirements. The ngVLA project will require the addition of storage nodes and changes in the metadata database.

Observatory Interfaces: This consists of web applications that provide retrieval interfaces and services constructed around the data stored in the Science Archive. This is also provided by the SRDP project, although extensions will be required, such as visualization and processing interfaces, to examine large images without having to download them first. It also includes VO-compatible programmatic interfaces.

Data Processing Management: This module includes several components required to manage and integrate the Data Processing Pipelines with the Science Archive. These infrastructural components will also be provided by the SRDP project. They include components to copy the data from the Archive file storage system to processing space, manage caches, implement workflows, track pipeline executions, etc.

Processing Resources: This module encapsulates high performance storage and processing hardware and associated management software. These resources include a local cluster in the Data Processing Center and external resources in services such as Amazon Web Services and XSEDE.

Data Processing Pipelines: These include pipelines for calibration, imaging, and catalog generation. The infrastructure will be based on the CASA package and the ALMA/EVLA Pipeline. The ngVLA project will require changes in algorithms and extensive improvements on parallelization and performance.

Quality Assurance Interfaces: This module includes interfaces to assess the quality of the data products generated by the Data Processing Pipelines, and support quality assurance operations. These will be provided by the SRDP project, although they may require extensions for ngVLA.

Data Analysis Tools: These are tools necessary to analyze ngVLA datasets and images, which will be provided as a package for users to download and install in their machines. This will be based on CASA, although extensions and modifications may be necessary to fulfill ngVLA requirements.

7.9.5 Data Stores

The data stores shown in Figure 27 are logical and are deployed into physical storage systems and databases depending on their requirements. The data stores include

- Proposal and Observation Database: This contains science proposals and scheduling blocks along with associated data structures such as source catalogs, user information, and telescope capabilities.
- Telescope Configurations and Calibrations Database: This database contains all configuration data necessary to bring the telescope to an operational state, including calibrations such as antenna position and the relative offsets to focal plane, antenna pointing parameters, delay models, etc.
- Science Data Archive: This includes visibility files, calibration tables, images, catalogs, and associated metadata.
- Engineering Data Store: This mainly includes monitoring data, alarms, and system logs.

7.9.6 Physical Architecture

A number of physical resources are required to support the preceding software systems and data stores. The most important of these are the elements of the Offline Subsystem, shown in Figure 29. The science data storage and processing cluster dominate the compute system cost estimate. The methods used to size and cost these systems are described in AD43, as is the sensitivity of the processing cluster to changes in the use cases and other cost modeling assumptions.

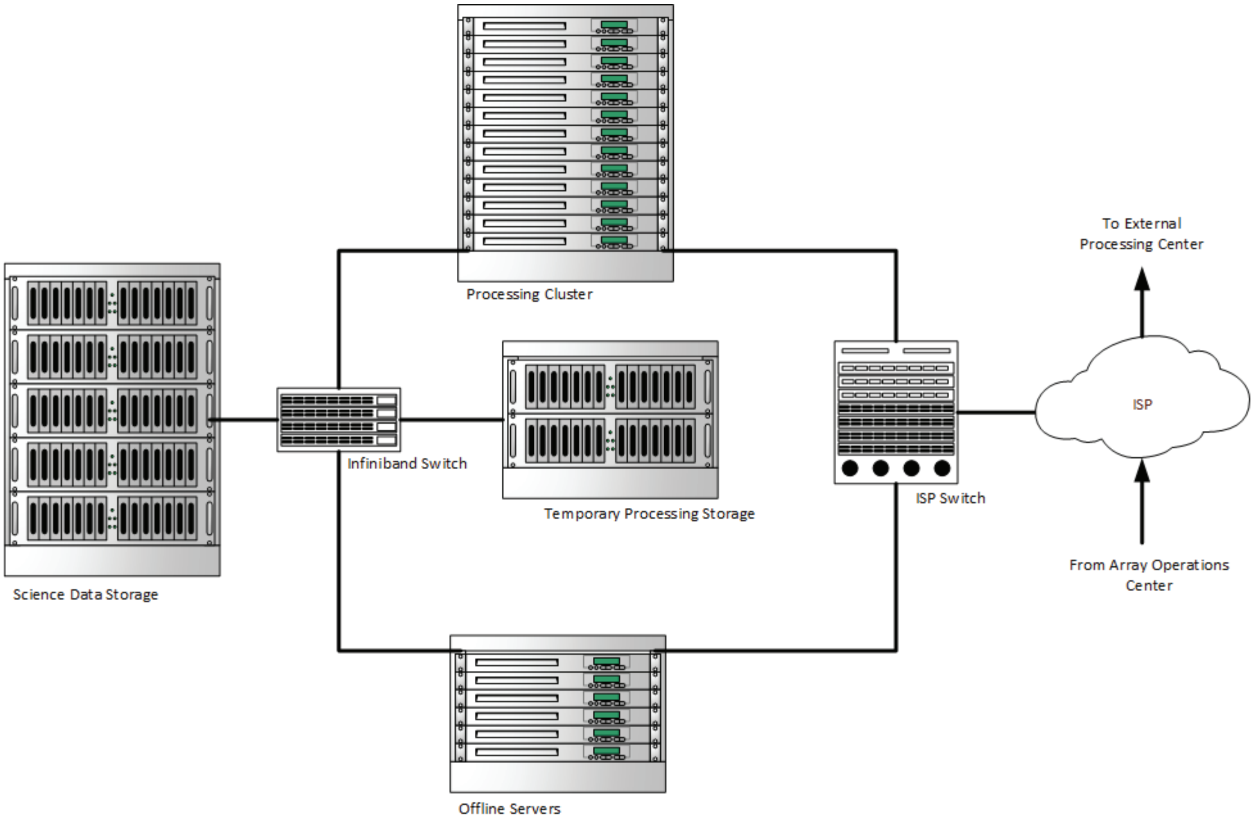

Figure 29 - Offline sub-system physical architecture.

7.9.7 Maintenance and Support Subsystem

The Maintenance and Support Subsystem is composed of the following modules:

Computerized Maintenance Management System (CMMS): This COTS software package maintains a database on observatory maintenance operations. This system provides several functions aimed to effectively organize maintenance operations.

CMMS Integration Module: This integrates the Engineering Database with the CMMS system.

Issue Tracking System: This COTS software maintains lists of issues and helps organize activities needed to resolve them. This may be provided by the issue tracking system already in use by NRAO.

Integrated Support Module: This module provides a centralized interface for support personnel to gather troubleshooting information, such as logs, alarms, and monitoring data.

7.9.8 Development Support Subsystem

This subsystem includes software modules that support software development activities. These generally include system simulators, concurrent versioning systems, continuous integration systems, testing infrastructure, build and deployment infrastructure, and quality assurance software packages.

7.10 Buildings and Array Infrastructure

The requirements and supporting reference design for the buildings and array infrastructure are described in [AD47], Buildings & Array Infrastructure: Reference Design Study, 020.60.00.00.01-0002-REP. The array infrastructure includes the foundations (see Figure 30), electrical infrastructure, fiber infrastructure, and ancillary structures necessary to support each antenna within the array. The buildings work package includes all structures required for array construction, commissioning, and operation.

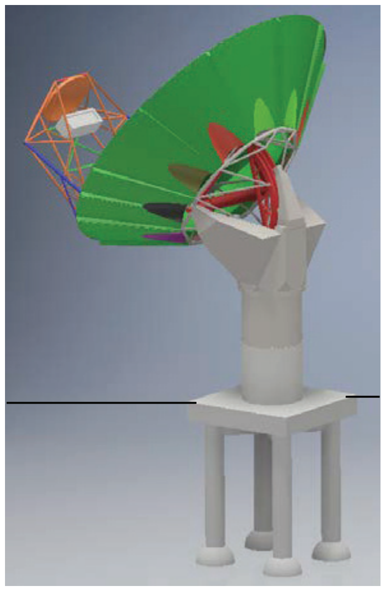

Figure 30 - Foundation design used for costing. The slab below the antenna is at ground level, with concrete caissons extending below grade.

Most ngVLA infrastructure and buildings will be located on the Plains of San Agustin. Over 70% of the antennas fit within the array's core and spiral arms. The electrical distribution system will be underground on the plains, with switchgears distributed around the array center, each servicing approximately 40 antennas (Figure 31). Redundant electrical paths will permit preventive maintenance on most switchgears without removing power to the rest of the array. The site will include a backup power plant to maintain operation during power outages.

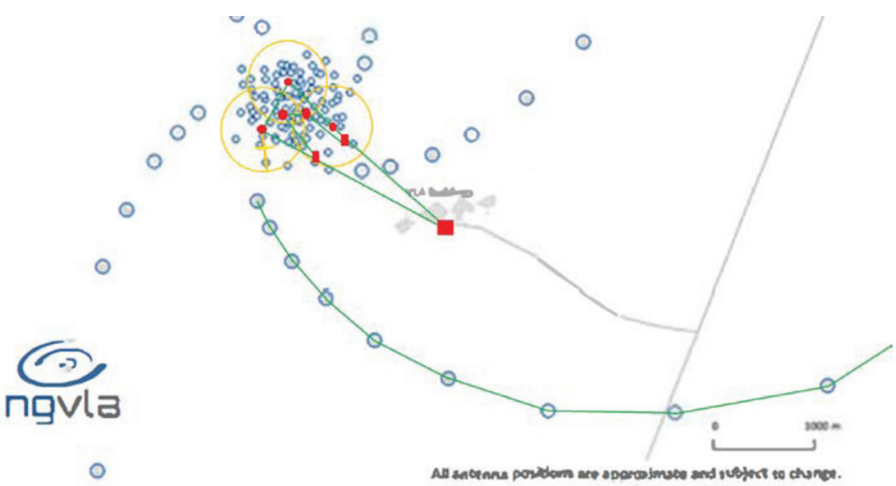

Figure 31 - Example locations of the backup power plant and switchgear locations (red) and utility trenching along arms (green).

Average total power load is estimated at 3.5MW for the array, central infrastructure, and off-site buildings combined. This is approximately three times the current VLA load. Significant savings are achieved in the design of the antenna electronics, correlator system, and computing cluster when compared to existing facilities. Estimates are based on a combination of parametric scaling from the VLA actual power loads and bottom-up estimates for new designs, apportioned as shown in Table 10. The main power source on the plains is expected to be grid power provided by the local utility company. Green power sources (photovoltaic and wind turbines) have been considered and are increasingly attractive on operating price metrics, but are presently outside the scope of construction.

Location	**Subtotal**
Array Antennas (SBA, MA, LBA)	1315 kW
Central Infrastructure (inc. CSP)	1066 kW
Off-Site Buildings (AOC, Data Center)	1070 kW
Grand Total (kW)	**3451 kW**

Table 10 - Approximate average electrical power load.

The fiber infrastructure will share the utility trench with the power distribution system. It is a start topology, with all fibers terminating at the central control building (housing the correlator). Other infrastructure systems at the site include water and waste systems, landfill, fire suppression, and service roads. Stations outside the plains will leverage existing infrastructure where available, with electrical infrastructure providing "last mile" connections, and fiber strung along existing pole line right-of-ways. Sites beyond 300 km from the core will rely on commercial fiber links for data backhaul as shown in Figure 24. Off-grid photovoltaic power and battery backup will be compared to "last mile" connections to existing utility systems and may be preferred for distances greater than a few kilometers.

An assessment of the existing buildings and infrastructure has been performed by a 3rd party AEC firm, providing recommendations for reuse of VLA infrastructure and new construction where appropriate. The buildings concept leverages the existing VLA buildings where reuse is most economical over the lifetime of the facility. Additional space is required at the VLA site (or nearby) for a central electronics and control building, warehouse and assembly area, and workshops for auto, grounds, machine, HVAC, electrical, Cryo, Servo, and antenna mechanics.

Additional operation centers are included within the building package required for facility operation. These include an Array Operations and Repair Station in Socorro, as well as a Science Center and Data Center in a remote metropolitan area.

8 Construction Cost Estimate

The integrated construction cost estimate is provided in [AD48], Integrated Construction Cost Estimate, 020.05.15.05.00-0004-BUD. This estimate was built from supporting information for each major subsystem:

- Antenna: Cost Estimate, 101-0000-001-MOD-001
- Short Baseline Array Antenna: Cost Estimate (Doc # TBD)
- Front End: Cost Estimate, 020.30.03.01.00-0002-BUD
- Cryogenic System: Cost Estimate, 020.30.10.00.00-0003-BUD
- Integrated Receiver Digitizer: Cost Estimate, 020.30.15.00.00-0003-BUD
- DBE & DTS: Cost Estimate, 020.30.25.00.00-0003-BUD
- Antenna Time & Frequency References: Cost Estimate, 020.35.20.00.00-0003-BUD
- DC Power Supply System: Cost Estimate, 020.30.50.00.00-0003-BUD
- Bins, Modules & Racks: Cost Estimate, 020.30.55.00.00-0003-BUD
- Environmental Control: Cost Estimate, 020.30.60.00.00-0003-BUD
- Time & Frequency Reference Distribution System: Cost Estimate, 020.35.00.00.00-0003-BUD
- Central Signal Processor: Cost Estimate, 020.40.00.00.00-0003-BUD
- Independent Phase Cal. System: Cost Estimate, 020.45.00.00.00-0003-BUD
- Computing & Software: Cost Estimate, 020.50.00.00.01-0001-REQ
- Monitor & Control: Cost Estimate, 020.30.15.00.00-0003-BUD
- Information Technology: Cost Estimate, 020.55.00.00.01-0001-BUD
- Array Infrastructure: Cost Estimate, 020.60.00.00.00-0001-BUD
- Operations Buildings: Cost Estimate, 020.65.00.00.00-0001-BUD

Prior to building this bottom-up budget for the reference design, a parametric model was built to inform key design choices and the system architecture. The parametric cost and performance model and supporting explanatory memo are contained in:

- ngVLA Quantitative eXchange Model – Report, 020.05.15.00.00-0004-REP
- ngVLA Quantitative eXchange Model – Spreadsheet, 020.05.15.00.00-0005-REP

The engineers' estimates enumerated above were adjusted to use common assumptions for learning, computing cost scaling, storage cost scaling, and other common parametric factors. Please consult [AD48] for current projected construction cost and more details on the cost methodology.

9 Operation Cost Estimate

The integrated operations cost estimate is detailed in [AD49], Integrated Operations Cost Estimate, 020.05.15.05.00-0007-BUD.

Prior to building this bottom-up budget for the reference design, a parametric model was built to inform key design choices. This model estimated full lifecycle costs, with the operations phase largely scaled from VLA and ALMA actual costs where they provided the best analogs. The parametric cost and performance model and supporting explanatory memo are contained in two documents:

- ngVLA Quantitative eXchange Model – Report, 020.05.15.00.00-0004-REP
- ngVLA Quantitative eXchange Model – Spreadsheet, 020.05.15.00.00-0005-REP

The operations cost estimate is consistent with the Operations Concept [AD08] discussed in Section 4. This will be further developed into an Operations Plan in future design stages. Please consult [AD49] for the current projected annual operations cost breakdown and details on the cost methodology.

10 Appendix

10.1 Acronyms and Abbreviations

Please consult the project lexicon [AD50] for a full list of acronyms and abbreviations.

Acronym	Description
ACFH	Axially Corrugated Feed Horn
AD	Applicable Document
AEC	Architecture, Engineering and Construction
ALMA	Atacama Large Millimeter/submillimeter Array
AMBSI	ALMA Monitor and Control Bus Standard Interface
ARCS	Advanced RFI Containment System
AST	Division of Astronomical Sciences (NSF)
BW	Band Width
CBF	Correlator Beam-Former
CDL	Central Development Laboratory
CoDR	Conceptual Design Review
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSP	Central Signal Processor
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
DBE	Digital Back End
DS	Decadal Survey
DSP	Digital Signal Processing
DTS	Data Transmission System
EDFA	Erbium-Doped Fiber Amplifiers
EIA	Electronics Industries Association/Electronics Industries Alliance
EIRP	Effective Isotropic Radiated Power
EMC	Electro-Magnetic Compatibility
ENOB	Effective Number of Bits
FDR	Final Design Review
FE	Front End
FOV	Field of View
FSA	Frequency Slice Architecture
FWHM	Full Width Half Max
GM	Gifford-McMahon
GPIO	General Purpose Input-Output
GW	Gravitational Wave
HPC	High Performance Computing
HVAC	Heating, Ventilation & Air Conditioning
I2C	Inter-Integrated Circuit (Interface)
IF	Intermediate Frequency
IRD	Integrated Receiver Digitizer
ISP	Internet Service Provider
KPP	Key Performance Parameters
KSG	Key Science Goals
LBA	Long Baseline Array
LNA	Low Noise Amplifier

Acronym	Description
LO	Local Oscillator
MA	Main Array
MoE	Measure of Effectiveness
MoP	Measure of Performance
MREFC	Major Research Equipment and Facilities Construction (NSF)
NDA	Non-Disclosure Agreement
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NRC	National Research Council Canada
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PDR	Preliminary Design REview
PLL	Phase Locked Loop
PSD	Power Spectral Density
PWV	Precipitable Water Vapor
QRFH	Quad Ridge Feed Horn
RD	Reference Document
RFI	Radio Frequency Interference
rms	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
RVTM	Requirements Verification Traceability Matrix
S/N	Serial Number
SAC	Science Advisory Council
SBA	Short Baseline Array
SEFD	System Equivalent Flux Density
SKA	Square Kilometer Array
SNR	Signal to Noise Ratio
SPI	Serial Peripheral Interface
SRDP	Science Ready Data Products
SWG	Science Working Group
SysML	Systems Modeling Language
TBC	To Be Confirmed
TBD	To Be Determined
VFD	Variable Frequency Drive
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer

Science Requirements

020.10.15.00.00-0001-REQ-SCIENCE_REQS

PREPARED BY	ORGANIZATION	DATE
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ngVLA Scientific Advisory Committee	Astronomy Community	2019-05-14

APPROVALS (Name and Signature)	ORGANIZATION	DATE
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E. Murphy, Project Scientist — Digitally signed by Eric J. Murphy Date: 2019.06.04 08:11:22 -04'00'	ngVLA/NM-Operations, NRAO	2019-05-16
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.06.03 16:34:51 -06'00'	Asst. Director, NM-Operations, NRAO	2019-05-19

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.06.03 16:35:08 -06'00'	Asst. Director, NM-Ops, NRAO	2019-05-20

Change Record

Version	Date	Sections	Change Description
1	2017-08-24	All	Initial Outline/Draft. Incorporated key science cases and text from Memo #19 by ngVLA Science Advisory Council (SAC).
2	2017-08-29	All	Updated text and added ADs and RDs.
3	2017-09-08	All	Edits throughout for clarity. Added definitions. Added to supporting requirements and requirements summary table.
4	2017-09-13	All	Edits to narrative, addressing review questions.
5	2017-09-19	1.4, 4	Working on definitions and summary table.
6	2017-09-20	3.4	Updated Figure 4.
7	2017-09-21	1.4, 3, 4	Cleaned up text and edits to summary table.
8	2017-10-10	All	Implemented edits based on comments from Kern, Condon, and additional requested information from SAC.
9	2017-11-09	All	Updated definitions with input from Condon & associated entries in the Table 1. Incorporated input from SAC.
10	2017-11-21	All	Based on feedback from Friday tag-up: Included mention of science use cases, traceability of requirements back to KSGs where applicable, SS definition included.
11	2017-11-22	TOC, 2.2	Minor updates for first release. Updated TOC. Added to Ref Docs. Cleaned up historical comments that were not relevant. Other minor edits.
12	2018-03-01	All	Updated Figure 3. Incorporated feedback from all-hands review: updated definitions in 1.3, split Table 1 into two tables (telescope features and performance metrics), added traceability between science requirements in Tables 1 and 3 to narrative in Section 3.
13	2018-03-05	All	Minor updates to various sections/requirement language based on comments. Version released internally for July reference design workshop.
14	2018-08-16	All	Updated template with ngVLA logo. Incorporated TB comments. Added NGA3 as a supporting use case for KSG3. Reconciled gaps identified by Christina Lorenzo. Added VLB science requirements. Updated continuum requirement for PP disks. Included molecular line list.
15	2019-02-25		Altered the transient mapping requirements. Added absorption spectroscopy requirements.
16	2019-03-27	All	A number of largely minor updated/edits. Reference to ROP in RDs. Changed "Accuracy" definitions to use "Error" and cast Sensitivities in units of rms noise (added new definition and made consistent throughout the text).
17	2019-05-13	Appendix	Fixed formatting on header, added to abbreviations table and open question in appendix.
18	2019-05-14	Appendix	Added subsection on a potential data latency requirement.
A	2019-05-20	All	Prepared document PDF for release.

Table of Contents

1 Introduction

1.1 Purpose

This document describes the Level 0 Science Requirements following a solicitation from the National Radio Astronomy Observatory (NRAO) to develop key science cases for a future US-led radio telescope, the next generation Very Large Array (ngVLA). These science use cases represent some of the fundamental astrophysical problems that require observing capabilities at millimeter and centimeter wavelengths well beyond those of existing, or already planned, telescopes.

The summary of this exercise has resulted in an ngVLA that should

- have roughly ten times the sensitivity of the Jansky VLA and ALMA,
- operate at frequencies from 1.2–116 GHz with up to 20 GHz of instantaneous sampled bandwidth,
- possess a compact core for good sensitivity to low surface-brightness emission, and
- use extended baselines of at least hundreds of kilometers and ultimately across the continent to provide high-resolution imaging.

The ngVLA will build on the scientific and technical legacies of the Jansky VLA, VLBA, and ALMA, and will be designed to provide the next major leap forward in our understanding of planets, galaxies, black holes, and the dynamic sky.

1.2 Scope

The scope of this document is the Level 0 Science Requirements necessary to carry out the ngVLA key science missions [AD01] as identified by the ngVLA Science Advisory Council (ngVLA-SAC) and the broader international astronomical community. This document does not present or discuss corresponding technical requirements or potential implementation paths to achieve these science requirements. Information on the technical requirements and supporting architecture is provided in the ngVLA Preliminary System Requirements document [RD07].

1.3 Definitions

Here we provide definitions to a number of quantities used to describe the science requirements.

1.3.1 Sensitivity

Continuum and line sensitivities are defined as $\frac{1}{\sigma_{rms}}$, where σ_{rms} is the rms noise in units of flux density per beam solid angle.

1.3.2 Sculpted Beam

A manipulation [e.g., (*u,v*)-tapering and/or various weighting algorithms] of the naturally weighted synthesized beam of the array such that there are no significant inflection points down to 10% of the peak. This in turn defines the main lobe of the sculpted beam.

1.3.3 Quality of the Synthesized Beam

The combined characterization of the (sculpted) synthesized beam shape down to low levels and the main synthesized beam efficiency B_{eff} as a function of angular scale. The synthesized beam efficiency is defined as the ratio of the power in the main lobe of the sculpted beam attenuation pattern a to the power in the entire beam attenuation pattern as a function of the FWHM of the synthesized beam θ:

$$B_{eff}(\theta) \equiv \frac{\int_{MB} a(\theta)^2 d\Omega}{\int_{4\pi} a(\theta)^2 \, d\Omega}$$

1.3.4 Image Fidelity

The normalized rms deviation of the image brightness I measured relative to a true sky brightness convolved with a Gaussian restoring beam M, weighted by the model brightness and integrated over the field:

$$F \equiv 1 - \frac{\sum_{pix} M_i \, |I_i - M_i|}{\sum_{pix} M_i I_i}$$

It is generally acknowledged that this quantity is exceedingly difficult to estimate in practice, since only well-understood effects can be included in a simulation. It is possible that poorly understood effects may dominate.

1.3.5 Photometric Error

The fractional error of the flux density in the image S_{img} relative to an adopted celestial flux density standard S_{std} measured for the integrated source brightness:

$$PE \equiv \frac{|S_{img} - S_{std}|}{S_{std}}$$

The photometric error is expected to vary as a function of the angular source size ϕ in units of the FWHM of the (sculpted) synthesized beam θ.

1.3.6 Positional Uncertainty

$$\sigma_{pos} \equiv \sqrt{\epsilon^2 + \sigma_n^2}$$

where $\sigma_n = \frac{\theta}{2\sqrt{\ln(2)}\, SNR}$ is the noise component of the positional uncertainty and depends on the signal-to-noise (SNR) ratio of the source, and ϵ is the rms calibration uncertainty in each coordinate and ultimately determines the astrometric accuracy of the system.

1.3.7 Timing Accuracy

The Allan standard deviation in time, relative to the adopted time standard over a given time internal.

1.3.8 Brightness Dynamic Range

The ratio of the quadrature sum of the peak brightnesses in the field relative to the rms noise of the quiescent-background (source-free regions) of the image:

$$DR_B \equiv \frac{\sum_i \sqrt{I_i^2}}{\sigma_{rms}}$$

1.3.9 Spectral Dynamic Range, Emissive

The ratio of the brightness in the strongest channel compared to the rms of the residual brightness in the instrument bandpass of nearby channels:

$$DR_{S,E} \equiv \frac{\max(I_E)}{\sigma_{rms,res}}$$

1.3.10 Spectral Dynamic Range, Absorptive

The ratio of the brightness in the strongest absorption channel to the rms of the brightness in the nearby continuum channels:

$$DR_{S,A} \equiv \frac{\max(I_A)}{\sigma_{rms,cont}}$$

1.3.11 Polarization Dynamic Range

The ratio of peak Stokes I brightness in the field to the residual polarized response (rms of stokes Q, U, V) for an unpolarized source:

$$DR_P \equiv \frac{\max(I)}{\sigma_{rms,pol}}$$

1.3.12 Instrumental Survey Speed

If σ_S is the point source rms noise on the sky achieved after an integration time τ for an interferometer having an effective area $A_e = \left(\frac{A_g}{\eta}\right)$, where A_g is the geometric collecting area of the array and η is the frequency-dependent aperture efficiency, system noise temperature T_S, and bandwidth $\Delta\nu$, the corresponding instrumental survey speed is given by:

$$\left(\frac{\dot{\Omega}}{\mathrm{deg}^2\ \mathrm{s}^{-1}}\right) \equiv \frac{\Omega_{\mathrm{FoV}}}{\tau} = \frac{\sigma_S^2 \Delta\nu}{4k_B^2}\left(\frac{A_e}{T_s}\right)^2 \Omega_{\mathrm{PB}}$$

where $k_B = 1.38 \times 10^{-23}$J/K is the Boltzmann constant and $\Omega_{\mathrm{FoV}} = \Omega_{\mathrm{PB}}/2$ is the effective field-of-view limited by the primary beam whose beam solid angle is $\Omega_{\mathrm{PB}} = \frac{\pi\theta_{\mathrm{PB}}^2}{4\ln 2}$ and $\theta_{\mathrm{PB}} \approx 1.02\left(\frac{\lambda}{D}\right)$ is the FWHM of the primary beam of a dish having diameter D. This quantity can also be expressed as a function of the System Equivalent Flux Density, $SEFD = 2k_B\left(\frac{T_s}{A_e}\right)$.

1.3.13 Triggered Response Time

The interval of time between when the trigger is received by the array to the time when the antennas are pointing in the correct direction on the sky, with the correct receiving set up, and acquiring data.

1.4 Requirement Definitions

The following definitions of requirement "levels" are used in this document.

Requirement Level	Definition
L0	User requirements expressed in terms applicable to their needs or use cases ("Science Requirements" or "Stakeholder Requirements")
L1	Requirements expressed in technical functional or performance terms, but still implementation agnostic ("System Level Requirements")
L2	Requirements that define a specification for an element of the system, presuming an architecture ("Subsystem Requirements")

2 Related Documents

2.1 Applicable Documents

The following documents are applicable to the extent specified. In the event of conflict between the documents referenced herein and the content of these requirements, the content of the requirements shall be considered superseding.

Reference No.	Document Title	Rev/Doc. No.
AD01	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19

2.2 Reference Documents

The following documents provide context or supporting material.

Reference No.	Document Title	Rev/Doc. No.
RD01	Science Working Groups Project Overview	ngVLA Memo #5
RD02	Science Working Group #1: The Cradle of Life	ngVLA Memo #6
RD03	Science Working Group #2: “Galaxy Ecosystems”: The Matter Cycle in and Around Galaxies	ngVLA Memo #7
RD04	Science Working Group #3: Galaxy Assembly through Cosmic Time	ngVLA Memo #8
RD05	Science Working Group #4: Time Domain, Fundamental Physics, and Cosmology.	ngVLA Memo #9
RD06	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD07	ngVLA: Preliminary System Requirements	V1.01
RD08	Use Case: Characterizing Planet-Disk Interactions	Use Case PF3
RD09	Use Case: Resolved Substructures in Protoplentary Disks	Use Case PF1
RD10	Use Case: Circumplanetary Disk Detection	Use Case PF5
RD11	Use Case: Prebiotic Chemistry	Use Case AC5
RD12	Use Case: Tracing the NH3 Snowline in Protoplanetary Disks: A Proxy for Water	Use Case AC1
RD13	Use Case: Deuteration in Starless and Protostellar Cores	Use Case AC4
RD14	Use Case: Mapping Molecular Emission in the Near- Nucleus Coma of Comets	Use Case AC6
RD15	Use Case: Giant Planet Atmospheres	Use Case SS06
RD16	Use Case: Mapping the Organic Content in a Protoplanetary Disk Midplane	Use Case AC2
RD17	Use Case: Complex molecules in Hot Molecular Cores/Corinos	Use Case AC3
RD18	Use Case: Cold Gas in High-z Galaxies 1 – The Molecular Gas Budget	Use Case HiZ1
RD19	Use Case: Mapping High-z CO Gas	Use Case HiZ5
RD20	Use Case: Atomic Hydrogen in the Local Universe	Use Case NGA2
RD21	Use Case: Parsec-Scale Cold Gas Structure Across the Whole Local Galaxy Population	Use Case NGA8
RD22	Use Case: Cold Gas in High-z Galaxies 2 – CO as Redshift Beacon	Use Case HiZ2

Reference No.	Document Title	Rev/Doc. No.
RD23	Use Case: Cold Gas in High-z Galaxies 3 – The Dense ISM	Use Case HiZ3
RD24	Use Case: Low-Surface-Brightness CO	Use Case HiZ6
RD25	Use Case: Continuum Surveys	Use Case HiZ7
RD26	Use Case: Observing AGN Feedback Over Cosmic Time Through Deep, Individual Observations	Use Case HiZ8
RD27	Use Case: Probing Obscured MBH Accretion and Growth at Cosmic Dawn	Use Case HiZ10
RD28	Use Case: A High-Resolution Kinematic View of Nearby Galaxy Nuclei	Use Case NGA5
RD29	Use Case: Star Formation in a Range of Extreme Physical Environments	Use Case NGA6
RD30	Use Case: Direct Measurements of Density and Temperature in Star-Forming Gas	Use Case NGA7
RD31	Use Case: A Complete Line Survey and Sub-pc Map of Every Local Group Molecular Cloud	Use Case NGA9
RD32	Use Case: Gas Density Across the Local Universe	Use Case NGA10
RD33	Use Case: Galactic Center Pulsars	Use Case TDCP1
RD34	Use Case: Gravitational Wave Follow-Up	Use Case TDCP2
RD35	Use Case: Dual Active Galactic Nuclei	Use Case TDCP5
RD36	Use Case: Pulsar Timing and Gravitational Waves	Use Case TDCP7
RD37	Use Case: Cosmic Explosions and Collisions in the ngVLA Era	Use Case TDCP8
RD38	Use Case: Accurate Massive Black Hole Mass	Use Case NGA12
RD39	Imaging Capabilities: High Redshift CO	ngVLA Memo #13
RD40	Use Case: Radio Continuum Emission from Galaxies: An Accounting of Energetic Processes	Use Case NGA3
RD41	ngVLA Reference Observing Program	020.10.15.05.10-0001-REP

3 The ngVLA Key Science Goals

The ngVLA SAC, a group of leading scientists with a wide range of interests and expertise appointed by NRAO, in collaboration with the broader international astronomical community, recently developed approximately 80 compelling science cases requiring observations between 1.2–116 GHz with sensitivity, angular resolution, and mapping capabilities far beyond those provided by the Jansky VLA, VLBA, ALMA, and the SKA. These science cases span a broad range of topics in the fields of planetary science, Galactic and extragalactic astronomy, as well as fundamental physics. Consequently, the primary science requirement for the ngVLA is to be flexible enough to support the breadth of scientific investigations that will be proposed by its creative scientist-users over the decades-long lifetime of the instrument.

Each science case was objectively reviewed via an online questionnaire and thoroughly discussed by the Science Working Groups within the ngVLA-SAC with the goal of distilling the top scientific goals for a future radio/mm telescope. The Key Science Goals (KSGs) were chosen to satisfy three criteria:

1. Each addresses an important, unanswered question in astrophysics that has broad scientific and societal implications.
2. Progress in each area is uniquely addressed by the capabilities of the ngVLA.

3. Each exhibits key synergies and complementarity with science goals being pursued by existing or planned facilities in the 2025 and beyond time frame.

The initial key science goals, along with the results from the entire list of approximately 80 science use cases [RD06] were then presented and discussed with the broader community at the ngVLA Science and Technology Workshop, June 26–29, 2017, in Socorro, NM.[1] The goal was to build consensus around a single vision for the key science missions of the ngVLA.

In this section, we describe the five KSGs to come out of this process along with their corresponding requirements. These include

- **KSG1:** Unveiling the Formation of Solar System Analogs on Terrestrial Scales
- **KSG2:** Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry
- **KSG3:** Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present
- **KSG4:** Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity
- **KSG5:** Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

In the following sections, we provide additional scientific background for each science goal, along with a summary of supporting requirements. A detailed description of ngVLA KSGs can be found in [AD01].

3.1 KSG1: Unveiling the Formation of Solar System Analogues on Terrestrial Scales

Summary: The ngVLA shall be able to measure the planet initial mass function down to a mass of 5–10 Earth masses and unveil the formation of planetary systems similar to our own Solar System by probing the presence of planets on orbital radii as small as 0.5 AU at the distance of 140 pc. The ngVLA shall also be able to reveal circumplanetary disks and sub-structures in the distribution of mm-size dust particles created by close-in planets and measure the orbital motion of these features on monthly timescales. [See RD08]

Driving Science Use Cases: PF3

Supporting Science Use Cases: PF1, PF5

Planets are thought to be assembled in disks around pre-main sequence stars, but the physical processes responsible for their formation are poorly understood. Only recently, optical, infrared, and (sub-)millimeter telescopes have achieved the angular resolution required to spatially resolve the innermost regions of nearby protoplanetary disks. These efforts resulted in the discovery of morphological features (rings, spirals, and crescents) in the distribution of circumstellar gas and dust with characteristic sizes larger than 20 AU (e.g., Casassus et al. 2013; van der Marel et al. 2013; Perez et al. 2014; ALMA Partnership 2015; Andrews et al. 2016; Isella et al. 2016).

These structures are suggestive of gravitational perturbations of yet unseen giant planets and provide a powerful tool to measure planet masses and orbital radii, study the circumplanetary environment, and investigate how forming planets interact with the circumstellar material (e.g., Jin et al. 2016). The angular resolution, frequency coverage, and sensitivity of current disk imagery is limited to probing for the presence of planets more massive than Neptune at orbital radii larger than 20–30 AU.

The next step forward in the study of planet formation is the ability to image the formation of super-Earths and giant planets across the entire disk, particularly within 10 AU from the central star, and to

[1] https://science.nrao.edu/science/meetings/2017/ngvla-science-program/index

probe for the presence of planets with masses as low as 5–10 Earth masses. Such capabilities are not achievable with ALMA or proposed space missions. The design of the ngVLA shall enable such imaging and permit measuring the initial mass and the birth radius functions of giant and massive rocky planets. Such observations will provide key information to understand the diverse demographics of exoplanetary systems and, ultimately, unveil the formation of planetary systems similar to our own Solar system.

Figure 1 illustrates the requisite capabilities of the ngVLA for imaging planetary systems in the act of forming. The figure compares simulated ngVLA observations at a frequency of 100 GHz to simulated ALMA observations at a frequency of 345 GHz, which provide the best compromise between angular resolution and sensitivity to the dust thermal emission. Observations with the ngVLA will be able to clearly reveal the presence of planets with masses as low as 10 Earth masses at orbital radii as small as 2.5 AU (central and right panels). These planets could not be detected by ALMA because of the high optical depth of the dust emission at 345 GHz, and the lower angular resolution of its observations at lower, optically-thin frequencies.

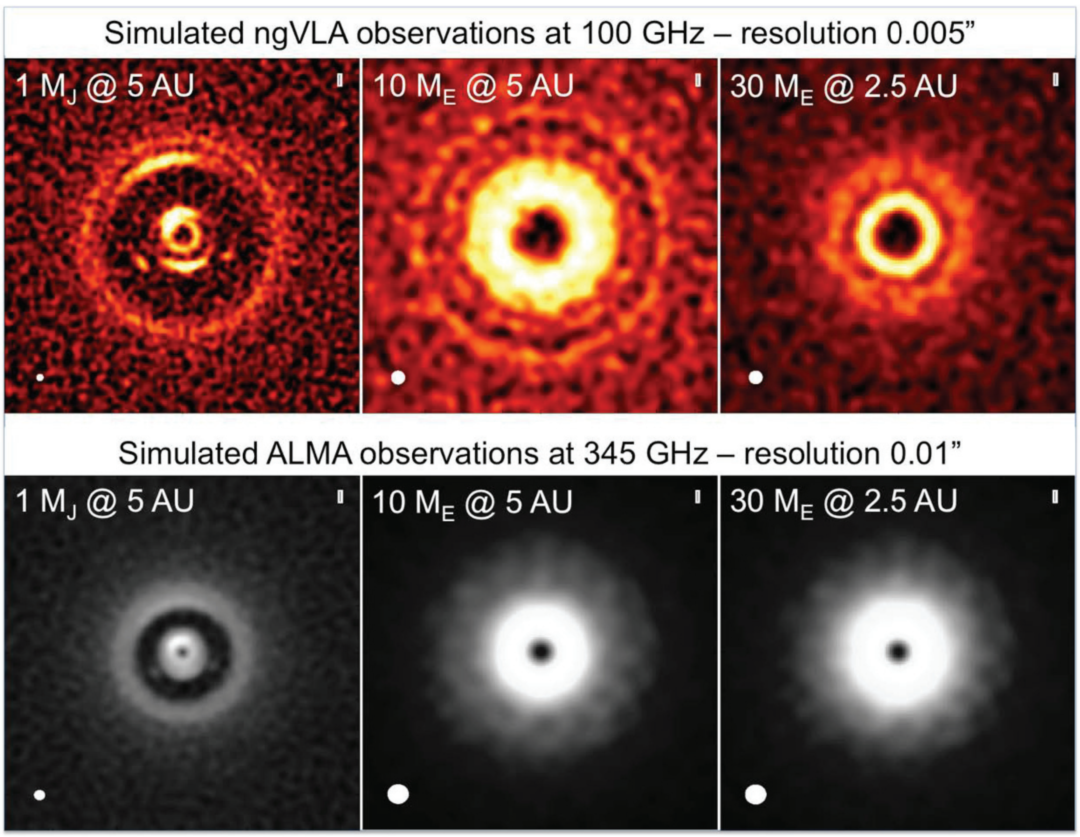

Figure 1 - Ricci et al. (2018): ngVLA–simulated (top row) and ALMA–simulated (bottom row) observations of the continuum emission of a protoplanetary disk perturbed by a Jupiter mass planet orbiting at 5 AU (left column), a 10 Earth mass planet orbiting at 5 AU (center column), and a 30 Earth mass planet orbiting at 2.5 AU (right column). The ngVLA observations were simulated with a 5 mas beam and an rms noise of 0.5 μJy/bm. ALMA observations were simulated using the most extended (16 km baseline) configuration and an rms noise of 8 μJy/bm.

The ngVLA shall also be superior to ALMA at imaging perturbations generated by giant planets orbiting close to the central star (left panels). In particular, the ngVLA shall have the potential to detect circumplanetary disks and Trojan satellites around young Jupiter analogs. With exquisite angular resolution, the ngVLA will enable the measurement of the orbital motions of all these structures on monthly timescales, opening a completely new dimension to the study of planet formation.

3.1.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG1-001**: Continuum observations for center frequencies between 20–110 GHz with angular resolution better than 5 mas at 100 GHz are required to study the formation of planets in the innermost 10 AU of nearby (<140 pc) proto-planetary disks.
- **KSG1-002**: Extensive simulations of the disks perturbed by planets (Ricci et al. 2018, Figure 1) suggest that an rms noise of 0.5 μJy/bm in the continuum at 100 GHz is required to map structures in the dust distribution created by planets of mass down to 10 Earth-masses and orbital radius of 2.5 AU in a couple hundred systems out to a distance of 400 pc. There is a desire to reach 0.3 μJy/bm to extend this work to several hundred systems out to a distance of 700 pc.
- **KSG1-003**: Matching resolution (i.e., 5 mas) and achieving a continuum rms noise of order 0.07 μJy/bm at 30 GHz will map the planet–disk interactions where the disk emission is expected to be optically thin. There is a desire to reach 0.04 μJy/bm to extend this work to a couple hundred systems out to a distance of 400 pc.
- **KSG1-004**: Observations would benefit from the largest possible aggregate bandwidth to maximize continuum sensitivity, and from full polarization capabilities to better constrain the properties of the dust grains.
- **KSG1-005**: A field of view larger than 2" is required to map the entire disk in a single pointing.
- **KSG1-006**: A maximum recoverable scale of at least 1"–2" is required to minimize the effects of spatial filtering.

3.2 KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

Summary: The ngVLA shall be able to detect predicted, but as yet unobserved, complex prebiotic species that are the basis of our understanding of chemical evolution toward amino acids and other biogenic molecules. It shall also allow us to detect and study chiral molecules, testing ideas on the origins of homochirality in biological systems. The detection of such complex organic molecules will provide the chemical initial conditions of forming solar systems and individual planets. [See RD11]

Driving Science Use Cases: AC5

Supporting Science Use Cases: AC1, AC4, AC6, SS06, AC2 (rms amended), AC3 (rms amended)

One of the most challenging aspects in understanding the origin and evolution of planets and planetary systems is tracing the influence of chemistry on the physical evolution of a system from a molecular cloud to a solar system. The ngVLA shall enable unprecedented observations of interstellar chemistry from the densest star-forming regions of the Galaxy to protoplanetary disks. Existing facilities have already shown the stunning degree of molecular complexity present in these systems.

With a unique combination of sensitivity and spatial resolution, the ngVLA shall permit the observation of both highly complex and very low-abundance chemical species that are exquisitely sensitive to the physical conditions and evolutionary history of their sources, which are out of reach of current observatories. In turn, by understanding the chemical evolution of these complex molecules, unprecedentedly detailed astrophysical insight can be gleaned from these astrochemical observations.

The ngVLA shall enable an unprecedented view into complex organic (prebiotic) chemical evolution in the ISM. Observations of a substantial number of predicted, but as yet undetected, complex prebiotic species are needed to truly understand chemical evolution toward amino acids and other biogenic molecules. We are rapidly approaching the point of diminishing returns at which deep observations with ALMA and the GBT will no longer reveal new spectral lines, due to a combination of sensitivity limits and line-confusion at higher frequencies. A unique combination of sensitivity and resolution is required to enable better depth than any pre-existing surveys for prebiotic molecules in the Galaxy. For example, the deepest current survey for prebiotic molecules is being done with the GBT, but its spatial resolution limitations preclude any benefits from pushing any deeper in sensitivity.

Both problems can be solved by sensitive observations in the cm-wave regime. State-of-the-art models predict these molecules will display emission lines with intensities that should be clearly detectable with the ngVLA, but well below the current detectability thresholds of existing telescopes including ALMA, GBT, and IRAM.

Figure 2 shows simulations of a representative set of the types of molecules whose discovery shall be enabled by the ngVLA: N, O, and S-bearing small aromatic molecules, direct amino acid precursors, biogenic species such as sugars, chiral molecules, and, possibly amino acids themselves. The simulation assumes column densities of 10^{12}–10^{14} cm^{-2} (with more complex molecules being assigned lower column densities), a temperature of 200 K, and 3 km/s linewidth.

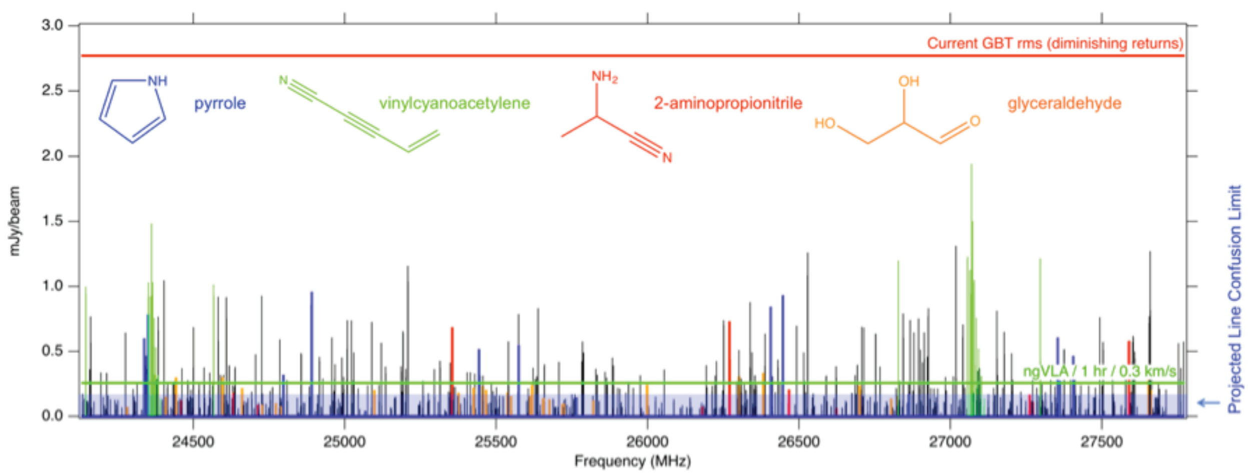

Figure 2 - A conservative simulation of a representative set of 30 currently undetected complex interstellar molecules (in black) that are likely to be detectable by the ngVLA above the confusion limit of an ngVLA survey in and around "hot" cores with source sizes typically of ~1"–4". These lines are not observable with current facilities. A few key molecules are highlighted in color.

A highlight of the unique prebiotic science that shall be made possible by the ngVLA is the study of chirality and its drivers, particularly the origin of homochirality in biological systems. Chiral molecules, that is, molecules whose mirror image is not identical to the original, are central to biological function. Indeed, the mystery of homochirality, nature's use of only one of the mirror images in most biological processes, plays a central role in our quest to understand the origins of life, as well as being considered a nearly unambiguous biomarker. There is no energetic basis for the dominance in life of one handedness of a chiral molecule over another, but rather, a slight excess was likely inherited at some point in the evolutionary process and amplified by life. Given that material in planetary systems has been shown to be inherited from their parent molecular clouds, an excess of a particular handedness in that cloud may be the spark that drives homochirality in a certain direction.

One possible route to generate a chiral excess is through UV-driven photodissociation of chiral molecules by an excess of left or right circularly polarized light. The ability not only to detect, but to image the abundance of chiral species at spatial scales commensurate with observations of circularly polarized light toward star-forming regions, would be a giant leap forward. Using known, polarization-dependent photodissociation cross sections from laboratory studies, these observations would enable quantitative estimates of potential UV-driven excess.

While such studies are well beyond the capability of existing observatories, they shall be achievable with the ngVLA. Chiral molecules, like other complex species detected earlier, are necessarily large, with propylene oxide, the only detected chiral species to date (McGuire et al. 2016), being perhaps the only example simple enough for detection with existing facilities. The ngVLA shall provide the sensitivity and angular resolution required to detect additional, biologically relevant chiral species, such as glyceraldehyde.

3.2.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG2-001**: An angular resolution on the order of 50 mas is needed near 30 GHz.
- **KSG2-002**: An rms of 30 μJy/bm/km/s for frequencies between 16–50 GHz is required.
- **KSG2-003**: A spectral resolution of 0.1 km/s is required, preferably concurrent with broadband (4+ GHz) observations.
- **KSG2-004**: Recovery of angular scales up to the expected range of 2”–10”.
- **KSG2-005**: At the desired sensitivity, the spectra must not be corrupted by spurious self-generated signals or changes in bandpass structure that cannot be removed through calibration.
- **KSG2-006**: An emissive spectral dynamic range better than 50 db is required to enable imaging of faint prebiotic molecules in the presence of bright line emission within the field of view.

3.3 KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

Summary: The ngVLA shall have the sensitivity to survey cold gas in thousands of galaxies back to early cosmic epochs, while simultaneously enabling routine sub-kiloparsec scale resolution imaging of their gas reservoirs. In doing so, the ngVLA will afford a unique view into how galaxies accrete, process, and expel their gas through detailed imaging of their extended atomic reservoirs and circumgalactic regions. The ngVLA shall also have enough sensitivity to map the physical and chemical properties of molecular gas over the entire local galaxy population. These studies will reveal the detailed physical conditions for galaxy assembly and evolution throughout the history of the universe. [See RD21, RD19.]

Driving Science Use Cases: HiZ1, HiZ5, NGA2, NGA8

Supporting Science Use Cases: HiZ2, HiZ3, HiZ6, HiZ7, HiZ8, HiZ10, NGA3, NGA5, NGA6, NGA7, NGA9, NGA10

The processes that lead to the formation and evolution of galaxies throughout cosmic history involve the complex interplay between hierarchical merging of dark matter halos, accretion of primordial and recycled gas, transport of gas within galaxy disks, accretion onto central super-massive black holes, and the formation of molecular clouds that subsequently collapse and fragment. The resulting star formation and black-hole accretion provide large sources of energy and momentum that not only light up galaxies but also bring about large changes in their gas reservoirs that we call feedback. How is gas accreted onto galaxies? What regulates the growth of galaxies throughout cosmic history? How is gas transported within galaxies and expelled by fountains and winds? How is gas inside galaxies influenced by local processes of star formation and black-hole accretion? How do the energetics, turbulent structure, self-gravity, density, and chemical state of the gas change as the gas cycles between different phases, and how do these processes depend on galaxy properties or location in a galaxy?

Observations of these processes not only constrain the dominant feedback mechanisms and timescales, but also establish useful chemical clocks and produce the observations necessary for interpreting spectroscopy across the universe out to the highest redshifts.

The ngVLA shall have the capability to carry out unbiased, large cosmic volume surveys at virtually any redshift down to an order of magnitude lower gas masses than currently possible, thus exposing the evolution of gaseous reservoirs from the earliest epochs to the peak of the cosmic history of star formation. The ngVLA shall have the sensitivity to detect and image small amounts of low-excitation molecular material, thereby opening up the study of the formation, growth, and evolution of disks through the influx and accretion of material in the form of minor mergers (Figure 3).

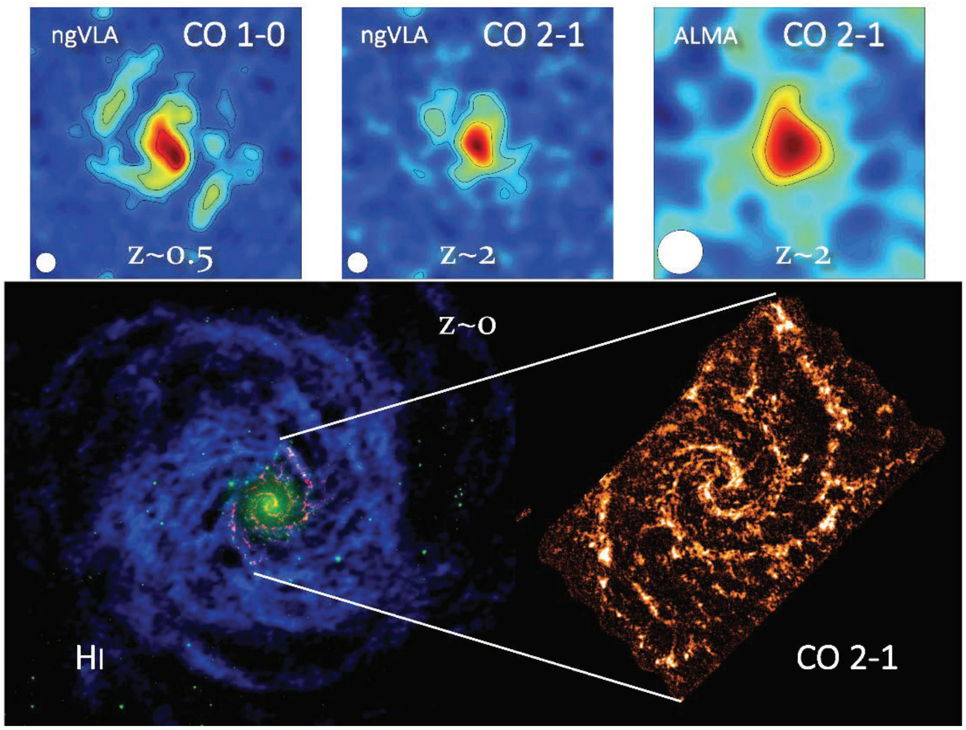

Figure 3 - ngVLA simulations of M51 (the Whirlpool Galaxy), top frames; and the grand-design spiral galaxy NGC 628 (M74), bottom frames. Details provided in main text.

The top panels of Figure 3 illustrate the results of simulations based on M51 (the Whirlpool galaxy) with molecular mass scaled by factors of 1.4 (z = 0.5) and 3.5 (z = 2) to match it to the lowest molecular mass galaxies currently observable at ALMA and NOEMA [RD39]. The corresponding SFR for the z = 2 model is 25 $M_\odot$/yr. The synthesized beam shown in the bottom left corner is (left to right) θ = 0.19", 0.20", and 0.43", corresponding to linear scales L = 1.2, 1.7, and 3.7 kpc, respectively. The corresponding maximum surface brightness is T_B = 6.7, 2.1, and 1.0 K, and the black contours enclose regions with SNR ≥ 3, 5, 10, and 20. The tapering of the beam is designed to provide the best compromise between angular resolution and SNR, and the integration times are 30 hours in all cases. The spatial and kinematic information recovered by the ngVLA allows the measurement of a precise rotation curve, which would only be possible to obtain from ALMA with an extremely large time investment. For full details see [RD39].

The bottom panels of Figure 3 show an example from the nearby universe: the grand-design spiral galaxy NGC 628 (M74) located 7.3 Mpc away. This composite illustrates the molecular disk imaged in CO by ALMA (red), the stellar disk imaged at 4.5 μm by *Spitzer* (green), and the atomic disk imaged in HI by the VLA (in blue), showing the atomic and molecular gas phases to which the ngVLA shall be sensitive. The right panel shows a close-up of the area mapped in CO $J = 2 \rightarrow 1$ at 1" resolution: the ngVLA would be capable of quickly producing a significantly deeper map at similar angular resolution that would include not only CO $J = 1 \rightarrow 0$, but also dense gas tracers, molecular isotopologues, and many other molecules throughout the λ = 3–4 mm band. In doing this, the ngVLA shall image the physical and chemical state and structure of the cold ISM at high resolution on statistically significant galaxy samples, providing unique insights into these processes.

By providing access to the cold molecular gas content and kinematics in galaxies at all redshifts, the ngVLA offers a critical missing component to high-resolution multi-wavelength studies that will be undertaken with 30 m class optical telescopes, JWST, ALMA, and upcoming large NASA missions to image the process of galaxy assembly throughout the formative times of cosmic history. The nearby universe, in particular, provides the ideal laboratory to study the mechanisms that drive some aspects of galaxy evolution. Galaxies continue to accrete material from their surroundings throughout their existence. This material gathers in their outer disks as HI gas, constituting the largest gas reservoir in galaxies. The ngVLA shall provide the combination of surface brightness sensitivity and resolution necessary to understand the physical makeup of these reservoirs (Figure 3) by being able to survey the structure of the cold, star-forming interstellar medium at the parsec-resolution of star-forming units beyond the Virgo cluster (~20–30 Mpc distances).

In addition to CO, the ngVLA shall have the sensitivity to image a host of other molecular tracers with transitions that are more than an order of magnitude weaker. These other molecular species provide a range of cold interstellar medium diagnostics that will yield maps of the motion, distribution, and physical and chemical state of the gas as it flows in from the outer disk, assembles into clouds, and experiences feedback due to star formation or accretion into central super-massive black holes. The ngVLA shall enable large systematic studies, taking advantage of chemical footprints that are beyond the limits of current capabilities to yield key insights on the processes that shape galaxies. The deep imaging of the atomic gas in the outskirts of galaxies, the outer regions that constitute the interface between the inner star-forming disk, and the cosmic web will distinguish between settled extended HI disks, compact high velocity clouds, merger remnants, and tidal dwarfs and other tidal features.

Simultaneous imaging of free-free and synchrotron continuum emission provides the full context of star formation and accretion activity. The ngVLA shall provide sensitive (i.e., rms noise of 0.15 μJy/bm at 33 GHz and 1" resolution) continuum imaging over multiple bands spanning the frequency range of 1.2–116 GHz to enable accurate separation of non-thermal and free-free emission. This in turn will yield star formation maps for a large, heterogeneous sample of nearby galaxies, delivering Hα-like images that optical astronomers have relied on heavily without having the additional complications of extinction and contamination by nearby [NII] emission. These maps would also significantly improve upon current integral field unit spectroscopic maps (e.g., CALIFA, MANGA, ATLAS^{3D}) that, even when able to extinction correct via the Balmer decrement, still miss the youngest and most heavily enshrouded star formation active in galaxies. At an rms noise of 0.15 μJy/bm at 33 GHz, such radio maps will reach a sensitivity of ~0.005 $M_\odot$/yr/kpc^2 out to a distance of Virgo (the nearest massive cluster at d ~16.6 Mpc), matching the sensitivity of extremely deep Hα images. Furthermore, at 1" resolution, which is similar to that delivered by ground-based optical facilities, such maps will sample ~100 pc scales out to the distance of Virgo which are the typical sizes of GMCs and giant HII regions.

Then ngVLA shall also be able to use the same data to create finer resolution (i.e., 0.1" or even higher for brighter systems) to perform the same multi-frequency radio continuum analysis for discrete HII regions and supernova remnants to complement high-resolution, spaced-based optical/NIR observations (e.g., HST, JWST, etc.). At 0.1" resolution, the data will sample ~10pc scales in galaxies out to the distance of Virgo to resolve and characterize (e.g., size, spectral shape, density, etc.) discrete HII regions and supernova remnants with a sensitivity to diffuse free-free emission of ~0.5 $M_\odot$/yr/kpc^2.

It is worth pointing out that neither ALMA nor the SKA Phase 1 have the power to carry out these observations. The ngVLA shall have a much broader frequency coverage than the SKA Phase I. And, although ALMA is able to tackle some of these observations, the ngVLA shall have enough collecting area to survey large samples of galaxies. ALMA Band 1, for example, is roughly equivalent to the Jansky VLA performance at Q-band, and ALMA Band 3 will be almost an order of magnitude less sensitive than the ngVLA at 90 GHz. Given these science requirements, only the ngVLA shall be able to study these processes on significant galaxy samples, distant or nearby.

3.3.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG3-001**: A line rms noise of ~46 μJy/bm/km/s at 0.1" and 1" angular resolution between 10–50 GHz with a spectral resolution of 5 km/s is required for detailed studies of CO kinematics of high-z galaxies and blind CO searches of >1000 galaxies, respectively.
- **KSG3-002**: A large instantaneous bandwidth (minimum 1.6:1 BW ratio, up to 20 GHz instantaneous bandwidth) to conduct wideband observations at 5 km/s resolution is required to efficiently perform blind surveys of large cosmic volumes in a single observation to provide routine access molecular species in addition to CO (e.g., HCN, HCO^+, or N_2H^+).
- **KSG3-003**: Frequency coverage to access the transitions of formaldehyde (5 GHz and 14 GHz), ammonia (23–27 GHz), methanol (particularly the 36 GHz masers), deuterated molecules (~ 70 GHz), and a host of dense gas tracers (~ 90 GHz) besides CO (115 GHz) and HI (1.4 GHz) are required.
- **KSG3-004**: Thermal line imaging of CO (115 GHz) with an rms noise of 0.75 K at 0.1" angular resolution and 1 km/s spectral resolution is required for detailed studies of CO in the nearby universe. A spectral dynamic range of 30 db is also required, while 40 db is desired.
- **KSG3-005**: Thermal imaging with an rms noise of 1–5 mK between 70 and 116 GHz at 1–5" angular resolution and 1–5 km/s spectral resolution is required to support studies of gas density across the local universe. A spectral dynamic range of 30 db is also required, while 40 db is desired.
- **KSG3-006**: Full 1.2–116 GHz frequency coverage is required to obtain accurate, simultaneous measurements of star formation rates from free-free continuum and radio recombination line (RRL) emission. A spectral dynamic range of better than 40 db is required for accurate RRL line-to-continuum ratios.
- **KSG3-007**: Angular resolutions of 0.1–1" for continuum imaging at all available frequencies are required.
- **KSG3-008**: A continuum rms noise of 0.15 μJy/bm at 33 GHz for a 1" synthesized beam is required for robustly studying star formation within nearby, star-forming galaxies. Given the expected 33 GHz peak brightnesses within such galaxies, the resulting dynamic range requirement is ~37dB.
- **KSG3-009**: Accurate recovery of flux density for extended objects on arcminute scales at all frequencies is required.
- **KSG3-010**: The ability is needed to make large mosaics or conduct on-the-fly line and/or continuum mappings of galaxies that extend beyond the area of a single primary beam.
- **KSG3-011**: A brightness dynamic range of 50 and 40 dB is required at 10 GHz for deep-field continuum studies of MW-like galaxies at "cosmic noon" to not be dynamic-range-limited in total and polarized intensity, respectively.
- **KSG3-012:** An absorptive dynamic range of 40 dB to measure the physical properties of Galactic neutral Hydrogen for ~1000 sight lines with a velocity resolution of 0.4 km/s and +/- 150 km/s velocity range at an angular resolution of 0.1".

3.4 KSG4: Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity

Summary: Pulsars in the Galactic Center represent clocks moving in the space-time potential of a super-massive black hole and would enable qualitatively new tests of theories of gravity. More generally, they offer the opportunity to constrain the history of star formation, stellar dynamics, stellar evolution, and the magneto-ionic medium in the Galactic Center. The ngVLA shall achieve a combination of sensitivity and frequency range, enabling it to probe much deeper into the likely Galactic Center pulsar population to address fundamental questions in relativity and stellar evolution. [See RD33.]

Driving Science Use Cases: TDCP1

Supporting Science Use Cases: N/A

Testing theories of gravity requires probing as close as possible to the strong field regime. This is illustrated in the left panel of Figure 4 where the abscissa shows the depth of the potential probed and the ordinate shows the space-time curvature for the orbit of a test mass around a central mass. It is by finding ways to probe as far as possible into the upper right corner of this figure that one can begin to highly constrain theories of gravity beyond General Relativity. Pulsars near Sgr A* (i.e., within 0.5"~0.02 pc) probe regimes comparable to the infrared S stars but, as they represent clocks, pulsars probe different aspects of theories of gravity. Pulsars in compact binaries, such as might form from three-body exchanges in the dense nuclear cluster, lie in the top right of the left panel of Figure 4. Consequently, pulsars in the Galactic Center offer a powerful way to test theories of gravity.

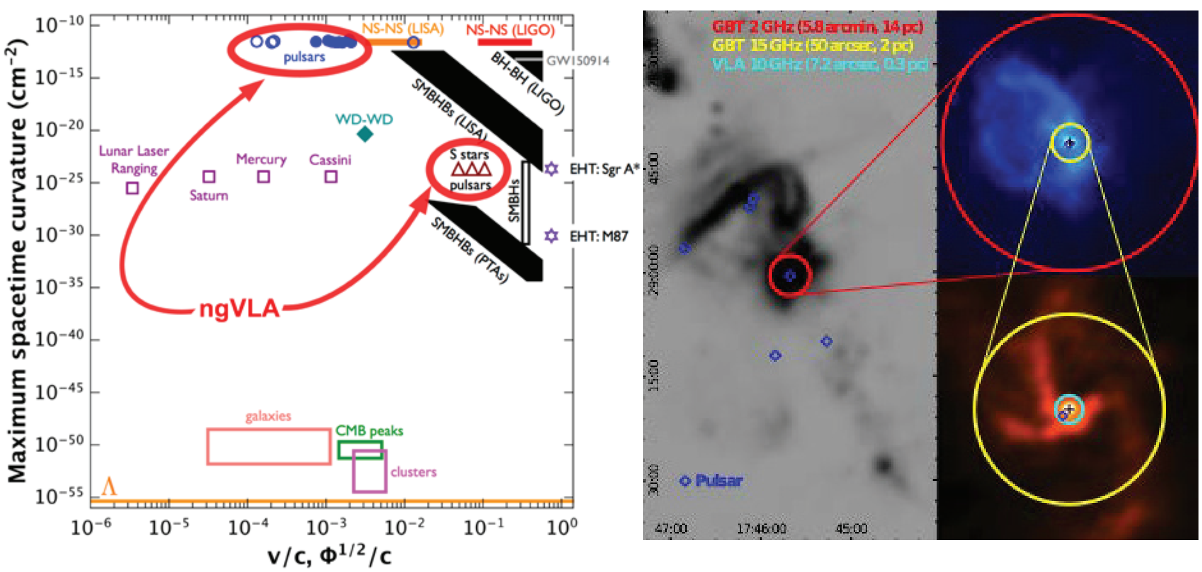

Figure 4 - Left: The abscissa shows the depth of the potential probed and the ordinate shows the spacetime curvature for the orbit of a test mass around a central mass—probing as far as possible into the upper right corner is most constraining on theories of gravity beyond General Relativity. Pulsars near Sgr A* (i.e., within 0.5"~0.02 pc) probe regimes comparable to the infrared S stars, but, as they represent clocks, pulsars probe different aspects of theories of gravity. Pulsars in compact binaries, such as might form from three-body exchanges in the dense nuclear cluster, are in the upper center of the figure. Right (credit: R. Wharton): The distribution of known pulsars near the Galactic center. Despite being the region of highest density in the Galaxy and despite having been searched multiple times at a range of frequencies with sensitivities comparable to that of the VLA, only a small number of pulsars are known. Even more puzzling, the closest pulsar to Sgr A* is the magnetar PSR J1745-2900, yet radio-emitting magnetars are an extremely rare sub-class of the field pulsar population (i.e., <1%).

Various indications suggest that the Galactic Center region contains several neutron stars. These range from the currently observed population of young, hot stars, to candidate pulsar wind nebulae and X-ray binaries, to estimates of the supernova rate derived from the diffuse X-ray emission. Millisecond pulsars in the inner Galaxy are the astrophysical alternative to dark matter annihilation to explain the observed γ-ray *Fermi* excess. Relevant reviews on the expectations for millisecond pulsars in the Galactic Center include Wharton et al. (2012) and Eatough et al. (2015). The resulting estimates for the number of active pulsars beamed toward the Earth are as high as 1,000. Notably, given the possibility of exotic compact binaries and the strong space-time potential near Sgr A*, it is possible for even canonical pulsars (with spin periods ~1 s) to provide useful measurements.

While as many as 1000 are predicted, only a handful of pulsars in the central half-degree of the Galaxy are currently known (right panel of Figure 4). Several factors make finding pulsars in the Galactic Center difficult. Pulsars are generally faint: pulsars at distances comparable to or greater than the distance to the Galactic Center represent only 20% of the current census (480/2613), and nearly half of these have been discovered in the past ten years even though pulsar searches have been conducted for half a century. The steady increase in the discovery of more distant pulsars results from a combination of larger and more sensitive telescopes, larger bandwidth systems, and improved detection algorithms.

Moreover, not only are pulsars faint, but the intense emission from other sources toward the inner Galaxy increases the system temperature substantially at lower frequencies, leading to searches generally being less sensitive. Finally, enhanced radio wave scattering toward the inner Galaxy further decreases the effective sensitivity of searches, by increasing both the dispersion measure smearing and pulse broadening. Indeed, the first magnetar (highly magnetized pulsar) discovered near Sgr A*, PSR J1745-2900, shows substantial pulse broadening relative to most other pulsar lines of sight, although it is below original estimations.

Observing at higher frequencies than those planned for the SKA can mitigate radio-wave scattering, but by itself the benefits are limited because of the generally steep radio spectra of pulsars. The ngVLA shall have the necessary collecting area at high (i.e., >3 GHz) frequencies to find these objects within the central 1 arcmin (50 pc) diameter surrounding the Galactic Center (Figure 4).

Beyond the Galactic center, the ngVLA shall have the capabilities to enable another approach to probing gravity via pulsar–black hole binaries, for which a small number are expected in the Galaxy. Given that they are likely to be rare and therefore distant (for example, in the current census of approximately 2,500 pulsars, no pulsar–black hole binaries are known, though there are several neutron star-neutron star binaries) any pulsar–black hole binaries in the Galactic disk could experience significant pulse broadening. Moreover, a significant limitation to finding highly relativistic binaries could be the accelerations experienced by the pulsars.

The ngVLA shall have imaging capabilities that enable hybrid approaches to finding pulsars, conducting a search first for compact sources (potentially with steep spectra), followed by a targeted periodicity search on candidates. For example, Bhatka et al. (2017) used this hybrid imaging periodicity technique in their recent successful detection of the recycled pulsar PSR 1751-2737. The achieved sensitivity of the ngVLA at radio frequencies of 3–30 GHz shall open a new door for the discovery and study of pulsars not only in orbit around Sgr A* but throughout the inner Galaxy.

3.4.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG4-001**: The ngVLA shall support pulsar search and timing observations from ~1 to 30 GHz for Galactic Center pulsars. Pulsar searching requires 100 μs scales (20 μs scales desired), while timing requires 20 μs resolution. While there are uncertainties and the distribution could be inhomogeneous, mitigating radio wave scattering is likely to require a frequency range that includes the lower range anticipated for the ngVLA (≥3 GHz).

- **KSG4-002**: A continuum rms noise of order 50 nJy/bm is desired at 20 GHz. This is a significant improvement compared to existing 100 m class radio telescopes that have found few pulsars, indicating that substantial additional sensitivity is necessary.
- **KSG4-003**: The system timing accuracy shall be better than 10 ns (1 ns desired) over periods correctable to a known standard from 30 minutes to ten years.
- **KSG4-004**: The array shall have the ability to make multiple (minimum ten) beams (i.e., phase centers within the primary beam) within a single sub-array, or distributed amongst multiple sub-arrays.
- **KSG4-005**: Timing multiple pulsars within a single primary beam is desirable. Support for five or more independent de-dispersion and folding threads is desired.

3.5 *KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy*

Summary: The ngVLA shall be able to survey everything from the remnants of massive stars to the supermassive black holes that lurk in the centers of galaxies, making it the ultimate black hole hunting machine. High-resolution imaging abilities are required to separate low-luminosity black hole systems in our local Universe from background sources, thereby providing critical constraints on the formation and growth of black holes of all sizes and mergers of black hole–black hole binaries. The ngVLA shall also be able to identify the radio counterparts to transient sources discovered by gravitational wave, neutrino, and optical observatories. This requires high-resolution, fast-mapping capabilities to make it the preferred instrument to pinpoint transients associated with violent phenomena such as supermassive black hole mergers and blast waves.

Driving Science Use Cases: TDCP2, TDCP5, TDCP7, TDCP8

Supporting Science Use Cases: NGA12

While we now know that black holes exist on practically all mass scales, the astrophysics of how these objects form and grow remains a mystery. LIGO is now detecting black holes that are substantially more massive than previously known stellar-mass black holes, and is observing black hole–black hole mergers, although we do not know how black hole binaries form. While supermassive black holes (SMBHs) are thought to be widespread in galaxy centers, we do not understand how their growth was seeded or how (and how often) these extreme objects merge. The ngVLA shall have the sensitivity and (high) angular resolution to make dramatic progress on answering these outstanding questions.

The ngVLA shall enable a census of black holes on all scales, from stellar-mass to supermassive. In the Milky Way Galaxy, the number of X-ray binaries (containing stellar-mass black holes) is only weakly constrained to be somewhere in the range 10^2–10^8 (Tetarenko et al. 2016), based on a small sample of just 20–30 known stellar-mass black holes (McClintock & Remillard 2006). Unaffected by dust obscuration, and with the angular resolution to separate Galactic sources from background objects using proper motions, the ngVLA shall be able to survey the Galaxy to detect jet-powered synchrotron emission from weakly accreting black holes and increase the black hole sample by at least an order of magnitude.

Simply measuring the size of the population would have profound implications for key parameters impacting binary black hole formation, such as common envelope evolution and the strength of dynamical "kicks" delivered to black holes at birth (caused by asymmetries in the parent core-collapse supernovae). These parameters are key inputs into one of the core problems that has already developed in gravitational wave astronomy—whether double black holes form through normal binary stellar evolution, or whether they require globular cluster formation mechanisms.

The ngVLA shall also directly measure black hole natal kicks through determination of proper motion and parallax. Finally, with these requirements, the ngVLA will be a superb tool for multi-wavelength follow-up of these discoveries to measure the black hole mass distribution. The ngVLA should be uniquely positioned for black hole survey science, as black holes in the Galaxy will be scatter broadened at lower frequencies precluding high-resolution imaging.

While SMBHs dwell at the centers of many, if not all galaxies, we still do not understand how black holes manage to grow to masses of 10^6–10^{10} $M_\odot$. Lead contender models include the merger of less massive black hole "seeds" (i.e., remnants of Population III stars) and direct collapse of more massive black holes in early dark matter halos (Volonteri et al. 2003). These models can be best tested by measuring the occupation fraction of SMBHs in nearby, low-luminosity galaxies. Deep, high-resolution imaging of nearby galaxies will provide proper motion distinction between nearby low-luminosity active galactic nuclei and background sources (~10 μas yr^{-1}). Thereby, the ngVLA shall enable the best search possible for SMBHs, measure their occupation fraction in dwarf galaxies, and test models of SMBH formation.

By enabling both pulsar timing arrays and high-resolution imaging, the ngVLA shall be able to survey the population of binary SMBHs, measure the rate of super-massive black hole mergers through their contributions to the stochastic gravitational wave background, and image the evolution of binary SMBHs in the lead up to merger. Recently, Bansal et al. (2017) made the first measurements of the orbit of a SMBH binary with the VLBA (Figure 5). With the specified sensitivity, the ngVLA will be able to identify and measure the proper motions of double AGN in much tighter orbits, where precision tests of General Relativity could be made. Meanwhile, the ngVLA will be a key facility for monitoring millisecond pulsars to detect and characterize the nanohertz gravitational wave background from SMBH mergers, and will be complementary to gravitational wave observatories in the kHz and mHz bands.

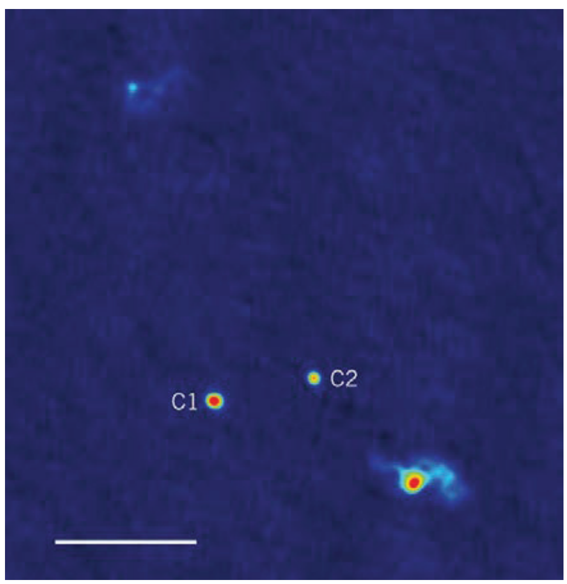

Figure 5 - The ngVLA should be an excellent tool for hunting black holes, including binary supermassive black holes. Here we show a binary system of SMBHs at z = 0.06. The black holes are separated by 7 pc (the white scale bar denotes 10 pc) with an orbital period of 30,000 yr, and jet emission is observed extending from the black hole C2. The ngVLA shall have the sensitity and high-resolution imaging capabilities to enable discovery of many more such systems, with intimate synergies to LISA and Pulsar Timing Arrays. Image from Taylor (2014).

3.5.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG5-001**: High-resolution (mas – μas) imaging with relative astrometric accuracy that is <1% of the synthesized beam FWHM or equal to the positional uncertainty in the reference frame, for a bright (SNR $\gtrsim$100) point source, is required for surveying black holes. Such high-resolution (mas – μas) imaging will enable proper motion separation of local black holes (both Galactic and in nearby galaxies, out to 15 Mpc) from background sources.
- **KSG5-002**: Long baselines are required to enable imaging the SMBH binaries that will be detected in gravitational waves by LISA and pulsar timing arrays. These astrometric science goals benefit from the implementation of very long baselines ($\gtrsim$1000 km for mas–μas accuracy). Associated VLBI recording capabilities shall be available for three or more beams (two calibrators and the science target).
- **KSG5-003**: While the key frequency range is 5–20 GHz, the availability of higher (20–50 GHz) frequencies are required for regions with high interstellar scatter broadening.
- **KSG5-004**: Multiple (i.e., a minimum of ten) sub-arrays with independent beams and pulsar timing support are desired. Precision timing of pulsars may not be sensitivity limited, but require long observations to oversample the pulse period and remove pulse jitter.
- **KSG5-005**: Pulsar timing will require 20 μs resolution and frequency coverage down to 1–2 GHz.
- **KSG5-006:** Mapping a ~7 square degree region (i.e., the localization uncertainty expected by gravitational wave detectors when ngVLA is operational; Nissanke et al. 2013) to a depth of ~1 μJy/bm at 2.5 GHz for detection of Adv. LIGO-detected NS-NS and NS-BH mergers is required. Completing the on-the-fly mapping of each epoch within ~10 hr is desirable.
- **KSG5-007:** Mapping a ~10 square degree region (i.e., the localization uncertainty expected by LISA; Lang et al. 2008) at 28 GHz to a depth of ~10 μJy/bm with on-the-fly mapping is required for localization of LISA-detected SMBH mergers. Completing the on-the-fly mapping of each epoch within ~10 hr is desirable.
- **KSG5-008**: The ability to receive and respond to external triggers rapidly is also an essential requirement to enable multi-messenger science. Triggered response time not to exceed ten minutes is required, while response time of better than three minutes is desired.
- **KSG5-009**: The ability to perform time-domain transient searchers (e.g., for fast radio bursts) requires a search capability on 100 μs scales, with 20 μs scales desired.
- **KSG5-010**: An rms noise of 0.23 μJy/bm at 10 GHz is required for a 0.6 mas beam to detect a source like GW170817 with a SNR $\approx$10 at the Adv. LIGO horizon distance of 200 Mpc and allow for the measurement of its expansion at the 5σ level.

4 Detailed Summary of Level-0 Science Requirements

Here we list specifically, and in more detail, the requirements necessary to carry out the key ngVLA science goals as identified by the community and discussed above. The Science Requirements are placed into two categories: Telescope Features (Table 1) and Performance Requirements (Table 2).

While specific integration times are not given, the science requirements must be able to achieve all five ngVLA Key Science Goals within ten years of full science operations as described in the ngVLA Reference Observing Program [RD41]. This list is meant to serve as a minimum set of requirements as there are instances where other science cases received may have needed more stringent requirements, so performance in excess of these minima are desired.

However, as stated in Section 3 above, the primary science requirement for the ngVLA is to be flexible enough to support the breadth of scientific investigations that will be proposed by its creative scientist-users over the decades-long lifetime of the instrument. Thus, it is vital that the observatory provide broad and balanced capabilities in order to allow for the unanticipated discoveries that have proven the most fundamental legacy of large astronomical observatories.

Parameter	Req. #	SciCase	Value
Frequency Coverage	SCI0001	All	The ngVLA should be able to observe in all atmospheric windows between 1.2 and 116 GHz. These frequency limits bracket spectral line emission from H_I and CO (J=1→ 0) respectively.
Observing Bands	SCI0002	KSG2-003, KSG3-003	ngVLA observing band edges should in all possible cases avoid astronomically interesting spectral lines for redshifts between z=0 and z=0.1 (See Appendix Section for a list of lines). Overlap of 1% in band edges is therefore desirable.
Frequency Selection	SCI0003	KSG1-001, KSG1-004 KSG2-003, KSG3-002, KSG3-003	The system shall support full bandwidth selection of the front end(s) without gaps in frequency coverage that is instantaneously available. Selectable bandwidth steps may be discrete if necessary. Observing multiple line diagnostics within a single band is also desirable.
Mosaics and On-the-Fly Mapping	SCI0004	KSG3-010, KSG5-006, KSG5-007	The system shall support both mosaicking and on-the-fly mapping of fields of view larger than the primary beam with full spectral capabilities in support of the survey speed requirement (SCI0106).
Triggered Observations	SCI0005	KSG5-008	The array shall have a mechanism to receive and rapidly respond to external triggers. Triggered response times not to exceed 10 minutes are required for transient science, while response times of 3 minutes are desired.
Observing Modes	SCI0006	All	The system shall observe in both narrow (spectral line) and wide-band (continuum) modes simultaneously. The goal is to maximize flexibility and sensitivity of both modes. This does not preclude a single configurable 'mode' that meets the requirements of both general use cases.
Phased Array Capability	SCI0007	KSG4-004, KSG5-004	The system shall operate both as an interferometer and phased-array simultaneously.
Beam Forming	SCI0008	KSG4-004, KSG5-004	The array shall have the ability to make multiple (minimum 10) beams (phase centers within the primary beam) within a single sub-array, or distributed amongst multiple sub-arrays, in the phased array mode.
Sub-Array Capabilities	SCI0009	KSG5-004	The system shall be divisible into multiple (i.e., at least 10) sub-arrays for operation and calibration purposes. All functional capabilities listed above should be available in a sub-array.
Sub-Array Commensality	SCI0010	N/A	Sub-arrays must concurrently function in different observing modes and should be supported at their full specification. In particular, full-bandwidth cross-correlation must be supported in a sub-array, concurrent with phased array and time-domain search capabilities in a separate sub-array.

Pulsar Timing Capabilities	SCI0012	KSG4-001 KSG4-005, KSG5-004, KSG5-005	Timing multiple pulsars within a single primary beam is required. Support for 5 or more independent de-dispersion and folding threads is desired.
Time Domain Search Capabilities	SCI0013	KSG4-001 KSG5-009	The system shall provide time-domain transient search capabilities on 100 μs scales in the phased array mode, with 20 μs scales desired.
Timing Capabilities	SCI0014	KSG4-001, KSG5-005	The system shall provide transient timing capabilities with resolution of order 20 μs.
Polarization Products	SCI0015	KSG1-004, KSG3-011	The system shall measure all polarization products simultaneously.
Solar Observation Capabilities	SCI0016	N/A	It shall be possible to observe the sun at all available frequencies.
VLBI Capabilities	SCI0017	KSG5-002 KSG5-010	It shall be possible to use the system for VLBI observations with a single element, or phased array output, at all available frequencies. Recording capabilities shall be included for a minimum of 3 beams (10 beams desired). The format should be compatible with expected VLBI arrays.
Multi-Frequency Observations	SCI0018	N/A	The system shall support either multi-frequency observations or rapid switching between bands. Switching time of 10–20 sec is desired.
Accessible Sky	SCI0019	All	The system shall be capable of observations from –40° declination to 90° declination, ensuring adequate overlap with planned southern hemisphere arrays.

Table 1 - Telescope features.

Parameter	Req. #	SciCase	Value
Continuum Sensitivity	SCI0100	KSG1-002, KSG1-003, KSG3-008, KSG4-002	An rms noise of ~0.07 μJy/bm @30 GHz and 0.5 μJy/bm @100 GHz is required for studying protoplanetary disks. See SCI01017 for corresponding VLB continuum sensitivity requirement.
Line Sensitivity	SCI0102	KSG2-002, KSG3-001, KSG3-004, KSG3-005	A line rms noise of 30 μJy/bm/km/s for frequencies between 10–50 GHz is required to support both astrochemistry studies and deep/blind spectral line surveys. A line rms noise of 1–750 mK at 5”–0.1” angular resolution and 1–5 km/s spectral resolution between 70 and 116 GHz is required to simultaneously support detailed studies of CO and variations in gas density across the local universe.
Angular Resolution	SCI0103	KSG1-001, KSG1-003, KSG5-001, KSG2-001	A synthesized beam having a FWHM ~5 mas with uniform weights is required at both 30 and 100 GHz. See SCI01018 for corresponding VLB angular resolution requirement.
Largest Recoverable Scale	SCI0104	KSG1-006, KSG2-004, KSG3-009	Angular scales of >20” x (116 GHz/ν) must be recovered at frequencies ν <116 GHz. A more stringent desire is accurate flux density recovery on arcminute scales at all frequencies.
Spectral Resolution	SCI0105	KSG2-003	A spectral resolution of at least 0.1 km/s is required. It is desirable that this spectral resolution be available over a broad (4+ GHz) bandwidth.
Survey Speed	SCI0106	KSG5-006, KSG5-007	The array shall be able to map a ~7 square degree region to a depth of ~1 μJy/bm @ 2.5 GHz and a 10 square degree region to a depth of ~10 μJy/bm @ 28 GHz within a 10 hr epoch.
Quality of the Synthesized Beam	SCI0107	All Imaging Cases	The (sculpted) synthesized beam shall be elliptical down to the attenuation level of the first side lobe and display a beam efficiency of >90% at all angular scales and frequencies, while still meeting continuum sensitivity requirements (SCI0100).
Imaging Fidelity	SCI0108	KSG1-001, KSG3-004, KSG3-005, KSG3-007, KSG3-009	The ngVLA should produce high fidelity imaging (>0.9) over a wide range of scales, spanning from a few arcmin to a few mas.
Snapshot Image Fidelity	SCI0109	KSG1-001, KSG3-005, KSG3-006	The ngVLA snapshot performance should yield high fidelity imaging on angular scales >100mas at 20 GHz for strong sources.
Photometric Error	SCI0110	KSG3-006	The photometric error for point sources shall be less than 1% at frequencies where a sufficiently accurate flux density scale is known for programs requiring highly accurate photometry.

Relative Astrometric Error	SC10111	KSG5-001 KSG5-002	The instrument shall achieve an astrometric error that is <1% of the synthesized beam FWHM or the positional uncertainty in the reference frame, for a bright (SNR $\gtrsim$100) point source.
Timing Error	SCI0112	KSG4-003	The system timing error shall be less than 10 ns (1 ns desired) over periods correctable to a known standard from 30 min to 10 yr.
Brightness Dynamic Range	SCI0113	KSG3-011 KSG3-008	The system brightness dynamic range shall be >50 db to support deep field studies at 10 GHz.
Polarization Dynamic Range	SCI0114	KSG3-011	The polarization dynamic range shall be >40 db to support deep field studies at the center of the field of view at 10 GHz.
Spectral Dynamic Range (Emissive)	SCI0115	KSG2-006	The emissive spectral dynamic range shall be >50 db to enable imaging of faint prebiotic molecules in the presence of bright emission lines within the field of view.
Spurious Spectral Features	SCI0116	KSG2-005	Self-generated spurious spectral feature flux density must be below ~95 μJy/bm in any 0.1 km/s channel, post calibration between 16–50 GHz.
VLB Continuum Sensitivity	SCI0117	KSG5-010	The continuum rms noise shall be less than ~0.23 μJy/bm at 10 GHz to detect GW events at a distance of 200 Mpc.
VLB Angular Resolution	SCI0118	KSG5-010	A 0.6 mas synthesized beam at 10 GHz is required to support measurement of proper motions for GW events at a distance of 200 Mpc
Spectral Dynamic Range (Absorptive)	SCI0119	KSG3-012	The absorptive spectral dynamic range shall be better than 40 db to measure the physical properties of Galactic neutral Hydrogen.

Table 2 - Performance requirements.

5 Appendix

5.1 Acronyms and Abbreviations

A limited set of basic acronyms used in this document are given below:

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter Array
AU	Astronomical Unit
BH	Black Hole
BW	Bandwidth
DR	Dynamic Range
FWHM	Full Width Half Max
GBT	Green Bank Telescope
GMC	Giant Molecular Clouds
GW	Gravitational Wave
IRAM	Institut de radioastronomie millimétrique
JWST	James Webb Space Telescope
KSG	Key Science Goal
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
mas	milli-arcsecond
NASA	National Aeronautics and Space Administration
NIR	Near-Infrared
ngVLA	next generation Very Large Array
NOEMA	NOrthern Extended Millimeter Array
NRAO	National Radio Astronomy Observatory
NS	Neutron Star
pc	parsec
RD	Reference Document
rms	root-mean-square
SAC	Science Advisory Council
SEFD	System Equivalent Flux Density
SKA	Square Kilometre Array
SMBH	Super Massive Black Hole
SWG	Science Working Group
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry

5.2 List of Important Molecular Lines

A more comprehensive list of molecular lines, including H and He recombination lines, is available.

Species	Chemical Name	Ordered Freq (GHz)	Resolved QNs		Species	Chemical Name	Ordered Freq (GHz)	Resolved QNs
C18O	Carbon Monoxide	109.7821734	1–0		**HNCO v=0**	Isocyanic Acid	21.9815726	1(0, 1)–0(0, 0)
13CO v=0	Carbon Monoxide	110.2013543	1–0		**HNCO v=0**	Isocyanic Acid	43.9630395	2(0, 2)–1(0, 1)
CO v=0	Carbon Monoxide	115.2712018	1–0		**HNCO v=0**	Isocyanic Acid	87.925237	4(0, 4)–3(0, 3)
					HNCO v=0	Isocyanic Acid	109.905749	5(0, 5)–4(0, 4)
HDO	Water	80.578295	1(1, 0)–1(1, 1)					
H2O v=0	Water	22.2350798	6(1, 6)–5(2, 3)		**SO2 v=0**	Sulfur dioxide	12.256583	1(1, 1)–2(0, 2)
					SO2 v=0	Sulfur dioxide	100.8781053	2(2, 0)–3(1, 3)
HCN v=0	Hydrogen Cyanide	88.631847	J=1–0		**SO2 v=0**	Sulfur dioxide	104.0294183	3(1, 3)–2(0, 2)
HNC v=0	Hydrogen Isocyanide	90.663568	J=1–0					
					SO 3Σ v=0	Sulfur Monoxide	13.0437	1(2)–1(1)
H13CO+	Formylium	86.7542884	1–0		**SO 3Σ v=0**	Sulfur Monoxide	30.0015235	1(0)–0(1)
HCO+ v=0	Formylium	89.1885247	1–0		**SO 3Σ v=0**	Sulfur Monoxide	100.02964	4(5)–4(4)
					SO 3Σ v=0	Sulfur Monoxide	109.25222	2(3)–1(2)
SiO v=0	Silicon Monoxide	43.42376	1–0					
SiO v=0	Silicon Monoxide	86.84696	2–1		**CN v=0**	Cyanide Radical	113.4881202	N=1–0, J=3/2–1/2, F=3/2–1/2
N2H+ v=0	Diazenylium	93.1737	J=1–0		**CH**	Methylidyne	3.3491926	J=1/2–1/2, Ω=1/2, F=1/2-–1/2+
N2D+	Diazenylium	77.1092433	J=1–0		**CH**	Methylidyne	4.8793511	J=5/2–5/2, Ω=3/2, F=5/2+–7/2-
					CH	Methylidyne	7.398618	J=3/2–3/2, Ω=1/2, F=3/2+–1/2-
CS v=0	Carbon Monosulfide	48.9909549	1–0					
CS v=0	Carbon Monosulfide	97.9809533	2–1		**OH v=0**	Hydroxyl	1.6122309	N=1-–1+, J=3/2–3/2, F=1–2
					OH v=0	Hydroxyl	1.6654018	N=1-–1+, J=3/2–3/2, F=1–1
H2CO	Formaldehyde	1.0658686	4(2, 2)–4(2, 3)		**OH v=0**	Hydroxyl	1.667359	N=1-–1+, J=3/2–3/2, F=2–2
H213CO	Formaldehyde	2.2381367	5(2, 3)–5(2, 4)		**OH v=0**	Hydroxyl	1.7205299	N=1-–1+, J=3/2–3/2, F=2–1
H2CO	Formaldehyde	2.483408	5(2, 3)–5(2, 4)					
H213CO	Formaldehyde	13.7788041	2(1, 1)–2(1, 2)		**HC3N v=0**	Cyanoacetylene	9.0981152	J=1–0
H2CO	Formaldehyde	14.488479	2(1,1)–2(1,2)		**HC3N v=0**	Cyanoacetylene	18.196226	J=2–1
H213CO	Formaldehyde	27.555673	3(1, 2)–3(1, 3)		**HC3N v=0**	Cyanoacetylene	27.294289	J=3–2
H2CO	Formaldehyde	28.974805	3(1,2)–3(1,3)					
H213CO	Formaldehyde	45.920064	4(1, 3)–4(1, 4)		**c-HCCCH v=0**	Cyclopropenylidene	18.343143	1(1, 0)–1(0, 1)
H2CO	Formaldehyde	48.284547	4(1,3)–4(1,4)		**c-HCCCH v=0**	Cyclopropenylidene	35.360929	4(4, 0)–4(3, 1)

Species	Chemical Name	Ordered Freq (GHz)	Resolved QNs		Species	Chemical Name	Ordered Freq (GHz)	Resolved QNs
H213CO	Formaldehyde	71.024788	1(0, 1)–0(0, 0)		**c-HCCCH v=0**	Cyclopropenylidene	46.6450454	5(5, 0)–5(4, 1)
H2CO	Formaldehyde	72.4090832	5(1,4)–5(1,5)		**c-HCCCH v=0**	Cyclopropenylidene	109.8738163	9(9, 0)–9(8, 1)
H2CO	Formaldehyde	72.837948	1(0,1)–0(0,0)					
H213CO	Formaldehyde	96.3757508	6(1, 5)–6(1, 6)		**CH3CN v=0**	Methyl Cyanide	18.397783	1(0)–0(0)
H2CO	Formaldehyde	101.332991	6(1,5)–6(1,6)		**CH3CN v=0**	Methyl Cyanide	36.7954747	2(0)–1(0)
					CH3CN v=0	Methyl Cyanide	91.9870876	5(0)–4(0)
H2CS	Thioformaldehyde	1.0464877	1(1, 0)–1(1, 1)		**CH3CN v=0**	Methyl Cyanide	110.3834999	6(0)–5(0)
H2CS	Thioformaldehyde	3.13938	2(1, 1)–2(1, 2)					
H2CS	Thioformaldehyde	10.46397	4(1, 3)–4(1, 4)		**NH3 v=0**	Ammonia	18.391562	6(1)0a–6(1)0s
H2CS	Thioformaldehyde	15.69512	5(1, 4)–5(1, 5)		**NH3 v=0**	Ammonia	18.884695	6(2)0a–6(2)0s
H2CS	Thioformaldehyde	21.97171	6(1, 5)–6(1, 6)		**NH3 v=0**	Ammonia	21.134311	4(1)0a–4(1)0s
					NH3 v=0	Ammonia	21.285275	5(3)0a–5(–3)0s
CH3OH vt=0	Methanol	12.178597	2(0, 2)–3(-1, 3)		**NH3 v=0**	Ammonia	21.7033582	4(2)0a–4(2)0s
CH3OH vt=0	Methanol	19.9673961	2(1, 1)–3(0, 3)		**NH3 v=0**	Ammonia	22.2345058	3(1)0a–3(1)0s
CH3OH vt=0	Methanol	44.901825	2(2, 0)–3(0, 3)		**NH3 v=0**	Ammonia	22.653022	5(4)0a–5(4)0s
CH3OH vt = 0	Methanol	48.376892	1(0, 1)–0(0, 0)		**NH3 v=0**	Ammonia	22.688312	4(3)0a–4(–3)0s
CH3OH vt=0	Methanol	96.74455	2(0, 2)–1(0, 1)		**NH3 v=0**	Ammonia	22.8341851	3(2)0a–3(2)0s
CH3OH vt=0	Methanol	97.582804	2(1, 1)–1(1, 0)		**NH3 v=0**	Ammonia	23.098819	2(1)0a–2(1)0s
CH3OH vt=0	Methanol	108.893963	0(0, 0)–1(-1, 1)		**NH3 v=0**	Ammonia	23.6944955	1(1)0a–1(1)0s
13CH3OH vt=0	Methanol	14.78227	2(0, 2)–3(-1, 3)		**NH3 v=0**	Ammonia	23.7226333	2(2)0a–2(2)0s
13CH3OH vt=0	Methanol	23.14544	4(0, 4)–3(1, 2)		**NH3 v=0**	Ammonia	23.8701292	3(3)0a–3(-3)0s
13CH3OH vt=0	Methanol	23.98025	2(1, 1)–3(0, 3)		**NH3 v=0**	Ammonia	23.6944955	1(1)0a–1(1)0s
13CH3OH vt=0	Methanol	47.20521	1(0, 1)–0(0, 0) + +		**15NH3**	Ammonia	22.6249295	1(1)0a–1(1)0s
13CH3OH vt=0	Methanol	47.20955	(0, 1)–0(0, 0)		**NHD2**	Ammonia	28.561699	2(1, 2)0s–2(0, 2)0a
13CH3OH vt=0	Methanol	71.15521	1(1, 0)–2(0, 2)		**NHD2**	Ammonia	38.738586	2(1, 2)0a–2(0, 2)0s
13CH3OH vt=0	Methanol	94.411016	2(0, 2)–1(0, 1)		**NH2D**	Ammonia	85.926278	1(1, 1)0s–1(0, 1)0a
13CH3OH vt=0	Methanol	95.20866	2(1, 1)–1(1, 0)		**NH2D**	Ammonia	110.153594	1(1, 1)0a–1(0, 1)0s
13CH3OH vt=0	Methanol	103.084391	2(-2, 1)–2(1, 1)		**NHD2**	Ammonia	110.81285	1(1, 0)0a–1(0, 1)0a
13CH3OH vt=0	Methanol	109.16412	0(0, 0)–1(-1, 1)		**NHD2**	Ammonia	110.8967	1(1, 0)0s–1(0, 1)0s

5.3 Remaining Questions

The following science requirements have been identified as possibly needing further input and will be addressed in future releases of this document.

5.3.1 Angular Resolution

Characterizing the evolution of black holes (ngVLA KSG5; Section 3.5) could benefit from more quantitative substantiation. It is currently thought that 2.5 mas angular resolution at 30 GHz may be required. This would allow for statistically significant proper motion measurements of nearby low-luminosity active galactic nuclei against background sources (~10 μas yr^{-1}) assuming <~1% relative astrometric accuracy for SNR~100 detection. This is currently accommodated by our 1000 km baselines.

5.3.2 Quality of the Synthesized Beam

Current requirement may be infeasible when combined with the sensitivity requirements. This needs to be reconciled during the internal configuration study.

5.3.3 OTF Mapping

Is full spectral resolution required in the OTF mode?

5.3.4 Data Latency Requirement

Is there a subset of science observations that require data be delivered to the PI in rapid fashion to enable self-triggering of new observations? Observational modes that support a "quick-look" reduction to trigger new observations on the ngVLA or other observatories may be required, and a maximum data delivery delay may need to be supported by the post-processing system. Such a latency requirement on data/science product delivery for certain science cases should be further explored.

Legacy Science Program

020.10.05.00.00-0004-PLA

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M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.06.03 16:33:27 -06'00'	Asst. Director, NM-Operations, NRAO	2019-05-19

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Change Record

Version	Date	Sections	Change Description
1	2017-08-04	All	Writing up the initial idea.
2	2017-11-13	All	Incorporating comments from GXH.
3	2018-03-02	All	Feedback from Sci Ops. Group and MM: execution of LSPs starts after First Look Science activities.
4	2018-09-18	All	Comments from SAC and STRR.
5	2019-02-25	Section 4	Including figures on archival data usage of NASA Great Observatories
A	2019-05-20	All	Replaced figures with higher-resolution versions and prepared document PDF for approval and release.

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1 Introduction

The next-generation Very Large Array (ngVLA) Legacy Science Program (LSP) is designed to support observing or archival projects that require significant resources (e.g., a dedicated team, computing, software development, etc.) to carry out those observations, develop tools, perform non-standard data reduction/processing, and associated analyses that are outside the reach of NRAO expertise and/or the scope of normal ngVLA Science Operations. Such projects will additionally be expected to provide the greater community with Enhanced Data Products (EDPs), analysis software, tools, and other services that go beyond what can be done through the NRAO Science Ready Data Product (SRDP) initiative.

This program is largely modeled after the highly successful NASA Legacy/Key Science Programs that have generated both tremendous science yields and community engagement across all wavelengths and scientific disciplines.

As such, this program is motivated by a desire to enable major science observing projects throughout the ngVLA operational lifetime, with the goal of creating a substantial and coherent collection of archived observations that can be used by subsequent ngVLA researchers, ultimately leading to new PI-led observing projects.

Legacy Science projects are distinguished from typical PI-led general observing investigations by the following fundamental principles:

- They are large and coherent science projects, not reproducible by any reasonable number or combination of smaller general observing investigations.
- They have general and lasting importance to the broader astronomical community for which the ngVLA data will yield a substantial and coherent database.
- They generate raw and pipeline-processed data that enter the public domain immediately upon NRAO processing and validation, thereby enabling timely and effective opportunities for follow-on observations and for archival research, with both the ngVLA and other observatories.
- They provide the community with some combination of deliverables, such as EDPs, analysis software/tools[1], etc.

Unlike general observing programs, ngVLA LSPs will be awarded funding to ensure that the programs are successfully completed in a timely manner, including the delivery of data products or analysis tools by the selected teams. The funding level shall be commensurate with the proposed work effort. Funding to support the LSP shall be included in the overall operations budget of the ngVLA.

2 Anticipated Number of Programs Awarded and Frequency

The number of LSPs shall not exceed the total funding cap for the designated period, with an expectation of about 1–3 awards every other year throughout the ngVLA's operational lifetime. This will commence after First Look Science (FLS), with the first call occurring during the later stages of Early Science operations when the system and its capabilities are better understood. We anticipate that Early Science LSPs will likely be smaller (in scope and longevity), given that the full array capabilities will not be available (e.g., see Table 1). As such, we assume they will require less financial support. Such a cadence will allow for programs to be completed prior to the commencement of additional programs, keeping annual observing pressure constant for LSPs (i.e. <15%) and proper management of the supporting budget.

[1] Any data analysis software/tools developed by the community will have to undergo a review process, be written under an agreed-upon open source license, and be delivered with the products.

The first round of LSPs executed during Early Science will provide a mechanism for the community to contribute to ngVLA commissioning efforts (e.g., by helping to enable and validate new observing modes). Such programs, along with FLS, will also allow for ngVLA data to be placed into the public domain early on, enabling the entire community to begin working with ngVLA data starting at first light. Having access to such data will both help build the ngVLA community and aid with the scientific and technical preparation of future PI-led proposals.

3 Anticipated Funding Support Levels

Funding to support LSPs shall be incorporated into the overall operations budget of ngVLA, similar to the ALMA development program, which sets aside about $5M annually for the development of future ALMA capabilities. The exact funding level per program shall be rigorously justified by each proposal and commensurate with the required work to successfully complete the project. The funding requests shall be evaluated as part of the peer-review process.

We anticipate funding levels for individual projects at the $2–4M level over about three years (see Table 1). We also expect that the first call will be released during the second half of Early Science, with three or so proposals each awarded at the $2M level. For full science operations, we assume having a call every other year with two or so programs at $3M supported for each call. This therefore requires $3M annually available for LSPs in the ngVLA operations budget.

Funding Period	Number of LSPs	Funding per LSP	Funding per Year	Total Money Required over the Period
First Look Science (2028–2031)	FLS Activities: Community provided with a series of science products that can be used to help inform any future LSP proposals.			
Early Science LSPs (2031–2034)	3	$2M	$2M	$6M
Cycle 1 (2034–2036)	2	$3M	$3M	$6M
Cycle 2 (2036–2038)	2	$3M	$3M	$6M
Cycle 3 (2038–2040)	2	$3M	$3M	$6M
Cycle 4 (2040–2042)	2	$3M	$3M	$6M
Cycle 5 (2042–2044)	2	$3M	$3M	$6M
Totals	**13**			**$36M**

Table 1 - Potential early science and first ten-year funding cycle.

4 Community Benefits

As discussed above, the ngVLA LSP provides significant benefits to the greater astronomical community. Placing ngVLA data immediately into the public domain gives all astronomers access to first-hand experience in reducing and analyzing ngVLA data for their particular science. This will help grow the ngVLA user base in several ways. For instance, having data readily available gives PIs the opportunity to construct more scientifically compelling and technically sound proposals for General Observing. Furthermore, by eventually having large, coherent sets of EDPs readily available from each LSP, astronomers will be able to take those data and incorporate them into their existing science.

EDPs have been shown to be heavily used by the community. This is evidenced in Figure 1, which plots the fraction of publications from NASA's Great Observatories resulting from archival data as a function of time. Currently, nearly half of all Great Observatories publications are completely dependent on archival data usage. Furthermore, in the case of Spitzer, over 50% of all Spitzer publications make use of their Legacy Program Products (see Figure 2). This productivity is a likely result of the EDPs being scientifically reliable and useable by anyone familiar with standard astronomical products and tools, therefore spreading their use well beyond the instrument's traditional user community. Consequently, there is every reason to anticipate a similar heavy usage of ngVLA LSP EDPs, especially given the additional complexities with processing and imaging interferometric data.

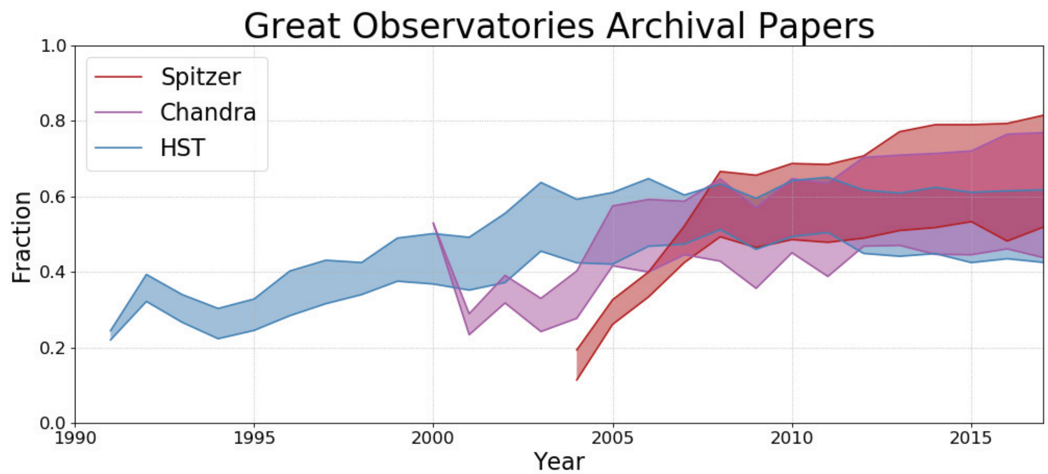

Figure 1 - The fraction of publications from NASA's Great Observatories resulting from archival data plotted as a function of time. The lower part of the shaded region represents the purely archival papers. The upper includes papers that had a mixture of PI and archival data.

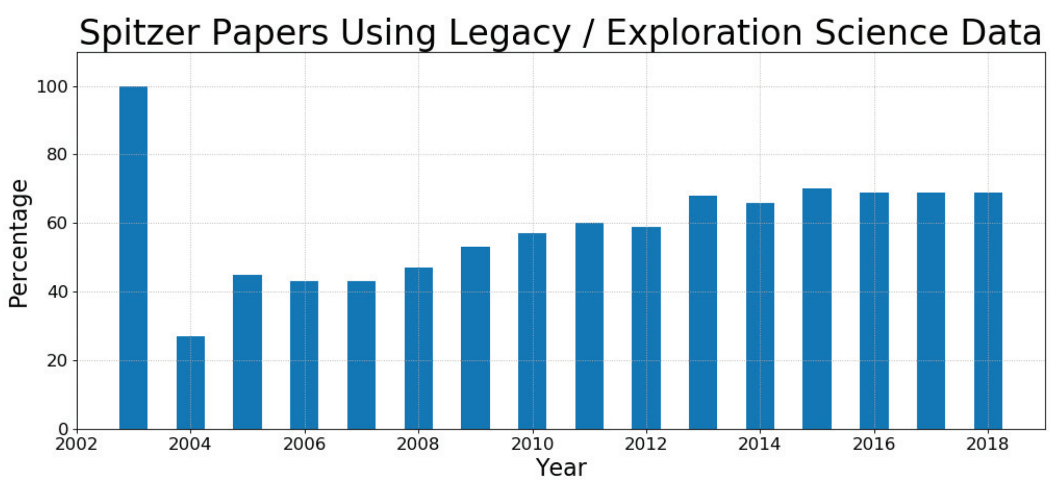

Figure 2 - The fraction of Spitzer publications that made use of Legacy Science products by year.

Creating a competitive process to obtain large amounts of ngVLA time and resources will ultimately help to build the ngVLA community across wavelengths. This is in large part because the ngVLA, by design, is an extremely flexible instrument with the ability to contribute significantly to many scientific areas, which should in turn lead to significant participation from the entire astronomical community. There is already evidence for this with ALMA, given the highly competitive nature of its general observing proposal cycle. Thus, the ngVLA LSP will bring more astronomers into the radio astronomy observer pool, which is healthy for the field intellectually and programmatically because it will help to grow the support and advocacy base.

By additionally making substantial funding available to support ngVLA LSPs, the user base will almost certainly expand to additional members of the community that are drawn to financial support. There is clear evidence that the community has the ability to become highly adaptable in taking advantage of funding opportunities independent of wavelength.

More importantly, such funding will also provide faculty members at US academic institutions the necessary resources to support students and postdocs, making them ngVLA users and increasing the numbers of astronomers in general. In doing so, the program will help alleviate some of the stress being felt by the astronomical community via a fixed amount of funding to support their science in a time when NSF research grants are tremendously competitive. This program will additionally invoke a competitive advantage to the U.S. community given that ngVLA will be open worldwide and that the EU is now offering large grants in support of scientific projects to EU-based teams.

Reference Observing Program

020.10.15.05.10-0001-REP

PREPARED BY	ORGANIZATION	DATE
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E. Murphy, Project Scientist Digitally signed by Eric J. Murphy Date: 2019.06.04 08:15:40 -04'00'	ngVLA/NM-Operations, NRAO	2019-05-16
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Version	Date	Reason
0.3	2019-02-14	Incorporate v0.3 ppt and weather conditions
1.0	2019-04-26	Mend English and pdf's missing equations, strange symbols
A	2019-05-20	Prepared document for release

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1 Charge and Approach

This document presents an analysis of whether or not the ngVLA Reference Design (Selina et al. 2018a) can reach the Key Science Goals (KSGs) in the array's first decade. The approach is to build an ngVLA Reference Observing Program (ROP). This involves systematically quantifying the technical and observing needs of the driving use cases of the KSGs identified in the ngVLA Science Requirements (Murphy et al. 2018). This analysis also folds in the ancillary information needed to evaluate the ROP.

It must be emphasized that this exercise is notional, intended only to gauge whether the ngVLA Reference Design can do what the community projects will be the highest priority science (Bolatto et al. 2017). The ROP should not be construed as dictating how science will play out during the array's first decade. As a proposal-driven facility, the ngVLA will be able to adapt to the evolving science landscape.

2 Assumptions

For context and simplicity, the analysis begins by casting the science time in Year 1 to Year 10 as wall-clock hours. A year holds ~365 days x 24 h/day ~8760 h, where h denotes hours. Barring a single-point failure, the ngVLA aims to achieve a science efficiency of 100% (Selina et al. 2018b). This means that at least one subarray will always be available for science observing. Realistically, it may take a few years to reach such perfection. Conservatively assuming a science efficiency of ~70% during the first three years, referred to as the "learning" years, thus implies ~6000 h of science observing during each of those years.

Assuming a technical readiness to begin key science observing on 2034-01-01, Year 1 is thus CY2034. To accommodate weather conditions, the ROP adopts the preliminary estimates for the science time available per Local Sidereal Time (LST) per band (Butler 2019). These estimates will be conveyed in later figures. To accommodate maintenance activities, the ROP assumes that a science subarray will observe with 95% of its antennas (Selina et al. 2018b).

The ROP assumes the science subarrays and their performance metrics as tabulated by Rosero (2019). To accommodate the quantized resolutions appearing in the performance tables, it will sometimes be necessary to modify the angular resolutions mentioned in the use cases. For the reader's convenience, Table 1 replicates Rosero's definitions of the science subarrays. In Table 1, LBA stands for Long Baseline Array, and the Mid-baseline subarray is defined as the Main subarray minus the Plains + Core subarray.

Science Subarray	Minimum Baseline (km)	Maximum Baseline (km)	Number of 18m Antennas
Main + LBA	0.027	8856.4	244
LBA	32.6[1]	8856.4	30
Main	0.027	1005.4	214
Mid-baseline	7.747	1005.4	46
Plains + Core	0.027	36.5	168
Core	0.027	1.3	94

Table 1 - ngVLA science subarray definitions.

1. Excluding the very short baselines within stations.

For other than the LBA, Table 2 shows the preliminary and conservative estimates for the calibration overheads *(Ove)* as a function of the angular resolution *(Res)* from Selena (2018b). For the LBA, phase referencing in the nodding style is assumed for Bands 1–5 and thus *Ove ~ 1.0* is adopted (Wrobel et al. 2000). *Ove* is defined in the sense that $T_{subarray} = T_{target} * (1+Ove)$, where $T_{subarray}$ is the time needed on a science subarray and T_{target} is the time needed on a science target.

Band 1		**Band 2**		**Band 3**		**Band 4**		**Band 5**		**Band 6**	
Res (mas)	*Ove*	*Res* (mas)	*Ove*	*Res* (mas)	*Ove*	*Res* (mas)	*Ove*	*Res* (mas)	*Ove*	*Res* (mas)	*Ove*
26000	0.20	7700	0.25	3800	0.50	2300	0.75	1500	0.75	700	1.00
2600	0.20	770	0.25	380	0.50	230	1.00	150	1.00	70	1.50
260	0.20	77	0.35	38	0.75	23	1.50	15	1.50	7	2.00

Table 2 - Calibration overhead as a function of angular resolution, per ngVLA band.

Band 6 is assumed to be viable from ~2 h after sunset until sunrise (Selena et al. 2018c).

For its initial release, it is assumed this document should devise a methodology and conduct a preliminary evaluation of the ROP for the "learning" years, labelled Year 1, 2 and 3. To that end, this document attempts to assign key science pilots that make significant progress toward the KSGs. Some use cases were quite quantitative, making it easy to suggest reasonable pilots. Other use cases were more aspirational, making it harder but not impossible to suggest reasonable pilots. The ROP assumes ~2000 h per year of key science, likely involving many known users. This leaves the balance of ~4000 h per year for open science, signaling that all users and all ideas are welcomed by this new world-class facility.

3 Build the Reference Observing Program

The ROP is expressed in terms of the subarray times needed by the driving use cases of the KSGs. This document first establishes the technical needs of the use cases. It then estimates the subarray times needed, per LST and per band, by folding in science subarray performance, maintenance activities, and calibration overheads.

Regarding technical needs, they were summarized in the Science Use Cases table in the Cost Model spreadsheet, with the latest update occurring on 2018-11-06. The technical needs are augmented with the sensitivity requirements quoted in submitted use cases or in later presentations or chapters of the ngVLA Science Book (Murphy 2018).

Regarding subarray time needs, the first step is to assign a science subarray to a use case by matching the case's required band, angular resolution, bandwidth, and sensitivity to the entries in the subarray performance tables. The tabulated sensitivity is then adjusted for antennas missing from the subarray due to maintenance activities. Next, the adjusted sensitivity is used to estimate T_{target}. If more than one subarray can meet the use case requirements, the subarray that will minimize T_{target} is generally picked. Then the calibration overhead *Ove* is applied to estimate $T_{subarray}$ and a suggestion is made regarding how to distribute that needed time over LSTs. Finally, the needed time is assigned to Year 1, 2, or 3, and added to the respective Figure 1, Figure 2, or Figure 3.

After completing this exercise for each of the driving use cases of the KSGs, the time needed by the ROP will be captured in Figure 1, Figure 2, and Figure 3. These figures are not classic pressure plots because time needs that overlap in LST are not being stacked.

Evaluating the viability of the ROP involves comparing its time needed per LST per band to the time available per LST per band. Estimates for the times available are provided for the months of Jan-Feb-Mar (Q1), Apr-May-Jun (Q2), Jul-Aug-Sep (Q3), and Oct-Nov-Dec (Q4). Separate estimates are provided for frequencies in Band 6 below and above 95 GHz, notionally labeled as Band 6a and 6b, respectively. The times needed during Years 1, 2, and 3 are thus separated into those four quarters and seven effective bands. Also, for each quarter, times available are adjusted by the science efficiency assumed for the "learning" years before adding those times to Figures 1, 2, and 3.

Two weather and sky bottlenecks are anticipated, namely KSG1 and KSG3 each need Band 6b, and KSG2, KSG4, and KSG5 each need Galactic Center LSTs. Staggering their pilots quarterly could help to mitigate these bottlenecks. Some degradation of weather conditions beyond the Plains of San Agustin is also anticipated. To adapt, the ROP will be on the lookout for use cases that involve point-like targets and low frequencies, and will consider forcing such cases onto the Mid-baseline subarray.

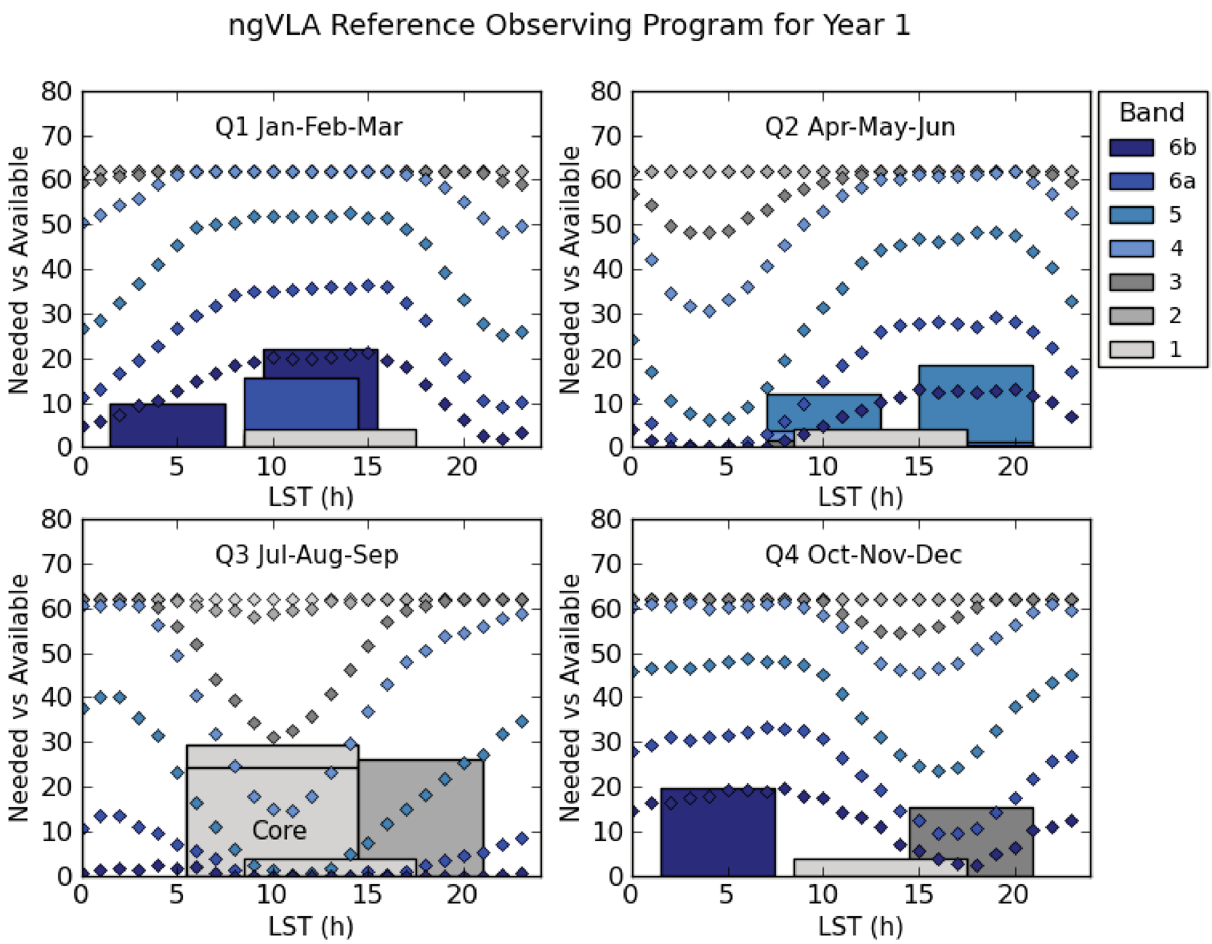

Figure 1 - Comparing the times needed (histograms) to the times available (lines) in Year 1 of the Reference Observing Program. The colors encode the bands and apply to both histograms and lines. The abscissa is the Local Sidereal Time for the Core subarray. The ordinate is the number of LST passes needed vs available. Three months offer no more than *6000 h / (4*24 h)* passes, thus ~62 passes.

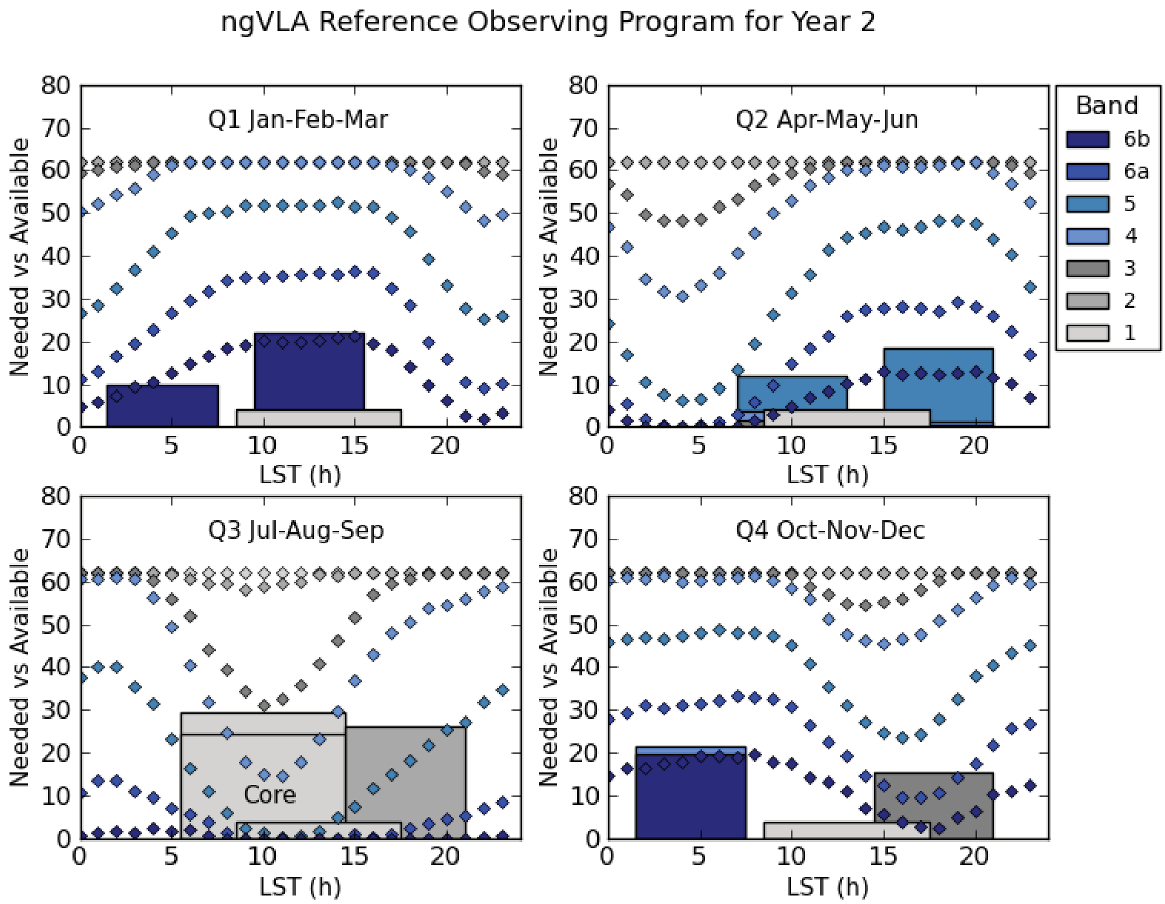

Figure 2 - Comparing the times needed (histograms) to the times available (lines) in Year 2 of the Reference Observing Program. The colors encode the bands and apply to both histograms and lines. The abscissa is the Local Sidereal Time for the Core subarray. The ordinate is the number of LST passes needed vs available. Three months offer no more than *6000 h / (4*24 h)* passes, thus ~62 passes.

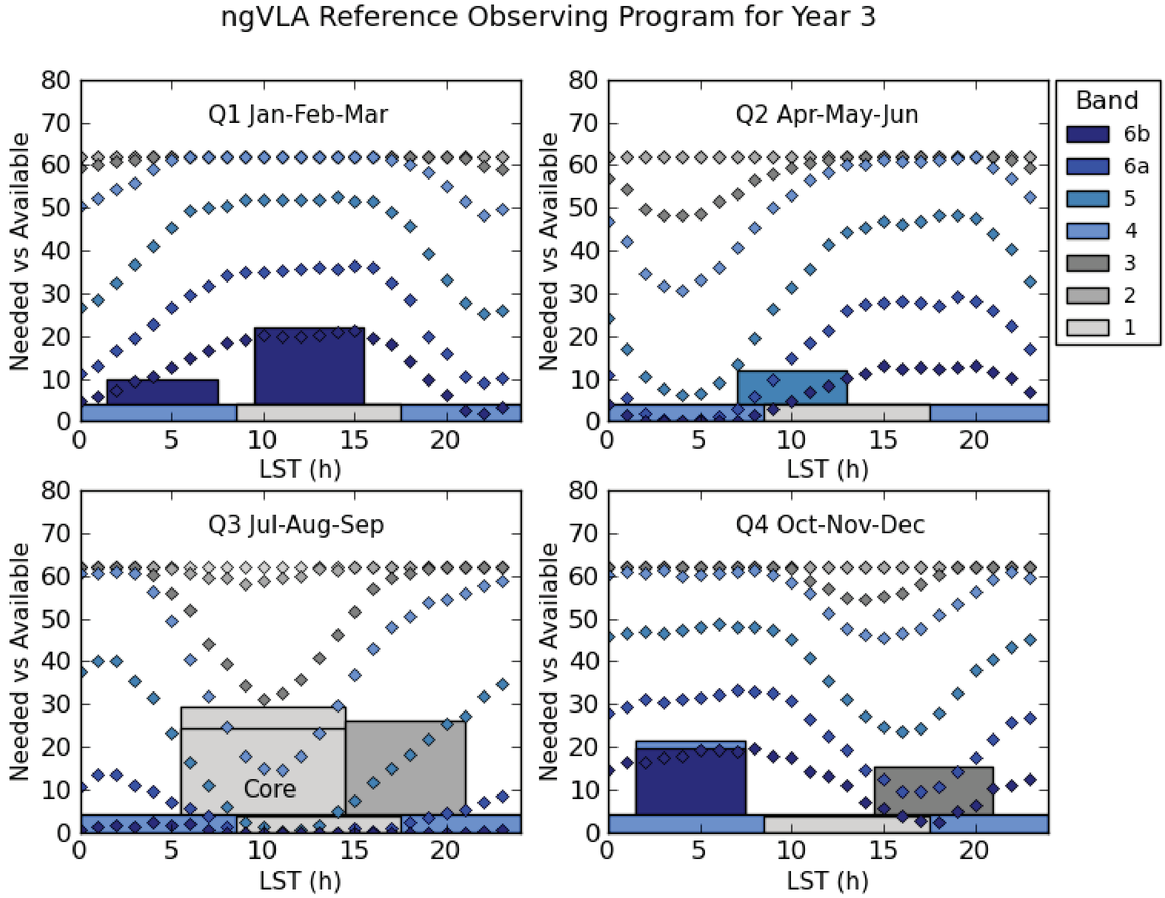

Figure 3 - Comparing the times needed (histograms) to the times available (lines) in Year 3 of the Reference Observing Program. The colors encode the bands and apply to both histograms and lines. The abscissa is the Local Sidereal Time for the Core subarray. The ordinate is the number of LST passes needed vs available. Three months offer no more than *6000 h / (4*24 h)* passes, thus ~62 passes.

3.1 KSG1: Unveiling the Formation of Solar System Analogs on Terrestrial Scales

The PF3 use cases, as updated by Ricci et al. (2018), require continuum observations at full bandwidths in Bands 6b and 4, plus a matched angular resolution of about 5 mas. Because the imaging performance tables are quantized in terms of tapered and robustly weighted resolutions (Rosero 2019), the ROP adopts 10 mas for the Main subarray. The science targets are individual protoplanetary disks. Ricci et al. (2018) suggest starting in Taurus at a distance of 140 pc, with ~100 disks in Band 6b and the brighter disks in Band 4. For such disks, the required rms sensitivities are 0.5 microJy/beam in Band 6b and 0.07 microJy/beam in Band 4. A pilot is assigned in Taurus, implying right ascension *RA ~ 4.5 h*, declination *Dec ~ +18 degrees (d)*, and a midnight transit near December 1st.

For Year 1, 15 looks in Band 6b are suggested to pursue demographics and movies. The time per look on a science target is $T_{target} \sim 3.9\ h$. The observing time needed is $T_{subarray} \sim 15 * 3.9\ h * (1{+}2.0) \sim 176\ h$, preferably discharged within ± 3 h near transit at night. Both Q1 and Q4 offer nighttime transits. The suggestion, then, is to conduct ten looks that need $T_{subarray} \sim 117\ h$ in Q4 and five looks that need $T_{subarray} \sim 59\ h$ in Q1, as conveyed in Figure 1.

It is suggested that Year 2 be like Year 1 in Band 6b and also explore four disks in Band 4. In Band 4, the time per disk on a science target is T_{target} *~ 12.9 h* and the net observing time needed is $T_{subarray}$ *~ 4 * 12.9 h * (1+1.5) ~ 129 h*. The bands' needs should be discharged within ± 3 h near transit at night, with Band 6b split between Q1 and Q4 as for Year 1 and with Band 4 placed fully in Q4. See Figure 2.

Year 3 should be like Year 2. See Figure 3.

3.2 KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

The AC5 use cases involve a blind search across Bands 5, 4, and 3 for molecular gas in the hot cores Sgr B2(N) at *RA ~ 18 h* and *Dec ~ –28 d*, and IRAS 16293 at *RA ~ 16.5 h* and *Dec ~ –24 d*. Spanning Bands 5, 4, and 3 requires five, three, and two frequency settings. Each band requires the same tapered and robustly weighted angular resolution of 100 mas. The rms sensitivity required for each band is said to be 30 microJy/beam/(0.1 km/s). But the predictions invoke spectral resolutions of 0.3 or 0.6 km/s and times per frequency setting of ~10 h in Band 5, 1 h in Band 4, and 1 h in Band 3 (AC5, McGuire et al. 2018).

The Main subarray is assigned and these per-setting times are adjusted for missing antennas. Band 5 requires five settings, takes T_{target} *~ 55 h*, and needs $T_{subarray}$ *~ 55 h * (1+1.0) ~ 110 h*. Band 4 requires three settings, takes T_{target} *~ 3.3 h*, and needs $T_{subarray}$ *~ 3.3 h * (1+1.0) ~ 6.6 h*. Band 3 requires two settings, takes T_{target} *~ 2.2 h*, and needs $T_{subarray}$ *~ 2.2 h * (1+0.5) ~ 3.3 h*. These needs total ~120 h and should be discharged within ± 3 h near transit during nights in Q2.

Year 1 should involve observing Sgr B2(N). The times needed are conveyed in Figure 1.

Year 2 should involve observing IRAS 16293. The times needed are conveyed in Figure 2.

This completes KSG2.

3.3 KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

3.3.1 Blind Search for CO Galaxies at High Redshift

The HiZ1 use cases require pointed mosaics for a blind search for CO across Bands 5, 4 and 3. Each band requires the same tapered and robustly weighted angular resolution of 1000 mas and rms sensitivity of 10 microJy/beam/(2 MHz). The science targets are CO galaxies at high redshift. The use case suggests reaching ~100 galaxies per pointing and eventually reaching ~1000 galaxies for the completed mosaic. The Plains + Core subarray is assigned, as is a pilot in COSMOS, implying *RA ~ 10 h, Dec ~ 0 d*, and a midnight transit near March 1st. One pointing per band per year is suggested.

For Year 1, the times on science targets are T_{target} *~ 41.9 h* in Band 5, T_{target} *~ 12.8 h* in Band 4, and T_{target} *~ 6.2 h* in Band 3. The observing times needed are $T_{subarray}$ *~ 41.9 h * (1+0.75) ~ 73.3 h* in Band 5, $T_{subarray}$ *~ 12.8 h * (1+0.75) ~ 22.4 h* in Band 4, and $T_{subarray}$ *~ 6.2 h * (1+0.5) ~ 9.3 h* in Band 3. These needs total ~105 h and should be discharged within ± 3 h near transit during Q2 nights, as shown in Figure 1.

Year 2 should be like Year 1. See Figure 2.

Year 3 should be like Year 1. See Figure 3.

3.3.2 Imaging Molecular Gas in CO Galaxies at High Redshift

The HiZ5 use cases require imaging CO, HCO+, and HCN in galaxies at high redshift *(z)*. Each transition requires the same tapered and robustly-weighted angular resolution of 100 mas and rms sensitivity of 10 microJy/beam/(30 km/s). The science targets are two CO-discovered galaxies at z ~ *2.5*. The Main sub-array is assigned, as is a pilot on the Spiderweb Galaxy (Emonts et al. 2016), implying *RA ~11.5 h, Dec ~ –26 d*, and a midnight transit near April 1st. The Spiderweb Galaxy is at z ~ *2.2* so its transitions for CO, HCO+, and HCN appear in Bands 6a, 5, and 4.

For Year 1, the times on the science target are T_{target} *~ 37.6 h* in Band 6a, T_{target} *~ 9.5 h* in Band 5, and T_{target} *~ 4.8 h* in Band 4. The observing times needed are $T_{subarray}$ *~ 37.6 h * (1+1.5) ~ 94 h* in Band 6a, $T_{subarray}$ *~ 9.5 h * (1+1.0) ~ 19 h* in Band 5, and $T_{subarray}$ *~ 4.8 h * (1+1.0) ~ 9.6 h* in Band 4. These needs total ~123 h and should be discharged within ± 3 h near transit during Q1 nights, as shown in Figure 1.

The second science target could eventually be identified from the COSMOS pilot.

3.3.3 Imaging Molecular Gas in Nearby Galaxies

The NGA8 use case requires imaging molecular gas in nearby galaxies in Band 6b at a tapered and robustly weighted angular resolution of 100 mas. Ideally, each galaxy would be mosaicked with tens to hundreds of pointings. A. Leroy (2018, private communication) suggests starting with the CO-brightest galaxies, an ALMA-like spectral resolution of 2 km/s, and a rms sensitivity of 0.75 K. The Plains + Core subarray is assigned, as is a pilot on a Virgo Cluster galaxy, implying *RA ~ 12.5 h, Dec ~ +12 d*, and a midnight transit near April 15th. Three pointings per year are suggested.

For Year 1, the time per pointing on a science target is T_{target} *~ 17.6 h*. The observing time needed is $T_{subarray}$ *~ 3 * 17.6 h * (1+1.5) ~ 132 h* and should be discharged within ± 3 h near transit during Q1 nights, as conveyed in Figure 1.

Year 2 should be like Year 1. See Figure 2.

Year 3 should be like Year 1. See Figure 3.

Notably, only one galaxy will have been partly done by the end of the pilot. This key science will thus experience slow progress.

3.3.4 HI Emission from Nearby Galaxies

This NGA2 use case requires imaging HI emission from nearby galaxies in Band 1 at a tapered and robustly-weighted angular resolution of 1000 mas and rms sensitivity of 50 microJy/beam/(1 km/s). The Plains + Core subarray is assigned, as is a pilot in the circumpolar M81 Group. Two pointings per year are suggested.

For Year 1, the time per pointing on a science target is T_{target} *~ 88.6 h*. The observing time needed is $T_{subarray}$ *~ 2 * 88.6 h * (1+0.2) ~ 213 h* and it could be discharged within ± 4.5 h near transit during Q3, as conveyed in Figure 1.

Year 2 should be like Year 1. See Figure 2.

Year 3 should be like Year 1. See Figure 3.

3.3.5 HI Emission Around Nearby Galaxies

This NGA2 use case requires pointed mosaics of HI emission around nearby galaxies in Band 1 at a tapered and robustly-weighted angular resolution of 60,000 mas. Pisano et al. (2018) state a required column density of 10^{17} cm^{-2} and a spectral resolution of 10 km/s, and say these measurements correspond to using the Core subarray for 600 h. After adjusting for missing antennas, the time on the science target becomes T_{target} *~ 660 h*. One pointing in the M81 Group is assigned as a pilot.

For Year 1, the time on the science target is T_{target} *~ 220 h*. The observing time needed is $T_{subarray}$ *~ 220 h * (1+0.2) ~ 264 h* and it could be discharged within ± 4.5 h near transit during Q3, as conveyed in Figure 1. This need is labeled "Core" to signal significant opportunities for co-observing with other subarrays.

Year 2 should be like Year 1. See Figure 2.

Year 3 should be like Year 1. See Figure 3.

3.4 KSG4: Using Pulsars in the Galactic Center as Fundamental Tests of Gravity

One TDCP1 use case requires continuum observations in Band 3 at full bandwidth to search for pulsars within 500 mas around Sgr A* at *RA ~ 18 h* and *Dec ~ –29 d*. Ten phased-array beams are required simultaneously. The phasing-up facilitates signal conditioning for pulsars. As updated by Ransom & Demorest (2018), each phased-array beam will offer a tapered, robustly-weighted resolution near 20 mas. The total number of such phased-array beams needed is *(pi * 500^2 mas^2)/(1.1331 * 20^2 mas^2) ~ 1730*. To ease data handling, the team will settle for the rms sensitivity delivered by the Main subarray after a 6-h track. A 26% pilot of 450 phased-array beams is assigned. The calibration overhead is a modest *Ove ~ 0.1*, because every 300 s the phasing can be touched up with a 30-s observation on Sgr A* (cf. Ku Band in the A configuration of the VLA).

For Year 1, 150 phased-array beams need $T_{subarray}$ *~ 15 * 6 h * (1+0.1) ~ 99 h*. This should be discharged in Q4 in the LST range 14.5 h to 21 h, as conveyed in Figure 1.

Year 2 should be like Year 1. See Figure 2.

Year 3 should be like Year 1. See Figure 3.

If any pulsars are found, timing them is required. Such follow-up needs cannot yet be estimated.

Another TDCP1 use case involves a pulsar search on degree scales in the inner Galaxy. Data from a black hole search, described below, could be shared for a use case for KSG5.

3.5 KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

3.5.1 Localize a LIGO Event

The TDCP2 use case requires full-bandwidth continuum observations in Band 1 to localize a LIGO event at a tapered and robustly weighted angular resolution of 1000 mas, and rms sensitivity of ~1 microJy/beam. Two looks are required to localize the LIGO transient. Completing each look in ~10 h is desirable. Each look involves on-the-fly mosaicking over an area of ~7 square degrees (Nissanke et al. 2013). The total number of primary beams to be covered is thus *~7 square degrees / (0.5665 * 0.41^2) square degrees ~ 74*. Assigning the Main subarray for an effective T_{target} *~ 0.1 h* per primary beam, the mosaic will be completed in ~10 h to a rms sensitivity of ~1.8 microJy/beam. Corsi et al. (2018) suggest eventually triggering on ≳10 events per year. A pilot of eight events per year is assigned.

For Year 1, its eight events need $T_{subarray}$ *~ 8 * 2 * 7.4 h * (1+0.2) ~ 142 h*. Two events per quarter are suggested. The areal density of known galaxies that might host LIGO events is generally higher toward the northern Galactic cap than the southern one (Dalya et al. 2018). Figure 1 thus notionally centers each 8.9-h track at an LST of 13 h, the *RA* of the North Galactic Pole.

Year 2 should be like Year 1. See Figure 2.

Year 3 should be like Year 1. See Figure 3.

3.5.2 Proper Motion of a LIGO Event

Once a LIGO event has been localized, some follow-up will ensue. For example, it may be desirable to constrain the event's proper motion. This TDCP8-inspired use case was quantified by T. Maccarone (2018, private communication). It requires full-bandwidth continuum observations with the LBA subarray near 10 GHz with an angular resolution of 0.6 mas and rms sensitivity of ~0.23 microJy/beam. At least two looks are required to constrain a proper motion. Band 3 and natural weighting leads to $T_{target} \sim 58.7\ h$ per look. For phase referencing in the nodding style, *Ove ~1.0* is adopted (Wrobel et al. 2000). A pilot is assigned to follow two events per year.

For Year 1, following up two events needs $T_{subarray} \sim 2 * 2 * 58.7\ h * (1+1.0) \sim 470\ h$. This LBA subarray can co-observe with a driving use case involving any subarray in Figure 1, even the Main subarray.

Year 2 should be like Year 1; co-observing can occur with any subarray in Figure 2

Year 3 should be like Year 1; co-observing can occur with any subarray in Figure 3.

3.5.3 Localize a LISA Event

This TDCP5-inspired use case was roughly quantified in Bolatto et al. (2017). It requires full-bandwidth continuum observations in Band 4 to localize a LISA event at a tapered and robustly-weighted angular resolution of 1000 mas, and rms sensitivity of ~10 microJy/beam. Two looks are required to identify the LISA transient. Completing each look in ~10 h is desirable. Each look involves on-the-fly mosaicking over an area of ~10 square degrees (Lang & Hughes 2008). The total number of primary beams to be covered is thus *~10 square degrees / (0.5665 * 0.037²) square degrees ~ 10⁴*. Assigning the Plains + Core subarray for an effective $T_{target} \sim 0.0001\ h$ per primary beam, the mosaic will be completed in ~10 h to a rms sensitivity of ~14 microJy/beam. Bolatto et al. (2017) mention that LISA will detect tens to hundreds of events per year. A pilot of eight events per year is assigned. LISA is expected to begin issuing event alerts in 2036, hence Year 3. LISA plans to be issuing alerts for at least four years; however, alerts could possibly occur for up to ten years (Amaro-Seoane et al. 2017).

For Year 3, its eight events need $T_{subarray} \sim 8 * 2 * 10\ h * (1+1.5) \sim 400\ h$. Two events per quarter are suggested. Radio counterparts to LISA events will be at cosmological distances, implying a uniform areal density. For want of a better approach, the needed times are spread across all LSTs in Figure 3.

3.5.4 Search for Black Holes and Pulsars in the Galactic Center

This search is in preparation for follow-up use cases for KSG4 and KSG5 in the Galactic Center.

Focusing on KSG5, the use case is mentioned in Bolatto et al. (2017) and quantified in Maccarone et al. (2018). The latter authors assume that recording media will be available, enabling a first correlation to refine positions of candidate black holes and a second correlation at those refined positions to initiate a proper motion study. However, such a dual-correlation mode is not planned. The lead author was consulted and agreed to revise their search approach as outlined below. This revised approach for KSG5 could also accommodate the search for KSG4 that was roughly quantified in the use case TDCP1.

The search requires full-bandwidth continuum observations in Band 2 to localize persistent sources with a tapered and robustly-weighted angular resolution of 1000 mas, and rms sensitivity of ~1 microJy/beam. Flat-spectrum sources found over an area of ~10 square degrees will become follow-up candidates for black hole proper motions for KSG5. Steep-spectrum sources found over a smaller area, ~4 square degrees defined by the Central Molecular Zone, will become follow-up candidates for pulsar timing for KSG4. The search will employ on-the-fly mosaicking.

A substantial pilot covering ~12 square degrees would help jumpstart the follow-up for KSG5. The total number of primary beams to be covered is thus *~12 square degrees / (0.5665 * 0.12²) square degrees ~*

1500. The Plains + Core subarray is assigned for an effective $T_{target} \sim 0.25\ h$ per primary beam to achieve the required sensitivity.

For Year 1, to cover ~4 square degrees or ~500 primary beams $T_{subarray} \sim 500 * 0.25\ h * (1+0.35) \sim 169\ h$ is needed. This should be discharged in the LST range 14.5 h to 21 h in Q3, as conveyed in Figure 1. This would formally complete the pulsar search on degree scales for KSG4.

Year 2 should be like Year 1. See Figure 2.

Year 3 should be like Year 1. See Figure 3.

3.5.5 Time Pulsars for the Pulsar Timing Array

This TDCP7-inspired use case was further quantified by Chatterjee et al. (2018). It involves Band 1 or 2, and can involve as little as one-fifth of the Main subarray. Each subarray will be phased up to facilitate signal conditioning for pulsars. There are ~200 pulsars currently known north of $Dec \sim -40\ d$ and the team would be willing to observe each of them for ~0.5 h per week in a one-fifth subarray. This case is assigned the Mid-baseline subarray: its 46 antennas comprise a one-fifth subarray and it is a good match to the point-like pulsars. A pilot of ten northern pulsars is assigned. The tapered and robustly-weighted angular resolution could be 100 mas in Band 1 or 2, but it will be finer in real time because the subarray will be phased up.

For Year 1, these ten pulsars need $T_{subarray} \sim 52 * 10 * 0.5\ h * (1+0.2) \sim 312\ h$. This Mid-baseline subarray can co-observe with a use case involving a Plains + Core subarray in Figure 1.

Year 2 should be like Year 1; co-observing can occur with a Plains + Core sub-array in Figure 2.

Year 3 should be like Year 1; co-observing can occur with a Plains + Core sub-array in Figure 3.

4 Evaluation of the Reference Observing Program

This document developed a notional observing program of three-year pilots for the driving use cases of KSG1 through KSG5. It was found that the driving use cases for KSG2 could be completed after only two years. It was also found that significant progress could be made discharging all but one of the many driving use cases for KSG1, KSG3, KSG4 and KSG5. As noted in KSG3's Section 3.3.3, that single exception occurs because only one galaxy will have been partially completed during its pilot, whereas the aspiration is to observe many galaxies eventually. The driving use case in Section 3.3.3 would thus experience slow science progress.

For optimal efficiency, a driving use case involving the Mid-baseline subarray can co-observe with a driving use case involving the Plains + Core subarray. Similarly, an LBA subarray can co-observe with a driving use case involving, for example, the Main subarray. Skipping over such Mid-baseline and LBA use, the $T_{subarray}$ totals for key science are 1549 h in Year 1, 1556 h in Year 2, and 1836 h in Year 3. These values approach the ~2000 h per year mentioned in Section 2. The desired balance of ≥4000 h per year would thus be available for open science. But if key science is discharged first, a worry is that not many hours would be left for open science in Bands 6a or 6b.

5 Next Steps

Only preliminary estimates for calibration overheads were available. It would be desirable to gain access to study-based estimates applicable to each science subarray.

The preliminary estimates for the available science time per LST per band involve only phase stability data on the Plains of San Agustin. It would be desirable to gain access to estimates that fold in wind and opacity data on the Plains, and also to fold in phase-stability, wind, and opacity data beyond the Plains.

The authors should re-read the ngVLA Science Book (Murphy 2018) cover to cover to ensure that this document has captured updates, if any, to the sensitivity requirements quoted in the driving use cases.

6 Appendix

6.1 Acknowledgments

V. Rosero and B. Butler are thanked for providing essential information in advance of its publication.

R. Selina is thanked for providing helpful feedback on drafts of this document.

6.2 Reference Documents

Amaro-Seoane, P., et al., 2017arXiv170200786A

Bolatto, A., et al. 2017, ngVLA Memo 19

Butler, B., 2019, ngVLA Memo, draft of 2019-01-18

Chatterjee, S., et al. 2018, ngVLA Memo 42

Corsi, A., et al. 2018, Science with a Next Generation Very Large Array, ASP Monograph 7, 689

Dalya, G., et al. 2018, *MNRAS*, 479, 2374

Emonts, B., et al. 2016, *Science*, 354, 1128

Lang, R., & Hughes, S. 2008, *ApJ*, 677, 1184

Maccarone, T., et al. 2018, Science with a Next Generation Very Large Array, ASP Monograph 7, 409

McGuire, B., et al. 2018, Science with a Next Generation Very Large Array, ASP Monograph 7, 245

Murphy, E., 2018, Science with a Next Generation Very Large Array, ASP Monograph 7

Murphy, E., et al. 2018, NRAO Doc. # 020.10.15.00-0001-REQ

Nissanke, S., et al. 2013, *ApJ*, 767, 124

Pisano, D., et al. 2018, Science with a Next Generation Very Large Array, ASP Monograph 7, 471

Ransom, S., & Demorest, P. 2018, ngVLA Memo, draft of 2018-01-05

Ricci, L., et al. 2018, Science with a Next Generation Very Large Array, ASP Monograph 7, 147

Rosero, V., 2019, ngVLA Memo 55

Selina, R., et al. 2018a, NRAO Doc. # 020.10.20.00.00-0001-REP

Selina, R., et al. 2018b, NRAO Doc. # 020.10.15.10.00-0003-SPE

Selina, R., et al. 2018c, NRAO Doc. # 020.10.15.10.00-0001-SPE

Wrobel, J., et al. 2000, VLBA Scientific Memo 24

Operations Concept

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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2016-11-18	Selina, Carilli	All	First draft incorporating text from Prospectus.
02	2016-11-23	Selina et al.	All	Expanded after discussions with Claire Chandler, Steven Durand, Alan Erickson, Wes Grammer, Jeff Kern, Wayne Koski, Dave Parker, Peggy Perley, Nathan Towne, and Denis Urbain.
03	2016-11-30	Selina, Grammer	6	Added maintenance model by Grammer.
04	2016-12-01	Selina, McKinnon	All	Format updates & adding DMS context Pulled From MM SPIE paper.
05	2016-12-07	Selina	5,6	Minor corrections for clarity before review.
06	2016-12-07	McKinnon	All	Corrections throughout; identified areas for additional development.
07	2017-10-02	Kepley	4	Complete rewrite of Section 4 to better incorporate Sci. Ops.
08	2017-10-12	Selina	2, 8	Added change log, appendix, reference documents section, etc.
09	2017-10-30	Selina	1, 8, 9, 10, 11	Started to update outline with ngVLA TAC input.
10	2017-10-30	Selina		Fixed ToC & minor typos.
11	2017-11-09	Ford, Murphy	1, 6, 8	Corrections and expansion on areas.
12	2017-11-13	Kern, Treacy	4–9	Input and expansions of various sections.
13	2017-11-15	Langley, Cole	9, 11	Operations and Site input.
14	2017-11-22	Selina	Appendix	Minor edit to commensal correlator modes.
15	2017-12-20	Treacy	Appendix	Moved operations planning material to Ops Plan, clean up comments, update science use table, overall coherence.
16	2018-02-05	Ford	2, 4, 13	Moved driving requirements and abbreviations to beginning of document.
17	2018-03-26	Ford	8–12	Elaboration of ideas from OWG input.
18	2018-04-09	Ford	All	Reorganization of documentation. Expanded on array & maintenance concepts, aligning the former with science operations. Add ngVLA Development section.
19	2018-04-25	Ford	Various	Incorporating feedback.
20	2018-05-25	Ball	All	Updated Science Operations based on subgroup work, tidied language and consistency throughout.

Version	Date	Author	Affected Section(s)	Reason
21	2018-05-29	Ball	All	Incorporating SciOps WG feedback.
22	2018-05-30	Ford	All	Additional incorporation of feedback.
23	2018-05-31	Kern	6.6, 8, 12	Clarifications.
24	2018-06-06	Wrobel	6	Added annual meeting at SOC, clarifications.
25	2018-06-08	Ball, Ford, Kepley, Kern, Koski, Perley, Treacy	All, 6.2	Final submission of clarifications by authors, author list revised. Clarified allocation of observing time to pre-defined subarrays.
A	2018-06-11	Ford	Title block, All	Revision change for release review, revision of capitalization.
A.1	2018-10-08	Treacy	many	Edits following StRR, RIDs tracked by JIRA Tickets under bugs.nrao.edu, JIRA Project ngVLA Stakeholder Requirements Review, JIRA ticket numbers of the form StRR-xx.
A.2	2018-10-18	Ford	Many	Revisions due to accepted SRR and Internal Pre-Decadal Submission Review RIDs.
A.3	2018-11-05	Ford	8, 12	Clarified maintenance tiers, described development program (which includes LSP funding).
B	2019-05-20	Lear	All	Incorporated PD's revisions and prepared document for final release.

Table of Contents

1 Executive Summary

The Next Generation Very Large Array (ngVLA) will be an astronomical observatory operating from 1.2 GHz to 116 GHz. The observatory will be a synthesis radio telescope constituted of approximately 263 reflector antennas; 214 each of 18 meters diameter in the main array, 19 antennas each of 6 meters diameter in a short baseline array (SBA) located near the core, and 30 antennas each of 18 meters diameter in a long baseline array (LBA) to provide continental-scale baselines. The instrument is capable of operating in a phased or interferometric mode. See [RD01].

The facility will be operated as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Regular calls will solicit observing proposals, which will be peer reviewed and assigned a rank based on scientific merit and technical feasibility. Trained staff will incorporate the approved observations into dynamically scheduled blocks based on environmental conditions and array status, and in accordance with the user's scientific requirements.

Three primary centers will support the operation and maintenance of the array. A Maintenance Center will be located with expedient access to the array core. Field Technicians from the Maintenance Center will provide day-to-day maintenance support for the antennas and associated array systems. An Array Operations Center and Repair Center will be located in Socorro, NM, and staff based there will repair failed system elements and provide system diagnostics and engineering support along with array operation and supervision. A Science Operations and Data Center will likely be located in a large metropolitan area and will be the base for science operations and support staff, software operations, and related administration. Research and development activities will be split between the Array Operations and Science Operations Centers as appropriate. Technicians responsible for maintaining remote long-baseline antennas may be based at additional small service depots (Remote Support Stations).

The central signal processor will be highly configurable and, in addition to a variety of interferometric modes, will include commensal observing capabilities to permit the division of the array into subarrays and the processing of single-dish and single-baseline data in multiple ways, such as concurrent cross-correlation and transient searches. Phased array modes will support VLBI recording, pulsar timing, pulsar searches, and transient searches with multiple beams within the antenna primary beam.

Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products; automated pipelines will calibrate raw data and create higher level data products (typically image cubes). Data and quality assured data products will be made available through an Observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

Through the delivery of quality assured Science Ready Data Products and the provision of standard observing strategies, the Observatory will aim to both support a broad community of scientific users that extends considerably wider than experts in radio interferometry, and to facilitate multi-wavelength and multi-messenger astronomy. Innovative, non-standard observations not accessible through the standard modes will also be supported where the scientific goals are of sufficient quality.

This Operations Concept informs the identification of ngVLA operational requirements through a subsequent Operations Plan, a Transition Plan, and a Development Plan. The Operations Plan will fully describe the operational model to be employed following ngVLA construction, while the Transition Plan will cover the transition from VLA operations to ngVLA operations. The Development Plan will describe the research and development activities necessary to advance the ngVLA's technical and user support capabilities after construction has ended and operations has begun.

2 Project Description

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter, and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

The ngVLA will open a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond (mas) resolution, as well as unprecedented broadband continuum polarimetric imaging of non-thermal processes.

The ngVLA will have approximately ten times the sensitivity of the JVLA and ALMA, with main array baselines of over 1,000 kilometers and long baselines of nearly 9,000 kilometers providing mas-resolution, plus a dense core on km-scales for high surface brightness sensitivity. Such an array bridges the gap between ALMA, a superb sub-mm array, and the future SKA1, which is optimized for longer wavelengths.

The majority of the antennas and the signal processing center of the array will be located at the VLA site, on the plains of San Agustin, NM. The main array will include stations in other locations throughout New Mexico, west Texas, southeastern Arizona, and northern Mexico. The high desert plains of the US Southwest at over 2000 m elevation provide excellent observing conditions for the frequencies under consideration. Long baseline stations will be located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Maintenance and operations will be conducted from a Maintenance Center located with expedient access to the core of the array (~30 km, likely in Magdalena, NM) and an Array Operations and Repair Center (AOC) in Socorro, NM, respectively. Additional technicians responsible for maintaining remote LBA and some mid-length baseline antennas will be based at remote sites to optimize operation expenses. Data processing and analysis will occur at a combined Science Operations and Data Center.

3 Related Documents

3.1 *Applicable Documents*

The following documents are applicable to this Operations Concept to the extent specified:

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Legacy Science Program	020.10.05.00.00-0004-PLA, Murphy, V01, 2017-10-23

3.2 *Reference Documents*

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	ngVLA System Reference Design	020.10.20.00.00-0001-REP
RD02	Summary of the Science Use Case Analysis	ngVLA Memo #18. Selina et al., 2017
RD03	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19. Bolatto et al., 2017
RD04	Gender-Based Systematics in HST Proposal Selection	arXiv:1409.3528. Reid, 2014
RD05	Gender Systematics in Telescope Time Allocation at ESO	arXiv:1610.00920. Patat, 2016
RD06	Gender-Related Systematics in the NRAO and ALMA Proposal Review Processes	arXiv:1611.04795. Lonsdale et al., 2016
RD07	ngVLA Computing Architecture	https://osf.io/pfw4c/ Kern, 2017
RD08	A Preliminary Operations Concept for the ngVLA	SPIE. McKinnon, 2016
RD09	Reference Study: ngVLA Buildings & Infrastructure	020.60.00.00.01-0002-REP
RD10	SRDP System Concept	530-SRDP-014-MGMT
RD11	ngVLA Transition Concept	020.10.05.00.00-0003-PLA
RD12	Principles for ALMA Development Program	AEDM 2011-023-O v2

4 Operations Concept and Scope

The ngVLA Operations Concept is described here using three perspectives: scientific and array operations, array maintenance and engineering, and array development. The combination of these three areas of effort forms the ngVLA operations definition and, therefore, the scope of this document. This specifically means that operations does not include efforts or planning associated with ngVLA construction. Other key assumptions and constraints are captured in the Appendix (Section 12.2).

This document generally uses the VLA array operation and maintenance model as a starting point. The ALMA operations model and experience has been equally informative, especially for science operations and the delivery of Science Ready Data Products (SRDP).

This Operations Concept assumes that ngVLA is a US-funded observatory operated on behalf of the scientific community by NRAO. The concept is subject to change if international partners join the ngVLA.

4.1 Scientific and Array Operations

Science operations are the user-facing services provided by the Observatory, including observation preparation, scheduling, archive access, scientific performance of the array, and the delivered data products. Array operations involves the day-to-day operations of the working array, including the management of and administration of all operations. It encompasses the execution of observations and initiation of corrective maintenance actions and delivers observational data to Science Operations.

Given there will be formal data delivery from Array Operations to Science Operations, an interface to define that delivery will need to be developed.

4.2 Array Maintenance and Engineering

The maintenance and engineering effort covers the performance monitoring of the array and includes responsibility for preventive and corrective maintenance by engineers and technicians.

4.3 Array Development

Development activities determine and provide community-supported upgrades of the array. Managed by scientific and array operations, this includes research and development of hardware, software, infrastructure, and operations methods and techniques.

5 Scientific Operations

The primary objective of ngVLA science operations will be the delivery of the program of executable observations of the highest scientific ranking to collect data for the research community that produces the greatest possible scientific impact.

The ngVLA science program will be driven by proposals from the scientific community in response to regular calls for submissions. Proposals will be assessed for scientific merit through a peer review process. It is anticipated that astronomers will be eligible to apply for and be awarded ngVLA time regardless of their institutional affiliation (Open Skies) as is the case for other NRAO facilities.

It is expected that 80–90% of the scientific program will use a diverse, but well-defined, set of standard observing capabilities or modes delivered during construction for which the calibration and data processing will be undertaken through an automated pipeline developed and run by the Observatory. Proposals will include the information necessary for scheduling the telescope, configuring the instrument, collecting the data appropriate to address the scientific goals, and in most cases for automatically generating the appropriate Science Ready Data Products (SRDPs). Data will be delivered to the Principle Investigators as quality-assured SRDPs through an Observatory Science Data Archive.

In full operations, the Observatory will provide a set of standard supported observing modes, which are a construction project deliverable, necessary to achieve the key ngVLA science goals. At the start of ngVLA early science, only a small number of these modes that have been verified to work end-to-end (including delivery of SRDPs) will be available to PIs. The number of modes available to users will increase as early science progresses, with all modes deliverable from the construction projects available in full operations. For standard observing modes, observing instructions (scheduling blocks) will be generated based on the scientific requirements specified by the PI in their submitted proposal.

In addition to the standard capabilities and modes, the Observatory will support innovative programs of sufficient scientific merit that require other instrument configurations and/or non-standard and non-automated data processing. It is anticipated that 10–20% of the science program may comprise such non-standard or Expert modes, and access to such time will require evidence of sufficient expertise and capability on the part of the proposers to deliver scientifically useful results. Non-standard observing modes will be severely restricted in early science operations, and may not be offered until full operations begins.

5.1 Proposal Submission and Assessment

As a proposal-driven instrument, the ngVLA will operate via a competitive peer review process similar to that of other large proposal-driven observatories such as ALMA, VLA, HST and JWST. Users will specify the scientific and technical requirements for their projects via an Observatory-supplied proposal tool. The proposal process will aim to minimize the need for PIs to have expert knowledge of the hardware, calibration and data processing issues specific to the ngVLA. The proposals will be evaluated for scientific merit by science review panels made up of experts from the broad astronomy research community, and a Time Allocation Committee will advise the Observatory of the scientific rankings of proposals.

Recent studies indicate differences between the outcomes from peer review processes for PIs of different gender [RD04], [RD05], [RD06]. The ngVLA proposal review process will adopt the best practices aimed at minimizing such differences.

Proposal attributes such as regular, large, triggered, monitoring, legacy [AD01], and joint (with other observatories) are expected to be supported once the Observatory reaches full operations, as will a diverse set of capabilities and observing modes. Different capabilities and observing modes will be made available in stages during the transition from construction through the start of science operations and the commencement of full operations. That transition is likely to take around ten years.

Observatory staff will schedule observations based on the scientific rankings of proposals, taking into consideration issues such as technical feasibility, data processing requirements, array status, and observing conditions. The Observatory Director will have the final responsibility for the scientific program that is executed.

5.2 *Scheduling and Observing*

A significant fraction of the array is expected to be available for scientific use at almost all times (once in full operation). Maintenance, testing, characterization, and capability development (including software) will primarily be done on a subset of the array, using subarrays where appropriate. A limited number of predefined science subarrays will be used by the Observatory to simplify scheduling of the scientific program, and allocation of observing time to subarrays may be recommended by the NRAO Time Allocation Committee based on the science goals of PI-defined projects. PIs will not be expected to request specific subarrays except for special circumstances. Subarray assignment will likely be used to balance observing pressure while maximizing the delivery of the data required to meet PIs' science goals.

The array will be dynamically scheduled in a fashion similar to the VLA and other modern instruments. Considerations will include the science ranking of projects, the most demanding projects that can be accommodated given the visible radio sky, the array status, and environmental conditions across the array or available subarrays.

A capability to interrupt the execution of the observing program in order to respond to a triggered observation with a higher scientific rank will be provided.

Submitted proposals will specify requirements based on scientific objectives (such as sensitivity, dynamic range and so on), but successful PIs will be awarded array time rather than guaranteed satisfaction of a scientific objective such as sensitivity. The Observatory will generally provide a defined observing strategy (including array characterization and calibration) for all standard modes and capabilities. Allocated time for standard observing modes will therefore generally be time on science target. Flexibility for PIs to make changes to the standard strategy—within limits and only when required to meet the scientific objectives—will be available.

5.3 *Data Processing and Products*

The standard method of delivery of scientific data from ngVLA to PIs will be automatically generated and quality-assured Science Ready Data Products. ngVLA data rates will be high enough to make data reduction at a PI's home institution challenging, but low enough that real-time processing of the visibilities (a la SKA) is not required [RD07]. Commercially available fiber will be used to transport the raw visibilities from the correlator (at the array core) to the Science Operations Center for data processing.

The Observatory will provide sufficient computing resources for the data processing associated with normal operations using standard modes and capabilities (including delivery of Science Ready Data Products to PIs) as well as reasonable reprocessing by PIs and a broader community of users of archival (public) data.

Delivery of a fully commissioned standard observing mode or capability will include an operational SRDP pipeline before it is offered for regular use through PI proposals.

The definition and delivery of ngVLA data products will be informed by NRAO's development of SRDPs via the ALMA data pipeline and the efforts already underway to extend this approach to the VLA [RD10].

Standard and optimized data products are anticipated to meet both the needs of the original PI for ngVLA observations, and the scientific goals of subsequent users of publicly available data from the Data Archive. Raw visibilities, calibration tables, and SRDPs will all be stored and made available through the Data Archive, as will some classes of user-generated data products where they can be suitably quality-assured.

Large and Legacy [AD01] scale projects will need to identify data processing requirements and resources, and may require additional computing resources to be made available from non-Observatory sources in order to be scheduled. Large and Legacy projects will likely not be offered until well after the start of science operations.

The Observatory will provide separate software packages to the user community for processing ngVLA visibilities and for data analysis. Both packages will be executable on Observatory computer resources and on non-Observatory computers, though the visibility processing software is likely to be aimed primarily at domain experts.

5.4 Data Archive

The Data Archive will be the point of interaction between Principal Investigators (and archival data researchers) and ngVLA data and data products. The raw visibilities, calibration tables, Science Ready Data Products, and Enhanced Data Products from Legacy projects will be archived. Archive functionality will allow users to inspect and select image data for download. Download of visibilities is expected to be rare. An interface to the Data Archive will allow scientists to initiate reprocessing of ngVLA data using Observatory-provided techniques and tools, and will include automated quality assurance processes.

PI access to data is expected to be protected by a proprietary period (nominally a year), after which the data and data products are fully and publicly accessible.

The Data Archive will have provisions for accepting user-produced data products where those products can be quality assured by the Observatory (such as products from Large or Legacy projects). In such circumstances, the Observatory will approve the user QA process, not the individual products.

Large and Legacy projects and some other special cases may have a different proprietary period. For Legacy projects, pipeline-processed data will likely enter the public domain immediately upon NRAO processing and validation, thereby enabling timely and effective opportunities for follow-on observations and archival research, for both the ngVLA and other observatories [AD01].

The Data Archive will provide a rich set of data and data products to support multi-wavelength astronomy and data reuse. Complementary data sets from surveys like WFIRST, LSST, and VLASS will also be available by the time ngVLA begins science operations. The Data Archive will be designed to interface easily with these and other similar archival systems to maximize the data discovery space. Where possible, interfaces to ngVLA data should favor processing the data in place, rather than transferring the data across the internet to the user.

5.5 Delivered Observer Capabilities

A defined set of standard capabilities will be developed, tested, and delivered during the construction project. Each delivered capability will include the observing sequence, calibration plan, and production of SRDPs. These sets of capabilities will include everything required to meet the most important science goals of the telescope.

The Observatory will release a set of First Look Science products—defined with input from the user community—ahead of PI access to the array.

Early PI access—or Early Science—is expected to commence when roughly a VLA's worth of collecting area is available, and will include the first set of delivered capabilities offered for PI use. Additional PI access will be offered at other significant milestones prior to the end of construction (for example when baselines expand beyond the Plains of San Augustin). The handover of the defined delivered capabilities to science operations is expected to be completed by the time the construction project ends.

5.6 User Support

Direct scientific support is required for any aspect of ngVLA use related to proposing, observing, data quality, processing, and analysis through to the publication of scientific results. This support will be provided at three principal levels. First, adequate online documentation will be provided remotely through help-desk queries, which will be responded to primarily by data analysts or observatory scientists. Second, face-to-face interactions will be available at the Science Operations Center. Third, indirect scientific support to enable the best science possible by array users and/or archival data will be provided through service observations, maintaining auxiliary data bases (such as calibrator lists), calibration planning, and the development of observing strategies and techniques.

The ngVLA user community will be updated and expanded by Observatory-initiated and supported education programs such as workshops and community days, both at the Science Operations Center and elsewhere, and through self-training documentation, internships, and visiting or resident scientist programs. The ngVLA will contribute to NRAO's core mission of training the next generation of scientists and engineers through support of the NRAO postdoctoral fellowship program and graduate fellowship program. The Legacy Science Program will also serve to train the next generation of radio astronomers in university programs through its cohesive approach to developing unique and appealing projects. Finally, to ensure the visibility of the Science Operations Center, the ngVLA will host an annual science meeting or user workshop.

5.7 Ongoing Capability Development

After the completion of construction, the Observatory will have a mechanism to develop new observing and data processing modes beyond the set of capabilities delivered by the construction project, but which do not rely on new ngVLA instrumentation. In addition to these "observatory developed capabilities" and Legacy Science Program deliverables, there will be a mechanism to allow the user community to propose and participate in defining, testing, and verification of new capabilities to further enhance the ngVLA.

5.8 Array Health and Status

Regular health and status checks on array elements, including antenna physical and electronics, central electronics, and correlator, will be largely automated (as described under Maintenance). Similar checks and, where appropriate, re-measurement of calibration and related scientific performance characteristics of the array, will be performed as an Observatory function using small subarrays of antennas, contemporaneously with larger subarrays conducting scientific observing. The results of these checks will be used to update parameters such as delays that need to be set prior to observing science targets and to identify misbehaving elements. These processes and associated parametrization of the array performance will be automated and the relevant parameters stored for later retrieval as needed. This will be an integral part of the data processing pipeline and quality assurance process.

It is anticipated that the need to use the full array for such Observatory support functions will be very limited, thereby maximizing the array time available for science observations.

6 Array Operations Concept

Array operations personnel are responsible for the proper function of the ngVLA telescope, delivering science data as requested through science operations while interfacing with array maintenance and engineering staff to keep the array operational. The ability to control and monitor the telescope remotely and to automate aspects of maintenance planning and problem diagnosis will allow operations to be conducted remotely from the AOC with a reduction in overall operations cost. Depending on the degree of human intervention required in array supervision, multiple Operators may divide the workload.

6.1 Concurrent Maintenance and Observations

To meet the desired goal of observing at all times, the ngVLA will use a concurrent maintenance and observation model. This means that a substantial fraction of the entire array will generally be available for science, while at the same time some portion of the array will be undergoing or supporting maintenance, or being used in one or more subarrays for testing, characterization, or other operations activity. There will still be a need for maintenance and testing across the entire array, wherein no observing can be done, as determined by the electrical and networking infrastructure for example, but such times will be minimized. The majority of maintenance will be scheduled dynamically based on need and priority.

Existing array operation models typically allocate full array time for testing, commissioning, and maintenance. For ngVLA, such activities will generally be scheduled only on smaller subarrays, allowing a more continuous concurrent implementation of science observations, maintenance, and testing. For example, when an antenna that is part of a science array develops a problem, it could be removed from the science array and placed together with a neighboring antenna in a two-element array for problem diagnosis and repair. Similarly, testing may employ any available antennas configured as a subarray, concurrently with a science observation on a different subarray.

The subarray design implications, especially for software systems, will be carefully considered and be fundamental to the operation of the ngVLA. For example, it must be possible to run different software system versions concurrently on different subarrays for software testing and commissioning purposes.

Some of the identified science cases driving the VLA design require only portions of the array, or want the array subdivided into multiple subarrays for concurrent multi-frequency or multi-field observations. Calibration concepts under consideration may also require that antennas leave and enter subarrays in a fluid rotation. The possibility of differing environmental conditions across the array is also proportional to the array's extent. Maintenance time will be dynamically scheduled based in part on adverse local observing conditions or on scheduled preventive maintenance needs that align with science observing priorities.

6.2 Array Supervision and Automation

Similar to the VLA, a human operator will oversee the array. The operator will supervise the scheduling tools and executor, ensuring that the intent of each observation is met and that the array is kept in a safe operating condition. There will not generally be an astronomer on duty. The operator will be provided with an alert screen to indicate array health. In the case of malfunction, the operator will be the "human in the loop" and will be informed regarding maintenance work order tickets.

However, due to the large number of antennas and subsystems compared to other arrays, and the correspondingly large set of performance data, continual analysis of array status and health will be largely automated and an automated maintenance scheduler will be the key source of maintenance tickets. The ngVLA operations staff will include a maintenance coordinator to oversee the initiation, triage, tracking, and closure of operations-based tickets. The maintenance coordinator will work closely with the engineering support staff and Array Operator to resolve tickets.

Effective coordination and scheduling of maintenance must include a maintenance system that provides a high degree of automation, monitoring, and integration of maintenance data with data from other observatory tracking systems. Data from other systems would include, but is not limited to, availability of staff, vehicles, specialized tools and equipment, configuration control, environmental and weather reports, and status and location of inventoried spares.

In addition to the automated array-monitoring, individual ngVLA antennas need to be more autonomous than is currently state of the art. The software architecture should accommodate an antenna supervisory system or equivalent, which would be responsible for controlling the antenna, evaluating its performance, calibrating, and solving routine problems. Examples of actions taken by the antenna supervisor include:

- identifying and restarting malfunctioning digital transmission and timing systems;
- performance monitoring, control, and optimization of the cryogenic system;
- monitoring point performance and failure trend analysis for use in predictive and preventive maintenance scheduling; and
- returning to an observational ready state after unplanned shutdowns, such as power outages.

6.3 Array Operations Performance Monitoring

Array operations personnel will be responsible for development and calculation of its operations performance metrics. These metrics are a measurement of various operations process characteristics that provide a quantitative understanding of a process and way to assess its performance against a baseline or other requirements. The Operations Plan will detail the specific metrics to be used such as array uptime, resource utilization, and operation costs per antenna.

7 Array Maintenance Concept

A primary constraint for both the design and the maintenance concept is increasing the collecting area and geographical extent of the array by factors of ten, compared to the VLA+VLBA, while minimizing the operations cost. This has resulted in cost goals for construction, operations, and maintenance budgets. The high-level driver for operations and maintenance is to keep these costs within a factor of three when compared to similar costs incurred for the VLA+VLBA.

Since operations costs are primarily determined by the staffing level, the maintenance efficiency must be improved over current observatory standards. For the ngVLA, the array maintenance efficiency will be improved (at a *minimum)* by a factor of three compared to the VLA through a reduction in the frequency and expense of maintenance visits in terms of resources required. Achieving these efficiency improvements requires careful operations planning and forward-looking design decisions long before the array is constructed and operational. The decision process includes a thorough understanding of expected equipment performance, system design to improve maintainability and repair, and an agile organization of maintenance personnel. Some types of maintenance efforts, which require specialized skills but only at part-time utilization, may be efficiently addressed through the retention of contracted vendors.

Preventive maintenance (PM) schedules and system Mean Time Between Failure (MTBF) estimates must be consistent with the expected staffing level for antenna systems expected to operate a year or more between PM visits. This requires an accurate calculation of Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) for major array components and systems, with a tradeoff in regards to resource costs. In other words, the limited number of maintenance staff will be checked against the expected failure rates during system design, and is likely to drive the overall system quality requirements. At the antenna, limited labor and equipment should be required for all but the most significant of overhaul procedures, with most tasks performed by two technicians in a standardized maintenance vehicle (truck or van).

Items not replaceable as LRUs must be identified in the unit's maintenance plan. These items will require periodic maintenance at predictable intervals and corrective maintenance due to unexpected failure. The maintenance plan shall incorporate both these aspects of maintenance in a way that will optimize use of maintenance resources. Monitoring within antenna cabins and other remote sites may include audio and video monitoring as well as monitor points on a data bus.

Consistent with the goal of efficient maintenance interaction, electronics will continue to be packaged as Line Replaceable Units (LRU), where LRU modules are interchanged at the antenna. Individual LRUs, and all other configurable items, will be electronically self-identifying to readily determine status, configuration, version, time-in-service, maintenance and history, and location tracking across the Observatory. Non-electronic items that require tracking will be uniquely identified through a system like a bar code, visible serial number, RFID tag, or other permanent marking impervious to its operational environment with a comparable level of detailed parameters readily available from the database under which they are managed.

LRUs will be centrally managed, tested, and repaired from the repair center (AOC). Maintenance work will be classified in tiers to assign the level of skill or equipment to fully resolve issues requiring corrective maintenance. This is similar to ALMA's three-tier approach that aligns with progressively more complex and distant diagnosis, repair, and testing. LRU design will be optimized to accommodate the tier-defined maintenance structure, ranging from swapping of LRUs or other *in situ* repair work at an antenna (Tier I), changing LRU sub-assemblies or replaceable components in a workshop (Tier II), and repair or replacement of individual components in a lab environment (Tier III). Diagnosis, repair, and calibration or acceptance testing is required at all tiers. Hardware and software will be designed to accommodate, recover, and initiate necessary firmware updates after hot swapping, with minimal interactions by the maintenance personnel.

The organization of the maintenance and repair teams will also be split to maximize efficiency of time spent on antenna visits and repair of equipment. Functional teams assigned to maintain and repair specific subsystems such as Front Ends or Cryogenic hardware will be employed for centralized repair, overhauls, and detailed troubleshooting of complex problems. This work will be done away from the array at the Repair Center. Separate cross-trained field services teams will perform most routine maintenance activities and any remaining troubleshooting at the antenna. Maintenance teams will be organized and scheduled based on the need for routine, constant preventive maintenance work and for critical corrective maintenance work, prioritized by their impact on science operations. The minimization of specialization by field service staff is desired to avoid disruption from personnel departures and to reduce delays due to resource unavailability. Maintenance work that does not align with core competencies of NRAO will be contracted to external parties, partners, or vendors if it is deemed more cost-effective. Examples of such consideration for the Operations Plan are automotive, carpentry, and HVAC compressor maintenance.

The ngVLA will employ a scheduled maintenance program for the antennas with a goal of minimizing repeat and unscheduled visits to each antenna. The program will be structured to incorporate both reliability data on critical components and actual performance of equipment. For example, cryogenic refrigerators and other components with a known service life will be replaced at a regularly scheduled maintenance intervals, regardless of their current operating condition. The components may also be replaced if analysis of their performance predicts an imminent failure. Both the maintenance scheduling and monitoring of array health are key parts of the maintenance concept and are elaborated upon below.

7.1 Maintenance Scheduling

The productivity of maintenance staff time must be adequate to meet the staffing and up-time requirements for an array on the ngVLA scale. As array time is dynamically scheduled, similar consideration should be given to optimizing maintenance staff time. Maintenance will be scheduled based on a combination of the severity of existing issues, required preventive maintenance, and predictions of pending problems within clusters of the array in order to reduce travel time and maintain system up-time. Data to support this planning hinges upon the integrity of MTBF, MTTR, and FMECA analysis during the design and construction phase. This data is assumed to be collected by ngVLA Systems Engineering personnel.

The large number of geographically distributed antennas lends itself to a continuous and ongoing program of periodic maintenance windows, scheduled by subarray rotation to allow maintenance days to interleave with continuous observing. Failure analysis is also a critical input to the operational budgeting for spares needed to support the array's 20-year lifetime. Failure analysis must include projected availability for spares, the time required to repair the failure, and viability of critical vendors with the threat of obsolescence taken into account for planning upgrades. Lifetime buys on critical items identified as not feasible or practical to redesign will be considered as part of spares planning.

Maintenance analysis must be automated, defining maintenance lists and scheduling maintenance crews. Maintenance task lists can be distilled from the diagnostics software output, combined with the operations schedule, road/weather conditions, technician location, spares availability, and other data. Such a system will reduce scheduling conflicts, wasted trips, and improve overall maintenance efficiency. Relationships to the maintenance scheduler are shown diagrammatically in Figure 1.

Automated diagnostics will be critical to making such a maintenance scheduler effective and are discussed in the context of the Monitor and Control (M&C) system.

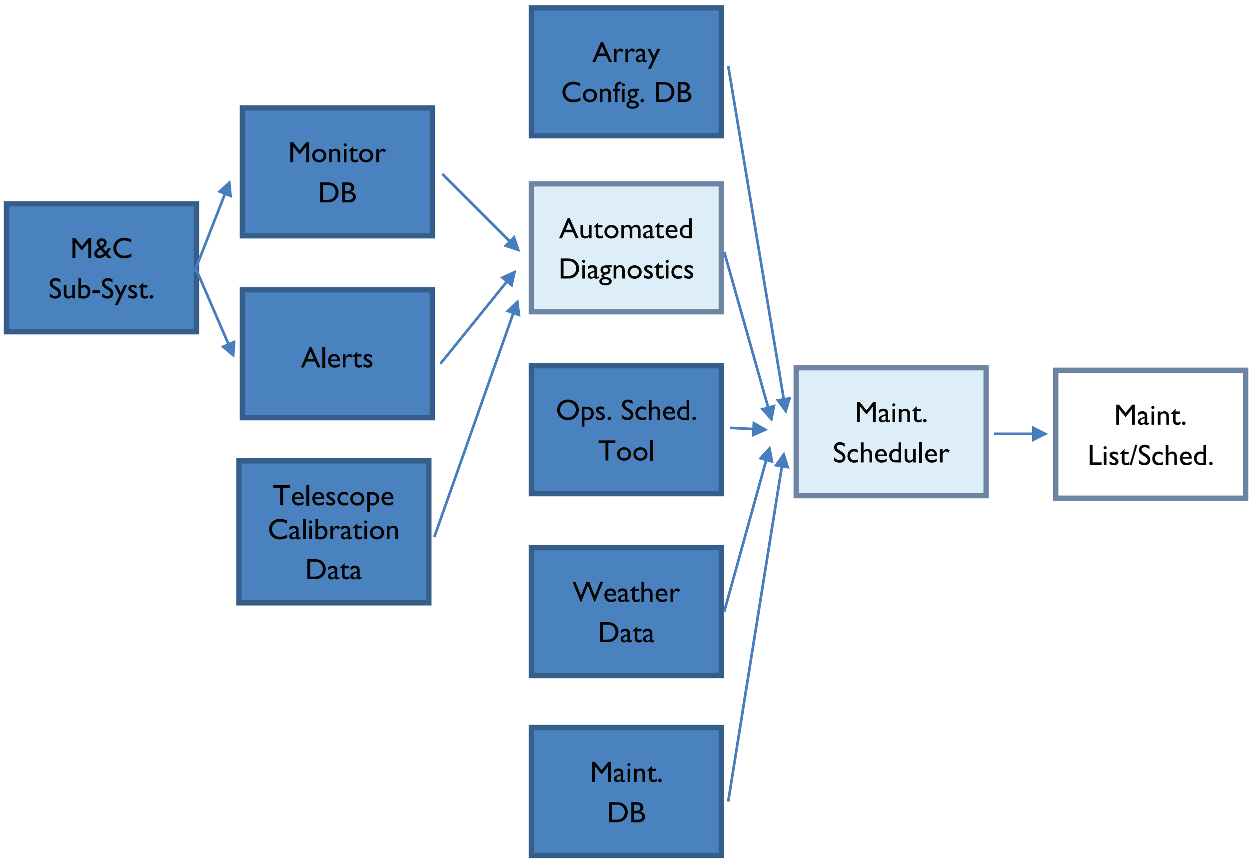

Figure 1 - Block diagram of the inputs and outputs of the maintenance scheduler.

7.2 *Maintenance Diagnostics*

The M&C system must be appreciably more sophisticated and have higher reliability than for existing arrays. The system must include more refined tools for remote automated monitoring and configuration management than presently exist in NRAO instruments. The automated diagnostic capabilities at the LRU and subsystem level are the primary means of troubleshooting and reporting system faults. LRUs and other subsystems must be smart devices with on-board diagnostics that can be accessed for troubleshooting via the M&C bus. The burden of remote fault monitoring and diagnostics must fall as much as possible upon intelligence within the LRU or item to ensure these goals are met within the constraints of the M&C Bus. The goal of remote diagnostic tools is to ensure that data is easily captured and analyzed so that the correct items are identified for replacement. This avoids interacting with functioning modules and reduces multiple repair trips to the same antenna.

Remote monitoring and diagnostic tools apart from the automated diagnostic capabilities shall include fast read out modes, providing a module-level oscilloscope function with buffers and triggers to monitor the time-varying nature of monitor points. This stream of data produced within the LRU will be delivered to the array M&C system through a standardized hardware and software interface layer. Consistent delivery of performance and operating diagnostics from each module or subsystem will allow the automated

Maintenance Scheduler to identify and prioritize maintenance issues and then create work orders. Work orders can be for both corrective and preventive maintenance since LRU and system performance data will be analyzed, such as through control charts, to identify pending failures and develop a knowledge base of system behavior. Automated diagnostics will also improve staff productivity by allowing engineers and scientists to focus solely on the most difficult problems that require human intervention and analysis.

The system configuration must also be remotely ascertainable from each major element of the system, so that the facility configuration can be tracked dynamically with minimal effort. Every LRU or large replaceable subsystem must be traceable in such a system, within reason, even those that do not typically have integrated diagnostic monitoring (e.g., cryogenic refrigerators). Otherwise, effort will be wasted in determining the makeup of systems when dealing with maintenance and development activities.

7.3 Failure/Anomaly Reporting Processing

In addition to errors detected by automated means, failures and anomalies will be reported by operators, data analysists, post-processing pipelines, and users. These reports, along with those generated by automated means, will be tracked in an issue tracking system with a corresponding database. Workflows will process new tickets to assign them to responsible maintenance personnel for problem identification and triage. Once a likely cause is identified and a severity assigned, these reports become inputs to an automated maintenance scheduler for eventual resolution and to be used to improve automated detections in the future.

7.4 Array Maintenance Performance Monitoring

Array maintenance groups will be responsible for development and calculation of their performance metrics as part of quality monitoring. These metrics provide a quantitative understanding of the maintenance process and way to assess its performance against a baseline or other requirements. The Operations Plan will detail the specific metrics to be used such as mean time to repair, resource utilization, and maintenances costs per antenna. Once a knowledge base is established through collection of metrics, trends will be identified which can be used to forecast budgetary and resource needs, also useful for forward quality monitoring and improvement.

8 Operations Infrastructure

The overall goal regarding operations infrastructure is to minimize the number of staff and the extent of operating equipment located on-site in lieu of working out of a nearby Maintenance Center (possibly in Magdalena, NM). A majority of, if not all, spare LRUs and equipment is expected to be located at the Maintenance Center and its warehouse. This means the array site will have only a small number of depots, garages, and storage buildings.

Items will be repaired offsite at a separate Repair Center, with "green-tagged" assets shuttled to and stored at the Maintenance Center. Shuttling of personnel from Repair Center and/or the Maintenance Center to the array will be minimized, as discussed in the Logistics section. Science, scientific and user support, and data analysis will be done remotely. Software support and research and development of hardware and software will likewise be done remotely.

Table 1 gives a breakdown of the type of work done and buildings and equipment needed at the various Operations locations. It starts with the work to be done at the array core and progressively moves further away.

At Array Core	Near Array	Within State	Anywhere
Personnel • On-shift security • Working O&M staff: techs, safety, EMT/firefighter • Visitor's Center staff	Personnel • Safety • Security • Field Techs/Engs • Infrastructure Techs/Engs	Personnel • Operations • Administration • Repair Techs/Engs • Correlator Support • Computing Support • Safety	Personnel • Scientists • Administration • Data Analysis • User Support • Data Management • Software
Buildings • Central Electronics • Garage • Depot • Security • Small medical clinic • Visitor's Center (nearby)	Buildings • Maintenance Center (parts depot, work space, garages) • Remote Support Stations	Buildings • Array Operations Center • Repair Center	Buildings • Science Center • Research & Development • Data Center
Equipment & Assets • Antennas • Correlator • Other Array Assets • Heavy equipment required at site at all time • Fire engine	Equipment & Assets • Spare LRU/Hardware • Small cryogenics lab • Vehicles • Equipment for testing, working on antenna, infrastructure, transferring parts	Equipment & Assets • Items under repair • Repair/test equipment • Repair components • Vehicles for shuttling assets and staff	Equipment & Assets • R&D equipment • Data storage • Data Processing Resources

Table 1 - Operations infrastructure overview.

8.1 Central Electronics Building

The ngVLA's Central Electronics Building would house the central signal processor (correlator), centralized IT infrastructure, and time and frequency distribution equipment. The footprint of the ngVLA equipment is expected to be appreciably smaller than VLA equipment on a per-antenna basis, and can be likely accommodated within comparable areas to the VLA equivalent systems.

The VLA Control Building is similar to the envisioned ngVLA Central Electronics Building and it may be feasible to reuse it. The current footprint is of order 2000 m^2 and is expected to remain unchanged. Priority should be given to housing the electronics systems onsite rather than personnel, who would be better located at the offsite Maintenance Center.

8.2 Central Support Buildings

Additional buildings located near the core of the array will include garages and depots for storing heavy equipment that cannot be easily delivered or driven from the nearby Maintenance Center. The buildings will also support the maintenance and repair staff temporarily on-site while performing their duties. To maintain site security, a guard booth will allow security staff to provide a constant security presence.

Buildings that are no longer required will be demolished and removed. For example, this would include the transporter shop and antenna barn, due to anticipated design of the ngVLA antennas.

8.3 Central Infrastructure

Supporting infrastructure will be required for the central site buildings. The existing electrical switchgear, sewer system, and landfill will be assessed for suitability to ngVLA operation and upgraded or replaced as necessary. Extensive additions for the electrical and networking operations of the array core are expected.

8.4 Visitor Center

The ngVLA's core will create an impressive display of radio astronomy technology, inspiring visitors to travel to the site. In order to accommodate this desire, while minimizing the impact of detrimental radio-frequency emissions, the ngVLA Visitor Center will be located very near the array, but at some distance from the center of the core. A candidate location would be near the current intersection of the VLA's north arm with US Highway 60. It is also desired that an ngVLA antenna be located close to the visitor center in order to encourage closer interaction with such a key element of the array. This arrangement would remove the building, NRAO staff, and the visitors from the immediate proximity of the bulk of the telescope while still allowing for an encompassing view of array and a close-by antenna to approach. Another possibility is the current effort to repurpose the existing cafeteria building at the VLA site into a VLA/ngVLA visitor center.

8.5 Maintenance Operations Center and Warehouse

Much of the current maintenance activity and related infrastructure found at the VLA will move to a Maintenance Center located at or near Magdalena, NM. This center will provide the duty station for safety, security, and maintenance personnel. The maintenance personnel include technicians and engineers responsible for antenna, central signal processing, and infrastructure maintenance. This center will serve as the node for maintenance activities and the storage of ready spares, but not for module repairs.

Garages for heavy equipment and vehicles will be part of the center. Where cost-effective, work packages will be contracted to other parties rather than conducted by array operations staff, or partnership arrangements may be used. Remaining service functionalities will also need to be justified as cost-effective. The equivalents of current VLA facilities that still will be located at the Maintenance Center include

- Machine Shop,
- Electrical Shop,
- Warehouse, and
- Antenna Mechanics.

The warehouse will house all available spare assemblies and LRUs used in array maintenance visits. It shall therefore include a loading dock to facilitate receipt of repaired LRUs and shipping of LRUs for repair. The warehouse specifications should consider requirements during the assembly and construction phase; it is likely that some elements of antenna integration may take place within this space if space at the array site does not become available in time for ngVLA construction. This will be determined as part of the Antenna Assembly and Integration Plan.

8.6 Array Operations Center

The AOC and perhaps other facilities located in Socorro, NM, will house approximately 250 staff and will incorporate the Repair Center with sufficient space to host offsite array operations and to transfer, diagnose, repair, and test electronic LRUs and other equipment. LRUs and other equipment that fail or are pulled from the array would be sent to the AOC/repair center for repair before returning to the Maintenance Center warehouse. The AOC would include a typical complement of office space, laboratory space, storage and transfer capabilities, and computing infrastructure.

The VLA DSOC has an approximate area of 6200 m^2. It presently houses of order 140 staff and has a footprint of order 45 m^2 per person. This building should be reused as part of the ngVLA Array Operations Center/Repair Center, but a substantial addition will be required to accommodate the new occupants and additional repair laboratory areas, such as servo and cryogenics.

8.7 Science Operations Center

The Science Operations Center (SOC) is likely to be co-located with the Data Center, and will house approximately 175 staff, largely scientists, data analysts, computing, software, and IT positions, and some administrative and management staff. The facility will primarily consist of office space and computing infrastructure.

The location of the SOC is not determined, but Boulder, Austin, Albuquerque, Tucson, Dallas, Houston, or another metropolitan area are examples of possible candidates.

8.8 Remote Support Stations

Finally, Remote Support Stations (RSS) will likely be located in southern New Mexico, west Texas, Arizona, and Mexico to service mid-baseline stations of the main array. RSSs will also be used to service each of the LBA stations. The number and location will depend on the array configuration and expected reliability of equipment. It may turn out that it is more effective, from a cost and operational standpoint, to send maintenance and repair personnel from a central site to remote antennas.

An RSS will be similar in many ways to a VLBA station in that each RSS will act as a central depot and duty station for remote site technicians. Each RSS will likely have a footprint of order 186 m^2, supporting workbenches, organized tools, supplies, and inventory including spare LRUs required for routine maintenance of a group of antennas. Other central infrastructure may also be co-located at the RSS, such as time and frequency distribution systems. The RSS should include a loading dock to facilitate shipping.

An alternative to explore and cost could include using uninhabited buildings that serve as depots and work areas for a cluster of remote antennas. Each cluster would have a small compound with temporary living quarters and indoor/outdoor work areas, for the use of visiting preventive maintenance teams. Normally, these stations would be unmanned, other than periodic inspections by security and safety personnel, to ensure they were in good condition. The required LRU spares, tools and heavy equipment would travel with the preventive maintenance team. Personnel might be out for several weeks, like VLBA Tiger Teams, working on several antennas in a given area before returning.

9 Operations Logistics

9.1 *Staff Logistics*

As described above, support staff will be located in groups depending on the nature of their interaction with the instrument in order to minimize unique instances of travel (and therefore operations costs) balanced against the fact that having a duty station close to a population center generally makes it easier to recruit and retain staff.

Technicians who need regular access to the antennas, central electronics, and infrastructure systems will be located close to their work responsibilities. For most such personnel, this will be at the Maintenance Center, although a small number may be based at Remote Support Stations.

To reach the array center, daily buses will run to the Maintenance Center in/near Magdalena from the Array Operations and Repair Center in Socorro. Staff will then use a fleet of maintenance and service vehicles to reach areas of the array requiring maintenance. The technicians located at the Maintenance Center will be cross-trained so that they service multiple systems on each required trip to an antenna.

Technicians and engineers who need regular access to components and LRUs—but only periodic access to the antennas, central electronics, and infrastructure systems—will be located at the Array Operations and Repair Center in Socorro. Unlike their counterparts assigned to the Maintenance Center, these staff are expected to be system specialists focused on the repair or overhaul of equipment that requires laboratory space with advanced test equipment. It is more efficient to move batches of components or equipment to the specialist personnel and labs than it is to move personnel closer to the distributed antennas and other equipment.

Scientists, hardware and software engineers, data specialists, and other support staff that do not need regular access to antenna-based hardware and infrastructure systems will be remotely located at the Science and Data Center. The chosen location should have a large pool of skilled workers to pull from, as well as schools and employment opportunities for their partners.

9.2 *Shipping and Inventory*

An inventory of commonly used supplies will be centrally maintained at the ngVLA warehouse. The inventory must be electronically tracked to determine usage rate and location of spares throughout the locations in the array.

Each logistics center will have central shipping and receiving and be integrated with an NRAO-run shipping system between sites. A regular shuttle will ship supplies and parts between the ngVLA site and the AOC daily. Logistical support to RSS stations will use a combination of commercial carriers and NRAO-run shuttles for larger freight. Spares should be managed in a Kanban-type method at each RSS, so that notice is sent to produce and deliver a new shipment of items as the RSS consumes them. Using NRAO-controlled shipping will ensure prioritization, possession, and safe handling of items during transit.

Standardized practices for shipping must be adopted where possible to reduce delays and damage. Pelican cases or equivalent packaging shall be considered for all LRUs. The shipping cases and packing practices shall provide ESD protection in addition to mechanical shock absorption.

9.3 *Spares Management and Maintenance Repair Process*

LRUs will be centrally managed, tested, and repaired from the Repair Center in Socorro, NM, but will be stored near the point of service at the ngVLA Maintenance Center and RSS locations. Maintenance tracking, which should be tied into the configuration management as discussed below, will indicate the status of each LRU (in the array, under repair, or available from spare inventory). This tracking will also indicate the nature and history of repair work done on the LRU or item.

Component-level spares will be stored in a warehouse near or at the AOC and provided on an as-needed basis to AOC-based repair staff. The warehouse will include the stock of spare components procured during the construction phase, and a lifetime supply of spare components should be included in the construction budget of each element, if possible. This lifetime supply should be based on predicted Mean Time Between Failures (MTBF), Failure Modes Effects and Criticality Analysis (FMECA), and Mean Time to Repair (MTTR) for the components and their operational environment. Storage shall be closely and automatically inventoried in order to minimize duplicate orders or loss of product.

During the repair process, testing and quality control procedures must be sufficient to mitigate process errors and address pending failures before components and systems are redeployed. Acceptance testing of software and hardware deliverables must occur before delivery to or installation on the array in order to minimize maintenance trips. Repair groups will provide acceptance test data to the groups responsible for either inventorying or using the repaired items. Maintenance leads for technical support groups responsible for particular subsystems and their components shall review the work done and accept the repaired article for restock at the warehouse. The associated repair log and test data shall be entered into a database prior to acceptance review and should be globally visible to all groups from any location, even out in the field at remote antennas. The equipment shall only be considered repaired and ready for use upon acceptance of this test data.

9.4 Configuration Management

Configuration management is critical to provide a history of versions deployed across the array, documentation associated with particular versions, forward and backward compatibility, physical facilities, and understanding sufficient to control the array's software and hardware performance and attributes. A configuration management system will be required to indicate which serial numbers of LRUs and other hardware items are in the array, under repair, or available from spare inventory as well as each configuration item's location, repair, and upgrade history. A configuration database of the software employed on the array will identify the software's functional attributes at various stages in the array's lifecycle while also providing control and traceability of any changes. The systems must be in place during the construction phase of the array. Specific information unique to each configuration item (for example, calibration data, lookup tables, etc.) shall be included in the configuration management strategy.

Configuration management will be a useful tool to plan upgrades, mitigate failures, and smoothly evolve the array to the configuration needed for commissioning.

9.5 Physical Security

Physical security for the ngVLA site and the remote sites will be provided through:

- Basic physical barriers (gates, locks, signs) and remote monitoring equipment;
- Regular threat assessments and training for local security personnel;
- Regular physical patrols where practical, especially in the array core, to cover gaps in remote monitoring;
- Procedures, plans, and training for fire hazards and fire-fighting;
- Design with resistance to the elements, consistent with a remote, unoccupied site; and
- Design strategies deterrent to infiltration and nesting by rodents, insects, birds, and other wildlife and vegetation that would interfere with site operation or deteriorate site integrity.

Remote monitoring equipment will include, at minimum:

- Door sensors and alerts for all antennas and remote sites
- Video surveillance using webcams or equivalent
- Microphones or other audio recording equipment
- Environmental monitors to inform need to stow antennas

An interface layer will identify data streams with interesting information (e.g., a change in the field of view). These streams will be recorded and also monitored either by an array operator or a security guard. In the event of an intrusion, local law enforcement will be contacted and relied upon for a response.

Each remote site should be fenced completely with a gated entrance. Trees and other vegetation should be cleared from the edges of the fences for protection of the site and to maintain clear sightlines.

9.6 Cybersecurity

ngVLA IT systems will be hardened against intrusion consistent with existing NRAO CIS policies. This security will protect ngVLA information and data transfer from disruption, malware, and exploitation of technical vulnerabilities. Given the dependency on computerized remote operations and maintenance, equipment is particularly vulnerable to cybersecurity attacks and breaches in ways not experienced on previous instruments. This presents a tremendous risk that must be given in-depth analysis by cybersecurity experts against monetary loss and instrument downtime, complete with a mitigation strategy and adequate cost to inform security design and operations planning.

9.7 Administrative and Other Shared Support

Operations will require various types of administrative and functional support from NRAO. These will be defined in the Operations Plan and will be allocated to the appropriate divisions and groups. Funding of the support will be done through overheads applied to the Operations effort. Examples of shared support include

- Program Management
- Computing and Information Services
- Human Resources
- Budgeting and Fiscal support
- Shipping and Receiving
- Contracts and Procurements
- Environmental, Safety, and Security
- Management Information Systems

10 Reuse of VLA and VLA-to-ngVLA Transition

To minimize the cost of the construction of the ngVLA, as well as reduce the cost of VLA decommissioning, ngVLA will endeavor to reuse existing VLA elements wherever suitable. All existing buildings and infrastructure systems will be assessed for suitability as part of a construction plan [RD09]. Assessments will be based on lifecycle cost analysis, assuming the need for an additional 20 years of operation. However, given the goal of minimizing the physical presence of staff and continuously operating equipment at the array core, extensive reuse is not expected.

The minimization of need for buildings or ngVLA operations support activities based at the array core will simplify the transition from VLA operations to ngVLA operations. It is expected that the VLA will shut down or enter a period of significantly simplified science operations as ngVLA construction activities ramp up. Obvious break points include when construction of the ngVLA reaches a point of unacceptable interference with VLA science operations, and the start of installation of the ngVLA correlator if it is to be in the existing VLA control building. The addition of extensive infrastructure will eventually require an interruption of existing service to the VLA. The Array Operations Center and operations staff will also have to transition in design and function as additional and different equipment is repaired and the remote operation of the ngVLA begins.

These issues and others will be identified in a Transition Concept [RD11] and will be fully addressed in a subsequent VLA-to-ngVLA Transition Plan. This plan will define milestones, resources, and costs for operations ramp-up of ngVLA activities while coordinating with the shutdown of the VLA and any decommissioning requirements.

11 Development Program

An ngVLA Development Program is needed to ensure the array's scientific growth throughout its lifetime. Using scientific and technical community proposals and other initiatives, the program will fund the competitive studies and projects designed to encourage three areas of development typically outside the scope of operations:

- Scientific development projects, focusing on scientific advancement and enhancements of capabilities of the array;
- Technical development projects, focusing on development of new or improved hardware, software, or techniques; and
- Legacy science program [LSP] projects, which are observing or archival projects that require significant resources.

Encompassing the Legacy Science Program [AD01], the Development program will allow for a clean separation between operations efforts and research and development initiatives. The Development Program will ensure that these activities do not compete against operating costs. Determination of the program's structure, funding profile, frequency of call for proposals, and management will be captured in an ngVLA Development Program Plan.

Potential scientific and technical development projects could be

- Complete new additions to the array;
- Extension of existing capabilities with more sensitivity, improved image quality, better dynamic range, etc.;
- Improvements to existing hardware or software systems resulting in enhanced availability and capability of ngVLA data; and
- Improved infrastructure that reduces risks, increases availability, and makes operation easier/less expensive.

Legacy Science Projects are observing or archival projects that are distinguished from typical PI-led observing investigations by the following fundamental principles:

- They are large and coherent science projects, not reproducible by any reasonable number or combination of smaller general observing investigations.
- They have general and lasting importance to the broader astronomical community for which the ngVLA data will yield a substantial and coherent database.
- They generate raw and pipeline-processed data that enter the public domain immediately upon NRAO processing and validation, thereby enabling timely and effective opportunities for follow-on observations and for archival research, with both the ngVLA and other observatories.
- They provide the community with some combination of deliverables, such as Enhanced Data Product (EDPs), analysis software/tools, etc.

11.1 Development Funding

The ngVLA Operations budget funds the ngVLA Development Program. Per [AD01], the Legacy Science Program anticipates funding needs of approximately $3M per year to support multiple individual projects. Scientific and technical development projects will require an additional $5M per year, based on the funding required to manage the similar aspects of the ALMA Development Program.

11.2 Technical Development Proposal Requirements

Each proposed technical development project must address the impact it will have on the scientific capability and or operational performance of the array.

In general, proposed projects should not increase the operations cost. However, each project will be evaluated on its own scientific merit, and operations costs will be considered in the prioritization of potential development projects.

Each project proposal must have a plan that addresses the following items, in addition to its science objectives:

- Cost (including AIV, commissioning and science verification)
- Schedule
- Safety plan
- PA/QA plan
- Software development plan
- Integration plan addressing also AIV, commissioning and science verification.
- Draft operation manual
- Maintenance plan

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter/sub-millimeter Array
AOC	Array Operation Center
CIS	Computing and Information Services
CSP	Central Signal Processing
DB	Database
EDP	Enhanced Data Products
FMECA	Failure Modes, Effects, and Criticality Analysis
LRU	Line Replaceable Unit
LSP	Legacy Science Program
LSST	Large Synoptic Survey Telescope
MTBF	Mean Time Between Failures
M&C	Monitor & Control
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
OWG	Operations Work Group
PI	Principal Investigator
QA	Quality Assurance
RAOC	Remote Array Operation Center
RD	Reference Document
RFI	Radio Frequency Interference
RFID	Radio Frequency Identification
RSS	Remote Support Station
SAC	Science Advisory Council
SKA	Square Kilometer Array
SRDP	Science Ready Data Products
TAC (ngVLA)	ngVLA Technical Advisory Council
TAC (NRAO)	NRAO Time Allocation Committee
TBD	To Be Determined
VLA	Jansky Very Large Array
VLASS	VLA Sky Survey
WFIRST	Wide Field Infrared Survey Telescope

12.2 Driving Requirements and Key Assumptions

A few high-level requirements and constraints for the ngVLA, as well as assumptions made by the authors, shape this operation concept. These are captured below. The requirements and constraints come from draft systems requirements or external guidance.

Requirement/Constraint
ngVLA shall be a proposal-driven, general purpose, pointed instrument.
ngVLA operations cost efficiency shall be improved with a goal of not exceeding $75M (FY17) per year, three times the VLA+VLBA operations cost.
The ngVLA shall replace the VLA, with VLA ceasing to operate.
The ngVLA core shall be located within the existing VLA site.
Operations lifetime shall be 20 years from completion of construction.
Antennas shall be non-relocatable.

Assumption
Governance and Management
The ngVLA is US-funded and operated by the NRAO on behalf of the astronomy research community. The concept is subject to change if international partners join.
Construction/Project/Transition
VLA will continue science operations (possibly with a reduced range of capabilities) until early science operations of ngVLA. Once ngVLA science operations starts, NRAO will cease operations of the VLA.
All stations will depend on commercially supplied power.
All stations will have high-speed network connectivity.
Integration of the existing observatory infrastructure and personnel is desirable.
The reuse of land leases/easements and the inner mile is expected, but not a requirement.
The reuse of VLA site infrastructure (roads, electrical, fiber, sewer, water, etc.) and buildings (CB, maintenance buildings, cafeteria, AOC, etc.) is desirable, but not required or expected. The design should be optimized for total lifecycle cost over the expected operational life defined above.
The construction budget will provide for the development of data pipelines for a defined set of capabilities through the construction and commissioning phase. Thereafter, further development must fit within the operations budget cap defined above.
Retention of construction staff for operations employment is highly desired where skills match the Observatory needs.
Antenna locations as presently approximated by the SW214 configuration.
Antenna manufacturing, whether off or on-site, will not impact VLA Operations.
Current VLA electrical infrastructure can supply 1/3rd of anticipated ngVLA power requirements at the core.
MTBF, MTTR, and FMECA analysis of construction items are done by ngVLA Systems Engineering staff.
Array Operations
There will be one major Maintenance Center near the array. If determined necessary, there may be multiple remote service depots.
Operations and repair centers will not be located near the array.

The number of staff and operating equipment located on the array will be minimized in lieu of working out of a nearby Maintenance Center.
Maintenance scheduling will be automated, based on array conditions and requirements.
Array assets will be repaired offsite where possible, with the exception of fixed items that are not easily removed and must be serviced in-situ.
Maintenance staff should consist of or be trained by construction staff.
Maintenance shall be both preventive and predictive based on monitored conditions of the array.
Science Operations
All elements of array design and operations, both hardware and software, must support operations of multiple subarrays for different purposes right from initial commissioning.
For the majority of projects (that use standard capabilities) ngVLA will deliver Science Ready Data Products through the use of automated processing pipelines.
Users will not be constrained to use standard modes. Where the science goals warrant it, non-standard observations that do not deliver SRDPs will be accommodated.
Standard calibration schemes will be provided for standard observing capabilities and modes.
PIs will be awarded time on science targets, not guaranteed sensitivities.
The Science Center and Data Center will likely be co-located, probably in a metropolitan center to maximize ability to recruit and retain highly specialized and mobile staff.
The Observatory will support scientific discovery through both PI-initiated observing projects and use of publically-available science data from the Observatory archive.
Operations Costs
The expected operating and maintenance requirements and costs of delivered products (HW, SW, Infrastructure) will be provided by the construction project participants or aggregated by the ngVLA Systems Engineering staff.
Service Level Agreements with NRAO groups will be required during operations and will be outlined in the plan.
Other
The array's subsystems may be heterogeneous in composition while still meeting system requirements. An example will be rolling upgrades of some electronics. Configuration of each system and subsystem is therefore critical and will be monitored by the M&C system.

Assembly, Integration, and Verification (AIV) Concept

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Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
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Change Record

Version	Date	Author	Affected Section(s)	Reason
1.0	2018-12-26	S. Durand, E. Ford, C. Langley	All	Initial Draft
1.1	2019-01-19	AIV-WG		Reorganized document and incorporated comments and additions from v1.0; draft provided to project office per scheduled deliverable
1.2	2019-02-27	AIV-WG		Further reorganization and streamlining, implemented suggestions from WG feedback
1.3	2019-03-27	AIV-WG	1.4, 6	Implemented suggestions from WG feedback
2	2019-05-30	A. Lear	All	Format and copyedit to prepare document for approvals and release
3	2019-07-09	M. McKinnon	All	Copyedited for clarity
A	2019-07-10	A. Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction

1.1 Purpose

This document provides a concept for the ngVLA system Assembly, Integration, and Verification (AIV). The description, approach, and functions associated with key organizational interfaces will be explored.

1.2 Scope

This document covers a qualitative view both of the overall AIV process and the activity and interactions between the AIV IPT and other ngVLA construction efforts. The assembly, verification, and handoff of the hardware and software systems will be described. Neither specific technical requirements, detailed product assurance requirements, nor budgetary information are considered within this document's scope.

1.3 AIV Working Group

A team comprised of expertise from NRAO science, technical, and program management staff has been formed to meet, discuss, outline, and produce this *Concept* for the assembly, integration, and verification of the major ngVLA construction deliverables. This qualitative document will be delivered in early 2019, and followed up with a more detailed *Plan* later in the year.

The AIV Working Group (AIV-WG) has representation from prior project teams, including ALMA, JVLA, and VLBA.

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Ex-Officio members include Rob Selina, ngVLA Project Engineer; Dana Dunbar, ngVLA Antenna IPT Lead; and Todd Hunter, ngVLA CSV-WG Lead.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents may not be directly referenced herein, but provide necessary context or supporting material.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA System Engineering Management Plan	020.10.00.00.00-0001-PLA
AD02	ngVLA Operations Concept	020.10.01.00.00-0002-PLA
AD03	ngVLA System Reference Design	020.10.20.00.00-0001-REP

2.2 Reference Documents

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	ALMA Product Assurance Requirements	ALMA-80.11.00.00-001-D-GEN
RD02	B. Lopez, R. Jager, N.D. Whyborn, L.B.G. Knee, J.P. McMullin. Assembly, Integration, and Verification (AIV) in ALMA: Series Processing of Array Elements.	
RD03	R.E. Hills, A.B. Peck. ALMA Commissioning and Science Verification.	Proc. SPIE 8444, Paper 90 (2012)
RD04	D. Rabanus, M. Keating. Observatory Facility Staff Requirements and Local Labor Markets.	Proc. SPIE 8449, Paper 18 (2012)
RD05	S. Durand, ngVLA Electronics IPT Schedule.	TBD

3 Assumptions

The items listed in this section are relevant assumptions or concepts that are not discussed elsewhere in this document.

1. There are on the order of 263 antennas in the array, each comprised of electronics, mechanical, and software system packages. A quantity of hardware spare components/assemblies will be provided by the IPTs with the delivered array.
2. Thorough design reviews will be conducted at major project milestones. These may include a Conceptual Design Review (CoDR), Technical Specification Review, Preliminary Design Review (PDR), Critical Design Review (CDR), Manufacturing Readiness Review (MRR), and an Operational Readiness Review (ORR). Delivery (Verification) and possibly Re-Verification reviews are also anticipated.
3. Existence of an independent Configuration Control Board (CCB).
4. Existence of a Product and Quality Assurance Role under Project Management.
5. IPT construction staff are to be readily available for support during early AIV activities. This typically involves an on-site presence during the first installation of the IPT's deliverable. Some AIV expertise is intended to be drawn from the IPTs, and thus IPTs are to plan for this provision by including sufficient staff within their budget and arranging for succession planning, if needed.
6. IPTs will deliver the hardware necessary for verification and integration capabilities on a schedule commensurate with the AIV plan. This may require partial or phased deliveries of key subsystems such as the central signal processor and signal generation and distribution system.
7. Establishing project acceptance policy does not fall within the responsibility of AIV. Any acceptance procedures suggested or referred to in this document are superseded by procedures established by the Project Manager's office.

4 Assembly, Integration, and Verification Process

AIV processes occur at multiple levels throughout the construction process, regardless of whether a construction activity takes place entirely internally to the project or partially at an external vendor. It is important to note that AIV does not dictate acceptance criteria but carries out the process that will result in a successful handover.

For example, construction of a power supply may be formulated as the acceptance of components from external vendors, assembly and integration in to a power supply, and verification that the assembled system meets specifications. In this document, we use AIV to refer to the process through which IPT Products (defined in Section 8.2) are accepted from the construction IPTs, assembled, and integrated first to Elements and then to the Telescope System; and finally the system being verified to meet system-level technical requirements.

4.1 Process Definition

Verification is the process of evaluating deliverables to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase. These conditions may include regulations, requirements, interfaces, and/or specifications that have flowed down from the project requirements. This may include satisfying imposed documentation requirements, the successful completion of design or specification reviews, and analysis or other inspections. Verification of the individual delivered products is not part of the AIV process, but rather is carried out internally before the handover of a product. It is an objective process that will help determine the overall quality of a deliverable.

In this context, Acceptance is the declaration by the receiving party that a deliverable has been verified as defined above, and that the AIV team may proceed to integration with reasonable expectation that the deliverable will meet the technical requirements. Prior to delivery, the IPTs shall submit a draft Verification and Validation (V&V) plan. Requirements will flow down from stakeholders and from the key science goals for the science requirements in accordance with the ngVLA Requirements Management Plan [AD01]. These will be incorporated into the subsystem Requirements Verification Traceability Matrix (RVTM), which reflects all criteria necessary for acceptance. Verification of products will occur at the IPT level, prior to delivery. Once acceptance has been achieved, the IPT's warranty period commences.[1]

Integration is the assembly of accepted products to form higher-level products (e.g., *articles* to *elements* or *elements* to the *telescope system*). Throughout the construction process, best practice dictates that an over-riding principle is that no group should be responsible for both the integration and acceptance of a product.

Finally, the integrated product must be *verified* to meet the system technical requirements, prior to delivery. The verification of system requirements will be performed on technical capabilities including interface compliance to ICDs and integrated functionality demonstrating that one or more technical requirement has been satisfied.

Systems with verified technical capabilities are delivered from the AIV process to the CSV process. As with the acceptance from the IPTs, an agreed Capability Verification Plan will be produced prior to delivery of capabilities to CSV.

1. To prevent deliverables from dwelling excessively long in the acceptance phase, some IPTs may stipulate that the warranty period automatically commences a fixed period of time after delivery.

4.2 IPT Deliverables

All IPTs (or other bodies) delivering products to the project will follow the same process. Most IPTs will have multiple types of deliverables. Deliverables include the hardware, software, firmware, test stands/equipment, test reports, supporting documentation.

4.2.1 Hardware

The IPTs are responsible for the design, verification, and delivery of their respective hardware to AIV. Upon design maturation, LRUs, Articles, and Sub-assemblies may be delivered directly to the antenna assembly location, to the project warehouse for storage until such time as it is scheduled to be integrated, or to another mutually agreed upon location. Packaging for delivered hardware shall ensure the safe storage of equipment in nominal warehouse conditions.

The warehouse, which may include buildings in more than one location, is under the purview of Operations, or an operations-like entity. A primary function of the warehouse is to store electronics and other assemblies delivered by the IPTs that require safe keeping prior to antenna integration, as well as to keep an accurate inventory of these items.

IPTs generally use the following documents to specify hardware:

1. specifications, which detail requirements of the hardware;
2. ICDs, which provide interfacing details between the IPT's Hardware and other subsystems; and
3. SOWs, which provide details about how the hardware will be produced, delivered, and warranted.

4.2.2 Software

All software and firmware delivered to the project must be version controlled and be delivered with suitable automated unit, integration, and regression testing suits. Maintenance of delivered software remains the responsibility of the delivering IPT, until the acceptance of the final product from the IPT. Development tools, compilers, source code, and the build system shall be delivered. All delivered software and firmware products should be appropriately and uniquely identified using the native tagging process of the version control system.

AIV may perform isolated integration testing of delivered software and hardware prior to integration to Elements or the full system. All Application Program Interfaces (API) or other software interfaces must be defined in an ICD. Automated testing for conformance to the ICD shall be delivered with the product.

4.2.3 Documentation

In addition to hardware and software products, IPTs (or other delivering groups) are responsible for authoring all procedures associated with their delivered article and sub-assemblies. AIV will use these documents to assure an acceptable level of product support, and to confirm prior performance tests. The complete delivery package will be defined in a separate product assurance document. Required documentation for hardware deliveries will include, but is not limited to, the following broad categories:

- Theory of Operation, including Hardware Design Document Package
- Product Specifications
- Interface Control Documents
- Article Test Procedures, Plans, and Results
- Maintenance Plans and Procedures

4.2.4 Product Test Stands and Equipment

Articles and other assemblies frequently require specialized test equipment to independently verify and validate their performance outside of their subsystem environment. The design and construction of the individual product test stands, including any necessary test software (LabView executables and other test routines or scripts), is the sole responsibility of the delivering IPT. These will be delivered at the time of the first article so as to verify functionality during the (re-)verification process.

These deliverables will be governed by the project acceptance standards and appropriate documentation shall accompany their delivery. That is, product test stands are expected to conform to the same documentation and acceptance requirements as hardware delivered by the IPT. Maintenance and calibration of the test stands is the responsibility of the delivering IPT during the array construction phase until acceptance of the final product delivery from the IPT. AIV is subsequently responsible for maintenance until delivery to Operations. Identical test stands shall be provided by the IPTs to any production or destination facilities they use for the purposes of verification testing. In cases where a subcontractor is used, an additional test rack may be required at their location.

Any test stand delivered to AIV must conform to the global project requirements that address safety, EMC/RFI, electrical, mechanical, etc. as applicable for the test stand. Test stand delivery is a special case for acceptance and shall be addressed by collaboration of the Project Engineer, AIV, and IPT Lead.

AIV is responsible for procuring any other test equipment that crosses IPT boundaries and is required during antenna integration.

4.3 General Acceptance Process

IPT-level construction and integration processes will follow best practices. This will be achieved in part with the help of a quality assurance (QA) team. The QA group will be a separate entity from the IPTs, although individual inspectors from the group will be embedded within each IPT to inspect workmanship, to assure all required documentation has been completed satisfactorily and all applicable standards have been addressed, and to verify that required testing prior to shipping has been successfully administered.

Each product that is provided from one group or IPT to another will undergo functional testing and document verification prior to the handoff (Figure 1). A successful verification, defined as when all responsible parties sign off on the verification document, must be achieved prior to handoff of a product to the receiving group. To assure no damage has occurred during transit, in cases where an item is shipped from one working group to another, the assembly may be required to undergo a re-verification. Verification and re-verification procedures and documents may be similar, but not necessarily identical.

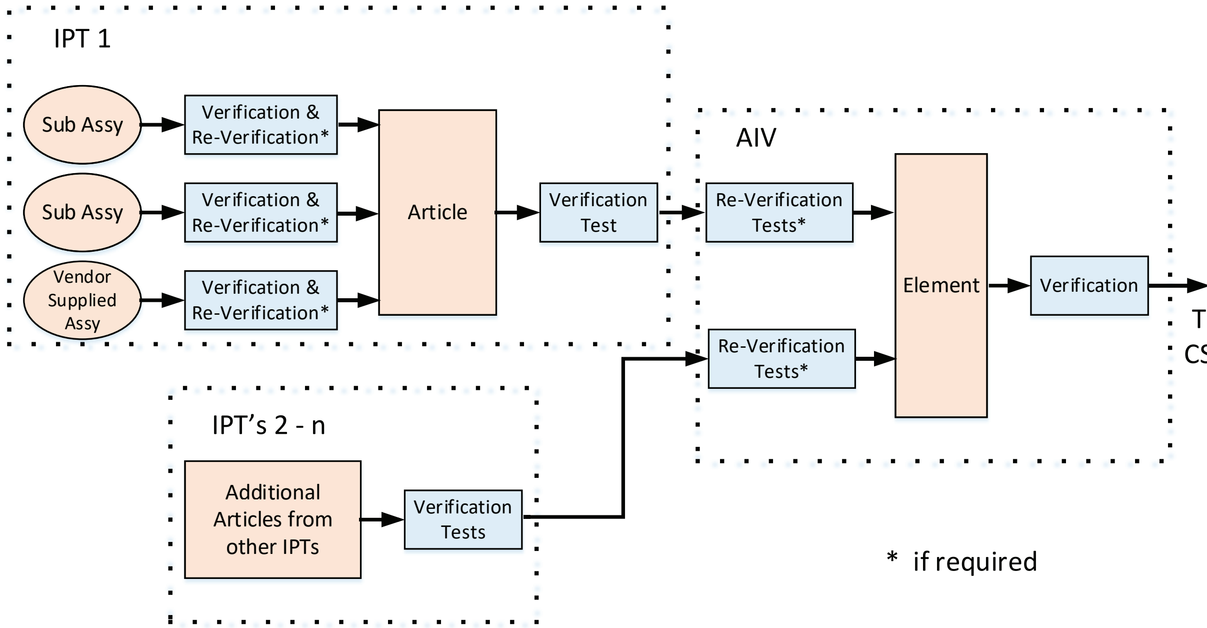

Figure 1 - Overview of ngVLA testing, verification, and acceptance processes.

Products are delivered to AIV by the individual IPTs. The delivering IPT will perform delivery verification. Within an IPT, this testing may occur more than one time along the product assembly path prior to product handoff from the IPT to AIV (or other receiving IPT), depending on the nature of the products and the location at which they are constructed. Possible re-verification on site may be required based on the Quality and Product Assurance plans. This preliminary acceptance is a milestonewhere AIV agrees that the product has been verified and is ready to take responsibility for it. Once the Telescope system is verified to support a previously defined set of Capabilities, the system is delivered to CSV. Final acceptance may take place after integration, when the Product has been demonstrated to meet all technical requirements.

5 AIV Group Activities

The AIV Process described above is fundamentally a project level activity with direction and contributions from the project office (e.g. Quality Assurance and System Engineering activities). An AIV Group is also required to execute many of the tasks associated with the AIV process.

The AIV group is responsible for:

- Participating in the Product Acceptance process (this process is led from a different group, likely Systems Engineering).
- Integration of these products into a Telescope System with defined technical capabilities.
- Performing the verification process to demonstrate that the Telescope System meets the system-level technical requirements.

Delivery of the Telescope System is the responsibility of the CSV team for commissioning and scientific validation. Additionally, the AIV team has the responsibility to produce procedures for their activities during assembly, integration, and verification.

The AIV group is finished when all technical capabilities and elements are delivered to the CSV group. This is expected to be near the end of the project construction phase.

5.1 Design and Development Phase

To assure performance and schedule success, AIV will fill key staffing roles prior to the integration and testing of the first antenna, as described later in this document.

Prior to element integration, the IPTs, AIV, and CSV will work concurrently to produce formal ICDs and to assure that all testing plans adhere to the project requirements and specifications.

Also during this period, AIV engineering and technical staff will specify, develop, and/or procure any test equipment that does not fall within the responsibility of the individual IPTs, but which will be necessary during integration and verification. Testing software will be developed in conjunction with this equipment.

In the latter stages of IPT design and development, a prototype antenna will be assembled on site well before the commencement of formal array construction. The prototype antenna subsystem will be installed on a close-in pad or dedicated test pad near the center of the future array. The IPTs, working closely with AIV, will install their prototype hardware on the antenna. This will allow the IPTs the opportunity to refine interfaces, better understand the environment, and perform initial performance testing, while giving AIV hands on training. The IPTs will use this information to finalize the test requirements to be transferred to AIV for formal construction. The IPTs will have an opportunity to remove and replace hardware as needed on the test antenna.

Should project funding and schedule constraints not allow for one or more prototype antennas to be outfitted and tested prior to formal construction, the planned activities will necessarily take place during the beginning of the production, or pre-production, phase.

5.2 Early Delivery Phase

The Early Delivery phase begins with the acceptance of the first products from the IPTs and continues through at minimum the delivery to CSV of the first Telescope System with sub-array capabilities. Throughout the Early Delivery Phase, the AIV and CSV teams will work together to refine the processes, verification tests, and procedures that will be used to verify future product deliveries.

Products delivered to the AIV Team will have already been verified by the IPT. AIV may complete spot checks or re-verification as required by the project Quality Assurance Plan (RD when it gets written).

The primary AIV tasks during this phase are to assemble and integrate the products into a functional telescope or small set of telescopes (although not yet capable of meeting all specifications), establish the initial technical performance, and ensure the stated technical requirements and capabilities are met.

AIV and CSV are responsible for developing and maintaining the software necessary to perform and automate verification tests. These programming environments may include LabView code, scripts, or similar diagnostic tools. These tools shall use the APIs delivered by the CSW IPT.

5.3 Delivery Phase

Once the first Telescope System with sub-arraying capabilities has been delivered, the CSV and AIV teams will begin to work more independently. At that time, the ngVLA shall be a functional telescope, although with restricted capabilities. As production increases and multiple Telescope Systems are undergoing assembly and integration, AIV will necessarily expand to several construction teams. When an antenna's integration approaches completion of the AIV process, CSV resources may be diverted to those systems that are close to the time of handoff. The AIV team will continue to integrate products to the system, integrating and delivering to CSV a system with increased capabilities. Some capabilities will continue to require refinement or development of the verification procedures (increasing baseline length, software capabilities) while others (such as the verification of integrated antenna elements) should become a routine and efficient process. Routine processes may be streamlined to improve efficiency at the discretion of the Project Engineer.

During the construction process, should IPT hardware suffer a failure after having been delivered to CSV, AIV will intervene to solve these problems by engaging the originating IPT.

5.4 Late Construction and Project Closeout

Only after all products have been delivered from the IPTs can the final assembly and verification be completed. During this period, where AIV is verifying the performance of the full ngVLA system, it may be efficient to have AIV and CSV again work closely together.

Once all technical capabilities of the full array have been verified, the AIV team will have completed its primary mission and complete a project closeout. AIV will continue to exist for approximately one year after all deliveries to CSV are complete. This will assure the group has adequate time to complete any remaining documentation requirements, and that they are present to support commissioning of the final elements. All procedures, test equipment, and test software shall be delivered to the Operations and Maintenance staff. It is expected that many key individuals from the AIV team will transition to the Operations and Maintenance staff to preserve the expertise and institutional knowledge developed during the construction project. An acceptance review of the AIV materials to Operations may be held independently or as part of the project-wide closeout review process.

6 AIV Group Organization

During the Design and Development phase, AIV will not be fully staffed and may only consist of the AIV manager and a few support staff. The AIV Lead should be in place three years prior to the first antenna article delivery, with the second-tier managers in place the following year. A detailed ramp up (and down) staffing plan is described in the AIV plan, and the overall timing of this ramp is tied to the delivery of sufficient products to begin assembly and integration of the first antenna element.

6.1 Staff Duties and Responsibilities

Multiple teams of engineers and technicians may be required to outfit and verify the various system Elements. While the number of teams is not yet determined and will be set by other timetables in the project, the following roles are expected to be required within the AIV team.

Position	Minimum Requirements	Responsibilities
AIV Lead	Advanced Engineer or Scientist	Process centered individual responsible for managing AIV including hiring, budget and reporting status. Has signature authority over the AIV budget.
AIV Commissioning Scientist	Scientist/Research Engineer	Responsible for insuring AIV is testing to specification. Interfaces with CSV and the AIV test staff.
AIV Software Lead	Software Engineer IV	Responsible for managing the team that integrates software and hardware deliverables. Oversees the development of AIV test software.
AIV Software Engineer	Software Engineer II	Responsible for development, maintenance and updates of V&V tools through production and installation. Performs tests of software and hardware integration.
AIV Electronics Lead	Electronics Engineer IV	Responsible for managing the team that integrates LRU/Sub-assemblies and articles. Performs tests, ensures testing reliability, calibration and documentation.
AIV Electronics Engineer	Electronics Engineer II	Responsible for the installation of the LRU/Sub-assemblies and articles. Performs tests.
AIV Electronics Technician	Electrical Technical Specialists II & III	Responsible for the installation of the LRU/Sub-assemblies and articles.
AIV Mechanical Lead	Mechanical Engineer IV	Responsible for the installation of the LRU/Sub-assemblies and articles.
AIV Mechanical Technicians	Mechanical Technical Specialist III & IV	Responsible for the installation of the LRU/Sub-assemblies and articles. Performs tests.

7 AIV Interactions with CSV

The primary deliverables from AIV to CSV are integrated telescope systems with verified system capabilities. Of course, to accomplish this integrated and characterized antennae elements, the supporting signal generation and transport must be verified and integrated. As discussed above, during the Early Delivery Phase of the project AIV and CSV will work closely together to develop procedures and tests to clearly define expectations for future handoffs. During this time, the two groups will co-develop the test plans and other handoff requirements and will achieve several common milestones, which may include the following (capabilities will be further detailed in the AIV plan):

- Initial tests of delivered components (prior to antenna availability), including WVR
- Single dish operations I: Pointing, tracking, focus
- Interferometry operations I: Two-element interferometry
- Simultaneous interferometry in multiple subarrays

Finally, by working essentially as a single group during these early deliveries, a path for efficient knowledge transfer between AIV and CSV will be established.

Once multiple subarray capabilities have been verified, CSV and AIV will begin independent operations.

8 Appendix

8.1 Abbreviations & Acronyms

Acronym	Description
AIV	Assembly, Integration, and Verification
API	Application Program Interface
RFI	Radio Frequency Interference
AE	Antenna Element
FE	Front End
BE	Back End
CCB	Change Control Board
CDR	Critical Design Review
CoDR	Conceptual Design Review
CSP	Central Signal Processor
CSV	Commissioning and Science Validation
CSW	Computing Software
ES&S	Environment, Safety, and Security
ICD	Interface Control Document
IPT	Integrated Product Team
IRD	Integrated Receiver/Downconverter and Digitizer
LRU	Line Replaceable Unit
MRR	Manufacturing Readiness Review
ngVLA	Next Generation VLA
ORR	Operational Readiness Review
PA	Product Assurance
PDR	Preliminary Design Review
PS	Pulsar Search
PT	Pulsar Timing
RA	Right Ascension
RSD	Reference Signal and Distribution
RVTM	Requirements Verification Traceability Matrix
SE	Systems Engineering
V&V	Verification and Validation
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

8.2 Glossary

Element: A functioning collection of Articles. A fully functioning and verified antenna, comprised of various articles and subsystems, is an ngVLA Array Element, (AE).

Hardware Article: Delivered as a complete package to AIV, an integrated collection of LRUs and Sub-assemblies which are designed for a specific function.

Integrated Product Team (IPT): An organizational group responsible for the design and delivery of a product.

IPT Product: An integrated subsystem designed for a specific function. Products are the fundamental deliverables of the IPTs, either to the AIV process or less frequently to another construction IPT.

Line Replaceable Unit (LRU): A modular component that typically fits into a larger assembly, with an ability to be replaced quickly with no required software/firmware modifications.

Scientific Capability: Integrated functionality meeting one or more of the system level scientific requirements.

Sub-Assembly: A separately assembled unit designed to be incorporated into a larger manufactured product or article.

Technical Capability: Integrated functionality meeting one or more of the system level technical requirements.

Telescope System: An integrated combination of software and hardware that is capable of performing one or more [Technical/Scientific] capabilities.

Commissioning and Science Validation Concept

020.10.05.00.00-0006-PLA-A-CSV_CONCEPT

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2019-02-08	T. Hunter	All	Initial version
02	2019-03-15	T. Hunter	All	Implemented suggestions received during and since the second telecon; moved holography details to Appendix A
03	2019-03-24	T. Hunter	All	Implemented suggestions received during the third telecon; removed dates in Sec. 2.3; added two assumptions
04	2019-03-29	T. Hunter	All	Additional corrections implemented; submitted to project office
05	2019-05-20	R. Carver, A. Lear	All	Converted to Word document for project office review
06	2019-07-08	M. McKinnon	All	Minor edits throughout
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Table of Contents

1 Introduction

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

The facility will be operated as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products: automated pipelines will calibrate raw data and create higher level data products (typically image cubes). Data and quality assured data products will be made available through an observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

The signal processing center of the array will be located at the Very Large Array site, on the Plains of San Agustin, New Mexico. The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Array Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will likely be located in a large metropolitan area and will be the base for science operations and support staff, software operations, and related administration. Research and development activities will be split among these centers as appropriate.

1.1 Purpose of this Document

This document describes the concept of the Commissioning and Science Validation (CSV) process envisioned for the ngVLA. It provides a qualitative expression of the approach that will be taken including the roles, duties, and organization of the team, and a preliminary list of the expected tests and milestones to be conducted on the way to delivering a functional observatory and a list of validated science observing modes as demonstrated by accompanying science-ready data.

This document also outlines the staffing, resources and support that will be required from other ngVLA work groups. In particular, it identifies the need for early participation by students and external experts from diverse backgrounds. A separate document (the ngVLA CSV Plan [AD07]) will develop the quantitative details of the proposed milestones and the level of staffing required at each point in the process.

1.2 Scope of Document

This document pertains to all activities associated with CSV, including participation in the Assembly, Integration and Verification (AIV) process, the formal start of CSV, through the start of Early Science in 2028 Q4, and on to the delivery of a specific list of validated science modes by the start of full operations in 2034.

1.3 Applicable Documents

The following project documents are applicable to this report and are incorporated by reference. In the event of conflict, the applicable document supersedes the content of this report.

Ref. No.	Document Title	Rev./Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	ngVLA System Reference Design	020.10.20.00.00-0001-REP
AD03	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD04	ngVLA Transition Concept	020.10.05.00.00-0003-PLA
AD05	Front End Technical Requirements	020.30.03.01.00-0001-REQ
AD06	The Next Generation Very Large Array: A Technical Overview	*SPIE* Volume 10700, id. 107001O
AD07	Commissioning and Science Validation Plan	TBD
AD08	ngVLA Reference Observing Program	020.10.15.05.10-0001-REP
AD09	ngVLA Antenna: Preliminary Technical Specifications	020.25.00.00.00-0001-SPE
AD10	Proposed lifecycle for new ngVLA observing modes	J. Hibbard
AD11	Monitor & Control System: Preliminary Requirements	020.50.25.00.00-0001-REQ
AD12	Central Signal Processor Preliminary Technical Specifications	020.40.,00.00.00-0001-SPE
AD13	Computing and Software Architecture: Reference Design	020.50.00.00.01-002-REP
AD14	Computing and Software: Preliminary Requirements	020.50.00.00.01-0001-REQ
AD15	Calibration Requirements	022.20.00.00.00-0001-REQ
AD16	Subsystem Reference Design Description: Digital Back End/Data Transmission System	020.30.25.00.00-0002-DSN
AD17	ngVLA Assembly, Integration, and Verification Concept	020.15.00.00.00-0005-PLA
AD18	ngVLA Legacy Science Program	020.10.05.00.00-0004-PLA
AD19	ngVLA LO Reference and Timing: Preliminary Technical Specifications	020.35.00.00.00-001-SPE
AD20	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ

1.4 Reference Documents

The following non-project documents are referenced in this report:

Ref. No.	Document Title	Origin
RD01	The Expanded Very Large Array	*Proc. IEEE*, Vol. 97, Issue 8, pp. 1448–1462
RD02	The Expanded Very Large Array: A New Telescope for New Science	*ApJ*, 739, L1
RD03	ALMA Commissioning and Science Verification Plan (Laing, 2007)	ALMA-90.00.00.00-007-D-PLA
RD04	ALMA CSV Implementation Plan (Hills & Peck, 2009)	ALMA-90.00.00.00-017-A-PLA
RD05	Holographic Measurement and Improvement of the Green Bank Telescope Surface (Hunter et al. 2011)	*PASP*, 123, 1087
RD06	Improvement of the Effelsberg 100 meter telescope based on holographic reflector surface measurement	*A&A*, vol. 167, Oct. 1986, p. 390-394.
RD07	Out-of-focus holography at the Green Bank Telescope (Nikolic et al. 2007)	*A&A*, vol. 465, p. 685
RD08	GBT Holography Simulation and Analysis of Lunar Scans (Schwab & Hunter 2007)	PTCS Project Note 59
RD09	EVLA Real-Time Science Software Requirements	EVLA-SW-005
RD10	ALMA Control Software Subsystem Science Requirements	Butler 2005
RD11	Removal of daytime thermal deformations in the GBT active surface via out-of-focus holography (Hunter et al. 2009)	2009 USNC/URSI annual meeting
RD12	Mapping the Large Millimeter Telescope primary reflector using photogrammetry: A first comparison with 12 GHz holography (Gale et al. 2016)	*SPIE* Volume 9912, id. 4F
RD13	The Paraboloidal Reflector Antenna in Radio Astronomy and Communication, J.W.M. Baars	Berlin: Springer, 2007

2 Overview

The work required to bring the ngVLA observatory from the period of construction through commissioning and into operations is divided among several groups. In brief, the Assembly, Integration, and Verification (AIV) group delivers functional capabilities, which includes verified hardware and accompanying software, while the CSV group develops the processes needed to demonstrate performance and validate science observing modes. The Operations group and Maintenance group operate concurrently with CSV and are responsible for managing and maintaining the array, respectively.

2.1 Definition, Goals, Challenges, and Philosophy of CSV

The purpose of the CSV activity is to test and optimize the various elements of the ngVLA observing system to ensure that it meets the scientific requirements. The inputs to CSV from AIV will be verified capabilities rather than individual components. These capabilities will typically include a set of hardware elements, for example, a group of antennas and a portion of a correlator along with their corresponding control software that supports a specific observing mode. By starting from verified capabilities, CSV will be able to focus primarily on measuring system performance on the sky and developing observing modes, rather than debugging basic operations.

The principal outputs of CSV are validated science observing modes, which includes the processes of observing and data reduction, along with the associated technical documentation and procedures essential for operation of ngVLA as a user facility. The documentation will include reports and memos quantifying the as-built performance, exceptions, recommendations for improvement, and a verification matrix showing the performance as measured against the science requirements [AD01]. The procedures will include checklists for activities such as re-integrating an antenna into the array after a receiver package replacement.

Although CSV will formally end once the initial set of science observing modes that define Full Operations has been validated, the observatory envisions an ongoing program to commission new observing modes that are motivated by future science developments (Section 8) [AD03,18]. These activities will follow the example established by CSV during construction.

The challenging path toward reaching these goals will be eased by having the AIV and CSV teams work together closely through the delivery of the first few antennas and the first working interferometer, including subarray capability. Good communication between the teams in this Early Delivery Phase of AIV [AD17] will build a level of trust and expectation that will benefit the subsequent rate of progress toward their respective goals. After this initial period, the CSV team will need to balance the competing desires of achieving a minimum performance level for Early Science (ES) versus fully understanding and eliminating oddities in the system. It will often be necessary to choose the "simple but reliable" approach over exploring a more optimal or novel approach.

Considering the large scale of this observatory, it will be essential for CSV to attack and retire the high technical risk items early. Two primary issues of concern arise from the technical challenges of operations beyond the traditional baseline lengths of the VLA:

- the fidelity and stability of the LO/IF system on long baselines of the Main Array and the Long Baseline Array (LBA), and
- the effectiveness and reliability of WVR correction in a variety of weather conditions across the array.

For example, the preliminary designs for the data transmission system do not treat the long baseline stations in detail [AD16]. Demonstrating these capabilities early in the CSV process will help to ensure continued support from the scientific and public community for this Observatory.

2.2 Assumptions

The concept for CSV outlined in this document draws in broad terms from the ngVLA system reference design [AD02]. To the extent that fundamental aspects of the design may change, for example the polarization basis of the receiver feeds or the allocation of paired array elements on the mid baseline stations, the details of this concept may need to be modified.

2.2.1 Uniformity of Receiver Packages

The details of a commissioning concept and plan depend on how capabilities will be delivered from AIV to CSV. A fundamental assumption for this observatory is that when a receiver package is installed into an antenna by AIV, it will contain all receiver bands [AD05] rather than a partial set like ALMA initially fielded. Of course, in order for all receiver bands to be useful for general-purpose CSV, they must be delivered with verified focus and collimation offsets, if necessary.

It is not yet decided if the initial delivery of antenna capabilities from AIV will include verification of all bands, or whether some will be verified later as a separate capability. Although much CSV could be pursued with a few antennas and only a single operational band, having multiple bands available will allow different commissioning tasks to use different receivers on different sets of antennas that are appropriate to the task. For example, in any given week, it may be most efficient to do holography and pointing in Band 3 (at 16 GHz), efficiency measurements in Bands 4 and 5 (at 27 and 40 GHz), or interferometry tests in Bands 1 and 2 (at 2.4 and 8 GHz), depending on the prevailing weather conditions.

2.2.2 Order of Antenna Deployment

The bulk of the initial deployment of antennas will occur on the inner pads (R <1.3 km) as has been envisioned by the AIV Concept [AD17] and assumed by the Transition Concept [AD04]. However, in order to retire the technical risk of long baseline performance, and to validate the process of outfitting remote stations of the Main Array and LBA, it will be essential to deploy at least one antenna (with all supporting electronics) into each category of distance of the Long Arms (50 km and 500 km) in a relatively early stage of the AIV process. These stations will be critical for fundamental tests of the LO/IF system, delay server, etc., during AIV. The CSV team should be prepared to use these antennas to test the efficacy of WVR correction and other calibration schemes on long baselines [AD15].

2.2.3 Verification of Antenna Surface Performance

Another important assumption is that all stations must meet the same performance specifications, including rms surface accuracy [AD09]. The degree to which this requirement impacts the feasibility and cost of verifying the performance of antennas at remote stations by AIV and CSV must be expressed and captured during the ongoing detailed design process. For example, we will need to practice (first at the Central Cluster site) how accurately we can assemble and align an antenna surface by passive means. We will (almost certainly) need to confirm the final surface setting after assembly at each remote station. While beam cuts across the Moon can provide initial information on the level of surface error on different length scales of the aperture [RD08], the determination of surface corrections requires more detailed methods. But the method chosen depends heavily on the antenna design. We describe the primary options in Section 9.2 of the Appendix.

2.2.4 Multiple Sub-Array Capability

Given the scale and complexity of the ngVLA project, scientific validation will require multiple activities to proceed simultaneously on the array. Subsets of antennas and other hardware must be able to be used independently of each other with minimal crosstalk to support parallel operations. Sub-arraying capability is a key early capability to be developed by the AIV process, and its delivery will mark the end of the Early Delivery Phase [AD17].

2.2.5 Verification of Offline Software by AIV

Because the AIV group delivers functional capabilities to the CSV group, AIV will be responsible for accepting both the online control software and the accompanying offline data processing pipeline before delivering a new capability to CSV. This step will help to shield the CSV group from experiencing glaring bugs. The CSV group will exercise and validate specific releases of the pipeline, finding the more subtle bugs and inadequacies. Feedback from CSV will inform the next release. Occasional patch requests from CSV to the pipeline team may be necessary to avoid overall project delay.

2.2.6 Commissioning of the Data Center Is Out of Scope

CSV is responsible for demonstrating that science observing modes can be processed from beginning to end through the same pipeline data path that PI data will follow, ultimately producing a set of predefined SRDPs. Further commissioning of data center capabilities such as producing additional products, managing CPU and storage load, servicing special user requests, and providing remote data access will be performed by a different group in the Science Support IPT (to be identified in the CSV plan).

2.2.7 Telescope Operators to Be Supplied by Operations Group

Because CSV tasks will require late-night (and in some cases 24-hour) operation, a skilled staff of telescope operators will be needed to perform routine duties and launching of Scheduling Blocks (SBs), and to ensure the safety of the array elements. The operators will formally report to the Operations group but with the goal of supporting the CSV work plan.

2.3 Timescales and Historical Basis

The expected sequence of major events that will provide the framework for CSV activities is listed below.

1. First prototype antenna delivered by vendor.
2. First production antenna delivered by AIV.
3. First fringes (AIV+CSV).
4. Initial CSP, RSD, and six antennas delivered by AIV.
5. Science Validation of first Early Science mode.
6. Early Science First Call for Proposals.
7. Early Science First Observations.
8. All Main array antennas delivered.
9. Completion of Main array (214-element, <1000 km).
10. Completion of entire array (including LBA).

The projected period between the first antenna delivery and completion of the 214-element Main Array is expected to be only ten years. This rate of commissioning may be considered daunting when one considers that this number of antennas is comparable to the sum contained in all similar interferometers to date. However, there is some historical basis for this value based on the commissioning of prior interferometers with a large range in total number of antennas. The commissioning of both SMA (with eight antennas) and ALMA (with 66 antennas) required eight years from first prototype antenna (1996 and 2003, respectively) to start of Early Science.

Similarly, MeerKAT (64 antennas) required nine years from first fringes to dedication. Furthermore, for ALMA, it took four additional years (for a total of 12) to acquire the first PI observations at the longest baselines. By comparison, ngVLA is targeting 11 years to LBA completion. In any case, the ongoing validation of new modes envisioned in Section 8 means that CSV-like activities will continue beyond the initial decade of commissioning, and will likely persist throughout the life of the observatory.

2.4 Key Statements from Other Concept Documents that Impact CSV

The CSV concept has been developed to match the operational goals of the observatory. Here we list the major goals from two other ngVLA concept and design documents that are most relevant, and briefly note their impact on CSV (in italics).

2.4.1 Operations Concept [AD03]

Section 6.0: "At the start of ngVLA Early Science, only a small number of these modes that have been verified to work end-to-end will be available to PIs. The number of modes available to users will increase as early science progresses, with all modes deliverable from the construction projects available in full operations." *–In order to facilitate Early Science, the Early Science observing modes need to be defined at an early stage (§ 7.2).*

Section 6.1: "Different capabilities and observing modes will be made available in stages during the transition from construction through... commencement of full operations." *–The Science Validation (SV) milestones shall be staged with specific observing modes in mind (§ 8).*

Section 6.3: "Delivery of a fully-commissioned standard observing mode will include an operational SRDP pipeline before it is offered for regular use through PI proposals." *–The Science Validation (SV) milestones include a demonstration of SRDP generation (§ 7.2).*

Section 6.5: "The Observatory will release a set of First Look science products—defined with input from the user community—ahead of PI access to the array." *–These will be the Science Validation targets (§ 7.2).*

Section 13.1: "All elements of array design and operations... must support operation of multiple sub-arrays for different purposes right from initial commissioning." *–Clearly, the commissioning of sub-array operation must have high priority. Up to ten subarrays are envisioned [AD12]. It should be possible to run different versions of software running in different arrays, with deployment and configuration management handled remotely in order to support efficient operations [AD13]. Indeed, the demonstration of sub-array operation marks the end of the Early Delivery Phase of AIV (§ 7.1).*

2.4.2 Technical Overview [AD06]

"...the long baseline antennas would fall into a VLBI station model with a number of local oscillator (LO) and data transmission stations located beyond the central core. These stations will be linked to the central timing system, correlator, and monitor and control system via long-haul fiber optics. Several options will be explored for precision timing and references at these stations, including local GPS-disciplined masers, fiber optic connections to the central site, and satellite-based timing." *–This is an important problem to be solved and will require placing one or more antennas on remote pads as early as possible during CSV to avoid delays in achieving long baseline science. While dedicated, controlled fiber connections are envisioned on the Central Cluster, Spiral Arms, and the nearer stations of the Long Arms (up to 300 km) [AD19], the more distant stations will be connected with commercial fiber. Because commercial fiber cannot provide sufficiently fine control required for LO transmission, the nominal plan is to outfit the LBA stations and the 17 other most distant stations on the Long Arms with hydrogen masers [AD02].*

2.4.3 ngVLA System Reference Design [AD02]

Section 7.9: "Calibration tables that compensate for large-scale instrumental and atmospheric effects in phase, gain, and bandpass shapes will be provided." *–The calibration database (see also [AD15]) will need to store additional antenna-based calibration parameters such as gain curves and polarization D-terms, while the calibrator database will need to store calibrator flux density histories and image models in order to support the online software selection of calibrators and their cycle times [RD09, RD10] and to support offline calibration. Both databases will need to be populated initially by CSV (Section 7.1) and accessible to SRDP (Section 7.2). Ideally, the calibrator database will also be accessible to proposal preparation and SB generation tools.*

3 Composition and Duties of the CSV Team

Because the telescope will present a broad range of capabilities and frequency coverage, and many aspects of the design and technology will differ significantly from other NRAO facilities, the experience of the CSV Team will need to be diverse, drawing from all areas of radio astronomy research including scientists of all ages with experience in RF, digital, and software engineering as well as single-dish and interferometric calibration and imaging. The members of the CSV team will be distributed among the following work activities, with group leaders appointed where necessary. This list of activities is meant to indicate the sorts of skills to seek when hiring new staff or assigning current staff.

1. Assess the implications of major design choices on CSV during the future detailed design phase.
2. Assess impact of CREs submitted by other subsystems during the construction phase, including obtaining and analyzing any necessary data.
3. Assist AIV teams with on-sky testing of hardware prior to delivery to CSV, including the prototype antenna, receiver, and correlator performance.
4. Devise and execute integrated performance tests of AIV-delivered items with specific pass/fail criteria.
5. Work with Computing to write observing scripts to achieve successful on-sky performance tests ("manual mode").
6. Develop utilities for performance data analysis (and temporary metadata fixes) as needed and manage them as a coherent package (similar to ALMA's analysisUtils).
7. Report system deficiencies encountered back to AIV and Maintenance for resolution via JIRA tickets.
8. Interact with hardware and software engineers to be aware of the latest status of problem investigations and fixes.
9. Devise and execute performance tests of the array as a whole (items of stability and fidelity that typically require long integrations or observing sequences).
10. Populate the observatory calibration database, such as primary beam models, flux calibrator image models, and polarization calibration information.
11. Write ngVLA memos and reports that summarize performance test procedures, results, and directions for future work.
12. Work with colleagues at ALMA and other facilities to better understand cutting-edge problems that each face.
13. Be familiar with the Reference Observing Program and the capabilities that these projects require.
14. Maintain familiarity with the calibration plan and provide feedback regarding feasibility.
15. Maintain familiarity with pipeline processing and development, and provide new requirements when necessary.
16. Deliver tested observing modes and work with the Operations group to achieve successful SV results.
17. Organization of CSV Team.

The extensive number of performance items that CSV needs to validate will be a daunting task. It will be a challenge to maintain focus on a few major issues at a time while simultaneously not allowing some items to receive no attention, which could raise the risk of significant rework at later stages of the project. Establishing a number of teams with a specific focus will help to expedite the CSV process. For example, it will be prudent to define a team that focuses on long-baseline issues and commissioning in order to expedite finding problems earlier in the process than might otherwise happen in the inevitable push to make the Central Cluster available for Early Science. Another example is a team responsible for flushing out all the issues associated with autocorrelation data, rather than leaving it for a later time. Similarly, additional groups will be needed for RFI and for short baselines. It will also be useful for members of the

CSV team to serve as members of other closely related groups such as the Array Calibration Group and the Control Software Group.

The leadership of the CSV group will include a division head and the leaders of the various teams, each with a scientific background. These leaders should be System Astronomers with previous experience in commissioning and an ability to interact efficiently with System Engineers in the AIV group. In order to promote an efficient organization of CSV effort, responsibility will be divided between the team members so that each person is encouraged to take ownership of one or a small number of specific commissioning items. That person will follow the natural workflow of proposing the tests to be run, executing the tests, analyzing the data and writing the report, and consulting with other members of the team and the wider scientific staff as needed at each stage.

Handing off items from one person to another in a turno style should be discouraged in order to avoid misunderstandings of what the next steps should be. On the other hand, we want to avoid single-point failures within the CSV staff, so defining cognizant deputies for the larger items will be necessary. Presence on site should not be a requirement for contributing to the CSV team, especially because skilled and conscientious staff working at remote locations can efficiently examine test data during the mornings immediately following test observations.

4 Communication Plan

Communication of progress on commissioning items will be recorded in a weekly log (compiled from the daily shift log [AD13]) that is distributed to the team and made available to other subsystems. Further progress details will be presented by team members both informally at weekly group meetings and to a wider audience through lunch talks at the science center. To enable and encourage remote participation, the weekly meeting will need to be held at a time and day convenient to all NRAO sites, likely 11AM or 2PM MT on a day that does not conflict with colloquia schedules. Once multiple antennas are available for CSV, a higher cadence coordination meeting (either Mon-Wed-Fri or daily) among the team leaders and the current and upcoming observers will likely be needed to assess the top priorities and plan the upcoming 24–48 hours of observing tests, but should be limited to 30 minutes as much as possible. A representative from the Computing group and Operations group should also be present.

As each major commissioning item is completed, reports or ngVLA memos will be written that summarize the performance test procedure, current results, and directions for future work. Team members should also give presentations of recent successes and ongoing vexing problems at outside institutions, particularly those with radio astronomers on the faculty. The latter venue may help prevent repeating mistakes of the past as well as increasing awareness of more efficient methods to make progress. Members of the CSV team should likewise be encouraged and enabled to maintain visibility in the science communities of their choice during their years of service.

5 Resource Requirements

The CSV Plan document [AD07] will specify resource requirements in more detail, such as the personnel effort and time required for various commissioning tasks and milestones. The following is a general list of items that will be needed, many of which will be supplied by other IPTs.

5.1 Software

The software needs of the CSV group to efficiently perform its work will include both in-house data analysis software and commercially available products. A preliminary list is provided below.

1. A system to report and track problems (such as JIRA).
2. A monitor data archive [AD11], with automatic filling and the capability to list and plot contents. Configurable monitoring and the ability to trigger high-frequency sampling for short periods (the "oscilloscope function") will be desirable (to be provided by Computing & Software (CS) [AD13]).
3. A centralized database to store system configuration data (including calibration models) under version control (will be provided by the CS group [AD13]).
4. A hardware revision control system, with history of LRU installations and repairs. It should be possible to find version and serial number for any hardware module installed on an antenna.
5. A science-oriented API (scripting interface) for calling high-level array functions, prior to the widespread use of Scheduling Blocks (SBs) (to be provided by CS group [AD13]).
6. Simulators to enable the development of observing scripts without the real system (to be provided by CS group [AD13]).
7. Interactive shell access to the calibration and imaging software (assumed to be CASA), and the python scientific stack running on an observatory-supported Linux OS (see Section 6.2.4).
8. Access to commercially licensed analysis tools if needed (MATLAB, etc.).
9. The importance of having VLA and ALMA providing contemporaneous flux densities, spectra, and polarization of calibrators in the various ngVLA bands should not be overlooked.

5.2 Hardware

5.2.1 Weather Stations and APM

The scheduling and interpretation of commissioning observations will rely on accurate knowledge of the weather at the Central Cluster, each station of the Main Array, and LBA sites. For the remote stations, webcams showing sky conditions would be helpful. An interferometric atmospheric phase monitor (APM) at the Central Cluster will also be essential to make efficient use of test observing time. An all-sky, mid-infrared cloud monitor located at the Central Cluster would be useful for detecting the presence of hydrosols during observations, which would help to commission the continuum fitting and removal function in the WVR phase correction software.

5.2.2 Staged Delivery of Correlator

Prototype correlators were important in the past for commissioning new interferometers (ALMA, WIDAR, and also the original VLA). But new correlator designs come in big chunks, and the prototype concept becomes rather different. For instance, a reasonable initial correlator for AIV and CSV purposes might well include all stations but a limited bandwidth (few hundred MHz) and only a couple of modes.

5.2.3 On-Site Control Room Workspace

During the Early Delivery Phase when AIV and CSV are working closely together on the first antennas, there will need to be a dedicated workspace provided in the local control room at the array site. Once the control system is established reliably, telepresence using a remote control room at the local science center should work well (as it did for the EVLA WIDAR project).

5.2.4 Computing

The remote control room used by CSV must contain a sufficient number of IT-supported workstations, in addition to the main multi-monitor control console where the operator sits. These machines will ensure that scientific staff have a place to work, either on the cluster nodes or interacting with real-time systems, while preparing for pending observational tests. We should avoid forcing people to carry their laptops back and forth to the control room in order to be able to do anything.

To process commissioning data promptly, CSV staff will require guaranteed access to high-performance computing cluster nodes and disk space. Provisions must also be made in the data center for CSV staff to access the visibility data outside of the automatic, non-interactive processing model that is envisioned for the steady-state operational mode in the Operations Concept document [AD03]. In this interactive access mode, having the ability to filter portions of the data easily will be important, especially because some problems may only begin to arise once large numbers of antennas are operating in one subarray.

5.3 Personnel

The list of personnel described in Section 4 will need to draw from scientists both inside and outside the observatory.

5.3.1 Internal Staff

We will expect contributions from the scientific staff of all NRAO sites (SO, CV, JAO) and many of the partner organizations. These scientists will both participate in CSV and mentor ngVLA research associates hired specifically for CSV. The research associates will provide the bulk of the daily testing, reporting, and CSV software effort. There should be a path for associates to join the ngVLA Operations team.

The staff scientists assigned (in part) to ngVLA will be relied upon to provide skeptical review of results, engage in problem solving efforts on fundamental interferometry issues, and provide experience in recognizing data anomalies. It will be important to recruit the top performing AIV staff into CSV roles, either scientist or engineer, in order to have a transition of expertise that will retain knowledge of the system. Outside the CSV team, we will require operational support from computing, maintenance, and other subsystems as needed.

5.3.2 External Staff

The CSV leadership may wish to invite visiting scientists, with demonstrated interest and experience on specific commissioning campaigns, to participate in commissioning campaigns. These invitations will be one way to augment the experience of the CSV staff, which may be too limited in some particularly specific areas. Such invitations will need to offer at least partial financial support for travel and other expenses.

In addition, it will be important to the observatory during the CSV phase to attract and engage graduate students and additional (non-ngVLA) research associates to help test the capabilities that serve their research interests. We recognize there will be competition for their attention with other facilities like SKA, and that this will require financial support, including travel and accommodations.

5.3.3 Operators

The Operations group will provide skilled telescope operators to assist with the execution of CSV observations and to ensure the safety of the array elements. The operator training process might involve some assistance by CSV staff, for example to explain the concepts and goals of current tests and how they can be most efficiently accomplished.

6 Milestones

The milestones are organized into three sections. First listed are the milestones for commissioning the general capabilities and measuring performance level of the observatory (enumerated by the "C" prefix), both of which are required for science validation to proceed. These milestones are based loosely on the ngVLA System Reference Design [AD02], so any significant changes to that design may necessitate a revision in the milestones.

Second are the milestones required to validate each observing mode (enumerated by the "SV" prefix). The order in which science modes are commissioned is described in Section 8. Finally, we list the milestones to prepare validated observing modes for Early Science ("ES" prefix).

6.1 Milestones for Commissioning

The list of commissioning milestones follows the expected flow of capabilities as systems are delivered from AIV. The Plan document will provide more detail including mapping the activities to specific items in the Science and Technical Specification documents and their respective pass/fail criteria. The order may not be sequential depending on the actual schedule of deliveries achieved. Also, the point of interface between AIV and CSV through the first four steps is likely to be somewhat fluid as the teams gain experience with the antennas and other systems.

For example, while AIV is responsible for delivering the pointing and focus model coefficients and the nominal antenna surface setting, it is not expected that a complete characterization of elevation dependence of antenna performance will be provided, so this will work fall to CSV. As a result, the first four milestones correspond to the Early Delivery Phase of AIV [AD17], during which the AIV and CSV teams will work closely together up until the point that multiple subarray operation is successfully demonstrated.

The list of milestones below will be presented in more detail in the ngVLA CSV Plan [AD07], with direct reference to the system technical requirements [AD20]. In general terms, we expect that the mid-frequency receiver bands (2–4) will be exercised the most in the early days as they supply a reasonably small primary beam for pointing and interferometry (21 61 on the 18m antennas), while avoiding the RFI at low bands and frequent tropospheric limitations in Bands 5 and 6.

6.1.1 Joint AIV+CSV Commissioning Milestones During the Early Delivery Phase

C1. Initial tests of delivered components (prior to antenna availability), including WVR.

C2. Begin single-dish operations.

- Most items in this category (alignment, pointing, focus, beam profiles, gain curves, surface performance) should eventually be done through interferometry, because it is easier and often more accurate. But we may be able to start some of the measurements before interferometry is possible.
- Also, we must remember that single-dish mapping using autocorrelation data is a required capability of the observatory.

C3. Begin Interferometry Operations I: Correlation of several Central Cluster antennas leading to a stable interferometer.

C4. Validate simultaneous multiple subarray operation.

- Acceptance of subarrays marks the split of CSV from AIV.

6.1.2 Subsequent Commissioning Milestones for CSV Group

C5. Begin array performance testing, typically requiring long integrations (stability of phase, bandpass, beam patterns).

C6. Demonstrate operation from Scheduling Blocks.

C7. Test fundamental calibration plan and report performance.

- Begin populating the calibrator and calibration databases.

C8. Begin Interferometry Operations II: Correlation of Spiral Arms with Central Cluster.

- Provide surface performance validation of remotely assembled antennas.

C9. Test polarization calibration of Central Cluster and Spiral Arm antennas and report performance.

- Will we apportion some of the correction to observatory-provided values and some that is experimentally measured?

C10. Begin testing first observing modes.

- Confirm the production of viable raw data in the Science Data Model (SDM).

C11. Test automated processing of each observing mode.

- Provide feedback to Pipeline and SRDP developers to facilitate subsequent SV milestones.

C12. Declare observing modes using Central Cluster and Spiral Arms ready for Science Validation.

- Present results for official acceptance by Operations, including calibrator and calibration databases.

C13. Begin Interferometry Operations III: Core antennas with remote stations of Long Arms and LBA.

- Provide a preliminary performance assessment.

C14. Test polarization and amplitude calibration plan of Long Arms and LBA and report performance.

- Demonstrating polarization angle and D-term calibration over this wide range of baseline lengths will be challenging.

C15. Declare Long Arm and LBA observing modes ready for Science Validation.

- Present results for official acceptance by Operations.

6.2 Milestones for Science Validation

Science Validation is the process of acquiring observations of well-known objects from Scheduling Blocks and processing them through Calibration, Imaging, and SRDP. It will follow the approach used successfully by ALMA. Unlike ALMA, for which no comparable facility existed, we will be able to quantitatively demonstrate agreement with prior observations from VLA and/or ALMA.

For each observing mode approved for Early Science by the project as a whole, the following tasks must take place. Steps 1–4 can be done as preliminary work before the array is ready. Step 5 (onward) will require a functioning, reliable interferometer of at least 25 antennas. Steps 3–6 require close collaboration with the Operations group. Whether Step 7 is performed for every observing mode or only a subset will likely depend on the resources available in the run up to the Call for Proposals.

The name suggested for those modes that include a public data release is First Look Science [AD18], which is applicable for the first few years of Early Science. In the final years of CSV and beyond, the name for such data from new modes will likely evolve to Public Science Verification or Demonstration Science

[AD10]. In both cases, there needs to be agreement with Operations on what constitutes successful, robust processing of a mode, perhaps in terms of Key Performance Indicators. The commissioning status of each science mode will be tracked with an integer code indicating its current level of support (see the definitions in Section 9).

SV1. Select Science Validation target fields and identify previous VLA and/or ALMA datasets.

- Gain scientific input from the user base, facilitated by the Project Scientist.

SV2. Select Science Validation calibration plan (in collaboration with the Calibration group).

SV3. Determine the list of inputs that will be required of the PI for this observing mode, or if any special data quality assurance (QA) considerations are needed.

SV4. Generate Science Validation SBs using the Observing Tool (with assistance from Operations).

SV5. Execute Science Validation SBs.

SV6. Perform initial quality assessment, adjusting, and repeating observations until successful (with assistance from the Operations group).

SV7. Demonstrate quality-assured Pipeline processing of successful SBs (with assistance from the Pipeline and SRDP groups).

SV8. Demonstrate quantitative agreement with previous VLA and/or ALMA datasets of same target fields.

- Subtle bugs are often discovered when two different observatories closely compare similar observations of the same target.

SV9. Demonstrate that the SV data can be successfully calibrated and imaged through the same processing path that the subsequent ES data will ultimately follow.

- The larger task of "commissioning the data center," including the generation of additional data products or viewing capabilities, will not be performed by CSV (see Section 2.2.6).

6.3 Milestones to Prepare Validated Modes for Early Science

As observing modes are validated, the CSV group will also need to participate in the following documentation and announcement activities, along with the Operations team.

ES1. Document any exceptions in the characteristics of the data that would invalidate the suitability of this mode to the pipeline.

ES2. Release of raw and processed data products to public (prior to the Call for Proposals).

ES3. Assist Operations group with writing the Technical Handbook (prior to the Call for Proposals).

ES4. Declare observing modes ready for Early Science (prior to the Call for Proposals).

ES5. Define Shared Risk Observing modes that do not meet the readiness criteria for Early Science (prior to the Call for Proposals).

ES6. Participate with the Operations team in popularizing the ngVLA and its observing modes via talks at other institutes (after the Call but before the Deadline).

ES7. Write IEEE and *PASP/ApJ* journal articles on the ngVLA as a whole (ALMA did not do this), modeled on the papers produced for the EVLA by Perley et al. 2009 [RD01], and Perley et al. 2011 [RD02].

For any observing modes not chosen to be offered for Early Science, but required to be delivered before the end of Construction, the steps above will need to be repeated.

7 Order of Science Observing Modes to Be Commissioned

It is essential for the ngVLA project to define a specific list of observing modes to be validated by CSV. The ngVLA Reference Observing Program (ROP) [AD08] provides examples of observations that support the Key Science Goals of the observatory. Because these examples cover a number of different science observing capabilities, it raises the question of the order in which these capabilities should be commissioned and made available to Science Validation and First Look Science (FLS).

At this stage of the project, it is premature to present a recommended order of commissioning of science modes, particularly because community workshops establishing the science goals of ngVLA are ongoing during 2019. Nevertheless, as a start, this section distills the science projects identified in the ROP into a preliminary list of science observing modes based simply on two components: sky coverage and spectral coverage. A possible third axis of distinction would be baseline length within the Main Array. Most likely, the general guideline is that smaller arrays will be commissioned first, which will naturally impact the order in which science observing modes are validated, and thus the order of release of FLS data. This concept will be further developed in the CSV Plan [AD07].

At present, the ROP does not convey which projects require SBA or Total Power observations, but these have been integrated into the list below where they seem most appropriate. Any special performance concerns are listed in italics alongside the associated science mode. Finally, we have assumed that the option of full polarimetry is delivered with each mode rather than being commissioned separately.

1. Single pointing interferometry
   - Continuum only: basic calibration needs to be established.
   - Spectral lines with continuum: spectral purity and correct labelling need to be established.
   - Imaging that includes SBA datasets: multi-aperture data combination needs to be established.
2. Pointed mosaic interferometry: accurate primary beam patterns will be essential
   - Continuum only
   - Spectral lines with continuum
   - Imaging that includes SBA datasets
3. Phased array
   - VLBI mode
   - Pulsar modes including timing and multiple phase centers
4. On-the-fly mosaic interferometry: accurate primary beam patterns will be essential
5. Rapid response to transient source alerts: *reduced time overhead in command and control*
6. Total Power (i.e. single dish continuum and spectral line imaging): antenna performance for rapid scanning is needed
   - Continuum only
   - Spectral lines with continuum
7. Single pointing LBA interferometry: stable LO reference and timing system at LBA sites
   - Continuum only
   - Spectral lines with continuum

8 Post-Construction Activities

Not all observing modes will be commissioned at the end of construction. CSV-like activities to commission further modes will be merged into the Ongoing Capability Development (OCD) effort, as defined in the Operations concept document (Section 6.7). Such new observing modes may include specific science areas such as advanced Pulsar modes. Since most of the CSV staff may have moved on to other projects, it will be important to transfer knowledge of the commissioning process to the Operations staff, and to solicit help from experts in the community.

The lifecycle of new modes will be clearly defined including the product delivered to the PI. The Lifecycle document [AD10] proposes the following categories, to which we have attached integer levels for easier reference:

- Level 3: Standard Mode Data Reduction (SMDR): SBs are automatically generated; data are fully pipeline-ready and have well defined SRDPs.
- Level 2: Non-Standard Data Reduction (NSDR): SBs are automatically generated; data are not pipeline-ready but can be processed by automatically-generated scripts and have defined SRDPs but are likely to be refined.
- Level 1: Shared Risk Observing (SRO): SBs require manual editing; data are not pipeline-ready but can be calibrated.
- Level 0: New Mode Test Observation (NMTO): an experimental stage that precedes SRO.

In addition, there is an option to have a mode called Principle Investigator Data Reduction (PIDR) for cases where specific complicated data reduction is required. In this mode, the SBs are automatically generated, but the observatory does not perform quality assurance.

9 Appendix

9.1 Abbreviations and Acronyms

Acronym	Description
AIV	Assembly, Integration, and Verification
ALMA	Atacama Large Millimeter/submillimeter Array
API	Application Programming Interface
APM	Atmospheric Phase Monitor
CASA	Common Astronomy Software Applications package
CRE	Change Request
CS	Computing and Software
CSP	Central Signal Processor
CSV	Commissioning and Science Validation
EDP	Early Delivery Phase (of AIV)
ES	Early Science
FLS	First Look Science
GBT	Green Bank Telescope
JAO	Joint ALMA Observatory
IF	Intermediate Frequency
KSG	Key Science Goal
LBA	(ngVLA) Long Baseline Array
LO	Local Oscillator
PI	Principal Investigator
QA0	Quality Assurance Level 0 (Data can be calibrated)
ROP	Reference Observing Program
RSD	Reference Signal and Distribution
SB	Scheduling Block
SBA	(ngVLA) Short Baseline Array
SDM	Science Data Model
SMA	SubMillimeter Array
SRDP	Science Ready Data Products
SV	Science Validation
WVR	Water Vapor Radiometer

9.2 Validating Antenna Surface Shape and Determining Panel Corrections

To illustrate the impact that antenna surface validation will have on the CSV concept, we briefly review the primary options for deriving surface corrections: photogrammetry and holography. Photogrammetry requires placing reflective tape at hundreds of positions across the surface (ALMA antennas have 1080 [RD13]), taking pictures at various angles and solving for the 3D surface [RD12], for which one part in 105 is readily achievable (180μm for an 18m primary). Holography requires measuring the complex beam pattern of the antenna using a strong signal source. Since we cannot feasibly build holography towers at every remote station, it would need to be either celestial or satellite holography which will require expertise of the CSV team.

In either case, obtaining a stable reference signal will be difficult if the nearest antenna is many tens or hundreds of kilometers away. In ngVLA configuration main-revC, there are seven antennas for which the nearest antennas is >100 km away (up to 284 km, in fact, for pad m083 = Kitt Peak) as shown in Figure 1. Rapid scans in an asterisk pattern through the target (as used by ALMA celestial holography) might mitigate the stability problems, but will need wide bandwidth to detect the source far enough off-axis to acquire the necessary complex beam pattern.

Another alternative is phaseless "Out-of-focus" holography (i.e. imaging a point source at multiple focus settings), which can recover large-scale dish surface deformations without the use of a reference receiver [RD07]. This technique is used to correct thermal deformations in the GBT surface prior to high-frequency observations [RD11]. But this method will likely not provide sufficient resolution for validating antenna surface assembly, which will inherently involve measuring the sharp alignment discontinuities at panel boundaries.

If neither photogrammetry nor celestial holography can provide sufficient results, then we may need to perform geostationary satellite holography on a Ku band beacon. This technique would require temporarily mounting a separate reference receiver and feed on the antenna (like the GBT uses [RD05]), or transporting and setting up a small fixed antenna near the antenna (like the Effelsberg 100m has used in the past [RD06]). This simplest solution for a backend would likely be a portable system containing a two-channel IF processor (with a single sideband downconverter and narrow band anti-aliasing filter), a 90-degree phase shifter, three-channel ADC, and a digital complex correlator. The autocorrelations and cross products would be stored on a local control computer and retrieved over the Internet for remote processing and archiving.

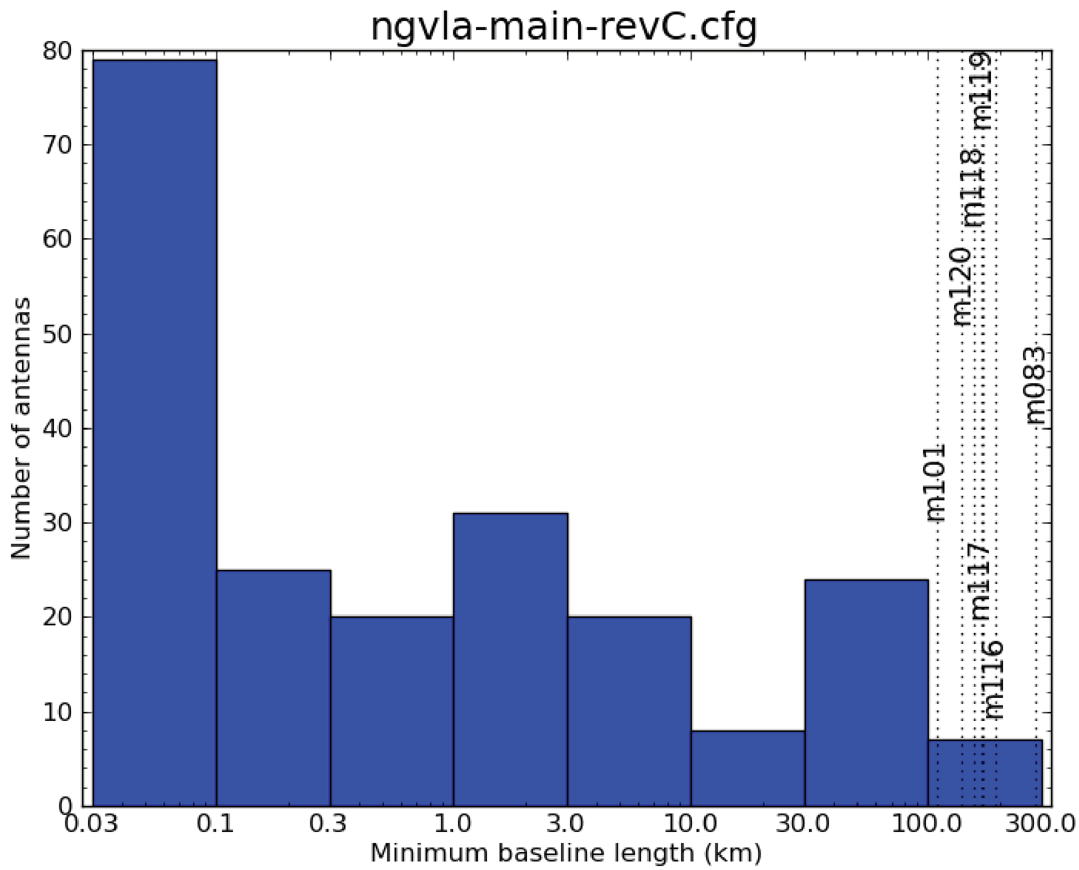

Figure 1 - Histogram of the shortest baseline of each ngVLA antenna in the Main Array of 214 antennas, using the main-revC.cfg file. The names of the seven pads where this length is >100 km are labeled.

Preliminary Stakeholder Requirements

020.10.15.01.00-0001-REQ-A-STAKEHOLDER_REQS

Status: **RELEASED**

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Change Record

Version	Date	Author	Notes/Changes
01	2018-06-01	Treacy	Initial version for Stakeholder Requirements Review (StRR)
02	2018-11-05	Treacy	In-progress draft addressing RIDS from StRR
03	2018-11-19	Zuckerberg, Selina, Hiriart	Addressed gap analysis, updates from RIDs, and major edits throughout for requirements quality. Reformatted to doc.
04	2018-11-26	Zuckerberg, Selina, Hiriart	Added new categories of requirements for organization. Finished major edits from StRR and team review.
05	2018-12-05	Selina, Hiriart, Zuckerberg	Updated numbering scheme for consistency with Requirements Management Plan. Updated traceability column entries. Minor updates to requirements flow-down strategy narrative.
06	2019-05-30	Lear	Prepared document for review.
07	2019-05-31	Selina	Minor edits for release.
08	2019-07-08	Selina	Addressing comments from MM review.
A	2019-07-09	Lear	Prepared document for approvals & release.

Table of Contents

1 Introduction

1.1 Purpose

This document aims to present a preliminary set of stakeholder requirements for the ngVLA that should guide the development of the facility.

Many requirements flow from the system life-cycle concept documents, especially the Operations and Maintenance Concept [AD02]. As other lifecycle concepts are developed to comparable levels of maturity, the associated requirements will be refined.

In addition, an attempt has been made to capture other stakeholder (programmatic, safety, regulatory compliance, etc.) requirements from representatives of various stakeholder groups. Where possible, traceability for these requirements is provided to a source, but this document should be considered a primary reference for stakeholder-level requirements.

1.2 Scope

The scope of this document is the entire ngVLA project over its full lifecycle. This includes not just the scientific facility, but the supporting infrastructure and personnel, with input at all stages of development from design, to operations, and disposal.

2 Related Documents

2.1 Applicable Documents

The following documents are applicable to this Requirements Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Requirements Specification, the content of the lowest level specification (in the requirements flow-down) shall be considered the superseding requirement for design elaboration and verification.

Reference No.	Document Title	Rev / Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD03	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD04	ngVLA Reference Observing Program	020.10.15.05.10-0001-REP
AD05	ngVLA Safety Requirements (L0)	020.10.15.10.00-0004-REQ
AD06	ngVLA Land Acquisition and Regulatory Compliance Requirements (L0)	020.70.00.00.00-0001-REQ

3 Overview of the Stakeholder Requirements

This document presents the stakeholder requirements of the ngVLA at the project level. The L0 Stakeholder Requirements along with explanatory notes are found in Section 6. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirement and should guide the requirements flow-down.

Stakeholder requirements are written in the stakeholder's language (i.e. non-technical) and are not always verifiable. The verification and validation strategy for ngVLA aims to capture the broad intent with stakeholder requirements, with sufficient specificity in the subsequent system-level requirements to enable their verification.

The system safety and regulatory compliance requirements are documented separately and incorporated by reference:

[AD05]	*ngVLA L0 Safety Requirements*	020.10.15.10.00-0004-REQ
[AD06]	*ngVLA Land Acquisition and Regulatory Compliance Requirements (L0)*	020.70.00.00.00-0001-REQ

4 Requirements Management

4.1 Requirement Definitions

The following definitions of requirement "levels" are used in this document.

Requirement Level	Definition
L0	User requirements expressed in terms applicable to their needs or use cases ("Science Requirements" or "Stakeholder Requirements")
L1	Requirements expressed in technical functional or performance terms, but still implementation agnostic ("System-Level Requirements")
L2	Requirements that define a specification for an element of the system, presuming an architecture ("Subsystem Requirements")

4.2 Requirements Flow Down

The L0 Requirements are captured in a pair of documents. The functional and performance requirements necessary to support the key science goals of the facility are captured in the L0 Science Requirements [AD01]. Other Stakeholder Requirements also influence or dictate design choices. Examples include programmatic requirements, regulatory compliance requirements, and the life-cycle concepts (e.g., the operations & maintenance concept [AD02]) for the facility, and these requirements are captured here.

The Science Requirements and Stakeholder Requirements fully encapsulate all known L0 requirements. The System Requirements and subordinates fully encapsulate all known L1 requirements.

Specifications for individual subsystems (L2) generally flow from the L1 System Requirements, and may not always be directly attributable to a single system requirement (e.g., phase drift specifications at the system level may be apportioned to multiple subsystems, or a subsystem specification may be in support of multiple higher-level requirements). In some cases, L2 requirements may flow directly from L0 requirements. This is permitted in order to not require duplication of requirements between the L0 and L1 levels, and to enable extraction of detailed requirements from the life-cycle concepts. Completeness of the L2 requirements is assessed at the requirements review of each subsystem.

Maintaining enumerated and traceable science requirements, system requirements, and subsystem specifications ensures this trade-off process is complete and well understood by the project team. The effect of a change in a subsystem specification can be analyzed at the system level, and thereafter the impact on a specific scientific program can be ascertained.

The details of the requirements management strategy can be found in [AD04].

5 Stakeholder Requirements

5.1 Programmatic Requirements

Parameter	Req. #	Value	Traceability
Construction Budget (Total, Maximum)	STK0100	The construction budget shall have a design target of less than $1.7B (2018)	[Directors Office, 2018]
Operations Budget (Annual, Maximum)	STK0101	The annual operations budget shall have a design target of less than $80M/yr. (2018)	[Directors Office, 2018]
Community Engagement	STK0102	The project and system architecture must be structured to permit community development and partner contributions.	[Directors Office, 2016]
Site/Location	STK0103	It is a goal to center the array near the existing VLA, on the plains of San Agustin, NM.	[Directors Office, 2016]
VLA Reuse	STK0104	It is a goal to reuse infrastructure and buildings built as part of the VLA or EVLA effort.	[Directors Office, 2016]
Design & Development Timeline	STK0105	The project shall aim to conclude design and development activities in a seven-year period ending in 2024.	[Directors Office, 2016]
Construction Timeline	STK0106	The project shall aim to begin construction by 2025, and conclude within a ten-year period in 2034.	[Directors Office, 2016]
Commissioning Scope	STK0107	Commissioning of the observatory shall be within the scope of the construction effort, not operations.	[NM-OPS]

5.2 Science Operations

Parameter	Req. #	Value	Traceability
Operations Concept	STK0200	The system shall be designed as a PI-driven and pointed general purpose instrument.	

5.3 System Lifecycle

Parameter	Req. #	Value	Traceability
ngVLA Transition Plan	STK0300	A Plan to transition from VLA Operations to ngVLA Operations shall be written. This plan shall define milestones and resources at a level of detail that costing can be determined for operations ramp-up of ngVLA activities while coordinating with the shutdown of the VLA and any decommissioning requirements.	

Parameter	Req. #	Value	Traceability
ngVLA Development Program	STK0301	A plan to address needs for a budgeted ngVLA Development Program shall be written. Using community proposals and other initiatives, the program will fund the studies and projects designed to encourage three areas of development typically outside the scope of operations: (1) Scientific advancement and enhancements of capabilities of the array, (2) Development of new or improved hardware, software, or techniques, and (3) Fostering and advancement of legacy science programs.	[020.10.05.00.00-0002-PLA-Sec12-Para1]
Material Selection and Sustainability	STK0302	The project shall consider the environmental sustainability of materials selected in the design of the instrument, and the environmental impact of the disposal phase.	
Design Life	STK0303	The system shall be designed for a design life and initial operations campaign of 20 years.	[Directors Office, 2016]
Projected Environment	STK0304	The system shall be designed to survive the environmental conditions expected over the Design Life of the instrument. Goal to withstand 50-year events (extreme weather, seismic, etc.).	

5.4 AIV

Parameter	Req. #	Value	Traceability
Provision of Assembly Verification Tools	STK0400	The project shall include the necessary test fixtures for component, assembly and subsystem verification within the scope of construction.	
Provision of Assembly/Integration Facilities	STK0401	The project shall include necessary assembly and integration facilities in the project scope. Goal to have dual use assembly/integration facilities that fulfill a necessary operations role (e.g., Assembly space in AIV transitions to Operations Warehouse or Repair Facility).	
Provision of System Verification Software Tools	STK0402	The project shall include the software interfaces and tools necessary to test system integration milestones, without the use of the full end-to-end software system (e.g., tools to generate and execute test scripts for first fringes; tools to see fringes in near real-time).	
Spare Parts	STK0403	The project shall include the provision of critical spares for the operating life of the facility within the scope of construction.	

5.5 CSV

Parameter	Req. #	Value	Traceability
First Look Science Products	STK0500	The Observatory shall release a set of first look science products ahead of PI access to the array.	[020.10.05.00.00-0002-PLA-Sec6.5-Para2]
Availability for Early Science	STK0501	Early PI access, or Early Science, is expected to commence when roughly a VLA's worth of collecting area is available, and will include the first set of delivered capabilities offered for PI use. Additional PI access shall be offered at other significant milestones prior to the end of construction (for example when baselines expand beyond the Plains of San Agustin).	[020.10.05.00.00-0002-PLA-Sec6.5-Para3]
Provision of Commissioning Tools	STK0502	The project shall include the software interfaces and tools necessary to achieve the commissioning and science validation milestones (e.g., tools to plot real-time calibration coefficients)	

5.6 Disposal

Parameter	Req. #	Value	Traceability
Disposal Costs	STK0600	Disposal costs shall be accounted for in any lifecycle optimization for the project.	

5.7 Observing Modes

Parameter	Req. #	Value	Traceability
Standard Modes: Time-Phased Availability	STK0700	In full operations the Observatory shall provide a set of standard supported observing modes, which are a construction project deliverable, necessary to achieve the key ngVLA science goals.	[020.10.05.00.00-0002-PLA-Sec6-Para4]
Standard Modes: Generation of Scheduling Blocks	STK0701	For standard observing modes, observing instructions (scheduling blocks) shall be generated based on the scientific requirements specified by the PI in their submitted proposal.	[020.10.05.00.00-0002-PLA-Sec6-Para4]
Non-Standard Observing Modes	STK0702	In operations, in addition to the standard observing modes, the Observatory shall support innovative programs of sufficient scientific merit that require other instrument configurations and/or non-standard and non-automated data processing.	[020.10.05.00.00-0002-PLA-Sec6-Para5]
Observing Awards: Array Time on Source	STK0703	Successful PIs shall be awarded array time on source rather than guaranteed satisfaction of a scientific objective such as sensitivity.	[020.10.05.00.00-0002-PLA-Sec6.2-Para6]

Parameter	Req. #	Value	Traceability
Standard Modes: Observing Strategy	STK0704	The Observatory shall generally provide a defined observing strategy (including array characterization and quantitatively known calibration overheads within an acceptable margin of error) for all standard modes and capabilities.	[020.10.05.00.00-0002-PLA-Sec6.2-Para7]
Standard Modes: Flexibility	STK0705	Flexibility for PIs to make changes to the standard strategy, within limits and only when required to meet the scientific objectives, will be available.	

5.8 Proposal Submission

Parameter	Req. #	Value	Traceability
Proposal Submission Criteria	STK0800	Proposals will include the information necessary for scheduling the telescope, configuring the instrument, collecting the data appropriate to address the scientific goals, and in most cases, for automatically generating the appropriate Science Ready Data Products (SRDPs).	[020.10.05.00.00-0002-PLA-Sec6-Para3]
Proposal Submission Tool	STK0801	Users shall specify the scientific and technical requirements for their projects via an Observatory-supplied proposal tool. Projects include both telescope time and/or compute resources (i.e. archive reprocessing).	
Proposal Assessment	STK0802	The proposals shall be evaluated for scientific merit by science review panels made up of experts from the broad astronomy research community, and a Time Allocation Committee will advise the Observatory of the scientific rankings of proposals.	
Mitigating Bias in Proposal Peer Review	STK0803	The ngVLA proposal review process shall adopt the best practices aimed at minimizing bias related to gender, culture, race and other potential sources of bias.	[020.10.05.00.00-0002-PLA-Sec6.1-Para2]
Proposal Attributes and Staged Capability	STK0804	The Observatory shall support proposal attributes such as regular, triggered, monitoring, large and legacy (see 020.10.05.00.00-0004-PLA), joint (with other observatories) once the Observatory reaches full operations, as will the goal include support for a diverse set of capabilities and observing modes.	[020.10.05.00.00-0002-PLA-Sec6.1-Para3]
Proposal Submission Concept	STK0805	The proposal process shall aim to minimize the need for PIs to have expert knowledge of the hardware, calibration and data processing issues specific to the ngVLA.	

5.9 Scheduling

Parameter	Req. #	Value	Traceability
Priority in Scheduling Observations	STK0900	Observations shall be scheduled based on the scientific rankings of proposals, taking into consideration issues such as technical feasibility, data processing requirements, array status, and observing conditions.	[020.10.05.00.00-0002-PLA-Sec6.1-Para4]
Priority for Triggered Observations	STK0901	A capability to interrupt the execution of the observing program in order to respond to a triggered observation with a higher scientific rank shall be provided.	[020.10.05.00.00-0002-PLA-Sec6.2-Para3]
Concurrent Maintenance and Observation	STK0902	In order to meet the goal of observing at all times, the ngVLA must use a concurrent maintenance and observation model.	[020.10.05.00.00-0002-PLA-Sec7.1-Para1]

5.10 Data Processing

Parameter	Req. #	Value	Traceability
Pipeline Use for Standard Observing Modes	STK1000	The goal will be that 80–90% of the scientific program will use a diverse but well-defined set of standard observing modes for which the calibration and data processing will be undertaken through an automated pipeline developed and run by the Observatory.	[020.10.05.00.00-0002-PLA-Sec6-Para3]
Computing Resources for Standard Modes: Reprocessing	STK1001	The Observatory shall provide sufficient computing resources for reasonable reprocessing of data requested by PIs.	
Computing Resources for Standard Modes	STK1002	The Observatory shall provide sufficient computing resources for the data processing associated with normal operations using standard modes and capabilities (including delivery of Science Ready Data Products to PIs).	[020.10.05.00.00-0002-PLA-Sec6.3-Para2]
Delivery of Operational SRDP Pipeline for Early Science	STK1003	Delivery of a fully-commissioned standard observing mode or capability shall include an operational SRDP pipeline before it is offered for regular use through PI proposals.	[020.10.05.00.00-0002-PLA-Sec6.3-Para3]
Support for Legacy Programs	STK1004	Large and Legacy scale projects will identify data processing requirements and resources, and may require additional computing resources to be made available from non-Observatory sources in order to be scheduled.	[020.10.05.00.00-0002-PLA-Sec6.3-Para5]
Data Delivery: Process in Place	STK1005	Where possible, interfaces to ngVLA data should favor processing the data in place rather than transferring the data across the internet to users.	

5.11 Data Archive

Parameter	Req. #	Value	Traceability
Data Product Types to Archive	STK1100	Raw visibilities, calibration tables, and SRDPs will all be stored and made available to PIs and archival researchers through the Data Archive.	[020.10.05.00.00-0002-PLA-Sec6.3-Para4]
ngVLA Data Archive Functionality: Image Selection and Download	STK1101	Archive functionality shall allow users to inspect and select image data for download.	[020.10.05.00.00-0002-PLA-Sec6.4-Para3]
Reprocessing and Automated QA via Archive	STK1102	The Data Archive shall provide an interface to allow scientists to initiate reprocessing of ngVLA archived data using Observatory-provided techniques and tools, and shall include automated quality assurance processes.	[020.10.05.00.00-0002-PLA-Sec6.4-Para2]
Proprietary Period for PI Data	STK1103	PI access to data will be protected by a proprietary period (nominally a year, but determined by Observatory policy), after which the data and data products are fully and publicly accessible.	[020.10.05.00.00-0002-PLA-Sec6.4-Para3]
User Produced Data Products	STK1104	The Data Archive shall have provisions for accepting user-produced data products where those products can be quality assured by the Observatory (such as products from Large projects or Legacy projects). In such circumstances the Observatory shall approve the user QA process, not the individual products.	[020.10.05.00.00-0002-PLA-Sec6.4-Para4]
Proprietary Period for Legacy Program Data	STK1105	Large and Legacy projects and some other special cases may have a different proprietary period, subject to Observatory-level proprietary policy changes.	[020.10.05.00.00-0002-PLA-Sec6.4-Para5]
Data Delivery via Observatory Archive	STK1106	Data shall be delivered to the Principal Investigators through an Observatory Science Data Archive.	[020.10.05.00.00-0002-PLA-Sec6-Para3]
Interfaces to Similar Archival Systems	STK1107	The Data Archive shall be designed to interface easily with WFIRST, LSST and VLASS and other similar archival systems to maximize the data discovery space.	[020.10.05.00.00-0002-PLA-Sec6.4-Para6]

5.12 User Support

Parameter	Req. #	Value	Traceability
Operational User Support	STK1200	The Observatory shall provide user support for any aspect of ngVLA use related to proposing, observing, data quality, processing and analysis through to the publication of scientific results.	[020.10.05.00.00-0002-PLA-Sec6.6-Para1]
Software Packages Available to User Community: Data Analysis	STK1201	The Observatory shall provide software tools to the user community for data analysis. The package shall be executable on Observatory compute resources and on external computers.	
Software Packages Available to User Community: Data Processing	STK1202	The Observatory shall provide software tools to the user community for processing ngVLA visibilities. The package shall be executable on Observatory compute resources and on external computers.	[020.10.05.00.00-0002-PLA-Sec6.3-Para6]

5.13 Calibration

Parameter	Req. #	Value	Traceability
Storage and Retrieval of Calibration Coefficients	STK1300	System parameters determined by calibration, such as delays or bandpass gains, shall be stored and automatically retrieved as needed.	
Automated Re-Measurement of Calibration Coefficients	STK1301	Re-measurement of calibration and related scientific performance characteristics of the array shall be automated and performed as an Observatory function using small subarrays of antennas, contemporaneously with science observing on larger subarrays.	[020.10.05.00.00-0002-PLA-Sec6.8-Para1]
Inclusion of Calibration Pipelines and Supporting Systems	STK1302	The design of online and offline calibration strategies for standard observing modes, including any supporting hardware and software, shall be a construction deliverable.	

5.14 Observational Efficiency

Parameter	Req. #	Value	Traceability
Subarrays for Maintenance	STK1400	Maintenance, testing, characterization and capability development (including software) will primarily be done on a subset of the array, using subarrays where appropriate.	[020.10.05.00.00-0002-PLA-Sec6.2-Para2]
Subarrays for Scheduling	STK1401	A limited number of predefined science subarrays will be used by the Observatory to simplify scheduling of the scientific program.	[020.10.05.00.00-0002-PLA-Sec6.2-Para3]
Observational Efficiency	STK1402	The system shall be designed to maximize the array's resources and time spent on science observations (vs. maintenance, testing, and development efforts.)	

Parameter	Req. #	Value	Traceability
Calibration Efficiency	STK1403	Within the portion of time spent on science observations, the system shall be optimized for time spent on the science target, with consideration given to minimizing operational and calibration overheads.	

5.15 Array Operations

Parameter	Req. #	Value	Traceability
Array Operations: Location	STK1500	Array operations shall be conducted from an Array Operations Center. It is a goal to reuse the Domenici Science Operations Center in Socorro, NM.	[020.10.05.00.00-0002-PLA-Sec7-Para1]
Array Operations: Subarray Use	STK1501	ngVLA Operation models regarding array time for testing, commissioning, and maintenance; shall generally schedule these activities only on smaller subarrays, allowing a more continuous concurrent implementation of science observations, maintenance, and testing.	[020.10.05.00.00-0002-PLA-Sec7.1-Para2]
Duties of the Operator	STK1502	A human operator shall oversee the array. The operator will supervise the scheduling tools and executor, ensuring that the intent of each observation is met and that the array is kept in a safe operating condition.	[020.10.05.00.00-0002-PLA-Sec7.2-Para1]
Performance Metrics Definition	STK1503	The operations plan shall detail the specific performance metrics to be used such as array uptime, resource utilization, and operations costs per antenna.	
Performance Metrics Reporting	STK1504	Array Operations shall be responsible for reporting its operations performance metrics.	[020.10.05.00.00-0002-PLA-Sec7.3-Para1]
Array Operations Interface to Array Maintenance and Engineering	STK1505	Array Operations and Science Operations shall coordinate priorities (initiation, triage, tracking, and closure of operationally-based tickets) to optimize the balance of science time and time required for maintenance.	[020.10.05.00.00-0002-PLA-Sec7-Para1]
Array Operations: Remote and Automated Functions	STK1506	Functions leveraging remote operations and automation of antenna functions shall be used when possible to reduce operations costs.	

5.16 Configuration Management

Parameter	Req. #	Value	Traceability
Remote Access of System Configuration	STK1600	The system configuration shall be remotely ascertainable from each major element of the system, even those that do not typically have integrated diagnostic monitoring (e.g., cryogenic refrigerators), so that the facility configuration can be tracked dynamically with minimal effort.	[020.10.05.00.00-0002-PLA-Sec8.2-Para2]
Configuration Management	STK1601	A configuration management system is required to indicate which serial numbers of LRUs and other hardware items are in the array, under repair, or available from spare inventory, as well as each configuration item's location, repair, and upgrade history.	[020.10.05.00.00-0002-PLA-Sec10.4-Para1-3]
Identification by Serial Numbers	STK1602	Individual LRUs, and all other configurable items, shall be uniquely identifiable to facilitate status and location tracking across the Observatory.	
Packaging as LRUs	STK1603	Electronics shall be packaged as Line Replaceable Units (LRU), where LRU modules are interchanged at the antenna.	[020.10.05.00.00-0002-PLA-Sec8-Para3]

5.17 Monitor and Control

Parameter	Req. #	Value	Traceability
Performance Analysis and Automated Maintenance Scheduling	STK1700	Array software systems shall provide a continual and largely automated analysis of array status and health, providing the key source of automatically generated maintenance tickets and automated maintenance scheduling.	[020.10.05.00.00-0002-PLA-Sec7.2-Para1]
Hot Swaps of LRUs	STK1701	Hardware and software shall be designed to accommodate and recover from hot swaps with minimal interaction required by the maintenance and operations personnel.	
Intelligent LRUs and Subsystems	STK1702	LRUs and other subsystems shall be smart devices with on-board diagnostics that can be accessed remotely for troubleshooting.	[020.10.05.00.00-0002-PLA-Sec8.2-Para1]
Interface between Operator and Operations Software	STK1703	The Operational software shall provide the operator with status and alert screens to indicate array health and the Operational software shall inform the operator regarding maintenance work order tickets.	[020.10.05.00.00-0002-PLA-Sec7.2-Para1]
Antenna Automation	STK1704	Individual antennas and subsystems within the array shall perform basic system configuration and monitoring functions without the need for human intervention.	

5.18 Maintenance Operations

Parameter	Req. #	Value	Traceability
Preventive Maintenance Schedules	STK1800	Preventive maintenance (PM) schedule estimates must be consistent with antenna systems operating for a year or more between PM visits.	[020.10.05.00.00-0002-PLA-Sec8-Para2]
Maintenance Tiers	STK1801	Maintenance tasks shall be classified in tiers to assign the level of skill or maintenance visit required. It is a goal that site-based maintenance be limited to lower levels, with high-skill work generally performed at the Repair Center by specialized staff and equipment under a higher degree of environmental and process control.	[020.10.05.00.00-0002-PLA-Sec8-Para3]
Optimization for Maintenance	STK1802	Organization of the maintenance and repair teams must be optimized to maximize efficiency of time spent on antenna visits and repair of equipment.	[020.10.05.00.00-0002-PLA-Sec8-Para4]
Criteria for Scheduling Maintenance	STK1803	Maintenance will be automatically scheduled based on a combination of the severity of existing issues, required preventive maintenance, and predictions of pending problems.	[020.10.05.00.00-0002-PLA-Sec8.1-Para1]
Use of Failure Analysis in Spares Planning	STK1804	Failure analysis shall be used in the planning of spares inventory. Factors considered shall include the projected availability for spares, the time required to repair the failure, and viability of critical vendors, with the threat of obsolescence taken into account for planning upgrades.	[020.10.05.00.00-0002-PLA-Sec8.1-Para2]
Reporting of Failures and Anomalies	STK1805	Failures and anomalies will be reported by operators, data analysists, post-processing pipelines, and users. These reports, along with those generated by automated means, shall be tracked in an issue tracking system with a corresponding database.	[020.10.05.00.00-0002-PLA-Sec8.3-Para1]
Maintenance Personnel Duty Stations: Antenna based	STK1806	Technicians who need regular access to the antennas, central electronics, and infrastructure systems shall be based close to their work responsibilities.	[020.10.05.00.00-0002-PLA-Sec10.1-Para1-2]
Maintenance Personnel Transportation: Array Site	STK1807	A fleet of maintenance and service vehicles will be used by staff to reach areas of the array requiring maintenance.	
Maintenance Personnel Transportation: Maintenance Center	STK1808	Daily transportation shall be provided to the Maintenance Center from the Array Operations and Repair Centers.	[020.10.05.00.00-0002-PLA-Sec10.1-Para3]

Parameter	Req. #	Value	Traceability
Maintenance Metrics Definition	STK1809	The operations plan shall detail the specific maintenance metrics to be used such as mean time to repair, resource utilization, and maintenances costs per antenna.	
Maintenance Metrics Reporting	STK1810	Array Maintenance groups will be responsible for reporting their performance metrics.	[020.10.05.00.00-0002-PLA-Sec8.4-Para1]

5.19 Quality Assurance and Quality Control

Parameter	Req. #	Value	Traceability
Quality Control Database	STK1900	The associated repair log and test data shall be entered into a database prior to acceptance review, and should be globally visible to all groups from any location, even out in the field at remote antennas. The equipment shall only be considered repaired upon acceptance of this test data.	
Quality Assurance of Repaired Items	STK1901	During the repair process, testing and quality control procedures must be sufficient to mitigate process errors and address pending failures before components and systems are redeployed.	[020.10.05.00.00-0002-PLA-Sec10.3-Para3]
Quality Control of Repaired Items	STK1902	Acceptance testing of software and hardware deliverables must occur before delivery to, or installation on, the array. Repair groups will produce the acceptance test data for review and acceptance by the groups responsible for either inventorying or using the repaired items.	

5.20 Facilities

Parameter	Req. #	Value	Traceability
Inclusion of a Visitor Center	STK2000	An ngVLA Visitor Center will be provided for public outreach and will be located near the array, but at some distance from the center of the core to mitigate RFI. It is a goal to renovate and reuse the VLA Cafeteria for this purpose.	[020.10.05.00.00-0002-PLA-Sec9.4-Para1]
Inclusion of a Maintenance Operations Center	STK2001	A Maintenance Operations Center shall provide the duty station for safety, security, and maintenance personnel. This center shall serve as the node for maintenance activities and the storage of LRUs, field tools and equipment.	[020.10.05.00.00-0002-PLA-Sec9.5-Para1]
Inclusion of a Warehouse	STK2002	A Central Warehouse shall provide controlled inventory of all components used for preventive and corrective maintenance.	[020.10.05.00.00-0002-PLA-Sec9.5-Para1]
Inclusion of a Repair Center	STK2003	The Repair Center will host staff and equipment necessary for the transfer, diagnosis, repair, and test of electronic LRUs and other equipment.	

Parameter	Req. #	Value	Traceability
Inclusion of an Array Operations Center	STK2004	An AOC shall provide sufficient space to host offsite array operations and a comparable complement of office space, laboratory space, storage and transfer capabilities, and computing infrastructure as in the existing DSOC.	[020.10.05.00.00-0002-PLA-Sec9.6-Para1-2]
Inclusion of a Science Operations Center	STK2005	A Science Operations Center (SOC) is required to house approximately 175 staff, largely scientists, data analysts, computing, software, and IT positions, and some administrative and management staff. The facility will primarily consist of office space and computing infrastructure.	[020.10.05.00.00-0002-PLA-Sec9.7-Para1-2]
Inclusion of Remote Operations Stations	STK2006	Remote Operations Stations (ROS) shall be located in southern New Mexico, west Texas, Mexico, and as needed to support LBA operations. Each ROS shall have a footprint to support workbenches, organized tools, supplies, and inventory including spare LRUs required for routine maintenance of a group of antennas.	[020.10.05.00.00-0002-PLA-Sec9.8-Para1-2]
Location of the Maintenance Operations Center	STK2007	The Maintenance Operations Center should be located near the array site in order to facilitate logistics, but sufficiently far away to mitigate RFI at the Array Core.	
Location of the Array Operations Center	STK2008	The Array Operations Center should be located within a few hours of the array site in order to facilitate logistics while providing an attractive location to recruit array operations personnel.	
Location of the Science Operations Center	STK2009	The Science Operations Center should be located at a site that facilitates personnel recruitment, such as an attractive metropolitan area. It may be co-located with the archive and data center (if the project selects local vs. cloud services).	
Location of the Repair Center	STK2010	The Repair Center should be located within a few hours of the array site in order to facilitate logistics while providing an attractive location to recruit array operations personnel. It may be co-located with the Array Operations Center.	
Location of the Warehouse	STK2011	The Warehouse should be located near the array site in order to facilitate logistics, but sufficiently far away to mitigate RFI at the Array Core. It may be co-located with the Maintenance Operations Center.	
Inclusion of a Guard Booth	STK2012	To maintain site security at the additional buildings near the core of the array, a guard booth will allow security staff to provide a constant security presence.	

Parameter	Req. #	Value	Traceability
Inclusion of Central Support Buildings	STK2013	Additional buildings near the array core shall provide for the storage and maintenance of heavy equipment that cannot be easily delivered or driven from the nearby Maintenance Center and will support the maintenance and repair staff temporarily on-site.	[020.10.05.00.00-0002-PLA-Sec9.2-Para1]

5.21 Logistics

Parameter	Req. #	Value	Traceability
Inventory Tracking System	STK2100	Inventory shall be electronically tracked to determine usage rate and location of spares throughout the locations in the array.	
Inventory of Consumables	STK2101	An inventory of commonly used supplies shall be centrally maintained at the ngVLA Warehouse.	[020.10.05.00.00-0002-PLA-Sec10.2-Para1]
Shipping and Receiving Logistics	STK2102	Each facility shall have central shipping and receiving and be integrated with a shipping system between sites.	[020.10.05.00.00-0002-PLA-Sec10.2-Para2]
Repair and Tracking of LRUs	STK2103	LRUs shall be centrally managed, tested, and repaired from the Repair Center, but will be stored near the point of service at the ngVLA Maintenance Center and ROS locations.	[020.10.05.00.00-0002-PLA-Sec10.3-Para1]
Inventory of Component Spares	STK2104	Component-level spares will primarily be stored at the ngVLA Warehouse and provided on an as-needed basis to the Repair Center.	[020.10.05.00.00-0002-PLA-Sec10.3-Para2]
Observatory-Controlled Logistics	STK2105	Observatory-controlled shipping resources shall be used to ensure prioritization, possession, and safe-handling of items during transit (i.e. rather than commercial carriers).	
Packaging Used for Shipping	STK2106	The shipping cases and packing practices will provide ESD protection in addition to mechanical shock absorption.	

5.22 Security

Parameter	Req. #	Value	Traceability
Physical Security Systems	STK2200	Site physical security systems will be recorded and also monitored either by an array operator or a security guard. In the event of an intrusion, local law enforcement will be contacted and relied upon for a response.	[020.10.05.00.00-0002-PLA-Sec10.5-Para3]
Physical Security Plans	STK2201	Physical security and monitoring for the ngVLA site and the remote sites shall be provided.	[020.10.05.00.00-0002-PLA-Sec10.5-Para1-2]
Cybersecurity	STK2202	ngVLA IT systems shall be hardened against intrusion consistent with existing NRAO CIS policies.	[020.10.05.00.00-0002-PLA-Sec10.6-Para1]

5.23 Local Stakeholders

Parameter	Req. #	Value	Traceability
Grassland & Water	STK2400	The project shall aim to minimize impact on grasslands and water within the plains of San Agustin. Special care should be given to the array core given the degree of disturbance.	[J&S Bruton, 2018-09-25 visit by PD.]
Roads	STK2401	Road widths and lengths should be minimized to reduce the destruction of top soil. The road design should aim to avoid the collection of water into new ditches or arroyos that will exacerbate soil erosion.	[J&S Bruton, 2018-09-25 visit by PD.]
Existing Roads	STK2402	Existing ranch roads should be assessed for suitability in both construction and operations. Goal to reuse existing roads where possible.	[J&S Bruton, 2018-09-25 visit by PD.]
Fences	STK2403	Any fences should not impede the flow of cattle and wildlife within and between neighboring ranches, or significantly increase the travel distance to water sources.	[J&S Bruton, 2018-09-25 visit by PD.]
Ranching Impact	STK2404	The project shall aim to reduce the environmental impact to cattle ranching as well as hunting/outfitting, which are both mainstays of local ranches.	[J&S Bruton, 2018-09-25 visit by PD.]
Core Site	STK2405	The specific location of the array core should account for the differences in the quality of lands on the plains.	[J&S Bruton, 2018-09-25 visit by PD.]

5.24 NRAO and Other Facility Integration

Parameter	Req. #	Value	Traceability
SRDP Integration	STK2500	The ngVLA project should use the SRDP project as pathfinder, with the expectation of adopting the architecture of SRDP Observatory-User interfacing systems for ngVLA.	
Facility Integration	STK2501	It is desirable for ngVLA to support joint (e.g., VLBI) observations with other NRAO facilities, as well as other global flagship facilities.	
DMS Integration	STK2502	The ngVLA project will adopt existing NRAO Data Management and Software (DMS) policies, with facility integration into Observatory infrastructure and standards, in order to promote reuse and maintainability.	

5.25 Radio Frequency Interference

Parameter	Req. #	Value	Traceability
Self-Interference	STK2600	The system shall be designed to prevent self-interference that will be detrimental to science operations.	
RFI Survival	STK2601	The system shall be designed to withstand, without damage or long-term degradation, the projected RFI environment over the life of the instrument.	
RFI Mitigation	STK2602	The system shall be designed to operate in the projected RFI environment while still achieving the Key Science Goals and the desired operational efficiencies.	
VLA Interference	STK2603	It is a goal to minimize interference with VLA operations during the construction/transition phase.	

5.26 Non-Functional Requirements

Parameter	Req. #	Value	Traceability
Design Consideration of the "-ilities"	STK2700	The project design shall consider manufacturability, reliability, maintainability, operability, extensibility, fault tolerance, interoperability, resilience, robustness, testability, and stability as nonfunctional requirements relevant to ngVLA system design.	[PMD AD, 2018]

5.27 Non-Traditional Use Cases

Parameter	Req. #	Value	Traceability
SSA Support	STK2800	It is desirable for the ngVLA to support non-traditional use cases related to space situational awareness, such as imaging of geostationary objects.	[Directors Office, 2016]
DSN Support	STK2801	It is desirable for the ngVLA to support non-traditional use cases related to spacecraft operation, such as Deep Space Network (DSN) downlink support for critical NASA missions.	[Directors Office, 2016]

5.28 Future Commensal Systems

Parameter	Req. #	Value	Traceability
Commensal Front Ends	STK2900	It is desirable that commensal front ends (e.g., ngLOBO) be considered in the design, and provisions/interfaces for future commensal front-ends be incorporated into the design. (i.e. not designed out)	[NRL, LWA, 2016]
Commensal Back Ends	STK2901	It is desirable that commensal back ends (e.g., RealFast) be considered in the design, and provisions/interfaces for future commensal back-ends be incorporated into the design. (i.e. not designed out)	

6 Appendix

6.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter/submillimeter Array
AST	Division of Astronomical Sciences (NSF)
CDL	Central Development Laboratory
EMC	Electro-Magnetic Compatibility
FOV	Field of View
FWHM	Full Width Half Max
HPC	High Performance Computing
IF	Intermediate Frequency
KPP	Key Performance Parameters
KSG	Key Science Goals
LO	Local Oscillator
MoE	Measure of Effectiveness
MoP	Measure of Performance
MREFC	Major Research Equipment and Facilities Construction (NSF)
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PWV	Precipitable Water Vapor
RD	Reference Document
RFI	Radio Frequency Interference
rms	Root Mean Square
RSS	Root of Sum of Squares
SAC	Science Advisory Council
SKA	Square Kilometer Array
SWG	Science Working Group
SNR	Signal to Noise Ratio
SRDP	Science Ready Data Products
TBC	To Be Confirmed
TBD	To Be Determined
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer

L0 Safety Requirements

020.10.15.10.00-0004-REQ-A-L0_SAFETY_REQS
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PREPARED BY	ORGANIZATION	DATE
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1	2018-05-07	J. Bolyard	All	Initial draft
1.1	2018-09-15	J. Bolyard	All	Updated changes
2	2019-01-16	J. Bolyard	All	Updated changes from pre-decadal review RIDs
2.1	2019-01-25	J. Baca	All	Formatted document
3	2019-05-30	A. Lear	All	Prepared document for review
4	2019-05-31	R. Selina	5	Updated numbering scheme to match requirements management standards
A	2019-07-17	A. Lear	All	Prepared PDF for approvals & release

Table of Contents

1 Introduction

1.1 Purpose

This document intends to identify and capture the requirements for safety instrumentation, including hardware, software, and processes/procedures through the entire lifecycle of the Next Generation Very Large Array (ngVLA) effort. The requirements are intended to address the ngVLA efforts through design including reviews and prototyping, construction, commissioning actions, operation, and ultimate decommissioning.

1.2 Scope

The scope of this document extends to all Integrated Product Teams (IPTs), project reviews, work practices in labs and worksites, and subcontractors who provide documentation, procedures, or work at any ngVLA site.

1.3 Project Background

The ngVLA is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 263 reflector antennas, 244 of 18 meters diameter and 19 of 6 meters diameter, operating in a phased or interferometric mode. The antenna count includes antennas of the Long Baseline Array (LBA).

Construction and integration will be distributed across several existing NRAO and partner sites and in new facilities for this purpose. Operations will be conducted from both the VLA site and an Array Operations Center.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Safety Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Safety requirement, the content of the reference documents shall take precedence.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	V1.0, 2017-03-30
AD02	Environment, Safety, and Security Policy and Program Manual	Version D, October 2016
AD03	ngVLA Safety Risk Analysis Procedures	020.80.00.00.00-0002-PRO

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	OSHA General Industry Standard	29 CFR1910
RD02	OSHA Construction Standard	29 CFR1926
RD03	Environmental Protection Agency Clean Air Act of 1963	33 U.S.C.: Navigable Waters
RD04	Environmental Protection Agency Clean Water Act of 1972	42 U.S.C. ch. 85, subch. I § 7401 et seq
RD05	National Fire Protection Association, Consensus Standards	

3 Safety Scope

The Safety IPT Work Package includes safety, physical security, ongoing environmental protection actions, sustainability, and identification of associated risks. In the context of this document, "safety" includes all the aforementioned program elements. The Safety IPT scope includes assessing the requirements for all phases of the ngVLA effort.

Per NSF and in accordance with Executive Order (EO) 13693, the ngVLA effort must include means and methods for sustainable operations including utility usage, waste disposal, and recycling services. Sustainable operations include all facilities that are used as office, laboratory, information technology room or center, or dormitory space.

The Safety IPT crosses all IPT boundaries and is anticipated to be integrated into all design packages, operational procedures, and extends through the lifecycle of the ngVLA. The ngVLA Safety IPT will assist to ensure compliance with federal, state and local safety requirements. In addition, the effort will examine compliance with international standards, such as may be applicable in Mexico.

The proposed ngVLA project will require compliance with AUI policies for safe planning and management of large facilities. Consequently, there must be significant collaboration with all other IPTs as the requirements influence the Safety support needed. In this document, NRAO will determine areas that need further development to meet the collaborating IPT ngVLA requirements.

4 Safety Across the ngVLA Lifecycle

All IPTs shall have a designated central point of contact for safety related issues and preparation of safety documentation for reviews. All personnel shall be alert to the need to identify potential safety hazards. Once identified, steps shall be taken to eliminate them, or reduce them to levels judged acceptable. The central point of contact for safety matters shall be the IPT safety liaison.

4.1 Safety IPT Review Support Requirements

The ngVLA Safety IPT is expected to support the Requirements Review for each subsystem to ensure that the relevant safety requirements are appropriate to the plan and meet the safety flow throughout the subsystem to the final system design. Additionally, the ngVLA Safety IPT will support the Preliminary Design Review to ensure that the design is mature enough from the safety perspective to proceed to prototyping and to ensure that the hazard analysis is sufficiently complete.

The following reviews shall have a Safety IPT member support:

- CDR to complete the safety compliance assessment and safety risk analysis.
- Manufacturing readiness review on final documentation and to offer signoff review of safe machinery.
- Test readiness review (TRR) to verify the test procedures are approved and the equipment and software under test are in their final deliverable configuration. The TRR shall include confirmation that the safety approval has been received.
- Product Acceptance to accept delivery from subcontractors, if applicable, and deliver the Safety Data Package documentation as part of the Acceptance Data Package. This package includes but is not limited to:
    - Safety Procedures, if not described in the operator manual;
    - Declaration of Conformance; and
    - Hazard Analysis in accordance with ngVLA Safety Risk Analysis Procedures.

4.2 Design Activities

Safety assurance matters shall conform to the requirements defined in the NRAO Environmental, Safety, and Security (ES&S) Policy and Program Manual [AD02], and with site-specific safety directives.

Potential hazards shall be identified as a part of the normal design process and eliminated or reduced as far as possible. Safeguards shall be determined for outstanding hazards, which will reduce their possible effects to the lowest reasonable level in accordance with ngVLA Safety Risk Analysis Procedures.

Any safety hazards that cannot be eliminated during the design process shall be reported to the Safety IPT Lead at the design review and ngVLA Project Office. Any progress shall be reported, including necessary proof that the relevant requirements have been satisfied.

4.3 Construction Activities

Construction work shall conform to requirements of the NRAO ES&S Policy and Program Manual [AD02] and Safety Work Plans provided by project contractors. Any design documentation affecting construction activities shall be provided in contract documents and procurement requirements. The Safety IPT shall support all construction activities with programmed meetings and reviews of contractor documentation, and shall sign off on acceptance of each completed construction site.

4.4 Operations Activities

Operations activities are not addressed in this document and shall follow NRAO ES&S Policies governing operational safety as described in the ES&S Policy and Program Manual [AD02].

5 Safety Requirements

The following requirements shall be fulfilled *as a minimum* to achieve acceptable levels of safety across the ngVLA project.

Requirement ID#	Requirement Name	Requirement
SAF0028	Design for all lifecycle phases safety	The ngVLA shall be designed to achieve the highest level of personnel health and safety performance in all phases of the project lifecycle in accordance with standards applicable to the work.
SAF0029	Comply with ES&S manual	All aspects of the design and construction shall comply with the ES&S Policy and Program Manual.
SAF0030	Develop safe procedures	Where appropriate, each IPT shall develop procedures for personnel and equipment safety throughout the design, construction, and operation phases to address working conditions and use procedures, as well as identify the design features, that impact safety, environmental protection, and sustainability.
SAF0031	Follow safe design priorities	The priority for safe design shall address safety of personnel, followed by safety of equipment, and then the integrity of the data.
SAF0032	Follow mitigation order of precedence	The ngVLA system shall govern the hazard analysis and safety practices in an order of precedence as follows: 1) Design for minimum risk: The primary means for mitigating risk shall be to eliminate the hazard through design. 2) Incorporate safety devices: Protective devices shall be used as part of system design to reduce hazard risks to an acceptable level where possible. 3) Provide warning devices: When neither design nor safety devices can effectively minimize a hazard risk, devices shall be used to detect the hazard condition and alert personnel of its presence. 4) Procedures and training: Only when it is impractical to substantially eliminate or reduce the hazard, or where the condition of the hazard indicates additional emphasis, special operating procedures and training shall be used. All such procedures shall be fully documented.
SAF0033	Develop operational safety plan	An operational safety plan shall be developed and implemented before the commissioning phase starts.

Requirement ID#	Requirement Name	Requirement
SAF0034	Follow safety design specification	The safety system specification must be followed during both the design of individual system components and integration of system elements.
SAF0035	Use safety design specification for validation	The safety system specification shall be used in validation of the integrated system elements for system validation.
SAF0036	Document safety compliance	Each completed design element must document safety compliance with the safety system specifications.
SAF0037	Describe process to achieve safe state	Each element must describe processes and address details to achieve safe state including potential sequencing of events.
SAF0038	Describe additional safety requirements	Each element must describe any additional measures required during validation, and describe consequences of failure to follow sequential processes.
SAF0039	Design facilities for safe operational use	The ngVLA Facility shall be designed to safely meet its technical requirements and operational specifications at the following physical locations. The Facility includes the main radio antennas, service areas, utility equipment, and all other infrastructure necessary to safely execute all the operational functions and secure all ngVLA assets. The Facility design must provide the space and functional equipment to maintain all system assets operating on the site.
SAF0040	Design controls for safe operation	The control capabilities throughout the system shall include both local and remote exclusive control modes for safe operation. Note this applies to any system that has potential for motion.
SAF0041	Ensure initial safe state for subsystem power up	Each Facility in the ngVLA Observatory shall implement a non-software-based safety system(s) in areas where injury or harm to personnel and or equipment can occur. Each subsystem when powered up shall be initialized into a known safe state without human intervention.
SAF0042	Ensure subsystems are standalone safe	Each subsystem shall be responsible for maintaining its own technical health, safety, and status without any other subsystem operational.
SAF0043	Address facility security in design	The project shall affirmatively address site and facility security needs in the design in accordance with the NRAO security policy(ies).
SAF0044	Address sustainability in design	The project shall affirmatively address sustainability goals in ngVLA design and ongoing operations.

6 Appendix

6.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
ES&S	Environment, Safety, and Security
ICD	Interface Control Document
IPT	Integrated Product Team
ngVLA	Next Generation VLA
NSF	National Science Foundation
OSHA	Occupational Safety and Health Administration
RD	Reference Document
RFI	Radio Frequency Interference
TBD	To Be Determined
VLA	Jansky Very Large Array

Preliminary System Requirements

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Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
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Eric Murphy, Project Scientist — Digitally signed by Eric J. Murphy Date: 2019.07.24 19:55:02 -04'00'	ngVLA/NM-Operations, NRAO	2019-07-23
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 09:44:22 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-23

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0.1	2016-08-10	R. Selina	All	Started first draft. Draws from ALMA Project System Level Technical Requirements, Rev C, 2012-12-10
0.2	2016-08-23	R. Selina	5.1	Updated phase drift analysis after conversation with C. Carilli
0.3	2016-08-24	R. Selina	6.1, 6.2	Started importing programmatic and functional requirements in to system requirements summary and detail sections
0.4	2016-08-25	R. Selina	6.3	Started importing performance requirements in to system requirements summary and detail sections
0.5	2016-10-25	R. Selina	All	Continuing first draft
0.6	2016-11-21	R. Selina	5.1	Distributed phase/delay error budgets. Calculated coherence table
0.7	2017-03-10	R. Selina	All	Heavy edit for POP milestone release. Added Key Performance Parameters section
0.8	2017-03-23	R. Selina	All	Incorporating feedback from E. Murphy and S. Durand. Removed general notes, moved into requirements discussion
0.9	2017-03-29	R. Selina	5	Incorporated feedback from C. Carilli; table from W. Grammer in 5.11.1; edits from S. Durand to 5.12–5.14
1.0	2017-03-30	R. Selina	5	Revised imaging dynamic range definition. Added computer floor requirements. Corrected antenna efficiencies, added secondary operating environment. Refined frequency band definitions.
02	2018-05-08	R. Selina	All	Major update for consistency with latest science requirements, 020.10.15.00.00-0001-REQ, Rev 13. Synced with Antenna Specs 020.25.00.00.00-0001-SPE Rev B (Released).
03	2018-05-10	R. Selina	All	Edits throughout before TAC review.
04	2018-11-21	R. Selina	All	Significant edits throughout to incorporate TAC feedback (Lamb, D'Addario, Kantor, Soriano, Weinreb) and RIDs from the IPDSR.
05	2018-12-04	R. Selina	5	Updated traceability to stakeholder reqs now that 020.10.15.01.00-0001-REQ is mature. Additional reqs from gap analysis between STK and SYS requirements.
06	2018-12-05	R. Selina	5, 8	Additional reqs from gap analysis between STK and SYS reqs. Updated verification table to match.
07	2019-06-01	R. Selina	5.15, 8	Fixed design column in verification table. Corrected mean measure in 5.15.
A	2019-07-22	A. Lear	All	Incorporated minor revisions from M. McKinnon. Prepared PDF for signatures and release.

Table of Contents

1 Introduction

1.1 Purpose

This document aims to present a preliminary set of system requirements for ngVLA that will guide the conceptual design of the facility. Many requirements flow down from the ngVLA Science Requirements documented by Murphy et al. [AD01]. These Science Requirements support the Key Science Goals [RD15] defined by the Science Advisory Council (SAC), and were informed by the Science Use Cases [RD16] submitted by the Science Working Groups (SWGs).

In addition, an attempt has been made to incorporate performance and functional requirements that support non-traditional users such as NASA/JPL, and the Near Earth Sensing (NES) community. Programmatic, operational, maintenance, and safety requirements are also reflected where they drive technical decisions. These stakeholder requirements are summarized in [AD02].

1.2 Scope

The scope of this document is the entire ngVLA system, from the reception of external signals to the generation and delivery of data products to the archive for storage and access by users. The content of these requirements is aimed at the system level, but this document describes subsystem functional or performance requirements where necessary. Some assumptions on the system architecture [AD04] are included here, but only to the degree necessary to define the system requirements.

This document is primarily aimed at the functional elements of the array rather than supporting infrastructure. These functional elements include:

- Hardware and software systems from the antenna and feed through to the data archive.
- Software and control systems required to monitor and operate the array.

Requirements for supporting operational infrastructure and personnel will flow directly from the Stakeholder Requirements [AD02] and are not enumerated here.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Requirements Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Requirements Specification, the content of the lowest level specification (in the requirements flow-down) shall be considered the superseding requirement for design elaboration and verification.

Reference No.	ngVLA Document Title	Rev/Doc. No.
AD01	Science Requirements	020.10.15.00.00-0001-REQ
AD02	Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD05	Environmental Specification	020.10.15.10.00-0001-SPE
AD06	System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD07	Requirements Management Plan	020.10.15.00.00-0001-PLA
AD08	Reference Observing Program	020.10.15.05.10-0001-REP
AD09	L0 Safety Requirements	020.10.15.10.00-0004-REQ
AD10	L1 Safety Requirements	020.80.00.00.00-0001-REQ

2.2 Reference Documents

The following documents provide supporting context.

Reference No.	Document Title	Rev/Doc. No.
RD01	EVLA Project Book	
RD02	Fast Switching Phase Calibration at 3mm at the VLA Site	ngVLA Memo No. 1
RD03	Calibration Strategies for the Next Generation VLA	ngVLA Memo No. 2
RD04	*Interferometry & Synthesis in Radio Astronomy*, Thomson, Moran, Swenson	Second Edition
RD05	Gain Stability: Requirements and Design Considerations	ALMA Memo 466
RD06	Radio Path Length Correction Using Water Vapour Radiometry	R.J Sault, https://arxiv.org/ftp/astro-ph/papers/0701/0701016.pdf
RD07	Convenient Formulas for Quantization Efficiency	A.R. Thompson, *Radio Science*, Vol. 42, RS3022
RD08	Reliability and MTBF Overview	Vicor Reliability Engineering
RD09	ngVLA Cost Model Memo	V3.0, February 24, 2017
RD10	ngVLA Cost Model Spreadsheet	V3.0, 2017-02-24
RD11	ngVLA Sensitivity	ngVLA Memo #21
RD12	Polarization Calibration with Linearly Polarized Feeds	ngVLA Memo #45
RD13	RFI Emission Limits for Equipment at the EVLA Site	EVLA Memo #106
RD14	RFI Emission Goals on Internally Coupled Signals	EVLA Memo #104

Reference No.	Document Title	Rev/Doc. No.
RD15	Key Science Goals for the ngVLA	ngVLA Memo #19
RD16	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD17	ngVLA Time-Domain Correlator Considerations	P. Demorest, 2018-01-05
RD18	ALMA Scientific Specifications and Requirements	ALMA-90.00.00.00-001-B-SPE
RD19	Synthesis Imaging In Radio Astronomy II	ASP Vol 180, 1998

3 Overview of the System Requirements

This document presents the technical requirements of the ngVLA telescope at the system level. These parameters determine the overall hardware and software performance of the telescope.

The L1 Requirements along with detailed explanatory notes are found in Section 5. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirement and should guide the verification procedures.

In many cases the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. In this way, the trade-space available is apparent to scientists and engineers who will guide the evolution of the ngVLA concept.

In certain cases parameters are simply noted with a TBD value. The goal in such cases is simply to identify parameters that will require definition once the science requirements coalesce, or associated technical issues are understood.

Section 7 identifies performance metrics that should be monitored throughout the conceptual design phase. These are metrics to assist in the trade-off analysis of various concepts, should tensions be identified between requirements.

The following system-level specifications are documented separately and incorporated by reference:

AD05	*Environmental Specification*	020.10.15.10.00-0001-SPE
AD06	*System EMC and RFI Mitigation Requirements*	020.10.15.10.00-0002-REQ
AD10	*L1 Safety Requirements*	020.80.00.00.00-0001-REQ

Additional system-level specifications will be documented during the development phase to specify requirements applicable to the design of the ngVLA system and supporting observatory infrastructure.

4 Requirements Management

4.1 *Requirement Definitions*

The following definitions of requirement "levels" are used in this document.

Requirement Level	Definition
L0	User requirements expressed in terms applicable to their needs or use cases ("Science Requirements" or "Stakeholder Requirements")
L1	Requirements expressed in technical functional or performance terms, but still implementation agnostic ("System Level Requirements")
L2	Requirements that define a specification for an element of the system, presuming an architecture ("Subsystem Requirements")

4.2 *Requirements Flow Down*

The L1 System Requirements generally flow from the L0 Science Requirements [AD01] for the facility. While these requirements dominate, other Stakeholder Requirements [AD02] also influence or dictate design choices. Examples include programmatic requirements, regulatory compliance requirements, and the life-cycle concepts (e.g., the Operations and Maintenance Concept [AD03]) for the facility.

The Science Requirements and Stakeholder Requirements fully encapsulate all known L0 requirements. These System requirements and subordinates included by reference [AD05, AD06] fully encapsulate all known L1 requirements. Supplemental L1 requirements may be developed in future subordinate documents.

Specifications for individual subsystems (L2) flow from the L1 System Requirements, and may not always be directly attributable to a single system requirement (e.g., phase drift specifications at the system level may be apportioned to multiple subsystems, or a subsystem spec may be in support of multiple higher-level requirements). Specifications at the L2 level may also flow directly from L0 requirements in some cases. Completeness of the L2 requirements is assessed at the requirements review of each subsystem.

While this is a top-down design process, the process is still iterative rather than a "waterfall" or linear process. The feasibility and cost of implementation of requirements and specifications leads to trade-offs that feedback to higher-level requirements. <u>The end goal is to build the most generally capable system within the programmatic constraints of cost and schedule</u>.

Maintaining enumerated and traceable science requirements, system requirements, and subsystem specifications ensures this trade-off process is complete and well understood by the project team. The effect of a change in a subsystem specification can be analyzed at the system level, and thereafter the impact on a specific scientific program can be ascertained.

The details of the requirements management strategy can be found in [AD07].

5 L1 System Requirements

System-level requirements apply to performance with all operational calibrations applied. The system can be assumed to be fully functioning, under the precision environmental conditions (defined in [AD05]). The system-level requirements are written in an implementation agnostic way whenever possible in order to not unduly constrain the conceptual design.

Subsystem requirements apply to performance before operational calibration corrections are applied. The accuracy of calibration that is needed to meet the higher-level system requirement is included in the system requirements notes and may be reflected in other functional or performance requirements.

The hardware subsystem requirements apply to a properly functioning system, under the precision operating environmental conditions, and assume that all parts of the system that would normally be in place during observations are working within their respective specifications (e.g., HVAC, RTP system).

Requirement traceability is shown to the relevant L0 requirements document, with SCI denoting Requirement IDs in the Science Requirements [AD01] and STK denoting requirements in the Stakeholder Requirements [AD02]. Where gaps in L0 requirements exist today, there may be additional notes in the traceability column that will be addressed in future versions of the document set.

A limited number of requirements listed here are not implementation agnostic but are consistent with the system architecture. These requirements are noted with an L2 in the Parameter column for future reconsideration. System-level L2 requirements can also be found in Section 6.

Note that requirements IDs are static once assigned and therefore not always in sequential order due to subsequent revisions of the associated requirements document.

5.1 Functional Operating Modes

Parameter	Req. #	Value	Traceability
Functional Modes	SYS0001	The system shall provide a set of defined Operating Modes that produce corresponding data products.	SCI0006, STK0200
Interferometric Mode	SYS0002	The system shall provide an Interferometric Operating Mode with concurrent computation of cross-correlations and self-correlations for arbitrary numbers of antennas with tunable spectral and time resolution.	SCI0006
Phased Array Mode	SYS0003	The system shall provide a Phased Sum Operating Mode that coherently sums the voltage streams from an arbitrary number of antennas and provides a time-tagged voltage data stream with an adjustable phase center on sky.	SCI0007, SCI0012, SCI0013
Pulsar Timing Mode	SYS0004	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is processed to time dispersed pulse profiles with a variable period.	SCI0012
Pulsar and Transient Search Mode	SYS0005	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is processed to search for dispersed pulse profiles without *a priori* knowledge of their period.	SCI0013

Parameter	Req. #	Value	Traceability
VLBI Mode	SYS0006	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is recorded in a VLBI-standard recording format for future processing in a VLBI correlator.	SCI0017
Total Power Mode	SYS0007	The system shall provide an Interferometric Operating Mode with computation of self-correlations on-source and off-source to quantify the total power spectral density of a fixed field.	SCI0104
On The Fly Mapping Mode	SYS0008	The system shall provide an Interferometric Operating Mode where areas larger than the antenna primary beam are mapped by a continuous scan of the field.	SCI0004
Solar Observing Mode	SYS0009	The system shall provide an Interferometric Operating Mode tailored to the observation of sources up to 30dB brighter than the cold sky.	SCI0016
Concurrent Interferometric and Phased Array Mode	SYS0202	The system shall provide an Operating Mode that supports the computation of limited cross-correlations simultaneous with the phased array capabilities described in SYS0003 through SYS0006. This mode may have restricted processed bandwidth, spectral and time resolution compared to the mode described in SYS0002.	SCI0007

5.2 *Sub-Array Functional Requirements*

Parameter	Req. #	Value	Traceability
Sub-Array Capabilities	SYS0601	The system shall be divisible into a minimum of 10 sub-arrays for operation, calibration, and maintenance purposes.	SCI0009
Phase Preservation	SYS0602	It shall be possible to preserve electronic phase when adding and/or subtracting an element from a sub-array.	STK1400, STK1403
Sub-Array Composition	SYS0603	It is desirable that the composition of a sub-array be configurable to any arbitrary combination of antennas from a single antenna to the full array.	SCI0009
Sub-Array Operating Modes	SYS0604	It is a goal that all Operating Modes be available in a sub-array.	SCI0009, SCI0010
Sub-Array Operating Mode Commensality	SYS0605	The system shall support the commensal sub-array combinations described in Table 1. It is a goal to permit full flexibility in commensal sub-array Operating Modes.	SCI0010
Sub-Array Configuration	SYS0606	It is a goal that the configuration of a sub-array be completely independent of all others, permitting different instances and versions of online software between sub-arrays.	STK1400

Given the extent of the ngVLA, it is likely that a significant portion of array observing will be conducted in sub-arrays. Many science cases will not require the full angular resolution available, or the weather across the array may be variable. The concept of operation also has a continuous maintenance element, so individual elements and sub-arrays will frequently be deployed for testing and/or diagnostic purposes.

The phase calibration strategy may also employ sub-arrays. It is therefore critical that adding or subtracting an element of a sub-array be possible without disturbing electronic system phase. As the concept of operation and the calibration strategies are further developed, it is expected that additional sub-array requirements will be identified.

Functional Modes	Interfer.	Phased Array	PA Timing	PA Search	VLBI	TP	OTF	Solar
Interfer. (SYS0002)	Full[1]	Limited[2]	Limited[2]	Limited[2]	Limited[2]	Full[1]	Full[1]	Full[1]
Phased Array (SYS0003)		Full[3]	Full[7]	Full[7]	Full[7]	Limited[2]	Limited[2]	Limited[2]
PA Timing (SYS0004)			Full[4]	Full[7]	Full[7]	Limited[2]	Limited[2]	Limited[2]
PA Search (SYS0005)				Full[5]	Full[7]	Limited[2]	Limited[2]	Limited[2]
VLBI (SYS0006)					Full[6]	Limited[2]	Limited[2]	Limited[2]
TP (SYS0007)						Full[1]	Full[1]	Full[1]
OTF (SYS0008)							Full[1]	Full[1]
Solar (SYS0009)								Full[1]

Table 1 - Required sub-array commensality.

Table 1 Notes:

1. Full flexibility within constraints of the maximum data input to the correlator back end (value TBD).
2. Minimum functionality must include full-bandwidth cross-correlation in one sub-array, concurrent with phased array in another. Phased array timing, search, and VLBI capabilities as constrained by SYS0203, SYS0301, SYS0401, and SYS0501.
3. Full flexibility within the constraints imposed by SYS0203.
4. Full flexibility within the constraints imposed by SYS0203 and SYS0301.
5. Full flexibility within the constraints imposed by SYS0203 and SYS0401.
6. Full flexibility within the constraints imposed by SYS0203 and SYS0501.
7. Full flexibility within the constraints imposed by SYS0203, SYS0301, SYS0401, SYS0501.
8. The Concurrent Interferometric and Phased Array Mode described in SYS0202 has the same restrictions as modes SYS0003 through SYS0006.

5.3 Interferometric Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Variable Spectral Resolution	SYS0101	The spectral resolution shall be tunable to permit variable resolution across the observed band, maximizing instantaneous bandwidth while still providing high spectral resolution over defined sub-bands.	SCI0006, SCI0003
Polarization Products	SYS0102	The system shall simultaneously compute both parallel-pol and cross-pol correlations over the full specified bandwidth, and measure all Stokes polarization products simultaneously.	SCI0015
Autocorrelation Products	SYS0103	It is desirable to provide autocorrelation products for all antennas within the interferometric array (TBC).	STK1700, STK1704
Commensal Processing	SYS0104	It is desirable to provide a connection for future commensal processing of visibilities (e.g., transient search) at the native temporal resolution of the observation (prior to any time or frequency averaging).	SCI0013, STK2901
Commensal Low-Frequency System	SYS0105	It is desirable to provide physical interfaces, data transmission and correlator bandwidth for a future commensal low-frequency (<1 GHz) front end.	STK2900

5.4 Phased Array Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Phased Aperture	SYS0201	The system shall provide phased array capabilities over the full extent of the array (1000km aperture).	SCI0007
Number of Beams	SYS0203	The system shall support a minimum of 10 beams distributed over 1 to 10 sub-arrays. It is desirable to support 50 beams distributed over 1 to 10 sub-arrays at reduced bandwidth per beam.	SCI0008, SCI0009

The need for phased array capability over the full aperture is due to the expected sub-array allocations. For example, should a subset of stations not be required for an interferometric observation, it may be desirable to phase them for pulsar timing—a mode that is rather indifferent to the shape of the synthesized beam.

5.5 Transient (Pulsar) Timing Operating Mode Requirements

Parameter	Req. #	Value	Traceability
Timing Capabilities	SYS0301	The system shall include a back-end timing instrument with a minimum of five independent de-dispersion and folding threads. Support for up to 50 de-dispersion and folding threads is desirable.	SCI0012
Timing Sys. Bandwidth	SYS0302	The timing system shall process a minimum of 8 GHz of bandwidth. Processing the full instantaneous bandwidth available in all bands is desirable.	SCI0012

Parameter	Req. #	Value	Traceability
Timing Sys. Frequency Resolution	SYS0303	The timing system shall support channelization for de-dispersion at a frequency resolution better than 1 MHz. Frequency resolution of 50 kHz is desired.	SCI0012
Pulse Profile Bins	SYS0304	The timing system shall support a minimum of 2048 pulse profile bins.	SCI0012
Polarization	SYS0305	The timing system shall, at a minimum, process the summed output of both polarizations. It is desirable to process both polarizations independently and provide full-stokes parameters.	SCI0012
Pulse Period	SYS0306	The timing system shall be capable of de-dispersion and folding for pulse periods spanning from 1msec to 30 sec.	SCI0012
Dump Rate	SYS0307	The timing system shall record to disk at periods no longer than every 10 seconds. It is desirable to record to disk every second.	SCI0012

Timing observations will refer to observations of sources of known position and pulse period. The array is phased with a beam located at the target source. The signal is processed into the specified frequency resolution, coherently dedispersed, detected, folded (averaged modulo the known pulse period) into the specified number of pulse phase bins, and recorded at the dump rate.

The target of 50 dedispersion and folding threads accommodates the most congested fields of view (currently 37 pulsars in a single cluster) and is consistent with the beamforming capabilities expressed in Section 5.4. The 8 GHz of bandwidth requirement is based on the projected band definition of the system. The intent is to ingest the full bandwidth of any receiver operating below 20 GHz.

Additional information supporting these requirement derivations can be found in [RD17].

5.6 Transient (Pulsar) Search Operating Mode Requirements

Parameter	Req. #	Value	Traceability
Search Capabilities	SYS0401	The system shall include a back-end search instrument which can process a minimum of 10 beams. It is desirable to process 50 beams.	SCI0013
Search Sys. Bandwidth	SYS0402	The search system shall process a minimum of 8 GHz of bandwidth. Processing the full instantaneous bandwidth available in all bands is desirable.	SCI0013
Search Sys. Frequency Resolution	SYS0403	The timing system shall support channelization for de-dispersion at a frequency resolution better than 1 MHz. Frequency resolution of 100 kHz is desired.	SCI0013
Search Sys. Time Resolution	SYS0404	The search system shall have time resolution of 100 µsec or better. Resolution of 20 µsec is desired.	SCI0013
Polarization	SYS0405	The search system shall, at a minimum, process the summed output of both polarizations. It is desirable to process both polarizations of each beam independently and provide full-Stokes parameters	SCI0013

Additional information supporting these requirements can be found in [RD17]. Note that this system needn't be a real-time processing capability if the resultant beams can be recorded to disk for post-processing.

5.7 VLBI Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
VLBI Recording Capabilities	SYS0501	It shall be possible to record data from a minimum of 3 beams over 1 to 3 sub-arrays in VLBI compliant formats. It is desirable to support this capability for 5 beams distributed over 1 to 5 sub-arrays.	SCI0017
eVLBI Capabilities	SYS0502	It is desirable, but not required, to interface with network-connected VLBI stations as real-time correlated elements of the ngVLA.	STK2501

The multi-beam recording capability stems from the projected size of the phased beam. Multiple synthesized beams are required to include both the science target and nearby calibration sources.

5.8 Observing Modes

Parameter	Req. #	Value	Traceability
Standard Observing Modes	SYS3001	Each functional Operating Mode shall have one or more Standard Observing Modes that can generate observing instructions based on PI-defined scientific requirements and produce quality-assured data products.	STK0700, STK0701
No. of Standard Observing Modes	SYS3002	It is a goal that Standard Observing Modes be developed to execute all planned observations in support of the KSG science use cases, as defined in the Reference Observing Program [AD08].	STK0700, STK0701
Non-Standard Observing Modes	SYS3003	It shall be possible for advanced users to access Non-Standard Observing Modes, and directly generate observing instructions for each functional Operating Mode that are processed by the system and record basic data products.	STK0702
Triggered Observations	SYS3004	The system shall include interfaces to receive external (network) triggers to execute previously approved Standard Observing Mode and Non-Standard Observing Mode instructions.	SCI0005
Triggered Observation Response	SYS3005	The system shall process a trigger and begin an observation (be configured and on source) in a period not to exceed 10 mins, with a goal of 3 mins or less.	SCI0005
Trigger Override	SYS3006	The trigger response mechanism shall provide a human Array Operator Override. The Override shall time-out and execute the triggered observation if the observation is not canceled within 60 seconds.	SCI0005

The definition of Standard Observing Modes and their associated requirements will be revisited after the completion of a Reference Observing Program, which will define specific observations in support of the ngVLA Key Science Goals (KSGs).

5.9 Data Products

The array will have a progressive series of data products suitable to different users groups. The data products may also change based on how well supported an Observing Mode is (see SYS0001, SYS3001). Common modes should have higher-level data products that add value to the user, while clearly not all permutations can benefit from such a degree of automation.

5.9.1 Low-Level Interferometric Data Product Requirements

Parameter	Req. #	Value	Traceability
Uncalibrated Data	SYS0701	The uncalibrated visibilities, as provided by the online system after required averaging, shall be recorded to disk in a standard format inclusive of meta data necessary for calibration (spec. TBD).	STK1100
Flagged Data Table	SYS0702	A flagging table shall be provided along with the visibility data to mark data that is suspected to be corrupted. Causes to be flagged include, but are not limited to, antenna off-source, RFI, or other known issues that would affect data integrity.	STK1100, STK1102

The emphasis in this section is on data products produced from interferometric observations. These low-level products shall be generated for all observations in the relevant functional Operation Modes defined in Section 5.1.

As with the VLA, the fundamental data products to be archived are uncalibrated visibilities. The online software system shall also produce flags to be applied to visibilities that identify known system problems such as antennas being late on source or the presence of RFI. A calibration pipeline should also produce calibration tables that compensate for direction-independent instrumental and atmospheric effects in phase, gain, polarization, bandpass, flux scale, etc., for observations using Standard Observing Modes.

5.9.2 High-Level Interferometric Data Product Requirements

Parameter	Req. #	Value	Traceability
Calibration Pipeline	SYS0703	For Standard Observing Modes within the Interferometric Operating Mode, there shall be a standard data reduction performed that produces a calibration table to apply direction-independent corrections that were supported by the observation, typically; delay/phase, gain/amplitude, polarization and bandpass corrections.	STK1000
Imaging Pipeline	SYS0721	For Standard Observing Modes within the Interferometric Operating Mode, there shall be a standard data reduction performed resulting in a calibrated image cube.	STK0100

To reduce the burden on users, when using Standard Observing Modes, higher-level data products will provide outputs that today would typically be generated by the user. This will also enable the facility to support a wider user base, possibly catering to astronomers who are not intimately aware of the nuances of radio interferometry, facilitating multi-wavelength science.

The high-level data products are difficult to define, and may be different for the individual PI and the data archive. For example, an astronomer may be interested in imaging only a limited field, but the most reusable data product, suitable for the archive, might be a full-field image. In general, the operations concept favors generating high-level data products that are tailored to the archive.

The ngVLA data will be delivered, by default, as Science Ready Data Products (SRDP). The NRAO SRDP Project is presently defining proposal submission criteria, data processing, and archiving structures. Proposals on all NRAO instruments will conform to SRDP requirements in order to benefit from publication ready data. These SRDP structures are expected to mature within the VLA and ALMA to the point of routine operations by the time ngVLA is commissioned. Requirements on the Archive that follow also support the delivery of SRDP.

5.9.3 Pulsar Timing and Search Data Product Requirements

Parameter	Req. #	Value	Traceability
Pulsar Timing Data Product	SYS0741	For Standard Observing Modes within Transient Timing operating mode, dispersion measures, dedispersed pulse profiles, and periods shall be generated and recorded in PSRFITS format.	SCI0012
Pulsar Search Data Product	SYS0742	For Standard Observing Modes within Transient Search operating mode, dispersion measures, dedispersed pulse profiles and periods shall be generated and recorded in PSRFITS format.	SCI0013

5.9.4 Data Archive Requirements

Parameter	Req. #	Value	Traceability
Archive Period	SYS0731	All low-level data products shall be archived for the life of the facility (as defined in SYS2801).	STK1106, STK1102
Archive Products	SYS0732	High-level data products that are suitable for reuse shall be archived for the life of the facility (as defined in SYS2801).	STK1100
Proprietary Data Rights	SYS0733	The archive shall permit the enforcement of a proprietary period for both low-level and high-level data products, permitting public access only after the proprietary period lapses.	STK1103
Archive Batch Reprocessing	SYS0734	The archive shall include an interface for batch re-processing of visibilities and to replace existing low-level and high-level data products.	STK1102
Archive Backup	SYS0735	A full backup (two copies total) of all archived data shall be incorporated into the design. The two copies shall not be co-located/co-managed to reduce the risk of simultaneous failures.	STK1100, STK1106
Archive User Reprocessing	SYS0736	The system shall include an interface for users to request limited reprocessing of data within supported Standard Observing Modes.	STK1102, STK1101
Proprietary Period	SYS0738	The proprietary period shall be tunable on a per-project and per-scan basis.	STK1103

The high-level goal of the data archive is to function as a science multiplier, making data collected by one PI available to another after a proprietary period lapses. Making data available through the archive eliminates duplicate observations, and maximize the opportunities for the community to make discoveries from historical observations. It also incentivizes the first PI to publish their work prior to the end of the proprietary period. Both effects boost the scientific productivity of the array. Similar to VLA practice, all low-level data products should be archived for the life of the facility. These fundamental data products can be broadly reused and their storage is consistent with the broad goals of the archive. This data should be archived for the life of the facility.

The requirements for storage of high-level data products is less clear. These products may need to be tailored to the individual science case proposed by the PI, which may reduce the opportunities for reuse. The broad goal is that reusable high-level data products should be archived along with the visibilities, but which products might meet this criteria are not yet defined. Storage requirements for high-level data products should be revisited after their requirements are defined by the SRDP project.

5.9.5 Data Processing Requirements

Parameter	Req. #	Value	Traceability
Data Processing Resources	SYS0751	The system shall provide data processing resources (both software tools and compute capacity) to generate the high-level data products from Standard Observing Modes.	STK1000, STK1202
Throughput & Latency	SYS0752	The data processing capacity for high-level data products shall be designed to match the expected average system throughput (defined in the Reference Observing Program), with no constraint on latency.	STK1001, STK1002
Heterogeneous Arrays	SYS0753	The data processing system shall support data reduction from heterogeneous arrays.	STK1002, SYS1304

5.9.6 Data Analysis Requirements

Parameter	Req. #	Value	Traceability
Data Analysis Resources	SYS0761	The system shall provide data analysis resources (both software tools and compute capacity) for users to inspect and analyze the high-level data products from Standard Observing Modes.	STK1201

5.10 Frequency Range and RF Coverage

Parameter	Req. #	Value	Traceability
System Frequency Range	SYS0801	System frequency range shall cover, at a minimum, the 1.2–50 GHz and 70–116 GHz windows.	SCI0001
Optimized Frequency Range	SYS0802	Sensitivity shall be maximized above 8 GHz.	SCI0100, SCI0102, STK2801
Freq. Span A	SYS0803	1.2–8 GHz	SCI0001, SYS0801
Freq. Span B	SYS0804	8–50 GHz	SCI0001, SYS0801
Freq. Span C	SYS0805	70–116 GHz	SCI0001, SYS0801
Continuity of Frequency Coverage	SYS0806	There shall be no gaps in frequency coverage within frequency spans (A, B, C) listed above. It is a goal that any band edges shall include 1% overlap in bandwidth.	SCI0001, SCI0002, SCI0003

While the system shall access all available frequencies in the 1 to 116 GHz, the 8-50GHz range (Frequency Span B) has the most demanding sensitivity requirements (Section 5.12). System performance should be optimized for these frequencies.

Note that these frequency spans are not "Bands," and are not meant to imply a specific receiver configuration. The frequency span division is due to atmospheric windows and different priority levels. Span A is the lowest priority given overlap with the SKA1 baseline design. However, these low frequencies are still required for KSG4 and KSG5 and must be supported by the ngVLA.

5.11 System Bandwidth and Frequency Tunability

Parameter	Req. #	Value	Traceability
Front End Bandwidth Ratio	SYS0901	A minimum bandwidth ratio of 1.5:1 is required, with a 3:1 goal over Frequency Span A.	SCI0100, SCI012
Instantaneous Digitized Bandwidth	SYS0902	It is desirable for the system to digitize the full bandwidth of each receiver band.	SCI0003, SCI0100
Total Instantaneous Processed Bandwidth	SYS0903	The system shall transmit and process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	SCI0100
Sub-Bands	SYS0904	If the digitized bandwidth exceeds the instantaneous transmitted and processed bandwidth, the system shall separate the digitized bandwidth into sub-bands for bandwidth selection, transmission, and processing.	SCI0003
Frequency Tunability	SYS0905	If the front-end bandwidth exceeds the instantaneous transmitted and processed bandwidth, it shall be possible to select discontinuous sub-bands for transmission and processing, i.e. transmitting both the top and bottom of the 70–116 GHz band.	SCI0003
Fixed Analog Tunings	SYS0906	While supporting the Frequency Tunability requirement, the analog system setup options shall be minimized to facilitate calibration from catalog values.	STK1403
Sub-Band Step Size	SYS0907	It is a goal to have sub-band selection and tunability at a granularity of 200 MHz.	SCI0003
Band Switching Time	SYS0908	Switching between any receiver bands shall be achievable within 20 seconds. Goal: <10 seconds.	SCI0018
Contiguous Bandwidth	SYS0909	Any bandwidth division for transmission and processing shall not create gaps in frequency coverage.	SCI0003

The Front End bandwidth ratio is most important at lower frequencies where total instantaneous bandwidth will be limited by the receiver rather than the data transmission system.

The 20GHz/pol instantaneous bandwidth goal is consistent with the expected bandwidth of the highest frequency receiver (Band 5) in Frequency Span B (30–50GHz). The requirement of 14 GHz approximates the expected Band 4 receiver. If the span of these receivers changes, the instantaneous sampled bandwidth requirement and goal should be adjusted to match.

If the full bandwidth of the front end is sampled, any tuning or filtering is expected to be digital only, and implemented in order to minimize data transmission and processing costs. Tunability within the correlator will be required to trade off bandwidth for spectral resolution.

If less than the full receiver bandwidth is sampled, there must be a mechanism in place to select any frequency over the observable window (e.g., tuned LOs). Any minimum tuning stepsize should be restricted by SYS0907.

5.12 Sensitivity Requirements

Parameter	Req. #	Value	Traceability
Effective Area/T_{sys} Ratio	SYS1001	The effective area/Tsys ratio of the system shall meet or exceed the values given in Figure 1 while operating in the precision environmental conditions defined in 020.10.15.10.00-0001-SPE and assuming 1mm of PWV. This requirement must be met over 80% of the bandwidth of any given receiver (i.e. band edges are exempted).	SCI0100, SCI0102, SCI0106

The driving sensitivity requirement is for raw system sensitivity measured in m^2/K [SYS0501]. The values in Figure 1 are based in part on expected degradation in aperture efficiency as a function of frequency and achievable system temperatures. Note that deviations at the edges of each receiver band are expected and allowable.

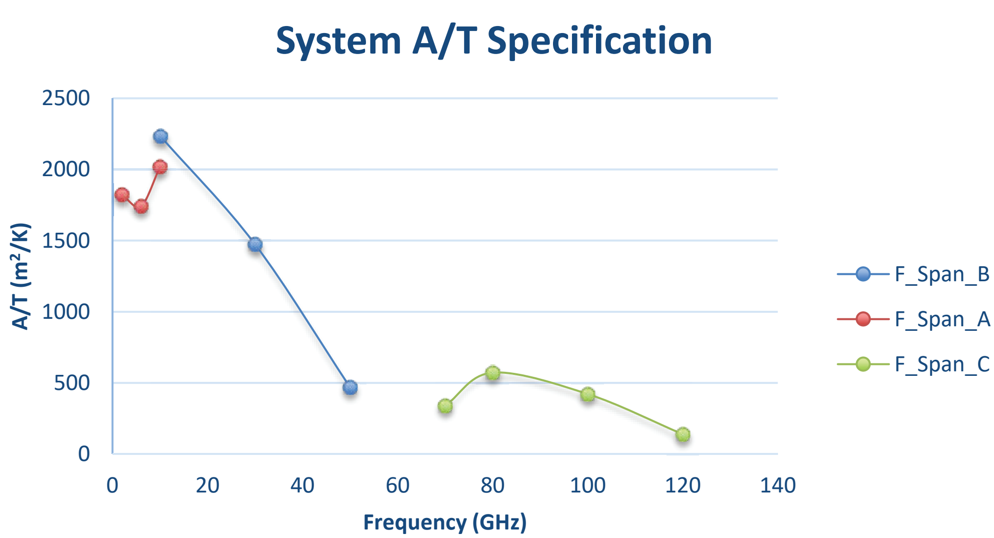

Figure 1 - System A/T specification in m^2/K.

When considering parameters that affect the effective collecting area of the ngVLA antennas or the overall system temperature, this is the measure that should remain constant and the parameters can be traded against each other (e.g., increasing effective area to accommodate an increase in Tsys). In the event that scope contingency is required to fit within cost constraints, this sensitivity requirement may be relaxed.

5.13 System Field of View

Parameter	Req. #	Value	Traceability
Instantaneous Field of View	SYS1101	The system instantaneous FOV (FWHM), when scaled by center frequency, shall be larger than 2 arcmin at 28 GHz.	SCI0106, SCI104
Accessible Field of View	SYS1102	The system shall be capable of observing at elevations of 12° to 89°, relative to the local horizon.	SCI0019
Slew Rates	SYS1103	The system shall be capable of slewing to any position within the accessible field of view in less than 2 minutes of time.	SCI0005
Tracking Rates	SYS1104	The system shall be capable of tracking objects and mapping an area of sky at 10x sidereal speeds when under 70 degrees in elevation.	SCI0004

Based on the survey speed requirements of the system, and the projected sensitivity, the FOV must be greater than 2 arcmin at 28 GHz, corresponding to an 18m aperture with a taper coefficient of 1.02.

5.14 Dynamic Range

Parameter	Req. #	Value	Traceability
Input Dynamic Range	SYS1201	The analog dynamic range of the receiving electronics shall have a minimum of 30 dB of headroom, defined at the 1 dB compression point. Goal to achieve spec at 1% compression point.	SCI0016
Gain Calibration System Dynamic Range	SYS1202	Any calibration strategy should also accommodate a 30 dB change in system temperature, so any calibration system injection requires a variable input power range of at least 30 dB.	SCI0016
Provision of Variable Attenuators	SYS1203	The system shall provide variable attenuators that accommodate the dynamic range specified in SYS1201, while maintaining the minimum number of bits specified in SYS1035.	SCI0016
Input Protection	SYS1204	The system shall survive exposure to signals at large as 55 dBm EIRP at a distance of 100m through sidelobes (G=1) with no damage to the receiving elements.	STK2601
High-Noise Path	SYS1205	It would be desirable to provide a high-noise/low-gain path that permits reception of signals outside the dynamic range requirement specified in SYS1201.	SCI0016

The dynamic range requirements flow down from both solar observations and mitigating the impacts of RFI. Dynamic range in this case will be defined as 1 dB compression to the system noise. Solar requirements depend to some degree on the definition of the Sun, given the large differences in output power as a function of solar activity. For the quiet Sun at 5780K, and a system temperature of order 30K, the implied analog dynamic range is of order 23 dB.

With an antenna SEFD of order 300 Jy, and an active Sun definition of 10^8 Jy, an analog dynamic range of 55 dB would be required for the active Sun. For the strongest signals, a high-noise path (bypassing the LNAs) would therefore be desirable. The Input Protection requirement is based on vehicular radar, which is permitted 55 dBm EIRP over the 76–77 GHz band. It likely represents a worst-case interfering signal in terms of power, other than a cell phone over the horn input during service.

5.15 Spatial Resolution and Spatial Frequency Coverage

Parameter	Req. #	Value	Traceability
Longest Baseline	SYS1301	The longest baseline between antennas in the main array shall be greater than 420 km with extended baselines (VLB) out to 8600 km.	SCI0103, SCI0118
Shortest Baseline	SYS1302	The shortest baselines between antennas shall be shorter than 22 m, with a goal of 10 m.	SCI0104
Zero Spacing/ Single Dish Total Power	SYS1303	It is a goal that the system measure total power spectral density in the field, with apertures larger than 1.5x the shortest baseline.	SCI0104
Integration Time Ratios	SYS1304	If achieving SYS1302 requires multiple array/antenna designs, each array shall sample overlapping spatial scales. The ratio of integration time on one array to the other on these overlapping scales shall not exceed a factor of four, with a goal of matched integration times.	STK1403
Fraction of Occupied Cells	SYS1306	The system shall fill at least 50% [TBC] of (u,v)-cells before gridding out to 36 km baselines in a snapshot continuum observation traversing the meridian with a 720kx720k pixel grid. Goal to achieve this fill ratio out to 420 km scales.	SCI0106, SCI0108, SCI0109
Distribution and Weighting of Visibilities	SYS1308	The system shall achieve a Gaussian distribution via weighting, with the quadratic mean of the weights greater than 0.5 over the full range of scales that correspond to 100 m to 420 km baselines on an 8 hr observation about the meridian. Quadratic mean of weights shall also be better than 0.05 at scales corresponding to 8600 km baselines.	SCI0100, SCI0102, SCI0103, SCI0108, SCI0118

The computation for maximum and minimum baselines corresponds to the required resolutions with a taper coefficient of 1.2.

The distribution of spatial frequency samples and their associated weights have significant implications for the physical configuration of the array and the overall system efficiency. The array must be constructed accounting for practical considerations like geological features, land ownership, proximity to population centers, etc. An idealized power-law distribution for an array of 420 km+ in extent is not practical. However, such a distribution is the standard by which the achievable array should be judged and measured against, and should be achievable on 36-km scales.

Non-unity weighting of array elements contributes to a loss of observational efficiency. Depending on the angular resolution of interest and the ideal synthesized beam, such non-unity weights will be required.

The shortest baseline requirement will most likely require a separate array of smaller apertures in addition to the main array. The single dish provides total power (power spectral density, PSD) measurements that fill in the “zero-spacing” point of the UV plane. The single dish should ideally sample angular scales greater than the shortest interferometric baseline, in order to minimize gaps in angular scale and resolve large scale structure faithfully.

The Fraction of Occupied Cells metric is an attempt to quantify the snapshot imaging fidelity on scales >100 mas at 20 GHz (SCI0109). A baseline of 36 km accommodates a taper coefficient of 1.2 while achieving the specified resolution. A 720,000 x 720,000 cell grid constrains the pixel size to 20 m, approximating the antenna diameter. Please consult [RD18] for additional information on this metric.

5.16 Spectral Resolution

Parameter	Req. #	Value	Traceability
Highest Spectral Resolution	SYS1401	The available spectral resolution shall be finer than 1 kHz/channel. Goal of 400 Hz/channel.	SCI0105
Number of Spectral Channels	SYS1402	A minimum of 240,000 channels shall be supported by the correlator and post processing systems. Goal of 400,000 channels.	SCI0105
Flexible Spectral Resolution	SYS1403	The spectral resolution shall be variable between sub-bands, maximizing instantaneous bandwidth while still providing high spectral resolution over selected sub-bands.	SCI0105, SCI0006
Doppler Corrections	SYS1404	The system shall include a method to correct/set Doppler corrections to a common reference frame.	SCI0105

The spectral resolution requirement defines the minimum channel bandwidth required for spectral line observations. The number of spectral channels proposed is derived from the minimum number of channels necessary to prevent bandwidth smearing during full band, full-beam imaging at the bottom of Frequency Span A [SYS0802] out to 1000-km scales. This computation should be revisited as the input parameters are refined.

The maximum channel width is defined as:

$$\Delta\nu_{channel} = \beta\, \nu_{low}\ D/B_{max}$$

where ν_{low} is the lowest frequency in the band, *D* is the diameter of the antenna, and B_{max} is the longest baseline. The unit-less parameter β is used to characterize the acceptable amount of time and bandwidth smearing:

$$\beta = \frac{\Delta\nu}{\nu}\frac{d\theta}{\theta_{beam}} = \delta t\omega_{earth}\frac{d\theta}{\theta_{beam}}$$

Here $\frac{d\theta}{\theta_{beam}}$ is the fraction of the primary beam to be imaged. Actual calculation of the effects of time and bandwidth smearing depend on the source and field structure. A value of β=0.5 is used as a simple parameterization. A more rigorous quantification of beta should be based on the required imaging fidelity, depending on source and field structure.

For β=0.5, $\nu_{low} = 1.2\, GHz$, $D = 18m$, and $B_{max} = 1000\ km$, the maximum channel width is of order 10kHz. Spanning 2.4 GHz of bandwidth would require of order 240k channels.

The goal of 400k channels will support blind spectroscopic surveys over a wide digitized bandwidth.

Doppler setting to a common reference frame is required since the spectral resolution supports velocity resolutions (100 m/s velocity resolution per SCI0105) that are small relative to the motion of local array coordinate frames (i.e. earth rotation and earth orbit).

5.17 Delay and Phase Stability Requirements

Parameter	Req. #	Value	Traceability
Delay/Phase Variations Magnitude	SYS1501	The delay variations caused by the instrument should be smaller than those caused by the natural environment for at least 90% of the time. These natural limits are those imposed by the residual delay fluctuations of the troposphere after all available corrections (e.g., fast switching, WVR, etc.) have been applied.	STK1402, STK1403, SCI0100
SNR Loss to Delay/Phase Variations	SYS1502	The instrumental delay/phase noise shall not degrade overall system SNR by more than 1%.	SCI0100, STK1403
Phase Noise	SYS1503	Total instrumental integrated phase noise shall not exceed 132 fsec rms.	SYS1502
Phase Drift Residual	SYS1504	The (relative) system phase drift residual shall not exceed 95 fsec rms per antenna over 300 seconds. Goal to meet this specification over a period of 1000 seconds.	SYS1501
Absolute Phase Drift	SYS1505	The absolute phase drift per antenna over 300 seconds shall not exceed 8 psec. Goal to meet this specification over 1000 seconds.	SYS1501

Delay and phase stability are closely related. A delay change produces a signal phase change that is proportional to frequency, arising, for example, from a change in cable length. Alternatively, all frequencies in a bandpass range can be shifted by the same phase if the phase of a local oscillator experiences a phase shift.

In these requirements, the expression "delay/phase" will be used for both situations, a path length or LO change. The time units will be used to express delay/phase stability, typically in femto-seconds (fsec; 10^{-15} sec). The resulting phase change can always be found by multiplying the delay by the appropriate frequency.

Variations in the instrumental delay/phase cause two effects:

- Loss of coherence and thus loss of sensitivity due to fluctuations faster than the elementary integrating time (**delay noise**), and,
- Errors in the phase of the calibrated visibility measurements due to fluctuations on longer time scales (**delay drift**), up to the length of a full calibration cycle.

For the requirements given here, the time scale division between delay/phase **noise** and delay/phase **drift** is defined as one second.

Variations in instrumental delay/phase (both noise and drift) arise from changes in the electronic equipment signal path and in various mechanical structures; these can be separated into two types:

- Variations which are a function of time, usually thermally or wind induced.
- Variations which are a function of antenna pointing angle, usually due to cable movement or twisting, structural deformations under changing gravity vector, or equipment deformation.

Delay/phase variations as a function of antenna pointing angle are further separated into systematic and random changes. By definition, random changes will tend to average towards zero with repeated observations, while systematic changes do not decrease, are more damaging, and should have a different level of constraint. Different requirements are necessary for small angle changes which impact phase calibration and large angle changes which impact antenna position determination and astrometric observations.

The large angle variations can be estimated from the residual phases after an antenna position determination; however, some systematic instrumental errors may be subsumed into any single antenna position solution. It is assumed that the temporal and antenna pointing angle phase error contributions are independent and therefore RSS additive. If this proves not to be the case, the derivation and allocation of error contributions throughout the system (i.e. the error budget) should be revised.

For both delay/phase changes with angle and with time, the quantity that is measured is the delay/phase difference of the signals processed through two antenna systems. Making the assumption that the phase variations in the two antennas are uncorrelated, and RSS additive, $1/\sqrt{2}$ of the measured delay/phase difference will be taken as the delay/phase variation of each individual antenna.

In these requirements, the limits on delay/phase variations always refer to the per antenna variations. A distinction is made between the *absolute* drift and any *residual* noise after subtraction of a linear fit (removing the known absolute drift). The absolute drift specification aims for less than 2π drift over a calibration cycle. The goal of these requirements is to always allow for the removal of predictably slow instrumental drifts.

5.17.1 Establishing Temporal Delay/Phase Stability Requirements

The requirements on temporal delay/phase noise and drift, on time scales up to 300 sec., flow from the two high-level requirements:

1. The delay variations caused by the instrument should be smaller than those caused by the natural environment for at least 90% of the time. These natural limits are those imposed by the residual delay fluctuations of the troposphere after all available corrections (e.g., fast switching, WVR, etc.) have been applied.
2. The instrumental delay/phase noise shall not degrade the overall system SNR by more than 1%.

Statistics of the tropospheric fluctuations at the VLA site are available from decades of observations. Simulations, using a range of atmospheric conditions, estimate the effects of rapid phase referencing to a nearby calibrator (fast switching; see [RD02]).

Five observing and phase calibration techniques have been considered for the ngVLA and are documented in [RD03]. For the purpose of establishing phase stability requirements, these can be split into three cases:

1. Single frequency fast switching. Phase calibrator observations are rapidly interspersed with target source observations at cycle time T_1, with both at the same frequency.
2. No fast switching with WVR. A phase calibrator is observed at interval T_2, and at the same frequency as the target. Another mechanism such as a WVR is used to correct tropospheric phase perturbations.
3. Reference Array or Paired Elements. A phase calibrator is observed at interval T_2, possibly at a different frequency than the target. Separate adjacent antennas observe the science target and a nearby phase calibrator to correct tropospheric phase perturbations on shorter time scales.

These different cases lead to different atmospheric delay/phase residuals and therefore different delay/phase stability requirements. The more stringent requirements are then selected to define the system level requirements.

In Case 1, the requirements are based primarily on simulations with $T_1 \cong 30$ sec. The fast switching calibrator observation simultaneously removes the tropospheric delay fluctuations and the instrumental phase, so the delay/phase drift is important for intervals $T_1 \sim 30$ seconds.

In Case 2, the calibrator observation cannot effectively remove the tropospheric fluctuations and serves mainly to calibrate the instrumental phase. It applies for example if the tropospheric effects are negligible or have been corrected by other means (e.g., WVR measurements). Then the instrumental phase drift at the single frequency is important at the calibration interval $T_2 \sim 300$ seconds.

ALMA experience is that for fast fluctuations on time scales $\gtrsim 1$ second, corrections based on water vapor radiometry alone produce residuals comparable with fast switching alone, so **Case 1** and **Case 2** may be equivalently stringent. Given the increased water vapor at the VLA site, comparable performance of a 22 GHz WVR is optimistic, but this leads to a conservative delay/phase stability specification.

In Case 3 the reference antenna or paired antenna is used to compensate for tropospheric fluctuations by continuously monitoring a phase calibrator. The science antenna observes the phase calibrator at interval $T_2 \sim 300$ seconds in order to calibrate the instrumental phase. The science antenna and the reference antenna may be operating at different frequencies, so drift in the LO system may not be coherent.

For paired elements or a reference array, residual phase fluctuations can be estimated based on the anticipated baseline, which we will assume to be of order 100 meters in this analysis.

Since the phase stability at 30 seconds will certainly be equal or better than the stability at 300 seconds, it is the **Case 3** requirements, which use the longer time scale of ~ 300 seconds, which are more demanding and should define the instrumental delay/phase drift requirements. The total system allocations are given as the bottom line of Table 1, the "Total Instrumental Error". Proof that **Case 3** is most stringent follows below.

The residual phase fluctuations for paired elements or a reference array can be compared as follows. The rms residual atmospheric phase after fast switching phase calibration is given by Eq (1),

$$\sigma_\phi = \sqrt{D_\phi(\frac{v_{atmos} * t_{cycle}}{2} + d)}$$

where D_ϕ is the structure function of atmospheric phase variations, v_{atmos} is velocity of the atmosphere at the height of the turbulent layer, t_{cycle} is the switching cycle time, and d is the linear distance between the lines of sight to the target source and the calibrator at the altitude of the turbulent layer.

Typical values for **Case 1** are v_{atmos} = 10 m/s and t_{cycle} = 30 sec; with the target and calibrator separated by 2 degrees, and the height of the turbulent layer 1000 m above ground, d is about equal to 35 meters. This means that the residual atmospheric phase is the root of the phase structure function evaluated at 185 meters. For baselines longer than this, atmospheric phase errors will be reduced to this level. For shorter baselines, fast switching at this rate will offer no improvement and should be avoided.

For **Case 3,** with continuous phase calibrator monitoring, the residuals are equivalent to the physical baseline (between the science antenna and calibration antenna) plus the separation between the calibrator and source at the height of the turbulent layer. These figures are 100m and 35m respectively in this comparison, resulting in the phase structure function with the same effective baseline of 135 m. Therefore, **Case 3** is the most stringent.

Note that if the physical baselines between paired elements or the auxiliary array and science array elements exceed 100 m, this analysis should be revisited.

[RD02] describes a simple model for σ_ϕ that scales with the effective baseline for short baselines:

$$\sigma_\phi \propto (b_{eff})^\beta$$

where β = 5/6. [RD02] also establishes that with 90th percentile conditions, at 100GHz, σ_ϕ = 7.5 degrees for t_{cycle} = 30 sec, which as described above is equivalent to the residual from an effective baseline of 185m. Scaling by the power law, we can estimate that for b_{eff} = 135m , σ_ϕ would be approximately 5.8 degrees. Using this approximation, and considering an observation at 120GHz, would yield an allowable phase residual of order 135 fsec per baseline, or roughly 95 fsec per antenna $(135/\sqrt{2})$.

For simplicity and consistency with the time over which such fluctuations occur, this figure will be used to define the system phase <u>drift</u> residual. Phase noise limits are defined below.

Note: The specification for phase drift may need to be more stringent than computed, since the instrumental drift induced error will be at least partially systematic in nature. For this instrumental drift term it is only the residual term, after calibration and subtraction of any linear trend, that affects eventual performance.

Note: This analysis has not accounted for the impact to imaging dynamic range. Rather, it aims to make the troposphere dominate any post-calibration residual. The calibration strategy proposed may be inadequate and needs to be compared to the science requirements.

5.17.2 Establishing a Phase Noise Requirement

As a first order approximation, we will limit phase noise so as to reduce system SNR by no more than 1%. The degradation in SNR due to phase variation is estimated in [RD04] as:

$$\mathcal{D} = 1 - \frac{1}{2}\langle\varphi_{mn}^2\rangle$$

where $\mathcal{D}$ is the degradation in SNR for a given phase variation φ on baseline mn, and the phase is in radians. A 1% reduction in SNR is equivalent to an rms phase variation of 8.1 degrees.

At our highest observing frequency of 120 GHz, this phase variation equates to 188 fsec. Assuming phase contributions from each antenna in baseline mn are independent processes, the contributions from each antenna sum in quadrature, and would therefore be 132 fsec $(188/\sqrt{2})$. The phase noise specification shall be integrated over the frequency range 1 Hz to 100 kHz.

Note: This analysis should be extended to evaluate the impact on high dynamic range imaging.

5.18 Gain and System Temperature Stability Requirements

The noise power delivered to the correlator is the product of the system gain and the system temperature, $G * T_{sys}$, where $T_{SYS} = T_{ATM} + T_{REC} + T_{SPILL} + T_{CMB} + T_{SRC}$. In the requirements discussed here, only the variations in *G* as a function of time and the pointing angle of the antenna are considered.

T_{sys} is expected to range from 18K at 10 GHz to 175K at 120 GHz at zenith, and will vary with atmospheric conditions and pointing elevation. The net system gain is defined [RD05] as:

$$G = P_{dig}/(k\, T_{sys}\, \Delta\nu)$$

where P_{dig} is the input power to the digitizer. If the nominal input level into the digitizer is 1 mW (0 dBm)[1] over an 8 GHz bandwidth, a net gain of 77 dB to 87 dB is required. Gross system gain will be of

[1] Current technology may require closer to –7 dBm at the input to the digitizer, but 0 dBm is illustrative.

order 110 dB to 120 dB, accounting for losses from power division, variable attenuators, padding (for matching), mixer losses, component insertion losses and connector/cable losses between the first stage and digitizer. Requirements on system gain stability flow down from the science requirements for

- accuracy of total power observations,
- photometric accuracy required, and
- dynamic range of interferometric observations (both brightness and polarization)

5.18.1 Total Power Observations

Parameter	Req. #	Value	Traceability
TP Antennas: Gain Stability	SYS1601	Antenna *d*G/G shall not exceed 10^{-3} over a 200 sec period. Goal to not exceed 10^{-4}.	SCI0104
TP Antennas: Gain Variations w/Antenna Pointing Angle	SYS1603	Antenna *d*G/G shall not exceed 10^{-2} at 10 GHz over a 4° change in elevation, scaled by frequency (TBC).	SCI0104, SCI0110
TP Antennas: System Temperature Stability over Time	SYS1604	TREC shall vary by no more than 0.1% over 200 sec period in precision operating conditions defined in 020.10.15.10.00-0001-SPE. (TBC)	SCI0104, SCI0110
TP Antennas: System Temperature Variations w/Antenna Pointing Angle	SYS1605	TSPILL and TREC shall vary by no more than 0.1% combined, over a 4° change in elevation in the precision operating conditions defined in 020.10.15.10.00-0001-SPE. (TBC)	SCI0104, SCI0110
TP Antennas: Gain Calibration Reference	SYS1801	The system shall provide a switched flux reference stable to 10^{-3} over a 20-minute period.	SCI0104, SCI0110

Total power observations are based on the difference of auto correlation spectral power (or perhaps analogue total power detector output) between two switched states. For example, these two switched states might be two pointing positions. They also might be the on-source measurements during an OTF scan versus the off-source measurements at the end of the scan. Y-factor measurements to a reference load are another example (see Section 5.18.1.2).

The power spectral density of Gaussian white noise has, by definition, a flat power spectrum, with power level proportional to the bandwidth of the system. In an ideal system, noise will decrease as $1/\sqrt{T}$.

Gain variations on time scales shorter than the switching period limit the extent to which the measurement accuracy decreases as $1/\sqrt{T}$. Gain variations on time scales longer than the switching period but shorter than the interval between external calibration impact the accuracy of the calibration of the total power observation and/or add noise when integrating for longer periods. The value of the total power gain stability requirements are stated in terms of the two-point Allan standard deviation of the fractional gain variation $\Delta G/G$, as a function of time.

5.18.1.1 Total Power Mode: Gain Stability over Short Time Scales

A goal for system gain stability is that total power mode sensitivity not be limited by instrumental gain fluctuations. Rather, the limiting factors should be receiver thermal noise and/or atmospheric perturbations. (See [RD05] for further discussion.)

However, gain fluctuations manifest themselves as $1/f$ noise in the power spectral density of the radiometer output. They add to the PSD at low frequencies, and can be a limiting factor in noise dropping by $1/\sqrt{T}$. Over long periods, this may set a floor on system noise, and noise may actually rise due to random walk fluctuations on sufficiently long timescales. The system gain stability should be specified over a gain calibration cycle. For the purpose of this analysis, this will be assumed to be of order 20 minutes.

At ngVLA operating frequencies, atmospheric introduced changes in T_{sys} can be quite small. At lower frequencies, T_{atm} is dominated by O_2, which is fairly stable, with relatively small contributions from precipitable water vapor (PWV). For example, for a 1-mm change in PWV, T_{atm} at 16 GHz may rise ~0.02 K [RD06]. With a system noise temperature of 20K, this equates to a fluctuation (dT_{atm}/T_{sys}) of 1e-3. So, in order to make atmospheric changes more dominant at all observed frequencies, gain stability (dG/G) of order 1e-3 would be required on antennas operating in a total power mode.

It should be noted that fluctuations in T_{SYS} due to expected changes in T_{REC} or T_{SPILL} have a similar effect on the total power measurements and therefore have comparable restrictions. In practice, they are expected to be larger in magnitude, as are changes in T_{ATM} as a function of elevation.

5.18.1.2 Total Power Mode: Flux Scale Calibration

Should the gain calibration noise source be well characterized in an absolute sense, it may also provide a reference for flux scale calibration. The system described above could be characterized by Y-factor measurements in the lab. Its behavior must be characterized over its entire range of operating temperatures. It would be desirable to limit this temperature range in order to simplify testing/characterization and eventual calibration. This feature is especially attractive for total power measurements as it can increase the calibration cycle time to an astronomical source.

5.18.1.3 Total Power Mode: Gain Variations with Antenna Pointing Angle

Gain variations with antenna pointing angle can produce an uncorrectable error over angles comparable to the distance between the source and gain calibrator. These could impact both image fidelity and flux calibration. This parameter will be explored in the future.

5.18.2 Interferometric Observations

Parameter	Req. #	Value	Traceability
Interferometric Antennas: Gain Stability	SYS4601	Antenna *dG/G* shall not exceed 10^{-3} over a 200 sec period. Goal to not exceed 10^{-4}.	SCI0113, SCI0114
Interferometric Antennas: Relative Gain Stability	SYS4602	Relative *dG/G* between polarization pairs shall not exceed 10^{-3} over a 200 sec period. Goal to not exceed 10^{-4}.	SCI0114
Gain Variations with Antenna Pointing Angle	SYS4603	Antenna *dG/G* shall not exceed 10^{-2} at 10 GHz over a 4° change in elevation, scaled by frequency (TBC).	SCI0110
Gain Calibration Reference	SYS4801	The system shall provide a switched flux reference stable to 10^{-3} over a 20-minute period.	SCI0110, SCI0113, SCI0114

The intent of the gain stability requirements is to constrain the system gain variations that would limit the accuracy of interferometry observations and calibration. Assuming the cross-correlation products are not normalized (as is the case with WIDAR), the cross-correlation power is

$$V_{ij} = \hat{g}_i \hat{g}_j^* < v_i v_j^* >$$

where v_i is the equivalent voltage at the input to an antenna, $\hat{g}_i = g_i e^{-i\theta_i}$ is the complex voltage gain of that antenna and V_{ij} is the complex visibility or correlation coefficient of the noise input signals of antennas *i* and *j*. The magnitude of V_{ij} is zero for completely uncorrelated noise signals and is a positive number for correlated noise.

The visibility is closely related to the cross power product of the noise input signals at antennas *i* and *j*, but is scaled by the complex voltage gain of the antennas. Therefore, it is essential to quantify the voltage gain and to track gain fluctuations at the antenna, and impose a limit on the residual uncorrected gain variation.

Represented as powers, the desired power product, P_{int}, represents the cross-power from the astronomical source only:

$$P_{int} = \sqrt{P_{src,i}P_{src,j}}$$

while the correlator output is scaled by root of the products of the two independent gains:

$$P_{corr} = \sqrt{g_i g_j} P_{int}$$

Uncorrected changes in $g_i\, g_j$ will artificially inflate or deflate the flux sensed on the baseline, which introduces ringing and other imaging artifacts that effectively reduce the SNR of the image.

5.18.2.1 Interferometric Mode: Gain Stability on Short Time Scales

A goal for system gain stability in interferometric modes is to support the imaging and polarization dynamic range requirements. SCI0113 calls for a brightness dynamic range of 50 dB over the field of view at 10 GHz. As laid out in Section 5.18.2, the complex gain term has a phase and amplitude. Both are equally important to meeting the brightness dynamic range requirement, as incorrect placement of flux in the field (due to a phase error) will raise the rms of the emission-free regions. As reported in [RD19] (p. 278), 10% phase errors are comparable to 20% amplitude errors in impact on interferometric dynamic range.

We will assume for the moment that self-calibration is available and that the phase errors, after calibration, are negligible for this analysis in order to put an upper limit of the gain errors that would support the dynamic range requirement. Per [RD19] (p. 279), the relationship of the dynamic range limit of the system scales to the typical amplitude error on any antenna and is given by:

$$D = \frac{N}{\sqrt{2}\,\varepsilon}$$

where *D* is the dynamic range limit, *N* is the number of antennas in the array, and ε is the typical amplitude error. Assuming an array of order 200 elements, the gain stability (*d*G/G) of a given antenna, after calibrations are applied, must approximate 1e-3 to support the higher dynamic range requirement. Accounting for imperfect phase calibration, gain amplitude stability of order 1e-4 would be desirable.

The period over which this stability must be maintained is typically related to the astronomical gain calibration cycle (~20 minutes), but can be reduced by transferring some of the stability requirements to a calibrated noise source as described in Section 5.18.3.

5.18.2.2 Interferometric Mode: Gain Stability between Polarization Pairs

Gain stability between polarization pairs in an individual antenna is required to support the polarization dynamic range requirement. SCI0114 calls for a polarization dynamic range of 40 dB at 10 GHz in the center of the field of view. Holding the relative gain stability between polarization pairs within a single antenna to 1e-3 should suffice for this requirement, based on similar arguments to those laid out in Section 5.18.2.1. This requirement should be explored in more detail in the future.

5.18.3 Short Cycle Gain Calibration

The effects of gain fluctuations may be correctible with a sufficiently precise active gain calibration system. This section explores the effect of switched power gain calibration.

In order for the switched power system to allow effective gain calibrations of order dG/G of 1e-3, SNR of order 3e3 is required (for a 3σ detection). With switched power of order 1% of T_{sys}, measuring gain fluctuations of *dG/G* of 3e-3 requires a noise reduction of 3e5.

$$\sigma \approx {T_{sys}}\Big/{\sqrt{\Delta \nu t}}$$

$$3e5 = \sqrt{\Delta \nu t}$$

Applied over a bandwidth of 1 GHz, the integration time required is of order 100 seconds. Assuming a duty cycle of 50%, 200 seconds of clock time, system gain stability would be required over 200-second periods.

The stability requirement for longer (>200-second scales) is transferred to the noise diode and its amplification/attenuation stages before coupling into the RF path. Noise diode-coupled power fluctuations on time scales shorter than the interval between external calibration (~20 min) impact the accuracy of the gain calibration and add noise. Note that the calibration will allow for the subtraction of any linear drift term, so it is only the residuals (rms) after linear term subtraction that will remain.

Passive temperature regulation of the noise diode attenuation/gain stage (if any)—adding significant thermal mass and insulation—may be adequate to meet this requirement.

5.19 Calibration Efficiencies

Parameter	Req. #	Value	Traceability
Calibration Efficiency	SYS1061	Overheads for system calibration shall be minimized, with a goal of 90% of time spent on source for Standard Observing Modes.	SCI0100, SCI0102, SCI0106, STK1403, STK0704
Calibration Parallelization	SYS1062	Any real-time calibration pipelines must permit parallelization at the antenna or baseline level.	STK1403
Calibration Recall	SYS1063	The system shall remember prior calibration corrections and apply them if their projected accuracy (given time elapsed) still meets the requirements for a given observation. (i.e. a scheduling block need not always include its own calibrators.)	STK1403
Relative Flux Scale Calibration Efficiency	SYS1064	The system shall permit relative flux scale calibration to 5% precision without the need for tipping scans in Standard (Interferometric) Observing Modes.	STK1403, STK0704
Polarization Calibration Efficiency	SYS1065	Polarization calibration shall be achievable with a single observation of a compact polarized source of unknown polarization angle for Standard (Interferometric Continuum) Observing Modes.	STK1403, STK0704

Parameter	Req. #	Value	Traceability
Bandpass Calibration Efficiency	SYS1066	The system shall have adequate gain stability to permit application of cataloged bandpass solutions for Standard (Interferometric Continuum) Observing Modes.	STK1403, STK0704
Gain Calibration Efficiency	SYS1067	Gain calibration shall be achieved with no more than a 2% degradation in system sensitivity as a function of clock time.	STK1403
Phase Calibration Efficiency	SYS1068	Phase calibration overheads shall not exceed 100% of on-source time for observations at 116 GHz when operating in the precision operating conditions. It is a goal to reduce phase calibration overheads to 10% of on-source time.	STK1403

Total observing efficiency will vary with each observation given its unique calibration needs. Care will be required in the design of the calibration system for phase, gain and other systematics, and the efficacy of each system should be judged by their impact on observational efficiency. Improvements to the phase calibration system that increase operational system efficiency can be compared to the cost of added collecting area, greater bit depth, improved antenna surface accuracy, or feed illumination efficiency.

However, hard limits for the observational efficiency are difficult to establish, so the calibration efficiencies are better thought of as technical parameters that should be optimized for general use cases. This is discussed further in Section 7.4.2.

5.20 Polarization Requirements

Parameter	Req. #	Value	Traceability
Polarization Purity	SYS1901	0.1% post-calibration on-axis residual linear pol leakage (amplitude), where leakage is defined as Stokes Q/I, U/I, or V/I. Goal of 0.01% residual on-axis polarization leakage.	SCI0114

As stated in requirement SCI0015, the system will measure all polarization (Stokes) products simultaneously. Per SCI0114, the system should achieve 40 dB polarization dynamic range.

This specification is both frequency and direction-independent and applied only at the center of the field and over 80% of a given receiver's bandwidth. It is expected that systematics will be greater as we approach the full-width half max of the beam, due to a degraded off-axis response with offset optical geometries. Band edge response of polarizers is also expected to degrade polarization performance.

How the error budget should be allocated amongst system elements should be determined once a polarization calibration strategy is developed. Assumptions about the calibration accuracy and the degree to which antenna based errors are independent will be necessary, and the polarization requirements will be closely tied to gain stability requirements, since any gain fluctuations that are not common to both polarizations will contribute to this error.

5.21 Temporal Requirements

Parameter	Req. #	Value	Traceability
On-The-Fly Mapping: Data & Control Rates	SYS0106	The system shall support on-the-fly (OTF) mapping rates of 2x sidereal at 28 GHz, with data dump rates and delay update rates <400 msec at the full system bandwidth. Goal to support rates <100 msec at reduced bandwidth or spectral resolution (i.e. fixed data output rate).	SCI004, SCI0106
On-The-Fly Mapping: Antenna Tracking Rate	SYS0107	The antenna and any motion control loops shall support on-the-fly tracking rates of 10x sidereal for elevations below 70° (2.5'/sec)	SCI004, SCI0106
Temporal Resolution	SYS2001	Correlator visibility integration time shall be tunable, with a range of 5 sec to 100 msec (possibly at reduced bandwidth), or better.	SCI0004, SCI0103
Temporal Accuracy	SYS2002	Data Product timestamps must be referred to an absolute time standard (e.g., GPS or TAI) with an error of at most 10 ns (goal of 1 ns). This correction can be retroactive; it is not necessary for it to be known in real time.	SCI0112, SCI0014, SCI0012

System temporal resolution may be set either by the need to prevent time and bandwidth smearing in imaging or by the rate of change in a time-variable source (such as FRBs). Short integration times are also required for on-the-fly mapping. Note that this requirement presumes that frequency resolution is traded for temporal resolution in order to keep total data rates practical.

There is a relationship between the maximum integration time and maximum baseline length which is limited by circumferential smearing. In order to keep the smearing low, a rule of thumb is to keep the integration time well below [RD09]:

$$\left(\omega_e D_\lambda / \theta_f\right)^{-1}$$

where ω_e is the Earth's rotation angular velocity, D_λ is the baseline length in wavelength units, and θ_f is the angular size of the sky image. For an 18m aperture, the maximum image size is approximately 1,000 km/18m ≈ 60,000 synthesized beams. Then, a minimum integration time equal to 50% of the above expression is of order 100 msec.

Note that on-the-fly mapping at a rate of 10*ω_e at this resolution would require a minimum integration time 10x smaller! However, OTF mapping is not required or expected at this resolution. The OTF rates assume that the interferometric delays (phase center) are updated as the antenna moves 1/10th of a primary beam, and visibility integrations as required to limit smearing. The 400 msec rate supports 2x sidereal scanning at 28 GHz with the natural beam of the main array, in support of SCI0106, while the 100msec rate supports 2x sidereal scanning at 116 GHz.

Temporal accuracy is required for astrometric observations and other studies of time-variable phenomena, where an absolute knowledge of the event time is necessary. This requirement will also support VLBI observations by providing a suitably small fringe search window.

5.22 Spurious Signals

Parameter	Req. #	Value	Traceability
Self-Generated Spurious Signal Power Level	SYS2104	Self-generated signals shall not exceed –43 dB relative to the system noise level on cold sky over a 1 MHz bandwidth.	SCI0116
LO Frequency and Sampler Clock Offsets	SYS2105	The system shall include provisions for frequency offsets and sampler clock offsets at the antenna level to provide additional attenuation of spurious signals.	SCI0115, SCI0113, SCI0108
Shielding & Emission Limits	SYS2106	System shielding and emission limits shall comply with 020.10.15.10.00-0002-REQ.	SCI0116

These requirements apply to self-generated spurious signals within the array and do not address external Radio Frequency Interference. Spurious signals may be coherent or incoherent signals. While both can affect system performance, coherent signals are more damaging, since they do not average out with more samples/time and need a more stringent specification.

Incoherent and coherent spurious signals could limit the spectral dynamic range. There is a scientific requirement, on spectral dynamic range of 100,000:1, for weak spectral lines in the presence of stronger spectral lines. Flowing down from this are two main technical requirements:

- the bandpass must be sufficiently stable in time that it gives no false appearance of weak lines, and
- there should be no self-generated spurious features in the output spectra.

In interferometry mode, spurious signals coherent between antennas can lead to

- spurious spectral features,
- closure errors that limit calibration accuracy and thus imaging dynamic range, and
- image defects, usually broad stripes and ripples throughout the field, that limit continuum sensitivity.

The relative spurious power in a given spectral bin will be calculated as (P–N)/IN, where P is the total power in the bin, and N is the average power in the adjacent two bins. The bin size will be chosen as large as possible to include broad spurs, while narrow enough to exclude microscale baseband ripples.

Adopting the methodology from [RD14], we set the interference to noise ratio to less than 0.1:

$$INR < 0.1$$

Harmful flux density can then be found from SCI0116:

$$S_H < \sigma_{rms} * INR$$

Since the specification is given as a flux density, this can be directly compared to the SEFD to determine the required signal-to-interferer ratio. At 30 GHz, the expected SEFD for the array is of order 2.1 Jy:

$$\frac{S}{I}(\Delta\nu) = 10 * \log\left(\frac{9.5\ \mu Jy}{2.1\ Jy}\right)\ dB = -53\ dB$$

Since the power and flux density are proportional, the power of the spurious signal must be no more than –53 dB above the signal level on cold sky over the established channel bandwidth (0.1 km/s = 10 kHz @ 30 GHz). This specification would apply to total-power measurements but can be relaxed for interferometric measurements by of order 20 dB due to phase winding/fringe washing (–53 dB + 20 dB = 33 dB/10 kHz). (See [AD06] for supporting derivation of interferometric attenuation factor.)

Extending the bandwidth over which the signal level is measured can increase the fidelity of the verification measurement, and a bandwidth of 1 MHz is adopted. The required attenuation will scale by the square root of the bandwidth:

$$\frac{S}{I}(1\ \text{MHz}) = \frac{S}{I}(10\ \text{kHz}) * \sqrt{\frac{1\ \text{MHz}}{1\ \text{kHz}}}$$

The end result is a spurious signal level of –43 dB/MHz for interferometric antennas. While the derivation above is given at 30 GHz, the requirement is comparable over the given frequency range.

Using LO-offsetting and 180° phase switching (Walsh switching) would further reduce the impact of spurious signal introduced after the first LO. Sampler clock offsets and LO-offsets combined would provide the highest degree of attenuation to self-generated spurious signals. A more stringent standard is not adopted for total power antennas given that the recovery of large-scale structure is more applicable on large mosaics with shallower integration.

5.23 Scientific Operations Requirements

Parameter	Req. #	Value	Traceability
Provision of Software Tools	SYS2201	The system shall include tools for the preparation of proposals, preparation of observations, reduction of data products, and the analysis of data products.	STK0801, STK1201, STK1202, STK0805

Tools need to be supplied for user interaction with the facility. As with current NRAO facilities, these are expected to include proposal preparation, observation preparation and data reduction. Revisions to existing tools, with similar requirements, are expected to be adequate. One difference may be the provision of computing resources. With larger data volumes, the project should provide computing resources for computationally demanding work such as data reduction. Data reduction should not require that users setup their own high performance computing (HPC) clusters, though this should also not be precluded for the most sophisticated use cases.

The design, allocation, and location of computing resources is an area where community engagement may be feasible (see Stakeholder Requirements). Computing resources could be hosted at major research universities in a distributed computing model. Community development of software tools, as part of a modular toolkit, may also be practical.

5.23.1 Proposal Submission and Evaluation

Parameter	Req. #	Value	Traceability
Proposal Submission: Standard Observing Modes	SYS2211	The proposal submission interface shall allow the user to specify their scientific requirements for standard observing modes, without specifying the technical implementation to those requirements.	STK0801, STK0800, STK0805
Proposal Submission: Non-Standard Observing Modes	SYS2212	For non-standard observing modes, it shall be possible for the user to define their technical observation parameters as part of their proposal.	STK0800, STK0801, STK0702
Scientific Proposal Evaluation	SYS2213	A tool shall be available for proposal evaluation and ranking, and permit anonymization of proposals during evaluation.	STK0802, STK0803

Parameter	Req. #	Value	Traceability
Technical Proposal Evaluation	SYS2214	The proposal evaluation tool shall include technical simulation tools to estimate the observing resources required (sub-arrays, time) to support the science requirements.	STK0802

5.23.2 Observation Preparation, Execution, and Scheduling

Parameter	Req. #	Value	Traceability
Observation Preparation: Standard Observing Modes	SYS2221	For standard observing modes, the system shall determine the technical configuration of the system and a supporting observation plan that meets the science requirements set by the proposer.	STK0805, STK0701
Observation Preparation: Non-Standard Observing Modes	SYS2222	The system shall include tools and interfaces to generate observation instructions for non-standard modes without the use of the end-to-end software system.	STK0402, STK0502
Observation Scheduling GUI	SYS2223	The observation scheduling system shall include a GUI to display completed and scheduled projects to the Operator and initiate manual overrides and other changes.	STK0901, STK1502
Observation Interrupt	SYS2224	It shall be possible to interrupt and cancel an in-progress observation through the observation scheduling system GUI and the Operator Console.	STK0901, STK1502
Observation Preparation: Standard Observing Mode Flexibility	SYS2225	For standard observing modes, the proposed observation plan shall be supplied to the user for review, and the user can propose modifications as necessary to support their science requirements.	STK0705
Observation Scheduling	SYS2302	System observations shall be automatically scheduled by an observation scheduling system. Manual overrides to scheduling shall also be possible.	STK0900, STK0901

5.24 Array Operation Requirements

Parameter	Req. #	Value	Traceability
Calibration Automation	SYS2303	The calculation and updating of parametric delay and pointing models shall be automated.	SYS1061, SYS1062, STK1506
Self-Calibrating Antenna	SYS2304	It is a goal that the antenna self-configure and self-calibrate, with limited intervention from the operator.	SYS1061, SYS1062, STK1506
Single Baseline Data Display	SYS2305	Graphical interfaces shall be provided to display single baseline fringe amplitude and phases in near real-time.	STK0402, STK0502

Parameter	Req. #	Value	Traceability
Calibration Data Display	SYS2306	Graphical interfaces shall be provided to tabulate and display common antenna calibration coefficients (delays, TSYS, PDIFF, etc.), and flag values that are possible outliers. The threshold for flagging shall be user tunable (e.g., 1s, 3s, etc.)	STK1700, STK0402, STK0502
Operator Console	SYS2307	An operator console shall be provided that provides visibility and control of scheduled maintenance and observations, as well as displays of the array configuration, weather, and system alerts.	STK1703

The requirements for ngVLA are broad, with a scientific operation concept similar to the VLA where observers request time for a specific study and define many observation parameters. This is distinct from a survey instrument with a more rigidly defined operation schedule and data product. This PI-driven model requires a flexible instrument and observation schedule that maximizes output given system and environmental conditions. The PI-driven general-purpose and flexible model is in tension with operations cost caps. As such, system operation should be automated where possible, enabling systems to self-monitor, self-configure, and self-calibrate to reduce the operations burden and staffing required. This has significant implications for the monitor and control system and supervisory software systems that must be elaborated in those requirements.

5.25 Array Maintenance Requirements

Parameter	Req. #	Value	Traceability
Antenna Maintenance Interval	SYS2401	The system shall be designed with a preventative maintenance interval of no shorter than one year.	STK1800
Array Element MTBF	SYS2402	The antenna, antenna electronics, array infrastructure, and signal processing system shall be designed with an expected number of failures to be less than four per array element per year.	STK1802, STK0101
Modularization	SYS2403	The system shall be modularized into Line Replaceable Units (LRUs) to facilitate site maintenance.	STK1802, STK1603
Predictive and Self-Diagnostic Function	SYS2405	The system shall incorporate predictive maintenance and self-diagnosis functions in the case of faults based on recorded monitor data.	STK1803, STK1702
Configuration Monitoring	SYS2406	The system shall include monitoring and tracking of the system configuration to the LRU level, including LRUs that are not network-connected for operation (e.g., refrigerators).	STK1600, STK1601
Engineering Console	SYS2407	The system shall include an engineering console for each major subsystem and/or LRU to communicate system status and assist in real-time diagnosis.	STK1700, STK1702, STK0402, STK0502

Parameter	Req. #	Value	Traceability
Engineering Database	SYS2408	The system shall record all monitor data at variable rates for automated use by predictive maintenance programs and for direct inspection by engineers and technicians.	STK1700, STK1702, STK0402, STK0502

To reduce the maintenance burden (and cost) the maintenance interval for the antenna systems must be appreciably longer than the VLA. A preventive maintenance cycle of one year is approximately a fourfold improvement. The MTBF for the associated systems should lead to no more than four failures per array element per year. This equates to an MTBF of around 2,190 hours and is expressed as:

$$MTBF_{sys} = t_{total}/N_{failures} = (N_{elem}\ t)/(4\ N_{elem})$$

The flow-down requirements can be quite stringent. If each array element has N_{LRU} line replaceable units (LRUs) that are essential to its operation (series analysis), the MTBF can be expressed as:

$$MTBF_{sys} = \sum_{k=1}^{N_{LRU}} \left(\frac{1}{MTBF_k}\right)^{-1}$$

For N_{LRU} = 16, in order to have an MTBF of the system of 2,190 hours, the MTBF per LRU required would be of order 35,040 hours (four years). Apportionment of failures throughout the system in order to have a maintainable array will require further study.

Specifying MTTFs rather than MTBFs may be more appropriate, with a goal of harmonizing the MTTF and the preventative maintenance schedule of the antenna so that maintenance is more closely tied to the preventive maintenance cycle than responsive to failures.

5.26 System Monitoring Requirements

Parameter	Req. #	Value	Traceability
LRU Monitoring	SYS3101	Each LRU shall provide on-board monitoring and diagnostics to determine the health and status of the unit.	STK1803, STK1702
LRU Alerts	SYS3102	When an LRU is out of specification, it shall generate a prioritized alert for processing by the operator and maintenance scheduler.	STK1803
Monitor Archive	SYS3103	Monitor data and alerts shall be archived at variable rates, depending on criticality, for the full life of the instrument. (SYS2801)	STK1700
Subsystem Monitoring Screens	SYS3104	Engineering consoles shall be provided for all major subsystems.	STK1600, STK1702, STK1506
Fast Read-Out Modes	SYS3105	Fast-read out modes shall be available for remote engineering diagnostics of all LRUs (i.e. an on-board oscilloscope function).	STK1702, STK1506

5.27 Environmental Monitoring Requirements

Parameter	Req. #	Value	Traceability
Weather Monitoring	SYS2501	Parameters that affect system scheduling or are used for calibration (wind speed, temperature, humidity and barometric pressure), shall be measured over the full extent of the array.	STK0900
Safety Weather Monitoring	SYS2502	Parameters that affect the health/safety of the array (wind, temperature) shall have redundant monitoring.	STK0304
Weather Archive	SYS2503	Weather data from all weather stations shall be archived at no less than 1-minute periods.	STK1403

Given the extent of the array, weather monitoring will be required at multiple sites to quantify the environmental conditions over the full extent of the array. All parameters that affect system scheduling or safety should be measured to manage the array operation.

5.28 System Availability

Parameter	Req. #	Value	Traceability
Antenna System Availability	SYS2601	Minimum of 90% availability for all antenna systems combined. Availability is defined as the percentage of time available for science operations, excluding scheduled and unscheduled maintenance downtime. Goal of maintaining 95% availability.	STK1402
Centralized Systems Availability	SYS2602	For all centralized systems (LO distribution, correlator, etc.) that are required for data collection, system availability shall be no less than 95%. See definition of availability above.	STK1402

The availability requirement aims to have 90% of antennas available for science. This is approximately equivalent to the current VLA "three antenna rule," with the goal of allowing for an appropriate amount of downtime to conduct preventive maintenance, repairs, and testing while also maximizing array output.

This requirement has a flow down need to be harmonized with the maintenance requirements established in Section 5.25. The mean time to repair (MTTR) must be calculated for common failures to determine downtime for each failure. A time allocation must also be made for preventive maintenance and testing allocations, and they must add up to no more than 10% of clock time.

Separate availability requirements are stipulated for antennas versus centralized systems, since failures of the latter are expected to preclude system operation. This assumption should be revisited later in the design: modularized architectures may be more flexible in responding to failures than has been assumed.

5.29 Safety and Security

Parameter	Req. #	Value	Traceability
Safety Specification	SYS2700	All subsystem designs shall comply with the System Safety Specification (Doc TBD)	(TBD)
Subsystem Self-Monitoring	SYS2701	All subsystems shall monitor system health and prohibit actions likely to cause damage.	STK1702
IT Security	SYS2702	The data processing, networking, and data archive systems will be engineered and operated in accordance with current IT Security best practices as defined by NSF-funded Center for Trustworthy Scientific Infrastructure (https://trustedci.org) and the AUI Cyber Security Policy.	STK2202
Physical Security	SYS2704	Physical security and monitoring shall be considered in the array design.	STK2201

The safety requirements fall into two broad categories: protecting the system and protecting personnel.

The system should self-monitor its condition, prohibit actions likely to cause damage, and respond to conditions that indicate imminent failure. An example would be to auto-stow the antenna if limits to the operational environment are reached, and not permit the operator to switch back to an operational mode until the condition subsides.

Given modern threats, the system should include provisions to protect against most common hacking attempts. The system should only respond to commands from authorized users and/or sources. Permissive control systems will not meet this standard.

The safety of operation and maintenance personnel should be considered at every level of the design. Hazard analysis shall be performed for all common services to motion, high-power, high-voltage, or otherwise high-risk systems. The findings from such an analysis shall be incorporated into the subsystem requirements and design.

5.30 System Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	SYS2801	The system shall be designed for an expected operational life of no less than 20 years.	STK0303
Cost Optimization	SYS2802	The system shall be designed to minimize total life-cycle costs over the projected design life, extending through system decommissioning/ disposal.	STK0303, STK0100, STK0101, STK0600
Sustainability	SYS2803	Sustainability and long-term environmental impact shall be considered in any material or design trade-study.	STK0302

The system is expected to operate for an initial mission of 20 years. Extension of the operating period would likely be tied to a renewal project to enable new capabilities to support the extended operating mission. Therefore, a 20-year design life will be used for all systems. It is desirable that major infrastructure elements such as the antenna and power distributions system have longer design lives in anticipation of future reuse, but this goal should not drive system cost or complexity.

The system shall be built with an accounting of the full life-cycle costs, while respecting the constraints for construction and operations cost. Decommissioning costs shall be included as part of this assessment.

Consideration should be given to financial investments that might reduce the operational cost of the array while still offering competitive lifecycle cost analysis. Examples might include the use of reusable energy generation, or energy-saving technologies for cryogenic or HVAC systems.

5.30.1 Assembly, Integration, and Verification Requirements

Parameter	Req. #	Value	Traceability
Test Fixtures	SYS2811	Each subsystem shall provide test fixtures and procedures for subsystem verification.	STK0400
Critical Spares	SYS2812	Each subsystem shall identify and provide critical spares and with sufficient inventory to support the facility for its operational life (SYS2801). Critical spares are defined as parts that are likely to be obsoleted over the operating life, are unlikely to have market substitutes, and cannot be produced/ordered in small volumes.	STK0403
System Verification Tools	SYS2813	Tools shall be developed to automate test execution and test reporting as part of array element verification. Such tools shall include near real-time data display for interactive diagnosis by engineers.	STK0402

6 L2 System Requirements

The following requirements flow from the L1 requirements listed in Section 5. These requirements are not implementation agnostic but provide sufficient allocation of L1 requirements to allow derivation of supporting subsystem requirements. These requirements may move to subsidiary documents in the future.

6.1 System Collecting Area

Parameter	Req. #	Value	Traceability
System Geometric Collecting Area	SYS1021	The system gross geometric collecting area shall be 62,000 m^2 or greater.	SCI0100, SCI0102, SCI0106

Note that this requirement would require ~244 18m antennas with unblocked apertures.

6.2 System Temperature

Parameter	Req. #	Value	Traceability
Maximum T_{SYS} in Freq. Span A	SYS1011	Not to exceed values in Table 2 in the precision operating environment, 45-deg elevation, and 1 mm of PWV.	SCI0100, SCI0102, SCI0106
Maximum T_{SYS} in Freq. Span B	SYS1012	Not to exceed values in Table 2 in the precision operating environment, 45-deg elevation, and 1 mm of PWV.	SCI0100, SCI0102, SCI0106
Maximum T_{SYS} in Freq. Span C	SYS1013	Not to exceed values in Table 2 in the precision operating environment, 45-deg elevation, and 1 mm of PWV.	SCI0100, SCI0102, SCI0106

The system temperature contributes to system sensitivity [SYS0501–SYS0504]. It is possible to compensate for added T_{SYS} with bandwidth and/or collecting area in an effort to optimize sensitivity as a function of cost.

The values given in Table 2 below are at the point frequency and assume the environmental conditions of the precision operating environment [AD05] at an elevation of 45-degrees and assuming 6 mm of PWV for SYS1011 and SYS1012. One mm of PWV can be assumed for SYS1013.

System temperature for Frequency Span A accommodates a ~20% degradation from EVLA performance. These figures are supported by developments at CSIRO and Caltech on 3:1 wideband feeds. The goal at low frequencies is to provide improved sensitivity relative to the VLA while not introducing an undue maintenance burden by doubling the receiver complement on the antenna.

Note that when comparing various receiver configurations, both the system temperature and the feed illumination efficiency should be equally considered in order to make fair comparisons. This is discussed further in Section 7.4.1.

System temperatures at Spans B and C [SYS1012, SYS1013] should be as low as practical, consistent with a desire to maximize sensitivity at these frequencies.

Frequency (GHz)	1.2	5	7.9	8	30	40	50	70	80	100	115
Max T_{SYS} (K)	27	28	30	25	32	42	90	125	75	75	135

Table 2 - T_{SYS} over frequency in precision environment.

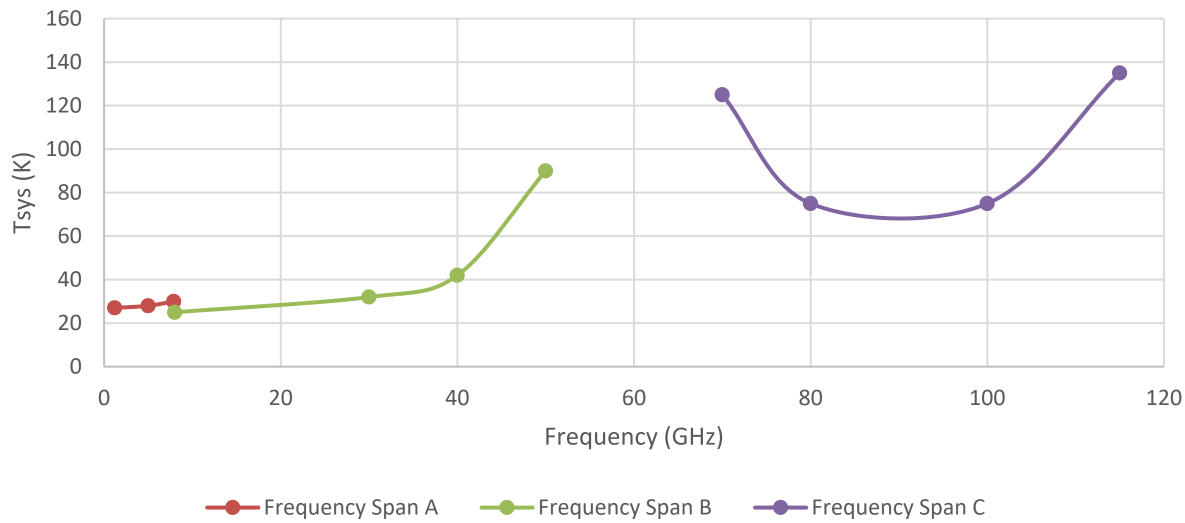

Figure 2 - T_{SYS} over frequency in precision environment.

6.3 *Analog and Digital Efficiency Requirements*

Parameter	Req. #	Value	Traceability
Antenna Efficiency: Precision Environment	SYS1031	The antenna efficiency in the precision operating environment shall exceed the values given in Table 3.	SCI0100, SCI0102, SCI0106
Antenna Efficiency: Normal Environment	SYS1032	The antenna efficiency in the normal operating environment shall exceed the values given in Table 4.	SCI0100, SCI0102, SCI0106
Minimum Interferometer Digital System Efficiency	SYS1033	0.96 minimum, including quantization and correlation losses (equivalent to 3.0 effective bits). It is desirable to approach 0.99 efficiency over narrow (<5 GHz) bandwidths for spectral line use cases.	SCI0100, SCI0102, SCI0106
Minimum Digital Quantization Levels: Narrow Bandwidths (<5 GHz)	SYS1034	28 (256 levels) when supported by the Front End sampler.	SYS1033
Minimum Digital Quantization Levels: Wide Bandwidths (>5 GHz)	SYS1035	24 (16 levels).	SYS1033
Correlator Precision	SYS1036	8-bit correlation minimum.	SYS1033

Efficiencies associated with calibration and imaging performance are addressed elsewhere in this specification. Antenna efficiency includes antenna reflector/structure losses and feed illumination losses. The antenna efficiency is specified at a single frequency within each Frequency Span (see Section 5.10) for simplicity, but elaborated in Section 6.3.1. The digital system efficiency includes quantization efficiency and any losses from requantization at various parts of the digital signal path. With 3-bit (8-level) effective quantization, efficiency of 0.96 is achievable [RD07].

6.3.1 Antenna Efficiency Allocations in Precision Environment

The allocation of antenna efficiency errors is shown in Table 3. Additional frequencies are included for clarity. The allocation of efficiencies is based on projected taper and spill contributions of candidate feeds with shaped optics. No allocation is included for blockage or polarization, as unblocked apertures are preferred.

The structural contributions include a surface error contribution, calculated with the Ruze formula, and a focus efficiency term for defocus as a result of deformations due to gravity. The focus efficiency is the minimum permitted over the full range of elevation. Total antenna efficiencies at each frequency are noted in the far right column.

	Antenna Efficiencies									
Freq.	Taper	Spill.	Block.	Pol.	**Illum.**	Focus	Surface	Ohmic	**Struct.**	**Total**
GHz	η_T	η_S	η_B	η_X	$\boldsymbol{\eta_T\eta_S\eta_B\eta_X}$	η_F	η_{RUZE}	η_{OHM}	$\boldsymbol{\eta_P\eta_{RUZE}}$	$\boldsymbol{\eta_A}$
2	0.95	0.83	1	0.98	**0.77**	1	1	1	**1**	**0.77**
6	0.95	0.83	1	0.98	**0.77**	1	1	1	**1**	**0.77**
10	0.95	0.92	1	0.99	**0.87**	1	1	1	**1**	**0.87**
30	0.95	0.92	0.99	0.99	**0.86**	0.99	0.96	1	**0.95**	**0.81**
50	0.95	0.92	0.99	0.99	**0.86**	0.99	0.89	1	**0.88**	**0.75**
80	0.95	0.92	0.99	0.99	**0.86**	0.97	0.75	0.99	**0.73**	**0.62**
100	0.95	0.92	0.99	0.99	**0.86**	0.96	0.64	0.99	**0.61**	**0.53**
120	0.95	0.92	0.99	0.99	**0.86**	0.94	0.52	0.99	**0.49**	**0.42**

Table 3 - Antenna efficiency budget as a function of frequency for precision environment.

6.3.2 Antenna Efficiency Allocations in Normal Environment

	Antenna Efficiencies									
Freq.	Taper	Spill.	Block.	Pol.	**Illum.**	Focus	Surface	Ohmic	**Struct.**	**Total**
GHz	η_T	η_S	η_B	η_X	$\boldsymbol{\eta_T\eta_S\eta_B\eta_X}$	η_F	η_{RUZE}	η_{OHM}	$\boldsymbol{\eta_P\eta_{RUZE}}$	$\boldsymbol{\eta_A}$
2	0.95	0.83	1	0.98	**0.77**	1	1	1	**1**	**0.77**
6	0.95	0.83	1	0.98	**0.77**	1	0.99	1	**0.99**	**0.77**
10	0.95	0.92	1	0.99	**0.87**	1	0.98	1	**0.98**	**0.85**
30	0.95	0.92	0.99	0.99	**0.86**	0.99	0.87	1	**0.86**	**0.74**
50	0.95	0.92	0.99	0.99	**0.86**	0.99	0.67	1	**0.66**	**0.57**
80	0.95	0.92	0.99	0.99	**0.86**	0.97	0.36	0.99	**0.35**	**0.30**
100	0.95	0.92	0.99	0.99	**0.86**	0.96	0.21	0.99	**0.20**	**0.17**
120	0.95	0.92	0.99	0.99	**0.86**	0.94	0.1	0.99	**0.09**	**0.08**

Table 4 - Antenna efficiency budget as a function of frequency for normal environment.

The antenna efficiency specification is relaxed in the secondary operating environment. The surface efficiency of the reflector is equivalent to a 300 μm rms surface error, reflecting the deformations expected due to differential thermal loading and/or wind loading.

6.4 Allocation of Delay/Phase Noise and Drift Requirements

Parameter	Req. #	Value	Traceability
Allocation of Delay/ Phase Noise & Drift	SYS5001	The allocation of instrumental delay/phase errors shall not exceed the values in Table 5.	SCI0100, SCI0102, SCI0106

The allocation of temporal delay/phase requirements among the electronics subsystems and the mechanical structure is given in Table 5. The various quantities are combined in an RSS sense. Initial allocations are equally distributed between systems. This should be revisited as the technical feasibility of each system is assessed.

Component	**Noise (rms)**	**Drift Residual (rms)** Up to 300 seconds	**Absolute Drift** Up to 300 seconds
Antenna Structure	76 fsec	42 fsec	4 psec
First LO: FE	76 fsec	42 fsec	0.5 psec
Digitizer Clock: FE	76 fsec	42 fsec	0.5 psec
Antenna RTP System	~0	42 fsec	0.5 psec
LO Distribution System	~0	42 fsec	2.5 psec
LO Reference	~0	TBD	TBD
Total Instrumental Error	**132 fsec**	**95 fsec**	**8 psec**

Table 5 - Allocation of temporal instrumental delay/phase errors (per antenna errors, in fsec).

Table 5 Notes:

1. The delay/phase drift requirements in Table 5 apply on a time scale up to 300 sec, which is taken to be the length of a complete instrumental calibration cycle. The drift residual term is an rms residual, after subtraction of any linear trend over the specified time period. It is desirable to meet the drift requirements over longer intervals so as to allow longer calibration cycles; a goal is to meet the delay/phase drift requirement on time scales of 1000 sec.
2. The phase noise specification should be integrated over the frequency range 1 Hz to 100 kHz.
3. The temporal delay/phase error allocation to "Antenna Structure" refers to the mechanical structure of the antenna, and arises from wind or thermal distortions of the antenna. The delay error is a function of the direction of the incident wave front and direction of the antenna distortion.
4. Phase noise is only allocated to the final oscillators in the system that are used for down conversion or data sampling. Note that the digitizer clock stability will scale proportional to the frequency down conversion, so the required stability of the actual digitizer clock for a 7 GHz baseband would be approx.: 76 fsec * 120 GHz/7 GHz = 1.3 psec.
5. It is assumed that the RTP system will provide slow corrections only, and that the phase noise of the LO distribution system will be largely eliminated by the narrow bandwidth of the PLL for the antenna LO. The antenna structure retains a contribution due to wind induced stochastic oscillations/jitter.
6. Allocations are an arbitrary equal allocation for contributing system elements. This should be revised based on further analysis and technical feasibility.
7. The phase drift specified exceeds the frequency stability of an active hydrogen maser: frequency stability of order to 10^{-14} equates to phase rms of 3 psec. Providing a coherent frequency reference over the main array scales described in SYS1301 (420 km extent) is required. Sensitivity on the longest baselines is relaxed to account for separate frequency references at each site.

If the Total Instrumental Error delay/phase noise requirement is met, the expected coherence of an interferometer pair is given in Table 6 at various observing frequencies. Note that these values do not include the contributions of the atmosphere.

Frequency	Coherence
1 GHz	99.99%
10 GHz	99.98%
50 GHz	99.48%
70 GHz	98.98%
120 GHz	97.04%

Table 6 - Expected coherence as a function of frequency.

The coherence is given by $C = e^{-\sigma^2/2}$ where σ is the rms phase error, in radians, of a pair of antennas, i.e. $\sqrt{2}$ times the error contribution of a single antenna. A single antenna's contribution is estimated as the RSS sum of the Phase Nose and Phase Drift Residual.

6.4.1 Calculating Delay/Phase Noise and Drift

When verifying performance to system or subsystem delay/phase noise and drift specifications, the following formalism shall be used.

The short period delay/phase **noise** requirement refers to the rms deviation delay/phase from a 10-sec average. The requirement applies to the integrated phase noise from the highest significant frequency (~1 MHz) down to 1 Hz.

The delay/phase **drift** requirement refers to the two-point Allan Standard Deviation with a fixed averaging time, τ, of 10 seconds and intervals, *T*, between 20 and 300 seconds:

$$\sigma^2(2, T, \tau) = 0.5 * \langle[\varphi_\tau(t+T) - \varphi_\tau(t)]^2\rangle$$

where φ_τ is the average of the absolute or differential phase over time τ = 10 seconds and $\langle[\varphi_\tau(t+T) - \varphi_\tau(t)]^2\rangle$ means the average over the data sample, which should extend to 10 or 20 times the largest value of the sampling interval *T* that is used.

Note that this usage of the name "Allan variance" and other related terms is somewhat non-standard. Strictly speaking, the Allan variance refers to the two-sample variance of fractional frequency and was introduced by David Allan in his studies of oscillator stability. Here the same formalism is used and the name Allan variance extended to mean the two-sample variance of phase and of gain.

6.5 *Allocation of Gain Stability Requirements*

Parameter	Req. #	Value	Traceability
LNA Gain Fluctuations w/ Temperature	SYS4901	The gain fluctuations as a function of temperature ((1/G) dG/dT) for cryogenic LNAs shall not exceed 0.03/K.	SYS1601, SYS4601
Warm Electronics Gain Fluctuations w/ Temperature	SYS4902	The gain fluctuations as a function of temperature ((1/G) dG/dT) for the warm electronics, from Dewar interface to the digitizer, shall not exceed 0.01/K.	SYS1601, SYS4601
Dewar Temperature Regulation	SYS4903	Magnitude of variations on second stage not to exceed 0.03 K over 200 seconds.	SYS1601, SYS4601

Parameter	Req. #	Value	Traceability
Warm Electronics Temperature Regulation	SYS4904	Magnitude of variations not to exceed 0.1 K over 200 seconds.	SYS1601, SYS4601

As described in Section 5.18, gain stability of 1e-3 is required over short (200 second) timescales (SYS1601, SYS4601). Typical gain fluctuations as a function of temperature ((1/G) dG/dT) for LNAs are of order 0.03/K for cryogenic devices and 0.01/K for warm devices.

To achieve dG/G of 1e-3 would require thermal regulation to 0.03 K within the Dewar and to 0.1 K for warm devices over 200-second scales.

These requirements can be traded against each other while still achieving the L1 requirements (SYS1601, SYS4601).

The inclusion of a gain calibration noise source has reduced the period over which this stability is required to 200 seconds as described in Section 5.18.3. This noise source, and any intervening electronics between the noise source and the coupler, must be stable to 1e-3 over 20-minute periods. This 20-minute period corresponds to the expected gain calibration cycle on astronomical sources.

6.6 Bandpass Requirements

Parameter	Req. #	Value	Traceability
Bandpass Stability	SYS1701	The bandpass amplitude shall be stable to 0.3% over 60 minutes. (TBC)	SCI0115, SYS1061
Bandpass Ripple	SYS1702	The analog bandpass ripple across a digitized band shall be constrained to less than 3 dB peak to peak.	SYS1033
Bandpass Flatness	SYS1703	The bandpass of an individual digitized band shall have slope no greater than 3 dB, measured across 80% of the bandwidth.	SYS1033
Sideband Separation	SYS1704	The sideband separation in any dual-sideband frequency conversion system shall be better than 30 dB. Goal of 40 dB separation.	SCI0115, SCI0113, SCI0116, SYS2104

The stability requirement is closely related to the spectral line performance as well as the imaging dynamic range. Both specifications require stable gains as a function of time. The bandpass ripple and flatness specifications are constrained to maintain the minimum effective number of bits of the sampler over the full sampled frequency band.

The sideband separation specification will need to support the spectral dynamic range requirement and imaging fidelity requirement. For spectrally flat sources, the effects would be minimal, but for sources with spectral structure, inadequate sideband separation could introduce both bandpass errors and imaging errors. A full 50 dB of separation for spectral line observations is not required since fringe washing will provide ~20 dB of attenuation of emitting sources in the field. LO offsets or sampler clock offsets could provide a further ~20 dB of attenuation.

6.7 Triggered Observation Requirements

Parameter	Req. #	Value	Traceability
Trigger Response Time Allocations	SYS5101	The trigger response time allocations for major activities shall be consistent with Table 7.	SYS3005

The control system will need ports to receive and process external triggers to meet SYS3004–SYS3005. The response time desired limits human intervention/assessment, so the system should process them automatically. Table 7 shows the budget for response time (typically meeting the 3-minute goal of SYS3005.

Action	Time Allocation	Cumulative Time	Notes
Reception of External Trigger	1 sec	1 sec	
Termination of Current Scheduling Block	20 sec	21 sec	
System Setup to New Scheduling Block	20 sec	41 sec	
Antenna Slew To Source	2 min max	161 sec	@ 90-deg/min Az., 45 deg/min El.; ignores acceleration time.
Antenna Settle Time	10 sec max	171 sec	
Receiver Band Selection	20 sec max	181 sec	during slew

Table 7 - Triggered response time budget.

The time budget above imposes the following subsystem requirements:

- Antenna slew rates of 90-deg/min in Azimuth and 45 deg/min in Elevation.
- Antenna settling time of 10 sec maximum.
- Requirement to permit band selection during an antenna slew. Impact on electrical system size.
- A scheduling block should be limited to 20 seconds and/or be interruptible by the control system.

7 Technical Performance Measures

This section provides the Technical Performance Measures (TPMs) that should be monitored throughout the design and development phase of the project. These are parameters that have a high influence on the eventual effectiveness of the facility, and are useful high-level metrics for trade-off decisions.

These parameters may also be useful for determining the relative priority of the requirements documented in Section 5, and can assist in the required analysis should tensions be identified between requirements, or reductions in capability be required to fit within cost constraints.

7.1 Definitions

Key Performance Parameters (KPPs): The most essential parameters to achieving the key science goals. These are capabilities or characteristics so significant that failure to reach the threshold value of performance can cause the system concept to be reevaluated, or even the program to be reassessed or terminated. Must have a threshold and an objective value. In a trade-study, everything can be traded-off except a KPP.

Measures of Effectiveness (MoEs): How well an astronomical observation is accomplished; can be expressed on a scale with no fixed threshold. Examples for ngVLA include sensitivity as a function of time, or survey speed.

Measures of Performance (MoPs): Components of, or contribute to, MoEs. An example of an MoP contributing to the MoEs above may be collecting area.

7.2 Key Performance Parameters

See ngVLA Science Requirements [AD01] for the KPPs associated with each Key Science Goal (KSG).

7.3 Measures of Effectiveness

Table 8 gives the measures of effectiveness identified for monitoring throughout the design phase.

Measures of Effectiveness	Req. #
Surface Brightness Sensitivity: Continuum	SCI0100
Surface Brightness Sensitivity: Spectral Line	SCI0102
Point Source Sensitivity: Continuum	SCI0100
Point Source Sensitivity: Spectral Line	SCI0102
Survey Speed	SCI0106
Largest Angular Scale	SCI0104
Maximum Resolution	SCI0103

Table 8 - ngVLA measures of effectiveness.

As estimates of each measure are updated, the impact on the KSGs identified in AD01 should be assessed.

7.3.1 Surface Brightness Sensitivity: Continuum

Surface brightness sensitivity expresses the array sensitivity scale in terms of the brightness temperature (in K) of an astronomical source that can be detected at a given angular resolution. Surface brightness sensitivity is highest when the aperture fill ratio (ratio of collecting area within a given array extent) is highest, and therefore changes as a function of angular scale.

This parameter can be explored two ways: either by fixing the surface brightness of the source and solving for the maximum angular resolution, or by solving for the source brightness that is detectable at a fixed angular scale.

The first case is most applicable from the scientific perspective. The distribution of targets in the sky as a function of temperature is relatively well known from surveys, so solving for the angular resolution gives an indication of the imaging performance of the array for the source of interest by defining the angular scale that fully exploits the array sensitivity.

Brightness temperatures should be explored on a logarithmic scale. Frequency and integration time must be fixed. For this analysis, one hour of observing time shall be used for all cases, at five frequencies of interest, as shown in Table 9 (which provides a template for recording this data).

Surface Brightness (Tb)	**Max. Resolution as a function of Frequency**				
	2 GHz	**10 GHz**	**30 GHz**	**80 GHz**	**100 GHz**
10^{-3} K					
10^{-2} K					
10^{-1} K					
10 K					
10^{2} K					
10^{3} K					
10^{4} K					
10^{5} K					

Table 9 - Example tracking table for SB sensitivity.

7.3.2 Surface Brightness Sensitivity: Spectral Line

This is similar to continuum surface brightness sensitivity but at fixed channel bandwidth corresponding to a spectral resolution, expressed as a velocity. This gives an accurate estimate of the brightness temperature of sources that can be investigated for spectral features at a given spectral resolution and frequency. As with continuum surface brightness sensitivity, it changes as a function of spectral resolution. The parameter will be fixed at 10 km/s spectral resolution for an observation of one hour. It is expressed in K, as a function of time, spectral resolution, and frequency (e.g., 0.3 K/hr @ 10 km/s @ 1 cm).

7.3.3 Imaging Sensitivity: Continuum

Imaging continuum sensitivity represents the rms noise of the synthesized beam, measured in units of Janskys/beam. As with other metrics, the rms decreases (improves) as a function of the square root of the number of samples, so a fixed observing time must be given. A one-hour observation will be used. Bandwidth will be based on the available bandwidth of the receiver containing the point frequency in question (most relevant if the center frequencies of the bands are used). It shall be parameterized as a function of frequency and angular scale, while meeting the beam quality metrics established in the Science Requirements.

7.3.4 Imaging Sensitivity: Spectral Line

Spectral line sensitivity relates closely to continuum sensitivity, but the bandwidth is limited by a given desired spectral resolution. A one-hour integration time and 10 km/s spectral resolution will be used in all cases. This figure has merit, compared to the point source continuum sensitivity, when deciding on the trade-off between various receiver configurations, since the fixed bandwidth makes this measure very sensitive to changes in illumination efficiency or system temperature.

7.3.5 Continuum Survey Speed

When mapping large areas, the FOV that can be imaged is important in addition to the continuum sensitivity. Rather than express the FOV, a survey speed is a more relevant parameter for mapping large areas at a given noise level. A 10 μJy continuum sensitivity limit will be used for this measure, expressed in deg^2/hr as a function of observing frequency.

Bandwidth will be based on the available bandwidth of the receiver containing the point frequency in question (most relevant if the center frequencies of the bands are used). It shall be parameterized as a function of frequency and angular scale, while meeting the beam quality metrics established in the Science requirements.

7.3.6 Largest Angular Scale

Interferometers are insensitive to large-scale structures since they are "resolved out" by the instrument. The largest angular scale that can be detected by the interferometric array is dictated by the shortest baseline. Expressed in arcsec, this parameter provides an indication of this fundamental limit, and the feasibility of combining the collected data with maps from other arrays or single dishes. Largest angular scale should be expressed as a function of frequency.

7.3.7 Maximum Angular Resolution

The maximum angular resolution that can be resolved by the array is dictated by the longest baselines present in the array. It will change as a function of frequency.

7.4 Measures of Performance

Table 10 lists Measures of Performance that support the MOEs above and have been identified for monitoring.

Measures of Performance	Req. #
Effective Aperture/T_{sys}	SYS1001
Distribution and Weighting of Visibilities	SCI1308
Observing/Calibration Efficiency	SYS1061
Instantaneous FOV (FWHM)	SYS1101
B_{MIN}	SYS1302
B_{MAX}	SYS1301

Table 10 - ngVLA measures of performance.

Interpretation notes for each are enumerated in the subsections below.

7.4.1 Effective Aperture/System Temperature

This measure indicates the sensitivity of the array independent of angular scale. It is most useful for engineers since it directly relates to the total collecting area, aperture efficiency, digital system efficiency, and system temperature.

All signal path efficiency measures shall be included in determining the effective aperture, including analog and digital system losses. However, calibration system losses will be excluded since they are not as easily quantifiable and are captured separately. Expressed in m^2/K, this parameter allows for easy trade-offs between efficiencies and noise performance.

7.4.2 Distribution and Weighting of Visibilities

The distribution and weighting of visibilities dictates the effective sensitivity of the array after beam sculpting. When combined with the previous estimates of sensitivity, the distribution and weighting of visibilities can be used to compute practical imaging sensitivity as a function of time on source. The weighting of visibilities shall be given over angular scale while supporting the beam quality metric laid out in the Science Requirements document.

7.4.3 Observing/Calibration Efficiency

The calibration efficiencies are the final MOP that allows an engineer to estimate the effective imaging sensitivity of the array as a function of wall clock time, not just time on source. When combined with the raw sensitivity metrics and the distribution and weighting of visibilities, the calibration efficiency allows the estimation of efficiency in typical observations and the projected scheduling time required for a suite of observations using standard observing modes.

This measure is intended to represent the likely calibration overheads in a standard observing mode. The goal is to reduce the time allocated to calibration while maintaining system performance. While actual observing efficiency will vary on a use case by use case basis, relative improvements in this parameter should broadly improve efficiency for most use cases.

Standard observing modes that should be parameterized for this MOP include full beam, full band, continuum observation at the standard frequencies used for the MOEs (2 GHz, 10 GHz, 30 GHz, 80 GHz, 100 GHz) and employing the full range of resolution of the array. Total observation time shall be one hour, to allow for combination of this efficiency factor with other metrics identified in this document.

The following calibration overheads shall be included:

- Phase
- Gain and Bandpass
- Relative Flux scale

Further assumptions that will be used for this estimation include:

- Observation shall traverse the meridian, at a declination of 0 degrees.
- All calibrators shall be 1 Jy sources.
- All calibrators shall be 2 degrees from the science target.

With a one-hour observation window, there is scope to improve both the time spent on each calibrator as well as the major cycle time between calibrator visits. Changes in either parameter will be apparent in the observing efficiency.

8 Verification

The design may be verified to meet the requirements by design (D), analysis (A) inspection (I), a demonstration (DM), or a test (T). The definitions of each are given below.

Verification by Design: The performance shall be demonstrated by a proper design, which may be checked by the ngVLA project office during the design phase by review of the design documentation.

Verification by Analysis: The fulfillment of the specified performance shall be demonstrated by appropriate analysis (hand calculations, finite element analysis, thermal modeling, etc.), which will be checked by the ngVLA project office during the design phase.

Verification by Inspection: The compliance of the developed system is determined by a simple inspection or measurement.

Verification by Demonstration: The compliance of the developed feature is determined by a demonstration.

Verification by Test: The compliance of the developed system with the specified performance shall be demonstrated by tests.

Multiple verification methods are allowed.

8.1 L1 System Requirements

The following table summarizes the expected verification method for each requirement. Separate verification procedures should be developed as part of the verification plan to elaborate on the verification strategy for each requirement, especially those that require analysis or tests.

The order of requirements in the table corresponds to the order in which they are found in Section 5.

Req. #	Parameter/Requirement	D	A	I	DM	T
SYS0001	Functional Modes	*				
SYS0002	Interferometric Mode				*	
SYS0003	Phased Array Mode				*	
SYS0004	Pulsar Timing Mode				*	
SYS0005	Pulsar and Transient Search Mode				*	
SYS0006	VLBI Mode				*	
SYS0007	Total Power Mode				*	
SYS0008	On the Fly Mapping Mode				*	
SYS0009	Solar Observing Mode				*	
SYS0202	Concurrent Interferometric and Phased Array Mode				*	
SYS0601	Sub-Array Capabilities				*	
SYS0603	Sub-Array Composition				*	
SYS0604	Sub-Array Operating Modes				*	
SYS0605	Sub-Array Operating Mode Commensality		*		*	
SYS0602	Phase Preservation					*
SYS0606	Sub-Array Configuration				*	
SYS0101	Variable Spectral Resolution				*	
SYS0102	Polarization Products				*	
SYS0103	Autocorrelation Products				*	

Req. #	Parameter/Requirement	D	A	I	DM	T
SYS0104	Commensal Processing			*		
SYS0201	Phased Aperture					*
SYS0203	Number of Beams				*	
SYS0301	Timing Capabilities			*		
SYS0302	Timing Sys. Bandwidth				*	
SYS0303	Timing Sys. Frequency Resolution				*	
SYS0304	Pulse Profile Bins				*	
SYS0305	Polarization				*	
SYS0306	Pulse Period					*
SYS0307	Dump Rate				*	
SYS0401	Search Capabilities			*		
SYS0402	Search Sys. Bandwidth				*	
SYS0403	Search Sys. Frequency Resolution				*	
SYS0404	Search Sys. Time Resolution				*	
SYS0405	Polarization				*	
SYS0501	VLBI Recording Capabilities				*	
SYS0502	eVLBI Capabilities		*			
SYS3001	Standard Observing Modes	*				
SYS3002	Number of Standard Observing Modes		*			
SYS3003	Non-Standard Observing Modes				*	
SYS3004	Triggered Observations	*				
SYS3005	Triggered Observation Response		*			
SYS3006	Trigger Time-Out				*	
SYS0701	Uncalibrated Data			*		
SYS0702	Flagged Data Table			*		
SYS0703	Calibrated Data Table			*		
SYS0721	Imaging Pipeline					*
SYS0741	Pulsar Timing Data Product	*				
SYS0741	Pulsar Search Data Product	*				
SYS0731	Archive Period		*			
SYS0732	Archive Products	*				
SYS0733	Proprietary Data Rights			*		
SYS0738	Proprietary Period			*		
SYS0734	Archive Batch Reprocessing			*		
SYS0736	Archive User Reprocessing				*	
SYS0735	Archive Backup		*	*		
SYS0751	Data Processing Resources		*			
SYS0752	Throughput & Latency		*			
SYS0753	Heterogeneous Arrays				*	
SYS0761	Data Analysis Resources				*	
SYS0801	System Frequency Range	*				
SYS0802	Optimized Frequency Range	*				
SYS0803	Freq. Span A	*				
SYS0804	Freq. Span B	*				
SYS0805	Freq. Span C	*				
SYS0806	Continuity of Frequency Coverage				*	

Req. #	Parameter/Requirement	D	A	I	DM	T
SYS0901	Front End Bandwidth Ratio	*				
SYS0902	Instantaneous Digitized Bandwidth			*		
SYS0903	Total Instantaneous Processed Bandwidth					*
SYS0904	Sub-Bands	*				
SYS0905	Frequency Tunability				*	
SYS0906	Fixed Analog Tunings	*				
SYS0907	Sub-Band Step Size	*				
SYS0909	Contiguous Bandwidth				*	
SYS0908	Band Switching Time					*
SYS1001	Effective Area/Tsys Ratio		*			
SYS1101	Instantaneous Field of View		*			
SYS1102	Accessible Field of View		*			
SYS1103	Slew Rates		*			
SYS1104	Tracking Rates		*			
SYS1201	Input Dynamic Range					*
SYS1202	Gain Calibration System Dynamic Range	*				
SYS1203	Provision of Variable Attenuators	*				
SYS1204	Input Protection	*	*			
SYS1205	High-Noise Path	*				
SYS1301	Longest Baseline	*				
SYS1302	Shortest Baseline	*				
SYS1303	Zero Spacing/Single Dish Total Power	*				
SYS1304	Integration Time Ratios		*			
SYS1306	Fraction of Occupied Cells		*			
SYS1308	Distribution and Weighting of Visibilities		*			
SYS1401	Highest Spectral Resolution	*				
SYS1402	Number of Spectral Channels	*				
SYS1403	Flexible Spectral Resolution	*				
SYS1404	Doppler Corrections				*	
SYS1501	Delay/Phase Variations Magnitude		*			
SYS1502	SNR Loss to Delay/Phase Variations		*			
SYS1503	Phase Noise		*			*
SYS1504	Phase Drift Residual		*			*
SYS1505	Absolute Phase Drift		*			*
SYS1601	TP Antennas: Gain Stability		*			*
SYS1603	TP Antennas: Gain Variations with Antenna Pointing Angle		*			*
SYS1604	TP Antennas: System Temperature Stability over Time		*			*
SYS1605	TP Antennas: System Temperature Variations with Antenna Pointing Angle		*			*
SYS1801	TP Antennas: Gain Calibration Reference		*			*
SYS4601	Interferometric Antennas: Gain Stability		*			*
SYS4602	Interferometric Antennas: Relative Gain Stability		*			*

Req. #	Parameter/Requirement	D	A	I	DM	T
SYS4603	Gain Variations with Antenna Pointing Angle		*			*
SYS4801	Gain Calibration Reference		*			*
SYS1061	Calibration Efficiency		*			
SYS1062	Calibration Parallelization	*				
SYS1063	Calibration Recall	*				
SYS1064	Relative Flux Scale Calibration Efficiency					*
SYS1065	Polarization Calibration Efficiency					*
SYS1066	Bandpass Calibration Efficiency					*
SYS1067	Gain Calibration Efficiency		*			
SYS1068	Phase Calibration Efficiency		*			
SYS1901	Polarization Purity		*			*
SYS2001	Temporal Resolution			*		
SYS2002	Temporal Accuracy		*			
SYS2104	Self-Generated Spurious Signal Power Level		*			*
SYS2105	LO Frequency and Sampler Clock Offsets				*	
SYS2106	Shielding & Emission Limits		*			*
SYS2201	Provision of Software Tools	*				
SYS2202	Provision of Computing Resources		*			
SYS2301	Operations Concept	*				
SYS2302	Observation Scheduling				*	
SYS2303	Calibration Automation				*	
SYS2304	Self-Calibrating Antenna	*				
SYS2401	Antenna Maintenance Interval		*			
SYS2402	Antenna MTBF		*			
SYS2403	Modularization	*				
SYS2404	Central Repair Facility	*				
SYS2405	Predictive and Self-Diagnostic function				*	
SYS2501	Weather Monitoring			*		
SYS2502	Safety Weather Monitoring			*		
SYS2601	Antenna System Availability		*			
SYS2602	Centralized Systems Availability		*			
SYS2701	Subsystem self-monitoring	*				
SYS2702	IT Security			*		
SYS2703	Hazard Analysis			*		
SYS2801	Design Life		*			
SYS2802	Cost Optimization		*			

8.2 L2 System Requirements

The following table summarizes the expected verification method for each requirement. Separate verification procedures should be developed as part of the verification plan to elaborate on the verification strategy for each requirement, especially those that require analysis or tests. The order of requirements in the table corresponds to the order in which they are found in Section 6.

Req. #	Parameter/Requirement	D	A	I	DM	T
SYS1021	System Geometric Collecting Area	*				
SYS1011	Maximum T_{SYS} in Freq. Span A:		*			*
SYS1012	Maximum T_{SYS} in Freq. Span B:		*			*
SYS1013	Maximum T_{SYS} in Freq. Span C:		*			
SYS1031	Antenna Efficiency: Precision Environment		*			*
SYS1032	Antenna Efficiency: Normal Environment		*			*
SYS1033	Minimum Interferometer Digital System Efficiency		*			
SYS1034	Minimum Digital Quantization Levels: Narrow Bandwidths (<5GHz)	*				
SYS1035	Minimum Digital Quantization Levels: Wide Bandwidths (>5GHz)	*				
SYS1036	Correlator Precision	*				
SYS5001	Allocation of Delay/Phase Noise & Drift		*			*
SYS4901	LNA Gain Fluctuations w Temperature					*
SYS4902	Warm Electronics Gain Fluctuations w/ Temperature					*
SYS4903	Dewar Temperature Regulation		*			*
SYS4904	Warm Electronics Temperature Regulation		*			*
SYS1701	Bandpass Stability					*
SYS1702	Bandpass Ripple			*		
SYS1703	Bandpass Flatness			*		
SYS1704	Sideband Separation					*
SYS5101	Trigger Response Time Allocations		*			*

9 Appendix

9.1 Abbreviations & Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter/submillimeter Array
AST	Division of Astronomical Sciences (NSF)
BW	Band Width
CDL	Central Development Laboratory
CSIRO	Commonwealth Scientific and Industrial Research Organization
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
EIRP	Effective Isotropic Radiated Power
EMC	Electro-Magnetic Compatibility
ENOB	Effective Number of Bits
FOV	Field of View
FWHM	Full Width Half Max
HPC	High Performance Computing
HVAC	Heating, Ventilation & Air Conditioning
IF	Intermediate Frequency
KPP	Key Performance Parameters
KSG	Key Science Goals
LO	Local Oscillator
MoE	Measure of Effectiveness
MoP	Measure of Performance
MREFC	Major Research Equipment and Facilities Construction (NSF)
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PLL	Phase Locked Loop
PSD	Power Spectral Density
PWV	Precipitable Water Vapor
RD	Reference Document
RFI	Radio Frequency Interference
rms	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SEFD	System Equivalent Flux Density
SKA	Square Kilometer Array
SWG	Science Working Group
SNR	Signal to Noise Ratio
SRDP	Science Ready Data Products
TBC	To Be Confirmed

TBD	To Be Determined
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer

9.2 Derivation Notes from the Level-0 Science Requirements

Derivations that support the science requirements are aggregated here. Information is duplicated from the main text but reorganized to better show the traceability to individual science requirements.

9.2.1 Functional Requirements

Parameter	Req. #	SciCase	Value
Frequency Coverage	SCI0001	All	The ngVLA should be able to observe in all atmospheric windows between 1.2 and 116 GHz. These frequency limits are bracketed by spectral line emission from H_I and CO respectively.

This functional requirement translates directly, requiring continuous frequency coverage from 1.2 GHz to 50 GHz, and from 70 GHz to 116 GHz (Figure 3). The 50 GHz and 70 GHz boundaries are soft, based on the atmospheric temperature and opacity of the O2 line. The band edges should be set by practicalities in the receiver design.

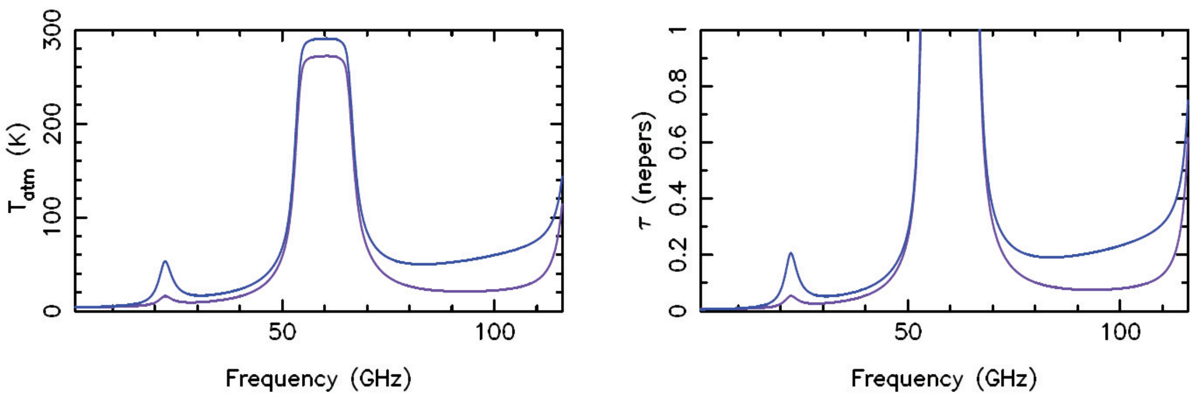

Figure 3 - Atmospheric temperature and opacity for wet (blue) and dry (purple) conditions. [RD11]

Parameter	Req. #	SciCase	Value
Observing Bands	SCI0002	KSG2-003, KSG3-003	ngVLA observing band edges should in all possible cases avoid astronomically interesting spectral lines for redshifts between z=0 and z=0.1. Overlap of 1% in band edges is therefore desirable.

The dominant requirement here is continuous frequency coverage with overlap of 1% at the band edge for all band transitions; i.e. a transition at 3.5 GHz would have a minimum overlap of 35 MHz. Meeting this requirement may require that any direct sampling architectures include variable sample rates to mitigate "dead zones" near the Nyquist zone boundaries.

In avoiding "astronomically interesting" spectral lines at band edges, the table in the AD01 Appendix lists spectral lines at z=0 below 50 GHz that should be avoided in verification of this requirement.

Parameter	Req. #	SciCase	Value
Front End Selection	SCI0003	KSG1-001, KSG1-004, KSG2-003, KSG3-002, KSG3-003	The system shall support full bandwidth selection of the front end(s) without gaps in frequency coverage that are instantaneously available. Selectable bandwidth steps may be discrete if necessary. Observing multiple line diagnostics within a single band is also desirable.

This is interpreted as requiring the capability to digitize and process an arbitrary bandwidth (trade-off with spectral resolution) that is accessible from the front end.

In an architecture that digitizes the full RF bandwidth, this implies bandwidth selection in a digital back end/formatter at the antenna, or in the correlator. Any digital band selection will use selectable, discrete bandwidth steps, which is permissible.

Selection of discontinuous sub-bands for Band 6 (which is wider than 20 GHz) would of necessity be selected before the DTS system, placing part of this bandwidth selection requirement on the digital back end/formatter at the antenna.

Parameter	Req. #	SciCase	Value
Mosaics and On-the-Fly Mapping	SCI0004	KSG3-010, KSG5-006, KSG5-007	The system shall support both mosaicking and on-the-fly mapping of larger fields of view with full spectral capabilities in support of the survey speed requirement (SCI0106).

Mosaics do not appear to impose any unique requirements upon the system beyond those of discrete pointings.

On-the-fly (OTF) mapping may have a number of flow-down requirements:

- Tracking rate and pointing error allowed by the ACU at super sidereal rates.
- Need for a functional mode for OTF in the ACU.
- Delay model management and update rate to support the tracking rate of the antenna.
- Minimum dump rate/integration period of the long-term accumulators in the correlator to support the tracking rate of the antenna.
- May set a minimum data rate between the correlator and archive (archive ingest rate.)

Of the survey speed cases described in SCI0106, the most demanding is a shallow survey to 10 μJy @ 28 GHz. The system must complete a single field of view (primary beam) in approximately 4.3 seconds. The delays must be updated as the antenna traverses 1/10th of a beam, resulting in 400-msec update rates for delays. Visibility data integration/accumulation is limited to the same rate, and a 400-msec rate limits time and bandwidth smearing appropriate for a 300 km aperture, well in excess of the natural beam width which is equivalent to ~165 km baselines.

At lower frequencies, the antenna scanning rate can become limiting. Supporting 10x sidereal rates on the motion control loop ensure the feasibility of shallow, fast surveys at low frequency.

Parameter	Req. #	SciCase	Value
Triggered Observations	SCI0005	KSG5-008	The array shall have a mechanism to receive and rapidly respond to external triggers. Triggered response times not to exceed ten minutes are required for transient science, while response times of three minutes are desired.

The control system will need to have ports to receive and process external triggers. The response time required will likely preclude human intervention/assessment, so it is preferred that the system process them in an automated fashion. Table 11 shows the approximate time budget for response time:

Action	Time Allocation	Cumulative Time
Reception of External Trigger	1 sec	1 sec.
Termination of Current Scheduling Block	20 sec.	21 sec.
System Setup to new Scheduling Block	20 sec.	41 sec.
Slew To Source	2 min max (@ 90-deg/min Az., 45 deg/min El. Ignores Acceleration time.	161 sec.
Settle Time	10 sec. max.	171 sec.
Band Selection	20 sec. max. (during slew)	181 sec.

Table 11 – Triggered response time budget.

The time budget above imposes the following requirements:

- Antenna slew rates of 90 deg/min in Azimuth and 45 deg/min in Elevation.
- Antenna settling time of 10 sec max.
- Requirement to permit band selection during an antenna slew. Impact on electrical system size.
- The time of a scheduling block should be limited to 20 seconds and/or be interruptible by the control system.

Parameter	Req. #	SciCase	Value
Observing Modes	SCI0006	All	System shall observe in both narrow (spectral line) and wide-band (continuum) modes simultaneously. Goal to maximize flexibility and sensitivity of both modes. This does not preclude a single configurable 'mode' that meets the requirements of both general use cases.

Continuum observations shall have sufficient spectral resolution to mitigate time-bandwidth smearing effects when imaging the full field of view at the lowest operating frequency of the array (1.2 GHz). The acceptable time and bandwidth smearing, β, will be assumed to be 0.5, where:

$$\beta = \frac{\Delta\nu}{\nu}\frac{d\theta}{\theta_{beam}} = \delta\omega_{earth}\frac{d\theta}{\theta_{beam}} = 0.5$$

A more rigorous quantification of beta should be based on the required imaging fidelity, depending on source and field structure. Beta of 0.5 is used as a starting point. With an 18m aperture and baselines of 1000 km in the main array, at 1.2 GHz, $\Delta\nu$ is approximately 10 kHz. At a bandwidth ratio of 3:1, this would require of order 240k channels.

The flexibility goal will be interpreted as a functional requirement for variable channel bandwidth, allowing for high spectral resolution near a spectral line of interest, with coarser spectral resolution over broader bandwidths as required for time and bandwidth smearing.

Parameter	Req. #	SciCase	Value
Phased Array Capability	SCI0007	KSG4-004, KSG5-004	System shall operate both as an interferometer and phased array simultaneously.

The commensal phased array and interferometric capabilities are a functional requirement imposed on the central signal processor of the array. Given other parameters of the system, it is assumed to require this capability over the main array aperture diameter (~1000 km), with the phased beam offset from the boresights anywhere within the antenna main beam.

The commensal interferometric capability is understood to ideally be at the full spectral resolution of the correlator. Any channelization of the beamforming mode is assumed to be post-beamforming in the commensal mode.

Parameter	Req. #	SciCase	Value
Beam Forming	SCI0008	KSG4-004, KSG5-003	The array shall have the ability to have multiple (minimum 10) beams (phase centers within the primary beam) within a single subarray, or distributed amongst multiple subarrays.

Parameter	Req. #	SciCase	Value
Sub-Array Capabilities	SCI0009	KSG5-003	System shall be divisible into multiple (i.e. at least 10) sub-arrays for operation and calibration purposes. All functional capabilities listed above should be available in a sub-array.

The combination of SCI008 and SCI009 suggest total beamforming capabilities of at least ten beams in aggregate. It would be desirable to have many more.

Combinations of functional capabilities between concurrent sub-arrays must be looked at closely because commensality of modes could be a design complexity/cost driver.

Parameter	Req. #	SciCase	Value
Sub-Array Commensality	SCI0010	N/A	Sub-arrays will need to concurrently function in different observing modes, and should be supported at their full specification. In particular, full-bandwidth cross-correlation must be supported in a sub-array, concurrent with phased-array and time-domain search capabilities in a separate subarray.

Meeting the full flexibility of SCO0009 could significantly impact the CSP design.

A reference observing program shall be developed showing allowable functional combinations of resources for the central signal processor. This requirement may prove expensive to meet, and may require a high degree of redundant resources within the correlator, but should be reconsidered once the impact is understood.

An attempt has been made to identify required commensal modes, and their expected practical limitations, shown in Table 1.

Parameter	Req. #	SciCase	Value
Pulsar Timing Capabilities	SCI0012	KSG4-001 KSG4-005, KSG5-003, KSG5-005	Timing multiple pulsars within a single primary beam is required. Support for 5 or more independent de-dispersion and folding threads is desired.

This imposes a functional requirement for a pulsar timing system that can support de-dispersion and folding for five beams over full receiver bandwidths. It is assumed that this requirement is only applicable to bands below ~20 GHz, limiting the bandwidth processed by this system to of order 8 GHz.

Parameter	Req. #	SciCase	Value
Time Domain Search Capabilities	SCI0013	KSG4-001 KSG5-009	System shall provide time-domain transient search capabilities on 100 μs scales in the phased array mode, with 20 μs scales desired.

This requirement is assumed to apply to phased-array modes only. Requires a blind/incoherent search capability, with a temporal resolution of 20–100 μs, and may require this capability over multiple beams. Given SCI0008, SCI0009, and SCI0010, a minimum of ten beams would have to be recorded or processed in real time. Multi-beam processing in search mode will be necessary to search a field in a practical time as outlined in [AD11], so processing more beams would be desirable.

Recording or real-time search must process 8 GHz of bandwidth per beam (maximum front end bandwidth below ~20 GHz), with a goal of processing 20 GHz per beam. See [AD11] for further elaboration of supporting requirements.

Parameter	Req. #	SciCase	Value
Timing Capabilities	SCI0014	KSG4-001, KSG5-005	The system shall provide transient timing capabilities with resolution of order 20 μs.

This requirement is for coherent timing modes. See [RD17] for further elaboration of supporting requirements.

Parameter	Req. #	SciCase	Value
Polarization Products	SCI0015	KSG1-004, KSG3-011	System shall measure all polarization products simultaneously.

Correlator must process parallel-hands and cross-hands simultaneously to produce the four Stokes polarization products.

Parameter	Req. #	SciCase	Value
Solar Observation Capabilities	SCI0016	N/A	It shall be possible to observe the Sun at all available frequencies.

This functional requirement will depend to some degree on the definition of the Sun, given the large differences in output power as a function of solar activity. For the quiet Sun at 5780K and a system temperature of order 30K, the implied analog dynamic range is of order 23 dB. With an antenna SEFD of order 300 Jy and an active Sun definition of 10^8 Jy, an analog dynamic range of 55 dB would be required for the active Sun.

To meet the sensitivity requirements for the array, no additional RF components shall be introduced in front of the first gain stage (LNA). The analog dynamic range of the receiving elements shall have a minimum of 30 dB of headroom with a goal of 50 dB. The former will support observations of the Sun under most conditions but would rely on offset antenna pointing for an additional 20 dB of signal attenuation (e.g., Sun in first side lobe).

Variable attenuation prior to the digitizer shall also have a range of 50 dB.

Any calibration strategy should also accommodate this change in source flux, so any calibration system injection requires a variable input power of at least 30 dB.

These dynamic range requirements are understood to be most applicable at lower frequency (Bands 1 and 2), with source flux for the active Sun having a frequency slope that reduces the power at high frequency.

Parameter	Req. #	SciCase	Value
VLBI Capabilities	SCI0017	KSG5-002	It shall be possible to use the system for VLBI observations with a single element, or phased array output, at all available frequencies. Recording capabilities shall be included for a minimum of 3 beams (10 beams desired). Format should be compatible with expected VLBI arrays.

This imposes a functional requirement for bandwidth and bit-rate selection on the phased-array modes, along with recording capabilities. Given the size of the array and resultant beam, it is necessary to record a minimum of three phased beams within a sub-array, permitting recording of both the science target and two calibrators simultaneously. Recording capabilities must match for all three beams (10 desired).

This capability should be viewed concurrently with the pulsar search capability requested in SCI0013. Recording demands for SCI0013 (if implemented as a post-processing capability) are likely more demanding than SCI0017 given expected VLBI observation bandwidths.

Parameter	Req. #	SciCase	Value
Multi-Frequency Observations	SCI0018	N/A	The system shall support either multi-frequency observations or rapid switching between bands. Switching time of order 10–20 seconds is desired.

This requirement will be met via rapid switching between bands, with a maximum switching time (worst case) of 20 seconds and a goal of typical band switching of ten seconds or less. Bands can be oriented in the Dewar to place expected multi-frequency complements in adjacent receiver cartridges.

Parameter	Req. #	SciCase	Value
Accessible Sky	SCI0019	All	The system shall be capable of observation from – 40° declination to 90° declination, ensuring adequate overlap with planned southern hemisphere arrays.

At the latitude of the VLA site (34° North) a declination of –40° is equivalent to a local elevation angle of 16°, where 0° is the local horizon and 90° is the local zenith. This imposes a maximum lower elevation limit for the antenna of order 12° in order to provide a minimal track length during an observation.

9.2.2 Performance Requirements

Parameter	Req. #	SciCase	Value
Continuum Sensitivity	SCI0100	KSG1-002	A continuum sensitivity of better than 0.02 μJy/bm at 30 GHz and 0.2 μJy/bm 100 GHz is required for studying protoplanetary disks.

This requirement bounds a number of system parameters. The ambiguity in allowable time will be resolved via the development of a reference observing program, but rough orders of magnitude will be developed here for context. Cases are shown below.

The System Equivalent Flux Density ($SEFD$) of a single antenna is computed as:

$$SEFD = 2\, k_B\, T_{sys}/(\, \eta_Q \eta_A\, A\,)$$

where k_B is Boltzmann's constant, η_Q is the digitizer quantization efficiency, η_A is the antenna efficiency, and A is the antenna's geometric collecting area.

The naturally weighted point source rms sensitivity is computed as:

$$\sigma_{NA} = SEFD/(\, \eta_C \sqrt[2]{N_{pol}\, \Delta\nu\, t\, N_{ant}\, (N_{ant} - 1)}$$

where η_C is the correlator efficiency (0.98), N_{pol} is the number of polarizations (2), $\Delta\nu$ is the bandwidth, t is the integration time in seconds, and N_{ant} is the number of antennas (214).

The weighted point source sensitivity is computed as:

$$\sigma_{rms} = \eta_{\text{weight}}\, \sigma_{NA}$$

9.2.2.1 *__Case A__: 0.02 μJy/bm @ 30 GHz:*

Assuming 214 18m apertures, with 0.85 aperture efficiency, 13.5 GHz of instantaneous bandwidth, T_{sys} of 33K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 110 hours on source.

Assuming η_{weight} of 0.5 increases integration time on source to of order 440 hours. <u>This is the most demanding of the identified sensitivity requirements.</u>

9.2.2.2 *__Case B__: 0.2 μJy/bm @ 100 GHz.*

Assuming 214 18m apertures, with 0.60 aperture efficiency, 14.0 GHz of instantaneous bandwidth, T_{sys} of 62K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in eight hours on source.

Assuming η_{weight} of 0.5 increases the integration time on source to of order 30 hours.

The 30 GHz requirement is appreciably more stringent and will be a limiting case for the array. Specifications for instantaneous bandwidth and A/T as a function of frequency can be derived from these two cases.

Instantaneous bandwidth is the simplest case, and should be set at a minimum to the available bandwidth with the 30 GHz receiver. This suggest a minimum of 14 GHz of instantaneous bandwidth. A goal of 20 GHz of bandwidth should be retained for consistency with previous messaging to the community.

A/T as a function of frequency requires a definition of time. We will arbitrarily set the maximum time on source to 100 hours for comparison to other cases. Using these parameters and instantaneous bandwidth of 14 GHz yields A/T values of 2947 m^2/K @ 30 GHz and 289 m^2/K at 100 GHz.

Parameter	Req. #	SciCase	Value
Line Sensitivity	SCI0102	KSG2-002, KSG3-001, KSG3-004, KSG3-005	A line sensitivity of 30 μJy/bm/km/s for frequencies between 10 and 50 GHz is required to support both astrochemistry studies and deep/blind spectral line surveys. A line sensitivity of 1–100 mK at 5"–0.1" angular resolution and 1–5 km/s spectral resolution between 70 and 116 GHz is required to simultaneously support detailed studies of CO and variations in gas density across the local universe.

The line width is computed as:

$$\Delta\nu = \Delta v / c$$

where the velocity resolution, Δv, and speed of light in a vacuum, c, are both in m/s.

Using the same input parameters as **Case A** (Section 9.2.2.1), we reduce the bandwidth to 1 km/s resolution at the center of the band (30 GHz). This restricts our channels to 100 kHz.

For a naturally weighted beam, the integration time on source is then of order seven hours. Assuming η_{weight} of 0.5 increases the integration time on source to of order 26 hours.

The most demanding case would be at 10 GHz since the specification is given in km/s, leading to narrow channels at the bottom of the specified range.

9.2.2.3 *Case C: line sensitivity of 30 μJy/bm/km/s at 10 GHz.*

Centered at 10 GHz, 1 km/s resolution would correspond to 33.3KHz channels. Assuming 214 18m apertures, with 0.77 aperture efficiency, T_{sys} of 25K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 14 hours on source.

Assuming η_{weight} of 0.5 increases integration time on source to of order 56 hours. If the integration time is held constant at 100 hours, the required A/T is 1,250 m²/K. Brightness temperature, in Kelvin, is computed as:

$$\sigma_{T_B} = 1.216\, \sigma_{rms} \,/\, \theta_{1/2}^2 / \, \nu^2$$

where σ_{RMS} is the point source sensitivity in μJy/bm, $\theta_{1/2}$ is the resolution (FWHM) of the synthesized beam in arcseconds, and ν is the center frequency in GHz. This is a simplification of:

$$\sigma_{T_B} = \left({c^2}/{2\, k_B\, \nu^2}\right)\left({\sigma_{rms}}/{\Omega_B}\right)$$

where $\Omega_B = \left({\pi}/{4\ln(2)}\right)\theta_{1/2}^2$ is the beam solid angle.

9.2.2.4 *Case D: Line sensitivity of 1mK at 5" angular resolution and 1 km/s spectral resolution at 90 GHz.*

1 km/s spectral resolution corresponds to 300 kHz. With 35% of the array contributing on 5" scales (η_{weight} of 0.35) 1mK brightness sensitivity is met with of order 4.2 hours on source.

9.2.2.5 *Case E: Line sensitivity of 100 mK 0.1" angular resolution and 5 km/s spectral resolution at 90 GHz.*

5 km/s spectral resolution increases our channel width to 1.5 MHz. With η_{weight} of 0.5, 100mK brightness sensitivity is reached in of order 254 hours on source. Significantly improving upon this performance would

require either increases in aperture efficiency (better dish surface), more antennas, or reductions in η_{weight} through improved imaging algorithms.

Since Case E is the most stringent 90–100GHz case, we will use this case to define the target A/T of the system at high frequency. We will arbitrarily set the maximum time on source to 100 hours. Using these parameters yields A/T values of 875 m^2/K at 90 GHz.

Parameter	**Req. #**	**SciCase**	**Value**
Angular Resolution	SCI0103	KSG1-001, KSG1-003, KSG5-001	A synthesized beam having a FWHM better than 5 mas with uniform weights is required at both 30 and 100 GHz.

The resolution (FWHM) of the longest baseline (B_{max}) is computed as:

$$\theta_{max} = k\lambda/B_{max}$$

If k = 0.6, 5 mas at 30 GHz corresponds to a baseline of order 687 km, setting a lower bound on the minimum extent of the array.

Parameter	**Req. #**	**SciCase**	**Value**
Largest Recoverable Scale	SCI0104	KSG1-006, KSG2-004, KSG3-009	Angular scales of >20" x (116 GHz/ν) must be recovered at frequencies ν < 116 GHz. A more stringent desire is accurate flux density recovery on arcminute scales at all frequencies.

Using the FWHM equation given above, 20" at 116 GHz suggests baselines shorter than 26 m are required. Cost modeling suggests the main array aperture should be relatively large (18–25 m) to meet the sensitivity targets, and minimum spacing requirements are of order 1.5 * D_{ANT} to avoid interference between antennas. This requirement will therefore be met by inclusion of a short baseline array (SBA) in the system architecture.

Note that a total power/single dish capability is not strictly required to recover the specified scales.

Parameter	**Req. #**	**SciCase**	**Value**
Spectral Resolution	SCI0105	KSG2-003	A spectral resolution of at least 0.1 km/s is required. It is desirable that this spectral resolution be available over a broad (4+ GHz) bandwidth.

A spectral resolution of 0.1 km/s, at 1.2 GHz, corresponds to a channel width of order 400 Hz.

At 3.2 GHz (lowest center frequency where 4 GHz of bandwidth could plausibly be sampled), the corresponding channel width is of order 1 kHz, necessitating of order 400k channels to ingest that broad of a bandwidth. This is the upper limit to the number of spectral channels required in the central signal processor.

Parameter	**Req. #**	**SciCase**	**Value**
Survey Speed	SCI0106	KSG5-006, KSG5-007	The array shall be able to map a ~10 square degree region to a depth of ~1 μJy/bm at 2.5 GHz and a depth of ~10 μJy/bm at 28 GHz within a 10 hr epoch using the naturally weighted beam.

The full width half maximum (FWHM) of the antenna beam is calculated assuming a uniform illumination pattern, consistent with the aperture efficiency computation as given by:

$$\Theta_{1/2} = 1.02\,\frac{\lambda}{D}$$

The taper coefficient of 1.02 has been verified empirically with the VLA for a shaped system with near-uniform aperture illumination.

Since the time metric applicable to the survey speed derivations are clock hours, a calibration efficiency term (observational efficiency) must be included. An efficiency of 0.9 will be assumed for both cases below.

9.2.2.6 *Case F: 10 deg² @ 1 μJy/bm @ 2.5 GHz, 10 hr epoch.*

Assuming 214 18m apertures, with 0.78 aperture efficiency and 2.3 GHz of instantaneous bandwidth, T_{sys} of 23K, η_Q of 0.96, η_C of 0.99, η_{calib} of 0.9, η_{weight} of 1.0, a single pointing reaches 1 uJy/bm in 11 minutes on source.

The primary beam FWHM is of order 23.4' wide, for an area of order 0.152 deg^2. Such a system would only map of order 8.2 deg^2 in a ten-hour period. Improvements in Tsys or collecting area would be required to meet this specification.

9.2.2.7 *Case G: 10 deg² @ 10 μJy/bm @ 28 GHz, 10 hr epoch.*

Assuming 214 18m apertures, with 0.85 aperture efficiency and 13.5GHz of instantaneous bandwidth, T_{sys} of 33K, η_Q of 0.93, η_C of 0.98, η_{calib} of 0.9, η_{weight} of 1.0, a single pointing reaches 10 μJy/bm in a mere two seconds on source. This case drives the on-the-fly mapping mode requirements discussed in Section 9.2.1.

The primary beam FWHM is of order 2.1' wide, for an area of order 0.001 deg^2 per pointing. Such a system would map of order 22.2 deg^2 in a ten-hour period.

Parameter	Req. #	SciCase	Value
Quality of the Synthesized Beam	SCI0107	All Imaging Cases	The (sculpted) synthesized beam shall be elliptical down to the attenuation level of the first side lobe and display a beam efficiency of >90% at all angular scales and frequencies, while still meeting continuum sensitivity requirements (SCI0100).

This parameter is reflected in the η_{weight} of 0.5 in all computations above, and captured in SYS1308, imaging weighting algorithms and the array configuration therefore must achieve this ratio while producing a sculpted beam with 90% of the power in the main lobe.

This requirement should be studied in greater detail, with an emphasis on the beam quality metrics and their relationship to other performance parameters.

Parameter	Req. #	SciCase	Value
Imaging Fidelity	SCI0108	KSG1-001, KSG3-004, KSG3-005, KSG3-007, KSG3-009	The ngVLA should produce high fidelity imaging (>0.9) over a wide range of scales, spanning from a few arcmin to a few mas.

This requirement needs to be studied in greater detail.

To first order, the constraints on the fraction of occupied cells (SYS1306) and the distribution and weighting of visibilities (SYS1308) both ensure that there are sufficient baselines over the arcmin to mass scales to sculpt a beam to meet the imaging fidelity requirement. However, the algorithmic complexity and sensitivity penalty implied are not yet well quantified.

Parameter	Req. #	SciCase	Value
Snapshot Image Fidelity	SCI0109	KSG1-001, KSG3-005, KSG3-006	The ngVLA snapshot performance should yield high fidelity imaging on angular scales >100 mas at 20 GHz for strong sources.

100mas at 20 GHz corresponds to baselines of order 31–51 km depending on the chosen taper value. Meeting this snapshot imaging performance requirement is feasible with a randomized or even distribution of antennas over an area of 31–51 km in diameter or larger, and is addressed in the fraction of occupied cells requirement.

The radial extent required to support the snapshot imaging fidelity requirement should be verified by simulation. An array with a centrally condensed core will by definition have far more visibilities back to the core, requiring a more even and randomized distribution over the high end of the given range (~50 km).

Parameter	Req. #	SciCase	Value
Photometric Accuracy	SCI0110	KSG3-006	The system photometric accuracy shall be better than 1% for programs requiring accurate photometry.

This photometric accuracy requirement must be met through flux-scale calibration. The specification implies absolute (rather than relative) accuracy, so a stable reference source (such as a temperature stabilized noise diode) must be provided to boot-strap values from known astronomical flux calibrators while monitoring changes in system gain. Changes in atmospheric opacity will also need to be monitored.

This requirement should be studied in more detail and evaluated in conjunction with the calibration strategy.

Parameter	Req. #	SciCase	Value
Relative Astrometric Accuracy	SCI0111	KSG5-001, KSG-002	The instrument shall achieve an astrometric accuracy that is <1% of the synthesized beam FWHM or the positional uncertainty in the reference frame, for a bright (SNR $\gtrsim$100) point source.

Astrometric accuracy is an RSS summation of the positional uncertainty in the reference frame, the centroid error (proportional to SNR), and other factors to be determined.

With 1000-km baselines, system resolution could be of order 2.1 mas at 30 GHz. 1% of synthesized beam would therefore correspond to of order 20 μas. This requirement may have implications for the delay model management, baseline orientation, antenna position errors, pressure and humidity monitoring in the atmosphere, and so forth. This requirement should be studied in more detail and evaluated in conjunction with the calibration strategy.

Parameter	Req. #	SciCase	Value
Timing Accuracy	SCI0112	KSG4-003	The system timing accuracy shall be better than 10 ns (1 ns desired) over periods correctable to a known standard from 30 minutes to 10 years.

The 30-minute requirement suggests frequency stability of order 3E-12 is required on 30-minute scales. Such a specification is readily achieved with the inclusion of a precision frequency reference such as an active hydrogen maser. The ten-year requirement suggests the system time must be corrected to GPS-derived UTC.

Parameter	Req. #	SciCase	Value
Brightness Dynamic Range	SCI0113	KSG3-011	The system brightness dynamic range shall be better than 50 dB deep field studies at 10 GHz.

The brightness dynamic range is met by controlling the variance in the complex voltage gains of the antenna (including atmospheric effects). Assuming the cross-correlation products are not normalized (as is the case with WIDAR), the cross-correlation power is

$$V_{ij} = \hat{g}_i \hat{g}_j^* < v_i v_j^* >$$

Where v_i is the equivalent voltage at the input to an antenna, $\hat{g}_i = g_i e^{-i\theta_i}$ is the complex voltage gain of that antenna, and V_{ij} is the complex visibility or correlation coefficient of the noise input signals of antennas *i* and *j*. The magnitude of V_{ij} is zero for completely uncorrelated noise signals and is a positive number for correlated noise.

The visibility is closely related to the cross power product of the noise input signals at antennas *i* and *j*, but is scaled by the complex voltage gain of the antennas. Therefore, it is essential to quantify the voltage gain and to track gain fluctuations at the antenna, and impose a limit on the residual uncorrected gain variation to support the brightness dynamic range required.

Represented as powers, the desired power product P_{int} represents the cross-power from the astronomical source only:

$$P_{int} = \sqrt{P_{src,i} P_{src,j}}$$

while the correlator output is scaled by root of the products of the two independent gains:

$$P_{corr} = \sqrt{g_i g_j} P_{int}$$

Uncorrected changes in $g_i\, g_j$ will artificially inflate or deflate the flux sensed on the baseline, which introduces ringing and other imaging artifacts that effectively reduce the SNR of the image. Both the gain and phase are equally important to meeting the brightness dynamic range requirement. As reported in [RD19] (p. 278), 10% phase errors are comparable to 20% amplitude errors in impact on interferometric dynamic range. We will assume for the moment that self-calibration is available (a functional requirement) and that the phase errors, after calibration, are negligible for this analysis in order to put an upper limit of the gain errors that would support the dynamic range requirement. Per [RD19] (p. 279), the relationship of the dynamic range limit of the system scales to the typical amplitude error on any antenna and is given by

$$D = \frac{N}{\sqrt{2}\,\varepsilon}$$

where *D* is the dynamic range limit, *N* is the number of antennas in the array, and ε is the typical amplitude error. Assuming an array of order 200 elements, the gain stability (*d*G/G) of a given antenna, after calibrations are applied, must approximate 1e-3 to support the higher dynamic range requirement. Accounting for imperfect phase calibration, gain amplitude stability of order 1e-4 would be desirable.

The period over which this stability must be maintained is typically related to the astronomical gain calibration cycle (~20 minutes), but can be reduced by transferring some of the stability requirements to a calibrated noise source as described in Section 5.18.3.

Parameter	Req. #	SciCase	Value
Polarization Dynamic Range	SCI0114	KSG3-011	The polarization dynamic range shall be better than 40 dB for deep field studies at the center of the field of view at 10 GHz.

Some possible implications of this requirement include

- Primary beam stability
- Stable polarization angle
- Functional corrections for parallactic angle, full Stokes imaging pipeline
- Relative gain stability between antennas of order 10^{-3} (TBC, using analysis for SCI0113)
- Relative gain stability of the two polarizations of 10^{-3} (TBC, using analysis for SCI0113)

This requirement should be studied in more detail and evaluated in conjunction with the calibration strategy.

Parameter	Req. #	SciCase	Value
Spectral Dynamic Range (Emissive)	SCI0115	KSG2-006	The spectral dynamic range shall be better than 50 dB to enable imaging of faint prebiotic molecules in the presence of bright emission lines within the field of view.

This requirement will impose limits on sideband separation and bandpass stability. The later must maintain an amplitude stability of order 0.3% (50 dB) after calibration. We will assume a calibration cycle of one hour.

The sideband separation specification will need to support the spectral dynamic range requirement and imaging fidelity requirement. For spectrally flat sources, the effects would be minimal, but for sources with spectral structure inadequate sideband separation could introduce both bandpass errors and imaging errors. A full 50dB of separation for spectral line observations is not required since fringe washing will provide ~20 dB of attenuation of adjacent emitting sources. LO offsets or sampler clock offsets could provide a further ~20 dB of attenuation.

Implementing LO-offsets and/or sampler clock offsets would therefore be highly desirable.

This requirement may also impose channel isolation requirements in the central signal processor, but this has not yet been evaluated. We expect that bandpass stability requirements will dominate.

Parameter	Req. #	SciCase	Value
Spurious Spectral Features	SCI0116	KSG2-005	Self-generated spurious spectral feature flux density must be below ~95 μJy/bm in any 0.1 km/s channel, post calibration between 16–50 GHz.

The intent of this requirement is that when the system rms noise reaches 95 μJy/bm in a 0.1 km/s channel, no system-generated spectral features are visible. The ratio of interfering signal power to the system radiometer noise must be established from this specification.

The relative spurious power in a given spectral bin will be calculated as (*P*–*N*)/*N*, where *P* is the total power in the bin, and *N* is the average power in the adjacent two bins. The bin size will be chosen as large as possible to include broad spurs, while narrow enough to exclude microscale baseband ripples.

Adopting the methodology from [RD14], we set the interference to noise ratio to less than 0.1.

$$INR < 0.1$$

Harmful flux density can then be found from SCI0116:

$$S_H < \sigma_{rms} * INR$$

Since the specification is given as a flux density, this can be directly compared to the SEFD to determine the required signal-to-interferer ratio. At 30 GHz, the expected SEFD for the array is of order 2.1 Jy:

$$\frac{S}{I}(\Delta\nu) = 10 * \log\left(\frac{9.5\ \mu\mathrm{Jy}}{2.1\ \mathrm{Jy}}\right)\ \mathrm{dB} = -53\ \mathrm{dB}$$

Since the power and flux density are proportional, the power of the spurious signal must be no more than –53 dB above the signal level on cold sky over the established channel bandwidth (0.1 km/s = 10 kHz @ 30 GHz). This specification will apply to total-power measurements, but can be relaxed for interferometric measurements by of order 20 dB due to phase winding/fringe washing (–53 dB + 20 dB = 33 dB/10 kHz). (See [AD06] for supporting derivation of interferometric attenuation factor.)

Extending the bandwidth over which the signal level is measured can increase the fidelity of the verification measurement, and a bandwidth of 1 MHz is adopted. The required attenuation will scale by the square root of the bandwidth:

$$\frac{S}{I}(1\ \mathrm{MHz}) = \frac{S}{I}(10\ \mathrm{kHz}) * \sqrt{\frac{1\ \mathrm{MHz}}{1\ \mathrm{kHz}}}$$

The end result is a spurious signal level of –43 dB/MHz for interferometric antennas. While the derivation above is given at 30 GHz, the requirement is comparable over the given frequency range.

System Environmental Specifications

020.10.15.10.00-0001-SPE

PREPARED BY	ORGANIZATION	DATE
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APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer R. Selina 2019.07.09 17:32:24 -06'00'	Electronics Div., NRAO	2019-07-09
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.11 07:07:58 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-09

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Version	Date	Author	Affected Section(s)	Reason
01	2017-10-02	R. Selina	All	Started first draft; used 020.25.00.00.00-0001-SPE-A as a template; pulling heavily from ALMA-80.05.02.00-001-B-SPE too
02	2017-10-12	R. Selina	1, 3, 4.	Incorporating suggestions from R. Treacy
03	2018-04-12	R. Selina	3.4	Clarified survival rain rate
04	2018-04-18	R. Selina	3.3	Clarified solar loads
04	2018-05-09	R. Selina	2, 3.4, 4.7	Updated survival rain rates
05	2018-05-11	R. Selina		Minor typos
06	2018-09-27	R. Selina	1.3, 3.1	Revised wind in Precision Environment to better reflect San Agustin Plains vs eastern NM used in initial analysis; updated introduction to match Ref. Design
07	2018-10-02	R. Selina	3.1	Revised Normal Environment wind conditions to better reflect San Agustin Plains
A	2019-07-09	A. Lear	All	Prepared document for review & approvals

Table of Contents

1 Introduction

1.1 Purpose

This document aims to present the system-level environmental specification, incorporating a set of definitions and requirements. This specification is a subsection of the preliminary ngVLA System Requirements [AD01], which in turn flow down from the preliminary ngVLA Science Requirements and ngVLA Stakeholder Requirements.

The environmental specification has been broken out into a separate document for ease of reference, since the environmental definitions and requirements shall be incorporated into the requirement specifications of multiple subsystems.

1.2 Scope

The scope of this document is all buildings, infrastructure and equipment that are located at the ngVLA core, as well as outlying stations. All related ngVLA system elements shall be specified to comply with this specification.

1.3 Project Background

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter, and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

The facility will be operated as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products; automated pipelines will calibrate raw data and create higher level data products (typically image cubes). Data and quality assured data products will be available through an Observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

The signal processing center of the array will be located at the Very Large Array site, on the Plains of San Agustin, New Mexico. The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US. Virgin Islands, and Canada.

Array Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will likely be collocated in a large metropolitan area and will be the base for science operations and support staff, software operations, and related administration. Research and development activities will be split amongst these centers as appropriate.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Technical Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Technical Specification, the content of the Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	International Standard: Protection Against Lightning	IEC 62305:2010

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	USGS Coterminous US Seismic Hazard Map – PGA 2% in 50 Years	ftp://hazards.cr.usgs.gov/web/nshm/conterminous/2014/2014pga2pct.pdf
RD02	NOAA ATLAS 14 Point Precipitation Frequency Estimates: NM	https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nm

3 Definitions of External Environmental Conditions

Based on historical weather data of the VLA site and other public weather databases, the following definitions of environmental conditions are adopted.

3.1 Precision Operating Conditions

Parameter	Req. #	Value
Solar Thermal Load	ENV0311	Nighttime only; no solar thermal load within last 2 hours.
Wind Speed	ENV0312	0 ≤ W ≤ 5 m/s average over 10 mins. 7 m/s peak gusts.
Temperature	ENV0313	–15 C ≤ T ≤ 25 C
Temperature Rate of Change	ENV0314	1.8°C/Hr.
Precipitation	ENV0315	No precipitation.

The precision operating environment defines the conditions under which the system is expected to meet the most stringent requirements and provide optimal system performance. The solar thermal load requirement limits this environment to two hours after sunset through sunrise, so long as the other requirements of this section are met. The two-hour restriction is intended to allow sufficient time for the system to equilibrate.

3.2 Normal Operating Conditions

Parameter	Req. #	Value
Solar Thermal Load	ENV0321	Exposed to full sun, 1200W/m^2.
Wind Speed	ENV0322	W ≤ 7 m/s average over 10 mins. 10 m/s peak gusts.
Temperature	ENV0323	–15 C ≤ T ≤ 35 C
Temperature Rate of Change	ENV0324	3.6°C/Hr.
Precipitation	ENV0325	No precipitation.

When the environment meets the constraints of the normal operating conditions, system performance requirements are relaxed but are still expected to provide adequate performance for operation below 50 GHz. The relevant performance specifications are discussed in [AD01].

3.3 Limits to Operating Conditions

Parameter	Req. #	Value
Solar Thermal Load	ENV0330	Exposed to full sun, 1200W/m^2
Wind	ENV0331	W ≤15 m/s average over 10 mins W ≤20 m/s gust
Temperature	ENV0332	–20 C ≤ T ≤ 45 C
Precipitation	ENV0333	5 cm/hr over 10 mins
Ice	ENV0334	No ice accumulation on structure

A third categorization will establish hard limits to the operating conditions. While outside the bounds of the normal operating environment but within this regime, no performance guarantees are expected, but the system shall still be capable of safe operation. Once these limits are exceeded, the antenna will be moved to its "stow-survival" orientation to prevent damage.

3.4 Survival Conditions

Parameter	Req. #	Value
Wind	ENV0341	0 m/s ≤ W ≤ 50 m/s average
Temperature	ENV0342	–30 C ≤ T ≤ 50 C
Radial Ice	ENV0343	2.5 cm
Rain Rate	ENV0344	16 cm/hr over 10 mins
Snow Load, Antenna	ENV0345	25 cm
Snow Load, Equipment & Bldgs.	ENV0346	100 kg/m^2 on horizontal surfaces
Hail Stones	ENV0347	2.0 cm
Antenna Orientation	ENV0348	Stow-survival, as defined by antenna designer

The survival conditions describe the environment that the antenna and all outside structures should be able to withstand without damage when placed in its least-vulnerable state. The designer must specify the antenna orientation that will result in minimum stress to the structure at the maximum wind speed and maximum snow and ice loading. Systems housed within or on the antenna shall assume this orientation.

The temperature limits, radial ice, snow load, and hail stone requirements are based on experience at the VLA site and a survey of conditions throughout the extent of the array.

3.5 Site Elevation

Parameter	Req. #	Value
Altitude Range	ENV0351	All system elements shall be designed for operation and survival at altitudes ranging from sea level to 2500m.

4 Environmental Protection Requirements

4.1 Lightning

Parameter	Req. #	Value
Lightning Protection, Structure	ENV0511	The antenna, buildings, and housed equipment shall be protected from both direct and nearby lightning strikes, achieving Protection Level I as defined in IEC 62305-1/3. [AD02]
Lightning Protection, Electronics Systems	ENV0512	The building and antenna electrical and electronics systems shall be protected against Lightning Electromagnetic Impulse (LEMP) in accordance with IEC 62305-4. [AD02]
Lightning Protection, Personnel	ENV0513	A safety hazard analysis shall be performed for anticipated preventive maintenance tasks that may place personnel at risk in the event of direct or nearby lightning strikes.

Given the extent of the array and the prevailing environmental conditions, direct and nearby lightning strikes, causing a lightning electromagnetic pulse (LEMP), should be anticipated and mitigated in the antenna design. The antenna and housed equipment shall be protected in any antenna orientation. All antenna bearings shall have bypass grounding connections. Grounding systems shall be designed to minimize ground loops. Multi-point grounding is a necessity imposed by the need for RFI shielding, but the effects should be minimized in signal paths wherever possible.

The lightning protection system shall be designed to achieve Protection Level I as defined by [AD02] IEC 62305-1—Protection Against Lightning. This level assures protection against 99% of strikes, with a residual risk of damage for strikes with parameters outside the defined range.

4.2 Seismic

Parameter	Req. #	Value
Seismic Protection	ENV0521	The system shall be designed to withstand a low-probability earthquake with up to 0.2g peak acceleration in either the vertical or the horizontal axis.

Low probability has been defined as a 2% probability of an event exceeding this magnitude over a 50-year period, consistent with data available from the USGS Seismic Hazard Model [RD01]. Equipment shall be designed to survive this standard in any operational condition and orientation.

4.3 Vibration

Parameter	Req. #	Value
Wind Vibration	ENV0531	Exposed equipment, including all equipment within the antenna, shall be designed to withstand persistent wind-induced vibration.
Transport Vibration	ENV0532	All line-replaceable units shall be designed to withstand transportation vibration.

The vibration mitigation requirement is especially applicable to all mechanical connectors. All cables shall be mechanically supported to mitigate vibration loosening of connectors (see Figure 1).

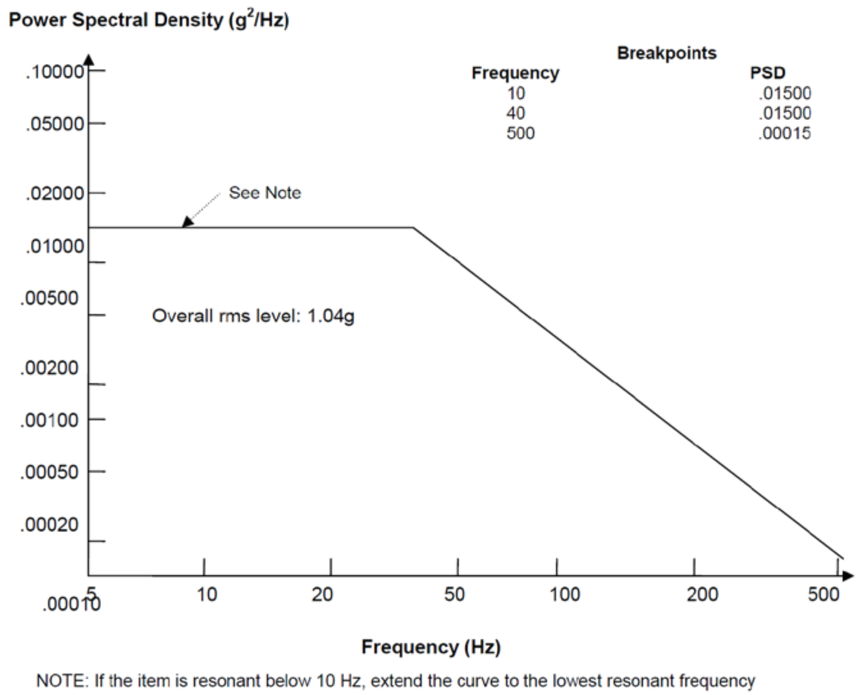

Figure 1 - Power spectral density of design spectra for vibration mitigation. Adopted from ALMA-80.05.02.00-001-B-SPE.

4.4 Dust

Parameter	Req. #	Value
Equipment Protection	ENV0541	Exposed equipment shall be protected against windblown dust, ashes, and grit.
Building Protection	ENV0542	Building envelopes shall be tight enough to mitigate penetration of dust. All air circulation penetrations shall be filtered.

4.5 Fauna

Parameter	Req. #	Value
Rodent Protection	ENV0551	Exposed equipment shall be designed to prevent rodent damage. At a minimum this may involve protecting all cables with flexible or rigid conduit or equivalent. Any penetration within enclosures and raceways shall mitigate the risk of rodent damage.
Large Mammal Protection	ENV0552	Exposed equipment shall be protected against damage by large mammals such as cows.

Note that the large mammal protection requirement needn't be met by all exposed equipment directly. For example, if a fence is provided around each antenna, equipment within the fence envelope can be built assuming that the fence provides adequate large mammal protection.

4.6 Solar Radiation

Parameter	Req. #	Value
Maximum Solar Flux	ENV0561	All equipment exposed to outside environment shall be designed for a maximum diurnal solar flux of 1200 W/m^2 from 0.3–60 µm.
Maximum UV Radiation	ENV0562	All equipment exposed to outside environment shall be designed for a maximum diurnal UV radiated flux of 100 W/m^2 from 280–400 nm.

4.7 Rain/Water Infiltration

Parameter	Req. #	Value
Rain/Water Infiltration	ENV0571	Exposed equipment enclosures shall be designed to withstand rainfall intensity up to 16 cm/hr., with droplets sized 0.5 to 4.5mm, at wind velocity of 15 m/s from the vertical to horizontal direction.

Survival rain rates correspond to 50-year events as defined in RD 02.

4.8 Mechanical Shock

Parameter	Req. #	Value
Transportation Environment	ENV0581	Equipment shall be designed to withstand typical loads and environments encountered during transportation as part of assembly or maintenance.
Mechanical Shocks	ENV0582	Equipment shall be designed to survive mechanical shock levels from handling as defined in Table 1.

Determination of typical loads will be the responsibility of the IPT lead and may be unique to each LRU.

Mass of Package	Type of Handling	Drop Height [cm]
0 to 9.1 kg	Manual Handling	76
9.2 to 18.2 kg	Manual Handling	66
18.3 to 27.2 kg	Manual Handling	61
27.4 to 36.3 kg	Manual Handling	46
36.4 to 45.5 kg	Manual Handling	38
45.5 to 68.1 kg	Mechanical Handling	31
68.2 to 113.5 kg	Mechanical Handling	26
>113.5 kg	Mechanical Handling	20

Table 1 - Shock levels during handling. Adopted from ALMA-80.05.02.00-001-B-SPE.

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CFD	Computational Fluid Dynamics
HVAC	Heating, Ventilation & Air Conditioning
LRU	Line Replaceable Unit
ngVLA	Next Generation VLA
RD	Reference Document
SAC	Science Advisory Council
TAC	Technical Advisory Council
TBD	To Be Determined
VLA	Jansky Very Large Array

System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements

020.10.15.10.00-0002-REQ-A-SYS_EMC_RFI_MITIGATION

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
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M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.16 20:40:22 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-09

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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2017-10-02	R. Selina	All	Started first draft; used 020.25.00.00.00-0001-SPE-A as a template
02	2017-10-12	R. Selina	2.1, 3, 4.1	Incorporated feedback from W. Grammer and R. Treacy
03	2018-05-09	R. Selina	3.1	Updated for consistency with case outlined in SCI0116
04	2018-09-27	R. Selina	1.3, 2.1, 3.1, 4.	Updated based on review by D. Mertely
A	2019-07-09	A. Lear	All	Prepared document for approvals & release

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1 Introduction

1.1 Purpose

This document presents system-level Electromagnetic Compatibility (EMC) and Radio Frequency Interference (RFI) mitigation requirements. This specification is a subsection of the preliminary Next Generation Very Large Array (ngVLA) System Requirements [AD01], which in turn flow down from the preliminary Science Requirements and Stakeholder Requirements.

1.2 Scope

This document covers all buildings, infrastructure, and equipment located at the ngVLA core and other outlying stations. All related ngVLA system elements shall be specified to comply with this specification.

1.3 Project Background

The ngVLA is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

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2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Technical Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Technical Specification, the content of the Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev / Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev / Doc. No.
RD01	RFI Emission Limits for Equipment at the EVLA Site	EVLA Memo #106. Perley, Brundage, Mertely.
RD02	Attenuation of Radio Frequency Interference by Interferometric Fringe Rotation	EVLA Memo #49. Perley.
RD03	Protection Criteria Used for Radio Astronomical Measurements	Recommendation ITU-R RA.769-2
RD04	Notes on RFI Emission Levels	VLA/VLBA Interference Memo #34

3 EMC/RFI Requirements

3.1 *Spurious Signals/Radio Frequency Interference Generation*

Parameter	Req. #	Value	Traceability
Spurious Signal Level	EMC0310	Not to exceed the equivalent isotropic radiated power limits in Table 1.	SYS2104, SCI0116

The electronics within the antenna must be shielded to avoid radio frequency interference (RFI) being received by the Front End electronics, degrading system sensitivity. The table below is based on the analysis presented in [RD01], updated for longer integrations consistent with SCI0116.

Freq. (GHz)	1	2	4	6	8	10	20	30
F_h (w/m²)	1.5E-19	1.1E-18	8.9E-18	2.9E-17	6.3E-17	1.2E-16	1.2E-15	4.3E-15
$EIRP_h$ (W)	1.9E-16	1.4E-15	1.1E-14	3.7E-14	7.9E-14	1.5E-13	1.6E-12	5.4E-12
$EIRP_h$ (dBm)	**–127**	**–119**	**–110**	**–104**	**–101**	**–98**	**–88**	**–83**

Table 1 - Allowable radiation power for electronic components.

The table is based on unity gain, assuming the RFI enters through a sidelobe of the antenna. F_h is the harmful power flux density level, and $EIRP_h$ is the harmful effective isotropic radiated power. The ratio of the emitting device EIRP to the harmful EIRP ($EIRP_h$) is the shielding required. For example, a device with an EIRP of 1nW @2GHz would require of order 59dB of shielding.

The table above assumes the radiator is 10 m from the antenna feed. For other distances, the $EIRP_h$ can be calculated as follows:

$$EIRP_h = \frac{4\pi r^2 S F_h}{G}$$

where r is the distance in meters, S is the device shielding ratio, G is equal to 1, and F_h is from Table 1.

Radiated Power shall be computed over a bandwidth that corresponds to a spectral resolution of 100 m/s. This can be calculated as 333 Hz * ν_G, where ν_G is the RF frequency in GHz.

3.2 *Electromagnetic Compatibility Requirements*

All ngVLA equipment shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility). Prevention of electromagnetic interference (EMI) between the antenna and other sub-systems (inter-system electromagnetic compatibility) is also critical.

The following requirements shall be fulfilled *as a minimum* to achieve both intra- and inter-system EMC, but the designer may propose alternatives if quantitative evidence is provided that they are at least as effective as those specified. Shielding requirements may be computed as described in Section 3.1.

Parameter	Req. #	Value	Traceability
Drive System Shielding	EMC0320	All motor leads, both power and control, shall be filtered.	SYS2104
Relay Contact Arcing	EMC0321	All relay contacts and actuators shall be properly bypassed with snubber circuits, shielded, and/or filtered.	SYS2104
Amplifiers & Oscillators	EMC0322	All amplifiers and oscillators shall be mounted in shielded enclosures that will provide effective shielding of radio frequency energy.	SYS2104
Silicone Controlled Rectifiers	EMC0323	Silicon-controlled rectifier switching devices shall not be used unless phase controlled and zero current crossing switching techniques are used.	SYS2104
Gaseous Discharge Devices	EMC0324	No gaseous discharge devices, except noise sources for test and calibration, shall be employed.	SYS2104
Static Discharge Mitigation	EMC0325	Means shall be employed to reduce static electricity and the consequent radio frequency noise generated in any rotating machinery.	SYS2104
Display Shielding	EMC0326	All displays (LCD, plasma, LED, CRT) shall have a RFI shield in front of the display to avoid radiated RFI. This requirement may be waived if the screen is powered off during typical operation and is used for maintenance purposes only. It must be possible to monitor and turn off such emitting devices remotely (via M&C System).	SYS2104
Digital Equipment Shielding	EMC0327	All digital equipment, whether a simple logic circuit, embedded CPU, or rack mounted PC shall be shielded and have its AC power line and communication line(s) filtered at the chassis.	SYS2104
EMC Test Frequencies	EMC0328	The frequency range to be covered by these design measures for radiated radio-frequency interference (RFI) suppression shall extend from 50 MHz up to 12 GHz. Demonstration of EMC above 12 GHz is not required because mitigation at 12 GHz and below is expected to be adequate at higher frequencies. An exception is made for the fundamental and harmonic frequencies of LO signals, which shall be tested up to 40 GHz.	SYS2104

The goal of these requirements is to limit the use of devices that are likely to cause harmful emission levels, shield the remaining necessary emitters, and establish practical testing standards. This list is not comprehensive, and the designer should exercise due diligence in limiting the harmful emissions generated by his/her design. Design for EMC/RFI mitigation is expected to be a significant effort in most electronic components of the ngVLA.

4 Appendix

4.1 Abbreviations & Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
CoDR	Conceptual Design Review
CFD	Computational Fluid Dynamics
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
FDR	Final Design Review
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IPT	Integrated Product Team
LRU	Line Replaceable Unit
ngVLA	Next Generation VLA
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares
SAC	Science Advisory Council
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
VLA	Jansky Very Large Array

4.2 Supporting Calculations: Derivation of RFI Generation Requirements

The EIRP limits listed in Section 3.1 are based on the analysis presented in [RD01]. The allowable emission limits are computed for an interferometer with attenuation of a stationary RFI source provided by phase winding. The specifications in Section 3.1 rely on this attenuation, and are not suitable for total power radiometry. The analysis in [RD01] uses an expression for the attenuation factor from [RD02]:

$$R = 12\sqrt{\tau \nu_G B_K \cos\delta}$$

where τ is the integration time in seconds, ν_G is the RF frequency in GHz, B_K is the maximum baseline in km, and δ is the source declination. The coefficient 12 is unique to the VLA, and must be recomputed for ngVLA. This coefficient was derived from equation 16 in [RD02]:

$$C = \frac{\sqrt{1000}}{1.34\sqrt{f}} = 12$$

The square root of 1000 accounts for the fact that RD02 Equation 16 is in MHz rather than GHz. f is the ratio of B_{MAX}/B_{MEAN} which, for VLA, is approximately 4.

The computation for ngVLA is complicated by the likely use of sub-arrays. The attenuation is minimized when the array is compact and the source is high in the sky. Standalone use of the compact core likely presents a conservative case, and the following input parameters (Table 2) were used to determine the attenuation factor:

Parameter	Value	Units	Notes
N_a	86		Core sub-array case. 40% of collecting area.
$B_{Max,K}$	2.0	km	Core sub-array case.
δ	85	degrees	Gets worse at high declination.
$B_{Min,K}$	0.032	km	Approx. 1.75 x D_{ANT}
f	63		Ratio of max to mean baseline, in core.

Table 2 - Input parameters to fringe rotation attenuation computation.

The ratio of max to mean baseline requires further knowledge of the array configuration. In this analysis, the ratio of the max and min baseline is used to provide an additional margin. This should be revisited once the configuration design is stable.

The remainder of the analysis follows the process outlined in [RD01]. An integration period of 46,800 seconds (13 hours) was used for consistency with SCI0116, and the emitter was placed at a distance of 10m from the receiver. Resolution bandwidth is also consistent with SCI0116.

ν_G (GHz)	1	2	4	6	8	10	20
T_{SYS} (K)	25	25	27	27	25	25	33
Δν (Hz)	333.33	666.67	1,333.33	2,000.00	2,666.67	3,333.33	6,666.67
σ_P (W) *single dish*	2.91E-23	4.12E-23	6.29E-23	7.70E-23	8.24E-23	9.21E-23	1.72E-22
$P_{HARM-SD}$ (W) *single dish*	2.91E-24	4.12E-24	6.29E-24	7.70E-24	8.24E-24	9.21E-24	1.72E-23
R [Attenuation Factor, Memo #49]	3.64E+02	4.75E+02	6.33E+02	7.54E+02	8.57E+02	9.47E+02	1.30E+03

$P_{HARM-INT}$ (W) ***interferometer***	1.06E-21	1.96E-21	3.98E-21	5.81E-21	7.05E-21	8.72E-21	2.23E-20
A_e (m^2)	0.007162	0.001790	0.000448	0.000199	0.000112	0.000072	0.000018
F_{HARM} (watt/m^2) ***interferometer***	1.5E-19	1.1E-18	8.9E-18	2.9E-17	6.3E-17	1.2E-16	1.2E-15
EIRP limit (watts) ***interferometer***	1.9E-16	1.4E-15	1.1E-14	3.7E-14	7.9E-14	1.5E-13	1.6E-12
EIRP (dBm) ***interferometer***	−127	−119	−110	−104	−101	−98	−88

Table 3 - Computed values that support the emission limit specification.

The parameters in Table 3 are described below, along with any constants used in their computation.

Parameter	Description
ν_G (GHz)	The point frequency applicable to this analysis.
T_{SYS} (K)	The system temperature
$\Delta\nu$ (Hz)	The bandwidth over which the RFI is integrated.
σP (W)	The noise power generated by the system, at the specified T_{SYS} and bandwidth, over a period of 46,800 seconds.
$P_{HARM-SD}$ (W)	The harmful emission threshold applicable to single-dish total power radiometry.
R	The interferometric attenuation factor, as described in EVLA Memo #49 [AD02].
$P_{HARM-INT}$ (W)	The harmful emission threshold applicable to interferometric measurements.
A_e (m^2)	An isotropic antenna's effective cross-section area.
F_{HARM} (W/m^2)	The harmful threshold in power flux density units.
EIRP (watts)	The limit in effective isotropic radiated power, expressed in watts, 10m from the receiver.
EIRP (dBm)	The limit in effective isotropic radiated power, expressed in dBm, 10m from the receiver.

L1 Safety Requirements

020.80.00.00.00-0001-REQ-A-L1_SAFETY_REQS

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
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Version	Date	Author	Affected Section(s)	Reason
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2	2019-05-30	A. Lear	All	Format and copyedit to prepare for approvals
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Table of Contents

1 Introduction

1.1 Purpose

This document provides the safety design requirements applicable to hardware, software, and processes/procedures through the entire ngVLA lifecycle. The document addresses the ngVLA safe design requirements through reviews and prototyping, construction, commissioning actions, operation, and ultimate decommissioning.

The essential ngVLA requirements for safety are described in a series of requirements listed in section 5. These have been proposed and adopted for the ngVLA Project as the design safety requirements (Level 1). Since a single device or article may contain hazards that are in several categories, several requirements may be applicable at the same time.

The requirements define the hazards to mitigate and the results to be attained but do not specify the technical solutions for doing so. For a wide range of items, the designer may choose standards that meet the essential requirements. This allows flexibility in choosing which standards to apply in the ngVLA project. The designers must document the standards they are working to and the choice of standards shall be reviewed and approved by the Safety IPT with Systems Engineering.

The flow-down of the relevant essential requirements must be based on the hazards applicable to a given product. Therefore, designers need to carry out a Hazard Analysis to determine the essential requirements applicable to the product. This analysis must be documented and included in the technical documentation.

1.2 Scope

The scope of this document extends to all Integrated Product Teams (IPTs), all project reviews, all work practices in labs and worksites, and all subcontractors that provide documentation, procedures, or work at any ngVLA site.

This specification defines the general safety requirements for all parties involved in ngVLA design. A major part of a design to meet the essential safety requirements is the work that involves identification of hazards and the means to prevent them. A document that lists such information is called a Hazard Analysis.

1.3 Project Background

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter for the Main Array and the Long Baseline Array (LBA), plus 19 antennas each of 6 meters diameter for the Short Baseline Array (SBA). All 263 antennas will operate in a phased or interferometric mode.

LBA antenna locations will likely include New Mexico, Texas, Arizona, and northern Mexico, as well as all ten current VLBA locations.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Safety Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Safety requirement, the latter shall take precedence.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	NRAO Environment, Safety, and Security Policy and Program Manual	Version D, Oct. 2016.
AD03	ngVLA Safety Risk Analysis Procedures	020.80.00.00.00-0002-PRO
AD04	ngVLA L0 Safety Requirements	020.10.15.10.00-0004-REQ

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	OSHA General Industry Standard	29 CFR 1910
RD02	OSHA Construction Standard	29 CFR1926
RD03	Environmental Protection Agency Clean Air Act of 1963	33 U.S.C.: Navigable Waters
RD04	Environmental Protection Agency Clean Water Act of 1972	42 U.S.C. ch. 85, subch. I § 7401 et seq
RD05	National Fire Protection Association, Consensus Standards	NFPA

3 Safety Scope

The Safety IPT work package includes safety, physical security, ongoing environmental protection actions, sustainability, and identification of associated risks. In the context of this document, "safety" includes all the aforementioned program elements. The scope of the Safety IPT includes an assessment of the requirements for all phases of the ngVLA effort.

The Safety IPT crosses all IPT boundaries and is anticipated to be integrated into all design packages and operational procedures. Safety extends through the lifecycle of the ngVLA. The ngVLA Safety IPT will assist to ensure compliance with federal, state and local safety requirements. In addition, the effort will examine compliance with international standards, such as may be applicable in Mexico.

The ngVLA proposed project will require compliance with the AUI policies for safe planning and management of large facilities. Consequently, there must be significant collaboration with all other Integrated Product Teams (IPTs) as the requirements influence the safety support needed.

4 Safety Across the ngVLA Lifecycle

All IPTs shall have a designated central point of contact for safety related issues and preparation of safety documentation for reviews. All personnel shall be alert to the need to identify potential safety hazards. Once identified, steps shall be taken to eliminate them, or reduce them to levels judged acceptable. The central point of contact for safety matters shall be the IPT Safety Liaison.

4.1 Design Activities

Safety assurance matters shall conform to the requirements defined in the NRAO Environment, Safety, and Security Policy and Program Manual [AD02], and with site-specific Safety directives.

Potential hazards shall be identified as a part of the normal design process and eliminated or reduced as far as possible. Safeguards shall be determined for outstanding hazards, which will reduce their possible effects to the lowest reasonable level in accordance with the ngVLA Safety Risk Analysis Procedures.

Any safety hazards that cannot be eliminated during the design process shall be reported to the Safety IPT Lead at the design review and to the ngVLA Project Office. Any progress shall be reported, including necessary proof that the relevant requirements have been satisfied.

4.2 Operations Activities

Operations activities are not addressed in this document and shall follow the NRAO ES&S Policies governing operational safety as described in the Environment, Safety, and Security Policy and Program Manual [AD02].

5 Essential Safety Requirements for Design

The following requirements shall be fulfilled *as a minimum* to achieve acceptable levels of safety across the ngVLA project.

Requirement ID#	Requirement Name	Requirement
SAF0028	Design for all Lifecycle Phase Safety	The ngVLA shall be designed to achieve the highest level of personnel health and safety performance in all phases of the project lifecycle in accordance with standards applicable to the work.
SAF0029	Comply with ES&S Manual	All aspects of the design and construction shall comply with the ES&S Policy And Program Manual.
SAF0030	Develop Safe Procedures	Where appropriate, each IPT shall develop procedures for personnel and equipment safety throughout the design, construction, and operation phases to address working conditions and use procedures, as well as identify the design features that impact safety, environmental protection, and sustainability.
SAF0031	Follow Safe Design Priorities	The priority for safe design shall address safety of personnel, followed by safety of equipment, and then the integrity of the data.
SAF0032	Follow Mitigation Order of Precedence	The ngVLA system shall govern the hazard analysis and safety practices in an order of precedence as follows: 1) Design for Minimum Risk: The primary means for mitigating risk shall be to eliminate the hazard through design. 2) Incorporate Safety Devices: Protective devices shall be used as part of system design to reduce hazard risks to an acceptable level where possible. 3) Provide warning Devices: when neither design nor safety devices can effectively minimize a hazard risk, devices shall be used to detect the hazard condition and alert personnel of its presence. 4) Procedures and Training: Only when it is impractical to substantially eliminate or reduce the hazard, or where the condition of the hazard indicates additional emphasis, special operating procedures and training shall be used. All such procedures shall be fully documented.
SAF0033	Develop Operational Safety Plan	An operational safety plan shall be developed and implemented before the commissioning phase starts.
SAF0034	Follow Safety Design Specification	The safety system specification must be followed during the design of both individual system components and integration of system elements.

Requirement ID#	Requirement Name	Requirement
SAF0035	Use Safety Design Specification for Validation	The safety system specification shall be used in validation of the integrated system elements for system validation.
SAF0036	Document Safety Compliance	Each completed element of design must document safety compliance with the safety system specifications.
SAF0037	Describe Process to Achieve Safe State	Each element must describe processes and address details to achieve safe state including potential sequencing of events.
SAF0038	Describe Additional Safety Requirements	Each element must describe any additional measures required to be utilized during validation, and describe consequences of failure to follow sequential processes.
SAF0039	Design Facilities for Safe Operational Use	The ngVLA Facilities shall be designed to safely meet its technical requirements and operational specifications at the following physical locations. The "Facility" includes the main radio antenna, service areas, utility equipment, and all other infrastructure necessary to safely execute all the operational functions and secure all ngVLA assets. The Facility design must provide the space and functional equipment to maintain all the system assets operating on the site.
SAF0040	Design Controls for Safe Operation	The control capabilities throughout the system shall include both local and remote exclusive control modes for safe operation. Note this applies to any system that has potential for motion.
SAF0041	Ensure Initial Safe State for Subsystem Power Up	Each Facility in the ngVLA Observatory shall implement a non-software-based safety system(s) in areas where injury or harm to personnel and or equipment can occur. Each subsystem when powered up shall be initialized into a known safe state without human intervention.
SAF0042	Ensure Subsystems are Standalone Safe	Each subsystem shall be responsible for maintaining its own technical health, safety, and status without any other subsystem operational.
SAF0043	Address facility security in design	The project shall affirmatively address site and facility security needs in the design in accordance with the NRAO security policy(ies).
SAF0044	Address Sustainability in Design	The project shall affirmatively address sustainability goals in the design and ongoing operations of the ngVLA project.

5.1 General Considerations

The design of the ngVLA system and subsystems shall comply with the essential safety requirements given in this document. It should be noted that additional ngVLA specifications on electrical design, environmental conditions, and environmental protection may have been prepared for specific safety requirements adopted for the ngVLA project. Each design shall meet the requirements contained in these additional ngVLA specifications.

A risk analysis shall be done for each subsystem. See the Applicable Documents for specific documents on the Risk Analysis procedures.

Requirements on workplace and construction safety that affect the subsystem design must be in compliance with applicable OSHA safety standards, National Electric Code requirements, and applicable construction codes.

5.2 Low-Voltage Electrical Equipment

5.2.1 Introduction

These requirements seek to ensure that electrical equipment within certain voltage limits provides protection for workers and visitors. These requirements cover electrical equipment designed for use with a voltage rating of between 50V and 1000V for alternating current and between 75V and 1500V for direct current. It should be noted that these voltage ratings refer to the voltage of the electrical input or output, not to voltages that may appear inside the equipment.

5.2.2 General Conditions for all Electrical Equipment

SAF0050: The essential characteristics ensuring that electrical equipment will be used safely and in applications for which it was made shall be marked on the equipment or, if this is not possible, on an accompanying notice.

SAF0060: The designers' brand name or trademark shall be clearly printed on the electrical equipment or, where that is not possible, on the packaging.

SAF0070: The electrical equipment, together with its component parts shall be made in such a way as to ensure that it can be safely and properly assembled and connected.

SAF0080: The electrical equipment shall be designed and manufactured such that protection against all hazards is assured, provided that the equipment is used in applications for which it was made and is adequately maintained.

5.2.3 Protection Against Hazards Arising from the Electrical Equipment

Measures of a technical nature should be prescribed in order to ensure compliance with the following:

SAF0090: Persons are adequately protected against danger of physical injury or other harm which might be caused by direct or indirect electrical contact.

SAF0100: Temperatures, arcs, or radiation that would cause a danger are not produced.

SAF0110: Persons and property are adequately protected against non-electrical dangers caused by the electrical equipment that are revealed by experience.

SAF0120: The equipment and wiring insulation must be suitable for foreseeable conditions.

5.2.4 Protection Against External Hazards on Electrical Equipment

SAF0130: The electrical equipment must meet the expected mechanical requirements in such a way that persons and property are not endangered.

SAF0140: The electrical equipment shall be resistant to non-mechanical influences in expected environmental conditions, so that persons and property are not endangered.

SAF0150: The electrical equipment shall not endanger persons and property in foreseeable conditions of overload.

5.3 Essential Health and Safety Requirements of Machinery/Equipment

5.3.1 General Remarks

This section identifies essential safety requirements for health and safety for operators and persons near machinery/equipment. These essential requirements are applicable to all ngVLA machines and equipment.

5.3.1.1 Definitions

- Machinery: An assembly of linked parts or components, which may move, with the appropriate actuators, control and power circuits, etc., joined together for a specific application.
- Danger zone: Any zone within and/or around machinery/equipment in which an exposed person is subject to a risk to his health or safety.
- Exposed person: Any person wholly or partially in a danger zone.
- Operator: The person or persons given the task of installing, operating, adjusting, maintaining, cleaning, repairing, or transporting machinery/equipment.

5.3.1.2 Principles of Safety Integration

SAF0160: Machinery/equipment must be constructed and fitted for its function, and able to be adjusted and maintained without putting persons at risk when operations are carried out under the conditions foreseen by the designer. The measures taken must eliminate risk of accident throughout the foreseeable lifetime of the machinery/equipment, including the phases of assembly and dismantling, even where risks of accident arise from foreseeable abnormal situations.

SAF0170: In selecting the most appropriate methods, the designer must apply the following principles, in the order given:

- Eliminate or reduce risks as far as possible (inherently safe machinery/equipment design and construction)
- Take the necessary protection measures in relation to risks that cannot be eliminated
- Inform users of the residual risks due to any shortcomings of the protection measures adopted, indicate whether any particular training is required and specify any need to provide personal protection equipment

SAF0180: When designing and constructing machinery/equipment, and when drafting the instructions, the designer must envisage not only the normal use of the machinery/equipment but also uses which could reasonably be expected. The machinery/equipment must be designed to prevent abnormal use if such use would engender a risk. In other cases, the instructions must draw the user's attention to ways in which the machinery/equipment should not be used.

SAF0190: Under the intended conditions of use, the discomfort, fatigue, and psychological stress faced by the operator must be reduced to the minimum possible taking ergonomic principles into account.

SAF0200: When designing and constructing machinery/equipment, the designer must take account of the constraints to which the operator is subject as a result of the necessary or foreseeable use of personal protection equipment (such as footwear, gloves, etc.).

SAF0210: Machinery/equipment must be supplied with all the essential special equipment and accessories to enable it to be adjusted, maintained and used without risk.

5.3.1.3 Material and Products

SAF0220: The materials used to construct machinery/equipment or products used and created during its use must not endanger exposed persons' safety or health. For example, where fluids are used, machinery/equipment must be designed and constructed for use without risks due to filling, use, recovery, or draining.

5.3.1.4 Lighting

SAF0230: The design must permit integral lighting suitable for the operations concerned where its lack is likely to cause a risk despite ambient lighting of normal intensity. The designer must ensure that there is no area of shadow likely to cause nuisance, that there is no irritating dazzle, and that there are no dangerous stroboscopic effects due to the lighting provided. Internal parts requiring frequent inspection, adjustment, and maintenance must be provided with appropriate lighting.

5.3.1.5 Design of Machinery/Equipment to Facilitate its Handling

SAF0240: Machinery/equipment or each component part thereof must be capable of being handled safely, or be packaged or designed so that it can be stored safely and without damage (e.g., adequate stability, special supports, etc.).

SAF0250: Where the weight, size, or shape of machinery/equipment or its various component parts prevents them from being moved by hand, the machinery/equipment or each component part must

- Be fitted with attachments for lifting gear, or
- Be designed so that it can be fitted with such attachments (e.g., threaded holes), or
- Be shaped in such a way that standard lifting gear can easily be attached.

SAF0260: Where machinery/equipment or one of its component parts is to be moved by hand, it must either be easily movable or be equipped for picking up (e.g., hand-grips, etc.) and moving in complete safety.

SAF0270: Special arrangements must be made for the handling of tools and/or machinery/equipment parts, even if lightweight, which could be dangerous (shape, material, etc.).

5.3.2 Protection Against Mechanical Hazards

5.3.2.1 Stability

SAF0470: Machinery/equipment, components, and fittings must be so designed and constructed that they are stable enough, under the foreseen operating conditions, for use without risk of overturning, falling or unexpected movement. If the shape of the machinery/equipment itself or its intended installation does not offer sufficient stability, appropriate means of anchorage must be incorporated and indicated in the instructions.

5.3.2.2 Risk of Breakup During Operation

SAF0480: The various parts of machinery/equipment and their linkages must be able to withstand the stresses to which they are subject when used as foreseen by the designer.

SAF0490: The durability of the materials used must be adequate for the nature of the work place foreseen by the designer, in particular as regards the phenomena of fatigue, ageing, corrosion, and abrasion.

SAF0500: The designer must indicate in the instructions the type and frequency of inspection and maintenance required for safety reasons. Where appropriate, indicate the parts subject to wear and the criteria for replacement.

SAF0520: Both rigid and flexible pipes carrying fluids and/or gases, particularly those under high pressure, must be able to withstand the foreseen internal and external stresses and must be firmly attached and/or protected against all manner of external stresses and strains. Precautions must be taken to ensure that no risk is posed by a rupture.

5.3.2.3 Risks Due to Falling or Ejected Objects

SAF0530: Precautions must be taken to prevent risks from falling or ejected objects.

5.3.2.4 Risks Due to Surfaces, Edges, or Angles

SAF0540: As far as their purpose allows, accessible parts of the machinery/equipment must have no sharp edges, no sharp angles, and no rough surfaces likely to cause injury.

5.3.2.5 Prevention of Risks Related to Moving Parts

SAF0570: Moving parts of machinery/equipment must be laid out to avoid hazards or fixed with guards or protective devices to prevent all risk of contact that could lead to accidents.

SAF0580: Necessary steps must be taken to prevent accidental blockage of moving parts involved in the work. In cases where a blockage may occur, specific protection devices or tools, the instruction handbook and possibly a sign on the machinery/equipment should be provided by the designer to enable the equipment to be safely unblocked.

5.3.2.6 Choice of Protection Against Risks Related to Moving Parts

SAF0590: Guards or protection devices to protect against moving parts must be selected on the basis of the type of risk. The following guidelines must be used to help make the choice.

SAF0600: Guards designed to protect exposed persons against the risks associated with moving transmission parts (such as pulleys, belts, gears, shafts, etc.) must be either fixed, or removable. Removable guards should be used where frequent access is foreseen.

SAF0610: Guards or protection devices designed to protect exposed persons against the risks associated with moving parts contributing to the work (such as cutting tools, moving parts of presses, cylinders, parts in the process of being machined, etc.) must be, where possible, fixed guards. Otherwise use movable guards or protection devices such as sensing devices (e.g., non-material barriers, sensor mats), remote-hold protection devices (e.g., two-hand controls), or protection devices intended automatically to prevent all or part of the operator's body from encroaching on the danger zone.

SAF0620: When moving parts directly involved in the process cannot be made completely or partially inaccessible during operation owing to operations requiring nearby operator intervention, where technically possible such parts must be fitted with fixed guards preventing access to the parts that are not used in the work, or adjustable guards restricting access to the sections of the moving parts that are strictly for the work.

5.3.3 Required Characteristics of Guards and Protection Devices

5.3.3.1 General Requirements

SAF0630: Guards and protection devices must

- Be of robust construction,
- Not give rise to any additional risk,
- Not be easy to bypass or render non-operational,
- Be located at an adequate distance from the danger zone,
- Cause minimum obstruction to the view of the production process, and
- Enable essential work to be carried out on installation and/or replacement of tools and also for maintenance by restricting access only to the area where the work has to be done, if possible without the guard or protection device having to be dismantled.

5.3.3.2 Special Requirements for Guards

SAF0640: Fixed guards must be securely held in place and fixed by systems that can be opened only with tools. Where possible, guards must be unable to remain in place without their attachment fixings.

SAF0650: Movable guards must, as far as possible, remain fixed to the machinery/equipment when open, and have an interlocking device to prevent moving parts starting up when the parts can be accessed and to give a stop command whenever they are no longer closed.

5.3.3.3 Adjustable Guards Restricting Access

SAF0670: Adjustable guards restricting access to those areas of the moving parts strictly necessary for the work must be adjustable manually or automatically according to the type of work involved, and be readily adjustable without the use of tools.

5.3.4 Protection Against Other Hazards

5.3.4.1 Electrical Supply

SAF0690: Where machinery/equipment has an electricity supply, it must be designed, constructed and equipped so that all hazards of an electrical nature are or can be prevented.

SAF0700: The specific requirements relating to electrical equipment designed for use within certain voltage limits applies to machinery/equipment that is subject to those limits.

5.3.4.2 Static Electricity

SAF0710: Machinery/equipment must be designed and constructed to prevent or limit the build-up of potentially dangerous electrostatic charges and/or be fitted with a discharging system.

5.3.4.3 Energy Supply Other than Electricity

SAF0720: Where machinery/equipment is powered by energy other than electricity (e.g., hydraulic, pneumatic or thermal energy, etc.), it must be so designed, constructed, and equipped to avoid all potential hazards associated with these types of energy.

5.3.4.4 Errors of Fitting

SAF0730: Errors likely to be made when fitting or refitting certain parts that could be a source of risk must be made impossible by the design of such parts or by information given on the parts themselves and/or the housings. The same information must be given on moving parts and/or their housings where the direction of movement must be known to avoid a risk.

SAF0740: Where a faulty connection can be the source of risk, incorrect fluid connections, including electrical conductors, must be made impossible by the design or, failing this, by information given on the pipes, cables, etc. and/or connector blocks.

5.3.4.5 Extreme Temperatures

SAF0750: Steps must be taken to eliminate any risk of injury caused by contact with or proximity to machinery/equipment parts or materials at high or very low temperatures.

SAF0760: Assess the risk of hot or very cold material being ejected. Where this risk exists, the necessary steps must be taken to prevent it or, if this is not technically possible, to render it non-dangerous.

5.3.4.6 Fire

SAF0770: Machinery/equipment must be designed and constructed to avoid all risk of fire or overheating posed by the machinery/equipment itself or by gases, liquids, dust, vapors or other substances produced or used by the machinery/equipment.

5.3.4.7 Explosion

SAF0780: Machinery/equipment must be designed and constructed to avoid any risk of explosion posed by the machinery/equipment itself or by gases, liquids, dust, vapors or other substances produced or used by the machinery/equipment.

SAF0790: The same precautions must be taken if the designer foresees use of the machinery/equipment in a potentially explosive atmosphere. Electrical equipment forming part of the machinery/equipment must conform, as far as the risk from explosion is concerned, to the provision of the specific requirements in force.

5.3.4.8 Noise

SAF0800: Machinery/equipment must be designed and constructed such that risks resulting from the emission of airborne noise are reduced to the lowest level taking account of technical progress and the availability of means of reducing noise, in particular at the source.

5.3.4.9 Vibration

SAF0810: Machinery/equipment must be designed and constructed such that risks resulting from vibrations produced by the machinery/equipment are reduced to the lowest level, taking account the availability of means of reducing vibration, in particular at the source.

5.3.4.10 Radiation

SAF0820: Machinery/equipment must be designed and constructed such that any emission of radiation is limited to the extent necessary for its operation and that the effects on exposed persons are non-existent or reduced to non-dangerous proportions.

5.3.4.11 Laser Equipment

SAF0840: Where laser equipment is used, the following provisions should be taken into account:

- Laser equipment on machinery/equipment must be designed and constructed so as to prevent any accidental radiation.
- Laser equipment on machinery/equipment must be protected so that effective radiation, radiation produced by reflection or diffusion and secondary radiation do not damage health.
- Optical equipment for the observation or adjustment of laser equipment on machinery/equipment must be such that no health risk is created by the laser.

5.3.4.12 Emissions of Dust, Gases, etc.

SAF0850: Machinery/equipment must be so designed, constructed and/or equipped such that risks due to gases, liquids, dust, vapors, and other waste materials which it produces can be avoided, contained and/or evacuated.

SAF0860: Where machinery/equipment is not enclosed during normal operation, the devices for containment and/or evacuation must be situated as close as possible to the source emission.

5.3.4.13 Risk of Being Trapped in a Machine

SAF0870: Machinery/equipment must be designed, constructed or fitted with a means of preventing an exposed person from being enclosed within it or, if that is impossible, with a means of summoning help.

5.3.4.14 Risk of Slipping, Tripping, or Falling

SAF0880: Parts of the machinery/equipment where persons are liable to move about or stand must be designed and constructed to prevent persons from slipping, tripping, or falling on or off these parts.

5.3.5 Maintenance

5.3.5.1 Machinery/Equipment Maintenance

SAF0890: Adjustment, lubrication and maintenance must be located outside danger zones. It must be possible to carry out adjustment, maintenance, repair, cleaning and servicing operations while machinery/equipment is at a standstill. If the above conditions cannot be satisfied for technical reasons, these operations must be possible without risk.

5.3.5.2 Access to Operating Position and Servicing Points

SAF0920: The designer must provide means of access (stairs, ladders, catwalks, etc.) to allow safe access to all areas used for production, adjustment, and maintenance operations.

5.3.5.3 Isolation of Energy Sources

SAF0930: All machinery/equipment must be fitted with means to isolate it from all energy sources. Such isolators must be clearly identified. They must be capable of being locked if reconnection could endanger exposed persons. In the case of machinery/equipment supplied with electricity through a plug capable of being plugged into a circuit, separation of the plug is sufficient. The isolator must be capable of being locked also where an operator is unable, from any of the points to which she or he has access, to check that the energy is still cut off.

SAF0940: After the energy is cut off, it must be possible to dissipate normally any energy remaining or stored in the circuits of the machinery/equipment without risk to exposed persons.

As an exception to the above requirements, certain circuits may remain connected to their energy sources in order, for example, to hold parts, protect information, light interiors, etc. In this case, special steps must be taken to ensure operator safety.

5.3.5.4 Cleaning of Internal Parts

SAF0960: The machinery/equipment must be designed and constructed in such a way that it is possible to clean internal parts which have contained dangerous substances or preparations without entering them; any necessary unblocking must also be possible from the outside. If it is absolutely impossible to avoid entering the machinery/equipment, the designer must take steps during its construction to allow cleaning to take place with the minimum of danger.

5.3.6 Indicators

5.3.6.1 Information Devices

SAF0970: The information needed to control machinery/equipment must be unambiguous and easily understood. It must not be excessive to the extent of overloading the operator.

SAF0980: Where the health and safety of exposed persons may be endangered by a fault in the operation of unsupervised machinery/equipment, the machinery/equipment must be equipped to give an appropriate acoustic or light signal as a warning.

5.3.6.2 Warning Devices

SAF0990: Where machinery/equipment is equipped with warning devices (such as signals, etc.), these must be unambiguous and easily perceived. The operator must have facilities to check the operation of such warning devices at all times.

SAF1000: The specific requirements concerning colors and safety signals must be complied with.

5.3.6.3 Warning of Residual Risks

SAF1010: Where risks remain despite all the measures adopted or in the case of potential risks which are not evident (e.g., electrical cabinets, radioactive sources, bleeding of a hydraulic circuit, hazard in an unseen area, etc.), the designer must provide warnings. Such warnings should preferably use readily understandable pictograms.

5.3.6.4 Marking

SAF1020: All machinery/equipment must be marked legibly and indelibly with the following minimum particulars:

- Name and address of the designer
- Designation of series or type
- Serial number, if any
- The year of construction
- Electric power data

SAF1030: Where the machinery/equipment is intended for use in a potentially explosive atmosphere, this must be indicated on the machinery/equipment.

SAF1040: Machinery/equipment must also bear full information relevant to its type and essential to its safe use (e.g., maximum speed of certain rotating parts, maximum diameter of tools to be fitted, mass, etc.).

SAF1050: Where a machine part must be handled during use with lifting equipment, its mass must be indicated legibly, indelibly, and unambiguously. Interchangeable equipment must bear the same information.

5.3.6.5 Instructions

SAF1060: All machinery/equipment must be accompanied by instructions including at least the following:

- A repeat of the information with which the machinery/equipment is marked, except the serial number, with any appropriate additional information to facilitate maintenance (e.g., addresses of the importer, repairers, etc.)
- Foreseen use of the machinery/equipment
- Workstation(s) likely to be occupied by operators
- Instructions for safe service, use, handling, assembly, dismantling, adjustment, maintenance, along with training instructions

Instructions should draw attention to ways in which the machinery/equipment should not be used.

SAF1080: The instructions must contain the drawings and diagrams necessary for putting into service, maintenance, inspection, checking of correct operation and, where appropriate, repair of the machinery/equipment and all useful instructions in particular with regard to safety.

SAF1090: Any literature describing the machinery/equipment must not contradict the instructions as regards safety aspects. The technical documentation describing the machinery/equipment must give information regarding the airborne noise emissions and, in the case of hand-held and/or hand-guided machinery/equipment, information regarding vibration.

SAF1100: Where necessary, the instructions must give the requirements relating to installation and assembly for reducing noise or vibration (e.g., use of dampers, type and mass of foundation block, etc.).

SAF1110: The instructions must give the information concerning airborne noise emissions by the machinery/equipment, either the actual value or a value established on the basis of measurements made on identical machinery/equipment.

SAF1120: If the designer foresees that the machinery/equipment will be used in a potentially explosive atmosphere, the instructions must give all the necessary information.

SAF1130: In the case of machinery/equipment that may also be intended for use by non-professional operators, the wording and layout of the instructions for use, while respecting the other essential requirements mentioned above, must take into account the level of general education and acumen that can reasonably be expected from such operators.

5.4 Additional Requirements

SAF1150: Requirements on workplace and construction safety that have an influence on the design must be followed according to OSHA Construction standards.

SAF1160: The designer of a product or subsystem shall identify which requirements apply. If no requirements are available that cover the scope of the product or subsystem, it must be determined what other legislation is needed to ensure a safe design.

SAF1170: In the case of buildings and the like, other norms and standards apply that do not fall under the scope of this document.

6 Appendix

6.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
ES&S	Environmental Safety and Security
ICD	Interface Control Document
IPT	Integrated Product Team
LBA	ngVLA Long Baseline Array
ngVLA	Next Generation VLA
OSHA	Occupational Safety and Health Administration
RD	Reference Document
RFI	Radio Frequency Interference
SBA	ngVLA Short Baseline Array
TBD	To Be Determined
VLA	Jansky Very Large Array
VLBA	Very Long Baseline Array

Preliminary System Architecture

020.10.20.00.00-0002-DWG

Status: **RELEASED**

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Change Record

Version	Date	Author	Notes/Changes
01	2018-02-28	RJS	Started first draft of MagicDraw SysML model export
02	2018-03-29	RJS	Number of corrections outside of the CSW work package; focus on BDDs and Context IBDs
03	2018-03-29	RJS	Added Back End Enclosure Assembly DWG
04	2018-08-15	RJS	Major edit after MagicDraw training; recast as functional, logical, and structural models
05	2018-08-16	RJS	Clean-up to match current Reference design; elaboration of CSW logical architecture, added DSP domain, added DBE IBD, etc.
06	2018-10-08	RAH, RJS	Export for Internal Pre-Decadal Review; updated CSW Architecture in both logical and structural model; other updates throughout
07	2019-02-08	RAH, RJS	Updates to SciOps model by RAH, reflecting latest CSW architecture; revised export format from DWG set to document, and restricted export to the highest-level drawings only
08	2019-03-29	RJS, RAH	Added documentation for major drawings included in restricted export
09	2019-04-01	RJS	Added Digital Signal Processing Domain Drawing
10	2019-04-03	RJS	Added 18m Reflector Antenna Scope DWGs
11	2019-04-04	RJS	Added logical system IBD to show interfaces at subsystem level
12	2019-04-15	RJS	Fixed cover for workflow; fixed paragraph alignment. Ready for workflow
A	2019-07-09	Lear	Incorporated minor edits by M. McKinnon; prepared document for approvals and release

Table of Contents

1 Introduction

1.1 Purpose

This document presents a preliminary architecture of ngVLA that should guide the development of the facility. The system-level architecture model is implemented in the Systems Modeling Language (SysML). This document is an export from that model and provides an abbreviated description of the system architecture. This document is intended as a primer, with the full details captured in the SysML model.

1.2 Scope

The scope of this document is the entire ngVLA project over its full lifecycle. This includes not just the scientific facility, but the supporting infrastructure and personnel, with input at all stages of development from design, to operations, and disposal.

2 Related Documents

2.1 Applicable Documents

The following documents are applicable to the extent specified.

Reference No.	Document Title	Rev / Doc. No.
AD01	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD02	Science Requirements	020.10.15.00.00-0001-REQ
AD03	Reference Observing Program	020.10.15.05.10-0001-REP
AD04	Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD05	System Requirements	020.10.15.10.00-0003-REQ
AD06	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK
AD07	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK
AD08	Product Breakdown Structure	020.10.10.05.00-0001-LIS
AD09	Requirements Verification Traceability Matrix	020.10.15.00.00-0002-REQ
AD10	Operations Concept	020.10.05.00.00-0002-PLA
AD11	Computing & Software Reference Design Architecture	020.50.00.00.01-0002-DSN

3 Overview of the System Architecture

This document is generated from the Systems Modeling Language (SysML) ngVLA architecture model and provides an abbreviated description of the system architecture. The full model includes over 100 diagrams that represent lower-level details of the architectural design, and the model should be inspected when seeking these lower-level details. This document aims to provide a high-level view of both the structure of the model and the system architecture it represents.

The model is structured with the long-term goal of providing sufficient definition of each system element to enable implementation by a domain expert/engineer. In most cases, this entails defining for each element:

1. the requirements it must satisfy,
2. the activities it must perform, and
3. the interfaces to other elements.

With this level of definition of each major system element, various implementations can be explored as part of the system conceptual design. The requirements allocation process and interface definition also allows traceability for verification, at both the system level and the element level.

Considering these goals, the model structure includes

1. the requirements for the system, their flow-down, and allocation to system elements;
2. a logical model that has the necessary elements to satisfy the functional requirements; and
3. a structural model that fully defines the proposed design for implementation.

The logical model intends to define the system behaviors and elements that are necessary to satisfy the requirements. This is a "black box" model that focuses solely on inputs, operations and outputs, without dictating any specific implementation of the element.

The structural model by necessity imposes an architectural solution, satisfying the functions identified in the logical model. The structural model is one solution among many, and as the design matures, multiple structural models may be built for specific subsystems as part of their trade studies. A complete structural model defines all the deliverables that make up the system.

The system architecture aims to be

1. loosely coupled, with high cohesion within subsystems, to enable parallel development with clean interfaces (i.e. elements that strongly depend on each other are aggregated into subsystems, and interfaces between subsystems aim to be well-defined and relatively simple);
2. flexible, scalable, and extensible to adjust to evolving requirements and programmatic constraints as the design progresses. As stated in the Science Requirements [AD02], "The primary science requirement for the ngVLA is to be flexible enough to support the breadth of scientific investigations that will be proposed by its creative scientist-users over the decades-long lifetime of the instrument"; and
3. maintainable over the lifetime of the instrument. Maintenance and operations activities are considered early in the design of the system, with flow-down from the maintenance concept [AD10] to the stakeholder requirements [AD04] and to the logical model.

The structural model presently describes an architecture that is consistent with the product breakdown structure (PBS) [AD08] of the ngVLA reference design. The architecture will continue to be developed and elaborated through the conceptual design phase of the project. Alternative structural models (i.e. implementations) will be explored at the subsystem level as part of the conceptual design of the facility.

This document is best read in conjunction with [AD11], [AD06], and [AD07]. These documents provide additional details on the architecture of the software and computing systems and the antenna electronics. These documents should be considered incorporated by reference.

4 Model Structure

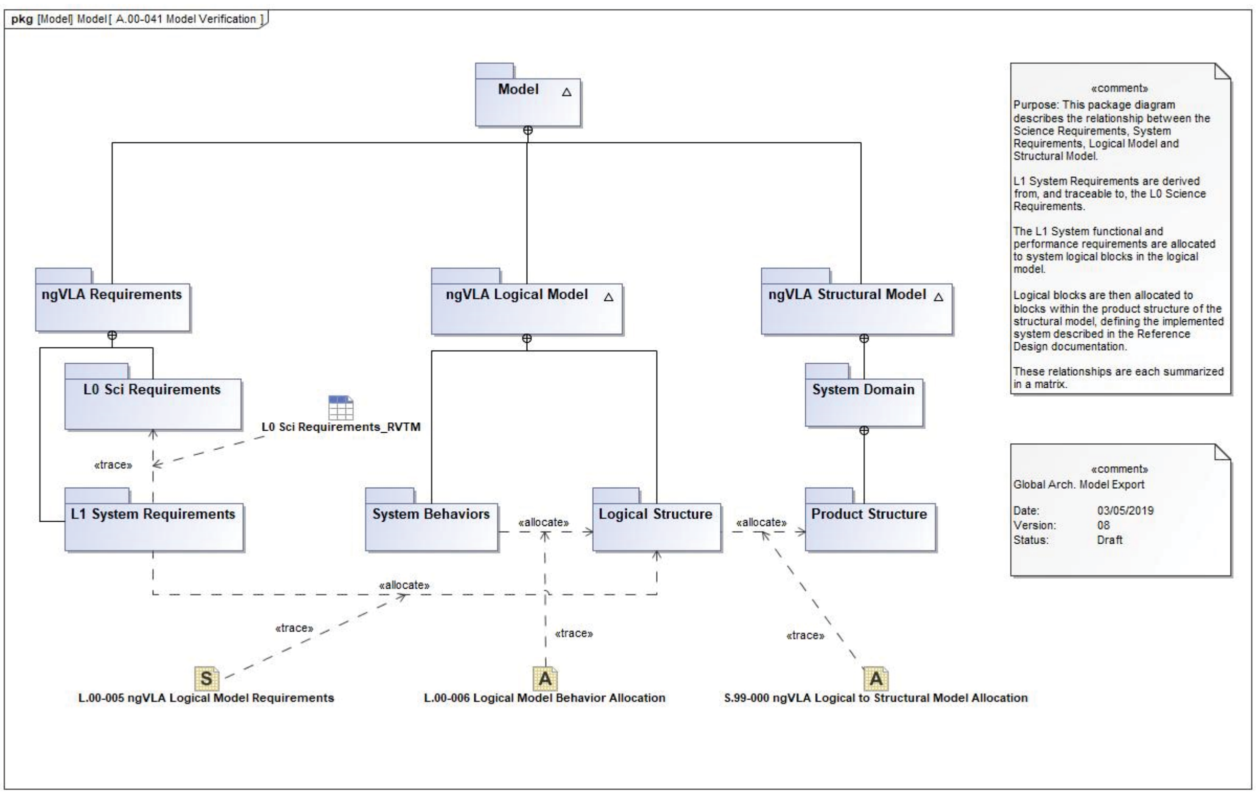
4.1 Diagram: A.00-041 Model Verification

Verification and traceability are integral to this architectural model. This package diagram describes the relationship between the Science Requirements, System Requirements, Logical Model and Structural Model.

The L1 System Requirements are derived from, and traceable to, the L0 Science Requirements. This traceability is captured in the Requirements Verification Traceability Matrix (RVTM) [AD09]. The L1 System functional and performance requirements are linked to system logical blocks in the logical model that must satisfy each requirement.

The functions of logical blocks are then allocated to blocks within the product structure of the structural model, defining the implemented system described in the design documentation. This maintains a separate implementation-agnostic logical structure and behavior model, while also documenting the implementation described in the design documentation (captured in the product structure of the structural model).

These relationships are each summarized in a "satisfy" or "allocation" matrix as appropriate. Any gaps in the current requirements flow down or allocation within the model are evident in these matrices and can be used as a metric for current design completeness and as a guide for future verification activities as the design matures. All three verification matrices are included in Appendix 8.2.



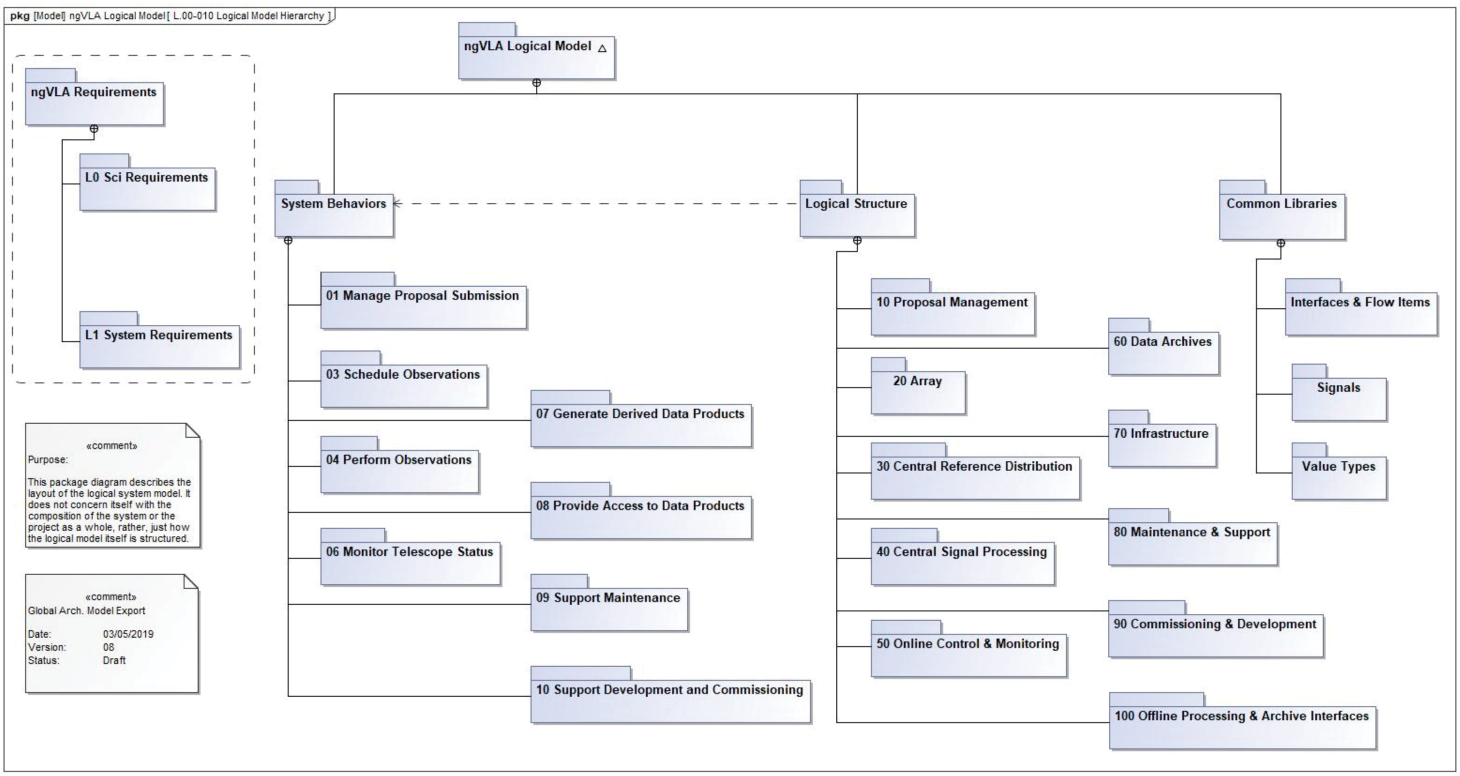
5 Logical Model

5.1 Diagram: L.00-010 Logical Model Hierarchy

As described previously, the logical model is an abstraction, identifying the system behaviors that are required to support the identified use cases from the life cycle models (maintenance, operation, commissioning, etc.) and science use cases.

The behaviors the system must perform are contained within the system behaviors package, and are aggregated into the various stages of a proposal's life from submission through execution and the delivery of data products. Support functions identified in the lifecycle concepts are also included, with an emphasis on maintenance, development and commissioning activities.

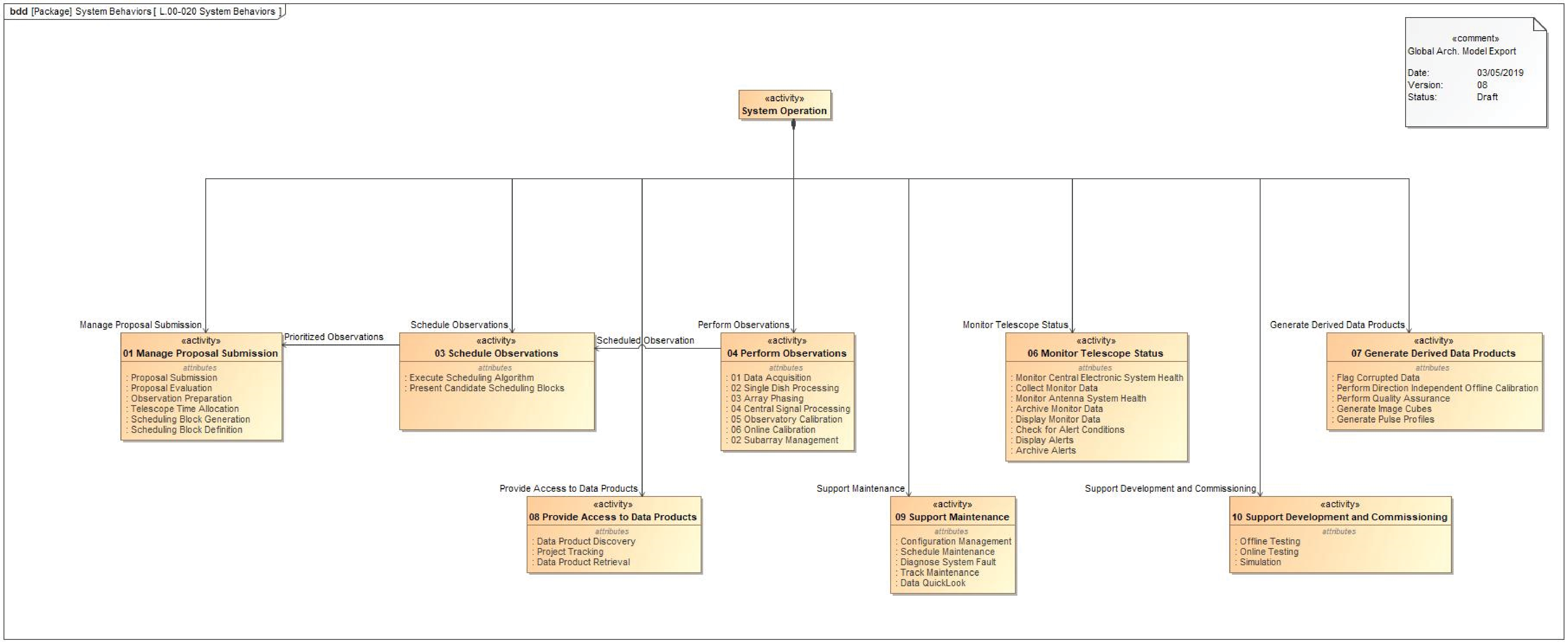
The logical structure includes packages tailored to performing the identified behaviors. At this level of abstraction, the implementation is not defined, solely that a system element must perform the identified action to complete the use case. This aids in the identification of functional blocks required within the system.



5.2 Diagram: L.00-020 System Behaviors

This block definition diagram describes the high-level activities that must be performed by the system in operation, starting with the various stages of a proposal's life from submission through execution and the delivery of data products. Support functions identified in the life cycle concepts (e.g., operations and maintenance concepts) are also described.

Each major activity is then decomposed into its respective sub-tasks. For example, the major activity "Manage Proposal Submission" includes the sub-tasks "Proposal Submission," "Proposal Evaluation," "Telescope Time Allocation," and so on. This hierarchical decomposition of activities continues until the lowest-level activities can be allocated to a single functional block in the logical architecture.



Selected elements:

Manage Proposal Submission: This activity addresses the preparation and submission of proposals by PIs, and the evaluation of proposals by Observatory staff. The process starts with the proposal data compilation and ends with a prepared observation(s) that has been approved for scheduling.

Schedule Observations: This activity concerns the scheduling of prepared observations based on established criteria such as the scientific priority, system configuration requirements, system status, and environmental conditions. It ends with the delivery of scheduling blocks for execution by the system.

Perform Observations: This activity accepts the delivered scheduling blocks and executes them. Multiple observations may be conducted simultaneously as determined by the scheduler through the use of sub-arrays. This high-level activity includes the entire data capture and processing chain. Processing may be single-dish or central (such as the summed array output or cross-correlation), and additional array phasing and on-line (near real-time) calibration activities are also included. This activity ends with the generation of fundamental data products, such as visibility data or summed array voltage streams.

Monitor Telescope Status: This activity includes the monitoring of system health and the environment, as well as the collection, archiving and display of this monitor data. The monitoring activity includes the processing of monitor data to identify values meaningful to operators and engineers through system alerts.

Generate Derived Data Products: This activity accepts the fundamental data products from activity block Perform Observations and combines these with monitor data to produce data flags and additional quality assurance corrections. These quality-assured data products are then processed to generate higher level data products such as image cubes or pulse profiles depending on operating mode.

Provide Access to Data Products: This activity provides access to fundamental or derived data products to users. This includes the search and discovery of relevant data products as well as their delivery.

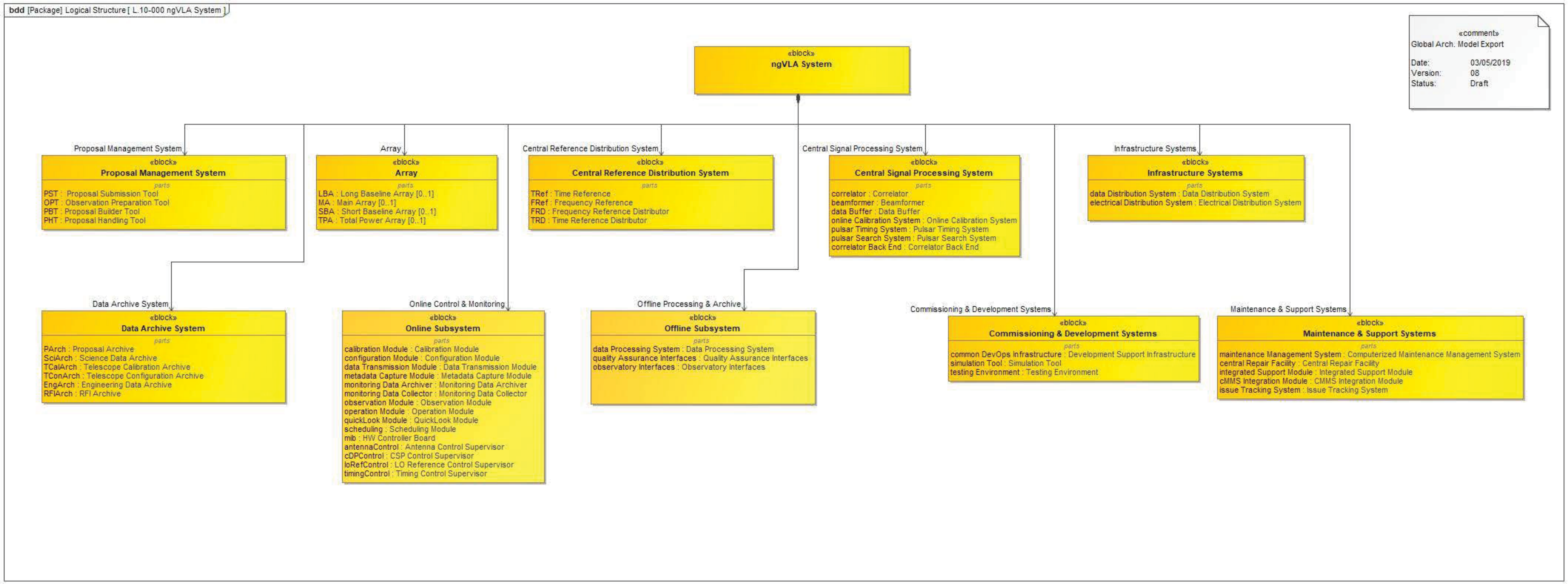
Support Maintenance: In addition to the functional operational activities, the system must support maintenance by operations and maintenance personnel. This activity block includes all ancillary activities necessary for system maintenance, such as tracking the system configuration status, scheduling maintenance activities, tracking maintenance activities, and diagnosing system faults.

Support Development and Commissioning: Development and commissioning activities are distinct from maintenance, and this activity block includes online and offline testing activities, and the simulation of observations.

5.3 *Diagram: L.10-000 ngVLA System*

This block definition diagram shows the major logical blocks of the system. Logical model blocks are allocated the behaviors described in diagram L.00-020 and its subordinates, ensuring that the lowest-level identified activities are completed by a single logical block. Complex activities may then be performed by composite assemblies (made up of multiple low-level blocks).

The logical architecture is structured in a parallel way to the activities, with proposal management activities performed by a proposal management system, and so on. The mapping from behaviors to logical model blocks is summarized in an allocation matrix, L.00-006, located in the appendix.



Selected elements:

Proposal Management System: The proposal management system and its sub-components execute the activities of the Manage Proposal Submission activity block.

Array: The array is the collection of antennas that perform the data acquisition and single dish processing activities within the Perform Observations activity block. It includes the currently defined major sub-arrays: the main array, the short baseline array and the long baseline array.

Central Reference Distribution System: The central reference distribution system provides the time and frequency references necessary to perform the array phasing within the Perform Observations activity block.

Central Signal Processing System: The central signal processing system performs the summed array, cross-correlation and other processing activities that manipulate multiple array elements in tandem. These activities are a subset of the Perform Observations activity block.

Infrastructure Systems: The infrastructure systems supply services, such as electrical power, to the array and central signal processing system.

Data Archive System: The data archive system stores the fundamental and derived data products and makes them available to users by performing the activities within the Provide Access to Data Products activity block.

Online Control & Monitoring: The online subsystem performs the Monitor Telescope Status activities, and the Generate Derived Data Products sub-activities that must be performed in near real-time.

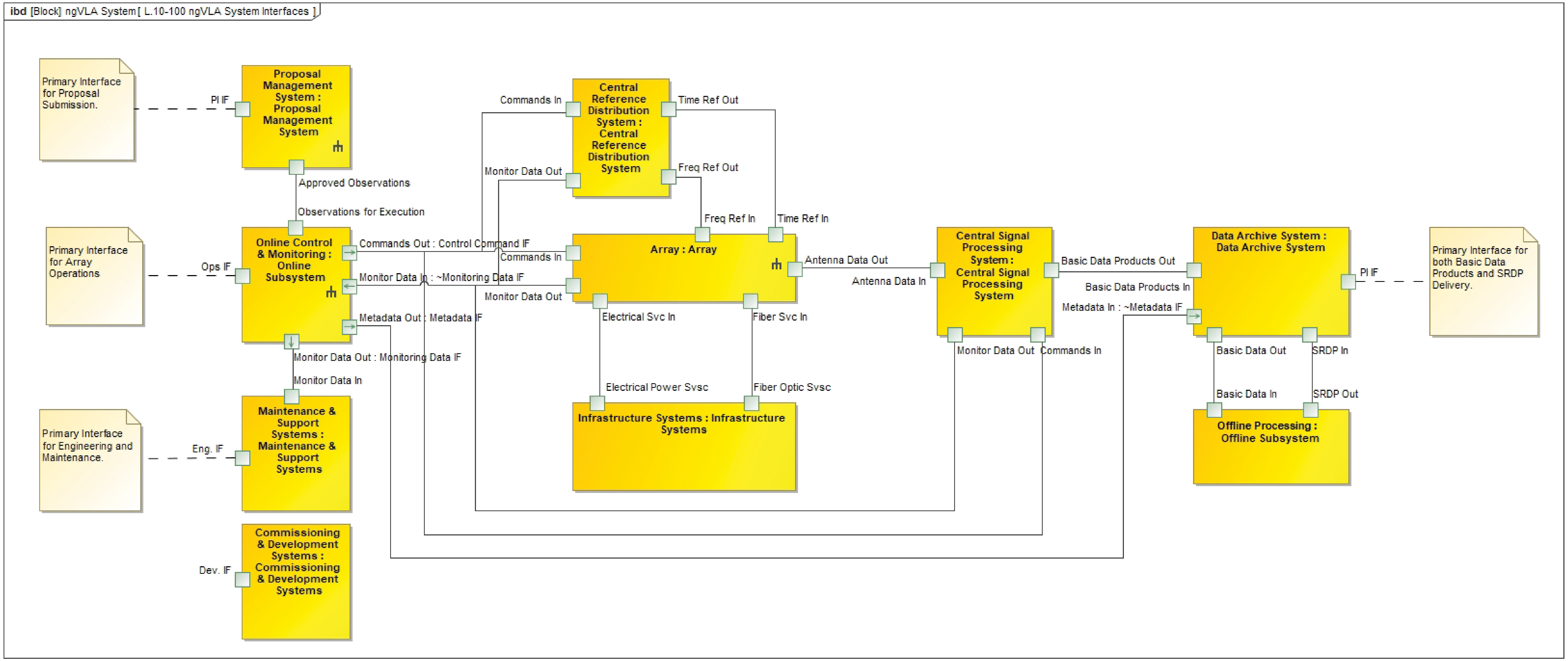
Offline Processing & Archive: The offline subsystem performs the Generate Derived Data Products sub-activities that can be performed post-facto from recorded data. This includes the generation of higher-level data products such as image cubes or pulse profiles depending on operating mode.

Commissioning & Development Systems: The commissioning and development system components execute the activities of the Support Development and Commissioning activity block.

Maintenance & Support Systems: The components of the maintenance and support systems block execute the activities of the Support Maintenance activity block.

5.4 Diagram: L.10-100 ngVLA System Interfaces

This internal block diagram identifies the interfaces between each major subsystem of the logical model. At this level of abstraction, the interfaces are clean and simple, with a high degree of containment within each subsystem and a minimal number of interactions. The primary input to the system are proposals in the upper left, with data products delivered to users at the far right. Operations and Maintenance group interfaces are also shown on the left hand side of the diagram.



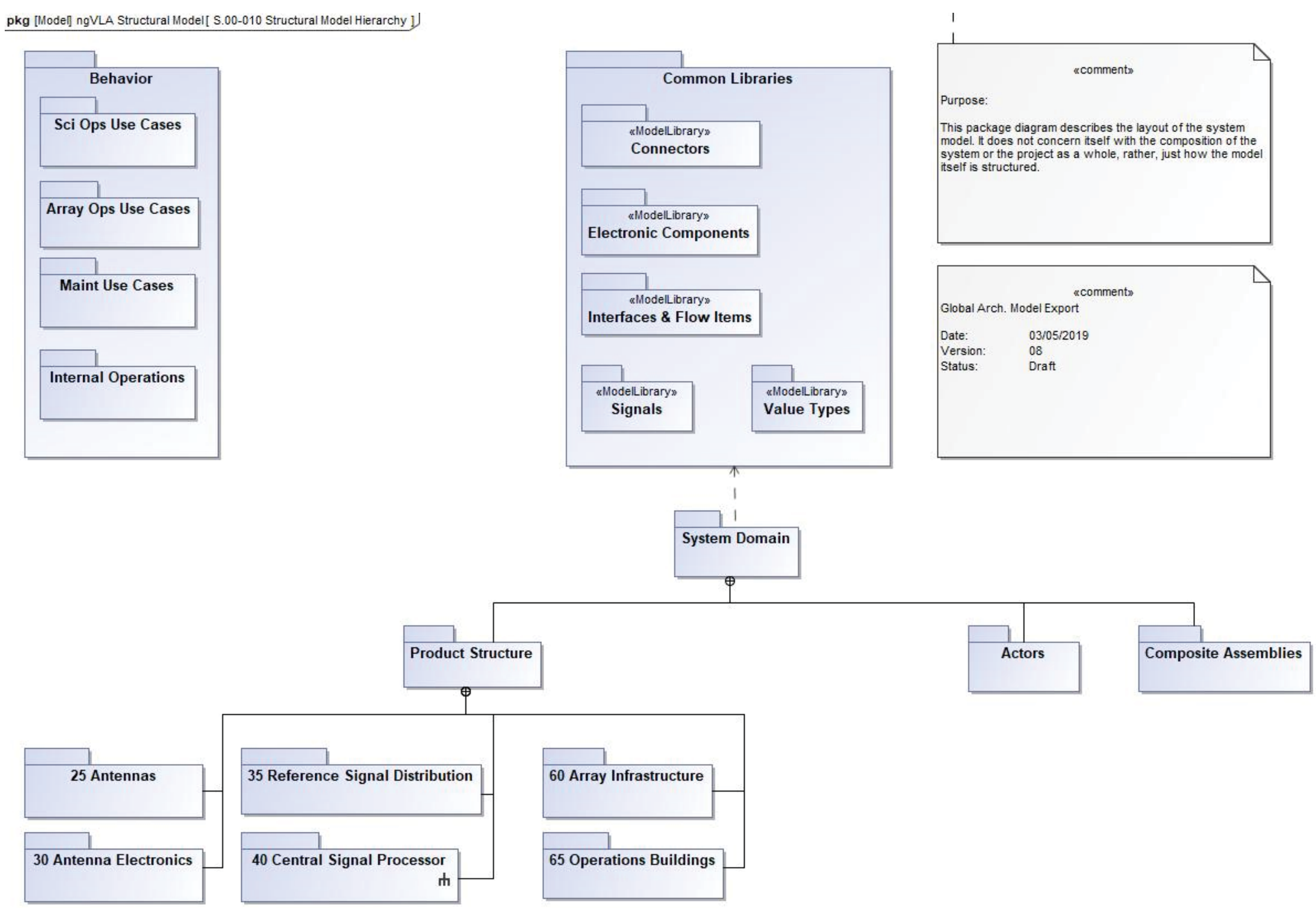
6 Structural Model

6.1 Diagram: S.00-010 Structural Model Hierarchy

This package diagram shows the layout of the structural model. This model best describes the proposed physical architecture. Rather than abstractions (like the logical model), each block in the structural model is a project deliverable (either hardware or software).

The structural model is representative of the implemented design and its lower levels are consistent with the Product Breakdown Structure (PBS). The Product Structure section of the model matches the organization of the project, with packages first sorted by IPT and then individual work packages from the PBS shown at the next level of the hierarchy.

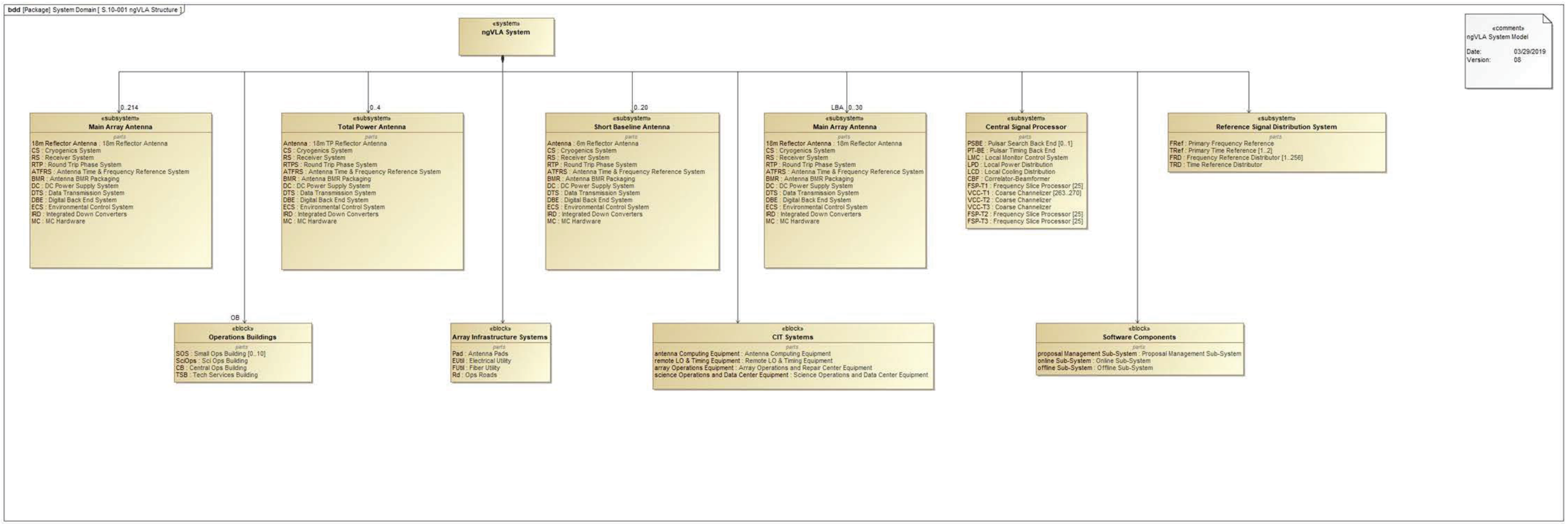
The model also includes actors who interact with the system (such as principal investigators, operators, maintenance technicians and engineers) and composite assemblies. The latter describe aggregated components in the system that are made up of deliverables from multiple work packages. An example is an array element, made up of the antenna, and each work package within the antenna electronics IPT (Front End, Cryogenics, Integrated Receiver Digitizer, etc.).



6.2 Diagram: S.10-001 ngVLA Structure

This block definition diagram is the highest-level view of the ngVLA System. It shows all components (both hardware and software) that make up the functioning facility in operation. Within each major block, individual components that are aggregated into the assembly are noted as parts. For example, a "Main Array Antenna" is made up of an 18m reflector antenna, a cryogenic system, a receiver system, and so on. Each of these parts is in-turn made up of many sub-components in the structural model hierarchy.

Where multiple copies of a part may exist in the architecture, this is shown with the multiplicity of the composition arrow. For example, anywhere from 0 to 214 Main Array Antennas could be included in an operational instance of the ngVLA system.



Selected elements:

MAA: All the antennas within the array share a common high-level architecture. They also share common receiving and single dish processing requirements in the current implementation. The Main Array Antenna consists of an 18m antenna structure and all electronics and embedded software necessary for antenna motion, data acquisition, and single-dish data processing.

TPA: The total power antenna shares the same overall architecture as the Main Array Antenna, but is designated with a different antenna structure, the TP Reflector Antenna. While this part differs in the model it is hoped that its requirements can be achieved with the 18m reflector antenna of the main array.

SBA: The short baseline array antenna shares the overall architecture of the Main Array Antenna with the exception of the antenna structure, which is replaced by a 6m reflector antenna.

LBA: The long baseline array antenna presently shares the architecture and parts of the main array antenna.

CSP: The Central Signal Processor block is the realization of the Central Signal Processing System in the logical model. It includes the NRCC FSA Correlator-Beamformer, a pulsar engine, and ancillary systems necessary for operation.

RSD: The reference signal distribution system is the realization of the Central Reference Distribution System in the logical model. It provides time and frequency references to the antennas in the array as well as to the central signal processor.

CIT: The scientific computing and information technology systems are the physical hardware on which the online and offline systems run. It also includes the necessary IT infrastructure to support the monitor and control system.

SW: The SW components are the realization of the Proposal Management system, Online System, and Offline System within the logical model. It includes both the software systems, compute resources and IT infrastructure necessary to execute the allocated activities.

OB: The operations buildings implement a subset of the Infrastructure Systems of the logical model that provide services to the central electronics (central signal processor, reference signal distribution system), along with other necessary buildings to satisfy the operations and maintenance concept.

AIS: The array infrastructure systems implement a subset of the Infrastructure Systems of the logical model that provide services to the antennas within the array such as power and fiber optic connectivity.

6.3 Diagram: S.10-101 Sci Ops Domain

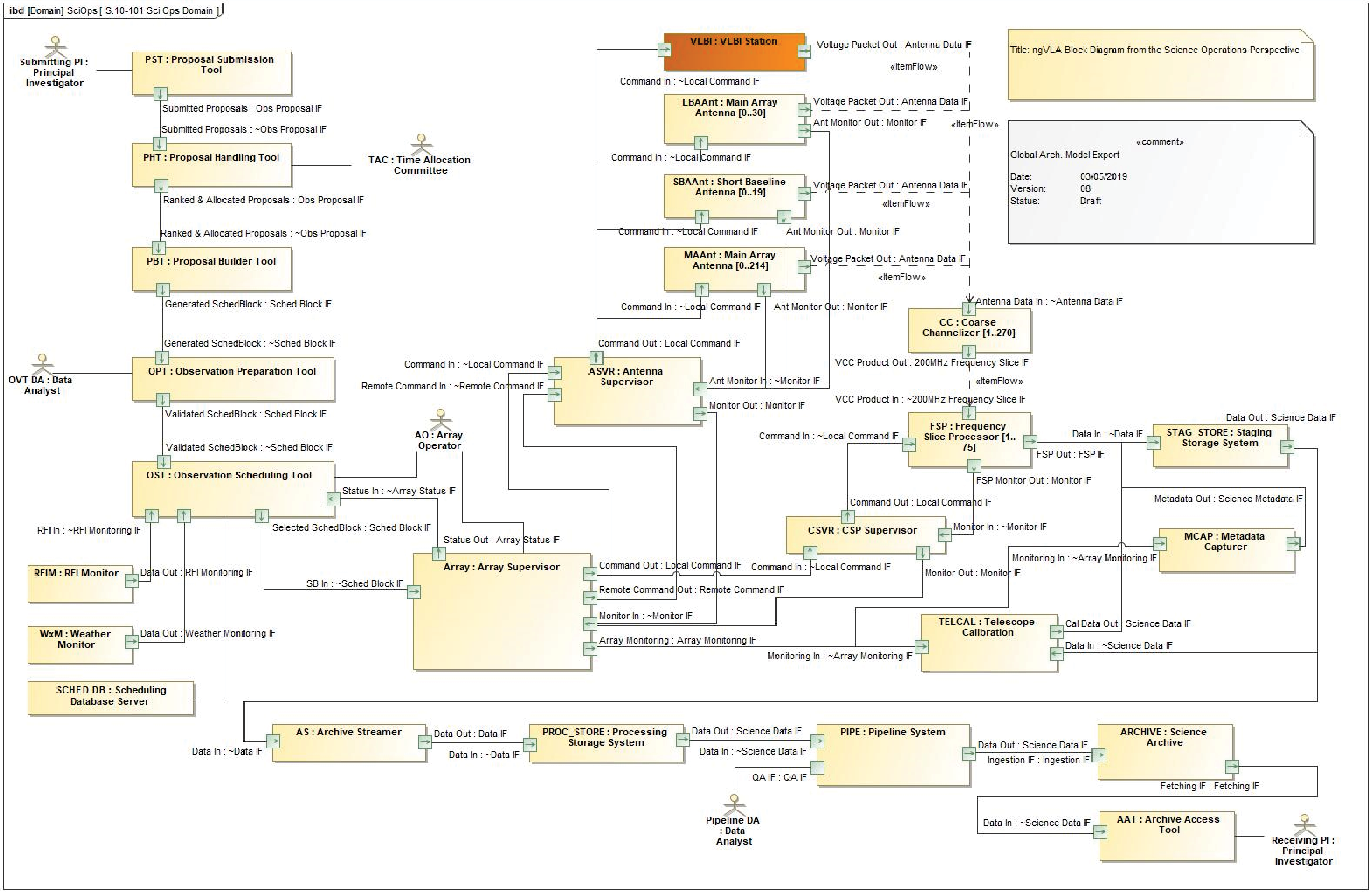
Within the structural model, the architecture can be represented for individual domains. This internal block diagram shows the Science Operations Domain, i.e. how the system looks from a science operations perspective, including the actors that are relevant to the science operations of the system.

The diagram provides an end-to-end view of the system starting with the submission of a proposal by a Principal Investigator (PI) using the Proposal Submission Tool, and ending with the PI accessing their science ready data products through the Archive Access Tool.

Proposals progress through a Time Allocation Committee and technical review, are built into suitable observations with QC checks, and are processed by a scheduling tool. An array supervisor configures the various array elements and the central signal processor, executes the observation, and stages the low-level data for archiving. Post processing systems prepare the high-level user data products that are stored in the same archive.

The interfaces shown note the directionality of flow from one system to another, and the definition of each interface. For example, "submitted proposals" flow from the PST to the PHT over an "Obs Proposal" Interface. These interfaces are proxy ports (abstractions) on this diagram for simplicity and readability, but lower levels of the architecture will include definitions of both the physical ports that provide interfaces and data definitions where appropriate. The model may be used for interface definition at more mature stages of the design.

Title: Preliminary System Architecture	**Authors:** Selina, Hiriart	**Date:** 2019-07-09
Document No.: 020.10.20.00.00-0002-DWG		**Revision:** A



Selected elements:

Submitting PI: The submitting PI is a principal investigator who prepares and submits a proposal for an observation. They interact with the proposal submission tool.

PST: The proposal submission tool is the primary tool for a principal investigator to prepare a proposal, in a standardized format, for evaluation.

PHT: The proposal handling tool retrieves proposals submitted by PIs and makes them accessible to the time allocation committee for evaluation. Its outputs are ranked and time-allocated proposals.

TAC: The TAC is the time allocation committee. This actor represents a member of the TAC who interacts with submitted proposals for evaluation purposes through a proposal handling tool.

PBT: The proposal builder tool takes the ranked and time-allocated proposals and parses the projects into scheduling blocks for execution.

OPT: The observation preparation tool allows a data analyst to verify and modify the scheduling blocks generated by the PBT and validate them prior to scheduling.

OVT DA: The Observation Validation Team Data Analyst evaluates the scheduling blocks generated by the PBT using an observation preparation tool, resulting in validated scheduling blocks than can be scheduled for observation.

OST: The observation scheduling tool takes the validated scheduling blocks and dynamically schedules their execution. The scheduling algorithm accounts for the expected presence of RFI during the observation, the weather conditions, the array status, and the project status.

RFIM: The RFIM block is the online processing system that catalogs known interferers in the accessible sky, their ephemerides, and signal properties.

WxM: The WxM is the collection of weather stations, the atmospheric phase interferometer, any ancillary environmental metrology systems, and associated monitoring software used to determine atmospheric conditions across the extent of the array.

SCHED DB: The scheduling database server provides the status of all approved projects, which scheduling blocks have been completed, which remain, and relevant metadata to prioritize scheduling blocks for execution.

Array: The array supervisor executes the scheduling blocks provided by the OST. It provides array status information to both the OST and the Array Operator, the latter through a GUI interface. Commands are issued to array antennas and other systems necessary for online operation.

AO: The array operator is the human supervisor of the array. The operators interact with both the observation scheduling tool to manipulate in progress or pending observations, as well as with the array supervisor software system to establish array status through a GUI interface.

ASVR: The antenna supervisor receives high-level commands from the array supervisor, determines the required configuration of the antenna subsystems, and dispatches local commands within the antenna.

MAAnt: The MAAnt is an instantiation of the main array antenna. Multiple antennas may be present in the array as indicated by the multiplicity property.

SBAAnt: The SBAAnt is an instantiation of the short baseline array antenna. Multiple antennas may be present in the array as indicated by the multiplicity property.

LBAAnt: The LBAnt is an instantiation of the main array antenna at a long baseline array site. Multiple antennas may be present in the array as indicated by the multiplicity property.

VLBI: The VLBI block is a representation of external resources (e.g., the GBT) that may be cross-correlated with the ngVLA in real time.

CC: The CC is a representation of a Very Coarse Channelizer in the Correlator-Beamformer of the Central Signal Processor.

FSP: The FSP is a representation of a Frequency Slice Processor node in the Correlator-Beamformer of the Central Signal Processor.

CSVR: The CSP Supervisor receives high-level commands from the array supervisor and turns them into to low-level commands for execution by the CSP subsystems such as the VCC and FSP blocks.

TELCAL: The telescope calibration system computes the near-real-time calibration solutions necessary for array phasing.

STAG_STORE: The staging storage system is a buffer system that ingests the high data rate delivered by the central signal processor and delivers it to the archive. Its input bandwidth is set by the highest data rate supported in a standard observing mode, while its output rate is matched to the average data rate expected across all modes.

MCAP: The metadata capture system captures ancillary data from the array monitoring system that is necessary for data calibration or verification and combines this metadata with the science data before storage.

AS: The archive streamer performs the necessary data formatting for ingestion.

PROC_STORE: The processing storage system is a buffer system that recovers projects from the archive and makes the data available to the pipeline system for processing.

PIPE: The pipeline system prepares the high-level (derived) data products that satisfy the proposal.

ARCHIVE: The science archive hosts both the low-level data products (visibilities) along with the high-level data products delivered by the pipeline system.

AAT: The archive access tool provides an online graphical interface to search for, and retrieve, data products from the archive.

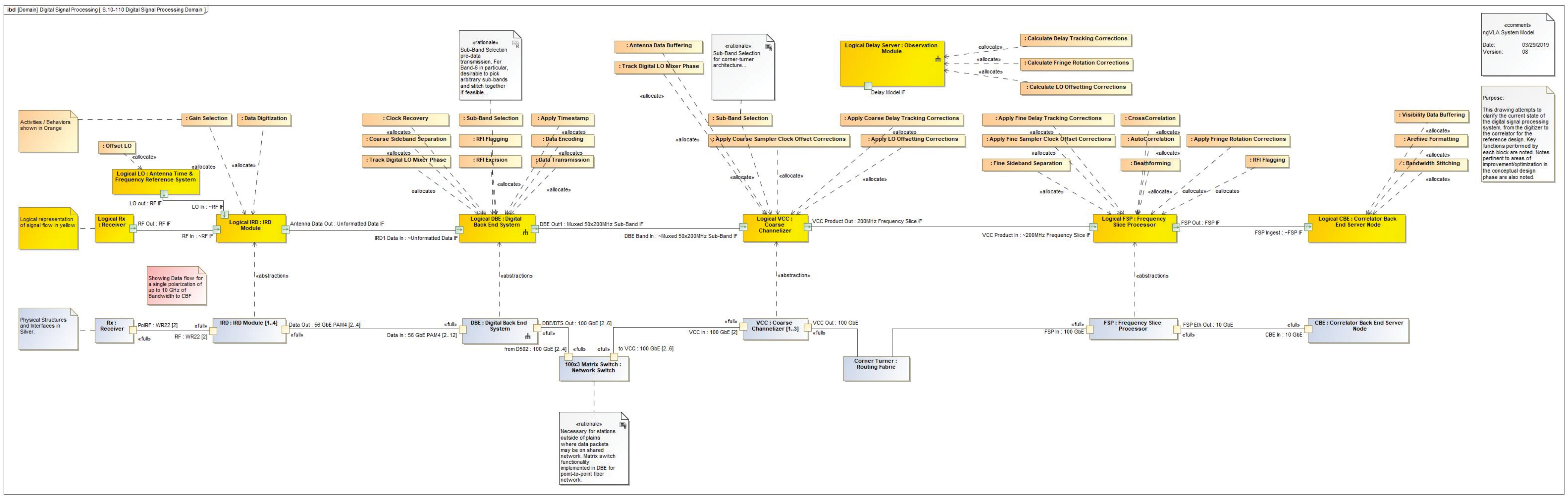
Receiving PI: The receiving principal investigator retrieves their data products from the archive access tool. These may be data products requested via a proposal, or based on a search of the public archive.

6.4 *Diagram: S.10-110 Digital Signal Processing Domain*

This internal block diagram shows the Digital Signal Processing Domain, i.e., how the system looks from a digital signal processing perspective, with an emphasis on operations/functions performed by each block, that block's logical inputs and outputs, and the physical interface that transports those inputs and outputs.

The diagram focuses on the signal flow from the digitizer through the correlator back end where the basic data products are delivered to the archive and post processing system. The diagram has three basic swim lanes, with the first noting activities/behaviors from the logical model, the second row providing a logical representation of the signal flow, and the third row showing the physical structures and interfaces that transport those data flows. E.g., while the data flow out from an Integrated Receiver Digitizer (IRD) is unformatted data, it is implemented on a 56 GbE PAM4 interface. Both these interfaces are shown in their respective swim lane, as are the functions the IRD performs from the logical model (Gain Selection & Data Digitization).

The signal flow shown is for a single polarization of up to 10 GHz of bandwidth. Future versions of this diagram may extend to include meta data capture and data formatting for the archive.



Selected elements:

Rx: The receiver captures the RF signal collected by the antenna and amplifies it for downconversion and digitization by the IRD module. Its main signal flow is an RF output, implemented over a coaxial SMA or rectangular waveguide interface depending on frequency band (WR22 shown on this drawing).

IRD: The integrated receiver digitizer performs gain selection and data digitization. It transmits data to the digital back end in an unformatted serial stream, with two streams per polarization implemented on a 56 GbE PAM4 link.

DBE: The digital back end recovers the clock from the unformatted data stream and deserializes the data. It performs a set of functions necessary for bandwidth selection and requantization before data encoding and transmission over a fiber network. The network may include commercial fiber links so an Ethernet interface is implemented.

VCC: The VCC is the coarse channelizer of the NRCC frequency slice architecture. It is intended to perform all band-specific processing functions as well as coarse channelization to 200 MHz frequency slices that are processed by the FSP. The VCC also provides a passive fiber routing fabric that forms the corner turner to the FSP. As can be seen in this figure, there is some overlap in functionality between the DBE and VCC that will be an area for optimization in the conceptual design stage.

FSP: The Frequency Slice Processor ingests the 200 MHz frequency slice provided by the VCCs (from all antennas in that sub-array) and produces a single VCC product—typically cross correlations or phased array beams consistent with its operating mode. It also performs a number of corrections that can only be done at the fine channelization stage of the FFX architecture.

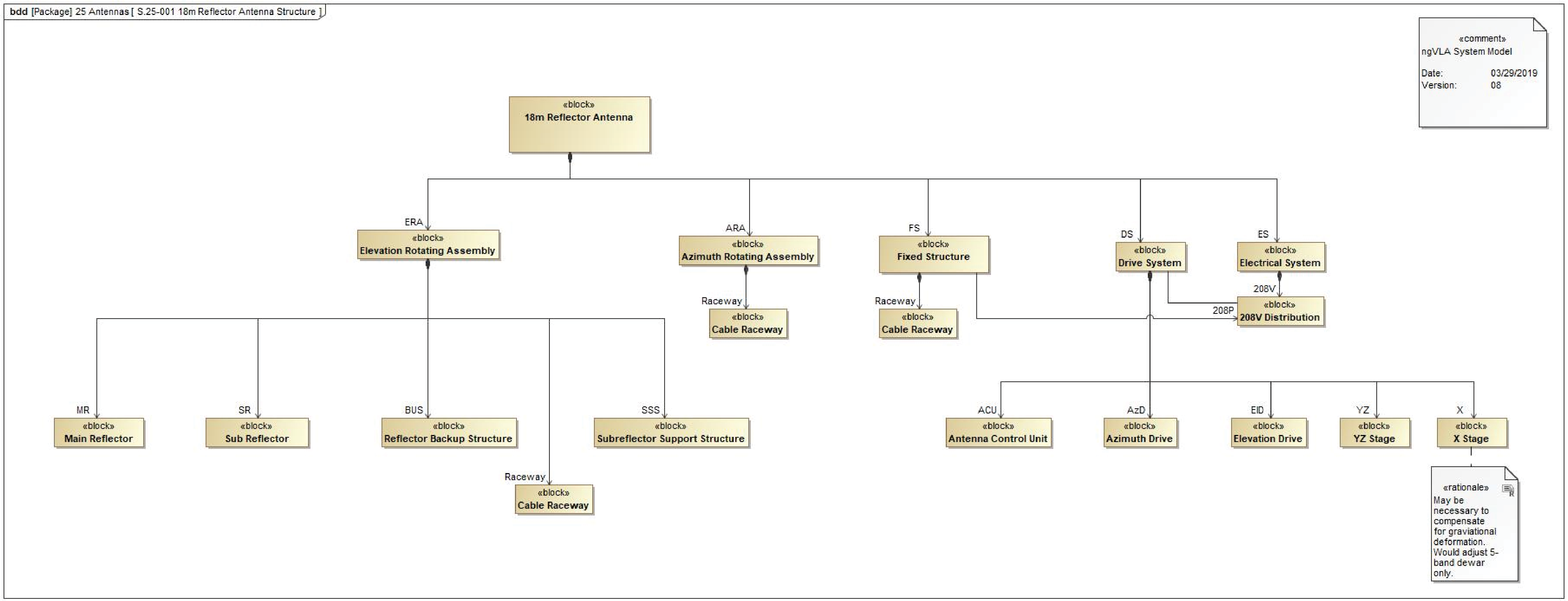
7 Subsystem Scope Definition

One of the goals with the development of this model is to define the scope of each work package to a sufficient degree to permit design elaboration by a domain engineer. For each major work package in the product structure of the structural model, a set of scope drawings will be developed to define the scope of the system within the structural model, the roles the subsystem or its components must satisfy in the logical model, their associated behaviors, and relevant L1 system requirements they must help satisfy.

This section of the report will be expanded as the design progresses with a goal of providing this definition for all subsystems by the conceptual design review.

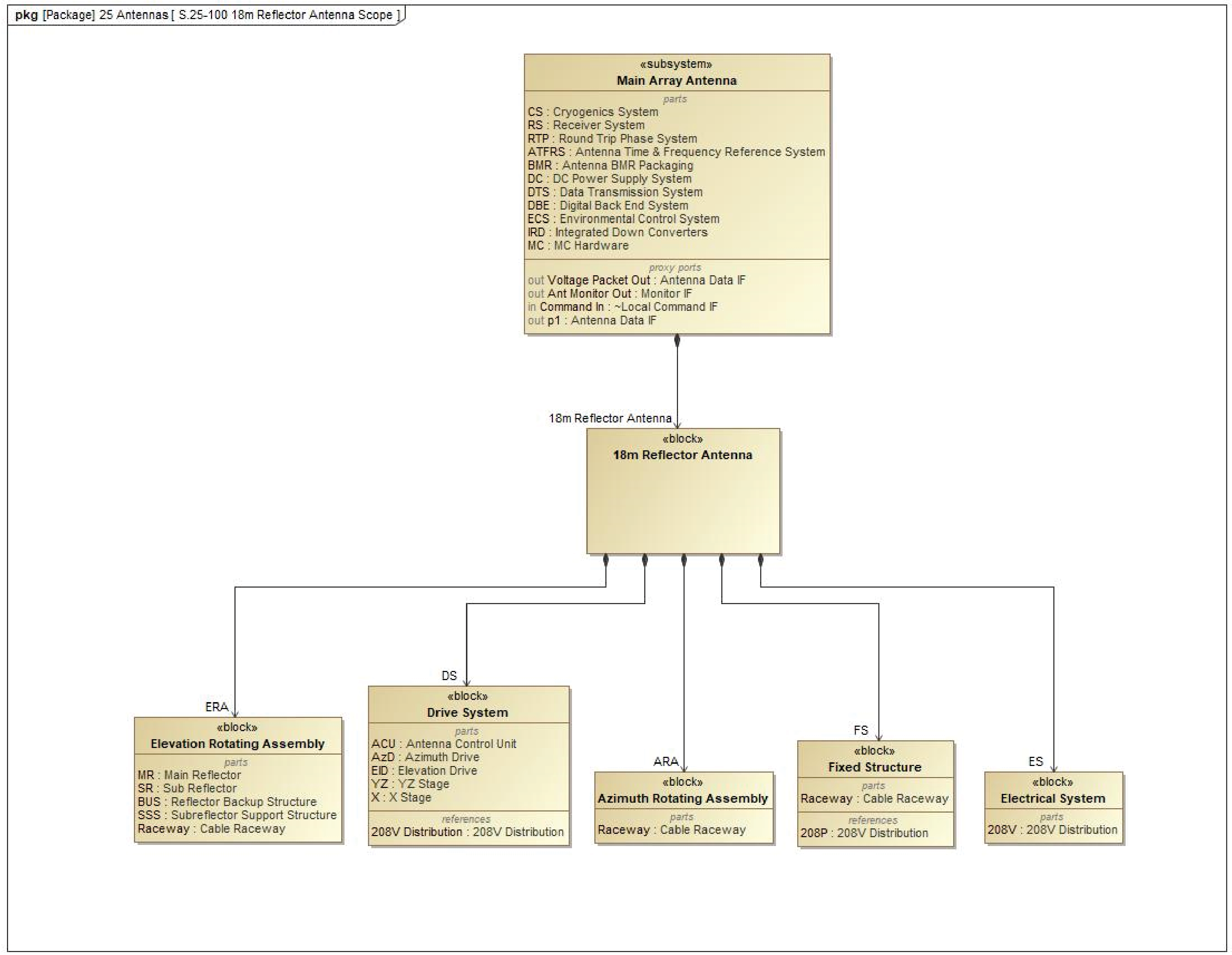
7.1 Diagram: S.25-001 18m Reflector Antenna Structure

This block definition diagram shows the components of the 18m reflector antenna in the structural model. In order to provide an initial architecture that is implementation agnostic, the structure is decomposed into an elevation rotating assembly, an azimuth rotating assembly, and a fixed portion of the structure. Such an architecture can accommodate both a wheel and track mount and various backup structure concepts. In addition to the structural elements the reflector antenna includes the drive system and the AC electrical distribution system necessary for antenna motion. The receiving electronics and all signal processing are outside the scope of this model element.



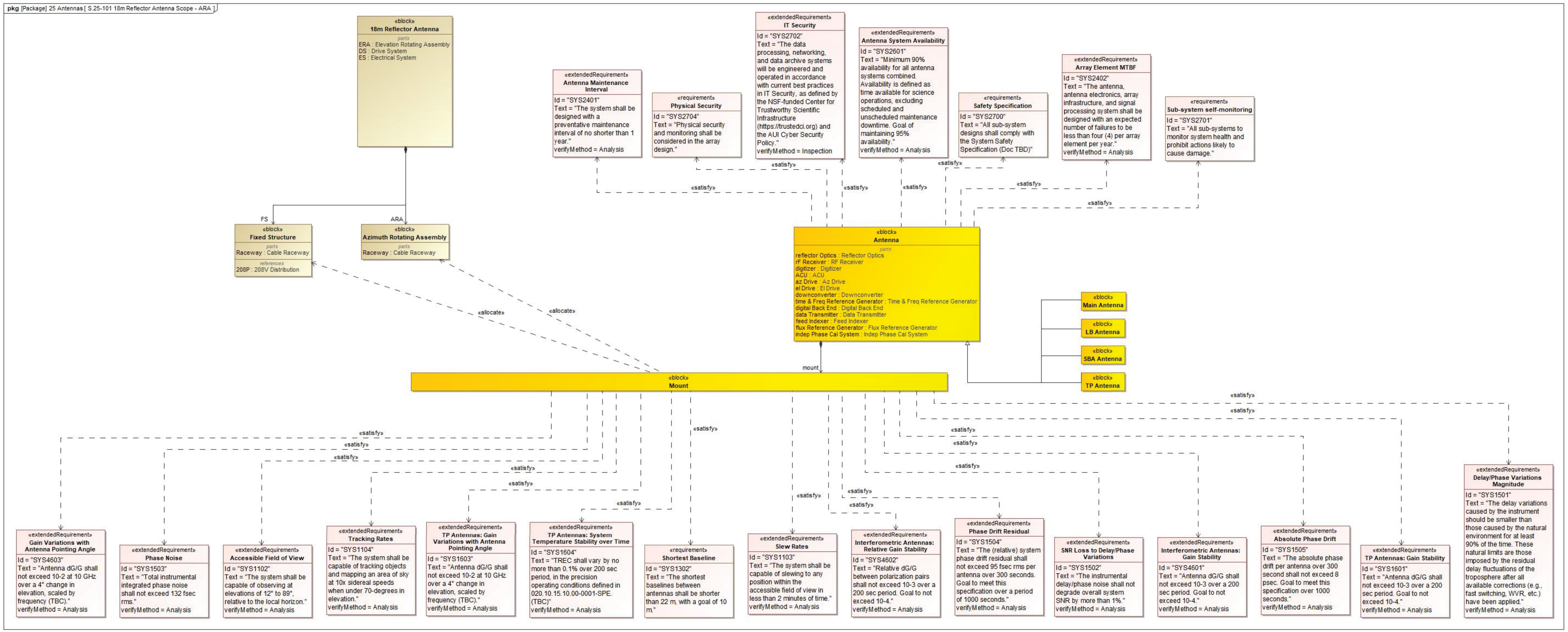
7.2 Diagram: S.25-100 18m Reflector Antenna Scope

This diagram and its subsidiaries show the scope of the 18m reflector antenna. The 18m reflector antenna has its constituent parts as shown on the preceding block definition diagram, and it is also a component itself of the Main Array Antenna Element. The 18m reflector antenna block has no direct relationships to the logical model, its behaviors, or requirements.



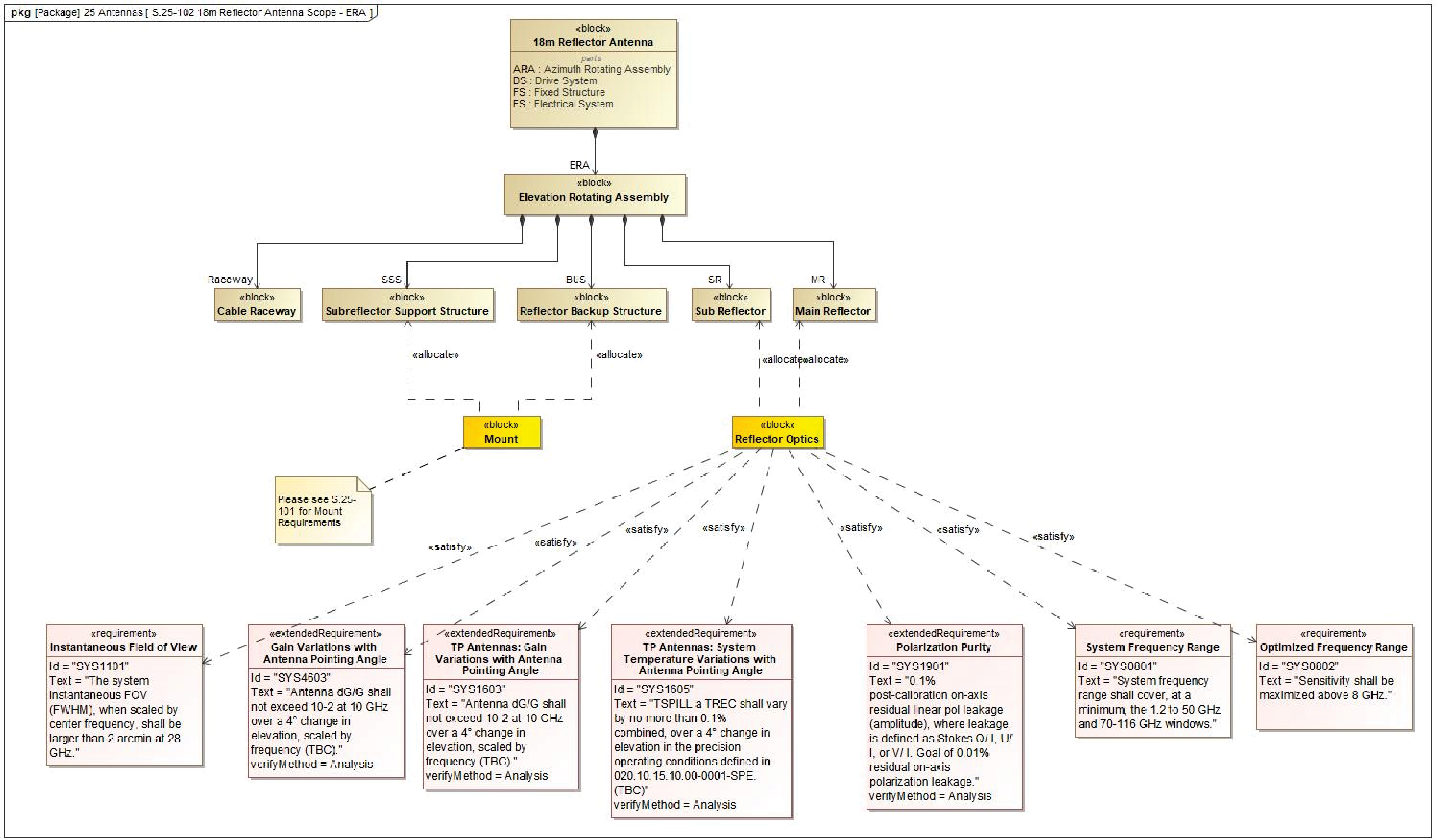
7.3 Diagram: S.25-101 18m Reflector Antenna Scope - ARA

This diagram depicts the scope of the Azimuth Rotating Assembly and Fixed Structure. Both are allocated the role of the mount in the logical model. The mount has a number of L1 requirements it must satisfy directly, noted at the bottom of the drawing. It is also a component of the Antenna block, which is a generalization of the four antenna types in the array. The antenna must satisfy a subset of requirements directly, which are noted above it. These requirements require flow-down to the lower elements of the model.



7.4 Diagram: S.25-102 18m Reflector Antenna Scope - ERA

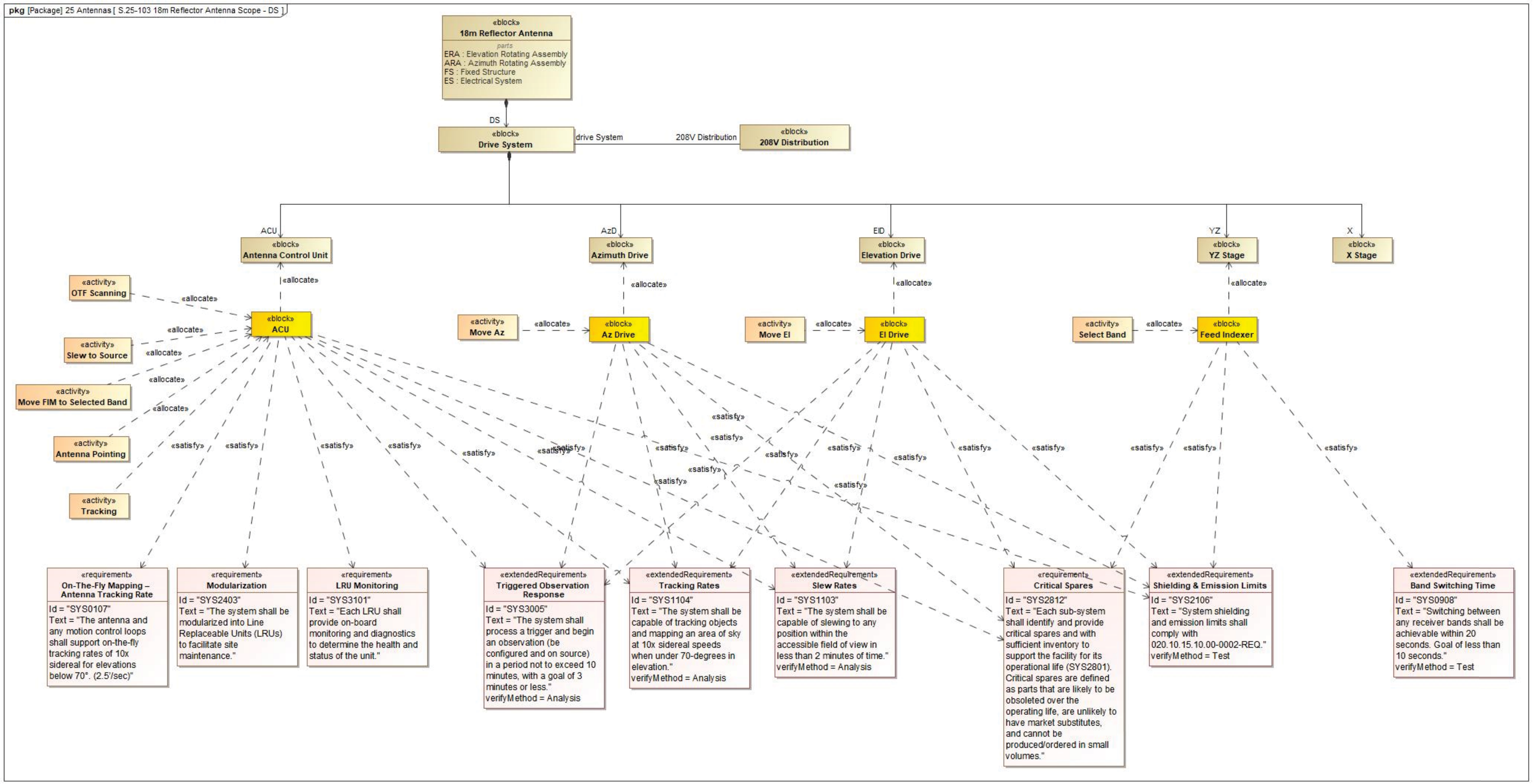
This diagram focuses on the scope of the Elevation Rotating Assembly. As with the Azimuth Rotating Assembly and Fixed Structure, this must also perform the functions of the Mount from the logical model. The associated requirements are shown on figure S.25-101 rather than repeated here. The Sub Reflector and Main Reflector must fulfill the role of the reflector optics whose associated requirements are shown at the bottom of the figure.



Title: Preliminary System Architecture	**Authors:** Selina, Hiriart	**Date:** 2019-07-09
Document No.: 020.10.20.00.00-0002-DWG		**Revision:** A

7.5 Diagram: S.25-103 18m Reflector Antenna Scope - DS

This diagram presents the scope of the Drive System and its subcomponents. The mapping from the drive system components to blocks in the logical model is shown with the allocate relationship. The activities each logical block must perform are also displayed, as are the L1 requirements with a satisfy relationship to each logical element.



8 Appendix

8.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CSP	Central Signal Processor
CSW	Computing and Software
DA	Data Analyst
FSA	Frequency Slice Architecture
FSP	Frequency Slice Processor
GBT	Green Bank Telescope
GUI	Graphical User Interface
HPC	High Performance Computing
IF	Interface (not Intermediate Frequency)
IPT	Integrated Product Team
LO	Local Oscillator
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
NRCC	National Research Council of Canada
OST	Observation Scheduling Tool
OVT	Observation Validation Team
PBS	Product Breakdown Structure
PBT	Proposal Builder Tool
PI	Principal Investigator
PHT	Proposal Handling Tool
PST	Proposal Submission Tool
QC	Quality Control
RD	Reference Document
RFI	Radio Frequency Interference
rms	Root Mean Square
RSS	Root of Sum of Squares
SRDP	Science Ready Data Products
TAC	Time Allocation Committee
TBC	To Be Confirmed
TBD	To Be Determined
TP	Total Power
VCC	Very Coarse Channelizer
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer

8.2 Notes

The following materials are included in this appendix. These matrices provide the model verification described in drawing **A.00-041 Model Verification**.

L.00-005 ngVLA Logical Model to Requirements Satisfy Matrix: This matrix has the L1 System Requirements in each column and the logical structure elements in each row. "Satisfy" relationships are shown, indicating which elements of the logical model have a role in satisfying a given requirement. The requirement may be satisfied directly by a part or may have an implied relationship: if a component of a system satisfies the requirement the relationship to the system is also shown. The distinction between direct and implied relationships can be seen directly in the architecture model if desired. The "Satisfy Relationships" row and column provide a verification summary, demonstrating that each requirement is satisfied by at least one element of the logical model. Most model elements are expected to satisfy a requirement, but this is not necessary for ancillary systems that support other elements of the model.

L.00-006 Logical Model Behavior Allocation Matrix: This matrix has the logical structure elements in each column and the system behaviors in each row. Behaviors are allocated to blocks within the system. The table shows both direct relationships and implied relationships: if a component of a system is allocated a behavior, this relationship is implied for the larger system too. This distinction can be seen in the architecture model if desired. The "Allocate Relationships" row and column provide a verifications summary, showing that each activity is allocated to at least one block in the model.

S.99-000 ngVLA Logical to Structural Model Allocation Matrix: This matrix has the elements of the structural model in each column and the elements of the logical model in each row. Where an element of the structural model is fulfilling the behaviors and requirements allocated to an element of the logical model, this allocation is shown. As with the previous two matrices, both implied and direct relationships are shown in this table. Given the added complexity of the structural model and the inclusion of ancillary systems necessary for complete operation, the structural model has additional elements and sub-components. Verification that the logical model is fully implemented by the structural model can be seen in the "Allocate Relationships" column, which shows that each logical element is allocated to at least one structural model element.

	L.00-005 Logical Model to Requirements - Satisfy Matrix	SATISFY RELATIONSHIPS	SYS2401 Antenna Maintenance Interval	SYS2402 Array Element MTBF	SYS2403 Modularization	SYS2405 Predictive and Self-Diagnostic Function	SYS2406 Configuration Monitoring	SYS2407 Engineering Console	SYS2408 Engineering Database	SYS2303 Calibration Automation	SYS2304 Self-Calibrating Antenna	SYS2305 Single Baseline Data Display	SYS2306 Calibration Data Display	SYS2307 Operator Console	SYS1061 Calibration Efficiency	SYS1062 Calibration Parallelization	SYS1063 Calibration Recall	SYS1064 Relative Flux Scale Calibration Efficiency	SYS1065 Polarization Calibration Efficiency	SYS1066 Bandpass Calibration Efficiency	SYS1067 Gain Calibration Efficiency	SYS1068 Phase Calibration Efficiency	SYS0761 Data Analysis Resources	SYS0731 Archive Period	SYS0732 Archive Products	SYS0733 Proprietary Data Rights	SYS0734 Archive Batch Reprocessing	SYS0735 Archive Backup	SYS0736 Archive User Reprocessing	SYS0738 Proprietary Period	SYS0751 Data Processing Resources	SYS0752 Throughput & Latency	SYS0753 Heterogeneous Arrays	SYS0703 Calibration Pipeline	SYS0721 Imaging Pipeline	SYS0701 Uncalibrated Data	SYS0702 Flagged Data Table	SYS0741 Pulsar Timing Data Product	SYS0742 Pulsar Search Data Product	SYS1501 Delay/Phase Variations Magnitude	SYS1502 SNR Loss to Delay/Phase Variations	SYS1503 Phase Noise	SYS1504 Phase Drift Residual	SYS1505 Absolute Phase Drift
SATISFY RELATIONSHIPS			11	11	30	8	5	6	6	9	3	3	3	3	5	3	7	16	16	20	17	3	6	3	7	3	9	3	7	3	4	4	3	4	4	9	9	3	3	19	18	15	19	19
Logical Structure::10 Proposal Management	Proposal Submission Tool	2																																										
Logical Structure::10 Proposal Management	Observation Preparation Tool	4																																										
Logical Structure::10 Proposal Management	Proposal Builder Tool	2																																										
Logical Structure::10 Proposal Management	Proposal Handling Tool	2																																										
Logical Structure::10 Proposal Management::Views	SciOps	6																																										
Logical Structure::20 Array::Antenna Structure	ACU	8			->																																							
Logical Structure::20 Array::Antenna Structure	Az Drive	5																																										
Logical Structure::20 Array::Antenna Structure	Data Transmitter	5			->																																							
Logical Structure::20 Array::Antenna Structure	Digital Back End	12			->																																							
Logical Structure::20 Array::Antenna Structure	Digitizer	23			->															->	->																				->	->	->	->	->
Logical Structure::20 Array::Antenna Structure	Downconverter	24			->															->	->																				->	->	->	->	->
Logical Structure::20 Array::Antenna Structure	El Drive	5																																										
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Logical Structure::20 Array::Antenna Structure	Indep Phase Cal System	7			->																																				->	->		->	
Logical Structure::20 Array::Antenna Structure	Mount	15																																							->	->	->	->	->
Logical Structure::20 Array::Antenna Structure	Reflector Optics	7																																										
Logical Structure::20 Array::Antenna Structure	RF Receiver	27			->														->	->	->																				->				->
Logical Structure::20 Array::Antenna Structure	Time & Freq Reference Generator	15			->																																				->	->	->	->	->
Logical Structure::20 Array::Antenna Types	Antenna	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array::Antenna Types	LB Antenna	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array::Antenna Types	Main Antenna	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array::Antenna Types	SBA Antenna	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array::Antenna Types	TP Antenna	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array::Env Monitors	Atm. Delay Monitor System	4																				->																							
Logical Structure::20 Array::Env Monitors	Weather Monitor System	6																																										
Logical Structure::20 Array	Long Baseline Array	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array	Main Array	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array	Short Baseline Array	61	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::20 Array	Total Power Array	62	->	->	->													->	->	->	->																				->	->	->	->	->
Logical Structure::30 Central Reference Distribution	Frequency Reference	5			->																																							->	->
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor	10			->																																				->	->		->	->
Logical Structure::30 Central Reference Distribution	Time Reference	4			->																																								
Logical Structure::30 Central Reference Distribution	Time Reference Distributor	7			->																																								
Logical Structure::40 Central Signal Processing	Beamformer	17			->																																								
Logical Structure::40 Central Signal Processing	Correlator	28			->																																								
Logical Structure::40 Central Signal Processing	Correlator Back End	6			->																																								
Logical Structure::40 Central Signal Processing	Data Buffer	4																																										
Logical Structure::40 Central Signal Processing	Online Calibration System	3																																										
Logical Structure::40 Central Signal Processing	Pulsar Search System	9			->																																								
Logical Structure::40 Central Signal Processing	Pulsar Timing System	12			->																																								
Logical Structure::50 Online Control & Monitoring	Calibration Module	8								->					->	->	->	->	->	->																									
Logical Structure::50 Online Control & Monitoring	Configuration Module	1					->																																					
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor	10				->		->		->	->																																	
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor	26				->		->		->																																		
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor	6				->		->		->																																		
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor	6				->		->		->																																		
Logical Structure::50 Online Control & Monitoring	Data Transmission Module	3																																										
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board	2																																										
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module	2																																	->	->								
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver	3							->																																			
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector	6							->																												->	->								

ngvla	L.00-005 Logical Model to Requirements - Satisfy Matrix	SATISFY RELATIONSHIPS	SYS2401 Antenna Maintenance Interval	SYS2402 Array Element MTBF	SYS2403 Modularization	SYS2405 Predictive and Self-Diagnostic Function	SYS2406 Configuration Monitoring	SYS2407 Engineering Console	SYS2408 Engineering Database	SYS2303 Calibration Automation	SYS2304 Self-Calibrating Antenna	SYS2305 Single Baseline Data Display	SYS2306 Calibration Data Display	SYS2307 Operator Console	SYS1061 Calibration Efficiency	SYS1062 Calibration Parallelization	SYS1063 Calibration Recall	SYS1064 Relative Flux Scale Calibration Efficiency	SYS1065 Polarization Calibration Efficiency	SYS1066 Bandpass Calibration Efficiency	SYS1067 Gain Calibration Efficiency	SYS1068 Phase Calibration Efficiency	SYS0761 Data Analysis Resources	SYS0731 Archive Period	SYS0732 Archive Products	SYS0733 Proprietary Data Rights	SYS0734 Archive Batch Reprocessing	SYS0735 Archive Backup	SYS0736 Archive User Reprocessing	SYS0738 Proprietary Period	SYS0751 Data Processing Resources	SYS0752 Throughput & Latency	SYS0753 Heterogeneous Arrays	SYS0703 Calibration Pipeline	SYS0721 Imaging Pipeline	SYS0701 Uncalibrated Data	SYS0702 Flagged Data Table	SYS0741 Pulsar Timing Data Product	SYS0742 Pulsar Search Data Product	SYS1501 Delay/Phase Variations Magnitude	SYS1502 SNR Loss to Delay/Phase Variations	SYS1503 Phase Noise	SYS1504 Phase Drift Residual	SYS1505 Absolute Phase Drift
Logical Structure::50 Online Control & Monitoring	Observation Module	17																																										
Logical Structure::50 Online Control & Monitoring	Operation Module	20											->	->																														
Logical Structure::50 Online Control & Monitoring	QuickLook Module	1										->																																
Logical Structure::50 Online Control & Monitoring	Scheduling Module	4																																										
Logical Structure::60 Data Archives	Engineering Data Archive	2							->																																			
Logical Structure::60 Data Archives	Proposal Archive	1																																										
Logical Structure::60 Data Archives	RFI Archive	1																																										
Logical Structure::60 Data Archives	Science Data Archive	11																						->	->	->	->	->	->	->						->	->	->	->					
Logical Structure::60 Data Archives	Staging Storage	1																																										
Logical Structure::60 Data Archives	Telescope Calibration Archive	4								->							->			->																								
Logical Structure::60 Data Archives	Telescope Configuration Archive	2				->	->																																					
Logical Structure::70 Infrastructure	Central Electronics Building	1																																										
Logical Structure::70 Infrastructure	Data Distribution System	1																																										
Logical Structure::70 Infrastructure	Electrical Distribution System	1																																										
Logical Structure::80 Maintenance & Support	Central Repair Facility	1																																										
Logical Structure::80 Maintenance & Support	CMMS Integration Module	0																																										
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System	0																																										
Logical Structure::80 Maintenance & Support	Integrated Support Module	1																																										
Logical Structure::80 Maintenance & Support	Issue Tracking System	0																																										
Logical Structure::90 Commissioning & Development	Development Support Infrastructure	1																																										
Logical Structure::90 Commissioning & Development	Simulation Tool	1																																										
Logical Structure::90 Commissioning & Development	Testing Environment	1																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Computational Resources	3																					->				->																	
Logical Structure::100 Offline Processing & Archive Interfaces	Data Analysis Tools	8													->		->	->	->	->	->	->	->																					
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Management	3																							->		->		->															
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Pipelines	6																							->		->							->	->	->	->							
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing System	19																					->		->		->		->		->	->	->	x	x	x	x							
Logical Structure::100 Offline Processing & Archive Interfaces	Observatory Interfaces	1																											->															
Logical Structure::100 Offline Processing & Archive Interfaces	Offline Calibration Tools	7													->		->	->	->	->	->	->																						
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Resources	5																					->				->				->	->												
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Storage Resources	1																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Quality Assurance Interfaces	2																																										
Logical Structure	Array	67	->	->	->													->	->	->	->																			->	->	->	->	->
Logical Structure	Central Reference Distribution System	15			->																																			->	->		->	->
Logical Structure	Central Signal Processing System	51			->																																							
Logical Structure	Commissioning & Development Systems	5																																										
Logical Structure	Data Archive System	24				->	->		->	->							->			->				->	->	->	->	->	->	->						->	->	->	->					
Logical Structure	Infrastructure Systems	6																																										
Logical Structure	Maintenance & Support Systems	6																																										
Logical Structure	ngVLA System	165	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->
Logical Structure	Offline Subsystem	23																					->		->		->		->		->	->	->	->	->	->	->							
Logical Structure	Online Subsystem	60				->	->	->	->	->	->	->	->	->	->	->	->	->	->	->																->	->							
Logical Structure	Proposal Management System	9																																										

ngvla	L.00-005 Logical Model to Requirements - Satisfy Matrix	SYS1201 Input Dynamic Range	SYS1202 Gain Calibration System Dynamic Range	SYS1203 Provision of Variable Attenuators	SYS1204 Input Protection	SYS1205 High-Noise Path	SYS2501 Weather Monitoring	SYS2502 Safety Weather Monitoring	SYS2503 Weather Archive	SYS0801 System Frequency Range	SYS0802 Optimized Frequency Range	SYS0803 Freq. Span A:	SYS0804 Freq. Span B:	SYS0805 Freq. Span C:	SYS0806 Continuity of Frequency Coverage	SYS0001 Functional Modes	SYS0002 Interferometric Mode	SYS0003 Phased Array Mode	SYS0004 Pulsar Timing Mode	SYS0005 Pulsar and Transient Search Mode	SYS0006 VLBI Mode	SYS0007 Total Power Mode	SYS0008 On The Fly Mapping Mode	SYS0009 Solar Observing Mode	SYS0202 Concurrent Interferometric and Phased Array Mode	SYS4601 Interferometric Antennas: Gain Stability	SYS4602 Interferometric Antennas: Relative Gain Stability	SYS4603 Gain Variations with Antenna Pointing Angle	SYS4801 Gain Calibration Reference	SYS1601 TP Antennas: Gain Stability	SYS1603 TP Antennas: Gain Variations with Antenna Pointing Angle	SYS1604 TP Antennas: System Temperature Stability over Time	SYS1605 TP Antennas: System Temperature Variations with Antenna Pointing Angle	SYS1801 TP Antennas: Gain Calibration Reference	SYS0101 Variable Spectral Resolution	SYS0102 Polarization Products	SYS0103 Autocorrelation Products	SYS0104 Commensal Processing	SYS0105 Commensal Low-Frequency System	SYS3001 Standard Observing Modes	SYS3002 Number of Standard Observing Modes	SYS3003 Non-Standard Observing Modes	SYS3004 Triggered Observations	SYS3005 Triggered Observation Response
SATISFY RELATIONSHIPS		13	12	13	12	12	1	1	8	13	13	12	12	12	16	4	7	7	8	8	7	7	8	6	9	15	15	17	12	15	16	15	14	12	14	3	3	3	15	5	5	5	3	19
Logical Structure::10 Proposal Management	Proposal Submission Tool																																											
Logical Structure::10 Proposal Management	Observation Preparation Tool																																											
Logical Structure::10 Proposal Management	Proposal Builder Tool																																											
Logical Structure::10 Proposal Management	Proposal Handling Tool																																											
Logical Structure::10 Proposal Management::Views	SciOps																																											
Logical Structure::20 Array::Antenna Structure	ACU																																											->
Logical Structure::20 Array::Antenna Structure	Az Drive																																											->
Logical Structure::20 Array::Antenna Structure	Data Transmitter																																					->					
Logical Structure::20 Array::Antenna Structure	Digital Back End														->																				->				->					
Logical Structure::20 Array::Antenna Structure	Digitizer			->											->											->	->	->		->	->	->												
Logical Structure::20 Array::Antenna Structure	Downconverter	->		->											->											->	->	->		->	->	->												
Logical Structure::20 Array::Antenna Structure	El Drive																																											->
Logical Structure::20 Array::Antenna Structure	Feed Indexer																																											
Logical Structure::20 Array::Antenna Structure	Flux Reference Generator		->																									->	->				->	->										
Logical Structure::20 Array::Antenna Structure	Indep Phase Cal System																																											
Logical Structure::20 Array::Antenna Structure	Mount																									->	->	->		->	->	->												
Logical Structure::20 Array::Antenna Structure	Reflector Optics									->	->																	->			->		->											
Logical Structure::20 Array::Antenna Structure	RF Receiver	->			->	->				->	->	->	->	->	->											->	->	->		->	->	->	->											
Logical Structure::20 Array::Antenna Structure	Time & Freq Reference Generator														->																													
Logical Structure::20 Array::Antenna Types	Antenna	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array::Antenna Types	LB Antenna	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array::Antenna Types	Main Antenna	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array::Antenna Types	SBA Antenna	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array::Antenna Types	TP Antenna	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array::Env Monitors	Atm. Delay Monitor System																																											
Logical Structure::20 Array::Env Monitors	Weather Monitor System						->	->	->																																			
Logical Structure::20 Array	Long Baseline Array	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array	Main Array	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array	Short Baseline Array	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::20 Array	Total Power Array	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure::30 Central Reference Distribution	Frequency Reference																																											
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor																																											
Logical Structure::30 Central Reference Distribution	Time Reference																																											
Logical Structure::30 Central Reference Distribution	Time Reference Distributor																																											
Logical Structure::40 Central Signal Processing	Beamformer																	->	->	->	->				->																			
Logical Structure::40 Central Signal Processing	Correlator																->					->	->		->										->	->	->	->	->					
Logical Structure::40 Central Signal Processing	Correlator Back End																																											
Logical Structure::40 Central Signal Processing	Data Buffer																																											
Logical Structure::40 Central Signal Processing	Online Calibration System																																											
Logical Structure::40 Central Signal Processing	Pulsar Search System																			->																								
Logical Structure::40 Central Signal Processing	Pulsar Timing System																		->						->																			
Logical Structure::50 Online Control & Monitoring	Calibration Module																																											
Logical Structure::50 Online Control & Monitoring	Configuration Module																																											
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor																						->	->																				->
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor																->	->	->	->	->	->	->	->	->																			->
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor																																											
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor																																											
Logical Structure::50 Online Control & Monitoring	Data Transmission Module																																											
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board																																											
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module																																											
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver								->																																			
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector								->																																			

	L.00-005 Logical Model to Requirements - Satisfy Matrix	SYS1201 Input Dynamic Range	SYS1202 Gain Calibration System Dynamic Range	SYS1203 Provision of Variable Attenuators	SYS1204 Input Protection	SYS1205 High-Noise Path	SYS2501 Weather Monitoring	SYS2502 Safety Weather Monitoring	SYS2503 Weather Archive	SYS0801 System Frequency Range	SYS0802 Optimized Frequency Range	SYS0803 Freq. Span A:	SYS0804 Freq. Span B:	SYS0805 Freq. Span C:	SYS0806 Continuity of Frequency Coverage	SYS0001 Functional Modes	SYS0002 Interferometric Mode	SYS0003 Phased Array Mode	SYS0004 Pulsar Timing Mode	SYS0005 Pulsar and Transient Search Mode	SYS0006 VLBI Mode	SYS0007 Total Power Mode	SYS0008 On The Fly Mapping Mode	SYS0009 Solar Observing Mode	SYS0202 Concurrent Interferometric and Phased Array Mode	SYS4601 Interferometric Antennas: Gain Stability	SYS4602 Interferometric Antennas: Relative Gain Stability	SYS4603 Gain Variations with Antenna Pointing Angle	SYS4801 Gain Calibration Reference	SYS1601 TP Antennas: Gain Stability	SYS1603 TP Antennas: Gain Variations with Antenna Pointing Angle	SYS1604 TP Antennas: System Temperature Stability over Time	SYS1605 TP Antennas: System Temperature Variations with Antenna Pointing Angle	SYS1801 TP Antennas: Gain Calibration Reference	SYS0101 Variable Spectral Resolution	SYS0102 Polarization Products	SYS0103 Autocorrelation Products	SYS0104 Commensal Processing	SYS0105 Commensal Low-Frequency System	SYS3001 Standard Observing Modes	SYS3002 Number of Standard Observing Modes	SYS3003 Non-Standard Observing Modes	SYS3004 Triggered Observations	SYS3005 Triggered Observation Response
Logical Structure::50 Online Control & Monitoring	Observation Module															->	->	->	->	->	->	->	->	->	->															->	->	->	->	->
Logical Structure::50 Online Control & Monitoring	Operation Module															->	->	->	->	->	->	->	->	->	->																			->
Logical Structure::50 Online Control & Monitoring	QuickLook Module																																											
Logical Structure::50 Online Control & Monitoring	Scheduling Module																																											
Logical Structure::60 Data Archives	Engineering Data Archive								->																																			
Logical Structure::60 Data Archives	Proposal Archive																																											
Logical Structure::60 Data Archives	RFI Archive																																											
Logical Structure::60 Data Archives	Science Data Archive																																											
Logical Structure::60 Data Archives	Staging Storage																																											
Logical Structure::60 Data Archives	Telescope Calibration Archive								->																																			
Logical Structure::60 Data Archives	Telescope Configuration Archive																																											
Logical Structure::70 Infrastructure	Central Electronics Building																																											
Logical Structure::70 Infrastructure	Data Distribution System																																											
Logical Structure::70 Infrastructure	Electrical Distribution System																																											
Logical Structure::80 Maintenance & Support	Central Repair Facility																																											
Logical Structure::80 Maintenance & Support	CMMS Integration Module																																											
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System																																											
Logical Structure::80 Maintenance & Support	Integrated Support Module																																											
Logical Structure::80 Maintenance & Support	Issue Tracking System																																											
Logical Structure::90 Commissioning & Development	Development Support Infrastructure																																											
Logical Structure::90 Commissioning & Development	Simulation Tool																																											
Logical Structure::90 Commissioning & Development	Testing Environment																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Computational Resources																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Analysis Tools																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Management																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Pipelines																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing System																																							->	->	->		
Logical Structure::100 Offline Processing & Archive Interfaces	Observatory Interfaces																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Offline Calibration Tools																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Resources																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Storage Resources																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Quality Assurance Interfaces																																											
Logical Structure	Array	->	->	->	->	->				->	->	->	->	->	->											->	->	->	->	->	->	->	->	->	->				->					->
Logical Structure	Central Reference Distribution System																																											
Logical Structure	Central Signal Processing System																->	->	->	->	->	->	->		->										->	->	->	->	->					
Logical Structure	Commissioning & Development Systems																																											
Logical Structure	Data Archive System								->																																			
Logical Structure	Infrastructure Systems																																											
Logical Structure	Maintenance & Support Systems																																											
Logical Structure	ngVLA System	->	->	->	->	->			->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->
Logical Structure	Offline Subsystem																																							->	->	->		
Logical Structure	Online Subsystem								->							->	->	->	->	->	->	->	->	->	->															->	->	->	->	->
Logical Structure	Proposal Management System																																											

	L.00-005 Logical Model to Requirements - Satisfy Matrix	SYS3006 Trigger Override	SYS0201 Phased Aperture	SYS0203 Number of Beams	SYS1901 Polarization Purity	SYS2700 Safety Specification	SYS2701 Sub-system self-monitoring	SYS2702 IT Security	SYS2704 Physical Security	SYS2221 Observation Preparation – Standard Observing Modes	SYS2222 Observation Preparation - Non-Standard Observing modes	SYS2223 Observation Scheduling GUI	SYS2224 Observation Interrupt	SYS2225 Observation Preparation – Standard Observing Mode Flexibility	SYS2302 Observation Scheduling	SYS2211 Proposal Submission – standard observing modes	SYS2212 Proposal Submission – non-standard observing modes.	SYS2213 Scientific Proposal Evaluation	SYS2214 Technical Proposal Evaluation	SYS2201 Provision of Software Tools	SYS1001 Effective Area / Tsys Ratio	SYS1301 Longest Baseline	SYS1302 Shortest Baseline	SYS1303 Zero Spacing / Single Dish Total Power	SYS1304 Integration Time Ratios	SYS1306 Fraction of Occupied Cells	SYS1308 Distribution and Weighting of Visibilities	SYS1401 Highest Spectral Resolution	SYS1402 Number of Spectral Channels	SYS1403 Flexible Spectral Resolution	SYS1404 Doppler Corrections	SYS2104 Self-Generated Spurious Signal Power Level	SYS2105 LO Frequency and Sampler Clock Offsets	SYS2106 Shielding & Emission Limits	SYS0601 Sub-Array Capabilities	SYS0602 Phase Preservation	SYS0603 Sub-Array Composition	SYS0604 Sub-Array Operating Modes	SYS0605 Sub-Array Operating Mode Commensality	SYS0606 Sub-Array Configuration	SYS2601 Antenna System Availability	SYS2602 Centralized Systems Availability	SYS0901 Front End Bandwidth Ratio	SYS0902 Instantaneous Digitized Bandwidth
SATISFY RELATIONSHIPS		3	3	3	15	18	18	20	11	5	5	3	3	6	3	4	4	3	9	6	2	2	12	3	2	2	2	5	7	7	7	14	13	31	11	7	10	7	7	13	11	6	12	12
Logical Structure::10 Proposal Management	Proposal Submission Tool															->	->																											
Logical Structure::10 Proposal Management	Observation Preparation Tool									->	->			->					->																									
Logical Structure::10 Proposal Management	Proposal Builder Tool									->	->																																	
Logical Structure::10 Proposal Management	Proposal Handling Tool																	->	->																									
Logical Structure::10 Proposal Management::Views	SciOps									->	->			->		->	->		->																									
Logical Structure::20 Array::Antenna Structure	ACU																																	->										
Logical Structure::20 Array::Antenna Structure	Az Drive																																	->										
Logical Structure::20 Array::Antenna Structure	Data Transmitter																																	->										
Logical Structure::20 Array::Antenna Structure	Digital Back End																																	->										
Logical Structure::20 Array::Antenna Structure	Digitizer																															->	->	->										->
Logical Structure::20 Array::Antenna Structure	Downconverter																															->		->										
Logical Structure::20 Array::Antenna Structure	El Drive																																	->										
Logical Structure::20 Array::Antenna Structure	Feed Indexer																																	->										
Logical Structure::20 Array::Antenna Structure	Flux Reference Generator																																	->										
Logical Structure::20 Array::Antenna Structure	Indep Phase Cal System																																	->										
Logical Structure::20 Array::Antenna Structure	Mount																						->																					
Logical Structure::20 Array::Antenna Structure	Reflector Optics				->																																							
Logical Structure::20 Array::Antenna Structure	RF Receiver				->																													->									->	
Logical Structure::20 Array::Antenna Structure	Time & Freq Reference Generator																															->	->	->										
Logical Structure::20 Array::Antenna Types	Antenna				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array::Antenna Types	LB Antenna				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array::Antenna Types	Main Antenna				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array::Antenna Types	SBA Antenna				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array::Antenna Types	TP Antenna				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array::Env Monitors	Atm. Delay Monitor System																																	->										
Logical Structure::20 Array::Env Monitors	Weather Monitor System																																	->										
Logical Structure::20 Array	Long Baseline Array				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array	Main Array				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array	Short Baseline Array				->	->	->	->	->														->									->	->	->							->		->	->
Logical Structure::20 Array	Total Power Array				->	->	->	->	->														->	->								->	->	->							->		->	->
Logical Structure::30 Central Reference Distribution	Frequency Reference																																											
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor																																	->	->		->							
Logical Structure::30 Central Reference Distribution	Time Reference																																											
Logical Structure::30 Central Reference Distribution	Time Reference Distributor																																	->	->		->							
Logical Structure::40 Central Signal Processing	Beamformer		->	->																															->	->	->	->	->	->				
Logical Structure::40 Central Signal Processing	Correlator																											->	->	->	->				->	->	->	->	->	->				
Logical Structure::40 Central Signal Processing	Correlator Back End																																											
Logical Structure::40 Central Signal Processing	Data Buffer																																											
Logical Structure::40 Central Signal Processing	Online Calibration System																																											
Logical Structure::40 Central Signal Processing	Pulsar Search System																																											
Logical Structure::40 Central Signal Processing	Pulsar Timing System																																											
Logical Structure::50 Online Control & Monitoring	Calibration Module				->																																							
Logical Structure::50 Online Control & Monitoring	Configuration Module																																											
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor																																							->				
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor																											->	->	->	->				->	->	->	->	->	->				
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor																																							->				
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor																																							->				
Logical Structure::50 Online Control & Monitoring	Data Transmission Module																																							->				
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board																																											
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module																																											
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver																																											
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector																																											

	L.00-005 Logical Model to Requirements - Satisfy Matrix	SYS3006 Trigger Override	SYS0201 Phased Aperture	SYS0203 Number of Beams	SYS1901 Polarization Purity	SYS2700 Safety Specification	SYS2701 Sub-system self-monitoring	SYS2702 IT Security	SYS2704 Physical Security	SYS2221 Observation Preparation – Standard Observing Modes	SYS2222 Observation Preparation - Non-Standard Observing modes	SYS2223 Observation Scheduling GUI	SYS2224 Observation Interrupt	SYS2225 Observation Preparation – Standard Observing Mode Flexibility	SYS2302 Observation Scheduling	SYS2211 Proposal Submission – standard observing modes	SYS2212 Proposal Submission – non-standard observing modes.	SYS2213 Scientific Proposal Evaluation	SYS2214 Technical Proposal Evaluation	SYS2201 Provision of Software Tools	SYS1001 Effective Area / Tsys Ratio	SYS1301 Longest Baseline	SYS1302 Shortest Baseline	SYS1303 Zero Spacing / Single Dish Total Power	SYS1304 Integration Time Ratios	SYS1306 Fraction of Occupied Cells	SYS1308 Distribution and Weighting of Visibilities	SYS1401 Highest Spectral Resolution	SYS1402 Number of Spectral Channels	SYS1403 Flexible Spectral Resolution	SYS1404 Doppler Corrections	SYS2104 Self-Generated Spurious Signal Power Level	SYS2105 LO Frequency and Sampler Clock Offsets	SYS2106 Shielding & Emission Limits	SYS0601 Sub-Array Capabilities	SYS0602 Phase Preservation	SYS0603 Sub-Array Composition	SYS0604 Sub-Array Operating Modes	SYS0605 Sub-Array Operating Mode Commensality	SYS0606 Sub-Array Configuration	SYS2601 Antenna System Availability	SYS2602 Centralized Systems Availability	SYS0901 Front End Bandwidth Ratio	SYS0902 Instantaneous Digitized Bandwidth
Logical Structure::50 Online Control & Monitoring	Observation Module																																		->					->				
Logical Structure::50 Online Control & Monitoring	Operation Module	->																																	->	->	->	->	->	->				
Logical Structure::50 Online Control & Monitoring	QuickLook Module																																											
Logical Structure::50 Online Control & Monitoring	Scheduling Module											->	->		->																									->				
Logical Structure::60 Data Archives	Engineering Data Archive																																											
Logical Structure::60 Data Archives	Proposal Archive																			->																								
Logical Structure::60 Data Archives	RFI Archive																		->																									
Logical Structure::60 Data Archives	Science Data Archive																																											
Logical Structure::60 Data Archives	Staging Storage																																											
Logical Structure::60 Data Archives	Telescope Calibration Archive																																											
Logical Structure::60 Data Archives	Telescope Configuration Archive																																											
Logical Structure::70 Infrastructure	Central Electronics Building																																	->										
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Logical Structure::80 Maintenance & Support	Central Repair Facility																																											
Logical Structure::80 Maintenance & Support	CMMS Integration Module																																											
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System																																											
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Logical Structure::80 Maintenance & Support	Issue Tracking System																																											
Logical Structure::90 Commissioning & Development	Development Support Infrastructure																																											
Logical Structure::90 Commissioning & Development	Simulation Tool																																											
Logical Structure::90 Commissioning & Development	Testing Environment																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Computational Resources																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Analysis Tools																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Management																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Pipelines																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing System																												->	->	->													
Logical Structure::100 Offline Processing & Archive Interfaces	Observatory Interfaces																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Offline Calibration Tools																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Resources																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Storage Resources																																											
Logical Structure::100 Offline Processing & Archive Interfaces	Quality Assurance Interfaces													->					->																									
Logical Structure	Array				->	->	->	->	->												->	->	x	x	->	->	->					->	->	->							->		->	->
Logical Structure	Central Reference Distribution System					->	->	->																										->	->		->					->		
Logical Structure	Central Signal Processing System		->	->		->	->	->																				->	->	->	->				->	->	->	->	->	->		->		
Logical Structure	Commissioning & Development Systems					->	->	->																																				
Logical Structure	Data Archive System					->	->	->											->	->																						->		
Logical Structure	Infrastructure Systems					->	->	->																										->								->		
Logical Structure	Maintenance & Support Systems					->	->	->																																				
Logical Structure	ngVLA System	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->
Logical Structure	Offline Subsystem							->						->					->	->									->	->	->													
Logical Structure	Online Subsystem	->			->	->	->	->				->	->		->					->								->	->	->	->				->	->	->	->	->	->		->		
Logical Structure	Proposal Management System							->		->	->			->		->	->	->	->	->																								

L.00-005 Logical Model to Requirements - Satisfy Matrix

ngvla	L.00-005 Logical Model to Requirements - Satisfy Matrix	SYS0903 Total Instantaneous Processed Bandwidth	SYS0904 Sub-Bands	SYS0905 Frequency Tunability	SYS0906 Fixed Analog Tunings	SYS0907 Sub-Band Step Size	SYS0908 Band Switching Time	SYS0909 Contiguous Bandwidth	SYS1101 Instantaneous Field of View	SYS1102 Accessible Field of View	SYS1103 Slew Rates	SYS1104 Tracking Rates	SYS2811 Test Fixtures	SYS2812 Critical Spares	SYS2813 System Verification Tools	SYS2801 Design Life	SYS2802 Cost Optimization	SYS2803 Sustainability	SYS3101 LRU Monitoring	SYS3102 LRU Alerts	SYS3103 Monitor Archive	SYS3104 Sub-System Monitoring Screens	SYS3105 Fast Read-Out Modes	SYS0106 On-The-Fly Mapping – Data & Control Rates	SYS0107 On-The-Fly Mapping – Antenna Tracking Rate	SYS2001 Temporal Resolution	SYS2002 Temporal Accuracy	SYS0401 Search Capabilities	SYS0402 Search Sys. Bandwidth	SYS0403 Search Sys. Frequency Resolution	SYS0404 Search Sys. Time Resolution	SYS0405 Polarization	SYS0301 Timing Capabilities	SYS0302 Timing Sys. Bandwidth	SYS0303 Timing Sys. Frequency Resolution	SYS0304 Pulse Profile Bins	SYS0305 Polarization	SYS0306 Pulse Period	SYS0307 Dump Rate	SYS0501 VLBI Recording Capabilities	SYS0502 eVLBI Capabilities
SATISFY RELATIONSHIPS		17	14	14	13	12	12	15	12	12	15	15	5	43	5	3	1	1	37	7	4	7	3	9	12	4	7	3	3	3	3	3	3	3	3	3	3	3	3	5	4
Logical Structure::10 Proposal Management	Proposal Submission Tool																																								
Logical Structure::10 Proposal Management	Observation Preparation Tool																																								
Logical Structure::10 Proposal Management	Proposal Builder Tool																																								
Logical Structure::10 Proposal Management	Proposal Handling Tool																																								
Logical Structure::10 Proposal Management::Views	SciOps																																								
Logical Structure::20 Array::Antenna Structure	ACU										->	->		->					->						->																
Logical Structure::20 Array::Antenna Structure	Az Drive										->	->		->																											
Logical Structure::20 Array::Antenna Structure	Data Transmitter													->					->																						
Logical Structure::20 Array::Antenna Structure	Digital Back End	->	->	->		->		->						->					->																						
Logical Structure::20 Array::Antenna Structure	Digitizer							->						->					->																						
Logical Structure::20 Array::Antenna Structure	Downconverter			->	->			->						->					->																						
Logical Structure::20 Array::Antenna Structure	El Drive										->	->		->																											
Logical Structure::20 Array::Antenna Structure	Feed Indexer						->							->																											
Logical Structure::20 Array::Antenna Structure	Flux Reference Generator													->																											
Logical Structure::20 Array::Antenna Structure	Indep Phase Cal System													->					->																						
Logical Structure::20 Array::Antenna Structure	Mount									->	->	->																													
Logical Structure::20 Array::Antenna Structure	Reflector Optics								->																																
Logical Structure::20 Array::Antenna Structure	RF Receiver													->					->																						
Logical Structure::20 Array::Antenna Structure	Time & Freq Reference Generator			->	->			->						->					->																						
Logical Structure::20 Array::Antenna Types	Antenna	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array::Antenna Types	LB Antenna	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array::Antenna Types	Main Antenna	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array::Antenna Types	SBA Antenna	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array::Antenna Types	TP Antenna	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array::Env Monitors	Atm. Delay Monitor System													->					->																						
Logical Structure::20 Array::Env Monitors	Weather Monitor System													->					->																						
Logical Structure::20 Array	Long Baseline Array	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array	Main Array	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array	Short Baseline Array	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::20 Array	Total Power Array	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure::30 Central Reference Distribution	Frequency Reference													->					->																						
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor													->					->																						
Logical Structure::30 Central Reference Distribution	Time Reference													->					->								->														
Logical Structure::30 Central Reference Distribution	Time Reference Distributor													->					->								->														
Logical Structure::40 Central Signal Processing	Beamformer	->												->					->																						
Logical Structure::40 Central Signal Processing	Correlator	->	->											->					->					->		->	->														->
Logical Structure::40 Central Signal Processing	Correlator Back End													->					->					->		->	->														
Logical Structure::40 Central Signal Processing	Data Buffer													->					->					->																->	
Logical Structure::40 Central Signal Processing	Online Calibration System													->					->					->																	
Logical Structure::40 Central Signal Processing	Pulsar Search System													->					->									->	->	->	->	->									
Logical Structure::40 Central Signal Processing	Pulsar Timing System													->					->														->	->	->	->	->	->	->		
Logical Structure::50 Online Control & Monitoring	Calibration Module																																								
Logical Structure::50 Online Control & Monitoring	Configuration Module																																								
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor																			->		->																			
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor																			->		->																		->	
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor																			->		->																			
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor																			->		->																			
Logical Structure::50 Online Control & Monitoring	Data Transmission Module																			->		->																			
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board																		->				->																		
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module																																								
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver																				->																				
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector																		->		->																				

	L.00-005 Logical Model to Requirements - Satisfy Matrix	SYS0903 Total Instantaneous Processed Bandwidth	SYS0904 Sub-Bands	SYS0905 Frequency Tunability	SYS0906 Fixed Analog Tunings	SYS0907 Sub-Band Step Size	SYS0908 Band Switching Time	SYS0909 Contiguous Bandwidth	SYS1101 Instantaneous Field of View	SYS1102 Accessible Field of View	SYS1103 Slew Rates	SYS1104 Tracking Rates	SYS2811 Test Fixtures	SYS2812 Critical Spares	SYS2813 System Verification Tools	SYS2801 Design Life	SYS2802 Cost Optimization	SYS2803 Sustainability	SYS3101 LRU Monitoring	SYS3102 LRU Alerts	SYS3103 Monitor Archive	SYS3104 Sub-System Monitoring Screens	SYS3105 Fast Read-Out Modes	SYS0106 On-The-Fly Mapping – Data & Control Rates	SYS0107 On-The-Fly Mapping – Antenna Tracking Rate	SYS2001 Temporal Resolution	SYS2002 Temporal Accuracy	SYS0401 Search Capabilities	SYS0402 Search Sys. Bandwidth	SYS0403 Search Sys. Frequency Resolution	SYS0404 Search Sys. Time Resolution	SYS0405 Polarization	SYS0301 Timing Capabilities	SYS0302 Timing Sys. Bandwidth	SYS0303 Timing Sys. Frequency Resolution	SYS0304 Pulse Profile Bins	SYS0305 Polarization	SYS0306 Pulse Period	SYS0307 Dump Rate	SYS0501 VLBI Recording Capabilities	SYS0502 eVLBI Capabilities
Logical Structure::50 Online Control & Monitoring	Observation Module																																								
Logical Structure::50 Online Control & Monitoring	Operation Module																																								
Logical Structure::50 Online Control & Monitoring	QuickLook Module																																								
Logical Structure::50 Online Control & Monitoring	Scheduling Module																																								
Logical Structure::60 Data Archives	Engineering Data Archive																																								
Logical Structure::60 Data Archives	Proposal Archive																																								
Logical Structure::60 Data Archives	RFI Archive																																								
Logical Structure::60 Data Archives	Science Data Archive																																								
Logical Structure::60 Data Archives	Staging Storage																							->																	
Logical Structure::60 Data Archives	Telescope Calibration Archive																																								
Logical Structure::60 Data Archives	Telescope Configuration Archive																																								
Logical Structure::70 Infrastructure	Central Electronics Building																																								
Logical Structure::70 Infrastructure	Data Distribution System	->																																							
Logical Structure::70 Infrastructure	Electrical Distribution System																																								
Logical Structure::80 Maintenance & Support	Central Repair Facility															->																									
Logical Structure::80 Maintenance & Support	CMMS Integration Module																																								
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System																																								
Logical Structure::80 Maintenance & Support	Integrated Support Module														->																										
Logical Structure::80 Maintenance & Support	Issue Tracking System																																								
Logical Structure::90 Commissioning & Development	Development Support Infrastructure														->																										
Logical Structure::90 Commissioning & Development	Simulation Tool												->																												
Logical Structure::90 Commissioning & Development	Testing Environment												->																												
Logical Structure::100 Offline Processing & Archive Interfaces	Computational Resources													->																											
Logical Structure::100 Offline Processing & Archive Interfaces	Data Analysis Tools																																								
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Management																																								
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Pipelines																																								
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing System													->										->																	
Logical Structure::100 Offline Processing & Archive Interfaces	Observatory Interfaces																																								
Logical Structure::100 Offline Processing & Archive Interfaces	Offline Calibration Tools																																								
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Resources													->																											
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Storage Resources													->																											
Logical Structure::100 Offline Processing & Archive Interfaces	Quality Assurance Interfaces																																								
Logical Structure	Array	->	->	->	->	->	->	->	->	->	->	->		->					->						->																
Logical Structure	Central Reference Distribution System													->					->								->														
Logical Structure	Central Signal Processing System	->	->											->					->					->		->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->
Logical Structure	Commissioning & Development Systems												->		->																										
Logical Structure	Data Archive System																																								
Logical Structure	Infrastructure Systems	->																																							
Logical Structure	Maintenance & Support Systems												->		->	->																									
Logical Structure	ngVLA System	->	->	->	->	->	->	->	->	->	->	->	->	->	->	x	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->
Logical Structure	Offline Subsystem													->										->																	
Logical Structure	Online Subsystem																		->	->	->	->	->																	->	->
Logical Structure	Proposal Management System																																								

L.00-006 Logical Model Behavior Allocation - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Proposal Submission Tool	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	SciOps	ACU	Az Drive	Data Transmitter	Digital Back End	Digitizer	Downconverter	El Drive	Feed Indexer	Flux Reference Generator	Indep Phase Cal System	Mount	Reflector Optics	RF Receiver	Time & Freq Reference Generator	Antenna	LB Antenna	Main Antenna	SBA Antenna	TP Antenna	Atm. Delay Monitor System	Weather Monitor System	Long Baseline Array	Main Array	Short Baseline Array	Total Power Array	Frequency Reference	Frequency Reference Distributor	Time Reference	Time Reference Distributor	Beamformer	Correlator	Correlator Back End	Data Buffer	Pulsar Search System	Pulsar Timing System	Calibration Module	Configuration Module	Antenna Control Supervisor	CSP Control Supervisor	LO Reference Control Supervisor	Timing Control Supervisor	Data Transmission Module	HW Controller Board	Metadata Capture Module	Monitoring Data Archiver	Monitoring Data Collector	Observation Module	Operation Module	QuickLook Module	Scheduling Module
ALLOCATE RELATIONSHIPS			4	4	5	3	6	20	16	13	26	14	14	16	18	14	15	0	0	13	16	50	50	50	50	50	4	17	50	50	50	50	1	14	1	1	33	36	26	14	16	16	32	3	49	28	25	5	4	32	4	7	7	54	20	4	20
System Behaviors	01 Manage Proposal Submission	7	->	->	->	->	->																																																			
System Behaviors::01 Manage Proposal Submission	Observation Preparation(context Observation Preparation Tool)	4		->			->																																																			
System Behaviors::01 Manage Proposal Submission	Proposal Evaluation(context Proposal Submission Tool)	4	->				->																																																			
System Behaviors::01 Manage Proposal Submission	Proposal Submission(context Proposal Submission Tool)	4	->				->																																																			
System Behaviors::01 Manage Proposal Submission	Scheduling Block Definition(context Observation Preparation Tool)	4		->			->																																																			
System Behaviors::01 Manage Proposal Submission	Scheduling Block Generation(context Proposal Builder Tool)	3			->																																																					
System Behaviors::01 Manage Proposal Submission	Telescope Time Allocation(context Proposal Handling Tool)	3				->																																																				
System Behaviors::02 Subarray Management	Allocate Central Signal Processing Resources	4																																												->								->			
System Behaviors::02 Subarray Management	Allocate Subarray Antennas	4																																											->									->			
System Behaviors::02 Subarray Management	Allocate Subarray Resources(context Observation Module)	7																																											->	->	->							x	->		
System Behaviors::02 Subarray Management	Configure Central Signal Processing Resources	4																																												->								->			
System Behaviors::02 Subarray Management	Configure Required Software Modules(context Observation Module)	3																																																				->			
System Behaviors::02 Subarray Management::Configure Subarray Antennas	Configure Downconverters	4																																											->									->			
System Behaviors::02 Subarray Management::Configure Subarray Antennas	Move FIM to Selected Band	16						->							->							->	->	->	->	->			->	->	->	->													->									->			
System Behaviors::02 Subarray Management::Configure Subarray Antennas	Tune LOs	4																																													->							->			
System Behaviors::02 Subarray Management	Configure Subarray Antennas(context Observation Module)	17						->							->							->	->	->	->	->			->	->	->	->													->		->							x			
System Behaviors::02 Subarray Management	Configure Subarray Resources(context Observation Module)	18						->							->							->	->	->	->	->			->	->	->	->													->	->	->							x			
System Behaviors::02 Subarray Management	Create sub-array partition schedule	4																																																					->		->
System Behaviors::02 Subarray Management	Free Subarray Resources	8																																											->	->	->							->	->		->
System Behaviors::02 Subarray Management	Instantiate Required Software Modules	7																																											->	->	->							->	->		
System Behaviors	02 Subarray Management	20						->							->							->	->	->	->	->			->	->	->	->													->	->	->							x	x		->
System Behaviors::03 Schedule Observations	Evaluate Atmospheric Conditions	8																									->	->																	->												->
System Behaviors::03 Schedule Observations	Evaluate Observation Priorities	5																																																							->
System Behaviors::03 Schedule Observations	Evaluate RFI Risk	5																																																							->
System Behaviors::03 Schedule Observations	Evaluate System Configuration	5																																																							->
System Behaviors::03 Schedule Observations	Execute Scheduling Algorithm(context Scheduling Module)	11																									->	->																	->												x
System Behaviors::03 Schedule Observations	Present Candidate Scheduling Blocks(context Proposal Builder Tool)	3			->																																																				
System Behaviors	03 Schedule Observations(context Scheduling Module)	13			->																						->	->																	->												x
System Behaviors	04 Perform Observations	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::04 Perform Observations::01 Data Acquisition	Antenna Pointing	18						->	->					->								->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::01 Data Acquisition	Data Digitization	16										->										->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::01 Data Acquisition	Data Encoding	16									->											->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::01 Data Acquisition	Data Transmission	16								->												->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::01 Data Acquisition	Frequency Tuning	17											->								->	->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::01 Data Acquisition	Gain Selection	17										->	->									->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::01 Data Acquisition	Provide Frequency Offsets	16																			->	->	->	->	->	->			->	->	->	->		->													->										
System Behaviors::04 Perform Observations::01 Data Acquisition	RF Signal Reception	17													->					->		->	->	->	->	->			->	->	->	->													x					x				x			
System Behaviors::04 Perform Observations::01 Data Acquisition	Select Band	16													->							->	->	->	->	->			->	->	->	->													->					->				->			

L.00-006 Logical Model Behavior Allocation - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Proposal Submission Tool	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	SciOps	ACU	Az Drive	Data Transmitter	Digital Back End	Digitizer	Downconverter	El Drive	Feed Indexer	Flux Reference Generator	Indep Phase Cal System	Mount	Reflector Optics	RF Receiver	Time & Freq Reference Generator	Antenna	LB Antenna	Main Antenna	SBA Antenna	TP Antenna	Atm. Delay Monitor System	Weather Monitor System	Long Baseline Array	Main Array	Short Baseline Array	Total Power Array	Frequency Reference	Frequency Reference Distributor	Time Reference	Time Reference Distributor	Beamformer	Correlator	Correlator Back End	Data Buffer	Pulsar Search System	Pulsar Timing System	Calibration Module	Configuration Module	Antenna Control Supervisor	CSP Control Supervisor	LO Reference Control Supervisor	Timing Control Supervisor	Data Transmission Module	HW Controller Board	Metadata Capture Module	Monitoring Data Archiver	Monitoring Data Collector	Observation Module	Operation Module	QuickLook Module	Scheduling Module
ALLOCATE RELATIONSHIPS			4	4	5	3	6	20	16	13	26	14	14	16	18	14	15	0	0	13	16	50	50	50	50	50	4	17	50	50	50	50	1	14	1	1	33	36	26	14	16	16	32	3	49	28	25	5	4	32	4	7	7	54	20	4	20
System Behaviors::04 Perform Observations	01 Data Acquisition	28						->	->	->	->	->	->	->	->					->	->	->	->	->	->	->			->	->	->	->					->	->							->					->				->			
System Behaviors::04 Perform Observations	02 Single Dish Processing	24									->										->	->	->	->	->	->			->	->	->	->		->			->	->							->	->	->			->				->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Apply Frequency Dependent Gain Corrections	15									->											->	->	->	->	->			->	->	->	->													->									->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Apply Timestamp	15									->											->	->	->	->	->			->	->	->	->													->									->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Clock Recovery	15									->											->	->	->	->	->			->	->	->	->													->									->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Coarse Sideband Separation	15									->											->	->	->	->	->			->	->	->	->													->									->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	FFT(context Digital Back End)	12									->											->	->	->	->	->			->	->	->	->																									
System Behaviors::04 Perform Observations::02 Single Dish Processing	Fine Sideband Separation	7																																			->	->								->								->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	High Power RFI Excision(context Digital Back End)	12									->											->	->	->	->	->			->	->	->	->																									
System Behaviors::04 Perform Observations::02 Single Dish Processing	Offset LO	18																			->	->	->	->	->	->			->	->	->	->		->											->		->							->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Provide Timestamp(context Time Reference Distributor)	3																																		->																					
System Behaviors::04 Perform Observations::02 Single Dish Processing	Requantization	14									->											->	->	->	->	->			->	->	->	->													->												
System Behaviors::04 Perform Observations::02 Single Dish Processing	RFI Excision	8																																			->	->								->											
System Behaviors::04 Perform Observations::02 Single Dish Processing	RFI Flagging	12																																			->	->	->				->														
System Behaviors::04 Perform Observations::02 Single Dish Processing	Sideband Separation(context Digital Back End)	19									x											->	->	->	->	->			->	->	->	->					->	->							->	->								->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Sub-Band Selection	16									->											->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Total Power Measurement	19									->											->	->	->	->	->			->	->	->	->						->							->	->				->				->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Coarse Delay Tracking Corrections	4																																			->	->																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Coarse Sampler Clock Offset Corrections	4																																			->	->																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Delay Tracking Corrections	4																																			x	x																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Doppler Tracking Correction	6																																			->	->																->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Fine Delay Tracking Corrections	4																																			->	->																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Fine Sampler Clock Offset Corrections	4																																			->	->																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Fringe Rotation Corrections	4																																			->	->																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply LO Offsetting Corrections	4																																			->	->																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Sampler Clock Offsetting Corrections	4																																			x	x																			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Timing Synchronization Corrections	4																																			->	->																			
System Behaviors::04 Perform Observations::03 Array Phasing	Calculate Delay Tracking Corrections	6																																									->											->			
System Behaviors::04 Perform Observations::03 Array Phasing	Calculate Fringe Rotation Corrections	4																																									->											->			
System Behaviors::04 Perform Observations::03 Array Phasing	Calculate LO Offsetting Corrections(context Observation Module)	3																																																				->			
System Behaviors::04 Perform Observations::03 Array Phasing	Track Digital LO Mixer Phase(context CSP Control Supervisor)	3																																												->											
System Behaviors::04 Perform Observations	03 Array Phasing	9																																			->	->					->											->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Antenna Data Buffering	4																																					->	->																	
System Behaviors::04 Perform Observations::04 Central Signal Processing	Archive Formatting(context Correlator Back End)	3																																					->																		

	L.00-006 Logical Model Behavior Allocation - Allocate Matrix	ALLOCATE RELATIONSHIPS	Proposal Submission Tool	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	SciOps	ACU	Az Drive	Data Transmitter	Digital Back End	Digitizer	Downconverter	El Drive	Feed Indexer	Flux Reference Generator	Indep Phase Cal System	Mount	Reflector Optics	RF Receiver	Time & Freq Reference Generator	Antenna	LB Antenna	Main Antenna	SBA Antenna	TP Antenna	Atm. Delay Monitor System	Weather Monitor System	Long Baseline Array	Main Array	Short Baseline Array	Total Power Array	Frequency Reference	Frequency Reference Distributor	Time Reference	Time Reference Distributor	Beamformer	Correlator	Correlator Back End	Data Buffer	Pulsar Search System	Pulsar Timing System	Calibration Module	Configuration Module	Antenna Control Supervisor	CSP Control Supervisor	LO Reference Control Supervisor	Timing Control Supervisor	Data Transmission Module	HW Controller Board	Metadata Capture Module	Monitoring Data Archiver	Monitoring Data Collector	Observation Module	Operation Module	QuickLook Module	Scheduling Module
ALLOCATE RELATIONSHIPS			4	4	5	3	6	20	16	13	26	14	14	16	18	14	15	0	0	13	16	50	50	50	50	50	4	17	50	50	50	50	1	14	1	1	33	36	26	14	16	16	32	3	49	28	25	5	4	32	4	7	7	54	20	4	20
System Behaviors::04 Perform Observations::04 Central Signal Processing	AutoCorrelation(context Correlator)	3																																				x																			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Bandwidth Stitching(context Correlator Back End)	3																																					->																		
System Behaviors::04 Perform Observations::04 Central Signal Processing	Beamforming(context Beamformer)	3																																		->																				
System Behaviors::04 Perform Observations::04 Central Signal Processing	Correlation(context Correlator)	3																																			->																			
System Behaviors::04 Perform Observations::04 Central Signal Processing	CrossCorrelation(context Correlator)	3																																			x																			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Data Decoding	4																																		->	->																			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Pulsar Searching(context Pulsar Search System)	3																																						->																
System Behaviors::04 Perform Observations::04 Central Signal Processing	Pulsar Timing(context Pulsar Timing System)	3																																							->															
System Behaviors::04 Perform Observations::04 Central Signal Processing	Visibility Data Buffering	4																																				->	->																	
System Behaviors::04 Perform Observations	04 Central Signal Processing	8																																		->	->	->	->	->	->															
System Behaviors::04 Perform Observations::05 Calibrations	Apply IQ Sideband Gain Coefficients	15									->											->	->	->	->	->			->	->	->	->					->	->																			
System Behaviors::04 Perform Observations::05 Calibrations	Calculate Geometric Delay	5																																				->				->														
System Behaviors::04 Perform Observations::05 Calibrations	Determine Antenna Positions(context Calibration Module)	3																																								->														
System Behaviors::04 Perform Observations::05 Calibrations	Determine Electronic Delay	5																																				->				->														
System Behaviors::04 Perform Observations::05 Calibrations	Determine Gain Calibration Coefficients	5																																				->				->														
System Behaviors::04 Perform Observations::05 Calibrations	Determine Pointing Model Ciefficients(context Calibration Module)	3																																								->														
System Behaviors::04 Perform Observations::05 Calibrations	Determine Primary Beam Patterns(context Offline Calibration Tools)	2																																																						
System Behaviors::04 Perform Observations::05 Calibrations	Determine TCals(context Offline Calibration Tools)	2																																																						
System Behaviors::04 Perform Observations::05 Calibrations	Estimate Atmospheric Delay	18															->					->	->	->	->	->		->	->	->	->	->							->				x											x			
System Behaviors::04 Perform Observations::05 Calibrations	Estimate WVR Atmospheric Delay Component	15															->					->	->	->	->	->			->	->	->	->											->											->			
System Behaviors::04 Perform Observations::05 Calibrations	Inject Flux Scale reference(context Flux Reference Generator)	12														->						->	->	->	->	->			->	->	->	->																									
System Behaviors::04 Perform Observations::05 Calibrations	Measure Flux Scale Reference(context Correlator Back End)	3																																				->																		
System Behaviors::04 Perform Observations::05 Calibrations	Optimize Antenna Surface(context Offline Calibration Tools)	2																																																						
System Behaviors::04 Perform Observations::05 Calibrations	Optimize Focus and Collimation	7																																								->														
System Behaviors::04 Perform Observations::05 Calibrations	Perform Delay Calibration	22															->					->	->	->	->	->		->	->	->	->	->							->				x											->			
System Behaviors::04 Perform Observations::05 Calibrations	Perform Gain Calibration	20														->						->	->	->	->	->			->	->	->	->							->				->														
System Behaviors::04 Perform Observations::05 Calibrations	Perform Polarization Calibration	7																																								->														
System Behaviors::04 Perform Observations::05 Calibrations	Perform Referenced Pointing Calibration	5																																								->														
System Behaviors::04 Perform Observations::05 Calibrations	Perform Tsys Calibration	7																																								->														
System Behaviors::04 Perform Observations	05 Observatory Calibration	22									->											->	->	->	->	->			->	->	->	->					->	->	->				->														
System Behaviors::04 Perform Observations	06 Online Calibration	23														->	->					->	->	->	->	->		->	->	->	->	->							->				->											->			
System Behaviors::04 Perform Observations	08 Data Recording	4																																																						
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	Move Az(context Az Drive)	12							->													->	->	->	->	->			->	->	->	->																									
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	Move El(context El Drive)	12												->								->	->	->	->	->			->	->	->	->																									

	L.00-006 Logical Model Behavior Allocation - Allocate Matrix	ALLOCATE RELATIONSHIPS	Proposal Submission Tool	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	SciOps	ACU	Az Drive	Data Transmitter	Digital Back End	Digitizer	Downconverter	El Drive	Feed Indexer	Flux Reference Generator	Indep Phase Cal System	Mount	Reflector Optics	RF Receiver	Time & Freq Reference Generator	Antenna	LB Antenna	Main Antenna	SBA Antenna	TP Antenna	Atm. Delay Monitor System	Weather Monitor System	Long Baseline Array	Main Array	Short Baseline Array	Total Power Array	Frequency Reference	Frequency Reference Distributor	Time Reference	Time Reference Distributor	Beamformer	Correlator	Correlator Back End	Data Buffer	Pulsar Search System	Pulsar Timing System	Calibration Module	Configuration Module	Antenna Control Supervisor	CSP Control Supervisor	LO Reference Control Supervisor	Timing Control Supervisor	Data Transmission Module	HW Controller Board	Metadata Capture Module	Monitoring Data Archiver	Monitoring Data Collector	Observation Module	Operation Module	QuickLook Module	Scheduling Module
ALLOCATE RELATIONSHIPS			4	4	5	3	6	20	16	13	26	14	14	16	18	14	15	0	0	13	16	50	50	50	50	50	4	17	50	50	50	50	1	14	1	1	33	36	26	14	16	16	32	3	49	28	25	5	4	32	4	7	7	54	20	4	20
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	OTF Scanning(context ACU)	18						x	->					->								->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	Tracking(context ACU)	18						x	->					->								->	->	->	->	->			->	->	->	->													->					->				->			
System Behaviors::04 Perform Observations	Archive Ingestion	9																																														->								
System Behaviors::04 Perform Observations	Metadata Capture	5																																																->						
System Behaviors::04 Perform Observations	Quality Assurance	5																																																					->	
System Behaviors::04 Perform Observations	Shift Logging	5																																																				->		
System Behaviors::05 Configure System	Apply Configuration Parameters	10																																								->	->	->	->	->		->							
System Behaviors::05 Configure System	Define Configuration Parameters	5																																								->													
System Behaviors::05 Configure System	Provide Frequency Reference(context Frequency Reference)	3																														->																								
System Behaviors::05 Configure System	Provide Timing Reference(context Time Reference)	3																																->																						
System Behaviors	05 Configure System	10																																								->	->	->	->	->		->							
System Behaviors::06 Monitor Telescope Status	Archive Alerts	6																																																->	->				
System Behaviors::06 Monitor Telescope Status	Archive Monitor Data	6																																																->	->				
System Behaviors::06 Monitor Telescope Status	Check for Alert Conditions	4																																																->	->				
System Behaviors::06 Monitor Telescope Status	Collect Monitor Data(context Metadata Capture Module)	3																																															->						
System Behaviors::06 Monitor Telescope Status	Display Alerts(context Operation Module)	3																																																			->		
System Behaviors::06 Monitor Telescope Status	Display Monitor Data(context Operation Module)	3																																																			->		
System Behaviors::06 Monitor Telescope Status	Measure Analog Monitor Point(context HW Controller Board)	3																																														->							
System Behaviors::06 Monitor Telescope Status	Monitor Antenna System Health	6																																									->					->		->	->				
System Behaviors::06 Monitor Telescope Status	Monitor Central Electronic System Health	9																																										->	->	->	->	->		->	->				
System Behaviors::06 Monitor Telescope Status	Read Digital Register(context HW Controller Board)	3																																														->							
System Behaviors	06 Monitor Telescope Status(context ngVLA System)	14																																									->	->	->	->	->	->	->	->	->		->		
System Behaviors::07 Generate Derived Data Products	De-Disperse Spectra	11																																						->	->															
System Behaviors::07 Generate Derived Data Products	Flag Corrupted Data	10																																								->														
System Behaviors::07 Generate Derived Data Products	Generate Image Cubes	8																																																						
System Behaviors::07 Generate Derived Data Products	Generate Pulse Profiles(context Pulsar Timing System)	11																																						->	x															
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Bandpass Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Flux Scale Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Gain Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Phase Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Polarization Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Tsys Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products	Perform Direction Dependent Offline Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products	Perform Direction Independent Offline Calibration	8																																																					
System Behaviors::07 Generate Derived Data Products	Perform Quality Assurance	9																																																					
System Behaviors	07 Generate Derived Data Products(context ngVLA System)	14																																						->	->	->														
System Behaviors::08 Provide Access to Data Products	Data Product Analysis(context Data Analysis Tools)	1																																																					
System Behaviors::08 Provide Access to Data Products	Data Product Discovery(context Observatory Interfaces)	3																																																					
System Behaviors::08 Provide Access to Data Products	Data Product Retrieval(context Observatory Interfaces)	3																																																					
System Behaviors::08 Provide Access to Data Products	On-demand Post-processing	8																																																					
System Behaviors::08 Provide Access to Data Products	Project Tracking	5																																																					
System Behaviors	08 Provide Access to Data Products(context ngVLA System)	5																																																					

	L.00-006 Logical Model Behavior Allocation - Allocate Matrix	ALLOCATE RELATIONSHIPS	Proposal Submission Tool	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	SciOps	ACU	Az Drive	Data Transmitter	Digital Back End	Digitizer	Downconverter	El Drive	Feed Indexer	Flux Reference Generator	Indep Phase Cal System	Mount	Reflector Optics	RF Receiver	Time & Freq Reference Generator	Antenna	LB Antenna	Main Antenna	SBA Antenna	TP Antenna	Atm. Delay Monitor System	Weather Monitor System	Long Baseline Array	Main Array	Short Baseline Array	Total Power Array	Frequency Reference	Frequency Reference Distributor	Time Reference	Time Reference Distributor	Beamformer	Correlator	Correlator Back End	Data Buffer	Pulsar Search System	Pulsar Timing System	Calibration Module	Configuration Module	Antenna Control Supervisor	CSP Control Supervisor	LO Reference Control Supervisor	Timing Control Supervisor	Data Transmission Module	HW Controller Board	Metadata Capture Module	Monitoring Data Archiver	Monitoring Data Collector	Observation Module	Operation Module	QuickLook Module	Scheduling Module
ALLOCATE RELATIONSHIPS			4	4	5	3	6	20	16	13	26	14	14	16	18	14	15	0	0	13	16	50	50	50	50	50	4	17	50	50	50	50	1	14	1	1	33	36	26	14	16	16	32	3	49	28	25	5	4	32	4	7	7	54	20	4	20
System Behaviors::09 Support Maintenance	Configuration Management(context Telescope Configuration Archive)	5																																																							
System Behaviors::09 Support Maintenance	Data QuickLook(context QuickLook Module)	3																																																						->	
System Behaviors::09 Support Maintenance	Diagnose System Fault	3																																																							
System Behaviors::09 Support Maintenance	Perform Tier 2 Repairs(context Central Repair Facility)	3																																																							
System Behaviors::09 Support Maintenance	Report Current Configuration	5																																																							
System Behaviors::09 Support Maintenance	Schedule Maintenance(context Computerized Maintenance Management System)	3																																																							
System Behaviors::09 Support Maintenance	Track Historical Configuration(context Telescope Configuration Archive)	3																																																							
System Behaviors::09 Support Maintenance	Track Issues(context Issue Tracking System)	3																																																							
System Behaviors::09 Support Maintenance	Track Maintenance(context Computerized Maintenance Management System)	3																																																							
System Behaviors	09 Support Maintenance(context ngVLA System)	11																																																						->	
System Behaviors::10 Support Development and Commissioning	Offline Testing	4																																																							
System Behaviors::10 Support Development and Commissioning	Online Testing(context ngVLA System)	1																																																							
System Behaviors::10 Support Development and Commissioning	Provide Development Environment(context Development Support Infrastructure)	3																																																							
System Behaviors::10 Support Development and Commissioning	Simulation(context Simulation Tool)	3																																																							
System Behaviors	10 Support Development and Commissioning(context ngVLA System)	5																																																							
System Behaviors::11 Provide Services	Transport Data(context Data Distribution System)	3																																																							
System Behaviors::98 Observations by Intent	Observe Flux Scale Calibrator(context ngVLA System)	1																																																							
System Behaviors::98 Observations by Intent	Observe Gain Calibrator(context ngVLA System)	1																																																							
System Behaviors::98 Observations by Intent	Observe Phase Calibrator(context ngVLA System)	1																																																							
System Behaviors::98 Observations by Intent	Observe Polarization Calibrator(context ngVLA System)	1																																																							
System Behaviors::98 Observations by Intent	Observe Science Targe(context ngVLA System)	1																																																							
System Behaviors::98 Observations by Intent	Observe Source(context ngVLA System)	1																																																							
System Behaviors::98 Observations by Intent	Slew to Source	14						->														->	->	->	->	->			->	->	->	->													->												
System Behaviors::99 Observing Modes	L.03-031 Perform Single Field Synthesis Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform Beamforming Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform Interferometric Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform On The Fly Mosaic Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform Pulsar Search Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform Pulsar Timing Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform Single Field Continuum Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform Spectral Line Single Field Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors::99 Observing Modes	Perform VLBI Observation(context ngVLA System)	48						->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->		->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->			->				->	->		->
System Behaviors	System Operation	83	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->			->	->	->	->	->	->	->	->	->	->	->	->	->		->			->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->	->	->	->	->

L.00-006 Logical Model Behavior Allocation - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Engineering Data Archive	Proposal Archive	RFI Archive	Science Data Archive	Staging Storage	Telescope Calibration Archive	Telescope Configuration Archive	Central Electronics Building	Data Distribution System	Electrical Distribution System	Central Repair Facility	CMMS Integration Module	Computerized Maintenance Management System	Integrated Support Module	Issue Tracking System	Development Support Infrastructure	Simulation Tool	Testing Environment	Computational Resources	Data Analysis Tools	Data Processing Management	Data Processing Pipelines	Data Processing System	Observatory Interfaces	Offline Calibration Tools	Processing Resources	Processing Storage Resources	Quality Assurance Interfaces	Array	Central Reference Distribution System	Central Signal Processing System	Commissioning & Development Systems	Data Archive System	Infrastructure Systems	Maintenance & Support Systems	ngVLA System	Offline Subsystem	Online Subsystem	Proposal Management System
ALLOCATE RELATIONSHIPS			8	4	6	6	1	21	11	0	1	0	3	4	4	3	3	3	4	3	16	17	17	17	33	6	16	16	15	5	50	17	54	5	45	1	9	177	38	100	10
System Behaviors	01 Manage Proposal Submission	7																																				->			->
System Behaviors::01 Manage Proposal Submission	Observation Preparation(context Observation Preparation Tool)	4																																				->			->
System Behaviors::01 Manage Proposal Submission	Proposal Evaluation(context Proposal Submission Tool)	4																																				->			->
System Behaviors::01 Manage Proposal Submission	Proposal Submission(context Proposal Submission Tool)	4																																				->			->
System Behaviors::01 Manage Proposal Submission	Scheduling Block Definition(context Observation Preparation Tool)	4																																				->			->
System Behaviors::01 Manage Proposal Submission	Scheduling Block Generation(context Proposal Builder Tool)	3																																				->			->
System Behaviors::01 Manage Proposal Submission	Telescope Time Allocation(context Proposal Handling Tool)	3																																				->			->
System Behaviors::02 Subarray Management	Allocate Central Signal Processing Resources	4																																				->		->	
System Behaviors::02 Subarray Management	Allocate Subarray Antennas	4																																				->		->	
System Behaviors::02 Subarray Management	Allocate Subarray Resources(context Observation Module)	7																																				->		->	
System Behaviors::02 Subarray Management	Configure Central Signal Processing Resources	4																																				->		->	
System Behaviors::02 Subarray Management	Configure Required Software Modules(context Observation Module)	3																																				->		->	
System Behaviors::02 Subarray Management::Configure Subarray Antennas	Configure Downconverters	4																																				->		->	
System Behaviors::02 Subarray Management::Configure Subarray Antennas	Move FIM to Selected Band	16																												->								->		->	
System Behaviors::02 Subarray Management::Configure Subarray Antennas	Tune LOs	4																																				->		->	
System Behaviors::02 Subarray Management	Configure Subarray Antennas(context Observation Module)	17																												->								->		->	
System Behaviors::02 Subarray Management	Configure Subarray Resources(context Observation Module)	18																												->								->		->	
System Behaviors::02 Subarray Management	Create sub-array partition schedule	4																																				->		->	
System Behaviors::02 Subarray Management	Free Subarray Resources	8																																				->		->	
System Behaviors::02 Subarray Management	Instantiate Required Software Modules	7																																				->		->	
System Behaviors	02 Subarray Management	20																												->								->		->	
System Behaviors::03 Schedule Observations	Evaluate Atmospheric Conditions	8	->																															->			->		->	
System Behaviors::03 Schedule Observations	Evaluate Observation Priorities	5		->																														->			->		->	
System Behaviors::03 Schedule Observations	Evaluate RFI Risk	5			->																													->			->		->	
System Behaviors::03 Schedule Observations	Evaluate System Configuration	5							->																									->			->		->	
System Behaviors::03 Schedule Observations	Execute Scheduling Algorithm(context Scheduling Module)	11	->	->	->				->																									->			->		->	
System Behaviors::03 Schedule Observations	Present Candidate Scheduling Blocks(context Proposal Builder Tool)	3																																				->			->
System Behaviors	03 Schedule Observations(context Scheduling Module)	13	->	->	->				->																									->			->		->	->
System Behaviors	04 Perform Observations	48						->														->			->		->				->	->	->		->			->	->	->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Antenna Pointing	18																												->								->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Data Digitization	16																												->								->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Data Encoding	16																												->								->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Data Transmission	16																												->								->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Frequency Tuning	17																												->								->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Gain Selection	17																												->								->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Provide Frequency Offsets	16																												->	->							->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	RF Signal Reception	17																												->								->		->	
System Behaviors::04 Perform Observations::01 Data Acquisition	Select Band	16																												->								->		->	

ALLOCATE RELATIONSHIPS	L.00-006 Logical Model Behavior Allocation - Allocate Matrix	ALLOCATE RELATIONSHIPS	Engineering Data Archive	Proposal Archive	RFI Archive	Science Data Archive	Staging Storage	Telescope Calibration Archive	Telescope Configuration Archive	Central Electronics Building	Data Distribution System	Electrical Distribution System	Central Repair Facility	CMMS Integration Module	Computerized Maintenance Management System	Integrated Support Module	Issue Tracking System	Development Support Infrastructure	Simulation Tool	Testing Environment	Computational Resources	Data Analysis Tools	Data Processing Management	Data Processing Pipelines	Data Processing System	Observatory Interfaces	Offline Calibration Tools	Processing Resources	Processing Storage Resources	Quality Assurance Interfaces	Array	Central Reference Distribution System	Central Signal Processing System	Commissioning & Development Systems	Data Archive System	Infrastructure Systems	Maintenance & Support Systems	ngVLA System	Offline Subsystem	Online Subsystem	Proposal Management System
ALLOCATE RELATIONSHIPS			8	4	6	6	1	21	11	0	1	0	3	4	4	3	3	3	4	3	16	17	17	17	33	6	16	16	15	5	50	17	54	5	45	1	9	177	38	100	10
System Behaviors::04 Perform Observations	01 Data Acquisition	28																													->		->					->		->	
System Behaviors::04 Perform Observations	02 Single Dish Processing	24																													->	->	->					->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Apply Frequency Dependent Gain Corrections	15																													->							->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Apply Timestamp	15																													->							->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Clock Recovery	15																													->							->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Coarse Sideband Separation	15																													->							->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	FFT(context Digital Back End)	12																													->							->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Fine Sideband Separation	7																															->					->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	High Power RFI Excision(context Digital Back End)	12																													->							->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Offset LO	18																													->	->						->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Provide Timestamp(context Time Reference Distributor)	3																														->						->			
System Behaviors::04 Perform Observations::02 Single Dish Processing	Requantization	14																													->							->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	RFI Excision	8			->																												->		->			->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	RFI Flagging	12			->																			->	->								->		->			->	->	->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Sideband Separation(context Digital Back End)	19																													->		->					->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Sub-Band Selection	16																													->							->		->	
System Behaviors::04 Perform Observations::02 Single Dish Processing	Total Power Measurement	19																													->		->					->		->	
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Coarse Delay Tracking Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Coarse Sampler Clock Offset Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Delay Tracking Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Doppler Tracking Correction	6																															->					->		->	
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Fine Delay Tracking Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Fine Sampler Clock Offset Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Fringe Rotation Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply LO Offsetting Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Sampler Clock Offsetting Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Apply Timing Synchronization Corrections	4																															->					->			
System Behaviors::04 Perform Observations::03 Array Phasing	Calculate Delay Tracking Corrections	6						->																											->			->		->	
System Behaviors::04 Perform Observations::03 Array Phasing	Calculate Fringe Rotation Corrections	4																																				->		->	
System Behaviors::04 Perform Observations::03 Array Phasing	Calculate LO Offsetting Corrections(context Observation Module)	3																																				->		->	
System Behaviors::04 Perform Observations::03 Array Phasing	Track Digital LO Mixer Phase(context CSP Control Supervisor)	3																																				->		->	
System Behaviors::04 Perform Observations	03 Array Phasing	9						->																									->		->			->		->	
System Behaviors::04 Perform Observations::04 Central Signal Processing	Antenna Data Buffering	4																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Archive Formatting(context Correlator Back End)	3																															->					->			

	L.00-006 Logical Model Behavior Allocation - Allocate Matrix	ALLOCATE RELATIONSHIPS	Engineering Data Archive	Proposal Archive	RFI Archive	Science Data Archive	Staging Storage	Telescope Calibration Archive	Telescope Configuration Archive	Central Electronics Building	Data Distribution System	Electrical Distribution System	Central Repair Facility	CMMS Integration Module	Computerized Maintenance Management System	Integrated Support Module	Issue Tracking System	Development Support Infrastructure	Simulation Tool	Testing Environment	Computational Resources	Data Analysis Tools	Data Processing Management	Data Processing Pipelines	Data Processing System	Observatory Interfaces	Offline Calibration Tools	Processing Resources	Processing Storage Resources	Quality Assurance Interfaces	Array	Central Reference Distribution System	Central Signal Processing System	Commissioning & Development Systems	Data Archive System	Infrastructure Systems	Maintenance & Support Systems	ngVLA System	Offline Subsystem	Online Subsystem	Proposal Management System
ALLOCATE RELATIONSHIPS			8	4	6	6	1	21	11	0	1	0	3	4	4	3	3	3	4	3	16	17	17	17	33	6	16	16	15	5	50	17	54	5	45	1	9	177	38	100	10
System Behaviors::04 Perform Observations::04 Central Signal Processing	AutoCorrelation(context Correlator)	3																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Bandwidth Stitching(context Correlator Back End)	3																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Beamforming(context Beamformer)	3																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Correlation(context Correlator)	3																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	CrossCorrelation(context Correlator)	3																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Data Decoding	4																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Pulsar Searching(context Pulsar Search System)	3																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Pulsar Timing(context Pulsar Timing System)	3																															->					->			
System Behaviors::04 Perform Observations::04 Central Signal Processing	Visibility Data Buffering	4																															->					->			
System Behaviors::04 Perform Observations	04 Central Signal Processing	8																															->					->			
System Behaviors::04 Perform Observations::05 Calibrations	Apply IQ Sideband Gain Coefficients	15																												->		->					->			
System Behaviors::04 Perform Observations::05 Calibrations	Calculate Geometric Delay	5																															->					->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Determine Antenna Positions(context Calibration Module)	3																																				->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Determine Electronic Delay	5																															->					->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Determine Gain Calibration Coefficients	5																															->					->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Determine Pointing Model Ciefficients(context Calibration Module)	3																																				->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Determine Primary Beam Patterns(context Offline Calibration Tools)	2																			->					->														
System Behaviors::04 Perform Observations::05 Calibrations	Determine TCals(context Offline Calibration Tools)	2																			->					->														
System Behaviors::04 Perform Observations::05 Calibrations	Estimate Atmospheric Delay	18																												->		->					->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Estimate WVR Atmospheric Delay Component	15																												->							->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Inject Flux Scale reference(context Flux Reference Generator)	12																												->							->			
System Behaviors::04 Perform Observations::05 Calibrations	Measure Flux Scale Reference(context Correlator Back End)	3																															->					->			
System Behaviors::04 Perform Observations::05 Calibrations	Optimize Antenna Surface(context Offline Calibration Tools)	2																			->					->														
System Behaviors::04 Perform Observations::05 Calibrations	Optimize Focus and Collimation	7						->														->					->								->			->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Perform Delay Calibration	22						->																	->						->		->		->			->	->	->	
System Behaviors::04 Perform Observations::05 Calibrations	Perform Gain Calibration	20						->																	->						->		->		->			->	->	->	
System Behaviors::04 Perform Observations::05 Calibrations	Perform Polarization Calibration	7						->																	->										->			->	->	->	
System Behaviors::04 Perform Observations::05 Calibrations	Perform Referenced Pointing Calibration	5						->																											->			->		->	
System Behaviors::04 Perform Observations::05 Calibrations	Perform Tsys Calibration	7						->																	->										->			->	->	->	
System Behaviors::04 Perform Observations	05 Observatory Calibration	22						->														->					->				->		->		->			->		->	
System Behaviors::04 Perform Observations	06 Online Calibration	23						->																	->						->		->		->			->	->	->	
System Behaviors::04 Perform Observations	08 Data Recording	4				->	->																												->			x			
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	Move Az(context Az Drive)	12																												->							->			
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	Move El(context El Drive)	12																												->							->			

	L.00-006 Logical Model Behavior Allocation - Allocate Matrix	ALLOCATE RELATIONSHIPS	Engineering Data Archive	Proposal Archive	RFI Archive	Science Data Archive	Staging Storage	Telescope Calibration Archive	Telescope Configuration Archive	Central Electronics Building	Data Distribution System	Electrical Distribution System	Central Repair Facility	CMMS Integration Module	Computerized Maintenance Management System	Integrated Support Module	Issue Tracking System	Development Support Infrastructure	Simulation Tool	Testing Environment	Computational Resources	Data Analysis Tools	Data Processing Management	Data Processing Pipelines	Data Processing System	Observatory Interfaces	Offline Calibration Tools	Processing Resources	Processing Storage Resources	Quality Assurance Interfaces	Array	Central Reference Distribution System	Central Signal Processing System	Commissioning & Development Systems	Data Archive System	Infrastructure Systems	Maintenance & Support Systems	ngVLA System	Offline Subsystem	Online Subsystem	Proposal Management System
ALLOCATE RELATIONSHIPS			8	4	6	6	1	21	11	0	1	0	3	4	4	3	3	3	4	3	16	17	17	17	33	6	16	16	15	5	50	17	54	5	45	1	9	177	38	100	10
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	OTF Scanning(context ACU)	18																													->							->		->	
System Behaviors::04 Perform Observations::99 Pointing Modes & Actions	Tracking(context ACU)	18																													->							->		->	
System Behaviors::04 Perform Observations	Archive Ingestion	9				->																	->		->					->					->			->	->	->	
System Behaviors::04 Perform Observations	Metadata Capture	5				->																													->			->		->	
System Behaviors::04 Perform Observations	Quality Assurance	5																												->								->	->	->	
System Behaviors::04 Perform Observations	Shift Logging	5	->																																->			->		->	
System Behaviors::05 Configure System	Apply Configuration Parameters	10							->																										->			->		->	
System Behaviors::05 Configure System	Define Configuration Parameters	5							->																										->			->		->	
System Behaviors::05 Configure System	Provide Frequency Reference(context Frequency Reference)	3																														->						->			
System Behaviors::05 Configure System	Provide Timing Reference(context Time Reference)	3																														->						->			
System Behaviors	05 Configure System	10							->																										->			->		->	
System Behaviors::06 Monitor Telescope Status	Archive Alerts	6	->																																->			->		->	
System Behaviors::06 Monitor Telescope Status	Archive Monitor Data	6	->																																->			->		->	
System Behaviors::06 Monitor Telescope Status	Check for Alert Conditions	4																																				->		->	
System Behaviors::06 Monitor Telescope Status	Collect Monitor Data(context Metadata Capture Module)	3																																				->		->	
System Behaviors::06 Monitor Telescope Status	Display Alerts(context Operation Module)	3																																				->		->	
System Behaviors::06 Monitor Telescope Status	Display Monitor Data(context Operation Module)	3																																				->		->	
System Behaviors::06 Monitor Telescope Status	Measure Analog Monitor Point(context HW Controller Board)	3																																				->		->	
System Behaviors::06 Monitor Telescope Status	Monitor Antenna System Health	6																																				->		->	
System Behaviors::06 Monitor Telescope Status	Monitor Central Electronic System Health	9																																				->		->	
System Behaviors::06 Monitor Telescope Status	Read Digital Register(context HW Controller Board)	3																																				->		->	
System Behaviors	06 Monitor Telescope Status(context ngVLA System)	14	->																																->			x		->	
System Behaviors::07 Generate Derived Data Products	De-Disperse Spectra	11																			->		->	->	->			->	->				->					->	->		
System Behaviors::07 Generate Derived Data Products	Flag Corrupted Data	10																			->		->	->	x			->	->									->	->	->	
System Behaviors::07 Generate Derived Data Products	Generate Image Cubes	8																			x		x	x	x			->	x									->	->		
System Behaviors::07 Generate Derived Data Products	Generate Pulse Profiles(context Pulsar Timing System)	11																			->		->	->	->			->	->				->					->	->		
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Bandpass Calibration	8																			->		->	->	x			->	->									->	->		
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Flux Scale Calibration	8																			->		->	->	x			->	->									->	->		
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Gain Calibration	8																			x		x	x	x			->	x									->	->		
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Phase Calibration	8																			->		->	->	x			->	->									->	->		
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Polarization Calibration	8																			->		->	->	x			->	->									->	->		
System Behaviors::07 Generate Derived Data Products::Offline Calibrations	Apply Tsys Calibration	8																			->		->	->	x			->	->									->	->		
System Behaviors::07 Generate Derived Data Products	Perform Direction Dependent Offline Calibration	8																			->		->	->	x			->	->									->	->		
System Behaviors::07 Generate Derived Data Products	Perform Direction Independent Offline Calibration	8																			x		x	x	x			->	x									->	->		
System Behaviors::07 Generate Derived Data Products	Perform Quality Assurance	9																			->		->	->	->			->	->	->								->	->		
System Behaviors	07 Generate Derived Data Products(context ngVLA System)	14																			->		->	->	->			->	->	->			->					x	->	->	
System Behaviors::08 Provide Access to Data Products	Data Product Analysis(context Data Analysis Tools)	1																				->																			
System Behaviors::08 Provide Access to Data Products	Data Product Discovery(context Observatory Interfaces)	3																								->												->	->		
System Behaviors::08 Provide Access to Data Products	Data Product Retrieval(context Observatory Interfaces)	3																								->												->	->		
System Behaviors::08 Provide Access to Data Products	On-demand Post-processing	8																			->		->	->	->	->		->										->	->		
System Behaviors::08 Provide Access to Data Products	Project Tracking	5				->																				->									->			->	->		
System Behaviors	08 Provide Access to Data Products(context ngVLA System)	5				->																				->									->			x	->		

L.00-006 Logical Model Behavior Allocation - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Engineering Data Archive	Proposal Archive	RFI Archive	Science Data Archive	Staging Storage	Telescope Calibration Archive	Telescope Configuration Archive	Central Electronics Building	Data Distribution System	Electrical Distribution System	Central Repair Facility	CMMS Integration Module	Computerized Maintenance Management System	Integrated Support Module	Issue Tracking System	Development Support Infrastructure	Simulation Tool	Testing Environment	Computational Resources	Data Analysis Tools	Data Processing Management	Data Processing Pipelines	Data Processing System	Observatory Interfaces	Offline Calibration Tools	Processing Resources	Processing Storage Resources	Quality Assurance Interfaces	Array	Central Reference Distribution System	Central Signal Processing System	Commissioning & Development Systems	Data Archive System	Infrastructure Systems	Maintenance & Support Systems	ngVLA System	Offline Subsystem	Online Subsystem	Proposal Management System
ALLOCATE RELATIONSHIPS			8	4	6	6	1	21	11	0	1	0	3	4	4	3	3	3	4	3	16	17	17	17	33	6	16	16	15	5	50	17	54	5	45	1	9	177	38	100	10
System Behaviors::09 Support Maintenance	Configuration Management(context Telescope Configuration Archive)	5							x					->																					->		->	->			
System Behaviors::09 Support Maintenance	Data QuickLook(context QuickLook Module)	3																																				->		->	
System Behaviors::09 Support Maintenance	Diagnose System Fault	3														->																					x	->			
System Behaviors::09 Support Maintenance	Perform Tier 2 Repairs(context Central Repair Facility)	3											->																								->	->			
System Behaviors::09 Support Maintenance	Report Current Configuration	5							->					->																					->		->	->			
System Behaviors::09 Support Maintenance	Schedule Maintenance(context Computerized Maintenance Management System)	3													->																						->	->			
System Behaviors::09 Support Maintenance	Track Historical Configuration(context Telescope Configuration Archive)	3							->																										->			->			
System Behaviors::09 Support Maintenance	Track Issues(context Issue Tracking System)	3															->																				->	->			
System Behaviors::09 Support Maintenance	Track Maintenance(context Computerized Maintenance Management System)	3													->																						->	->			
System Behaviors	09 Support Maintenance(context ngVLA System)	11							->				->	->	->	->	->																		->		->	x		->	
System Behaviors::10 Support Development and Commissioning	Offline Testing	4																	->	->														->				->			
System Behaviors::10 Support Development and Commissioning	Online Testing(context ngVLA System)	1																																				->			
System Behaviors::10 Support Development and Commissioning	Provide Development Environment(context Development Support Infrastructure)	3																->																->				->			
System Behaviors::10 Support Development and Commissioning	Simulation(context Simulation Tool)	3																	->															->				->			
System Behaviors	10 Support Development and Commissioning(context ngVLA System)	5																->	->	->														->				x			
System Behaviors::11 Provide Services	Transport Data(context Data Distribution System)	3									->																									->		->			
System Behaviors::98 Observations by Intent	Observe Flux Scale Calibrator(context ngVLA System)	1																																				x			
System Behaviors::98 Observations by Intent	Observe Gain Calibrator(context ngVLA System)	1																																				x			
System Behaviors::98 Observations by Intent	Observe Phase Calibrator(context ngVLA System)	1																																				x			
System Behaviors::98 Observations by Intent	Observe Polarization Calibrator(context ngVLA System)	1																																				x			
System Behaviors::98 Observations by Intent	Observe Science Targe(context ngVLA System)	1																																				x			
System Behaviors::98 Observations by Intent	Observe Source(context ngVLA System)	1																																				->			
System Behaviors::98 Observations by Intent	Slew to Source	14																													->							x		->	
System Behaviors::99 Observing Modes	L.03-031 Perform Single Field Synthesis Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform Beamforming Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform Interferometric Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform On The Fly Mosaic Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform Pulsar Search Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform Pulsar Timing Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform Single Field Continuum Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform Spectral Line Single Field Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors::99 Observing Modes	Perform VLBI Observation(context ngVLA System)	48						->														->			->		->				->	->	->		->			x	->	->	
System Behaviors	System Operation	83	->	->	->	->		->	->				->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->	->		->	->	->	->	->

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S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Barometric Pressure	Frozen Water	Liquid Water	Public Networks	PWV	RFI	Sources	Temperature	VLBI Station	Weather	Wind	Back End Assembly	Front End Assembly	Main Array Antenna	Short Baseline Antenna	Total Power Antenna	Digital Signal Processing	ngVLA System	ngVLA System Context	Azimuth Rotating Assembly	Antenna Control Unit	Azimuth Drive	Elevation Drive	X Stage	YZ Stage	Drive System	Primary Backup Structure	Primary Reflector	Secondary Reflector	Secondary Support Structure	Elevation Rotating Assembly	Fixed Structure	6m Reflector Antenna	Cable Raceway	Azimuth Rotating Assembly	Antenna Control Unit	Azimuth Drive	Elevation Drive	X Stage	YZ Stage	Drive System	208V Distribution	Electrical System	Elevation Rotating Assembly	Cable Raceway	Main Reflector	Reflector Backup Structure	Sub Reflector	Subreflector Support Structure	Fixed Structure	Cable Raceway	18m Reflector Antenna	18m Reflector Antenna Context	18m TP Reflector Antenna	Band1Feed	Band2Feed	Band3Feed	Band4Feed	Band5Feed	Band6Feed	Bias Supply
ALLOCATE RELATIONSHIPS			0	0	0	0	0	0	0	0	0	0	0	0	0	24	19	18	14	93	93	12	12	12	12	0	12	15	12	12	12	12	13	12	12	0	12	12	12	12	0	12	15	0	0	13	0	12	12	12	12	12	0	17	18	0	0	0	0	0	0	0	0
Logical Structure::10 Proposal Management	Proposal Submission Tool	2																		->	->																																										
Logical Structure::10 Proposal Management	Observation Preparation Tool	2																		->	->																																										
Logical Structure::10 Proposal Management	Proposal Builder Tool	2																		->	->																																										
Logical Structure::10 Proposal Management	Proposal Handling Tool	2																		->	->																																										
Logical Structure::10 Proposal Management::Views	SciOps	2																		->	->																																										
Logical Structure::20 Antenna Array::Antenna Structure	ACU	9														->				->	->		->					->												->					->											->	->								
Logical Structure::20 Antenna Array::Antenna Structure	Az Drive	9														->				->	->			->				->													->				->											->	->								
Logical Structure::20 Antenna Array::Antenna Structure	Data Transmitter	5														->	->	->		->	->																																										
Logical Structure::20 Antenna Array::Antenna Structure	Digital Back End	6														->	->	->	->	->	->																																										
Logical Structure::20 Antenna Array::Antenna Structure	Digitizer	6														->	->	->		->	->																																										
Logical Structure::20 Antenna Array::Antenna Structure	Downconverter	6														->	->	->		->	->																																										
Logical Structure::20 Antenna Array::Antenna Structure	El Drive	9														->				->	->				->			->														->			->											->	->								
Logical Structure::20 Antenna Array::Antenna Structure	Feed Indexer	9														->				->	->						->	->																->	->											->	->								
Logical Structure::20 Antenna Array::Antenna Structure	Flux Reference Generator	12														->	->	->		->	->																																										
Logical Structure::20 Antenna Array::Antenna Structure	Indep Phase Cal System	1																																																					->								
Logical Structure::20 Antenna Array::Antenna Structure	Mount	17														->	->			->	->	->							->			->	->	->	->		->									->			->		->	->		->	->								
Logical Structure::20 Antenna Array::Antenna Structure	Reflector Optics	11														->				->	->									->	->		->													->		->		->				->	->								
Logical Structure::20 Antenna Array::Antenna Structure	RF Receiver	14														->	->	->	->	->	->																																										
Logical Structure::20 Antenna Array::Antenna Structure	Time & Freq Reference Generator	6														->	->	->	->	->	->																																										
Logical Structure::20 Antenna Array::Antenna Types	Antenna	48														->	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array::Antenna Types	LB Antenna	48														X	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array::Antenna Types	Main Antenna	48														X	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array::Antenna Types	SBA Antenna	48														->	X	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array::Antenna Types	TP Antenna	48														->	->	X	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array::Env Monitors	Atm. Delay Monitor System	2																		->	->																																										
Logical Structure::20 Antenna Array::Env Monitors	Weather Monitor System	2																		->	->																																										
Logical Structure::20 Antenna Array	Long Baseline Array	48														->	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array	Main Array	48														->	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array	Short Baseline Array	48														->	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::20 Antenna Array	Total Power Array	48														->	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure::30 Central Reference Distribution	Frequency Reference	2																		->	->																																										
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor	2																		->	->																																										
Logical Structure::30 Central Reference Distribution	Time Reference	2																		->	->																																										
Logical Structure::30 Central Reference Distribution	Time Reference Distributor	2																		->	->																																										
Logical Structure::40 Central Signal Processing	Beamformer	2																		->	->																																										
Logical Structure::40 Central Signal Processing	Correlator	2																		->	->																																										

S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Barometric Pressure	Frozen Water	Liquid Water	Public Networks	PWV	RFI	Sources	Temperature	VLBI Station	Weather	Wind	Back End Assembly	Front End Assembly	Main Array Antenna	Short Baseline Antenna	Total Power Antenna	Digital Signal Processing	ngVLA System	ngVLA System Context	Azimuth Rotating Assembly	Antenna Control Unit	Azimuth Drive	Elevation Drive	X Stage	YZ Stage	Drive System	Primary Backup Structure	Primary Reflector	Secondary Reflector	Secondary Support Structure	Elevation Rotating Assembly	Fixed Structure	6m Reflector Antenna	Cable Raceway	Azimuth Rotating Assembly	Antenna Control Unit	Azimuth Drive	Elevation Drive	X Stage	YZ Stage	Drive System	208V Distribution	Electrical System	Elevation Rotating Assembly	Cable Raceway	Main Reflector	Reflector Backup Structure	Sub Reflector	Subreflector Support Structure	Fixed Structure	Cable Raceway	18m Reflector Antenna	18m Reflector Antenna Context	18m TP Reflector Antenna	Band1Feed	Band2Feed	Band3Feed	Band4Feed	Band5Feed	Band6Feed	Bias Supply
ALLOCATE RELATIONSHIPS			0	0	0	0	0	0	0	0	0	0	0	0	0	24	19	18	14	93	93	12	12	12	12	0	12	15	12	12	12	12	13	12	12	0	12	12	12	12	0	12	15	0	0	13	0	12	12	12	12	12	0	17	18	0	0	0	0	0	0	0	0
Logical Structure::40 Central Signal Processing	Correlator Back End	2																		->	->																																										
Logical Structure::40 Central Signal Processing	Data Buffer	2																		->	->																																										
Logical Structure::40 Central Signal Processing	Pulsar Search System	2																		->	->																																										
Logical Structure::40 Central Signal Processing	Pulsar Timing System	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Calibration Module	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Configuration Module	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Data Transmission Module	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Observation Module	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Operation Module	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	QuickLook Module	2																		->	->																																										
Logical Structure::50 Online Control & Monitoring	Scheduling Module	2																		->	->																																										
Logical Structure::60 Data Archives	Engineering Data Archive	2																		->	->																																										
Logical Structure::60 Data Archives	Proposal Archive	2																		->	->																																										
Logical Structure::60 Data Archives	RFI Archive	2																		->	->																																										
Logical Structure::60 Data Archives	Science Data Archive	2																		->	->																																										
Logical Structure::60 Data Archives	Staging Storage	2																		->	->																																										
Logical Structure::60 Data Archives	Telescope Calibration Archive	2																		->	->																																										
Logical Structure::60 Data Archives	Telescope Configuration Archive	2																		->	->																																										
Logical Structure::70 Infrastructure	Central Electronics Building	2																		->	->																																										
Logical Structure::70 Infrastructure	Data Distribution System	2																		->	->																																										
Logical Structure::70 Infrastructure	Electrical Distribution System	2																		->	->																																										
Logical Structure::80 Maintenance & Support	Central Repair Facility	2																		->	->																																										
Logical Structure::80 Maintenance & Support	CMMS Integration Module	2																		->	->																																										
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System	2																		->	->																																										
Logical Structure::80 Maintenance & Support	Integrated Support Module	2																		->	->																																										
Logical Structure::80 Maintenance & Support	Issue Tracking System	2																		->	->																																										
Logical Structure::90 Commissioning & Development	Development Support Infrastructure	2																		->	->																																										
Logical Structure::90 Commissioning & Development	Simulation Tool	2																		->	->																																										

S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Barometric Pressure	Frozen Water	Liquid Water	Public Networks	PWV	RFI	Sources	Temperature	VLBI Station	Weather	Wind	Back End Assembly	Front End Assembly	Main Array Antenna	Short Baseline Antenna	Total Power Antenna	Digital Signal Processing	ngVLA System	ngVLA System Context	Azimuth Rotating Assembly	Antenna Control Unit	Azimuth Drive	Elevation Drive	X Stage	YZ Stage	Drive System	Primary Backup Structure	Primary Reflector	Secondary Reflector	Secondary Support Structure	Elevation Rotating Assembly	Fixed Structure	6m Reflector Antenna	Cable Raceway	Azimuth Rotating Assembly	Antenna Control Unit	Azimuth Drive	Elevation Drive	X Stage	YZ Stage	Drive System	208V Distribution	Electrical System	Elevation Rotating Assembly	Cable Raceway	Main Reflector	Reflector Backup Structure	Sub Reflector	Subreflector Support Structure	Fixed Structure	Cable Raceway	18m Reflector Antenna	18m Reflector Antenna Context	18m TP Reflector Antenna	Band1Feed	Band2Feed	Band3Feed	Band4Feed	Band5Feed	Band6Feed	Bias Supply
ALLOCATE RELATIONSHIPS			0	0	0	0	0	0	0	0	0	0	0	0	0	24	19	18	14	93	93	12	12	12	12	0	12	15	12	12	12	12	13	12	12	0	12	12	12	12	0	12	15	0	0	13	0	12	12	12	12	12	0	17	18	0	0	0	0	0	0	0	0
Logical Structure::90 Commissioning & Development	Testing Environment	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Computational Resources	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Data Analysis Tools	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Management	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Pipelines	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing System	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Observatory Interfaces	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Offline Calibration Tools	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Resources	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Storage Resources	2																		->	->																																										
Logical Structure::100 Offline Processing & Archive Interfaces	Quality Assurance Interfaces	2																		->	->																																										
Logical Structure	Array	48														->	->	->	->	->	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure	Central Reference Distribution System	2																		->	->																																										
Logical Structure	Central Signal Processing System	2																		->	->																																										
Logical Structure	Commissioning & Development Systems	2																		->	->																																										
Logical Structure	Data Archive System	2																		->	->																																										
Logical Structure	Infrastructure Systems	2																		->	->																																										
Logical Structure	Maintenance & Support Systems	2																		->	->																																										
Logical Structure	ngVLA System	48														->	->	->	->	x	->	->	->	->	->		->	->	->	->	->	->	->	->	->		->	->	->	->		->	->			->		->	->	->	->	->		->	->								
Logical Structure	Offline Subsystem	2																		->	->																																										
Logical Structure	Online Subsystem	2																		->	->																																										
Logical Structure	Proposal Management System	2																		->	->																																										

S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	NoiseDiodeAssy-Band1	NoiseDiodeAssy-Band2	NoiseDiodeAssy-Band3	NoiseDiodeAssy-Band4	NoiseDiodeAssy-Band5	NoiseDiodeAssy-Band6	Receiver	Receiver System	Receiver System Context	Receiver-Band1	Receiver-Band2	Receiver-Band3	Receiver-Band4	Receiver-Band5	Receiver-Band6	Compressor	Cryogenics System	Cryogenics System Context	Dewar A	Dewar B	Helium	Helium Fitting	Refrigerator	Vacuum Pump	Vacuum Valve	Integrated Down Converters	Integrated Down Converters Context	IRD Module	IRD-2SB4	IRD-2SB5	IRD-2SB6	IRD-2SB7	IRD-2SB8	IRD-2SB9	IRD-2SB10	IRD-2SB11	IRD-2SB12	IRD-SSB-N1	IRD-SSB-N2	IRD-SSB-N3	Digitizer-Serializer ASIC	SFP	Step Attenuator	Channelizer	Clock Recovery	Complex Mixer	Data Aligner	Data Heuristics	DBE Data Receiver	DBE Framework	DBE Optical Combiner	DBE Processing	DeMux	Digital Back End System	Digital Back End System Context	FFT	Formatter	IQ Sideband Bandpass Corrections	IQ-UL Converter	Multiplexer	Network Switch	Oversampling Polyphase Filter Bank	Requantizer	Resampler
ALLOCATE RELATIONSHIPS			12	12	12	12	12	12	12	13	0	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0
Logical Structure::10 Proposal Management	Proposal Submission Tool	2																																																																		
Logical Structure::10 Proposal Management	Observation Preparation Tool	2																																																																		
Logical Structure::10 Proposal Management	Proposal Builder Tool	2																																																																		
Logical Structure::10 Proposal Management	Proposal Handling Tool	2																																																																	
Logical Structure::10 Proposal Management::Views	SciOps	2																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	ACU	9																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Az Drive	9																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Data Transmitter	5																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Digital Back End	6																																																				->										
Logical Structure::20 Antenna Array::Antenna Structure	Digitizer	6																									->																																							
Logical Structure::20 Antenna Array::Antenna Structure	Downconverter	6																									->																																							
Logical Structure::20 Antenna Array::Antenna Structure	El Drive	9																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Feed Indexer	9																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Flux Reference Generator	12	->	->	->	->	->	->		->																																																									
Logical Structure::20 Antenna Array::Antenna Structure	Indep Phase Cal System	1																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Mount	17																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Reflector Optics	11																																																																	
Logical Structure::20 Antenna Array::Antenna Structure	RF Receiver	14							->	x		->	->	->	->	->	->																																																	
Logical Structure::20 Antenna Array::Antenna Structure	Time & Freq Reference Generator	6																																																																	
Logical Structure::20 Antenna Array::Antenna Types	Antenna	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array::Antenna Types	LB Antenna	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array::Antenna Types	Main Antenna	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array::Antenna Types	SBA Antenna	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array::Antenna Types	TP Antenna	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array::Env Monitors	Atm. Delay Monitor System	2																																																																	
Logical Structure::20 Antenna Array::Env Monitors	Weather Monitor System	2																																																																	
Logical Structure::20 Antenna Array	Long Baseline Array	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array	Main Array	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array	Short Baseline Array	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::20 Antenna Array	Total Power Array	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure::30 Central Reference Distribution	Frequency Reference	2																																																																	
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor	2																																																																	
Logical Structure::30 Central Reference Distribution	Time Reference	2																																																																	
Logical Structure::30 Central Reference Distribution	Time Reference Distributor	2																																																																	
Logical Structure::40 Central Signal Processing	Beamformer	2																																																																	
Logical Structure::40 Central Signal Processing	Correlator	2																																																																	

S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	NoiseDiodeAssy-Band1	NoiseDiodeAssy-Band2	NoiseDiodeAssy-Band3	NoiseDiodeAssy-Band4	NoiseDiodeAssy-Band5	NoiseDiodeAssy-Band6	Receiver	Receiver System	Receiver System Context	Receiver-Band1	Receiver-Band2	Receiver-Band3	Receiver-Band4	Receiver-Band5	Receiver-Band6	Compressor	Cryogenics System	Cryogenics System Context	Dewar A	Dewar B	Helium	Helium Fitting	Refrigerator	Vacuum Pump	Vacuum Valve	Integrated Down Converters	Integrated Down Converters Context	IRD Module	IRD-2SB4	IRD-2SB5	IRD-2SB6	IRD-2SB7	IRD-2SB8	IRD-2SB9	IRD-2SB10	IRD-2SB11	IRD-2SB12	IRD-SSB-N1	IRD-SSB-N2	IRD-SSB-N3	Digitizer-Serializer ASIC	SFP	Step Attenuator	Channelizer	Clock Recovery	Complex Mixer	Data Aligner	Data Heuristics	DBE Data Receiver	DBE Framework	DBE Optical Combiner	DBE Processing	DeMux	Digital Back End System	Digital Back End System Context	FFT	Formatter	IQ Sideband Bandpass Corrections	IQ-UL Converter	Multiplexer	Network Switch	Oversampling Polyphase Filter Bank	Requantizer	Resampler
ALLOCATE RELATIONSHIPS			12	12	12	12	12	12	12	13	0	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0
Logical Structure::40 Central Signal Processing	Correlator Back End	2																																																																
Logical Structure::40 Central Signal Processing	Data Buffer	2																																																																
Logical Structure::40 Central Signal Processing	Pulsar Search System	2																																																																
Logical Structure::40 Central Signal Processing	Pulsar Timing System	2																																																																
Logical Structure::50 Online Control & Monitoring	Calibration Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Configuration Module	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring	Data Transmission Module	2																																																																
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board	2																																																																
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver	2																																																																
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector	2																																																																
Logical Structure::50 Online Control & Monitoring	Observation Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Operation Module	2																																																																
Logical Structure::50 Online Control & Monitoring	QuickLook Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Scheduling Module	2																																																																
Logical Structure::60 Data Archives	Engineering Data Archive	2																																																																
Logical Structure::60 Data Archives	Proposal Archive	2																																																																
Logical Structure::60 Data Archives	RFI Archive	2																																																																
Logical Structure::60 Data Archives	Science Data Archive	2																																																																
Logical Structure::60 Data Archives	Staging Storage	2																																																																
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Logical Structure::80 Maintenance & Support	Central Repair Facility	2																																																																
Logical Structure::80 Maintenance & Support	CMMS Integration Module	2																																																																
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System	2																																																																
Logical Structure::80 Maintenance & Support	Integrated Support Module	2																																																																
Logical Structure::80 Maintenance & Support	Issue Tracking System	2																																																																
Logical Structure::90 Commissioning & Development	Development Support Infrastructure	2																																																																
Logical Structure::90 Commissioning & Development	Simulation Tool	2																																																																

S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	NoiseDiodeAssy-Band1	NoiseDiodeAssy-Band2	NoiseDiodeAssy-Band3	NoiseDiodeAssy-Band4	NoiseDiodeAssy-Band5	NoiseDiodeAssy-Band6	Receiver	Receiver System	Receiver System Context	Receiver-Band1	Receiver-Band2	Receiver-Band3	Receiver-Band4	Receiver-Band5	Receiver-Band6	Compressor	Cryogenics System	Cryogenics System Context	Dewar A	Dewar B	Helium	Helium Fitting	Refrigerator	Vacuum Pump	Vacuum Valve	Integrated Down Converters	Integrated Down Converters Context	IRD Module	IRD-2SB4	IRD-2SB5	IRD-2SB6	IRD-2SB7	IRD-2SB8	IRD-2SB9	IRD-2SB10	IRD-2SB11	IRD-2SB12	IRD-SSB-N1	IRD-SSB-N2	IRD-SSB-N3	Digitizer-Serializer ASIC	SFP	Step Attenuator	Channelizer	Clock Recovery	Complex Mixer	Data Aligner	Data Heuristics	DBE Data Receiver	DBE Framework	DBE Optical Combiner	DBE Processing	DeMux	Digital Back End System	Digital Back End System Context	FFT	Formatter	IQ Sideband Bandpass Corrections	IQ-UL Converter	Multiplexer	Network Switch	Oversampling Polyphase Filter Bank	Requantizer	Resampler
ALLOCATE RELATIONSHIPS			12	12	12	12	12	12	12	13	0	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0
Logical Structure::90 Commissioning & Development	Testing Environment	2																																																																
Logical Structure::100 Offline Processing & Archive Interfaces	Computational Resources	2																																																																
Logical Structure::100 Offline Processing & Archive Interfaces	Data Analysis Tools	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Management	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Pipelines	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing System	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Observatory Interfaces	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Offline Calibration Tools	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Resources	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Storage Resources	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Quality Assurance Interfaces	2																																																															
Logical Structure	Array	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure	Central Reference Distribution System	2																																																															
Logical Structure	Central Signal Processing System	2																																																															
Logical Structure	Commissioning & Development Systems	2																																																															
Logical Structure	Data Archive System	2																																																															
Logical Structure	Infrastructure Systems	2																																																															
Logical Structure	Maintenance & Support Systems	2																																																															
Logical Structure	ngVLA System	48	->	->	->	->	->	->	->	->		->	->	->	->	->	->											->																												->										
Logical Structure	Offline Subsystem	2																																																															
Logical Structure	Online Subsystem	2																																																															
Logical Structure	Proposal Management System	2																																																															

S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Return to Phase Monitor	RFI Detector / Exciser	Timestamp Generator	Data Transmission System	Data Transmission System Context	DTS Optical Mux	DTS Transmitters	Optical Amplifiers	Antenna Time & Freq Reference System Context	Antenna Time & Frequency Reference System	LO Generator	Primary Reference Generator	Sampler Clock Generator	Antenna Round Trip Phase System Context	Optical Reflector	Round Trip Phase System	RTP Monitor	MC Hardware	MC Hardware Context	MC Interface Board	MC Interface Module	48V Supply	DC Distribution Module	DC Power Supply System	DC Power Supply System Context	Antenna BMR Packaging	Antenna BMR Packaging Context	Back End Bin	Back End Environmental Enclosure	Back End Rack	BE Fiber Bulkhead	BE Rack Bulkhead	Coax Splitter/Combiner	FE Fiber Bulkhead	Front End Environmental Enclosure	Front End Fixed Platform	IRD Bin A	IRD Bin B	MC Bin	WR10-Splitter	WR22-Splitter	Back End Thermal Regulator	Environmental Control System	Environmental Control System Context	Front End Thermal Regulator	WVR Feed	WVR Receiver	WVR Reflector	WVR Spectrometer	WVR System	Frequency Reference Distributor	Primary Frequency Reference	Primary Time Reference	Reference Signal Distribution System	Reference Signal Distribution System Context	Time Reference Distributor	Central Signal Processor	Central Signal Processor Context	Coarse Channelizer	Correlator-Beamformer	Frequency Slice Processor	Local Cooling Distribution	Local Monitor Control System	Local Power Distribution	Network Switch
ALLOCATE RELATIONSHIPS			0	0	0	12	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	3	3	3	6	34	3	6	17	0	4	0	0	0	0	0
Logical Structure::10 Proposal Management	Proposal Submission Tool	2																																																																
Logical Structure::10 Proposal Management	Observation Preparation Tool	2																																																															
Logical Structure::10 Proposal Management	Proposal Builder Tool	2																																																														
Logical Structure::10 Proposal Management	Proposal Handling Tool	2																																																															
Logical Structure::10 Proposal Management::Views	SciOps	2																																																														
Logical Structure::20 Antenna Array::Antenna Structure	ACU	9																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Az Drive	9																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Data Transmitter	5				->																																																	->			->							
Logical Structure::20 Antenna Array::Antenna Structure	Digital Back End	6																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Digitizer	6																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Downconverter	6																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	El Drive	9																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Feed Indexer	9																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Flux Reference Generator	12																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Indep Phase Cal System	1																																																->															
Logical Structure::20 Antenna Array::Antenna Structure	Mount	17																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Reflector Optics	11																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	RF Receiver	14																																																					->										
Logical Structure::20 Antenna Array::Antenna Structure	Time & Freq Reference Generator	6										->																																												->										
Logical Structure::20 Antenna Array::Antenna Types	Antenna	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array::Antenna Types	LB Antenna	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array::Antenna Types	Main Antenna	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array::Antenna Types	SBA Antenna	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array::Antenna Types	TP Antenna	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array::Env Monitors	Atm. Delay Monitor System	2																																																															
Logical Structure::20 Antenna Array::Env Monitors	Weather Monitor System	2																																																															
Logical Structure::20 Antenna Array	Long Baseline Array	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array	Main Array	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array	Short Baseline Array	48				->						->																																						->					->			->							
Logical Structure::20 Antenna Array	Total Power Array	48				->						->																																						->					->			->							
Logical Structure::30 Central Reference Distribution	Frequency Reference	2																																																		->		->	->			->							
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor	2																																																	->			->	->			->							
Logical Structure::30 Central Reference Distribution	Time Reference	2																																																			->	->	->			->							
Logical Structure::30 Central Reference Distribution	Time Reference Distributor	2																																																				->	->	->		->							
Logical Structure::40 Central Signal Processing	Beamformer	2																																																					->		->			->					
Logical Structure::40 Central Signal Processing	Correlator	2																																																					->		->			->					

	S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix	ALLOCATE RELATIONSHIPS	Return to Phase Monitor	RFI Detector / Exciser	Timestamp Generator	Data Transmission System	Data Transmission System Context	DTS Optical Mux	DTS Transmitters	Optical Amplifiers	Antenna Time & Freq Reference System Context	Antenna Time & Frequency Reference System	LO Generator	Primary Reference Generator	Sampler Clock Generator	Antenna Round Trip Phase System Context	Optical Reflector	Round Trip Phase System	RTP Monitor	MC Hardware	MC Hardware Context	MC Interface Board	MC Interface Module	48V Supply	DC Distribution Module	DC Power Supply System	DC Power Supply System Context	Antenna BMR Packaging	Antenna BMR Packaging Context	Back End Bin	Back End Environmental Enclosure	Back End Rack	BE Fiber Bulkhead	BE Rack Bulkhead	Coax Splitter/Combiner	FE Fiber Bulkhead	Front End Environmental Enclosure	Front End Fixed Platform	IRD Bin A	IRD Bin B	MC Bin	WR10-Splitter	WR22-Splitter	Back End Thermal Regulator	Environmental Control System	Environmental Control System Context	Front End Thermal Regulator	WVR Feed	WVR Receiver	WVR Reflector	WVR Spectrometer	WVR System	Frequency Reference Distributor	Primary Frequency Reference	Primary Time Reference	Reference Signal Distribution System	Reference Signal Distribution System Context	Time Reference Distributor	Central Signal Processor	Central Signal Processor Context	Coarse Channelizer	Correlator-Beamformer	Frequency Slice Processor	Local Cooling Distribution	Local Monitor Control System	Local Power Distribution	Network Switch
ALLOCATE RELATIONSHIPS			0	0	0	12	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	3	3	3	6	34	3	6	17	0	4	0	0	0	0	0
Logical Structure::40 Central Signal Processing	Correlator Back End	2																																																																
Logical Structure::40 Central Signal Processing	Data Buffer	2																																																																
Logical Structure::40 Central Signal Processing	Pulsar Search System	2																																																					->		->								
Logical Structure::40 Central Signal Processing	Pulsar Timing System	2																																																					->		->								
Logical Structure::50 Online Control & Monitoring	Calibration Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Configuration Module	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor	2																																																																
Logical Structure::50 Online Control & Monitoring	Data Transmission Module	2																																																																
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board	2																																																																
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver	2																																																																
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector	2																																																																
Logical Structure::50 Online Control & Monitoring	Observation Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Operation Module	2																																																																
Logical Structure::50 Online Control & Monitoring	QuickLook Module	2																																																																
Logical Structure::50 Online Control & Monitoring	Scheduling Module	2																																																																
Logical Structure::60 Data Archives	Engineering Data Archive	2																																																																
Logical Structure::60 Data Archives	Proposal Archive	2																																																																
Logical Structure::60 Data Archives	RFI Archive	2																																																																
Logical Structure::60 Data Archives	Science Data Archive	2																																																																
Logical Structure::60 Data Archives	Staging Storage	2																																																																
Logical Structure::60 Data Archives	Telescope Calibration Archive	2																																																																
Logical Structure::60 Data Archives	Telescope Configuration Archive	2																																																																
Logical Structure::70 Infrastructure	Central Electronics Building	2																																																																
Logical Structure::70 Infrastructure	Data Distribution System	2																																																																
Logical Structure::70 Infrastructure	Electrical Distribution System	2																																																																
Logical Structure::80 Maintenance & Support	Central Repair Facility	2																																																																
Logical Structure::80 Maintenance & Support	CMMS Integration Module	2																																																																
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System	2																																																																
Logical Structure::80 Maintenance & Support	Integrated Support Module	2																																																																
Logical Structure::80 Maintenance & Support	Issue Tracking System	2																																																																
Logical Structure::90 Commissioning & Development	Development Support Infrastructure	2																																																																
Logical Structure::90 Commissioning & Development	Simulation Tool	2																																																																

	S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix	ALLOCATE RELATIONSHIPS	Return to Phase Monitor	RFI Detector / Exciser	Timestamp Generator	Data Transmission System	Data Transmission System Context	DTS Optical Mux	DTS Transmitters	Optical Amplifiers	Antenna Time & Freq Reference System Context	Antenna Time & Frequency Reference System	LO Generator	Primary Reference Generator	Sampler Clock Generator	Antenna Round Trip Phase System Context	Optical Reflector	Round Trip Phase System	RTP Monitor	MC Hardware	MC Hardware Context	MC Interface Board	MC Interface Module	48V Supply	DC Distribution Module	DC Power Supply System	DC Power Supply System Context	Antenna BMR Packaging	Antenna BMR Packaging Context	Back End Bin	Back End Environmental Enclosure	Back End Rack	BE Fiber Bulkhead	BE Rack Bulkhead	Coax Splitter/Combiner	FE Fiber Bulkhead	Front End Environmental Enclosure	Front End Fixed Platform	IRD Bin A	IRD Bin B	MC Bin	WR10-Splitter	WR22-Splitter	Back End Thermal Regulator	Environmental Control System	Environmental Control System Context	Front End Thermal Regulator	WVR Feed	WVR Receiver	WVR Reflector	WVR Spectrometer	WVR System	Frequency Reference Distributor	Primary Frequency Reference	Primary Time Reference	Reference Signal Distribution System	Reference Signal Distribution System Context	Time Reference Distributor	Central Signal Processor	Central Signal Processor Context	Coarse Channelizer	Correlator-Beamformer	Frequency Slice Processor	Local Cooling Distribution	Local Monitor Control System	Local Power Distribution	Network Switch
ALLOCATE RELATIONSHIPS			0	0	0	12	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	3	3	3	6	34	3	6	17	0	4	0	0	0	0	0
Logical Structure::90 Commissioning & Development	Testing Environment	2																																																																	
Logical Structure::100 Offline Processing & Archive Interfaces	Computational Resources	2																																																																
Logical Structure::100 Offline Processing & Archive Interfaces	Data Analysis Tools	2																																																																
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Management	2																																																																
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing Pipelines	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Data Processing System	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Observatory Interfaces	2																																																																
Logical Structure::100 Offline Processing & Archive Interfaces	Offline Calibration Tools	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Resources	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Processing Storage Resources	2																																																															
Logical Structure::100 Offline Processing & Archive Interfaces	Quality Assurance Interfaces	2																																																															
Logical Structure	Array	48				->						->																																							->					->			->							
Logical Structure	Central Reference Distribution System	2																																																		->	->	->	x	->	->		->							
Logical Structure	Central Signal Processing System	2																																																						->		x			->					
Logical Structure	Commissioning & Development Systems	2																																																																	
Logical Structure	Data Archive System	2																																																																
Logical Structure	Infrastructure Systems	2																																																																
Logical Structure	Maintenance & Support Systems	2																																																																
Logical Structure	ngVLA System	48				->						->																																							->	->	->	->	->	->	->	->	->		->					
Logical Structure	Offline Subsystem	2																																																																
Logical Structure	Online Subsystem	2																																																																
Logical Structure	Proposal Management System	2																																																																

	S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix	ALLOCATE RELATIONSHIPS	Pulsar Search Back End	Pulsar Timing Back End	PWR	COTS Integration	COTS Software	CMMS	CMMS Integration Module	Issue Tracking System	Support Module	Offline Sub-System	Workflow Manager	Pipeline System	Archive Access Tool	QA Tool	Archive Ingestor	Archive Streamer	Data Fetcher	Fetching IF	Ingestion IF	QA IF	Science Archive	Online Sub-System	Telescope Calibration	Antenna Supervisor	Array Monitoring IF	Array Monitoring Packet	Array Supervisor	CSP Supervisor	Metadata Capturer	Science Metadata	Science Metadata IF	RFI Monitor	Weather Monitor	RFI Monitoring Data Packet	RFI Monitoring IF	Observation Scheduling Tool	Weather Data Packet	Weather Monitoring IF	Proposal Management Sub-System	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	Proposal Submission Tool	Software Components	Antenna Computing Equipment	Antenna Network	Antenna Rack Power Distribution	Antenna Supervisory Computer	Antenna Switch	Module Interface Board	Array Operations and Repair Center Equipment	Calibration Support Server	CMMS Server	Configuration Database Server	Correlator Back End Server Node	Correlator Back End Switch	Correlator Back End System	CSP Supervisory Computer	Dark Fiber Antenna Switch	Engineering Database Server	General Services Server	ISP Antenna Switch	LO and Timing Supervisory Computer	Maintenance and Support Server	Monitoring Server
ALLOCATE RELATIONSHIPS			3	3	0	3	4	3	3	3	3	4	0	2	0	1	1	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	7	4	3	3	4	12	5	0	0	4	0	3	31	5	3	6	0	0	4	4	0	6	0	0	5	3	3
Logical Structure::10 Proposal Management	Proposal Submission Tool	2																																						->				->	->																					
Logical Structure::10 Proposal Management	Observation Preparation Tool	2																																						->	->				->																					
Logical Structure::10 Proposal Management	Proposal Builder Tool	2																																						->		->			->							->														
Logical Structure::10 Proposal Management	Proposal Handling Tool	2																																						->			->		->																					
Logical Structure::10 Proposal Management::Views	SciOps	2																																						->	->			->	->																					
Logical Structure::20 Antenna Array::Antenna Structure	ACU	9																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Az Drive	9																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Data Transmitter	5																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Digital Back End	6																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Digitizer	6																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Downconverter	6																																																															
Logical Structure::20 Antenna Array::Antenna Structure	El Drive	9																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Feed Indexer	9																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Flux Reference Generator	12																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Indep Phase Cal System	1																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Mount	17																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Reflector Optics	11																																																															
Logical Structure::20 Antenna Array::Antenna Structure	RF Receiver	14																																																															
Logical Structure::20 Antenna Array::Antenna Structure	Time & Freq Reference Generator	6																																																															
Logical Structure::20 Antenna Array::Antenna Types	Antenna	48																																																															
Logical Structure::20 Antenna Array::Antenna Types	LB Antenna	48																																																															
Logical Structure::20 Antenna Array::Antenna Types	Main Antenna	48																																																															
Logical Structure::20 Antenna Array::Antenna Types	SBA Antenna	48																																																															
Logical Structure::20 Antenna Array::Antenna Types	TP Antenna	48																																																															
Logical Structure::20 Antenna Array::Env Monitors	Atm. Delay Monitor System	2																																																															
Logical Structure::20 Antenna Array::Env Monitors	Weather Monitor System	2																																																															
Logical Structure::20 Antenna Array	Long Baseline Array	48																																																															
Logical Structure::20 Antenna Array	Main Array	48																																																															
Logical Structure::20 Antenna Array	Short Baseline Array	48																																																															
Logical Structure::20 Antenna Array	Total Power Array	48																																																															
Logical Structure::30 Central Reference Distribution	Frequency Reference	2																																																															
Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor	2																																																															
Logical Structure::30 Central Reference Distribution	Time Reference	2																																																															
Logical Structure::30 Central Reference Distribution	Time Reference Distributor	2																																																															
Logical Structure::40 Central Signal Processing	Beamformer	2																																																															
Logical Structure::40 Central Signal Processing	Correlator	2																																																															

S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix

		ALLOCATE RELATIONSHIPS	Pulsar Search Back End	Pulsar Timing Back End	PWR	COTS Integration	COTS Software	CMMS	CMMS Integration Module	Issue Tracking System	Support Module	Offline Sub-System	Workflow Manager	Pipeline System	Archive Access Tool	QA Tool	Archive Ingestor	Archive Streamer	Data Fetcher	Fetching IF	Ingestion IF	QA IF	Science Archive	Online Sub-System
ALLOCATE RELATIONSHIPS			3	3	0	3	4	3	3	3	3	4	0	2	0	1	1	1	0	0	0	0	0	0
Logical Structure::40 Central Signal Processing	Correlator Back End	2																						
Logical Structure::40 Central Signal Processing	Data Buffer	2																						
Logical Structure::40 Central Signal Processing	Pulsar Search System	2	->																					
Logical Structure::40 Central Signal Processing	Pulsar Timing System	2		->																				
Logical Structure::50 Online Control & Monitoring	Calibration Module	2																						
Logical Structure::50 Online Control & Monitoring	Configuration Module	2																						
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor	2																						
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor	2																						
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor	2																						
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor	2																						
Logical Structure::50 Online Control & Monitoring	Data Transmission Module	2																						
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board	2																						
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module	2																						
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver	2																						
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector	2																						
Logical Structure::50 Online Control & Monitoring	Observation Module	2																						
Logical Structure::50 Online Control & Monitoring	Operation Module	2																						
Logical Structure::50 Online Control & Monitoring	QuickLook Module	2																						
Logical Structure::50 Online Control & Monitoring	Scheduling Module	2																						
Logical Structure::60 Data Archives	Engineering Data Archive	2																						
Logical Structure::60 Data Archives	Proposal Archive	2																						
Logical Structure::60 Data Archives	RFI Archive	2																						
Logical Structure::60 Data Archives	Science Data Archive	2																						
Logical Structure::60 Data Archives	Staging Storage	2																						
Logical Structure::60 Data Archives	Telescope Calibration Archive	2																						
Logical Structure::60 Data Archives	Telescope Configuration Archive	2																						
Logical Structure::70 Infrastructure	Central Electronics Building	2																						
Logical Structure::70 Infrastructure	Data Distribution System	2																						
Logical Structure::70 Infrastructure	Electrical Distribution System	2																						
Logical Structure::80 Maintenance & Support	Central Repair Facility	2																						
Logical Structure::80 Maintenance & Support	CMMS Integration Module	2				->			->			->												
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System	2					->	->																
Logical Structure::80 Maintenance & Support	Integrated Support Module	2									->	->												
Logical Structure::80 Maintenance & Support	Issue Tracking System	2					->			->														
Logical Structure::90 Commissioning & Development	Development Support Infrastructure	2																						
Logical Structure::90 Commissioning & Development	Simulation Tool	2																						

		ALLOCATE RELATIONSHIPS	Telescope Calibration	Antenna Supervisor	Array Monitoring IF	Array Monitoring Packet	Array Supervisor	CSP Supervisor	Metadata Capturer	Science Metadata	Science Metadata IF	RFI Monitor	Weather Monitor	RFI Monitoring Data Packet	RFI Monitoring IF	Observation Scheduling Tool	Weather Data Packet	Weather Monitoring IF	Proposal Management Sub-System	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	Proposal Submission Tool	Software Components
ALLOCATE RELATIONSHIPS			1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	7	4	3	3	4	12
Logical Structure::40 Central Signal Processing	Correlator Back End	2																						
Logical Structure::40 Central Signal Processing	Data Buffer	2																						
Logical Structure::40 Central Signal Processing	Pulsar Search System	2																						
Logical Structure::40 Central Signal Processing	Pulsar Timing System	2																						
Logical Structure::50 Online Control & Monitoring	Calibration Module	2	->																					
Logical Structure::50 Online Control & Monitoring	Configuration Module	2																						
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor	2		->																				
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor	2						->																
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor	2																						
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor	2																						
Logical Structure::50 Online Control & Monitoring	Data Transmission Module	2																						
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board	2																						
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module	2																						
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver	2																						
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector	2																						
Logical Structure::50 Online Control & Monitoring	Observation Module	2																						
Logical Structure::50 Online Control & Monitoring	Operation Module	2																						
Logical Structure::50 Online Control & Monitoring	QuickLook Module	2																						
Logical Structure::50 Online Control & Monitoring	Scheduling Module	2																						
Logical Structure::60 Data Archives	Engineering Data Archive	2																						
Logical Structure::60 Data Archives	Proposal Archive	2																						
Logical Structure::60 Data Archives	RFI Archive	2																						
Logical Structure::60 Data Archives	Science Data Archive	2																						
Logical Structure::60 Data Archives	Staging Storage	2																						
Logical Structure::60 Data Archives	Telescope Calibration Archive	2																						
Logical Structure::60 Data Archives	Telescope Configuration Archive	2																						
Logical Structure::70 Infrastructure	Central Electronics Building	2																						
Logical Structure::70 Infrastructure	Data Distribution System	2																						
Logical Structure::70 Infrastructure	Electrical Distribution System	2																						
Logical Structure::80 Maintenance & Support	Central Repair Facility	2																						
Logical Structure::80 Maintenance & Support	CMMS Integration Module	2																						->
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System	2																						->
Logical Structure::80 Maintenance & Support	Integrated Support Module	2																						->
Logical Structure::80 Maintenance & Support	Issue Tracking System	2																						->
Logical Structure::90 Commissioning & Development	Development Support Infrastructure	2																						
Logical Structure::90 Commissioning & Development	Simulation Tool	2																						

		ALLOCATE RELATIONSHIPS	Antenna Computing Equipment	Antenna Network	Antenna Rack Power Distribution	Antenna Supervisory Computer	Antenna Switch	Module Interface Board	Array Operations and Repair Center Equipment	Calibration Support Server	CMMS Server	Configuration Database Server	Correlator Back End Server Node	Correlator Back End Switch	Correlator Back End System	CSP Supervisory Computer	Dark Fiber Antenna Switch	Engineering Database Server	General Services Server	ISP Antenna Switch	LO and Timing Supervisory Computer	Maintenance and Support Server	Monitoring Server
ALLOCATE RELATIONSHIPS			5	0	0	4	0	3	31	5	3	6	0	0	4	4	0	6	0	0	5	3	3
Logical Structure::40 Central Signal Processing	Correlator Back End	2							->						->								
Logical Structure::40 Central Signal Processing	Data Buffer	2							->						->								
Logical Structure::40 Central Signal Processing	Pulsar Search System	2																					
Logical Structure::40 Central Signal Processing	Pulsar Timing System	2																					
Logical Structure::50 Online Control & Monitoring	Calibration Module	2							->	->													
Logical Structure::50 Online Control & Monitoring	Configuration Module	2							->			->											
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Antenna Control Supervisor	2	->			->																	
Logical Structure::50 Online Control & Monitoring::Control Supervisors	CSP Control Supervisor	2							->							->							
Logical Structure::50 Online Control & Monitoring::Control Supervisors	LO Reference Control Supervisor	2							->												->		
Logical Structure::50 Online Control & Monitoring::Control Supervisors	Timing Control Supervisor	2							->												->		
Logical Structure::50 Online Control & Monitoring	Data Transmission Module	2							->														
Logical Structure::50 Online Control & Monitoring::Hardware Controllers	HW Controller Board	2	->					->															
Logical Structure::50 Online Control & Monitoring	Metadata Capture Module	2							->														
Logical Structure::50 Online Control & Monitoring	Monitoring Data Archiver	2							->									->					->
Logical Structure::50 Online Control & Monitoring	Monitoring Data Collector	2	->			->			->							->					->		
Logical Structure::50 Online Control & Monitoring	Observation Module	2							->														
Logical Structure::50 Online Control & Monitoring	Operation Module	2							->														
Logical Structure::50 Online Control & Monitoring	QuickLook Module	2							->														
Logical Structure::50 Online Control & Monitoring	Scheduling Module	2							->														
Logical Structure::60 Data Archives	Engineering Data Archive	2							->									->					
Logical Structure::60 Data Archives	Proposal Archive	2							->														
Logical Structure::60 Data Archives	RFI Archive	2							->									->					
Logical Structure::60 Data Archives	Science Data Archive	2																					
Logical Structure::60 Data Archives	Staging Storage	2							->														
Logical Structure::60 Data Archives	Telescope Calibration Archive	2							->			->											
Logical Structure::60 Data Archives	Telescope Configuration Archive	2							->			->											
Logical Structure::70 Infrastructure	Central Electronics Building	2																					
Logical Structure::70 Infrastructure	Data Distribution System	2																					
Logical Structure::70 Infrastructure	Electrical Distribution System	2																					
Logical Structure::80 Maintenance & Support	Central Repair Facility	2																					
Logical Structure::80 Maintenance & Support	CMMS Integration Module	2																					
Logical Structure::80 Maintenance & Support	Computerized Maintenance Management System	2							->		->											->	
Logical Structure::80 Maintenance & Support	Integrated Support Module	2																					
Logical Structure::80 Maintenance & Support	Issue Tracking System	2																					
Logical Structure::90 Commissioning & Development	Development Support Infrastructure	2																					
Logical Structure::90 Commissioning & Development	Simulation Tool	2																					

	S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix	ALLOCATE RELATIONSHIPS	Pulsar Search Back End	Pulsar Timing Back End	PWR	COTS Integration	COTS Software	CMMS	CMMS Integration Module	Issue Tracking System	Support Module	Offline Sub-System	Workflow Manager	Pipeline System	Archive Access Tool	QA Tool	Archive Ingestor	Archive Streamer	Data Fetcher	Fetching IF	Ingestion IF	QA IF	Science Archive	Online Sub-System	Telescope Calibration	Antenna Supervisor	Array Monitoring IF	Array Monitoring Packet	Array Supervisor	CSP Supervisor	Metadata Capturer	Science Metadata	Science Metadata IF	RFI Monitor	Weather Monitor	RFI Monitoring Data Packet	RFI Monitoring IF	Observation Scheduling Tool	Weather Data Packet	Weather Monitoring IF	Proposal Management Sub-System	Observation Preparation Tool	Proposal Builder Tool	Proposal Handling Tool	Proposal Submission Tool	Software Components	Antenna Computing Equipment	Antenna Network	Antenna Rack Power Distribution	Antenna Supervisory Computer	Antenna Switch	Module Interface Board	Array Operations and Repair Center Equipment	Calibration Support Server	CMMS Server	Configuration Database Server	Correlator Back End Server Node	Correlator Back End Switch	Correlator Back End System	CSP Supervisory Computer	Dark Fiber Antenna Switch	Engineering Database Server	General Services Server	ISP Antenna Switch	LO and Timing Supervisory Computer	Maintenance and Support Server	Monitoring Server
ALLOCATE RELATIONSHIPS			3	3	0	3	4	3	3	3	3	4	0	2	0	1	1	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	7	4	3	3	4	12	5	0	0	4	0	3	31	5	3	6	0	0	4	4	0	6	0	0	5	3	3
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	S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix	ALLOCATE RELATIONSHIPS	Observation Execution Server	Observation Support Server	Operations Console	Other Networking Equipment	Scheduling Database Server	Staging Storage Infiniband Switch	Staging Storage Node	Staging Storage System	CIT Systems	Remote LO & Timing Equipment	LO and Timing Supervisory Computer	Science Operations and Data Center Equipment	Archive Services Server	Continuous Integration Server	General Services Server	Infiniband Switch	Metadata Database Server	Observatory Interfaces Server	Other Networking Equipment	Permanent Storage System	Processing Cluster	Processing Cluster Node	Processing Management Server	Processing Storage Node	Processing Storage System	Proposal Management Database Server	Proposal Management Server	Quality Assurance Support Server	Science Archive Servers	Software Configuration Management Server	Software Development Services Server	Software Test Server	Antenna Foundation	Electrical Interface	Fiber Interface	Antenna Pads	Array Infrastructure Systems	Array Infrastructure Systems Context	Electrical Utility	Fiber Utility	Ops Roads	API	Env Monitor System	RFI Monitor	Weather Station	Chiller Loop	Shielded Chamber	Shielded Chamber HVAC	Shielded Chamber UPS	Central Ops Building	Central Ops Building Context	Central Repair Building	Operations Buildings	Sci Ops Building	Small Ops Building	Tech Services Building	SciOps
ALLOCATE RELATIONSHIPS			3	7	3	0	5	0	3	3	51	4	4	25	4	3	0	0	3	4	0	3	6	5	4	5	5	9	7	5	3	3	3	5	0	0	0	0	4	22	3	3	0	1	2	0	1	0	0	0	0	1	10	3	4	0	0	0	44
Logical Structure::10 Proposal Management	Proposal Submission Tool	2									->			->														->	->																														->
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Logical Structure::20 Antenna Array::Antenna Structure	Data Transmitter	5																																						->																			->
Logical Structure::20 Antenna Array::Antenna Structure	Digital Back End	6																																																									->
Logical Structure::20 Antenna Array::Antenna Structure	Digitizer	6																																																									->
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Logical Structure::20 Antenna Array::Antenna Structure	Reflector Optics	11																																						->																			->
Logical Structure::20 Antenna Array::Antenna Structure	RF Receiver	14																																																									->
Logical Structure::20 Antenna Array::Antenna Structure	Time & Freq Reference Generator	6																																																									->
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Logical Structure::20 Antenna Array::Antenna Types	LB Antenna	48																																						->																			->
Logical Structure::20 Antenna Array::Antenna Types	Main Antenna	48																																						->																			->
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Logical Structure::20 Antenna Array::Env Monitors	Atm. Delay Monitor System	2																																										->	->														
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Logical Structure::30 Central Reference Distribution	Frequency Reference Distributor	2																																																									
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Logical Structure::40 Central Signal Processing	Correlator	2																																																		->						

	S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix	ALLOCATE RELATIONSHIPS	Observation Execution Server	Observation Support Server	Operations Console	Other Networking Equipment	Scheduling Database Server	Staging Storage Infiniband Switch	Staging Storage Node	Staging Storage System	CIT Systems	Remote LO & Timing Equipment	LO and Timing Supervisory Computer	Science Operations and Data Center Equipment	Archive Services Server	Continuous Integration Server	General Services Server	Infiniband Switch	Metadata Database Server	Observatory Interfaces Server	Other Networking Equipment	Permanent Storage System	Processing Cluster	Processing Cluster Node	Processing Management Server	Processing Storage Node	Processing Storage System	Proposal Management Database Server	Proposal Management Server	Quality Assurance Support Server	Science Archive Servers	Software Configuration Management Server	Software Development Services Server	Software Test Server	Antenna Foundation	Electrical Interface	Fiber Interface	Antenna Pads	Array Infrastructure Systems	Array Infrastructure Systems Context	Electrical Utility	Fiber Utility	Ops Roads	API	Env Monitor System	RFI Monitor	Weather Station	Chiller Loop	Shielded Chamber	Shielded Chamber HVAC	Shielded Chamber UPS	Central Ops Building	Central Ops Building Context	Central Repair Building	Operations Buildings	Sci Ops Building	Small Ops Building	Tech Services Building	SciOps
ALLOCATE RELATIONSHIPS			3	7	3	0	5	0	3	3	51	4	4	25	4	3	0	0	3	4	0	3	6	5	4	5	5	9	7	5	3	3	3	5	0	0	0	0	4	22	3	3	0	1	2	0	1	0	0	0	0	1	10	3	4	0	0	0	44
Logical Structure::40 Central Signal Processing	Correlator Back End	2									->																																																
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Logical Structure::40 Central Signal Processing	Pulsar Timing System	2																																																		->						
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	S.99-000 Logical Model to Structural Model Mapping - Allocate Matrix	ALLOCATE RELATIONSHIPS	Observation Execution Server	Observation Support Server	Operations Console	Other Networking Equipment	Scheduling Database Server	Staging Storage Infiniband Switch	Staging Storage Node	Staging Storage System	CIT Systems	Remote LO & Timing Equipment	LO and Timing Supervisory Computer	Science Operations and Data Center Equipment	Archive Services Server	Continuous Integration Server	General Services Server	Infiniband Switch	Metadata Database Server	Observatory Interfaces Server	Other Networking Equipment	Permanent Storage System	Processing Cluster	Processing Cluster Node	Processing Management Server	Processing Storage Node	Processing Storage System	Proposal Management Database Server	Proposal Management Server	Quality Assurance Support Server	Science Archive Servers	Software Configuration Management Server	Software Development Services Server	Software Test Server	Antenna Foundation	Electrical Interface	Fiber Interface	Antenna Pads	Array Infrastructure Systems	Array Infrastructure Systems Context	Electrical Utility	Fiber Utility	Ops Roads	API	Env Monitor System	RFI Monitor	Weather Station	Chiller Loop	Shielded Chamber	Shielded Chamber HVAC	Shielded Chamber UPS	Central Ops Building	Central Ops Building Context	Central Repair Building	Operations Buildings	Sci Ops Building	Small Ops Building	Tech Services Building	SciOps
ALLOCATE RELATIONSHIPS			3	7	3	0	5	0	3	3	51	4	4	25	4	3	0	0	3	4	0	3	6	5	4	5	5	9	7	5	3	3	3	5	0	0	0	0	4	22	3	3	0	1	2	0	1	0	0	0	0	1	10	3	4	0	0	0	44
Logical Structure::90 Commissioning & Development	Testing Environment	2									->			->																				->																									
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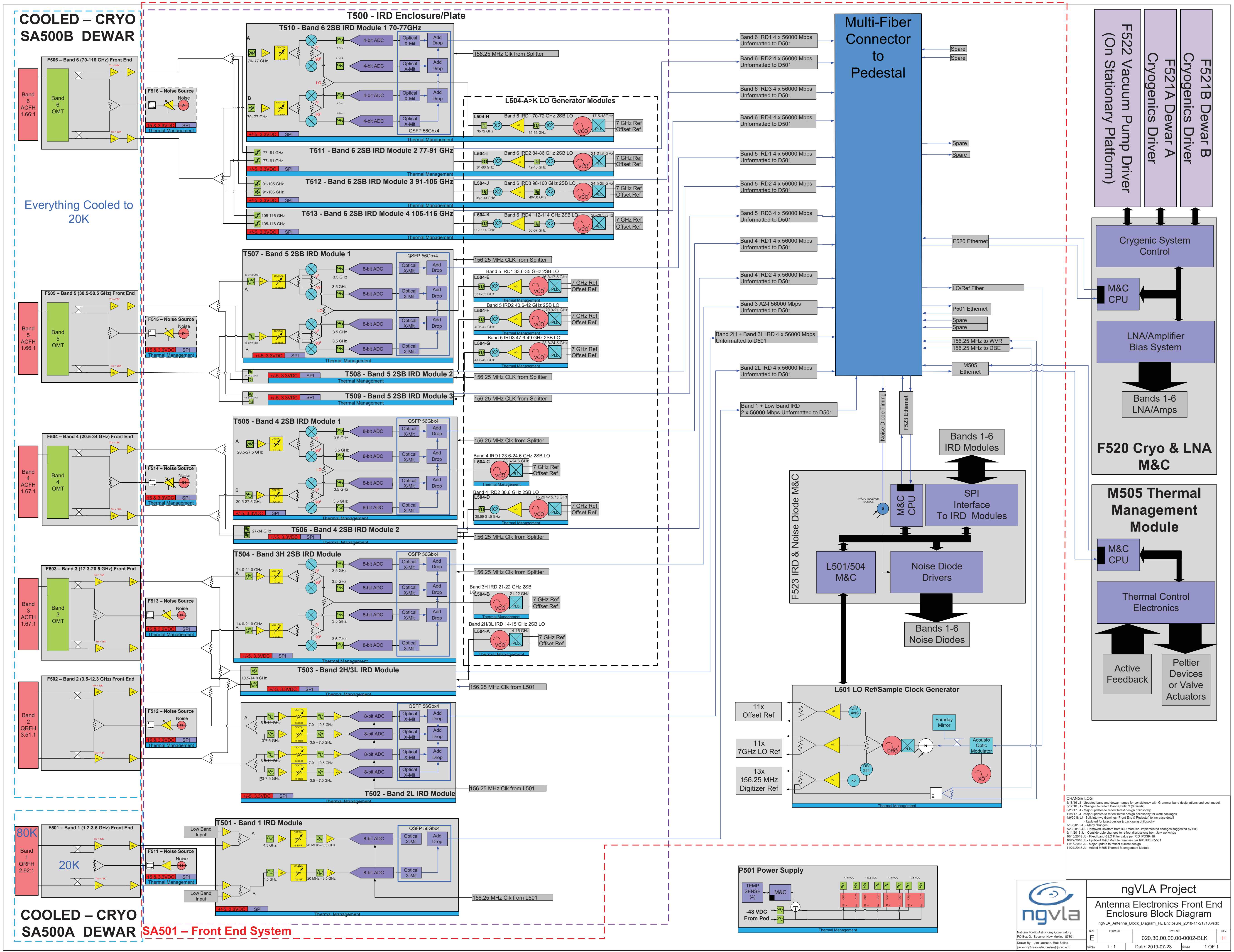
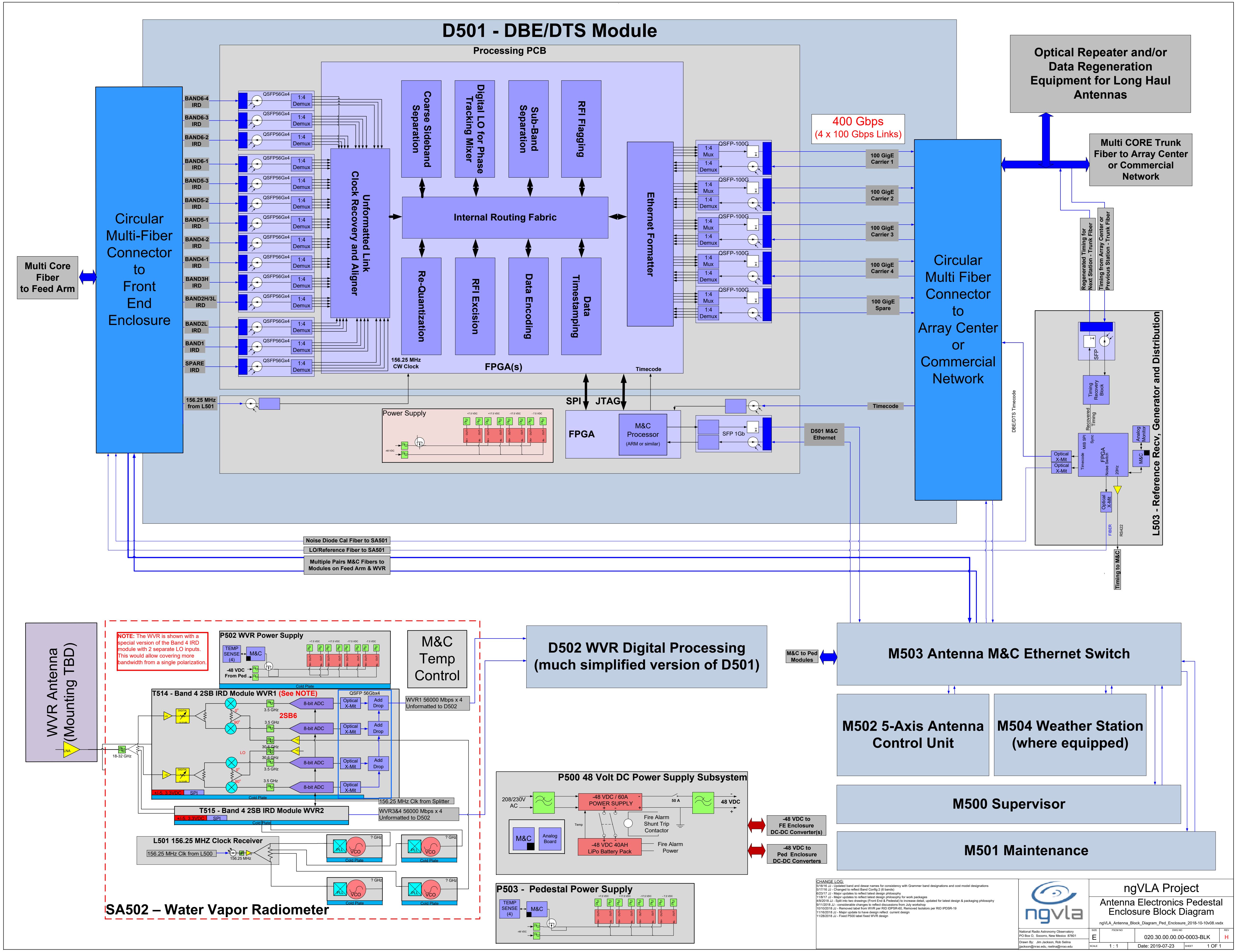

COOLED – CRYO SA500B DEWAR
T500 - IRD Enclosure/Plate
T510 - Band 6 2SB IRD Module 1 70-77GHz
T511 - Band 6 2SB IRD Module 2 77-91 GHz
T512 - Band 6 2SB IRD Module 3 91-105 GHz
T513 - Band 6 2SB IRD Module 4 105-116 GHz
L504-A>K LO Generator Modules
T507 - Band 5 2SB IRD Module 1
T508 - Band 5 2SB IRD Module 2
T509 - Band 5 2SB IRD Module 3
T505 - Band 4 2SB IRD Module 1
T506 - Band 4 2SB IRD Module 2
T504 - Band 3H 2SB IRD Module
T503 - Band 2H/3L IRD Module
T502 - Band 2L IRD Module
T501 - Band 1 IRD Module
F506 – Band 6 (70-116 GHz) Front End
F505 – Band 5 (30.5-50.5 GHz) Front End
F504 – Band 4 (20.5-34 GHz) Front End
F503 – Band 3 (12.3-20.5 GHz) Front End
F502 – Band 2 (3.5-12.3 GHz) Front End
F501 – Band 1 (1.2-3.5 GHz) Front End
Everything Cooled to 20K
80K
20K
COOLED – CRYO SA500A DEWAR
SA501 – Front End System
Multi-Fiber Connector to Pedestal
F522 Vacuum Pump Driver (On Stationary Platform)
F521A Dewar A Cryogenics Driver
F521B Dewar B Cryogenics Driver
Crygenic System Control
M&C CPU
LNA/Amplifier Bias System
Bands 1-6 LNA/Amps
F520 Cryo & LNA M&C
M505 Thermal Management Module
Thermal Control Electronics
Active Feedback
Peltier Devices or Valve Actuators
F523 IRD & Noise Diode M&C
Bands 1-6 IRD Modules
SPI Interface To IRD Modules
L501/504 M&C
Noise Diode Drivers
Bands 1-6 Noise Diodes
L501 LO Ref/Sample Clock Generator
11x Offset Ref
11x 7GHz LO Ref
13x 156.25 MHz Digitizer Ref
P501 Power Supply
ngVLA Project
Antenna Electronics Front End Enclosure Block Diagram
020.30.00.00.00-0002-BLK
Date: 2019-07-23
1 OF 1

2


D501 - DBE/DTS Module
Processing PCB
Circular Multi-Fiber Connector to Front End Enclosure
Multi Core Fiber to Feed Arm
Coarse Sideband Separation
Digital LO for Phase Tracking Mixer
Sub-Band Separation
RFI Flagging
Internal Routing Fabric
Unformatted Link Clock Recovery and Aligner
Re-Quantization
RFI Excision
Data Encoding
Data Timestamping
Ethernet Formatter
FPGA(s)
156.25 MHz CW Clock
Timecode
Power Supply
SPI
JTAG
FPGA
M&C Processor (ARM or similar)
SFP 1Gb
D501 M&C Ethernet
400 Gbps (4 x 100 Gbps Links)
100 GigE Carrier 1
100 GigE Carrier 2
100 GigE Carrier 3
100 GigE Carrier 4
100 GigE Spare
Circular Multi Fiber Connector to Array Center or Commercial Network
Optical Repeater and/or Data Regeneration Equipment for Long Haul Antennas
Multi CORE Trunk Fiber to Array Center or Commercial Network
L503 - Reference Recv, Generator and Distribution
Timing to M&C
Noise Diode Cal Fiber to SA501
LO/Reference Fiber to SA501
Multiple Pairs M&C Fibers to Modules on Feed Arm & WVR
WVR Antenna (Mounting TBD)
P502 WVR Power Supply
M&C Temp Control
T514 - Band 4 2SB IRD Module WVR1 (See NOTE)
T515 - Band 4 2SB IRD Module WVR2
L501 156.25 MHZ Clock Receiver
SA502 – Water Vapor Radiometer
NOTE: The WVR is shown with a special version of the Band 4 IRD module with 2 separate LO inputs. This would allow covering more bandwidth from a single polarization.
D502 WVR Digital Processing (much simplified version of D501)
M&C to Ped Modules
M503 Antenna M&C Ethernet Switch
M502 5-Axis Antenna Control Unit
M504 Weather Station (where equipped)
M500 Supervisor
M501 Maintenance
P500 48 Volt DC Power Supply Subsystem
-48 VDC / 60A POWER SUPPLY
-48 VDC 40AH LiPo Battery Pack
-48 VDC to FE Enclosure DC-DC Converter(s)
-48 VDC to Ped Enclosure DC-DC Converters
P503 - Pedestal Power Supply
ngVLA Project
Antenna Electronics Pedestal Enclosure Block Diagram
020.30.00.00.00-0003-BLK
Date: 2019-07-23

Calibration Strategy and Requirements

020.22.00.00.00-0001-REQ-A-ARRAY_CALIBR_STRATEGY_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
C. Hales	ngVLA/DSOC, NRAO	2019-08-02

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.08.02 10:00:49 -06'00'	Electronics Division, NRAO	2019-08-02
E. Murphy, Project Scientist Digitally signed by Eric J. Murphy Date: 2019.08.05 10:55:05 -04'00'	ngVLA/NM-Operations, NRAO	2019-08-02
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.08.06 10:35:01 -06'00'	Asst. Director, NM-Operations, NRAO	2019-08-02

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.08.06 10:35:18 -06'00'	Asst. Director, NM-Operations, NRAO	2019-08-02

Change Record

Version	Date	Author	Affected Sections	Reason
01	2018-11-01	Hales	All	Initial framework based on ALMA Calibration Specifications and Requirements [RD01].
02	2019-05-28	Hales	All	First complete draft.
03	2019-07-12	Hales	1,6	Minor clarifications and corrections following review by the Calibration Working Group. Revised pointing requirements.
A	2019-08-02	Hales, Lear	All	Updated cover page and headers in preparation for approvals and release.

Table of Contents

1 INTRODUCTION

1.1 Purpose

This document presents preliminary calibration strategies and associated requirements for the ngVLA.

The calibration requirements flow-down from the initial draft of the ngVLA Science Requirements [AD01], the ngVLA Stakeholder Requirements [AD02], and the ngVLA Preliminary System Requirements [AD03].

The preliminary requirements presented in this document will guide the design of the facility including hardware, software, and operational elements. This document will form part of the submission of the ngVLA Reference Design documentation package.

Some revisions to the System Requirements are anticipated as the facility concept matures. Similarly, the Science and Stakeholder Requirements may change depending on the degree of alignment with the National Academy of Sciences Astro 2020 Decadal Survey goals.

1.2 Scope

The scope of this document is the set of key quantities that will need to be measured or taken into account in order to collect and calibrate ngVLA data.

This document does not explicitly address all calibration parameter space. Instead, it focuses on key aspects of calibration that drive design and are necessary to support the higher-level science, stakeholder, and system requirements. These in turn yield implicit constraints on performance throughout the remaining parameter space.

This document does not explicitly define observing modes, nor calibration strategies for particular observing modes, nor does it lay out work for commissioning, operating, or maintaining the telescope. This document does, however, provide a foundation for addressing/constraining each of these aspects.

This document focuses primarily on interferometric requirements for ngVLA. Requirements for single dish capabilities are currently under consideration and will be addressed in a future version.

This document represents a snaphot in time in the design evolution of the ngVLA. There are known inconsistencies between the requirements derived in this document and capabilities presented elsewhere in the Reference Design package. These differences will form the basis for future decisions as the facility concept matures.

2 RELATED DOCUMENTS

2.1 Applicable Documents

The following documents may not be directly referenced herein, but provide necessary context or supporting material.

Reference No.	Document Title	Rev. / Doc. No.
AD01	ngVLA Science Requirements	020.10.15.05.00-0001-REQ
AD02	ngVLA Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD03	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD04	ngVLA System Reference Design	020.10.20.00.00-001-REP
AD05	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD06	ngVLA Environmental Specifications	020.10.15.10.00-0001-SPE
AD07	ngVLA Reference Observing Program	020.10.15.05.10-0001-SPE
AD08	ngVLA System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD09	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD10	ngVLA Front End Reference Design Description	020.30.03.00.00-0003-DSN

2.2 Reference Documents

The following references provide supporting context.

Reference No.	Document Title	Rev. / Doc. No.
RD01	ALMA Calibration Specifications and Requirements (Version D, 5/18/2006)	ALMA-90.03.00.00-001-A-SPE
RD02	Taperability Study for the ngVLA and Performance Estimates	Rosero, 2019, ngVLA Memo 55
RD03	Image Dynamic Range Limits Arising From Visibility Errors	Hales, 2019, ngVLA Memo 60
RD04	Antenna Tolerance Theory – A Review	Ruze, 1966, Proc. IEEE, 54, 633
RD05	The Primary Antenna Elements	Napier, 1999, Synthesis Imaging in Radio Astronomy II, 180, 37

Reference No.	Document Title	Rev. / Doc. No.
RD06	Fast Switching Phase Calibration at 3mm at the VLA Site	Carilli, 2015, ngVLA Memo 1
RD07	Interferometry and Synthesis in Radio Astronomy	Thompson, Moran & Swenson, 2017, Springer, 3rd Ed.
RD08	Microarcsecond Radio Astronomy	Reid & Honma, 2014, ARAA, 52, 339
RD09	Astrometric Effects of Secular Aberration	Kopeikin & Makarov, 2006, AJ, 131, 1471
RD10	A new concept of the International Celestial Reference Frame: the epoch ICRF	Xu et al., 2013, MNRAS, 430, 2633
RD11	The pointing self calibration algorithm for aperture synthesis radio telescopes	Bhatnagar & Cornwell, 2017, AJ, 154, 197B
RD12	Wide-field wide-band Interferometric Imaging: The WB A-Projection and Hybrid Algorithms	Bhatnagar et al., 2013, ApJ, 770, 91
RD13	Requirements for Subreflector and Feed Positioning for ALMA Antennas	Butler, 2003, ALMA Memo 479
RD14	Temporal and Spatial Tropospheric Phase Fluctuations at the VLA (and Beyond) and Implications for Phase Calibration	Hales, 2019, ngVLA Memo 61
RD15	Calibration Errors in Interferometric Radio Polarimetry	Hales, 2017, AJ, 154, 54
RD16	Phase calibration and water vapor radiometry for millimeter-wave arrays	Lay, 1997, A&AS, 122, 547
RD17	Astrometry and Geodesy with Radio Interferometry: Experiments, Models, Results	Sovers et al., 1998, Rev. Mod. Phys., 70, 1393
RD18	Temporal and Spatial Ionospheric Phase Fluctuations at the VLA (and Beyond) and Implications for Phase Calibration	Hales, 2019, ngVLA Memo 62 (in prep.)
RD19	Spectra of L-band ionospheric scintillation over Nanjing	Fang et al., 2012, Chin. Sci. Bull., 57, 3375
RD20	A Search For Sub-Second Radio Variability Predicted To Arise Toward 3C84 From Intergalactic Dispersion	Hales et al., 2016, ApJ, 823, 93
RD21	Measurement of the Parallax of PSR B0950+08 Using the VLBA	Brisken et al., 2000, ApJ, 541, 959
RD22	An ionospheric index suitable for estimating the degree of ionospheric perturbations	Wilken et al., 2018, J. Space Weather Space Clim., 8, A19

Reference No.	Document Title	Rev. / Doc. No.
RD23	How Close to the Sun Should We Observe With the VLA?	Butler, 2005, VLA Test Memo 236
RD24	An Accurate Flux Density Scale from 1 to 50 GHz	Perley & Butler, 2013, ApJS, 204, 19
RD25	Flux Density Models for Solar System Bodies In CASA	Butler, 2012, ALMA Memo 594
RD26	Atmospheric Opacity at the VLA	Uson, 1986, VLA Sci. Memo 157
RD27	Temporal and Spatial Tropospheric Opacity Fluctuations at the VLA (and Beyond) and Implications for Amplitude Calibration	Hales, 2019, ngVLA Memo 63 (in prep.)
RD28	On Determining Visibilities from Correlation Products	Perley, 2010, EVLA Memo 145
RD29	The ALMA Calibrator Database I: Measurements Taken During the Commissioning Phase of ALMA	van Kempen et al., 2014, ALMA Memo 599
RD30	Understanding radio polarimetry. II. Instrumental calibration of an interferometer array	Sault et al., 1996, A&AS, 117, 149
RD31	CASA Interferometric Pipeline Polarization Calibration & Imaging Requirement & Design Specifications	Hales, 2017, ALMA Memo 603
RD32	Radio circular polarization of active galaxies	Rayner et al., 2000, MNRAS, 319, 484
RD33	The Synthesis Radio Telescope at Westerbork. Methods of Polarization Measurement	Weiler, 1973, A&A, 26, 403
RD34	Determining full EVLA polarization leakage terms at C and X bands	Sault & Perley, 2013, EVLA Memo 170
RD35	Integrated Polarization Properties of 3C48, 3C138, 3C147, and 3C286	Perley & Butler, 2013, ApJS, 206, 16
RD36	Polarimetric calibration and dynamic range issues	Sault & Perley, 2014, EVLA Memo 177
RD37	Dipole Alignment Tolerance for the JVLA's Low-Band System	Perley, 2016, EVLA Memo 200
RD38	ALMA EOC Polarization Commissioning Report	Cortes et al., 2015, ALMA Tech. Note (draft version Nov 23)

Reference No.	Document Title	Rev. / Doc. No.
RD39	Polarization Calibration of the VLBA Using the D-terms	Gomez et al., 2002, VLBA Sci. Memo 30
RD40	JVLA calibration stability at L-band over 5.5 years	Hales & Stephenson, 2019, EVLA Memo 208
RD41	Dual differential polarimetry. A technique to recover polarimetric information from dual-polarization observations	Marti-Vidal et al., 2016, A&A, 593, A61

3 REQUIREMENTS MANAGEMENT

3.1 Requirements Definitions

Requirement Level	Definition
L0	User requirements expressed in terms applicable to their needs or use cases ("Science Requirements" or "Stakeholder Requirements")
L1	Requirements expressed in technical functional or performance terms, but still implementation agnostic ("System Level Requirements")
L2	Requirements that define a specification for an element of the system, presuming an architecture ("Sub System Requirements")

3.2 Requirements Flow Down

The L1 System Requirements generally flow from the L0 Science Requirements [AD01] for the facility. While these requirements dominate, other Stakeholder Requirements [AD02] also influence or dictate design choices. Examples include programmatic requirements, regulatory compliance requirements, and the life-cycle concepts (e.g. the Operations and Maintenance Concept [AD05]) for the facility.

The Science Requirements and Stakeholder Requirements fully encapsulate all known L0 requirements. The System Requirements [AD03], subordinates [AD06,AD08], and this document fully encapsulates all known L1 requirements. Supplemental L1 requirements may be developed in future subordinate documents.

Specifications for individual sub-systems (L2) flow from the L1 System Requirements, and may not always be directly attributable to a single system requirement (e.g. phase drift specifications at the system level may be apportioned to multiple sub-systems, or a sub-system specification may be in support of multiple higher-level requirements). Specifications at the L2 level may also flow directly from L0 requirements in some cases. Completeness of the L2 requirements is assessed at the requirements review of each sub-system.

While this is a top-down design process, the process is still iterative rather than a 'waterfall' or linear process. The feasibility and cost of implementation of requirements and specifications lead to trade-offs that feedback to higher-level requirements. The end goal is to build the most generally capable system within the programmatic constraints of cost and schedule.

Maintaining enumerated and traceable science requirements, system requirements, and sub-system specifications ensures this trade-off process is complete and well understood by the project team. The effect of a change in a sub-system specification can be analyzed at the system level, and thereafter the impact on a specific scientific program can be ascertained.

Details of the requirements management strategy can be found in AD09.

4 OVERVIEW OF CALIBRATION REQUIREMENTS

Calibration is the process of removing corrupting effects from measured data, with the aim to produce corrected data that resembles within acceptable limits the true input signals that would have been measured in vacuum by a perfect system. Corrupting effects include the atmosphere, electronics, physical hardware such as antennas and how they perform under varying observing conditions, and signal propagation effects such as solar gravitational deflection and even secular aberration.

This document presents the technical requirements for calibration of the ngVLA telescope. These requirements determine the overall form of the calibration strategy and, in-turn, aspects of the hardware, software, and operational elements of the Reference Design.

Section 5 presents system level requirements (L1) and associated explanatory notes. Section 6 presents sub-system level requirements (L2) and associated explanatory notes. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirements and should guide the verification process. For ease of identification, all L1 requirements in this document are prefixed with CAL01. The L2 requirements begin at CAL02. Note that requirement IDs are static once assigned and therefore not always in sequential order due to subsequent revisions of the associated documents.

The notes contain an explanation or an analysis of how the numeric vales of the requirements were derived. For brevity and clarity, each derivation typically only considers the most demanding scenario(s) under which the requirement of interest influences the system. Where numbers are not well substantiated, this is documented in the notes. In this way, the trade-space available is apparent to scientists and engineers who will guide the evolution of the ngVLA calibration strategy and overall system design.

Traceability is indicated for each requirement. This is not exhaustive; typically only the major drivers are identified.

The requirements presented in this document have been developed by converting science and stakeholder requirements into performance requirements for the ngVLA system. This process has resulted in some requirements that are more demanding than can be delivered by the current Reference Design. These differences will be addressed as the facility concept matures. This document informs the trade-space for potential future compromises between science performance, technical capabilities, project risk, and cost. If, however, the ngVLA can be delivered with better performance than required below, while remaining within cost limitations, then this should be pursued.

5 L1 CALIBRATION REQUIREMENTS

This section presents system-level requirements that are relevant to calibration (broader context is provided by the material referenced in Section 2). Traceability is shown to the relevant L0 requirements document, with SCI denoting Requirement IDs in the Science Requirements [AD01] and STK denoting requirements in the Stakeholder Requirements [AD02]. Where gaps in L0 requirements exist today, there may be additional notes in the traceability column that will be addressed in future versions of the document set.

System-level requirements apply to performance with all operational calibrations applied. The system can be assumed to be fully functioning, under the precision environmental conditions (defined in AD06). The system-level requirements are written in an implementation agnostic way whenever possible in order to not unduly constrain the conceptual design.

5.1 Observing Modes

Parameter	Req. #	Value	Traceability
Observing Modes	CAL0101	The goal is for $> 80\%$ of the scientific program to use a diverse but well-defined set of standard observing modes. Flexibility shall be provisioned, where justified, for PIs to make changes to support non-standard instrument configurations and/or non-standard data processing.	STK0700, STK0702, STK0704, STK0705
Triggered Observations	CAL0102	Capability to perform rapid automated calibration with minimal set of necessary parameters (e.g. limited bandwidth or lack of robust amplitude calibration), or where possible full solutions, to support triggered observations that interrupt the execution of another observing program.	STK0901

The standard observing modes are defined in the Preliminary System Requirements [AD03]. These are: Interferometric, Phased Array, Pulsar Timing, Pulsar and Transient Search, VLBI, Total Power, On The Fly Mapping, Solar, and Concurrent Interferometric and Phased Array. The commensality matrix for these modes is presented in AD03.

5.2 Computing

Parameter	Req. #	Value	Traceability
Provision of Software Tools	CAL0103	The system shall include tools for the preparation and calibration of observations, and the reduction and analysis of data products.	STK1201, STK1202, STK0801, STK0805

Parameter	Req. #	Value	Traceability
Pipeline Use for Standard Observing Modes	CAL0104	Calibration and data processing for standard observing modes will be undertaken through an automated pipeline developed and run by the Observatory.	STK1000, STK1302, SYS2201

5.3 Operations

Parameter	Req. #	Value	Traceability
Storage and Retrieval of Calibration Coefficients	CAL0105	Parameters for standard mode observations determined by calibration (such as delays or bandpasses) shall be stored and automatically retrieved as needed, i.e. there shall be a calibration database. This database may also be useful for non-standard observations, though this is not guaranteed.	STK1300
Automated Re-Measurement of Calibration Parameters	CAL0106	Re-measurement of calibration and related scientific performance characteristics of the array shall be automated and performed as an Observatory function, possibly using small subarrays of antennas contemporaneously with science observing on larger subarrays.	STK1301
Calibration Recall	CAL0107	The system shall apply prior calibration corrections if their projected accuracy (given time elapsed) still meets the requirements for a given observation. (i.e., a scheduling block need not always include its own calibrators.)	STK1403, SYS1063

Parameter	Req. #	Value	Traceability
Automated Observation Preparation	CAL0108	The system shall have an automated procedure for defining the appropriate calibration strategy for any given standard observing mode. This system will account for current and predicted future atmospheric and interplanetary conditions.	STK0701, STK0805, STK1506, SYS2221, SYS2304
Environmental Monitoring	CAL0109	Parameters that affect system scheduling or are used for calibration (e.g. wind speed, temperature, pressure, solar activity, ionospheric stability) shall be measured over the full extent of the array and utilized accordingly.	STK0900, SYS2501
Antenna Automation	CAL0110	Individual antennas and sub-systems within the array shall perform basic system configuration and monitoring functions without the need for human intervention.	STK1704

5.4 Observational Efficiency

Parameter	Req. #	Value	Traceability
Observational Efficiency	CAL0111	The system shall be designed to maximize the array's resources and time spent on science observations (vs maintenance, testing, development efforts, and calibration).	STK1402
Calibration Efficiency	CAL0112	Overheads for system calibration shall be minimized, with a goal of 90% of time spent on source for Standard Observing Modes.	SCI0100, SCI0102, SCI0106, STK1403, STK0704, SYS1061

Parameter	Req. #	Value	Traceability
Bandpass Calibration Efficiency	CAL0113	The system shall have adequate gain stability to permit application of cataloged bandpass solutions for Standard (Interferometric Continuum) Observing Modes.	STK1403, STK0704, SYS1066
Complex Gain Calibration Efficiency	CAL0114	Complex gain calibration overheads (involving source adjacent to science target) shall not exceed 100% of on-target time for observations at 116 GHz when operating in the precision operating conditions.	STK1403, SYS1068
Polarization Calibration Efficiency	CAL0115	Polarization calibration overheads shall be minimized.	STK1403, STK0704, SYS1065
Subarrays for Scheduling	CAL0116	A limited number of predefined science subarrays will be used by the Observatory to simplify scheduling of the scientific program.	STK1401

Regarding CAL0112, note that 90% observing efficiency implies an allowance of 10% of real-time (2.4 hours/day or 3 days/month) to be allocated to calibrations and array maintenance.

5.5 Bandwidth

Parameter	Req. #	Value	Traceability
Total Instantaneous Processed Bandwidth	CAL0117	The system shall transmit and process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	SCI0100, SYS0903
Spectral Resolution	CAL0118	A spectral resolution of 0.1 km/s must be supported (and in conjuction with CAL0125).	SCI0105

5.6 Calibration Accuracy

Parameter	Req. #	Value	Traceability
Photometric Accuracy	CAL0119	The system shall be capable of delivering 1% absolute flux density accuracy for programs requiring accurate photometry. The system shall be capable of delivering 6% absolute flux density accuracy in Standard (Interferometric) Observing Modes, without the need for specialized observations.	SCI0110, STK1403, STK0704, SYS1064
Polarization Purity	CAL0120	0.01% post-calibration on-axis residual linear polarization leakage (amplitude), where leakage is defined as Stokes Q/I, U/I, or V/I. Goal of minimizing off-axis residual polarization leakage (including on-axis contribution) to within 0.1% at any point within the -5 dB primary beam power contour.	SCI0114, SYS1901
Relative Astrometric Accuracy	CAL0121	The instrument shall achieve an astrometric accuracy that is $< 1\%$ of the synthesized beam FWHM for a bright (SNR $>$ 100) point source.	SCI0111
Amplitude/Phase Variation Magnitudes	CAL0122	Amplitude and phase variations caused by the instrument should be smaller than those caused by the natural environment for at least 90% of the time. The natural limits are those imposed by the residual amplitude and phase fluctuations after all available corrections have been applied (e.g. troposphere, ionosphere).	STK1402, STK1403, SCI0100, SYS1501

CAL0119 is traced to SCI0110 which calls for 1% photometric error. According to the definition in AD01, this is not the fractional error in absolute flux densities, but rather the fractional error in the observed flux densities prior to scaling by a flux density standard. SCI0110 therefore effectively implies that if we measure the flux density for a target source with infinite signal to noise in several independent observations, the absolute amplitude calibration scale maintained internally by the telescope over the time period encompassing all the observations should be sufficiently stable to deliver flux densities within 1% of each other. However, while theoretically possible, it is unrealistic to demand of the ngVLA a stable internal amplitude scale over indefinite time periods. Therefore, periodic referencing of a celestial flux density standard will be inevitably required. As a result, the accuracy in the measured flux densities will be affected by not only the amplitude stability of the instrument, but also the accuracy at which the celestial calibrator's absolute flux density is known (unlikely to be better than 1%, e.g. RD24) as well as any variability that the calibrator might exhibit. To avoid complicating the requirements while satisfying the objective of SCI0110, CAL0119 is defined more conservatively in terms of absolute flux density.

CAL0120 refers to continuum polarimetry. Largely unavoidable degradation in spectral residual polarization leakage is expected due to the band edge response of polarizers.

5.7 Dynamic Range

Parameter	Req. #	Value	Traceability
Brightness Dynamic Range	CAL0123	The brightness dynamic range in total intensity shall be better than 50 dB to support deep field studies at 10 GHz.	SCI0113
Polarization Dynamic Range	CAL0124	The brightness dynamic range in linear and circular polarizations shall be better than 40 dB to support deep field studies at the center of the field of view at 10 GHz.	SCI0114
Spectral Dynamic Range	CAL0125	The spectral dynamic range in total intensity shall be better than 50 dB to enable imaging of faint prebiotic molecules in the presence of bright emission lines within the field of view, with particular focus in the frequency range 16–50 GHz.	SCI0115

Brightness dynamic range in total intensity refers to the ratio between peak brightness in the field relative to the rms noise in a source-free region. Polarization dynamic range refers to the ratio for a given source between Stokes I and artifacts in linear polarization (Stokes $L = \sqrt{Q^2 + U^2}$) or circular polarization (Stokes V). Spectral dynamic range refers to the ratio between the brightest source in one channel relative to the rms in a line-free channel.

6 L2 CALIBRATION REQUIREMENTS

This section presents sub-system level requirements. These are implementation-specific in that they are calculated using numeric values for fundamental parameters such as antenna diameter, number of antennas, and maximum baseline length. General assumptions are presented in Section 6.1. Other assumed values are stated in each case. The L2 requirements, and possibly the associated calibration strategies, will therefore need to be reassessed if the parameter values change significantly in the future.

6.1 Assumptions

Parameter	Value	References
Antenna	All antennas shall be alt-az mounted without third axis rotation (i.e. without dish rotators).	AD04
Feed Basis	All antennas shall be equipped with dual orthogonal linear feeds in all frequency bands.	AD04
Receiver Bands	Front end 6 band design spanning the following frequency ranges: 1.2 – 3.5 GHz (band 1), 3.5 – 12.3 GHz (band 2), 12.3 – 20.5 GHz (band 3), 20.5 – 34.0 GHz (band 4), 30.5 – 50.5 GHz (band 5), 70.0 – 116.0 GHz (band 6).	AD10
Sensitivity	A canonical array of 123×18 m antennas shall be used for deriving L2 requirements below.	SCI0100, SCI0102, SCI0103, SCI0108, SCI0118, CAL0116
Self-Calibration	Requirements shall be derived without allowing for potential benefits from self-calibration, as easy application may not be possible in every standard observing scenario.	—

The Reference Design [AD04] calls for alt-az antennas and linearly polarized feeds. The latter is to facilitate larger bandwidth ratios than circular feeds, though this is only strictly relevant for the lower frequency bands. Linear feeds are not necessarily required at the higher bands, though the choice removes the additional complication of requiring conversion between linear to circular polarization, which in turn reduces cost and improves performance (circular polarizers will slightly degrade sensitivity). This document will assume the use of alt-az antennas and linearly polarized feeds. However, given the significance of polarization feed basis to the overall facility design, Section 6.6 provides an independent and unbiased justification of the choice to use linear feeds from a calibration perspective, and also investigates the optimal orientation of the linear feeds.

Several L2 requirements in the following sections are driven by the number of antennas in the array. The most demanding ngVLA science cases are expected to use most if not all antennas to achieve objectives of resolution and/or sensitivity. Imaging performance simulations [RD02] indicate that the bulk sensitivity resulting from tapering to achieve a nominated angular resolution scale will be provided by approximately half of the collecting area. The full (reference) array contains 244×18 m antennas and 19×6 m antennas [AD04], equivalent to 246×18 m antennas (0.06 km^2 collecting area). Therefore, the L2 requirements below will assume a canonical array with 123×18 m antennas.

The L2 requirements presented below have been developed without including potential benefits from self-calibration (direction independent or dependent). This is because it cannot be assumed that self-calibration can be used in all cases for ngVLA observations. For example, direction-independent gain self-calibration may be difficult for extended targets especially if they are not fully spatially sampled. Similarly, direction-dependent pointing self-calibration may be difficult for fields in which there is negligible off-axis emission.

6.2 Antenna Characteristics

Antenna requirements are presented below for Pointing, Surface Setting and Primary Beam, Feed Positioning, and Motion. See AD06 for definitions of Precision and Normal operating conditions.

6.2.1 Pointing

Parameter	Req. #	Value	Traceability
Antenna Pointing	CAL0201	Precision: $18''$ blind, $3''$ offset; Normal: $42''$ blind; $7''$ offset. These are 2D errors. The offset values must be satisfied over a 3° angle.	CAL0123

Parameter	Req. #	Value	Traceability
Spectral Line Noise Leakage (Arising From Pointing)	CAL0202	Implement software and heuristics for estimating worst-case noise level leaked from strong spectral lines at different spatial locations due to limited pointing accuracy.	CAL0201, CAL0125

Antenna pointing will be affected by several slowly varying systematic terms such as imperfections of the antenna and the pad, gravitational forces, wind loading arising from the mean wind velocity, and thermal loading from the sun. Depending on the needs of the astronomical observation, these slowly varying effects can be removed by frequent offset pointing observations. In addition, there will also be random pointing errors arising from more rapidly varying effects such as wind gusts (about the mean wind velocity) and anomalous refraction. Random errors will also be present at some level due to the limited mechanical repeatability of antenna pointing, arising for example from solar orientation and thermal gradients.

Errors in antenna pointing will lead to amplitude and spectral index errors. Accurate pointing is important for high dynamic range observations and for mosaiced observations, particularly at the higher frequencies where the beam size is smaller. It is anticipated that a significant fraction of ngVLA observations will be mosaiced, perhaps 60% overall and involving all frequency bands [AD07].

When required, pointing calibration must be performed prior to astronomical observations or else the data will be corrupted. In general, pointing solutions cannot be interpolated backwards in time (this can be mitigated in some cases by performing pointing self-calibration [RD11], which requires emission to be present at locations throughout the primary beam). This makes pointing calibration critical for observations that require offset pointing. When needed, pointing solutions must be updated on a timescale that is short enough to over-sample all slowly-varying dynamic effects.

Requirement CAL0123 calls for 50 dB imaging dynamic range[1] at 10 GHz. This can be translated to a pointing requirement by first considering the (idealized) relationship between the dynamic range limit for a Stokes image (e.g. Stokes I) from a snapshot observation, D, and antenna-based amplitude errors (correlated for both polarizations on a given antenna), ϵ, for an array comprising N antennas, given by RD03 as

$$D \approx \frac{\sqrt{N}}{\epsilon} \,. \tag{1}$$

Next, by approximating the true profile of an antenna's primary beam (e.g. Airy disk or cosine-squared) with a Gaussian, the relationship between pointing error β and the resulting amplitude error can be

[1] Note that the anticipated continuum sensivity of the ngVLA using $N = 123$ antennas will be sufficient to deliver 50 dB dynamic range in 1 hour on unresolved sources as faint as 130 mJy in band 6 and 35 mJy in band 3 [AD04].

estimated using

$$\epsilon \approx 1 - \exp\left(-4\beta^2 \ln 2\right) \ , \tag{2}$$

where $\beta = \Delta\theta/\mathrm{HPBW}$ is the fractional error in units of primary beam HPBW arising from pointing offset $\Delta\theta$. These relationships indicate that to achieve 50 dB dynamic range with $N = 123$, the induced amplitude errors must be less than 0.011% and pointing errors must satisfy $\beta < 1/160$. This translates to $\Delta\theta = 3''$ with 18 m dishes at 8 GHz (center of 8 GHz bandwidth between 4 GHz to 12 GHz, encompassing the target 10 GHz from CAL0123) and sets the ngVLA requirement for pointing accuracy under the most favourable observing conditions.

Prior to examining the requirements for pointing under less optimal conditions, the effects of observing with pointing accuracy $\Delta\theta = 3''$ are explored below with focus on mosaics and frequency dependence.

For pointing error $\beta = 1/160$, the amplitude errors per polarization per antenna resulting from a point source located at the nominal primary beam -0.1 dB, -2 dB, and -12 dB contours (radial offsets HPBW/10, $\mathrm{HPBW}/\sqrt{6}$, and HPBW) will range between approximately 0.3%, to 0.6%, and 0.01%, respectively. These errors will be important when imaging extended sources, reconstructing spectral indices, and attempting high dynamic range imaging of single-pointing fields if there are strong sources located off-axis. They will also be important for mosaiced observations.

For a hexagonal mosaic with pointing separation $\mathrm{HPBW}/\sqrt{2}$ (typical widest separation sufficient to obtain approximately uniform mosaic sensitivity), and assuming that each contributing primary beam is only imaged out to the HPBW (imaging further provides negligible sensitivity gain), the worst-case amplitude error in the mosaic will be located equidistant from 3 contributing pointings at their overlapping -2 dB primary beam contours. For $\beta = 1/160$ with $N = 123$, the dynamic range limit in a single pointing that contains a point source located at the -2 dB contour is 33 dB. Thus, the dynamic range range limit in a mosaic with $\mathrm{HPBW}/\sqrt{2}$ beam throw could be as low as 35 dB, despite the 50 dB dynamic range limit expected at the center of each individual pointing. (Note that this calculation assumes that pointing errors from contributing pointings are statistically independent. This is likely to be approximately true because a common source would sample different locations in each antenna's primary beam in each pointing.)

For reference, Table 1 presents dynamic range limitations for imaging scenarios in which a single point source is located at the center of a single pointing, D_1, at the -2 dB primary beam contour in a single pointing, D_2, and at the overlapping -2 dB contours in a hexagonal mosaic (described above), D_3, for frequencies f specified at band edges in the 6 band reference design. The estimates assume an array with 123 antennas, precision offset pointing accuracy $\Delta\theta = 3''$, no other errors, and no self-calibration. Note that the D_2 and D_3 values represent approximately worst-case dynamic range limits for single pointing and mosaiced images, in which the brightest source in the visibility data is located near a pointing's -2 dB primary beam contour.

f (GHz)	D_1 (dB)	D_2 (dB)	D_3 (dB)
1.2	66	41	43
3.5	56	36	39
12.3	45	31	33
20.5	41	28	31
34	37	26	29
50.5	33	25	27
70	30	23	25
116	26	21	23

Table 1: Dynamic range limitations arising from $3''$ precision offset pointing errors.

These limits may be improved in certain cases, for example by performing on-the-fly observations to scan over the vicinity of a strong source while sampling as many different primary beam locations as possible (i.e. attempting to 'average out' the pointing error for each antenna), or by employing pointing self-calibration if there is sufficient signal-to-noise within the primary beam to obtain pointing solutions on sufficiently short timescales to sample the true pointing variability. Heuristics will need to be developed to identify appropriate observing and pointing conditions for every proposed observation, including the option to employ pointing self-calibration in post-processing when it is likely to be beneficial.

Importantly, it should also be noted that for continuous observations that effectively comprise M statistically-independent snapshots (where M depends on the dynamical timescale of antenna pointing variations as well as the timescale for rotation of each baseline), Equation 1 will be improved by factor $\sqrt{M}$ [RD03]. This will lead to improvement beyond the values derived above, perhaps by an order of magnitude or more in dynamic range over the course of a few hour observation. This improvement should therefore enable 50 dB image dynamic range across a full mosaic at 10 GHz. For example, if dynamic wind loading produces statistically independent pointing errors on timescales no slower than 20 sec over the course of a 15 hour observation (see Section 6.3.2.1 for motivation behind 15 hours), then $M = 2700$ and the off-axis dynamic range limits for D_2 and D_3 will rise to 50 dB. The benefit from $\sqrt{M}$ is neglected in the calculations presented earlier in order to derive robust worst-case pointing requirements that will support high dynamic range from short observations.

Antenna pointing errors can be separated into systematic errors (i.e. statistical accuracy, requiring offset pointing corrections to account for slowly-varying systematic effects) and statistical errors (i.e. statistical precision). There are 4 states for which pointing requirements are needed, spanning the matrix of normal and precision operating conditions, and blind and offset pointing modes. The precision offset pointing requirement is defined by requiring that CAL0123 will be satisfied under precision operating conditions; as described earlier, this requires $\Delta\theta = 3''$ to satisfy $\beta = 1/160$ with 18 m dishes at 10 GHz. The normal offset pointing requirement is driven by the desire to support a reduced dynamic range of 40 dB at 10 GHz without requiring precision conditions; this requires $\beta = 1/50$ which translates to $\Delta\theta = 7''$. To obtain good offset pointing solutions, historical analogues (including the VLA) suggest that systematic pointing errors cannot be larger than approximately 6 times the statistical pointing errors. Note that this is only applicable at frequencies where the statistical and systematic pointing errors are not substantial fractions of the primary beam width. For example, consider performing offset pointing in band 4, where the HPBW is $100''$ for an 18 m dish at the upper frequency bound at 34 GHz. The normal offset pointing requirement of $7''$ is then approaching HPBW/10. This should be sufficient to obtain good pointing solutions. This also suggests that it will not be appropriate to calculate offset pointing corrections using band 5 in normal observing conditions. However, assuming factor 6, if the systematic pointing error is $42''$, this is a substantial fraction of the $50''$ half-power half-width, suggesting that band 3 is likely preferred for calculating offset pointing corrections. Assuming factor 6, to support offset pointing at 10 GHz, the blind pointing requirements are $\Delta\theta = 18''$ in precision conditions and $\Delta\theta = 42''$ in normal conditions. These requirements have implications for array scheduling. For comparison with Table 1, Table 2 presents 'worst-case' dynamic range limits arising from normal blind pointing with accuracy $\Delta\theta = 42''$.

f (GHz)	D_1 (dB)	D_2 (dB)	D_3 (dB)
1.2	43	29	32
3.5	33	25	27
12.3	23	19	22
20.5	18	17	20
34	15	15	17
50.5	12	12	15
70	11	11	13
116	10	10	13

Table 2: Dynamic range limitations arising from $42''$ normal blind pointing errors.

The offset requirements must be satisfied over a $3°$ slew. This is necessary to support gain calibration for which the antennas must repeatedly slew between a science target and adjacent calibrator. A maximum angle of $3°$ will facilitate gain calibration up to and including band 6 (see Section 6.2.4). No requirement for minimum timescale is placed on the offset pointing requirements because this is an operational matter that depends on the quality of the observing conditions; degraded observing conditions will require more frequent pointing calibration observations to track systematic antenna pointing changes.

Finally, requirement CAL0125 calls for 50 dB spectral dynamic range (emissive) at up to 50 GHz. For observations in which only a single spatial position exhibits a strong spectral line, 50 dB spectral dynamic range can be facilitated without requiring the imaging dynamic range limit to be anywhere near 50 dB. However, it is possible that multiple spatial locations in a cube could exhibit a 50 dB spectral line with respect to the nominal channel noise level, where the spectral lines may peak in different channels. At 50 GHz, under the most favourable precision offset observing conditions with $\Delta\theta = 3''$, the per-channel image dynamic range limits will be 33 dB if sources are confined to the center of a single pointing, 25 dB if sources are located at the -2 dB primary beam contour in a single pointing, and 27 dB if sources are located at the overlapping -2 dB contour in a hexagonal mosaic (following details presented above). Taking an example in which two spectral lines are detected at the 0 dB (on-axis) and -2 dB contours in a single pointing, with each detected at a different frequency, then the spectral dynamic range in the on-axis spectrum will be limited to 25 dB (rather than 33 dB) when taking the ratio between the line peak and the noise level in the channel corresponding to the line peak of the off-axis source. The dynamic range will still remain 50 dB when taking the ratio between the line peak and other channels. Thus a form of noise leakage will occur in which bright spectral features in one spatial source will affect the spectra of other spatial sources. Heuristics will need to be developed to identify these situations and to estimate the impact on spectra throughout a single pointing or mosaiced cube. Note that the benefit from $\sqrt{M}$ described earlier will certainly minimize this effect. However, some contamination may still occur, and it is highly likely that an investigator interested in detecting faint spectral lines at 50 dB would also be interested in knowing where in the cube potential spurious detections might be located, even if the amplitude of these effects may be uncertain within some factor.

6.2.2 Primary Beam and Surface Setting

Parameter	Req. #	Value	Traceability
Primary Beam Model Accuracy	CAL0203	Determine the power pattern for each polarization on each antenna to a measureable and repeatable accuracy of better than 0.1% of the boresight response and within phase error $0.03°$, at all points within the -10 dB power contour (-5 dB voltage contour), under precision conditions. This means that at the -10 dB power point the accuracy of a power measurement is 1%. These power patterns must be measured at different parallactic angles, elevation angles, and sampled with sufficient frequency resolution to enable a global model to be developed per antenna. This is a requirement for band 2 and a goal for all other bands. Best achievable accuracy beyond -10 dB is desired.	CAL0120, CAL0123, CAL0124

Parameter	Req. #	Value	Traceability
Antenna Surface Setting	CAL0204	Precision: $170\,\mu$m, Normal: $400\,\mu$m (primary and secondary surfaces combined); Error scatter pattern: Equation 4 on-axis (satisfying this requirement may require smaller surface errors than $170\,\mu$m and $400\,\mu$m)	CAL0123

Errors in the assumed model of the primary beam will lead to spectral index errors and dynamic range limitations in single pointing and mosaiced observations. Surface errors will scatter power from the main beam into the sidelobes, reducing the surface efficiency and limiting dynamic range. Surface errors can be thought of as leading to statistical errors about the systematic assumed primary beam model.

Visibility errors will arise from errors in the assumed primary beam model (see terms in the numerator sum in Equation 7 from RD12). To satisfy 50 dB image dynamic range at 10 GHz (CAL0123; this will also satisfy CAL0124), the antenna power (proportional to voltage squared) pattern for each polarization needs to be known to better than 0.1%. This requirement needs to apply out to the point in the beam where the power response is 10% of the peak, so as to support high dynamic range imaging for single pointing observations and mosaiced observations. This requirement is calculated by considering Equation 1 with $N = 123$ and with the additional improvement factor $\sqrt{M}$ [RD03]. Conservatively, it is unlikely that sources will be viewed through less than $M \sim 100$ statistically-independent primary beam alignments throughout an observation lasting a few hours (as relevant to deep field studies that drive the 50 dB requirement), regardless of whether the ngVLA dish surfaces will be constructed from multiple panels or a single mold. Antenna elevation and wind loading will contribute to M here, as will baseline rotation. The resulting requirement for power pattern accuracy is then 0.1% of the boresight power response. The corresponding requirement on phase errors is half this [RD03], namely 0.03°. These calculations assume that primary beam model errors are statistically independent per polarization and antenna, which should be approximately true. The power patterns must be measured at different parallactic angles, elevation angles, and sampled with sufficient frequency resolution to enable a global model to be developed per antenna. Future work is required to assess requirements for primary beam accuracy in far-out sidelobes. Future work is also required to assess implications for primary beam accuracy arising from scenarios that require offset pointing (i.e. differential heating over an antenna).

Accuracy in the primary beam model is also called for by CAL0120, which requires 0.01% on-axis post-calibration residual linear polarization leakage and a goal of 0.1% off-axis. The on-axis residual is given by $\sigma_d/\sqrt{N}$ in the linear feed basis [RD15], where σ_d is the accuracy (systematic residual after averaging all channels in a band for one polarization) with which antenna leakage moduli are known (see Section 6.6.3), while the off-axis residual will arise from the approximately quadrature sum of the antenna leakage accuracy and the primary beam model accuracy. Assuming $N = 123$, $\sigma_d = 0.1\%$ (yielding on-axis residual leakage 0.01%), and taking the primary beam model accuracy 0.1% from above, the spurious off-axis linear polarization residual is expected to be $\sim 0.1\%$. This result is dominated by the off-axis residual. Note that the interplay between primary beams and feeds (the latter dominating the on-axis leakage component) will need to be carefully considered to account for possible feed changes. For example, a maintenance visit may result in a swapped integrated receiver and digitizer (IRD) package (see also Section 6.6.3).

Surface errors must be minimized in order to maximize the forward gain of an antenna and limit amplitude errors arising from the antenna scatter response. The surface efficiency is given by Ruze [RD04] as

$$\eta_{\rm sf} = \exp\left[-\left(\frac{4\pi\sigma}{\lambda}\right)^2\right] , \tag{3}$$

where σ is the rms surface error for the primary and secondary reflectors combined, and where σ will produce a path length error of 2σ in the aperture plane. A surface error of 170 μm is required to deliver no worse than -3 dB loss at 116 GHz (i.e. $\sigma = \lambda/15.1$). The equivalent surface error at 50 GHz is 400 μm. Losses within -3 dB are preferred to avoid primary beam aberrations that may force the need for correction schemes like A-projection [RD12] at modest or even low dynamic range limits.

More restrictive values of σ may be required to offset the presence of correlated surface errors. For reflector diameter D with errors correlated over distances D/R (e.g. due to panel setting errors, or setting errors in the backing structure fixture points that support a single-piece mold surface), a scatter pattern will be produced that is R times broader than the diffraction-limited main lobe [RD04, RD05]. Antenna surfaces with larger number of R segments will exhibit larger and less symmetric near-in sidelobes which must be compensated using a more restrictive surface error requirement.

To satisfy CAL0123 following a similar argument as for primary beam model accuracy above, the error scatter response $E(\theta)$ on-axis[2] (where $\theta = 0$) must satisfy

$$E(\theta = 0) < 10 \log_{10}\left(\sqrt{100\, N_{\rm ant,indep}}\right) - 50 \ \ {\rm dB} \ , \tag{4}$$

where the contribution of -50 dB is given by the dynamic range requirement, $N_{\rm ant,indep}$ is the number of antennas with statistically independent surface errors, and where $M = 100$ has been assumed and incorporated into the equation. In the most extreme case $N_{\rm ant,indep} = 1$ and $E(\theta = 0) < -40$ dB, for example if all antennas are cast from the same full-surface mold, attached to infinitely rigid backup structures, transported to each station without deformation, and mounted identically. In the opposite extreme, if $N_{\rm ant,indep} = 123$, then the requirement is $E(\theta = 0) < -30$ dB. A requirement for error scatter response therefore depends on the choice of antenna design. If Equation 4 is satisfied, then the error scatter response will not dominate pointing or primary beam model errors.

[2]For simplicity, Equation 4 assumes that the off-axis scatter response is approximately the same as the on-axis response. In reality the off-axis response will be lower, but this difference is unlikely to be significant until beyond the HPBW.

6.2.3 Feed Positioning

Parameter	Req. #	Value	Traceability
Feed Setting	CAL0205	Positioner errors shall distort the primary beam power pattern by no more than 0.05% of the boresight response and $< 0.01°$ phase within the -10 dB power response.	CAL0203, CAL0121
Band Switching	CAL0206	It shall be possible to regularly (every few minutes) switch between frequency bands (particularly bands 1 and 2) within a few seconds including settling time.	CAL0303

The ngVLA antenna reference design for both the 6 m and 18 m dishes incorporates a fixed subreflector and a motorized adjustable feed positioner (X-Y plane). Accurate setting of the feed positioner is required to prevent loss in efficiency and primary beam abnormalities.

Errors in feed positioning will lead to systematic distortions in primary beam power and phase patterns. To ensure that these distortions remain within the error budget calculated for CAL0203, variations in the power and phase patterns arising from positioner errors must be kept to within 0.05% of the boresight power response and $0.01°$ for each polarization on each antenna. If total errors are approximated by adding the systematic and statistical errors in quadrature, this requirement will ensure that feed positioner errors contribute no more than $\sim 15\%$ to the error budget.

Note that feed positioning errors are also relevant for in-beam calibration. CAL0121 requires relative astrometric accuracy $< 1\%$ of the synthesized beam FWHM for a bright ($\mathrm{SNR} > 100$) point source (this requirement is discussed further in Section 6.3.1). Phase differences between two points within the -10 dB primary beam must therefore be kept within $0.01 \times 360° = 3.6°$. Assuming worst-case feed positioning errors that lead to correlated primary beam errors between polarizations, there are N statistically independent primary beams over the array. Thus for $N = 123$, the requirement is that any phase gradient per antenna polarization arising from a feed positioning error must be less than $40°$. This is satisfied by the much stricter requirement above.

RD13 presents equations to convert between positioner error and efficiency loss. To satisfy CAL0205, a similar model will need to be developed to convert between feed setting errors in physical units and the primary beam distortions examined above.

The motivation behind CAL0206 is presented in Section 6.3.2.2.

6.2.4 Motion

Parameter	Req. #	Value	Traceability
Antenna Motion	CAL0207	Slew 3° in 7 sec in precision conditions, including time to settle within offset pointing error.	CAL0112

In order to calibrate fluctuations in atmospheric delay (described in more detail in Section 6.3.2), the antennas must be capable of repeatedly switching between a science target and nearby calibrator, transferring the atmospheric delay on the calibrator to the science target within a cycle time that is short compared to the atmospheric stability timescale. This demands fast slew and settle rates to maximize observing efficiency (time on science target). Antennas with fast slew rates are also needed to minimize time spent slewing between widely separated sources, minimize time spent performing offset pointing calibration (slew to calibrator, raster scan, return), and to enable rapid cancellation of atmospheric fluctuations when observing in total power mode (slew across extended source).

While there are technical solutions for maximizing time between calibrator scans (such as water vapor radiometry), which will in turn minimize required slew rates without sacrificing observing efficiency, the fast switching approach must remain feasible and part of ngVLA design in order to minimize overall project risk. Assessment of the fast switching approach therefore drives this anntena motion requirement, regardless of the technique that will be ultimately implemented for calibrating fluctuations in atmospheric delay.

The most demanding requirement for antenna motion arises from considering slew rates for gain calibration at the highest frequencies, where radio source counts are lower and angles to suitable nearby calibrators are larger. In an early design study, RD06 concluded that a 1 minute cycle time between science target and calibrator should be sufficient to correct for atmospheric delay in band 6 at night throughout most of the year. RD06 also found that a suitable calibrator with minimum required 3 sec integration time should be available within 2° of any position in the sky. This observing strategy is incompatible with CAL0112, which states a goal for observing efficiency greater than 90% in standard observing modes. However, for the sake of deriving a risk-mitigating antenna motion requirement, it is justified to consider fast switching that delivers lower observing efficiency. Assuming a 1 minute switching timescale and 6 sec integration time on the calibrator (double 3 sec because RD06 assumes $N = 200$ antennas rather than $N = 123$), 70% efficiency can be obtained by requiring that antennas are capable of slewing 3° and settling at the new desired pointing location within 7 sec. This requirement must be satisfied under precision conditions, suitable for observing in the highest frequency band. While 70% efficiency does not satisfy the goal from CAL0112, it does satisfy the firm requirement from CAL0114.

6.3 Delay

The ngVLA is envisaged to operate as a quasi-connected-element[3] interferometer, including over continental scale baselines, with correlation taking place in near real-time. Delays must therefore be calculated and applied at the time of observing. Their calculation must account for several contributions, including source position, earth orientation, atmosphere (neutral and ionized), station locations, antenna structure, and electronics. Each of these contributions must be correctly calculated or measured.

There is an additional fluctuating portion of delay due to the atmosphere, antenna, and electronics. Delay fluctuations limit resolution, limit the dynamic range of images, introduce artifacts, and reduce sensitivity by decorrelation. Without effective calibration of these fluctuations, the maximum usable baseline (exhibiting say $> 90\%$ coherence) at 116 GHz would be only 380 m [RD07 Equation 13.118].

In this document, the term "delay" τ will be used to implicitly indicate requirements for both delay and phase. A delay (or change in delay) will produce a (change in) signal phase ϕ that is proportional to frequency ν, namely $\phi = 2\pi\nu\tau$, arising for example from the presence (or change in length) of a cable. Alternatively, all frequencies in a bandpass range can be shifted by the same phase if the local oscillator experiences a phase shift.

Delay can be specified in units of path length and time. These are connected by the speed of light $c \approx 300\,\mathrm{nm/fs}$ and can be used interchangeably. The corresponding fractional phase change is given by $\phi/(2\pi) = \tau_{\mathrm{path}}/\lambda = \tau_{\mathrm{time}}\nu$. At 116 GHz, a phase change of 1 deg corresponds to a delay of 24 fs.

The requirements presented below refer to antenna-based delays. This document will assume uncorrelated variations in antenna-based delays, in which case the resulting baseline-based delays will be $\sqrt{2}$ larger. If this condition will not be met in practice, then the calculations below will need to be re-evaluated.

Furthermore, the requirements presented below are separated into delay drift (accuracy) and delay noise (precision), reflecting the systematic and stochastic components of delay, respectively. The drift component includes fluctuations that do not integrate down with time in the way that white noise would. The timescale for differentiating between these components is defined where appropriate in the sections below. The delay requirements below imply measurement and application with residuals within the specified values. The drift component may refer to residuals after a trend has been removed (e.g. subtract linear trend between scans on an astronomical calibrator), or in some cases (e.g. electronics) refer to deviations from common-mode drift. None of the drift requirements below refer to absolute drift.

[3] It is anticipated that multiple masers will be required over the array, with a single maser supplying antennas within the central ~ 300 km and others supplying more distant antennas [AD04].

6.3.1 Source Location

Parameter	Req. #	Value	Traceability
Geometric Delay	CAL0301	0.8 ps drift, 40 fs noise	CAL0121
Coordinate Equinox	CAL0302	J2000.0 but with flexibility to change in future	–

CAL0121 requires relative astrometric accuracy $< 1\%$ of the synthesized beam FWHM for a bright $(\mathrm{SNR} > 100)$ point source. The astrometric accuracy of an observation results from a combination of statistical errors (uncertainty in calibrator positions, centroid measurement) and systematic errors (reference frame positioning). Uncertainty in calibrator position will not be considered here; note that both first and second order effects can be important [RD07 Sec. A12.2, RD08 Sec. 5.4]. The centroid error within a reference frame is given by $\mathrm{FWHM}/(2\,\mathrm{SNR})$, which is $< 0.5\%$ of the beam for $\mathrm{SNR} > 100$. To ensure that the combination of all position errors remains below the 1% requirement, the reference frame must be accurately positioned, in turn requiring accurate calculation of the geometric delay τ_g (among other delays).

For absolute astrometry, the precision of the applied geometric delays (i.e. delay model accountability, or knowledge of the precise delays that were applied as a function of time) is of greater importance than their accuracy because the latter can be corrected (within reason, as examined below) in post-processing as part of the delay model fitting procedure. For maximum baselines $B = 9000$ km at 116 GHz, the synthesized beam FWHM is 60 μas. To point the delay tracking center to within 0.5% of a beam ($\Delta\theta = 0.3\ \mu$as), it is required that the applied geometric delay is known to within $\Delta\tau_g < B\Delta\theta/c = 40$ fs. This requirement will ensure that geometric delays do not limit the absolute astrometry down to 1% of the FWHM.

The relative astrometric accuracy can be estimated by considering gain calibration, where the delay toward a target source will be corrected using the delay toward an adjacent calibrator located at separation angle θ_{sep}. The relative astrometric uncertainty will be dictated by any delays that differ at the two locations, in this case focusing on inaccurate geometric delay tracking. The relative positional uncertainty is calculated using the equation for absolute positional uncertainty, but improved by the factor θ_{sep} [RD07 Sec. 12.2.3, RD08 Sec. 4.1]. Thus, assuming a worst-case 3° separation, the required accuracy for geometric delay is given by $\Delta\tau_g < B\Delta\theta/(c\,\theta_{\mathrm{sep}}) = 0.8$ ps. This is the accuracy needed for correlation.

Both the 0.8 ps accuracy and 40 fs precision requirements are needed in order to satisfy the most flexible reading of CAL0121; absolute astrometry is effectively relative to a global reference frame.

The ngVLA should plan to use J2000.0 coordinates, including full corrections for time and motion of the Earth and solar gravitational deflection [RD07 Sec. 12]. However, it is possible that an IAU adopted frame replacing J2000.0 may become available during the lifetime of the ngVLA (perhaps even as a result of ngVLA measurements). For example, the clear detection of galactic acceleration (secular aberration[4]) in the existing J2000.0 frame (> 150 μas over 30 years) has motivated the proposal for an epoch ICRF [RD10]. Thus, flexibility should be provisioned; nowhere in the project should J2000.0 be assumed.

For radio sources located within approximately 30 light years, the near-field effect of the curvature of the wave front will need to be accommodated in the delay model (e.g. see Section III.A.2 from RD17).

6.3.2 Atmosphere

Parameter	Req. #	Value	Traceability
Atmospheric Delay	CAL0303	*Neutral:* 7 fs drift over 5 min, 190 fs noise in 1 s; *Ionized:* $0.2/\nu^2$ ps drift over 5 min, $6/\nu^2$ ps noise in 1 s, where ν is in units of GHz	CAL0112, CAL0123
Tropospheric Delay Measurement	CAL0304	Radiometers are required (e.g. 22 GHz WVR). These must be capable of full radiometric correction (i.e. including path between calibrator and target) and must be situated on every antenna.	CAL0303
Amplitude and Phase Coherence Over Multiple Observations	CAL0305	The observatory scheduling process and data reduction pipeline shall be capable of executing an observing strategy and processing the resulting data in which the flux density scales and positional (phase) reference frames are aligned over multi-epoch observations.	CAL0123

[4] Peculiar acceleration arising from the motion of the Sun with respect to the local standard of rest is expected to be an order of magnitude smaller than galactocentric acceleration [RD09].

Parameter	Req. #	Value	Traceability
Ionospheric Delay Measurement	CAL0306	The pipeline shall be capable of measuring and correcting for ionospheric delay fluctuations using frequency-switched (where required) band 1 observations of a phase calibrator located on-axis. Goal is to achieve this over an arbitrary field in which the brightest source may not be located on-axis. The scheduler shall ensure sufficient time on calibrator to achieve the necessary solution accuracy from CAL0303.	CAL0303
Ionospheric Disturbance Monitoring	CAL0307	The scheduler shall ingest and utilize a real-time spatio-temporal map of ionospheric disturbances on ~ 5 min timescales over the array.	CAL0303, CAL0109
Proposal Content: Estimated Dynamic Range	CAL0308	Proposals for ngVLA observing time must specify the required image dynamic range, which shall then be used by the scheduler to make informed decisions about optimal project selection including early termination if weather conditions deteriorate.	CAL0303, CAL0111
Scheduler Start/Stop/Restart	CAL0309	The scheduler shall be designed to make informed decisions about early termination of scheduling blocks if weather conditions deteriorate, and to account for previously stopped observations in the ranking process.	CAL0308, CAL0111
Interplanetary Medium Monitoring	CAL0310	The scheduler shall ingest and utilize real-time estimates of conditions in the interplanetary medium to avoid observing certain projects too close to the Sun.	CAL0303, CAL0109

Radio waves from an astronomical source must pass through intergalactic, interstellar, interplanetary, and terrestrial atmospheric media. The neutral and ionized components of these media will each produce a delay relative to propagation in vacuum. However, it is only in the immediate vicinity of the Earth that ray paths propagating toward Earth-based antennas will exhibit an appreciable difference in their delays. These differential delays will perturb the wavefront, causing decorrelation and leading to a degradation in dynamic range. Differential delays must be compensated to minimize these effects.

The image dynamic range limit for uncorrelated antenna-based phase errors ϕ is given by [RD03]

$$D \approx \frac{\sqrt{MN}}{2\phi} \, , \tag{5}$$

where the factor M represents the number of statistically independent successive snapshots in an observation. In the present context, M is related to the atmospheric coherence time over which phase fluctuations remain below a nominated threshold. Requirement CAL0123 calls for 50 dB imaging dynamic range at 10 GHz.

Phase fluctuations in the neutral atmosphere are predominantly caused by temporal variations in tropospheric water vapor (dry atmospheric gases also contribute, as do ice particles when present). Phase fluctuations in the ionized atmosphere are mostly caused by variations in total electron content in the ionosphere. These neutral and ionized contributions to atmospheric delay are examined in turn below.

6.3.2.1 Troposphere

Radio waves propagating through the Earth's neutral atmosphere are most affected by the troposphere, located below altitudes of approximately 10 km, and in particular by water vapor that is poorly mixed in the troposphere. Tropospheric phase fluctuations can be treated as turbulent eddies that remain fixed as the atmospheric layer advects over the ground at a characteristic velocity aloft.

RD14 examines statistics of tropospheric phase fluctuations at the VLA during best-case observing conditions in winter and worst-case conditions in summer. RD14 infer from these data, together with worldwide water vapor statistics, a general equation that conservatively predicts the growth of rms phase fluctuations on a baseline over time that is independent of baseline length, time of day, time of year, and geographic location (including altitude). This equation is relevant to ngVLA where the size and geographic distribution of the array implies that subsets of antennas will concurrently experience different atmospheric conditions. Using the rms phase growth relationship, RD14 assesses several phase calibration strategies for their capacity to support a 50 dB image dynamic range requirement. The phase calibration strategies examined were fast switching (rapid transfer of phase solutions from nearby calibrator to target), paired array calibration (where a subset of antennas view a nearby calibrator while the others view the target), self-calibration (using a bright unresolved source in the field of view), simultaneous multi-frequency observations (effectively self-calibration but utilizing an in-beam source that is brighter in a lower frequency band), and radiometric phase correction (e.g. using the 22 GHz water line, see RD07 Sec 13.3.2). RD14 find that at 10 GHz, tropospheric phase fluctuations must be tracked with approximately 1 sec cadence in order to attain 50 dB image dynamic range from a 15 hour observation (i.e. $M = 54000$). The corresponding antenna-based phase error in Equation 5 is $\phi < 0.7°$. An observation length of 15 hours is selected for two reasons. First, this is the approximate timescale over which the anticipated continuum sensitivity of the ngVLA at 10 GHz [AD04] with $N = 123$ is expected to yield 50 dB image dynamic range for an unresolved source with flux density 10 mJy. And second, as derived in RD14, 10 mJy is the approximate flux density threshold at which the noise within a 1 second self-calibration solution will induce phase errors in Equation 5 that exceed the threshold necessary to achieve 50 dB dynamic range (i.e. self-calibration will not be suitable with unresolved sources fainter than 10 mJy). RD14 conclude that the only calibration strategy capable of sampling phase fluctuations on a 1 sec timescale and in turn supporting a 50 dB image dynamic range requirement is water vapor radiometry (WVR). To achieve similar performance using fast switching on the most optimistic 10 sec calibration timescale, an order magnitude longer observation would be required. This would in turn lead to thermal noise limits that are wastefully below the dynamic range floor. Additionally, RD14 conclude that a radiometer must be placed on every antenna[5], because tropospheric phase fluctuations on 1 sec timescales will be independent over ~ 10 m distances. This length scale is less than the shortest anticipated baseline length between ngVLA antennas, which have proposed diameters 6 m and 18 m.

Using Equation 6 from RD14 with $N = 123$ and $M = 54000$ (1 sec calibration over 15 hours), the image dynamic range limit as a function of frequency ν in GHz arising from tropospheric phase fluctuations, independent of weather conditions (short of observing through thunderstorms), is predicted to be

$$D_{tropo} \approx \frac{10^6}{\nu} \quad . \tag{6}$$

Antenna-based phase errors $\phi < 0.7°$ at 1 sec cadence at 10 GHz are required to achieve this performance. This requires[6] antenna-based delay noise within 190 fs. In addition to the stochastic contribution, systematic delay drifts will arise from slowly-varying contributions such as the bulk neutral atmosphere (e.g. from differential elevation, particularly when viewing a low elevation target using long baselines) and systematics within the WVRs. The timescale over which delay drifts can be corrected is given by the timescale over which standard calibrator referencing will be performed. To satisfy 90% on-target observing efficiency (CAL0112) while seeking to attain 50 dB dynamic range at 10 GHz, and assuming a worst-case 30 sec calibrator referencing scan including slew times, this requires a minimum 5 min cycle time. The stochastic contribution on a 1 sec timescale will integrate down to 11 fs on a 5 min timescale. To ensure that the quadrature sum of the systematic and time-integrated stochastic parts does not exceed by more than 20% the time-integrated stochastic part alone, the systematic delay must be less than 7 fs. To relax this requirement, more frequent calibrator referencing will be required, but this will

[5] Of secondary concern here, but worth noting: placement of a WVR on every antenna will increase cost, but it will also reduce costs through reduced project complexity. All antennas will be the same, and overheads for optimizing dynamic scheduling to ensure there is at least one WVR-equipped antenna per grouping of adjacent antennas will not be required.

[6] Note that this requirement has been derived assuming that contributions from atmospheric constituents other than water vapor are negligible. While this is likely to be appropriate, further study is needed to determine the relative contribution toward the 50 dB dynamic range requirement from density and temperature fluctuations in the dry atmosphere. For example, if the dry contribution is within 50 fs, the total tropospheric delay will remain within 3% of 190 fs, otherwise wet delay tracking on timescales faster than 1 sec will be required to satisfy the 190 fs requirement.

come at the expense of reduced on-target observing efficiency. The delay measurement error σ_τ resulting from observation of an unresolved source with flux density S and single-baseline single-polarization flux density error σ_{bp} over bandwidth $\Delta\nu$ is given by $\sqrt{3}\sigma/(\pi S\sqrt{N}\Delta\nu)$ [RD07 Equation 9.178]. Assuming a 4 GHz RFI-free bandwidth, and taking expected $\sigma_{bp} = 1.1$ mJy/b in 15 sec in band 2, a strong calibrator with minimum flux density 2 Jy is required to measure delays to within 7 fs. This will be challenging to satisfy because the sky density of strong calibrators is sparse. However, it should be noted that this 7 fs requirement is based on a worst-case calculation and is likely an overspecification. This will be revisited in future iterations of this requirements flowdown.

Note that full radiometric correction (the ability to connect phases between targets) will be required to account for the change in path between target field and calibrator [e.g. RD16]. This will likely drive the most demanding aspects of radiometer design. Without full correction, large phase errors resulting from traditional phase transfer between calibrator and target field will be imparted to the target visibility data, leading to excessive variability in the positional (phase) reference frames for observations of the target field between calibrator scans, and dramatically reducing the overall image dynamic range limit. Note that absolute radiometry requires careful control over factors like elevation gain dependence and temperature stabilization.

Differences in the positional reference frames between observations in a multi-epoch dataset could, when the data are combined in the visibility domain, limit high dynamic range imaging. To attain 50 dB image dynamic range at 10 GHz (CAL0123), phase errors must be minimized [RD03].The maximum acceptable systematic phase offsets between multiple observations can be estimated as follows. To satisfy CAL0123, Equation 5 indicates that systematic antenna-based phase errors must be smaller than $0.006°$, assuming $N = 123$ antennas, 4 observations of 4 hours each (total observing time ~ 15 hours, as motivated earlier), and where 4 hours is selected as a modest scheduling block length accounting for weather and declination. The phase measurement error σ_ϕ resulting from observation of an unresolved source with flux density S and flux density measurement error σ is given by $\sigma_\phi = \sigma/S$ [RD07 Equation 9.67]. The anticipated full-bandwith continuum sensitivity in just 1 min at 10 GHz using $N = 123$ antennas will be sufficient to deliver 0.0005% flux density uncertainty on a 0.5 Jy unresolved calibrator, yielding $0.003°$ per antenna. Therefore, there should always be sufficient signal to noise on the complex gain calibrator to obtain suitable phase self-calibration solutions per observation and in turn align the positional reference frames between observations. While this strategy invokes self-calibration (cf. Section 6.1), this is only required to accurately align multiple observations, rather than being necessary within any given observation. Section 6.4.2 presents a similar calculation but with a focus on amplitude calibration. CAL0305 requires the observatory to deliver scheduling and pipeline capabilities to ensure, where necessary for high dynamic range projects, alignment of flux density scales (and positional reference frames) across multi-epoch observations.

For a 22 GHz WVR to sense the same 18 m atmospheric patch as viewed by an 18 m dish at an assumed height of 1500 m, it will need to be supported by a ~ 1 m dish. Similarly, a 6 m dish will sense a 6 m atmospheric patch. However, if tropospheric delay corrections are only required every 1 sec, and if the tropospheric advection speed is ~ 10 m/s, then a tropospheric patch of 10 m can be tolerated for a 6 m dish without degrading capabilities, in turn reducing the required size of the WVR dish to approximately 2 m. Furthermore, as earlier, the tropospheric delay requirements are based on worst-case calculations that will be revisited in a future iteration of this requirements flowdown. It is likely that a 2 sec timescale will also be sufficient, in which case a 1 m WVR will also be suitable for the 6 m dishes. This is desireable for reasons of uniformity over the array, maintenance, and cost.

If tropospheric delay corrections are only required every 1 sec, and if the tropospheric advection speed is ~ 10 m/s, then there may be a small number of statistically independent tropospheric delay patches over each 18 m dish; this will not be the case for the 6 m dishes. However, as above, it is likely that 2 sec timescales will also be sufficient. Therefore, direction-dependent (wide-field) corrections for the troposphere do not appear to be required.

Additionally, anomalous refraction is unlikely to be of concern. Anomalous refraction describes the wandering of source positions on timescales of seconds, due to refractive wedges of the troposphere with size equal to the antenna diameter moving across the antenna aperture. Anomalous refraction effectively contributes to the pointing error budget (as well as atmospheric delay errors, which are accounted for above). The rms value of the differential phase shift from a wedge is given by the root phase structure function $\sqrt{D_\phi(d)}$ (units of radians) evaluated at a distance given by the antenna diameter d_a. In the case of 3D turbulence (suitable here for ngVLA antenna diameter length scales, e.g. see RD14), the rms value of the anomalous refraction ξ at zenith angle z is given by [RD07 Equation 13.111, corrected without factor $\sqrt{2}$ because $\sqrt{D_\phi(d)}$ is already direction-independent]

$$\xi \approx \frac{\frac{\lambda}{2\pi}\sqrt{D_\phi(d_a)\,\sec z}}{d_a}\ \ \mathrm{rad}\ , \tag{7}$$

where λ is the observing wavelength needed to convert $\sqrt{D_\phi(d)}$ to path length delay in units of distance. The ngVLA reference design incorporates antennas with diameters 6 m and 18 m. When combined with $\sqrt{D_\phi(d)}$ given by Equation 3 from RD14 and assuming a typical tropospheric advection speed of 10 m/s [e.g. RD14], this becomes

$$\xi \approx 2.6\,\frac{\sqrt{\sec z}}{d_a^{0.2}}\ \ \mathrm{arcsec}\ . \tag{8}$$

This relationship is independent of observing frequency. Assuming $z = 60^\circ$ the anomalous refraction is approximately 2.6″ for a 6 m dish and 2.1″ for an 18 m dish. Given that these values are approximately the same as the precision offset pointing requirement (see CAL0201), and that the timescale < 2 sec for anomalous refraction over dish diameters < 20 m will deliver factor M in Equation 5 that is much larger than the sample calculation for pointing errors presented in Section 6.2.1, anomalous refraction is unlikely to affect the ability to satisfy the 50 dB image dynamic range requirement. Therefore, anomalous refraction will not be considered further here.

6.3.2.2 Ionosphere

The ionized portion of the Earth's atmosphere consists of the ionosphere from about 60–1000 km and the plasmasphere which extends to the plasmapause at approximately geosynchronous altitude. The electron column density is dominated by the ionosphere, which can be approximated by a thin shell at a weighted altitude of ~ 400 km. The ionosphere exhibits structure on all scales ranging from centimeters to the fractional-Earth-circumference bulge caused by the Sun's radiation, with corresponding fluctuation timescales from sub-seconds to hours, and three dimensional drift velocities from m/s to km/s. The ionosphere exhibits strong seasonal and regional dynamics due to the solar cycle, solar inclination, day-night cycle, ionospheric anomalies arising from perturbations such as lightning and tropospheric waves, and the dynamics of ionospheric structures like plasma bubbles, gradients, and traveling ionospheric disturbances. Like the troposphere, ionospheric disturbances can be viewed as a spatial pattern translating across the ground and evolving more slowly in its own reference frame, although unlike the troposphere the diversity of patterns described above makes it difficult to construct generalized predictions for spatiotemporal properties.

The ionized atmosphere will induce an excess delay in units of distance given by [e.g. RD17]

$$\tau_{ion} = -\frac{c^2 r_0}{2\pi\nu^2}\int n_e(l)dl \ \ , \tag{9}$$

where c is the speed of light, r_0 is the classical electron radius, ν is the observing frequency, and the integral over the electron number density n_e yields the total number of electrons per unit area along the line of sight, known as the slant total electron content (STEC). The delay is negative indicating that a monochromatic signal will experience a phase advance relative to vacuum. The corresponding difference in phase between two antennas on a baseline is then given by

$$\Delta\phi_{ion} \approx 480\,\frac{\Delta N_e}{\nu} \ \ \mathrm{deg}\ , \tag{10}$$

where ν is in units of GHz, and N_e is the STEC in units of 'unit' TEC where $1\ \mathrm{TECU} = 10^{16}\,e^{-}/m^2$. Assuming uncorrelated lines of sight to each antenna, antenna-based phases will be a factor $\sqrt{2}$ smaller. This assumption is suitable here when focusing on small phase fluctuations on short timescales because GPS observations exhibit a power law of temporal fluctuations extending to sub-second timescales (e.g. RD19; see also the high time resolution VLA observations of ionospheric scintillation presented by RD20). From Section 6.3.2.1, to satisfy CAL0123, antenna-based phase errors must be kept below 0.7° on 1 sec timescales over a 15 hour observation ($M = 54000$) with $N = 123$ antennas to enable 50 dB image dynamic range at 10 GHz. To ensure that ionospheric phase fluctuations do not contribute more than 5% toward the quadrature sum of ionospheric and tropospheric contributions, ionospheric phase fluctuations on 1 sec timescales must remain below $\phi < 0.2^\circ$ at 10 GHz. Using the antenna-based phase-STEC relationship, this requires that STEC can be tracked within 0.006 TECU, or that the observed STEC values will remain below this value on 1 sec timescales throughout an observation. This also translates to antenna-based delay noise $6/\nu^2$ ps where ν is in units of GHz. For CAL0123 specified at 10 GHz, the requirement for antenna-based delay noise arising from the ionosphere is therefore 60 fs on 1 sec timescales. Slower variations in the ionospheric electron content must also be removed. As with the troposphere, the timescale over which delay drifts can be corrected is given by the timescale over which standard calibrator referencing will be performed, taken again to be minimum 5 min to satisfy CAL0112. The stochastic contribution on a 1 sec timescale will integrate down to 3.5 fs on a 5 min timescale. To ensure that the quadrature sum of the systematic and time-integrated stochastic parts does not exceed by more than 20% the time-integrated stochastic part alone, the systematic delay must be less than 2 fs at 10 GHz, or $0.2/\nu^2$ ps where ν is in units of GHz. To relax this requirement, more frequent calibrator referencing will be required, but this will come at the expense of reduced on-target observing efficiency.

The dynamic range limit as a function of frequency ν in GHz arising from ionospheric phase fluctuations can be predicted by combining the above limit for ionospheric phase fluctuations ($\phi < 0.2°$) with Equation 5, assuming that this limit on 1 sec cadence is satisfied independent of baseline length, antenna location, and ionospheric conditions (assessed below), and assuming $M = 54000$ and $N = 123$, giving

$$D_{ion} \approx 3.7 \times 10^4 \, \nu \quad . \tag{11}$$

Note that this does not include additional benefits from self-calibration using bright sources (which are typically more plentiful at 1 GHz than 10 GHz; for comparison, note from RD14 that self-calibration is not a viable approach for attaining 50 dB dynamic range in deep fields at 10 GHz). Combining Equations 6 and 11 assuming that phase errors from the troposphere ($0.07° \, \nu$) and ionosphere ($2°/\nu$) add in quadrature, where ν is in GHz, the dynamic range limit between 1–116 GHz arising from atmospheric phase fluctuations is predicted to be

$$D_{atmos} \approx \frac{10^6 \, \nu}{\sqrt{816 + \nu^4}} \quad . \tag{12}$$

The dynamic range peaks at 51 dB at 5.3 GHz, passing through 50 dB at 10 GHz, and dropping to 45 dB at 1.2 GHz and 39 dB at 116 GHz.

To assess whether the 60 fs delay noise requirement is realistic or not, the following preliminary material is presented from RD18 (in prep.) which focuses on statistics of the ionosphere and implications for phase calibration (i.e. the ionospheric equivalent of RD14). The following data provide a useful and robust reference point, but require further evaluation and comparison with other data before the conclusions should be fully accepted. VLA observations of the calibrator 3C84 presented by RD20 were obtained. The data selected for analysis were observed on 2 Jan 2015 at 00:10 UTC (5:10 pm local time) in C configuration (maximum 3 km baselines) at 1.4 GHz over 100 MHz bandwidth in a single polarization for duration 2 min with 1 sec time sampling. These data exhibit ionospheric scintillation (see RD20). This epoch is near the peak of solar cycle 24, and at a time when the solar elongation was $133°$. The X-ray Sensor on board the *GOES*-15 satellite indicates that all solar flares in the 5 days preceding the observation were of mid-range C class or lower. Reconstructed vertical total electron content (VTEC) data from the International Global Navigation Satellite System Service (IGS), interpolated spatially at the VLA site from GPS data sampled every 2 hr on a grid $2.5° \times 5°$ (lat. $\times$ long.), indicate a rapid drop in electron content with rate 8 TECU/hr over a period of 2 hr centered on 00:00 UTC (typical of conditions at sunset). STEC values, interpolated from the VTEC maps, are around 23 TECU with line-of-sight differences between antennas of no more than 0.03 TECU. The phase time series for each baseline was recovered following RD14, yielding temporal structure functions (growth of rms phase fluctuations on a baseline over time) binned by baseline lengths in the ranges < 0.2 km, 0.2–2 km, and 2–3 km. The brief 2 min duration of the input data implies that statistics are degraded at time lags greater than a few seconds. However, this is sufficient here where the focus is on 1 sec timescales. The data indicate baseline-based phase fluctuations $< 0.7°$ on 1 sec timescales at 1.4 GHz, independent of baseline length. Using Equation 10 this equates to STEC fluctuations < 0.002 TECU.

This value is a third of the requirement presented earlier. However, it is not yet clear whether the magnitude of fluctuations revealed above are typical or atypical. Similarly, the present data do not answer whether 0.006 TECU fluctuations at 1 second cadence are rare or not. This requires an investigation into the scaling (or lack thereof) with overall STEC values, and with baseline length (e.g. over continental scales), for a range of representative observing conditions. The observations above took place during a time of rapid recombination of the ionosphere, under reasonably active solar conditions (though without significant flaring or coronal mass ejection contributions), so it is reasonable to assume that the ionosphere was in a more excited state than usual. However, there are examples of ionospheric disturbances that become enhanced under quiet solar conditions (solar minimum) such as equatorial spread F (a Rayleigh-Taylor like instability prevalent near the magnetic equator in which the underside of the F region becomes highly turbulent during the post-sunset period, and which is suppressed by solar activity; similar phenomena may exist at the $\sim 40°$ magnetic latitude of the VLA site).

Thus, the tentative conclusion is that ionospheric phase fluctuations will not be a significant impediment to satisfying CAL0123. Furthermore, these fluctuations on fast 1 sec timescales will not need to be explicitly tracked. However, changes in the ionosphere on the delay drift timescale (5 min) will need to be tracked. GPS-derived VTEC maps from the IGS or other similar services have best-case accuracies $\sim 1\%$. These will not be sufficient to achieve 2 fs drift accuracy at 10 GHz (these are, however, sufficient to correct for ionospheric Faraday rotation which is sensitive to the STEC above each antenna rather than the much smaller difference in STECs between antennas on a baseline; see Section 6.6.3). Instead, the ionospheric delay $\propto \nu^{-2}$ will need to be measured from the observational data (i.e. by fitting the phase change $\propto \nu^{-1}$ in the parallel hand visibility data over an observing band; see e.g. RD21). This leads to several demands on design.

First, the optimal band for performing such measurements is band 1 where ionospheric delay fluctuations will be largest. $0.2/\nu^2$ ps implies a phase difference of $0.04°$ over the frequency range 1.2–3.5 GHz. Taking into account the anticipated sensitivity of the ngVLA in band 1 with $N = 123$ antennas, and using the relationship between phase measurement error σ_ϕ resulting from observation of an unresolved source with flux density S and flux density measurement error σ given by $\sigma_\phi = \sigma/S$ [RD07 Equation 9.67], the flux density necessary to measure antenna-based $\sigma_\phi < 0.01^\circ$ within a 200 MHz bandwidth in 10 sec is $S > 2$ Jy. This is realistic for a nearby phase calibrator in band 1. Note that this flux density is an upper limit because the true delay fit uncertainty may be better estimated using the full band 1 bandwidth (an order magnitude larger than 200 MHz). This leads to two options when considering how to implement this in band 2 (or higher frequency bands if ionospheric conditions are particularly poor): the feed could be designed to switch rapidly between bands, or the feed could be designed to support simultaneous observations. The former option would prevent tracking of fluctuations on timescales faster than 5 min (unless CAL0112 can be relaxed), though this could be offset by suitable monitoring of ionospheric conditions as described below. The latter option is not supported in the current reference design, though it is not strictly ruled out in the future (in the current design, when not on-axis, the band 1 feed points to open sky; modifications to facilitate some forward gain are likely to incur significant complexity and cost penalties). If it were available, the band 1 feed would be out of focus during band 2 on-axis observations, but the wide field of view from 18 m dishes could in principle enable ionospheric phase fluctuations to be tracked on timescales shorter than 5 mins and perhaps tens of seconds (depending on signal to noise over that interval). This would enable the ionosphere to be tracked in a similar way to that of the troposphere using radiometry. CAL0206 focuses on the former option and requires the ability to perform regular and rapid band switching (which will have implications for maintenance). CAL0306 requires an automated pipeline data analysis capability to measure and correct for ionospheric delay fluctuations using observations of a calibrator at the phase center, with the goal to expand this capability to arbitrary fields (where requirements on those fields are yet to be defined; the wide field of view of an 18 m dish combined with the high sky density of bright sources in band 1 should ensure that a sufficiently strong celestial signal should always be available regardless of pointing vector).

Second, the ratio of only 3 between the maximum allowable STEC fluctuations (0.006 TECU) and the observed STEC fluctuations (0.002 TECU) indicates that, for contingency, regular monitoring of regional ionospheric conditions must be facilitated for scheduling. CAL0307 requires real-time spatio-temporal GPS-derived monitoring data to be utilized when scheduling observations on the ngVLA, for example using an index like the ROTI (rate of TEC index; e.g. available from the Ionosphere Monitoring and Prediction Center[7]) or the DIXSG (disturbance ionosphere index spatial gradient; RD22). Another useful tracer is the planetary K index.

And third, to ensure optimal scheduling, CAL0308 requires the proposal process to capture the estimated image dynamic range limit, so that degraded ionospheric conditions may be utilized where appropriate. Similarly, CAL0309 requires the scheduler to be capable of starting and stopping scheduling blocks depending on weather conditions across the array, and to account for previously stopped observations in the queue ranking process. Note that it is not clear that adding GPS receivers to ngVLA antennas will be of sufficient benefit, unless they can be programmed to accurately track phase fluctuations by selecting GPS satellites close to the real-time antenna pointing vector. In this case, GPS units could be utilized in an equivalent manner to WVRs. This approach is not yet strictly ruled out, but it is not promoted here because of the larger complexity, risk, and cost compared to measurement of ionospheric

[7] `https://impc.dlr.de/`

phases from the observational data.

The ~ 400 km height of the ionosphere implies that the electron column density will differ for different lines of sight toward the same antenna (the half-power half-beam-width for an 18 m dish at 10 GHz is $3'$, which corresponds to a lateral distance ~ 350 m at the height of the thin-shell ionosphere). If it is accepted from the results presented earlier that the ionosphere is not dominant at 10 GHz, then CAL0123 does not strictly demand the availability of direction-dependent corrections to account for wide-field distortions from the ionosphere. However, as argued above, it remains plausible (pending further investigation) that the ionosphere could exhibit larger fluctuations that would reduce the dynamic range limit below 50 dB at 10 GHz. These time periods could (perhaps) be sufficiently frequent that they would be difficult to avoid through scheduling choices. A requirement to implement direction-dependent calibration capabilities in the workflow is not currently recommended, though this requires further study before a final decision should be made. Direction-dependent calibration capabilities would certainly be useful in band 1.

6.3.2.3 Interplanetary Medium

While not part of the Earth's atmosphere, the ionized interplanetary medium is turbulent and will induce phase fluctuations over the array. This may be of scientific interest to some observers and problematic for others. CAL0310 requires that estimates of the minimum acceptable angular offset from the Sun shall be calculated (e.g. RD23) from real-time data sources and fed into the scheduler for optimal array management. This will also need to account for real-time transient alerts for events like solar flares and coronal mass ejections (e.g. using the CACTus quicklook catalog[8] from the LASCO instrument on board the *Solar and Heliospheric Observatory* satellite).

6.3.3 Antenna Location

Parameter	Req. #	Value	Traceability
Antenna Location	CAL0311	90 μm	CAL0123, CAL0117, CAL0122
Timing Accuracy Across Array	CAL0312	0.2 μs	CAL0311

The relative positions of the antennas must be accurately determined so that geometric delays can be correctly calculated and supplied to the correlator. Residual delays due to incorrect antenna locations will result in phase errors which change across the observing band, as well as differential phase errors

[8] `http://sidc.oma.be/cactus/`

between two different sources on the sky (e.g. calibrator and target).

A phase difference $\Delta\phi$ across a bandwidth will reduce the coherence to $\mathrm{sinc}[\Delta\phi/2]$. To facilitate 50 dB dynamic range (CAL0123) and effectively ensure that instrumental delay variations are smaller than residual atmospheric contributions (CAL0122), the antenna-based amplitude errors in Equation 1 must be $< 0.011\%$, assuming $N = 123$ antennas. This requires $\Delta\phi < 3^\circ$. For ngVLA, with a maximum instantaneous bandwidth of up to $\Delta\nu = 20$ GHz (CAL0117), and assuming a limit of 3° for the phase difference across the band, the required baseline accuracy is $c\Delta\phi/(2\pi\Delta\nu) \sim 125$ μm. The error on an individual antenna location determination must then be less than 90 μm, assuming that the errors add in quadrature (not true for any given baseline, but this is a reasonable assumption when averaged over the array).

The differential phase error $\Delta\phi$ between two sources on the sky with angular separation $\theta_{\rm sep}$ in the presence of baseline error ΔB at frequency ν is approximately $2\pi\nu\theta_{\rm sep}\Delta B/c$ [RD07 Sec 12.2.3]. At the highest frequency $\nu = 116$ GHz, with maximum source separation $\theta_{\rm sep} = 5^\circ$, and taking $\Delta\phi = 2.8^\circ$ (one third of the anticipated $0.07^\circ\,\nu$ tropospheric delay from RD14) as the maximum allowable phase error (equivalent to 20μm of path or 67 fs delay), the error in the baseline must be less than approximately 230 μm. The error on an individual antenna location determination must then be less than 160 μm.

The more stringent limit above is selected. Efforts will be required to properly understand how the antenna locations change with time.

The antenna location accuracy also provides a requirement for the timing accuracy across the array Δt constrained by $\Delta B \sim \omega_e \Delta t B_{\rm max}$, where ω_e is the rotation rate of the Earth and $B_{\rm max}$ is the maximum baseline. For 125 μm accuracy over 9000 km baselines this implies a timekeeping accuracy of $\sim 0.2\,\mu$s. Note that $0.2\,\mu$s is orders of magnitude faster than anticipated integration times of order fractions of a second. For example, 0.1 s integration time is required to keep time smearing loss below -20 dB at the primary beam half-power contour for 18 m dishes over 1000 km baselines, independent of frequency [RD07 Equation 6.81]. For 6 m antennas over 100 m baselines the maximum integration time is 300 s, again independent of frequency.

6.3.4 Antenna Structure

Parameter	Req. #	Value	Traceability
Antenna Structure Delay	CAL0313	7 fs drift over 5 min, 90 fs noise, for motions over 3° on the sky	CAL0207, CAL0303

The antenna structures and their motion will contribute delay (e.g. RD17). These can be thought of as modifications to the antenna location. For example, as noted by RD17, the Earth's orbital velocity $10^{-4}c$ must be taken into account to achieve mm accuracy. This motion causes Lorentz effects of order

$10^{-4}L$, which for a 10 m axis offset is 1 mm or 3 ps.

Repeatable parts of the antenna structure delay include the change of main reflector shape with elevation or azimuth, axis non-intersection, illumination offset, bearing runout, and bearing alignment. Most of this repeatable component can be accurately predicted through careful measurements. Non-repeatable (and typically not predictable) parts of the antenna structure delay include thermal[9] and wind deformation of the main reflector shape and feed position, and bearing non-repeatability. The magnitude of each of these contributions, particular from the non-repeatable factors, will likely only be determined by experimentation over time with the final ngVLA antennas.

In order for the delay budget to be dominated by the atmosphere (190 fs; CAL0303) rather than the instrument (CAL0122), the stochastic part of the antenna structure delay must be less than 90 fs so that its quadrature sum with the atmosphere inflates the total by less than 10%. It is reasonable to expect that the stochastic component will be randomized on 1 sec timescales, in which case the requirement can be derived from the 1 sec 190 fs tropospheric requirement so that both integrate down in proportion with time. The repeatable components are likely to be of the same order, but because these should be predictable, it is reasonable to allocate only a small fraction of this to any true residual systematic delay offsets. The timescale over which such systematic delays can be corrected is given by the 5 min calibrator referencing timescale justified in Section 6.3.2.1. To ensure that the quadrature sum of the systematic and time-integrated stochastic parts does not exceed by more than 20% the time-integrated stochastic part alone over a 5 min period, the systematic delay residual must be less than 7 fs. To relax this requirement, more frequent calibrator referencing will be required, but this will come at the expense of reduced on-target observing efficiency. Both the systematic and stochastic requirements relate to motions within a 3° solid angle on the sky, following the justification presented for CAL0207.

6.3.5 Electronics

Parameter	Req. #	Value	Traceability
Electronics Delay	CAL0314	7 fs drift over 5 min, 90 fs noise	CAL0303

There is a component of delay introduced because of the electronics between the feeds on the antennas and the samplers. This will need to be measured for each antenna, receiver, and polarization. The electronics and particularly the local oscillator must be designed so that they are more phase stable than the atmosphere (CAL0122). As in the previous section, this requires the stochastic part to contribute less than 90 fs and the systematic part to contribute less than 7 fs, the latter over stability timescales 5 min.

[9] A rough estimate for the expected thermal expansion rate can be obtained by multiplying the dish diameter by the thermal expansion coefficient, which for a steel 18 m dish is approximately 0.6 ps/$^{\circ}$C.

6.4 Amplitude

Parameter	Req. #	Value	Traceability
Noise Diode Amplitude Stability	CAL0401	1% drift over 1 month, 0.05% stability over 5 min.	CAL0123, CAL0122
Elevation Gain Dependency	CAL0402	Model elevation gain dependency per antenna to within 0.1% in all frequency bands, and to within 0.01% at 10 GHz.	CAL0123, CAL0201
Default Amplitude Calibration	CAL0403	Deliver best-case 1% absolute flux density accuracy added in quadrature with the accuracy at which celestial flux density standards are known at the frequency of interest, for Standard (Interferometric) Observing Modes using database calibration without overheads, i.e. without needing optimized scheduling (e.g. observing near constant elevation) or specialized calibrations (e.g. offset pointing, antenna dips, observations of celestial flux density standards). Using this approach, deliver no worse than 6% (total) absolute flux density accuracy.	CAL0107, CAL0119
Calibrator Database: Flux Density Standards	CAL0404	Monitor celestial flux density standards and their flux density ratios every 1 month, with sufficient sources in each frequency band to identify variability in any source.	CAL0107, CAL0405

Parameter	Req. #	Value	Traceability
Internal Absolute Amplitude Scale	CAL0405	Maintain stable internal scaling between cross-product spectral power and spectral flux density on 1 month timescales using a switched power system, utilizing noise diode stability (CAL0401) and elevation-dependent aperture efficiencies (CAL0402) tied to regular monthly observations of celestial absolute flux density standards. This shall include the capability to return an antenna to the array following an inactive period (e.g. due to maintenance).	CAL0107, CAL0403
Switched power RFI mitigation	CAL0406	Implement signal processing/filtering to prevent RFI from contaminating the switched power system at levels equivalent to greater than 0.05% in noise diode amplitude stability over 5 min.	CAL0405

Two forms of amplitude calibration must be considered. First is the need to deliver accurate relative amplitude calibration, namely stability in the amplitudes measured during an observation. Second is the need to place corrected visibilities onto an accurate absolute flux density scale.

6.4.1 Relative Amplitude Calibration

Relative amplitude calibration is required to ensure amplitude stability within an individual observation in a given instrumental tuning, including in a general sense where that observation could range in elevation from zenith to horizon. To maintain a stable amplitude scale, fluctuations in electronic gain, antenna aperture efficiency, and atmospheric opacity must be considered (e.g. see Equation 1 in RD24). These are addressed in turn below.

Noise diodes placed upfront in the signal path can be used to track changes in electronic gains. The ngVLA Reference Design incorporates one temperature-stabilized noise diode per antenna, with associated bias circuitry to optimize stability in switched power. The noise diodes need to be sufficiently stable to prevent amplitude errors that can limit image dynamic range. The image dynamic range limit resulting from antenna-based amplitude errors (correlated for both polarizations on a given antenna) is given by Equation 1. When modified to include the M factor (number of statistically independent samples) from RD03, this is given by

$$D \approx \frac{\sqrt{NM}}{\epsilon} \,. \tag{13}$$

To satisfy CAL0123 (50 dB image dynamic range at 10 GHz) to levels better than the atmosphere (CAL0122), adopting a dynamic range target of 55 dB, antenna-based amplitude errors ϵ must be no larger than 0.05%, assuming $N = 123$ antennas, and assuming that the errors are randomized on timescales of ~ 5 min (calibrator referencing timescale) throughout a 15 hour observation (see Section 6.3.2.1 for motivation behind 15 hours).

Gravitationally induced deformation of an antenna's surfaces and support structures will lead to loss in forward gain. This loss is largely predictable as a function of elevation angle. When this elevation gain dependency for an antenna is combined with factors like the illumination taper[10] introduced by the feed, the frequency- and elevation-dependent antenna aperture efficiency can be calculated. As the typically dominant contributor to fluctuations in aperture efficiency, the elevation gain dependency of each antenna must be known accurately in order to minimize amplitude errors and in turn raise image dynamic range limits. Importantly, the combination of accurate elevation-dependent aperture efficiencies and noise diode stability can be used to provide a stable internal absolute flux density scale. The accuracy with which the elevation gain dependency can be predicted from an empirical model is given by the pointing error (e.g. see Fig. 2 from RD24). With 3″ pointing at 10 GHz on an 18 m dish (CAL0201), Equation 2 indicates that antenna-based amplitude errors (on-axis) will be 0.01% (the equivalent error is 0.2% at 50 GHz, and 1.3% at 116 GHz). It will therefore be possible to model the elevation gain dependency to better than 0.01% accuracy (or better than 1.3% at 116 GHz) because this model will be generated by averaging over pointing errors. Accuracy in the prediction step will then be given by the pointing error at that moment. With antenna-based gain amplitude errors of 0.01%, the dynamic range limit from Equation 13 with $N = 123$ and $M = 1$ is 50 dB. The dynamic range limit will in fact be higher because the 0.01% error arises from pointing, which will randomize on short timescales ($M > 1$).

The transparency of the troposphere is affected by water vapor and molecular oxygen. The opacity varies as a function of observing frequency (e.g. see Figure 13.7 from RD07). It also varies as a function of time, primarily as a result of changes in water vapor content, ranging from fluctuations on fast-changing second timescales to slow-changing diurnal timescales. To faciliate 55 dB image dynamic range (as above), Equation 13 with $N = 123$ indicates that antenna-based amplitude errors arising from opacity fluctuations on 1 min timescales over a 15 hour observation must be corrected to within 0.1%. For comparison, to assess whether this is a realistic target, the limited investigation by RD26 found that opacity at the VLA site at 23 GHz can vary by 0.5% over 30 mins. More detailed statistics of opacity fluctuations are currently being investigated using EVLA switched power data [RD27, in prep.]. The results presented by RD26 indicate the need for a capability to track and correct for changes in opacity

[10] If the aperture illumination exhibits significant systematic changes with the antenna pointing vector, then like the elevation gain dependency these will need to be modeled so that aperture efficiency can be accurately predicted.

on 1 min timescales. Atmospheric brightness temperatures scale exponentially with atmospheric opacity (e.g. Section 13.1.3 in RD07). This relationship is approximately linear for small changes in atmospheric opacity. If the atmosphere dominates the system temperature, then the requirement above can be facilitated by a switched power system underpinned by noise diodes with stability better than 0.1% on 5 min timescales. This is effectively supported by the electronic gain requirement (CAL0401). Note that this argument assumes that visibility errors are dominated by system noise rather than correlated celestial signals; the present discussion is driven by the need to support deep field imaging at 10 GHz, for which sufficiently strong sources are not expected (for strong targets, regular tracking of a nearby blank sky region may be required). Note also that a switched power system is capable of differentiating between changes in electronic gains and atmospheric opacity [RD28].

Ideally, long timescale fluctuations in atmospheric opacity will also need to be tracked by the switched power system (on timescales of an individual observation, or even weeks as described in the next section), such that the use of model opacities or empirical opacities from antenna dips (tipping scans) will not be required. However, this requires future investigation. It may become evident that accuracy under this scheme can only be maintained by calibrating the internal opacity tracking with data from tipping scans. There may also be a need to combine the tipping data with an atmospheric temperature (or better, a vertical temperature profile), because the atmosphere is mostly transparent down to the horizon at frequencies up to 116 GHz and therefore cannot be used to directly infer the atmospheric opacity. If this is required, further investigation will be needed to determine whether atmopsheric models will be sufficient for this purpose, or whether sensing data (e.g. publicly available radiosonde data, or oxygen sounders operating in the wings of the 60 GHz absorption lines) will be required to ensure sufficient accuracy. If it becomes evident that additional calibrations like tipping scans will need to be added to scheduling blocks to facilitate certain scientific objectives (like high dynamic range), then it may be useful to define a new 'enhanced' amplitude calibration procedure to differentiate from the default procedure in CAL0403. Note that to satisfy CAL0123, the residual systematic antenna-based amplitude error per observation must be within 0.01%. While this level of uncertainty in the amplitude scale between antennas may not be achieved using the internal diode stabilized system (e.g. consider observations performed near the end of the month between celestial re-calibration, when consistency in the amplitude scale maintained by the noise diodes may have degraded), the inclusion within the scheduling block of a celestial flux density calibrator (and other scans like tipping) might not be required because there will likely be sufficient signal to noise on the regularly-observed gain calibrator to align the time-dependent antenna-based amplitude scales. Further work is required to verify these arguments and, if necessary, refine the proposed amplitude calibration procedures and requirements.

Absorption in the ionosphere arises from collisions between electrons with ions and neutral particles and is $\sim 2\%$ at 100 MHz during periods of high ionospheric activity [RD07 Sec. 14.1.4]. This varies with the inverse square of the frequency (i.e. 0.0002% at 10 GHz) and can therefore be neglected here.

6.4.2 Absolute Amplitude Calibration

Uncertainty in the absolute flux density scale assigned to an observation will translate to variability in flux densities measured from the same field at different times, or at different frequencies (unless multiple bands can be observed simultaneously). It is not practical to consider maintaining absolute flux density calibration over an indefinite time period using an instrumental reference source. However, this approach is realistic using noise diodes over approximately monthly timescales, when tied to regular observatory (service mode) observations of celestial flux density standards. CAL0119 calls for the ability to deliver 1% absolute flux density accuracy (consult CAL0119 and the text below it for more details). If a celestial flux density standard is observed on approximately monthly timescales (at high signal to noise, and employing all necessary optimizations to ensure high accuracy such as observing under precision conditions, minimizing the elevation range over which observations are obtained and avoiding low elevations, and including additional calibrations like regular tipping scans and offset pointing), then the absolute flux density scale can be transferred to the instrumental standard and in turn applied to observations during the month-long time window. Note that at any one time, a number of antennas may be removed from the array for maintenance. To reintegrate these antennas into the array, there will need to be a capability to transfer the internal scale maintained by all active antennas to the returned antennas. This could be achieved using regular (as short as daily) brief service-mode observations of bright calibrators with the full array, e.g. in between science blocks. Alternatively, it may be possible to accomplish this using complex gain calibrator data from the science blocks themselves. Heuristics will need to be developed.

To satisfy CAL0119 using the approach above, assuming N statistically independent noise diodes over $N = 123$ antennas (i.e. common between polarizations on any receiver), the noise diode amplitudes per antenna must remain stable and not drift beyond 10% of their $t = 0$ values over a 1 month period (i.e. stable to 1% when averaged over all antennas). To compensate for any possible systematics between diodes at the few percent level on long timescales (not expected, but not impossible), the requirement is 1% per-antenna. This approach has an additional benefit: uncertainty in the flux density scale between observations performed within the 1 month period between celestial recalibration will be 1% or better (whether the noise diodes are statistically independent or if they exhibit some smaller deviation about a systematic 1% error), independent of the intrinsic accuracy to which the flux density of the celestial standard is known. This feature will likely be of particular interest to those in the community that seek to observe transient phenomena over timespans up to a few weeks (e.g. rising or decaying target brightness). Note that intrinsic accuracy in the flux density scale is currently at best 1%–3% depending on frequency between 1–50 GHz [e.g. RD24], rising to near 5% at 116 GHz [e.g. RD25]. The intrinsic accuracy is approximately 1% at 10 GHz.

To improve observing efficiency (CAL0107), CAL0403 defines a default amplitude calibration procedure that minimizes overheads. To illustrate the wording of CAL0403, the absolute photometric accuracy for any individual observation will be given by the quadrature sum of (say) worst-case 1% instrumental stability and (say) 3% uncertainty for a celestial flux density standard at the frequency of interest, yielding 3.2%. This uncertainty (or the worst-case 6% value indicated by CAL0403) also reflects the typical variation expected between flux densities measured from observations taken more than 1 month apart (assuming celestial recalibration takes place on this timescale), though note that uncertainty in the flux density of a celestial standard may be somewhat time-stable (i.e. systematic, yielding improved coherence between observations, with relevance to the transient comment earlier).

To satisfy CAL0403 using the combination of an instrumentally-maintained absolute flux density scale tied down by regular observations of celestial standards, absolute flux densities for celestial standards at all frequencies of interest (1–116 GHz) must be known to better than 5% (currently satisfied, as above), celestial standards must be monitored every month, there must be a capability to identify and handle (unexpected) variability in celestial standards, and (as would be expected to maintain high accuracy) observations of celestial standards must employ all necessary optimizations and additional calibrations as highlighted above.

To achieve this, a grid containing a reasonably small number of stable (including slowly varying) flux density calibrators situated across the sky will need to be monitored regularly, with flux densities stored in a calibration database (e.g. RD29). There will need to be at minimum a few standard sources available in each frequency band. Observations of all flux density standards should be performed as close together in time as possible (e.g. within 24 hours). Should any of the 'standards' exhibit unexpected variability, this will need to be detected by comparing light curves for flux density ratios between sources. The light curve data should be used to inform decisions about whether to base the internal flux density scale on a (possibly temporarily) reduced subset of 'standard' sources. A timescale of 1 month is required between reobserving the celestial standards so as to minimize impacts on science observing efficiency (note CAL0112 and text below it) while ensuring that variability in flux density standards can be detected (and interpolated where necessary) with sufficient time resolution.

Accounting for all uncertainties, including noise diode stability (CAL0401) used to track fluctuations in electronic gain and opacity, and the predictive accuracy of elevation gain dependencies (CAL0402) used to calculate accurate antenna aperture efficiencies, the absolute flux density uncertainty without the final contribution from intrinsic uncertainty in the celestial scale (between 1%–5%, see earlier) is anticipated to be less than 1% in all frequency bands, irrespective of observing conditions (even for $42''$ blind pointing in normal conditions at 116 GHz, for example considering a 20 second pointing randomization timescales across a 15 hour observation). When combined with up to 5% uncertainty from the celestial flux density scale at 116 GHz, the total absolute flux density uncertainty could be as large as 6%.

Future detailed analyses are required to validate the anticipated 1% best-case and 6% worst-case absolute flux density uncertainties targeted above, and to decide if the default amplitude calibration scheme will be sufficient in all cases. If not, an 'enhanced' scheme may be required.

Finally, it is important to note that differences in the absolute amplitude scale between observations in a multi-epoch dataset could, when the data are combined in the visibility domain, limit high dynamic range imaging. To attain 50 dB image dynamic range at 10 GHz (CAL0123), amplitude errors must be minimized [RD03]. The maximum acceptable systematic offset between amplitude scales in multiple observations can be estimated as follows. To satisfy CAL0123, Equation 13 indicates that systematic antenna-based amplitude errors must be smaller than 0.02%, assuming $N = 123$ antennas and 4 observations of 4 hours each (following the similar calculation for systematic phase errors in Section 6.3.2.1). The anticipated full-bandwith continuum sensitivity in just 1 min at 10 GHz using $N = 123$ antennas will be sufficient to deliver 0.0005% flux density uncertainty on a 0.5 Jy unresolved calibrator, yielding 0.006% per antenna. Therefore, there should always be sufficient signal to noise on the complex gain calibrator to obtain suitable amplitude self-calibration solutions per observation and in turn align the flux density scales between observations. While this strategy invokes self-calibration (cf. Section 6.1), this is only required to accurately align multiple observations, rather than being necessary within any given observation. CAL0305, presented earlier in Section 6.3.2.1 with equivalent focus on phase reference frame matching, requires observatory scheduling and data reduction capabilities (pipeline) to ensure, where necessary for high dynamic range projects, coherence in flux density scales across multi-epoch observations.

6.5 Bandpass

Parameter	Req. #	Value	Traceability
Default Bandpass Calibration	CAL0501	Apply bandpass from calibration database. Do not include bandpass scans in science observation scheduling blocks, nor use calibrators from the data to measure the bandpass.	CAL0107, CAL0113
Bandpass Accuracy	CAL0502	The observatory shall measure bandpasses with accuracies 1% in amplitude and 0.3° in phase within 0.1 km/s channels across all frequency space, taking care to ensure that tropospheric and ionospheric systematics are removed to within these accuracies. To enable more accurate solutions to be obtained over broader channels by averaging the 0.1 km/s solutions, the latter will need to be measured and stored in a way that enables accountability of various filter responses (baseband, subband).	CAL0125

Parameter	Req. #	Value	Traceability
Bandpass Stability	CAL0503	The instrumental contribution to the bandpass shall be stable to 0.3% amplitude and $0.08°$ phase per polarization over hourly and monthly timescales.	CAL0122, CAL0123
Calibration Database: Bandpass	CAL0504	The observatory shall supply bandpasses satisfying CAL0502 and CAL0503 in a calibration database, updating solutions where appropriate (e.g. if the advertised accuracy is no longer satisfied due to slow degradation over time or a step change arising from antenna maintenance).	CAL0105, CAL0501
Proposal Content: Estimated Dynamic Range Per Channel	CAL0505	Spectral line proposals must specify the required dynamic range in a single spectral channel. This shall be used by the observatory to decide if the default bandpass calibration procedure is suitable or if custom bandpass calibration is required (note that an 'enhanced' bandpass calibration procedure may yet need to be defined, depending on the outcome of future investigations).	CAL0111, CAL0501

The analog and digital electronics will impose an instrumental spectral imprint on an astronomical signal. The troposphere and ionosphere will also contribute to this imprint. These effects must be measured and removed. The exact shape of the bandpass is not of key importance, as long as it is stable and can accommodate high spectral dynamic range. CAL0125 calls for 50 dB spectral dynamic range to enable imaging in the presence of bright emission lines, with particular focus in the frequency range 16–50 GHz. CAL0118 calls for this dynamic range to be supported for channels as narrow as 0.1 km/s (5 kHz at 16 GHz, or 17 kHz at 50 GHz).

To improve observing efficiency (CAL0113), CAL0501 defines a default bandpass calibration procedure that minimizes overheads by utilizing observatory-supplied bandpasses accessed from a calibration database (CAL0107). These cataloged bandpasses need to be supplied with sufficient accuracy to support the majority of anticipated Standard Observing Mode spectral line projects. Support for CAL0125 (50 dB spectral dynamic range) can be provided without requiring per-polarization per-channel amplitude accuracy anywhere near 0.01% (38 dB, for dual polarizations on $N = 123$ antennas). A more reasonable target for per-polarization per-channel bandpass amplitude accuracy is $\Delta s = 1\%$. This target is not strongly constrained, though the calculation below indicates significant challenges in delivering greater accuracy due to higher signal to noise requirements (at which point atmospheric and pointing limitations will arise). The accuracy in the bandpass is given by

$$\Delta s = \frac{\sigma_{cal}}{S_{cal}} \sqrt{2N} \ , \tag{14}$$

where S_{cal} is the flux density of the bandpass calibrator, σ_{cal} is the array sensitivity (all baselines) for the bandpass calibrator observation, and the factor of 2 represents statistically-independent bandpasses for each polarization on N antennas. To achieve $\Delta s = 1\%$ with $N = 123$, the signal to noise on the bandpass calibrator must be 1500 (32 dB). The anticipated thermal noise of the ngVLA using $N = 123$ antennas over a 30 min integration in a 0.1 km/s channel is approximately 0.85 mJy/beam in the frequency range between 16–50 GHz [AD04]. A 30 min integration is selected here because it may be necessary to quickly recalibrate an antenna following maintenance, e.g. following replacement of an IRD package. This could be achieved using regular brief service-mode observations of bright calibrators with the full array, e.g. in between science blocks (note similar need in Section 6.4.2). Alternatively, if a longer timescale between maintenance and reintegration into the array is acceptable, such as 1 week or 1 month (this will depend on the anticipated fraction of out-of-service antennas in any week or month), then bandpasses can be recalibrated during these windows using longer integration times and in turn fainter sources. Accepting here the worst-case 30 min timescale (per band per maximum number of concurrently observed 0.1 km/s channels), a calibrator with flux density $S_{cal} > 1.3$ Jy will therefore be required for bandpass calibration. This should not be problematic. The corresponding requirement on bandpass phase accuracy is half this [RD03], namely $0.3°$. CAL0502 calls for these accuracies to be maintained within 0.1 km/s channels across all ngVLA frequency space. The various filter responses (baseband, subband) will need to be taken into account in order to average these 0.1 km/s solutions to improve accuracies when using broader channel widths. The calibrations for delay and amplitude described in the previous sections will need to be applied to the data prior to bandpass measurement, so as to remove systematics associated with the troposphere (differential opacity across band) and ionosphere (phase change $\propto 1/\nu$ across band); i.e. bandpasses stored in the calibration database should only contain the instrumental contribution described at the start of this section. It is expected that there will be sufficient accuracy in the delay and amplitude calibrations to remove the atmospheric contributions to the bandpass to well within the target accuracies above. However, this expectation should be subjected to further scrutiny in future investigations. When applying the cataloged bandpasses under the default calibration procedure (CAL0501), the effects of the atmosphere should again be handled by other portions of the calibration workflow.

For reference, the dynamic range limit within a single spectral channel which is limited by errors in continuum subtraction caused by bandpass errors is given by

$$D_s \approx S_{line} \left(\frac{\Delta s}{\sqrt{2N}} S_{cont} \right)^{-1} \quad , \tag{15}$$

where S_{line} is the flux density of the peak of the line and S_{cont} is the continuum flux density of the source. Assuming for argument's sake $S_{line} = 0.1$ mJy/beam, $S_{cont} = 10$ mJy/beam, $N = 123$, and $\Delta s = 1\%$, the channel dynamic range will be $D_s \approx 12$ dB. To improve this dynamic range, greater accuracy in the bandpass will be required. This calculation suggests that either the cataloged bandpasses will require greater accuracy than $\Delta s = 1\%$ to support a wider range of plausible observational scenarios, or instead it may argue for the creation of an 'enhanced' bandpass calibration procedure in which justified proposals can request suitable observations of a bandpass calibrator. Further work is required to compare these alternatives and, if necessary, refine the proposed calibration procedures and requirements (noting as earlier that atmospheric and pointing limitations combined with practical observing time limitations will ultimately prevent significantly improved accuracy beyond $\Delta s = 1\%$ for even wide channel widths). To ensure optimal scheduling, and in anticipation of a decision regarding the options above, CAL0505 requires the proposal process to capture the estimated dynamic range per spectral channel so that a decision can be made as to whether the observatory should supply a more accurate bandpass at the frequency of interest (eventually building up more accurate bandpasses across the full frequency space), or whether custom bandpass calibration procedures should be included in the scheduling blocks for that particular project.

Bandpasses must be stable on short timescales to prevent errors caused by effective amplitude variations (resulting in reduced spectral line and image dynamic ranges) and stable on long timescales to enable reuse of solutions from the calibration database (to optimize observing efficiency). To ensure that systematic errors in bandpass amplitudes (i.e. a systematic offset for all channels across a bandpass) do not limit image dynamic range to less than 53 dB (CAL0123, also CAL0122), bandpass amplitudes must be stable to within 0.3% over 1 hour timescales (calculated using Equation 13 assuming a 15 hour observation of a fractional bandwidth that is spanned in the worst-case by only a single statistically-independent bandpass; recall Section 6.3.2.1 for the motivation behind 15 hours). The corresponding requirement on phase is half this [RD03], namely 0.08°. These requirements also extend to 1 month timescales (or ideally much longer) so as to minimize the frequency of bandpass recalibration and maximize observing efficiency.

6.6 Polarization

Parameter	Req. #	Value	Traceability
Feed Basis	CAL0601	All antennas shall be equipped with dual orthogonal linear feeds in all frequency bands. In each frequency band, all feeds over the array shall be nominally aligned to a common specified orientation with respect to the sky frame (e.g. X feed aligned at specified angle 0° from the meridian at zero parallactic angle).	CAL0111, CAL0112, CAL0115
Default Polarization Calibration	CAL0602	Apply leakages from calibration database and measure crosshand bandpass phase from internal pulsed comb generators. Do not include polarization calibration scans in science observation scheduling blocks, nor use calibrators from the data to measure polarization parameters.	CAL0105, CAL0107, CAL0112, CAL0115, CAL0601
Leakage Accuracy	CAL0603	The observatory shall measure absolute leakages within complex error modulus 1% within 10 km/s channels across all frequency space. To enable more accurate solutions to be obtained over broader channels by averaging the 10 km/s solutions, the latter will need to be measured and stored in a way that enables accountability of spectral features.	CAL0120, CAL0123, CAL0124
Leakage Stability	CAL0604	Stable within band-averaged leakage modulus error 0.07% for at least 3 months. Goal: indefinite.	CAL0107, CAL0120, CAL0123, CAL0124

Parameter	Req. #	Value	Traceability
Calibration Database: Leakages	CAL0605	The observatory shall supply absolute leakages satisfying CAL0603 and CAL0604 in a calibration database, updating solutions where appropriate (e.g. if the advertised accuracy is no longer satisfied due to slow degradation over time or a step change arising from antenna maintenance).	CAL0105, CAL0602
Calibrator Database: Polarization Calibrators	CAL0606	Maintain register of sources used for leakage, circular polarization, and feed alignment calibrations and capture their polarimetric properties. This information shall be used only for guidance, not for calibration purposes; for example to determine if they exhibit variability (in which case they should be avoided).	CAL0604
Relative Gain Amplitude Stability	CAL0607	Stability between polarization pairs within 0.05% over 5 min.	CAL0123, CAL0124, CAL0401
Crosshand Bandpass Phase Stability	CAL0608	Pulsed comb generator calibration system installed in all receivers on all antennas, delivering channelized crosshand phase error 0.5° per second with sufficient channel width (spectral resolution) to sample all crosshand bandpass features.	CAL0111, CAL0112, CAL0115, CAL0116, CAL0123, CAL0124
Feed Mechanical Alignment	CAL0609	Setting within 2° rms from target alignment (CAL0601) per antenna.	CAL0123, CAL0124
Rotation of Feed Platform	CAL0610	Rotation within 0.01° rms from target alignment (CAL0601) under all environmental conditions.	CAL0112, CAL0123, CAL0124
Pipeline Ingestion of GPS VTEC	CAL0611	The pipeline shall ingest and make use of GPS-derived VTEC data with ~ 5 min time resolution to account for ionospheric Faraday rotation.	CAL0123, CAL0124

Parameter	Req. #	Value	Traceability
Antenna Re-Calibration Following Maintenance	CAL0612	When finalizing ngVLA procedures and designs, consider implications for re-calibrating parameters for antennas that have been recently serviced, for example following an IRD swap. A globally optimized schedule likely argues for a regular (e.g. weekly) 'calibration day', despite some antennas remaining idle between calibration days.	CAL0106, CAL0111, CAL0112

The polarization properties of an astronomical signal will be modified by the polarimetric response of the telescope. Ionospheric Faraday rotation will also contribute toward this imprint. These effects must be measured and removed through polarimetric calibration. There are several antenna-time-frequency dependent parameters of interest: leakage, crosshand bandpass phase, and absolute alignment of linear polarization position angles. These are described below.

Polarization calibration typically requires good coverage in parallactic angle so that the astronomical source contributions which vary sinusoidally in the antenna frame can be separated from the antenna-fixed instrumental contributions. There are a range of possible polarimetric calibration strategies, each somewhat different depending on the receptor feed basis (linear, circular), and each yielding solutions with slightly different degeneracies that result in slightly different errors in calibrated data. For reference, RD31 presents detailed step-by-step procedures for automating a suite of polarimetric calibration strategies in the linear and circular feed bases (designed for the CASA[11] ALMA and EVLA pipelines). RD15 presents a summary of interferometric radio polarization fundamentals, as well as a detailed examination of the roles of parallactic angle coverage and calibrator signal to noise in minimizing on-axis image leakage residuals and linear polarization position angle errors.

The leakage terms ('dipole' terms or d-terms) describe imperfections in the on-axis polarimetric response of each feed, quantifying the degree to which each feed is sensitive to an orthogonally polarized signal (cross-talk). The imperfections can arise from telescope geometry (e.g. asymmetries in antenna illumination, feed horn, optical alignment) and electronic hardware (e.g. polarization splitter, linear to circular polarization converter if present). Leakage solutions can be 'absolute' or 'relative', depending on whether there are sufficient observational constraints to uniquely determine all real and imaginary leakage components, or whether there are two remaining unconstrained degrees of freedom [RD30]. To overcome the degeneracy in the latter case, the real and imaginary components for one feed on one antenna (typically on the bandpass/gain reference antenna) can be (arbitrarily) set to zero, yielding relative leakages for all other feeds. When sufficient constraints are available to uniquely determine all leakage components,

[11] https://casa.nrao.edu/

absolute leakages will be obtained. Crosshand bandpass phase describes the relative phase between two orthogonally polarized feeds on an antenna (this can be separated into delay and phase and solved for independently in the measurement equation; for simplicity here, the term phase will strictly refer to the residual nonlinear frequency dependent part). A crosshand phase arises because the measurement equation is typically refactored to the relative phase frame of the bandpass/gain reference antenna, on which the phases for both polarizations are set to zero (the crosshand bandpass phase for the reference antenna is then propagated over the array). Finally, external calibration is required to determine the absolute alignment of linear polarization in the same way that an interferometer cannot self-calibrate the absolute flux density scale. In the circular feed basis, this requires observation of a celestial source with known position angle. However, in the linear feed basis, this is not always required. Instead, position angle calibration can be satisfied by obtaining absolute leakages (or accepting larger position angle uncertainty using relative solutions) and ensuring that feeds are nominally aligned with respect to the sky frame. See RD15 (and below) for more details regarding these parameters.

Before examining ngVLA requirements related to leakage, crosshand bandpass phase, and absolute position angle, the motivating factors behind the overall proposed polarimetric calibration strategy and related choice of hardware feed basis are described. The following will temporarily ignore the assumption of linear feeds from Section 6.1 and instead identify which of the circular, homogeneously-aligned linear, or heterogeneously-aligned linear feed bases is best suited for ngVLA design.

6.6.1 Motivating Factors for Calibration Strategy

A key requirement for ngVLA design is that polarimetric calibration overheads must be minimized (CAL0112, CAL0115). This must be satisfied regardless of whether a short or a long polarization science observation is requested, i.e. both must be supported. This effectively requires polarimetric calibration overheads (most importantly, leakages) to be decoupled from science observing blocks, for the following reasons. First, options to obtain sufficient parallactic angle coverage are problematic. For short science observing blocks, either the observing block timeframes would need to be artificially inflated, or other science blocks would need to be interrupted to enable the polarization calibrator to be viewed over a range of parallactic angle slices. This would lower observational efficiency and increase scheduling complexity, in turn arguing against such a scheme. And second, calibration using a short observation of a calibrator with known Stokes vector is also problematic. It will be onerous to maintain a database of polarization calibrators with known Stokes vectors (including 'unpolarized' calibrators). While possible, the observational overheads and complexity required to account for source variability in all frequency bands suggests that calibration schemes that require availability of such a database should be disfavored.

For completeness, potential solutions to support short polarimetric science observations are as follows, though these are not advocated here because they require calibration overheads to be included in each science observation. First, it is conceivable to perform leakage calibration using a single observation of a resolved polarized source with spatially varying and unknown (though non-zero) fractional polarization

[RD30]. A second possibility is to utilize the differential parallactic angle over the array to enable calibration using a short observation of a polarized source. However, these two schemes are not generally applicable because it cannot be assumed that all standard mode science observations will require long baselines. While the long baselines could be employed for only the calibration observations, this would require interrupting likely concurrent long baseline science observations and would lead to a reduction in overall observing efficiency. A third possibility in the case of linear feeds is to provide instantaneous parallactic angle coverage over arbitrarily short baselines by (permanently) rotating the mechanical alignments for a subset of the feeds in the array [e.g. RD33]. This heterogeneously-aligned linear feed basis would enable calibration using a short observation of a polarized source. However, this is a complex and potentially costly approach because it would affect designs for the front end including cryostat sizing (or possibly rotation of the entire dewar assembly including positioner), manufacturing scalability, and maintenance. Furthermore, if the need to perform leakage calibration in a snapshot observation is removed, then the need for this additional complexity is also removed because standard calibration techniques can be performed instead (utilizing sufficient parallactic angle during observatory service time).

Instead, to improve observing efficiency (CAL0115), CAL0602 defines a default leakage calibration procedure that minimizes overheads by utilizing observatory-supplied leakages accessed from a calibration database (CAL0105). If the leakages, crosshand bandpass phase, and absolute position angle alignment can be known a priori, and if they remain stable or can be updated as needed with time, then polarimetric calibration overheads will not need to be included in any science scheduling blocks. To achieve this, observatory-managed calibration observations must ensure that sufficient time is dedicated to sampling sufficient parallactic angle coverage to yield accurate leakages. This parallactic angle coverage is needed not only to optimally separate the instrumental and source contributions, but also to provide optimal uv coverage so that resolved source structure can be accounted for in the solutions. This process must yield absolute leakages, regardless of whether circular or linear feeds are selected, to prevent dynamic range limitations at the ~ 30 dB level in polarization[12] [RD36]. A feature of the approach above is that the observatory will only need to identify a small number of ideally highly linearly fractionally polarized sources (as few as one) per frequency band to be utilized as leakage calibrators. Infrequent monitoring of these sources will be required, but only to ensure that their fractional linear polarization has not diminished below a few percent prior to any necessary future leakage re-calibrations.

6.6.2 Choice of Feed Basis

The details of how to implement the strategy above, including effects on overall observing efficiency, depend on the choice of polarization feed basis. Having dispensed of the heterogeneously-aligned linear feed option above, the choice remains between circular and homogeneously-aligned linear feeds. In the following, the term ‘linear’ will assume the parallel alignment configuration. Historically there have

[12] To first order in the product between d-terms and Stokes Q or U, when observing in the circular or linear feed basis, total intensity image dynamic range will be unaffected when comparing between relative and absolute leakages (cf. RD36). However, this assumes careful calibration so that gain corrections do not prevent cancellation of orthogonal d-terms.

been a number of arguments for choosing circular feeds over linear feeds (e.g. see discussion in RD30). However, (as made clear by RD30) these are based on a number of assumptions that require more careful evaluation for ngVLA, especially when considering the ideal strategy described above. First is the argument that to measure high accuracy linear or circular polarization, a circular or linear configuration, respectively, is desirable. However, for telescopes with good gain stability (as is required for the ngVLA; see in particular Section 6.4), the distinction becomes negligible. A concern in the linear basis might be that the switched power system at low frequencies could become corrupted by RFI (albeit unlikely given that it would need to mimic slow parallactic angle rotation of a polarized source), but this can be addressed by suitable RFI mitigation (i.e. CAL0406). Second, a similar concern is sometimes raised regarding the ability to self-calibrate calibrated total intensity data in the linear basis, due to the need to incorporate knowledge of the target's linear polarization properties (though note that this issue is not strictly relevant here because, following Section 6.1, this document purposely seeks solutions that do not require self-calibration to meet ngVLA performance requirements). There are of course two solutions: iterate using polarization-independent gains (CASA 'T' gains) so that the (slightly incorrect) polarization and leakage contributions in the parallel hands will be mostly canceled (consider $V_{XX}+V_{YY}$ in equations below), or perform full-polarization self-calibration. Third, polarimetric calibration procedures are often simpler in the circular feed basis, but this is only true if relative leakages are acceptable. It is not true if absolute leakages are desired (e.g. see overheads in RD34), as required for ngVLA (see above). Finally, consider absolute position angle calibration. In the circular feed basis, a calibrator with known position angle must be observed. However, this will likely present a challenge for ngVLA because a source model (or set of models for a small number of sources) will need to be measured (and presumably maintained) to ensure that resolved source structure is properly accounted for over the large range of array baseline lengths. While not impossible (especially if motivated as a dedicated observatory deliverable; consider RD35 as a starting point, combined with common VLBI procedures), an easier alternative is provided in the linear feed basis. There, the need for celestial position angle calibration can be simplified if all feeds are aligned to the sky within some mechanical alignment tolerance (e.g. X nominally aligned at a specified angle[13] from the meridian at zero parallactic angle). As with the circular basis, a linearly polarized source will be required to measure the crosshand bandpass phase, but unlike the circular basis, the position angle of this source will not need to be known as the objective is simply to detect the phase difference between the signal paths from the two orthogonal feeds [RD30]. Indeed, because the position angle of the source does not need to be known, an instrument-generated polarization calibration signal can be used in the linear basis to determine the crosshand bandpass phase.

Therefore, from a calibration perspective for ngVLA, there are no strong arguments for ruling out circular or linear feeds, and there is a slight preference for the latter. The unbiased considerations above lend support to the current ngVLA Reference Design, in which all antennas are equipped with dual orthogonal linear feeds in all frequency bands. Given the considerations above, CAL0601 stipulates that all feeds in any given frequency band shall be oriented with the same nominal alignment against the sky frame (i.e. the homogeneously-aligned case).

[13] When the specified angle is $0°$, the X and Y feeds may also be termed the vertical V and horizontal H feeds, respectively.

The assumption of linear feeds in the current ngVLA Reference Design is therefore strongly supported by the combination of calibration arguments above, the desire to access wider usable bandwidths than available from circularly polarized feeds (enabling coverage between 1.2 GHz to 116 GHz with fewer receivers), and by the desire to optimize sensitivity and reduce complexity due to lack of polarization conversion from the native linear sampling.

6.6.3 Implications

Implications for ngVLA design will be examined below, motivated by consideration of absolute leakage, crosshand bandpass phase, and absolute position angle calibrations assuming parallel linear feeds.

Following notation from RD15, the model visibilities for a single baseline (antennas indices i and j) corrupted by parallactic angle ψ, complex leakage d_{Ak} (indicating the fraction of orthogonal polarization B sensed by feed A on antenna k), and crosshand phase ρ are given by

$$V_{XX} = (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Xi} + d^*_{Xj}) \tag{16}$$
$$V_{XY} = [(\mathcal{U}_\psi + i\,\mathcal{V}) + \mathcal{I}\,(d_{Xi} + d^*_{Yj}) - \mathcal{Q}_\psi\,(d_{Xi} - d^*_{Yj})]\,e^{i\rho} \tag{17}$$
$$V_{YX} = [(\mathcal{U}_\psi - i\,\mathcal{V}) + \mathcal{I}\,(d_{Yi} + d^*_{Xj}) + \mathcal{Q}_\psi\,(d_{Yi} - d^*_{Xj})]\,e^{-i\rho} \tag{18}$$
$$V_{YY} = (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Yi} + d^*_{Yj}) \tag{19}$$

where Stokes $\mathcal{Q}_\psi \equiv \mathcal{Q}\cos 2\psi + \mathcal{U}\sin 2\psi$, Stokes $\mathcal{U}_\psi \equiv \mathcal{U}\cos 2\psi - \mathcal{Q}\sin 2\psi$, and terms multiplied by second order leakages (e.g. $d_{Xi}\,d^*_{Xj}$) are neglected. The terms above are frequency dependent. Antenna feeds are typically engineered with great care to be orthogonal such that $d_{Xi}+d^*_{Yi}=0$. The approximate level of spurious post-calibration linear ($\mathcal{L}_\epsilon$) or circular ($\mathcal{V}_\epsilon$) polarization for an on-axis target with total flux density $\mathcal{I}$ is given by

$$\frac{\mathcal{L}_\epsilon}{\mathcal{I}} \approx \frac{\mathcal{V}_\epsilon}{\mathcal{I}} \approx \frac{\sigma_d}{\sqrt{N}} \approx \frac{\sigma_{dc}}{\sqrt{N N_c}}\ , \tag{20}$$

where N is the number of antennas in the array, and $\sigma_d = \sigma_{dc}/\sqrt{N_c}$ is the real-valued magnitude of the residual complex error for one polarization on one antenna after band-averaging channelized complex leakage errors with typical magnitude σ_{dc} over N_c channels [RD15]. This equation implicitly assumes $M = 1$ (see notation from RD03), namely that leakages are constant throughout the observation (examined further below).

CAL0120 and CAL0124 call for 40 dB brightness dynamic range in a continuum image of linear or circular polarization. CAL0123 calls for 50 dB brightness dynamic range in total intensity. These requirements place constraints on d-term accuracy. Assuming conservatively $N_c = 200$ channels across a frequency band (note that the edge $\sim 10\%$ of channels in any band will likely exhibit degraded performance) with $N = 123$ antennas, channelized $\sigma_{dc} = 1\%$ ($\sigma_d = 0.07\%$) is required to attain 42 dB image dynamic range in linear or circular polarization. This will also be sufficient to satisfy CAL0123; -42 dB residual leakage from Stokes I to linear polarization implies that, for targets with $\sim 10\%$ linear polarization (approximate upper limit relevant for extragalactic sources in CAL0123 deep field studies), residual leakage from linear polarization to Stokes I will be below -52 dB (e.g. consider forming Stokes I from Equations 16 and 19).

Absolute leakages are necessary for two key reasons. First, as motivated earlier, they are required to facilitate high dynamic range imaging. If relative leakages are obtained, the unknown real and imaginary d-term offsets will limit image dynamic range[14] to ~ 30 dB in polarization [RD36]. For example, the polarization limit can be crudely estimated by considering amplitude errors arising from corruption of Equation 17. Assuming 2% band-averaged leakages[15] per polarization per antenna, in which case the relative real offset over the array will be $\sim 2\%$, and assuming a 5% linearly polarized target, the polarimetric dynamic range will be limited to $1/(0.02 \times 0.05) \approx 30$ dB. And second, absolute leakages are required to set the zero-point for circular polarization. If relative leakages are obtained, the unknown imaginary component of the d-term on the reference antenna's X feed (arbitrarily set to zero in CASA, and propagated over the array) will translate to an unknown offset in circular polarization. External calibration is required to determine this offset, in the same way that an interferometer cannot self-calibrate the absolute flux density scale. Ideally this would be accomplished using an observation of an absolute circularly polarized flux density calibrator. However, no such sources are known. Rather than attempt to identify and monitor such sources, an alternative is to apply a statistical constraint by observing a sample of circularly polarized sources (per frequency band) and assuming that the Universe has no preferred handedness for circular polarization [e.g. RD32]. If this is the case (or, if not, assuming that any systematic handedness is at a level below the accuracy required here for the imaginary leakage component), then the imaginary component can be set by the mean level (zero-point) of circular polarization over the sample. The required accuracy in band-averaged imaginary leakage offset is 0.01% to yield unbiased 40 dB circular polarization dynamic range. Therefore, a sample of ~ 100 sources exhibiting $\sim 0.1\%$ fractional circular polarization (typical level for sources investigated by RD32) will be required to yield an uncertainty in their mean (zero-point) of 0.01%. This does not seem unreasonable for an observatory program.

For completeness, it should be noted that absolute leakages will deliver more accurate absolute position angle alignment than relative leakages, although unlike above this is not a key motivation for seeking absolute leakages. If relative leakages are obtained, the unknown real component of the d-term on the reference antenna's X feed (arbitrarily set to zero in CASA, and propagated over the array) will translate to an unknown offset in absolute position angle given by the magnitude of the true $\mathrm{Re}(d_{X,\mathrm{ref}})$ [e.g. RD15]. For example, assuming 2% band-averaged leakages, the resulting absolute position angle uncertainty when using relative leakage solutions will be $\sim 1^\circ$. This is unlikely to be significant for scientific position angle measurements. This error will be systematic for any given observation. Changes

[14]Strictly, as discussed by RD36, there are circumstances in which dynamic range will not be limited, but rather fidelity (i.e. a systematic difference between the reconstructed and true sky). Absolute leakages are therefore further motivated by the desire to avoid such subtleties between the types of errors incurred.

[15]If channelized leakage amplitudes are 2% and there are minimal frequency-dependent variations in leakage phase across the band, then the band-averaged systematic leakage will be of the same magnitude.

in absolute position angle alignments between observations in a multi-epoch dataset will degrade polarimetric image dynamic to ~ 30 dB (see calculation below assuming $\Delta\theta = 1^\circ$ and neglecting the factor $1/\sqrt{N}$), though this can be mitigated in software by ensuring that the selected reference antenna is available in each observation. However, whether relative or absolute leakages are recovered, accuracy in the d-term solutions for each epoch will also produce differences in absolute position angle alignment between epochs. To illustrate, consider effective gain errors in Stokes U that will lead to degraded polarimetric dynamic range. Assuming fractional linear polarization $L/I = \sqrt{Q^2+U^2}/I = 5\%$ where $\vec{L} = Q + iU = Le^{i2\theta}$ with position angle θ, observations at zero parallactic angle and nominal Stokes $U = 0$ without loss of generality, $\sigma_d = 0.07\%$ (as above), $N = 123$ antennas, and absolute position angle variation between observations $\Delta\theta = 0.004^\circ$ arising from systematic offset $\sigma_d/\sqrt{N} = 0.006\%$, variations in Stokes U in the combined dataset will be $\Delta U/I = \sin(2\Delta\theta)\,L/I = 0.007\%$. Assuming these differences are randomized over at least 4 observations (following motivation in Section 6.3.2.1 for ~ 4 hour scheduling blocks over a total of 15 hours), the effective dynamic range limit in linear polarization will be ~ 55 dB. This is sufficient to satisfy CAL0124.

An additional systematic position angle offset will be present, even if absolute leakages are obtained, even if these leakages are known with zero error, and indeed even if these leakages are identically zero, because each antenna in the array will exhibit a nonzero error in mechanical feed alignment about their design orientation (i.e. even if the dipoles on any given antenna are perfectly aligned with respect to each other, they may be misaligned with respect to a neighbouring antenna; antenna leakages are antenna-based and do not capture this information). This will lead to an offset between the assumed and true sky frames. In principal, external absolute position angle calibration is required to account for this offset. However, if mechanical offsets are sufficiently small, then external position angle calibration will be unnecessary. From an engineering perspective, it is very difficult (and therefore costly) to set the alignment of each feed to better than 1° rms. An uncertainty of 2° rms is considered to be a reasonable target (e.g. as demonstrated by ALMA; RD38). For an array with $N = 123$ antennas, 2° rms implies a systematic position angle offset of 0.2°, which exceeds any reasonable scientific expectations for position angle accuracy. However, differences in feed alignments across the array will also produce gain errors that will limit image dynamic range. Following notation from RD15, incorporating characteristic difference $\alpha = \sqrt{2}\beta$ in the otherwise common parallactic angles viewed by two antennas over a baseline where β is the rms feed alignment uncertainty per antenna, ignoring leakages, and assuming (without loss of generality) observation at zero parallactic angle, the relationship between the four reconstructed Stokes parameters (primed) and the Stokes parameters that would be measured from ideal visibilities (unprimed) is given by[16]

$$
\begin{aligned}
I' &= I\cos\alpha - iV\sin\alpha && (21)\\
Q' &= Q\cos\alpha + U\sin\alpha && (22)\\
U' &= U\cos\alpha - Q\sin\alpha && (23)\\
V' &= V\cos\alpha - iI\sin\alpha\ . && (24)
\end{aligned}
$$

[16] See also RD37 for a derivation of these equations, though note errors in sign and in the interpretations of the equations.

The effects are as follows. Amplitude calibration will offset antenna-based gains by mean $\cos\alpha$, but the scatter in these solutions will yield antenna-based gain errors[17] $(1-\cos\beta)$ that will limit image dynamic range to approximately $\sqrt{N}/(1-\cos\beta)\approx 43$ dB (using Equation 1) for $\beta=2^\circ$ and $N=123$ antennas (or 49 dB for engineering minimum $\beta=1^\circ$). Feed alignment errors must be within 0.6° to deliver 53 dB and in turn satisfy CAL0122 and CAL0123. Equations 22 and 23 indicate that linearly polarized intensity will be unaffected (i.e. $L'=\sqrt{(Q')^2+(U')^2}=L$). Similarly, the mean polarization position angle over all baselines will be unaffected, though position angles measured along all baselines to any given antenna will exhibit scatter with magnitude[18] $\beta/2$. This scatter will lead to errors in linear polarization entering Equations 16–19 and in turn degrade image dynamic range in all Stokes parameters. A worst-case dynamic range limit can be estimated using the relationship for $\Delta L/I$ above and assuming a target with fractional linear polarization $\sim 10\%$, giving $\sqrt{N}/(L/I\times\sin\beta)\approx 35$ dB for $\beta=2^\circ$ and $N=123$ antennas (or 38 dB for engineering minimum $\beta=1^\circ$). Feed alignment errors must be within 0.03° to deliver 53 dB and in turn satisfy CAL0122 and CAL0123. Finally, Equation 24 indicates that $I\sin\alpha$ will contaminate the real part of the cross-hand visibilities (Equations 17 and 18), namely linear polarization (Stokes V will be unaffected), with zero systematic mean offset (due to the odd function of $\sin\alpha$) and non-zero scatter. The scatter will yield effective antenna-based gain errors that will lead to dynamic range limitations when imaging linear polarization. These gain errors can be estimated by $\sqrt{N}/(\sin\beta)\approx 25$ dB for $\beta=2^\circ$ and $N=123$ antennas (or 28 dB for engineering minimum $\beta=1^\circ$). Feed alignment errors must be within 0.03° to deliver 43 dB and in turn satisfy CAL0124.

It will not be possible to deliver mechanical feed alignment accuracy within $\beta=0.03^\circ$. However, this can be accomplished using celestial calibration. Engineering mechanical feed alignment can then be relaxed to a realistic target of 2° rms. Feed alignment calibration requires a linearly polarized source with antenna-based SNR $(2\beta)^{-1}\approx 30$ dB (RD07 Equation 9.67 with factor 2 for position angles). Assuming a target calibrator with fractional linear polarization no less than 6%, this implies a calibrator with antenna-based total SNR 42 dB. This is at the approximate polarization dynamic range limits described earlier, and will therefore require careful examination to determine if more accurate leakage calibration is required (though this may be satisfied automatically using the calibration database leakages described below; database narrow channel leakages can be averaged together over wider channels relevant here, further improving the polarization dynamic range limit). The thermal noise of the ngVLA using $N=123$ antennas in a 1 hour period with 50% fractional bandwidth is anticipated to be no worse than 2 μJy/beam. A calibrator with total flux density greater than 0.4 Jy is therefore required. The absolute position angle of the calibrator does not need to be known. However, the calibrator must be spatially unresolved on all baseline lengths of interest so that they all see the same position angle. This may be challenging to ensure over short baselines; however, this can be overcome by specifying a minimum baseline length for the calibration and extending the time period for the observation accordingly. Calibrators exhibiting variability over hourly timescales must be avoided.

[17] Gain errors scale with β rather than α because the former is the typical misalignment that an antenna will see against the average misalignment from all other antennas (i.e. against $\beta/\sqrt{N-1}\approx 0^\circ$).

[18] The factor of 2 arises because position angles are periodic in 180°.

Feed alignments must remain stable indefinitely, accommodating in particular any quasi-static systematic antenna deformations (e.g. thermal deformation) that could lead to systematic rotation in the feed platform. It is reasonable to expect (and require) that this can be satisfied by antenna design, which must support blind pointing under normal conditions within $< 0.01^\circ$ (see requirements in Section 6.2.1). Note the alternative: if feed alignment stability cannot be maintained, calibration will need to be performed regularly during science observations (e.g. tracking antenna deformations sampled by offset pointing calibration), resulting in an unacceptable decrease in observing efficiency (CAL0112). Short-term instability may be acceptable as long as it integrates down to within 0.01° over the time period of interest (e.g. wind loading, and perhaps sunrise/sunset where differential heating/cooling may temporarily 'inflate'/'deflate' the structure in an unpredictable manner before settling within a steady state). CAL0610 highlights this issue in a formal requirement.

The absolute leakages will need to be supplied to science observations through a calibration database, with sufficient spectral resolution to support Standard Observing Mode projects. There are no requirements on this spectral resolution, so 10 km/s over all ngVLA frequency space will be assumed (33 kHz at 1 GHz, 3.3 MHz at 100 GHz); this may be subject to change in the future. The various filter responses (baseband, subband) will need to be taken into account so that stored solutions can be averaged as required to supply science observations with channel widths greater than 10 km/s. Such averaging will also improve leakage accuracy, but only down to the level of atmospheric and pointing limitations associated with the leakage calibrator observations. Interpolation may be used to support narrower widths, though reduced accuracy will need to be accepted in these cases. Should these derived products be insufficient for some Standard Observing Mode projects, it may be necessary to consider the creation of 'enhanced' polarization calibration procedures in which justified proposals can request suitable observations of polarimetric calibrators.

To deliver leakage amplitude accuracy $\sigma_{dc} = 1\%$ per channel with $N = 123$ antennas, the signal to noise on the leakage calibrator must be $\sqrt{2N}/\sigma_{dc} \approx 1600$ (32 dB). The thermal noise of the ngVLA using $N = 123$ antennas in a 20 min integration is anticipated to be no worse than 0.75 mJy/beam within a 10 km/s channel in any frequency band. A calibrator with flux density $S_{cal} > 1.2$ Jy will therefore be required for leakage calibration. This should not be problematic.

Additional requirements for the observatory-managed procedure to measure absolute leakages are as follows. Only (ideally strongly) linearly polarized calibrators can be accepted for absolute leakage calibration; position angle calibration (solving for the real component of the d-term on the reference feed) cannot be performed with an unpolarized source (as intuitively expected). Selected leakage calibrators must contain a compact polarized component that is detectable over all baseline lengths. Any selected leakage calibrator must be observed with sufficiently wide parallactic angle coverage so that intrinsic source structure (i.e. baseline dependence) will be taken into account in the solutions (similar to CAL0702). It will be necessary to account for (and ideally utilize for improved constraints) differential parallactic angle coverage over long baselines and the likely resolved fractional polarization structure of calibrators (see related comments in Section 6.6.1). To enable efficient calibration over all frequency space, 20 min integration time per bandwidth range (as above) can be interleaved over a multi-hour observing block. This will also need to include a circular polarization calibrator survey (as above). Care will need to be taken to account for, or avoid, sources that exhibit variability on short timescales, possibly minutes (e.g. see the polarimetric intraday variable in Figure 2 in RD32); variability on timescales associated with gathering parallactic angle coverage (hours) may be prevalent in the bright source population used to measure leakages and circular polarization. Polarization properties of leakage and circular polarization calibrators should be stored in a calibrator database, though only for the purpose of identifying variability (and thus potentially avoiding them in the future; see also comment at end of Section 6.6.1); quantitative details from these records should not be used when obtaining any new calibration solutions. Stability requirements for leakage solutions are addressed futher below.

The leakage solutions will be affected by Faraday rotation in the lower frequency bands. When linearly polarized radiation traverses a birefringent medium such as a magnetized thermal plasma, it will undergo Faraday rotation, resulting in a rotation of the position angle of linear polarization. The rotation arising from signal passage through the plasmasphere and ionosphere (dominated by the latter; see Section 6.3.2.2) is given by

$$\begin{aligned} \Delta\theta_f &= \frac{e\,c\,r_0}{2\pi m_e \nu^2} \int B_{los}(l)\, n_e(l)\, dl && (25) \\ &\approx \frac{1.35}{\nu^2}\, B_{los}\, N_e \;\; \mathrm{deg} \;\; , && (26) \end{aligned}$$

where e is the electron charge, c is the speed of light, r_0 is the classical electron radius, and m_e is the electron mass. The approximation in Equation 26 is for a thin shell ionized atmosphere with representative line of sight magnetic field B_{los} in units of gauss (positive when pointed toward the observer, and which can be suitably estimated by taking the Earth's $B_{los}(l)$ at the height of the weighted-column thin-shell; RD18), where ν is the observing frequency in units of GHz and N_e is the STEC in units of TECU (recall definitions from Equation 10). Alternatively, Equation 26 can be written in terms of rotation measure,

$$RM \approx 0.26\, B_{los}\, N_e \;\; \mathrm{rad/m^2} \;\; . \tag{27}$$

The STEC above each antenna can be estimated by combining GPS-derived VTEC maps, available from external sources such as the IGS, with a model of the Earth's magnetic field, such as that provided by the International Geomagnetic Reference Field (IGRF). The IGS 'Final' maps aggregate results from several analysis centers worldwide with 2 hour time resolution that are published with ~ 2 week latency. The Jet Propulsion Laboratory (JPL) Global Differential GPS System (GDGPS[19]) publishes real-time VTEC maps every 5 mins. Similarly, the Massachusetts Institute of Technology (MIT) Automated Processing of GPS (MAPGPS[20]) service publishes VTEC maps every 5 mins, but these differ from the sources above in that data are only provided along slightlines where satellites were present rather than interpolating to produce standardized TEC maps that are regularly sampled in latitude and longitude. Diurnal variations

[19] http://www.gdgps.net/products/tec-maps.html
[20] https://www.haystack.mit.edu/atm/arrays/gps/index.html

in VTEC at the VLA site typically range from a maximum of ~ 50 TECU to a third of this value at night (with further modulation from various dynamics highlighted in Section 6.3.2.2). STEC values rise with increasing zenith angle to within factor 5, or ~ 250 TECU, at $\sim 80°$. VTEC data such as that provided by the IGS typically exhibit uncertainties within ~ 2 TECU (best-case ~ 1 TECU, worst-case ~ 5 TECU). STEC uncertainties are then typically within ~ 10 TECU. The Earth's line of sight magnetic field at the VLA site ranges between 0 G to $+0.4$ G with typical value $+0.2$ G over the sky at the IGS-assumed 450km height of the thin-shell ionosphere [RD18]. The equations above indicate that changes in STEC and B_{los} throughout a long observation could lead to antenna-based variations as large as ~ 20 rad/m^2 in rotation measure, or equivalently $\sim 1°$ in position angle when observing at 10 GHz (band 2, relevant for CAL0123 and CAL0124). If GPS-derived VTEC data with 10 TECU STEC uncertainties are used to remove these variations when calibrating the telescope data, the residual errors could be as large as 1 rad/m^2, or respectively $0.4°$ and $0.04°$ at the lower (3.5 GHz) and upper (12.3 GHz) ends of band 2.

Variability in ionospheric Faraday rotation will cause position angles to be rotated above each antenna as a function of time, leading to scatter in Stokes Q and U and in turn degrading image dynamic range in all Stokes parameters. This is analogous to feed misalignment errors described earlier, characterized by Equations 22 and 23. The dynamic range limit arising from antenna-based rms fluctuations in position angle γ is then given by $\sqrt{MN}/(L/I \times \sin\gamma)$ where M is the number of statistically independent samples throughout the observation. This implies worst-case $\gamma < 0.1°$ to satisfy the 50 dB total intensity imaging requirement from CAL0123 (and automatically the 40 dB polarization imaging requirement from CAL0124), assuming $N = 123$ antennas, a target with 10% fractional linear polarization, and worst-case $M = 7$ for a 15 hour observation (recall Section 6.3.2.1 for the motivation behind 15 hours) over which the ionosphere deviates from a given VTEC model (e.g. IGS) with 2 hour coherence timescale. However, in reality, the ionosphere will exhibit a power spectrum of TEC fluctuations that will extend to much shorter timescales. Assuming a 5 min coherence timescale ($M = 60$), and assuming that this is tracked by GPS VTEC data that is sampled on a similar timescale (so that fluctuations on longer timescales will be removed), the requirement becomes $\gamma < 0.8°$. These results indicate that to satisfy CAL0123 and CAL0124, the ngVLA data reduction pipeline will need to ingest VTEC data to correct for ionospheric Faraday rotation. The results also indicate that the typical ~ 2 TECU accuracy of external GPS-derived VTEC data will be sufficient to satisfy CAL0123 and CAL0124; ionospheric Faraday rotation will not need to be measured using array observations of polarized calibrators, in turn avoiding the need for calibrator polarization selection criteria and associated monitoring and database overheads. Access to VTEC data with low latency at 5 min time resolution (e.g. GDGPS or MAPGPS, latter with improved spatial resolution) is required in order to minimize deviations between the true STEC values and the GPS-derived model, and more importantly to eliminate complications for ngVLA data reduction scheduling that would arise from the need to accommodate the 2 week latency of the IGS data. Careful commissioning will be required to ensure that any systematic biases in the ingested VTEC data are identified and removed, for example by comparing VTEC data with band 1 observations of a calibrator with known position angle (e.g. 3C286); it is known that there are systematic differences (~ 2 TECU) between the IGS, GDGPS, and MAPGPS reconstructed VTEC values. This is important for interpretation of the dynamic range calculations above, which assume fluctuations that integrate down with time, as well as the following. If fluctuations integrate down like white noise, then any residual leakage offset per observation along the real axis will be given by $\gamma/\sqrt{MN} \approx 0.005^{\circ}$ when assuming $M = 60$, $N = 123$, and $\gamma = 0.4^{\circ}$ (i.e. the worst-case value at 3.5 GHz). Following the calculation presented earlier for dynamic range limitations arising from absolute position angle differences between 4 observations, the dynamic range limit in linear polarization will be ~ 54 dB. This is sufficient to satisfy CAL0124. Finally, note that errors of 1 rad/m^2 arising from STEC uncertainties of 10 TECU imply position angle errors $\sim 4^{\circ}$ at 1.2 GHz. The associated dynamic range limit in total intensity is then ~ 43 dB. Celestial calibration may help to improve this limit, though note the similar 45 dB limit at 1.2 GHz arising from phase calibration (Equation 12).

If the true leakages are sufficiently stable with time, then calibration database solutions will remain valid for an extended period of time and re-calibration overheads can be minimized (CAL0107, CAL0115). Ideally, leakages should only need to be measured once, with results valid for years, or at minimum over the time period between antenna/receiver maintenance. Leakage solutions are expected to be stable with time because their origins are rooted in antenna and feed geometry (and good engineering). Variations arising from antenna deformation (e.g. differential heating, which gives rise to the need for offset pointing) or elevation changes (e.g. changing aperture illumination) are not expected to be significant within the leakage accuracy required here (systematic $\sigma_d = 0.07\%$). CAL0604 states this in a formal requirement. This stability will need to be demonstrated during the ngVLA commissioning phase. RD39 found that leakages on the Very Long Baseline Array (VLBA) were stable over a period of 16 months. Similarly, RD40 examined calibration stability for the Jansky Very Large Array (JVLA) at L-band over a period of 5.5 years, finding that leakages for each antenna remained stable over multiple years unless affected by a receiver change.

Some forms of antenna maintenance, and particularly changes in an antenna's IRD package, will result in new leakages for that antenna. When such events occur, the leakages (and other antenna-based calibration parameters) will need to be recalibrated. Several antennas may be serviced in any given week. A detailed service-mode calibration schedule will need to be developed to optimize the approach for re-calibrating these antennas and returning them to science observations (including ensuring compatibility with the needs of other calibrations like absolute amplitude and bandpass; recall Sections 6.4.2 and 6.5). For example, the highest overall efficiency may be achieved by targeting IRD replacements early in the week followed by a weekly 'calibration day', even if this means that one or two antennas could remain idle for up to a few days. A multi-hour (e.g. 10 hour) calibration run (which may not require the full array) could be performed every Wednesday with the aim to (automatically) process the data overnight and subsequently (semi-automatically) assess the results and update the calibration database on Thursday. This would provide regularity for personnel, and sufficient observing time to ensure that factors such as parallactic angle and frequency space can be sufficiently sampled without significantly affecting overall science observing efficiency. Alternatively, if absolute leakages can be calibrated using a very short observation (e.g. by taking into account the constraints provided by the majority of unaffected antennas with unchanged leakages), then antennas could be rapidly returned to science observations after completion of their maintenance visit.

Relative gain amplitude stability between polarization pairs on any given antenna is required to ensure that Stokes parameters and polarization calibration parameters can be accurately calculated. Stability is also required to satisfy image dynamic range limits, so that all correlation products can be calculated within the same levels of uncertainty. The requirement for crosshand gain amplitude stability is therefore the same as for noise diode stability (CAL0401).

The crosshand phase frame must remain stable to prevent corruption of the recovered Stokes parameters and leakages. To maximize observing efficiency (CAL0111, CAL0112, CAL0115), crosshand bandpass phase calibration must be performed using an instrument-generated calibration signal rather than repetetive observations of celestial calibrators. This can be accomplished by installing a pulsed harmonic comb generator [e.g. RD07 Sec. 9.5.7] in every receiver on every antenna. This system will inject an RF test signal as early as possible in each signal path. The injected signal can be sampled approximately every second to track changes in crosshand phase on the nominated reference antenna. This system must be installed on all antennas to minimize complexities associated with reference antenna changes within observations and between multi-epoch observations, and also for simplicity in design, scaling for production, and maintenance (e.g. IRD swapping). The inclusion of this hardware in all receivers on all antennas will also be invaluable for remote testing of system integrity; indeed, a requirement for pulsed comb generators on all receivers and antennas may be justified solely by the need to accurately diagnose problems over the full signal path prior to arranging (expensive) antenna maintenance visits (CAL0110). For this solution to be viable, it must be possible to build a comb generator with significant output at RF frequencies up to 116 GHz. Historically this has not been feasible, but recently the ngVLA project has become aware of a promising commercial vendor. If the pulsed comb generator approach remains unachievable in band 6, then the proposed strategy above will need to be reassessed, for example falling back to celestial calibration using a polarized source (with acceptable unknown position angle).

Crosshand phase measurement errors will behave similarly to leakage errors, leading to image dynamic range limitations (CAL0123, CAL0124). Equation 20 can therefore be rewritten as

$$\frac{\mathcal{L}_\epsilon}{\mathcal{I}} \approx \frac{\sigma_\rho}{\sqrt{M}} \approx \frac{\sigma_{\rho c}}{\sqrt{M N_c}} \;\;, \tag{28}$$

where $\sigma_\rho = \sigma_{\rho c}/\sqrt{N_c}$ is the residual crosshand phase error on one antenna after band-averaging statistically-independent channelized crosshand phase errors $\sigma_{\rho c}$ over N_c channels, M is the number of statistically independent time samples, and the number of antennas in the array (N) is not present (unlike Equation 20) because crosshand phase is propagated from the reference antenna over the array. For consistency with the leakage accuracy calculation presented earlier, it will be assumed here (conservatively) that $N_c = 200$ channels are sufficient to sample all crosshand bandpass features across a frequency band. Assuming 1 second sampling with errors that will integrate down over a 5 min. period (conservatively $M = 300$) so that accurate calibration may be achieved over a short observation (e.g. relevant for any rapid calibrations such as the leakage re-calibration approach described above), $\sigma_{\rho c} < 0.5°$ is required to satisfy CAL0124. Therefore each pulsed comb generator should ideally deliver channelized uncertainty $0.5°$ on a ~ 1 second timescale. This calculation will need to be reassessed if any of these assumptions are inappropriate, for example if channelized phase errors will not be statistically independent.

Finally, it is worth noting that the ngVLA could offer parallel-hand only observations (XX and YY only; e.g. see L4 calibration strategy in RD31, as used by ALMA), for example to reduce data rates or trade full cross-product correlation for increased spectral resolution. The ngVLA's amplitude stability, crosshand gain stability, and database leakages could be used facilitate this strategy (see also e.g. RD41).

6.7 Calibrator Structure

Parameter	Req. #	Value	Traceability
Calibrator Search and Characterization	CAL0701	Facilitate rapid (∼minutes) blind search and characterization (e.g. histogram of amplitude ratios over binned baseline lengths) of complex gain calibrators within 3° of any (accessible) sky coordinate. Prioritize re-detection of promising (minimally-variable) previously known calibrators from the calibration database.	CAL0102, CAL0108, CAL0704
Modeling of Calibrator Structure	CAL0702	Facilitate rapid (∼minutes) modeling of calibrator internal structure in total intensity (with a goal to perform this in full polarization).	CAL0102, CAL0108
Array Configuration Snapshot Performance	CAL0703	Ensure ngVLA antenna configuration is optimized to support robust snapshot calibrator modeling.	CAL0702
Calibrator Database: Source Ingest	CAL0704	Ingest new calibrator models into the calibrator database, noting that these will likely be time-dependent and so must be stored in a manner suitable for examining light curves and changes in source structure.	CAL0111, CAL0702

The wide range of baseline lengths proposed for the ngVLA will make it necessary to take into account the likely resolved structure of any given calibrator prior to using it for complex gain referencing or other purposes. Fortunately, the ngVLA's excellent snapshot uv coverage (arising from a rather random, non-geometric distribution of antenna locations) should enable rapid calculation of robust models of source internal structure from snapshot observations. CAL0701 requires the ability to quickly scan around a target region of sky to find a suitable calibrator. This will be of use in the automated preparation of both standard observing modes and triggered modes. CAL0702 requires the ability to rapidly derive a model of the calibrator's internal structure in total intensity, with a goal to perform this in full polarization (a side benefit of this effort will be a scientifically interesting database). CAL0703 is defined to ensure that the ability to derive a robust calibrator model from a snapshot observation is accounted for when optimizing the final fixed ngVLA antenna configuration. CAL0704 requires calibrator models to be compiled within a calibrator database so as to improve observational efficiency for future observations. Note however that this will likely only minimize the time required for calibrator search. Modeling of calibrator structure will likely need to take place every time a calibrator is used, to account for variability (particularly at higher frequencies).

6.8 Summary

The key L2 requirements are summarized as follows:

Pointing:	$3''/7''$ offset, $18''/42''$ blind, in precision/normal conditions
Primary Beam:	0.1% of boresight response within -10 dB power contour
Surface:	170 μm precision conditions, 400 μm normal conditions
Motion:	Slew $3°$ in 7 seconds including time to settle within offset pointing error
Baseline:	125 μm
Timing Accuracy:	0.2 μs over array
Feed Basis:	Linear feeds in all frequency bands with common alignment over array
Bandpass:	1% in 0.1 km/s channels
Polarization:	0.01% leakage and $< 0.2°$ angle on-axis; snapshot polarimetry supported
Amplitude:	Absolute flux density accuracy 1% best-case, 6% worst-case
Phase:	$0.7°$ in 1 second at 10 GHz (scaling $\propto \nu$ troposphere, $\propto 1/\nu$ ionosphere)
Amplitude Stability:	Internal switched power amplitude scale tied $\leq$monthly to celestial scale
Phase Stability:	Troposphere: WVRs on all antennas; Ionosphere: frequency switching
Crosshand Stability:	Amplitude: Switched power; Phase: Pulsed harmonic comb generators
Calibration Overheads:	Observatory maintained calibration database for maximal efficiency
Dynamic Range:	50 dB image at 10 GHz, 50 dB spectral in all bands
Automation:	Automated scheduling and pipeline data processing for standard modes
Antenna Reintegration:	Regular 'calibration day' to reintegrate antennas following maintenance

7 APPENDIX

7.1 Abbreviations & Acronyms

Acronym	Description
ALMA	Atacama Large Millimeter/submillimeter Array
CASA	The Common Astronomy Software Applications package
DIXSG	Disturbance ionosphere index spatial gradient
EVLA	Expanded Very Large Array
FWHM	Full-width at half-maximum
GDGPS	Global Differential GPS System
GPS	Global Positioning System
HPBW	Half-power beam-width
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IF	Intermediate frequency
IGRF	International Geomagnetic Reference Field
IGS	International Global Navigation Satellite System Service
IRD	Integrated receiver and digitizer
JPL	Jet Propulsion Laboratory
JVLA	Jansky Very Large Array
MAPGPS	MIT Automated Processing of GPS
MIT	Massachusetts Institute of Technology
RF	Radio frequency
RFI	Radio frequency interference
rms	Root mean square
ROTI	Rate of TEC index
SNR	Signal to noise ratio
STEC	Slant total electron content
TEC	Total electron content
TECU	Total electron content unit
uv	Spatial frequency plane coordinates
VTEC	Vertical total electron content
VLBA	Very Long Baseline Array
VLBI	Very long baseline interferometry
WVR	Water vapor radiometer/radiometry

Array Configuration: Preliminary Technical Requirements

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PREPARED BY	ORGANIZATION	DATE
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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-07-05	Carilli		Preliminary Reference Design Review
02	2018-07-09	Selina	All	Corrections to first draft throughout; mostly excisions of irrelevant pieces of the template; significant edits to Section 4
03	2018-07-17	Mason	3.4.1, 4.4	Clarified SBA, TP requirements; fixed other minor typos
04	2018-07-17	Rosero	All	Editorial corrections; added most of E. Murphy's suggestions/comments
05	2018-09-17	Rosero	3.2, 3.3, 3.5, 4.1, 4.2	Updated information about the current configuration; rewrote section 3.3
06	2018-11-30	Carilli, Rosero, Erickson	All	Respond to RIDs from reference design review
07	2019-05-31	Selina	3.5, 4	Updated Req. IDs and traceability
A	2019-07-09	Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction

1.1 Purpose

This document presents a set of technical requirements for the ngVLA Array Configuration Reference Design. Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn flow down from the preliminary ngVLA Science Requirements [AD01].

The Science goals are presently being elaborated by the Science Advisory Council (SAC) and Science Working Groups (SWGs), and are captured in a series of draft use cases. A preliminary analysis of these use cases, and the flow down recursively to the science, system, and subsystem requirements, is reflected in this draft.

1.2 Scope

The scope of this document is the ngVLA array configuration. Described in the Design Description Document [AD04], it is designed to meet the science requirements determined in the detailed community analysis of the broad ngVLA science case, as captured in the science use case spreadsheet [RD01] and summarized in ngVLA memos 17, 18, and 19, and in [AD01] and [AD02].

The requirements establish the performance and functional requirements applicable to the ngVLA array configuration based on the science program analysis. These requirements then dictate the reference design, described in [AD04].

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Technical Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Technical Specification, the content of this Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Array Configuration Reference Design	020.23.00.00.00-0002-DSN
AD05	Antenna Preliminary Technical Requirements	020.25.00.00.00-0001-SPE
AD06	Short Baseline Array Antenna Preliminary Technical Requirements	020.47.05.00.00-0001-SPE

2.2 Reference Documents

The configuration requirements draw extensively from work presented in the ngVLA memo series. The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	Science Use Case Parameterization Spread Sheet	2017-06-20 V24
RD02	ngVLA Reference Design Development & Performance Estimates	ngVLA Memo #17
RD03	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD04	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19
RD05	Image Capabilities: High Redshift CO	ngVLA Memo #13
RD06	Investigating the Early Evolution of Planetary Systems with ALMA and the Next Generation Very Large Array	ngVLA Memo #33
RD07	More on Synthesized Beams and Sensitivity	ngVLA Memo #16
RD08	ngVLA Dynamic Range	ngVLA Memo #30
RD09	Deep Fields at 8GHz	ngVLA Memo #35
RD10	Initial Imaging Tests of the Spiral Configuration	ngVLA Memo #41
RD11	Resolution and Sensitivity of ngNLA-revB	ngVLA Memo #47
RD12	The ngVLA Short Baseline Array	ngVLA Memo #43
RD13	Fast Switching Phase Calibration at 3mm at the VLA Site	ngVLA Memo #1
RD14	Possible Configurations for the ngVLA	ngVLA Memo #3

We refer the reader to these memos for more details on science simulations that relate to the configuration design and characterization of the design.

3 Overview of the Array Configuration Technical Requirements

3.1 Document Outline

This document presents the technical requirements of the ngVLA array configuration. These parameters determine the overall form and performance of the array configuration.

The functional and performance specifications, along with detailed explanatory notes, are found in Section 4. The notes elaborate on the meaning, intent, and scope of the requirements. These notes form an important part of the requirements definition and should guide the verification procedures. In many cases the notes explain or analyze how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. In this way, the required analysis and trade-space available is apparent to scientists and engineers who will guide evolution of the ngVLA array configuration concept.

Section 3.4 identifies Key Performance Parameters (KPP) that should be estimated and monitored throughout the design phase. These metrics facilitate trade-off analysis of various concepts and help identify and resolve tensions between requirements as the design progresses.

3.2 Project Background

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 cm to 0.26 cm, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a non-reconfigurable synthesis radio telescope operating in a phased or interferometric mode.

The signal-processing center and the majority of antennas will be located at the Very Large Array site on the Plains of San Agustin, New Mexico. Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM.

3.3 General Array Configuration Description

The description of the array that satisfies the following requirements can be found in the subsystem Reference Design Description document. We briefly review it here for completeness.

The ngVLA array design includes three fundamental subarrays: the main interferometric array, the short baseline array, and the long baseline array. Antennas within the main array are distributed over a range of physical scales and with different geometries in order to fulfill different science use cases:

- A dense core which provides high surface brightness sensitivity at ~1,000 mas resolution.
- A multi-arm spiral capable of high-fidelity snapshot imaging at ~10 mas scales.
- Longer arms which provide mid-scale baselines for imaging at ~1 mas.

The main array will be augmented by a compact array of smaller antennas that will provide sensitivity on larger angular scales, and four antennas of the main array will be equipped to measure total power in order to fill in the center of the (u,v)-plane. Additionally, a long baseline array (LBA) consisting of several outlying stations will provide intercontinental-scale baselines for achieving resolutions of ~0.1 mas.

3.4 Key Performance Parameters

This section provides Key Performance Parameters (KPPs) that the designer should estimate and NRAO should monitor throughout the project design phase. The KPPs strongly influence the eventual effectiveness of the facility and are useful high-level metrics for trade-off decisions. These parameters are of higher importance to NRAO, so improved performance above the requirement is desirable. Section 4 discusses the KPPs' impact on system-level performance.

The technical requirements are generally specified as *minimum* values to give the designer latitude in optimization for a balanced design. Understanding anticipated performance of the array configuration (not just its specified minimum) based on these parameters assists in system-level analysis and performance estimation. These parameters may also be useful for determining the relative priority of the requirements documented in Section 4 and can assist in the required analysis should tensions be identified between requirements, or reductions in capability be required to fit within cost constraints.

Table 1 shows the KPPs identified for monitoring. For the configuration imaging performance, the primary points of reference are the simulations of sensitivity vs. resolution, with weighting appropriate to obtain a synthesized beam adequate to perform the Key Science Programs. This analysis will be presented in an Imaging Performance Report. Figure 1 shows the current analysis on sensitivity versus resolution.

Key Performance Parameter	Req. #
Highest angular resolution, Main Array @ 30 GHz	SYS1310, SCI0103, SCI0108
Highest angular resolution, LBA @ 30 GHz	SCI0118
rms/rms_{NA} versus angular resolution	SCI0100, SCI0102, SCI0107
Largest Recoverable Scale with the SBA	SCI0104
Fiber Utility Length	-
Percentage of Sites off Private or BLM land	-

Table 1 - Key performance parameters for monitoring during design.

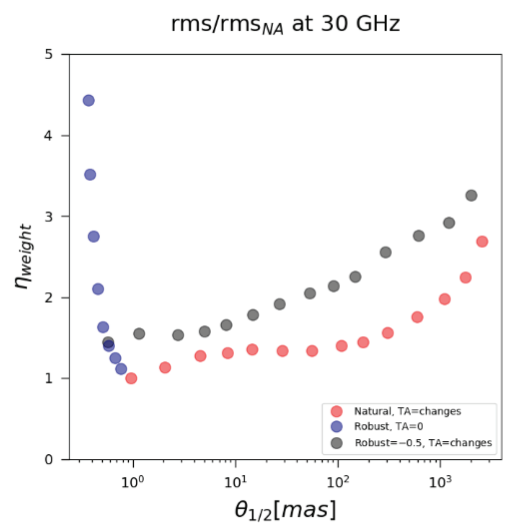

Figure 1 - Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz. The noise has been scaled relative to that of the naturally weighted image (rms_{NA}). The red symbols correspond to use of a uv-taper and natural weights, and the blue symbols to Briggs robust weighting without a taper. The gray symbols are for Briggs robust = –0.5 and a varying uv-taper, which has a large effect on beam quality.

3.5 Summary of Array Configuration Requirements

Following is a summary of the major requirements in order to provide the reader with a high-level view of the desired system. Should there be a conflict between the requirements listed here and the descriptions in Section 4, the latter shall take precedence.

The array configuration is designed to perform the broad range of science programs, ranging from:

1. very high resolution (10 mas at 30 GHz), sensitive observations of exoplanets forming on AU-scales (T_B ~3 K in one hour at 10mas resolution at 30GHz in continuum), to
2. good surface brightness sensitivity observations at 100 mas of molecular gas in distance galaxies (T_B ~8K at 100mas resolution at 30GHz and 10 km s^{-1} spectral resolution), to
3. imaging of large scale structures in nearby galaxies at ultra-low surface brightness at 1000 mas resolution (T_B ~1mK in one hour in the continuum at 30GHz).

The reference design reflects the multi-scale requirements from the array science case. The ultimate sensitivity as a function of resolution will depend critically on the specific synthesized beam for the science application in question, but as a guiding principle, we have adopted the goal of roughly a factor two loss in sensitivity from spatial resolutions ranging from ~0.3 mas to 1000 mas at 30 GHz. For the PSF metric, we have adopted the goal of a <10% skirt at a radius from the beam center = FWHM. Current simulations suggest this is adequate for many of the key science goals. Further testing is in progress in this area.

The primary parameter defining the configuration is total collecting area, which dictates the ultimate sensitivity of the array. Related to this is the distribution of antennas across the array, which dictates the relative sensitivity at a desired spatial resolution. This total collecting area requirement derives ultimately from spectral line sensitivity requirements (SCI0102), which states: *A line sensitivity of 30 μJy/bm/km/s for frequencies between 10 and 50 GHz is required to support both astrochemistry studies and deep/blind spectral line surveys. A line sensitivity of 1–100 mK at 5"–0.1" angular resolution and 1–5 km/s spectral resolution between 70 and 116 GHz is required to simultaneously support detailed studies of CO and variations in gas density across the local universe.*

The maximum baseline requirement flows from the angular resolution requirement, SCI0103: *A synthesized beam having a FWHM better than 5 mas with uniform weights is required at both 30 and 100 GHz.*

The number of antennas on the Plains is dictated by image fidelity requirements and sensitivity on scales of 100 mas at 30 GHz, SCI0108: *The ngVLA should produce high fidelity imaging (>0.9) over a wide range of scales, spanning from a few arcmin to a few mas*. The snap shot fidelity requirement, SCI0109, states: *The ngVLA snapshot performance should yield high fidelity imaging on angular scales >100 mas at 20 GHz for strong sources.*

The diameter and number of antennas in the core is set by surface brightness sensitivity requirements, SCI0113: *The system brightness dynamic range shall be better than 50 dB deep field studies at 10 GHz.*

The parameters for the SBA and total power system are derived to perform very low surface brightness observations of extended objects. The details relating to the science and the requirements are given in ngVLA memo 43. The requirements flow from the Largest Recoverable Scale (SCI0104), and the need to have matched surface brightness sensitivity on the longer baselines of the SBA and the main array core. For reference, SCI0104 states: *Angular scales of >20" x (116 GHz/ν) must be recovered at frequencies ν<116 GHz. A more stringent desire is accurate flux density recovery on arcminute scales at all frequencies.*

3.5.1 General Functional Specifications

Parameter	Req. #	Summary of Requirement	Reference Reqs.[1]
Geometric collecting area, main array	AAC0001	The system gross geometric collecting area shall be 61,700 m^2 or greater.	SYS1021, SYS1308, SCI0100, SCI 0102, SCI0106
Maximum baseline, main array	AAC0002	The longest baseline between antennas shall be greater than 650 km. It is a goal to have baselines longer than 1000 km.	SYS1310, SCI0103, SCI0108
Geometric collecting area, core array	AAC0003	The system shall include a compact core. A minimum of 40% of array collecting area shall be located within 1.25 km of array vertex.	SYS1305, SCI0104, 0102, 0106
Maximum baseline, core	AAC0004	1.25 km	SCI0104, SCI0106
Geometric collecting area, Plains array (includes core)	AAC0005	46,300 m^2	SYS1306, SCI0106, SCI0109, SCI0108

3.5.2 Other General Desirables

Antenna locations should, as best as possible, conform to practical considerations in terms of access, roads, power, fiber, interference environment, safety and security. The site quality should also allow for observations up to 116 GHz.

Parameter	Req. #	Value	Reference Reqs.
Station proximity to appropriate power lines	AAC0010	2 km distance	TBD
Station proximity to high bandwidth optical fiber network	AAC0011	2 km distance	TBD
Station access for construction (roads, land rights)	AAC0012	TBD	TBD
Good performance up to 3mm	AAC0013	Opacity <10% at 90 GHz for >30% of the year. Phase stability allows for residual rms phase <30 deg using fast switching phase calibration with 30 sec cycle time at 90 GHz, for >30% of the year.	ngVLA Memo #1 SCI0001
Maximum baseline, Plains array	AAC0014	36 km	ngVLA Memo #13 SCI0108
Geometric collecting area, LBA	AAC0015	7634 m^2	SCI0117
Maximum baseline, LBA	AAC0016	8856 km	SCI0118
Geometric collecting area, SBA	AAC0017	530 m^2	ngVLA Memo #43 SCI0104

[1] All the SCI requirement numbers and the KSG cases are listed in [AD01]. The SYS numbers are listed in [AD02].

Parameter	Req. #	Value	Reference Reqs.
Maximum Baseline, SBA	AAC0018	44 m	ngVLA Memo #43 SCI0104 KSG1-006, KSG2-004, KSG3-009
Minimum Baseline SBA	AAC0019	The shortest baselines between antennas shall be shorter than 16 m, with a goal of <10 m.	SYS1302 SCI0104 ngVLA Memo #43
Total power antennas	AAC0020	Measure total power with apertures larger than 1.5x the shortest baseline.	SYS1303, SCI0104 ngVLA Memo #43
Total power sensitivity	AAC0021	Total power antenna(s) shall have sufficient sensitivity in aggregate to match the surface brightness sensitivity of SBA in observing times that are equal within a factor of four with a goal of equal times.	SCI0104 ngVLA Memo #43

4 Array Configuration Functional and Performance Requirements

These requirements apply to a properly functioning system, under the normal operating environmental conditions unless otherwise stated.

4.1 Total Collecting Area and Antenna Requirements

Parameter	Req. #	Value	Traceability
Main interferometric antenna aperture	AAC0101	18 m diameter	ANT0202, SCI0104, SCI0100, SCI0102
Main interferometric array: number of elements	AAC0102	214 elements	ANT0401, SCI0100, SCI0102
Long baseline antenna aperture	AAC0105	18 m diameter	SCI0118
Long baseline array: Number of elements	AAC0105	30 elements	SCI0118
Short baseline antenna aperture	AAC0103	6 m diameter	SBA0202
Short baseline array: Number of elements	AAC0104	19 elements	SBA0401

Note that the total number of elements within the main interferometric array and short baseline array can be adjusted so long as the total system construction and operations cost requirements (STK0100-0101) are not violated. Values in AAC0102 and AAC0104 are derived from these requirements, as defined in the antenna and short baseline requirements respectively. Aperture diameters are provided here as requirements based on the selected system architecture with traceability back to the antenna requirements. Both aperture sizes can be revisited within small ranges but have practical constraints that are accounted for in AAC0101 and AAC0203.

4.2 Spatial Scales

Parameter	Req. #	Value	Traceability
Main interferometric array: Longest baseline	AAC0201	The longest baseline between antennas shall be greater than 650 km, preferably longer than 1000 km.	SYS1301, SCI0103, [KSG1-001, KSG1-003, KSG2-001]
Main interferometric array: Shortest baseline	AAC0202	The shortest baselines between antennas in the main interferometric array shall be no less than 30 m.	ANT0301, SCI0104
Long baseline array: Longest Baseline	AAC0205	8856 km	SCI0118 [KSG5-001, KSG5-002]
Short baseline array: Shortest Baseline	AAC0203	The shortest baselines between antennas shall be no less than 11 m.	SBA0301, SCI0104, KSG3-005 KSG2-004
Zero spacing/single dish total power	AAC0204	It is a goal that the system measure total power, with apertures larger than 1.5x the shortest baseline.	SYS1303, SCI0104, KSG3-005, KSG2-004

The combination of spatial scales, when combined with practicalities of the antenna design, lead to a multi-component configuration:

1. A main interferometric array of 214 x 18 m apertures,
2. A long baseline array of 30 x 18 m apertures,
3. A short baseline array of 19 x 6 m apertures, and
4. A total power array of 4 x 18 m apertures (that are part of the 214 main array).

4.3 Distribution of Collecting Area

Parameter	Req. #	Value	Traceability
Fraction of occupied cells	AAC0301	It is a goal to fill at least 50% [TBC] of (u,v)-cells before gridding out to 36 km baselines (out to the longest baseline) in a snapshot observation traversing the meridian. Goal to achieve this fill ratio out to 50 km+ scales.	SYS1306, SCI0108 SCI0109 SCI0107
Compact core	AAC0302	The system shall include a compact core. At minimum, 40% of the array collecting area shall be located within 1.25 km of the array vertex.	SYS1305 SCI 0104
Distribution of baselines	AAC0303	TBD (Need to describe desired radial distribution function)	SYS1307, SCI 0107
Integration time ratios	AAC0304	The main interferometric array, short baseline array, and total power array shall sample overlapping spatial scales. The ratio of integration time on one array to the other on these scales shall not exceed a factor of four with a goal of matched integration times.	SYS1304, SCI0104
Weighting of visibilities	AAC0305	It is a goal to achieve a Gaussian distribution via weighting, with the geometric mean of the weights greater than 0.5 over the full range of scales that correspond to 1 km to 650 km baselines on an 8 hr. observation.	SYS1308 SCI0108 SCI0109 SCI0107

The array collecting area is distributed to provide high surface brightness sensitivity on a range of angular scales spanning from approximately 10 mas to 1000 mas. A large fraction of the collecting area is in a randomly distributed core to provide high snapshot imaging fidelity and there are arms extending asymmetrically out to ~1000 km baselines to fill the (u,v)-plane via Earth rotation and frequency synthesis.

4.4 Total Power Recovery

Parameter	Req. #	Value	Traceability
TP antennas	AAC0401	Total power antennas and subsystems will be identical to antennas of main interferometric array to extent possible. TP antennas are included as part of the 244 main array.	SCI0104
TP-specific needs	AAC0402	TP antennas will accommodate the specific requirements of TP observing such as rapid, accurate slewing (for OTF) and relatively higher signal stability.	SCI0104

4.5 *Site Selection Performance Requirements*

Parameter	Req. #	Value	Traceability
Performance up to 3 mm: Opacity	AAC0501	It is desired that all sites have Opacity <10% at 90 GHz for >30% of the year.	SCI0001 SCI0100 SCI0102
Performance up to 3 mm: Phase stability	AAC0502	It is desired that all sites have phase stability that allows for residual rms phase <30 deg using fast switching phase calibration with a 30 sec cycle time at 90 GHz, for >30% of the year.	SCI0001 SCI0100 SCI0102

4.6 *Site Selection Regulatory Requirements*

Parameter	Req. #	Value	Traceability
Land ownership	AAC0601	It is desired that sites on private and BLM land be prioritized. USFS and Tribal properties shall be avoided when possible.	
Environmental impact	AAC0602	Sites shall be screened for environmental impact, such as overlap with identified endangered species habitat.	

4.7 *Site Selection Logistics and Interface Requirements*

Parameter	Req. #	Value	Traceability
Station access roads	AAC0701	It is desired that all sites be within 2 km of an existing road or access point.	
Maintenance access	AAC0702	Sites shall have clear access for maintenance at all times. I.e. no predicted access restrictions or seasonal roads.	
Station proximity to power lines	AAC0703	It is desired that all sites be within 2 km of an existing three-phase power line.	
Station proximity to high bandwidth optical fiber	AAC0704	It is desired that all sites be within 2 km of an existing fiber optic network.	
Fiber optic transmission lengths	AAC0705	Sites shall be selected assuming “home run” fibers are required from the site to the correlator. Total fiber transmission distances shall be minimized through shared right-of-way and trenches.	
RFI mitigation	AAC0706	It is desirable that sites limit line of sight to public roads, transmitters, and other known sources of RFI.	
Site safety and security	AAC0707	It is desirable that sites have rural neighbors who may provide indirect site security checks.	

Antenna positions should be such that access is readily available for regular and emergency maintenance visits. Antennas should be located as best as possible away, or terrain-shielded, from significant sources of terrestrial interference, such as cell phone towers, radio transmitters, airport or other radars, and related.

5 Documentation Requirements

5.1 Technical Documentation

All documentation and electronic files related to array configuration shall meet the following requirements:

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use metric units or decimal lat/lon.
- The electronic document formats are Microsoft Word and Adobe PDF.

Any deviation from the above shall be agreed to by the ngVLA project office.

5.2 Software and Software Documentation

The primary configuration analysis software will be supported within the CASA package. Deliverables will include:

- Configuration file for the ngVLA interferometric array (244 18m antennas).
- Configuration files for the components of the main array, i.e. core only (94 18m antennas), core + Plains (168 18m antennas).
- Configuration file for the SBA (19 6m antennas).
- Configuration file for the LBA (30 18m antennas).
- Support of the SIMOBSERVE tool, and related tools, to generate simulated observations of relevant astronomical sources.
- Support of the imaging tools in CASA that optimize the array performance (image sensitivity and dynamic range as a function spatial resolution).

6 Open Questions

- Need to better quantify the PSF metric for high fidelity imaging.
- Need further development of imaging and deconvolution algorithms that do not require a Gaussian PSF (i.e. to avoid loss of sensitivity when sculpting the beam).
- Additional performance parameters:
  - Astrometry accuracy: Does other than longest baseline have an impact on it?
  - Pulsar timing: core phasing?
  - Transient searches: non-imaging?
  - May be some relationship between configuration and these capabilities, e.g., the ability to phase the core reasonably, or to perform µas astrometry.

7 Appendix

7.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
BLM	Bureau of Land Management
CDR	Critical Design Review
CoDR	Conceptual Design Review
EIRP	Equivalent Isotropic Radiated Power
EM	Electro-Magnetic
FDR	Final Design Review
FOV	Field of View
FWHM	Full Width Half Max (of Primary Beam Power)
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
KSG	Key Science Goal
MTTR	Mean Time To Repair
ngVLA	Next Generation VLA
PSF	Point Spread Function
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SBA	Short Baseline Array
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
TP	Total Power
USFS	United States Forest Service
VLA	Jansky Very Large Array

Array Configuration: Reference Design Description

020.23.00.00.00-0002-DSN

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
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M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.11 07:05:55 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-09

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-07-06	Carilli	All	Reference Design Review
02	2018-07-09	Selina	All	Updates throughout; Cleaned up template, some format fixes, etc.
03	2018-07-17	Mason	4.3	Updated Fig. 3
04	2018-07-17	Murphy	Various	Minor editorial corrections
05	2018-07-17	Rosero	All	Editorial corrections; updated figures using Rev B; reference figures within the text; updates in section 4.1; added Table 1; edited section 4.6
06	2018-07-23	Erickson	4.5	Added content
07	2018-09-17	Rosero	4	Updated/added figures and text using current configuration (Spiral 214 + LBA); added Fig. 8
08	2018-11-30	Carilli, Rosero, Erickson	4	Revised to address RIDS from Reference Design Review
09	2019-05-31	Selina	5	Minor edits and corrected figure locations
A	2019-07-09	Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction

1.1 Purpose

This document describes the ngVLA Array Configuration reference design. It covers the design approach, predicted performance, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the design of the array configuration, specifically, the configuration design and its key constituents. It does not include specific technical requirements, which are addressed separately in [AD04].

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents inform this reference design:

Reference No.	Document Title	Rev / Doc. No.
AD01	Science Requirements	020.10.15.00.00-0001-REQ
AD02	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Array Configuration Preliminary Technical Requirements	020.23.00.00.00-0001-REQ

2.2 Reference Documents

The configuration reference design draws extensively from work presented in the ngVLA memo series. We refer the reader to these memos for more details on science simulations that relate to the configuration design and characterization of the design. These memos provide much of the provenance for the reference configuration in terms of scientific analysis and simulation verifying performance in key science areas.

The following documents provide additional supporting analysis or context that informed the reference design of the array configuration:

Reference No.	Document Title	Rev / Doc. No.
RD01	ngVLA Science Use Case Parameterization Spread Sheet	2017-06-20 V24
RD02	ngVLA Reference Design Development & Performance Estimates	ngVLA Memo #17
RD03	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD04	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19
RD05	Image Capabilities: High Redshift CO	ngVLA Memo #13
RD06	Investigating the Early Evolution of Planetary Systems with ALMA and the Next Generation Very Large Array	ngVLA Memo #33
RD07	More on Synthesized Beams and Sensitivity	ngVLA Memo #16
RD08	ngVLA Dynamic Range	ngVLA Memo #30

Reference No.	Document Title	Rev / Doc. No.
RD09	Deep Fields at 8GHz	ngVLA Memo #35
RD10	Initial Imaging Tests of the Spiral Configuration	ngVLA Memo #41
RD11	Resolution and Sensitivity of ngVLA-revB	ngVLA Memo #47
RD12	The ngVLA Short Baseline Array	ngVLA Memo #43
RD13	Fast Switching Phase Calibration at 3mm at the VLA Site	ngVLA Memo #1
RD14	Possible Configurations for the ngVLA	ngVLA Memo #3

3 Subsystem Overview

The array configuration is a basic property of the array. It is an abstraction, defining the locations of antennas within the array. The cost of the antennas and supporting infrastructure is included within other packages of the reference design.

The longest baselines set the ultimate resolution of the array, while the shortest determine the largest-scale structures that can be imaged. The antenna distribution then sets the sensitivity as a function of spatial resolution and the shape of the synthesized beam (point spread function), as determined by weighting of the uv-data.

The array reference design will not be reconfigurable, yet it must perform a broad range of science programs with a wide range in spatial resolutions as a function of frequency, as summarized in ngVLA Memo #18. To perform this broad range of science programs, the array configuration design requires essential capabilities such as:

- very high resolution (10 mas at 30 GHz) for sensitive observations of exoplanets forming on AU-scales;
- high surface brightness sensitivity observations at 100 mas of molecular gas in distance galaxies; and
- imaging of large-scale structures in nearby galaxies at ultra-low surface brightness at 1000 mas resolution.

The reference design reflects the multi-scale demand on the array science case. The ultimate sensitivity as a function of resolution will depend critically on the specific synthesized beam for the science application in question. As a guiding principle, we have adopted the goal of roughly a factor two loss in sensitivity relative to natural weighting, for spatial resolutions ranging from ~0.3 mas to 1000 mas at 30 GHz. The array performance for several key science programs has been documented in the memo series, as listed in the reference documents above.

4 Array Configuration Design

4.1 Sub-Components of the Array Configuration

The range of angular scales that the array must be sensitive to cannot be accessed with any practical homogeneous array. A heterogeneous array is therefore required, consisting of four main components (Figure 1):

- Main Interferometric Array of 214 18m reflector antennas (also referred as the Spiral 214 array),
- Long Baseline Array (LBA) of 30 18m reflector antennas,
- Short Baseline Array (SBA) of 19 6m reflector antennas, and
- Total Power Array of four 18m reflector antennas (included as part of the Spiral 214 main array).

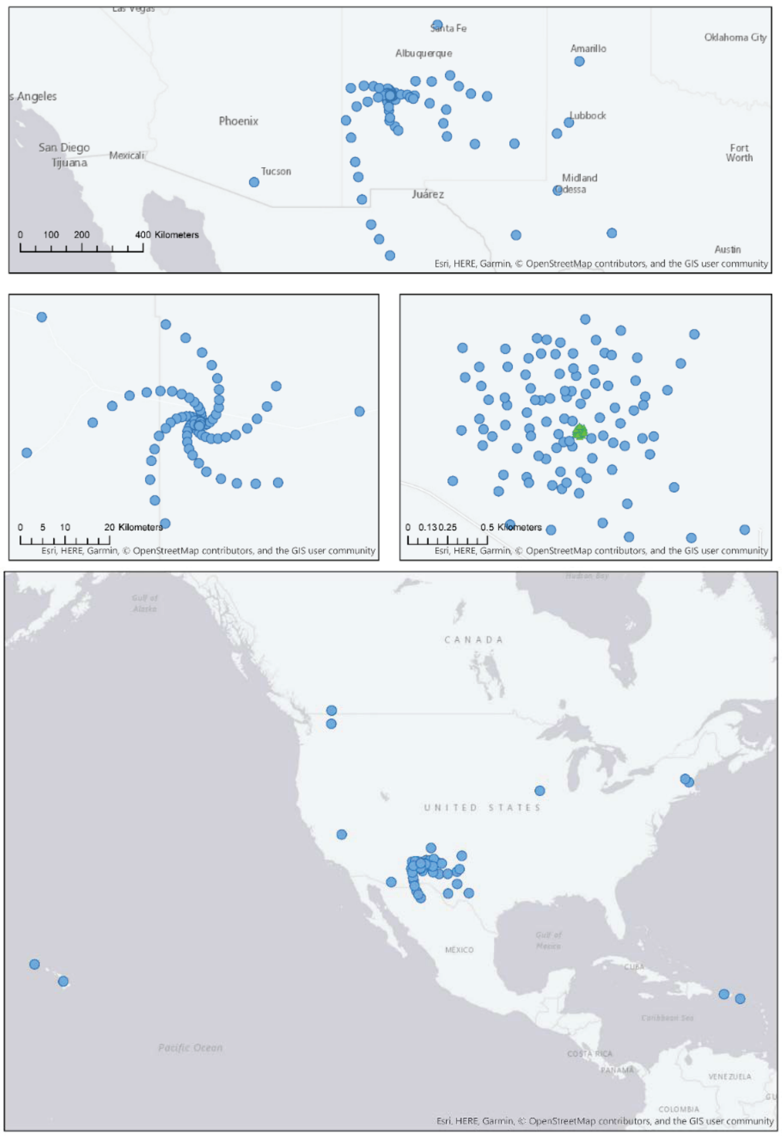

Figure 1 - Top three panels: main interferometric array (Spiral214) composed of a compact core (top right; short baseline array antennas are shown in green), a five-arm spiral spanning the Plains of San Agustin (top left), and a rough spiral that extends to Texas, northern Mexico and Arizona (top). Bottom: view of the main array and the long baseline array (244 18m antennas total). Each LBA station has two or more antennas.

Table 1 summarizes the ngVLA array configuration elements. The design is practical, accounting for such logistic limitations as topography, utility access, local RFI sources, and land management/availability.

Component Name	Aperture Diameter (m)	Quantity	B_{min} (m)	B_{max} (km)
Long Baseline Array	18	30	32.6	8856
Main Interferometric Array	18	214	30.6	1005
Short Baseline Array	6	19	11.0	0.06
Total Power/Single Dish	18	4[1]	--	--

Table 1 - Summary of elements within the ngVLA array configuration.

The main interferometric array will have three discrete components (see Table 2). A compact, dense core (extent ~1.3 km) will have roughly ~45% of the antennas. Another ~35% of the antennas on the Plains of San Agustin will extend about ~15 km from the core for about 36 km maximum baselines. The remaining ~20% of the antennas will be in mid-baseline stations extending to maximum baselines of ~1000 km.

Component Name	Max. Baseline (km)	Distribution Pattern	# Antennas
Core	1.25	Random	94
Plains	36	5-arm spiral	74
Mid-Baselines	~1000	~3-arm spiral	46

Table 2 - Main interferometric array components.

The main array location in the Southwest US and Mexico is well suited for observations up to 116 GHz due to generally high elevations and low water vapor content. Figure 2 shows an example of the site quality for observations at 90 GHz. These tests show that using fast switching calibration provides acceptable calibration results (ϕ_{rms}<40°) for observations at day or night during most of the year.

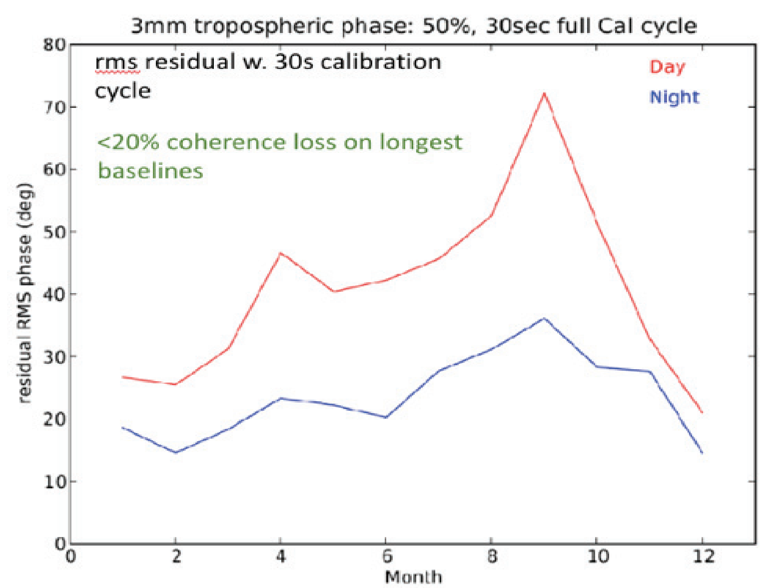

Figure 2 - RMS phase residuals after fast switching calibration predicted for the VLA site at 90 GHz based on decades of phase monitoring with the Atmospheric Phase Interferometer (ngVLA memo 1).

[1] The four total power antennas are a subset of the 214 antennas of the main array.

4.2 Main Interferometric Array

The core of the main interferometric array will be located at the current VLA site, in a dense configuration optimized for image quality, with maximum baselines of ~1.25 km. The Plains array is comprised of a five-arm spiral to ~15 km radius from the VLA center. This spiral is also optimized for quality imaging (see ngVLA memos 30, 41, and 47). The outer antennas of the main array that expand from ~15 km out to ~1000 km baselines are distributed in a rough three-arm spiral, extending mostly south into Mexico and Texas.

Figure 1 shows the reference design configuration of the multi-scale array, which has a naturally weighted beam with three very different spatial scales:

1. a narrow spike with high resolution (~0.3 mas at 30 GHz),
2. the first skirt due to the Plains array extending to (100 mas at 30 GHz) at the 50% to 20% level, and
3. the second skirt due to the core extending to (1000 mas at 30 GHz) in the 20% to 10% range.

The challenge for imaging is to optimize uv-data weighting to obtain a reasonable synthesized beam while maintaining sensitivity. For a reasonable synthesized beam, several numerical simulations have shown that high dynamic range imaging can be obtained by keeping the broad skirt to below 10% at a radius from the beam peak = FWHM of the beam. The project is performing a broader suite of simulations to quantify this metric, while algorithmic development is ongoing to optimize the imaging and science return for multi-scale arrays in general.

The ngVLA Main Array reference configuration has the interesting property that the core, with 45% of the antennas, is located at the northern extremity of the configuration, as Figure 1 shows. Hence, the behavior of sensitivity and beam shape with uv-weighting is very different than ALMA or the VLA. Tests show that, as the uv-data weighting is varied to obtain resolution from ~0.5 mas to 1000 mas at 30 GHz (see Figure 4), the sensitivity remains roughly constant and within a factor of about 2 of Natural weighting.

This behavior is predictable, in retrospect, since at 1000 mas one is using just the core, which has 45% of the collecting area, while at 0.5 mas one is correlating the long baseline antennas to all the core antennas, thereby obtaining high resolution without a dramatic sacrifice of sensitivity.

4.3 SBA and TP array

The ngVLA Short Baseline Array (SBA) comprises 19 6m antennas and 4 18m total power antennas (included as part of the main 214-antenna array; see Figure 3). This array was designed to adequately "feather" or be jointly deconvolved with the main array core (i.e. matched surface brightness sensitivity on scales of the shortest core baselines). This also improves sensitivity to large structures, up to 70 arcsec at 90GHz, for the SBA alone, and raster imaging of even large structures with the total power antennas.

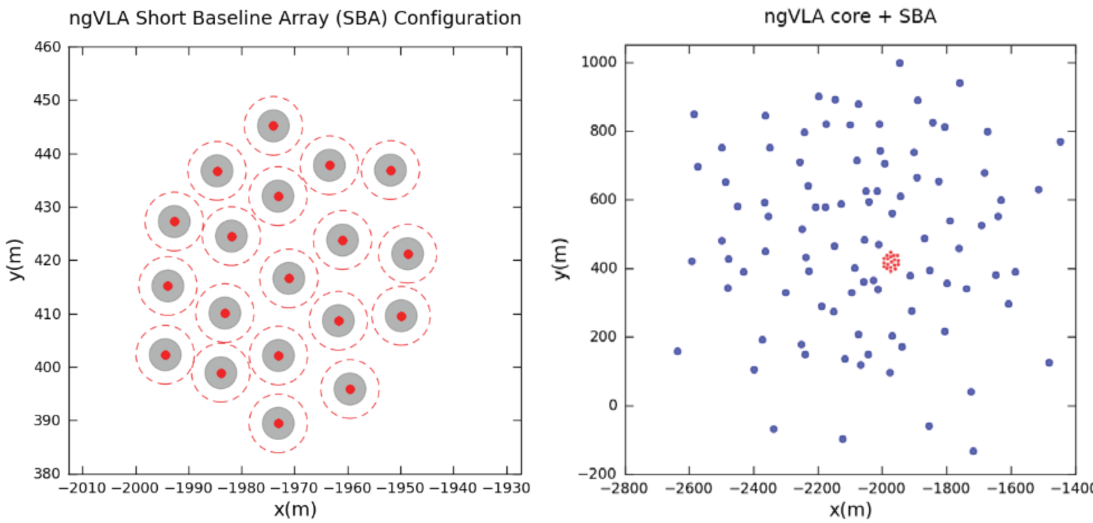

Figure 3 - SBA reference design (left) and notional placement within ngVLA core revB (right). SBA antennas are shown by red solid lines, with their clearance zones shown by red dotted lines. ngVLA 18m antennas are shown by blue solid dots.

Simulations show that the SBA interferometer will provide good supporting data for the ngVLA with total integration times 1.3x those of the ngVLA main array, and total power integration times 2.3x those of the main ngVLA array (ngVLA Memo 43). Given reasonable expectations of the distribution of requested science use cases, these approaches are viable options to provide the larger spatial scale information required by 20% to 30% of identified ngVLA science use cases.

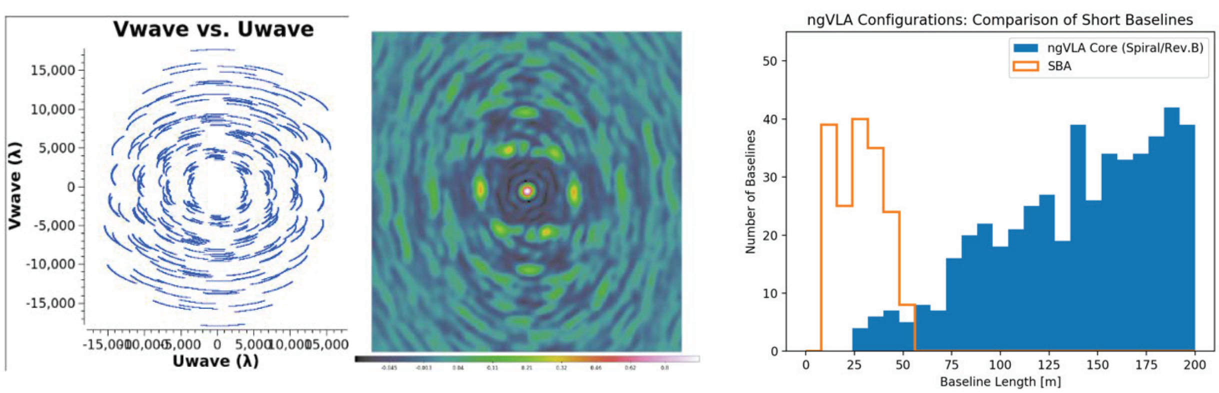

Figure 4 - Left: uv-coverage of the SBA at 100 GHz for a 1000 s observation at Dec = –17° along with the resulting synthesized beam. Center: the NA weighted synthesized beam, with a FWHM = 10". Right: the number of baselines in the core and the SBA vs. baseline length.

4.4 Long Baseline Array

The long baseline array is composed of 30 additional 18m antennas at ten different sites (see Table 3). Clustering antennas at each site is a cost-effective way to increase the array's sensitivity while sharing the operations infrastructure per site. Clustering also allows unique capabilities such as simultaneous observations of the scientific target and the calibration source or simultaneous frequency coverage across the same set of baselines. Additionally, the clusters could be used individually as small phased arrays for "single dish" observations such as pulsar timing.

The LBA by itself provides several spacings such as continental scale (B_{max} ~8860 km) baselines, intermediate scales of ~1000 km and short spacings of ~30 m within the sub-array, making it suitable for both astrometry and imaging projects and enabling the LBA to function effectively as a standalone array or as an integrated part of the main array.

Antenna Quantity	Location	Reference Design Site
3	Puerto Rico	Arecibo Observatory
3	St. Croix	VLBA Site
3	Kauai, Hawaii	Kokee Park Geophysical Observatory
3	Hawaii, Hawaii	NOT on Mauna Kea. New site.
2	Hancock, NH	VLBA Site
3	Westford, MA	Haystack Observatory
2	Brewster, WA	VLBA Site
3	Penticton, BC	Dominion Radio Astrophysical Observatory
4	North Liberty, IA	VLBA Site
4	Owens Valley, CA	Owens Valley Radio Observatory

Table 3 - Reference design antenna sites of the ngVLA long baseline array.

4.5 Array Performance

Figure 5 shows the distribution of number of baselines versus baseline length, and the collecting area as a function of baseline length for the main array plus the LBA. The distribution of collecting area shows the preponderance of the core, tapering smoothly to lower values to 1000 km distances. The resulting baseline distribution is relatively uniform from 100 m to a few thousand kilometers.

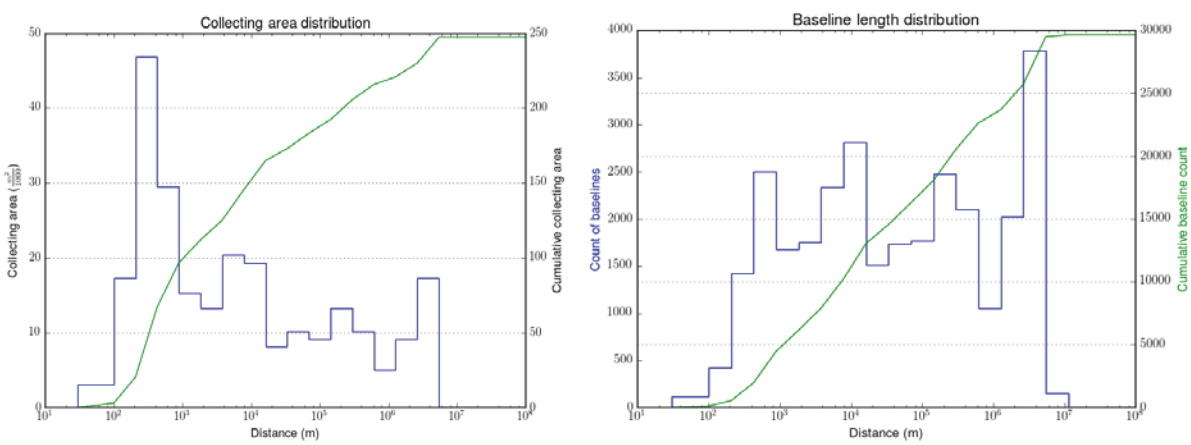

Figure 5 - The left graph shows collecting area versus radial distance from the core center, with log bins (blue). The green line is the cumulative distribution. The right graph shows the number of baselines versus baseline length for the full 18m ngVLA reference design (main+LBA) array, using logarithmic bin sizes (blue line). The green line is the cumulative distribution.

Imaging sensitivity will depend on the required resolution and imaging fidelity. Figure 6 and Figure 7 show the effects of adjusting imaging weights to vary resolution and PSF quality. These figures are based on a four-hour simulation at 30 GHz using the 244 antenna array configuration, for a source at +24° declination observed during transit. The reported beam size is the geometric mean of the major and minor full width at half maximum (FWHM) of the synthesized beam as parameterized by Gaussian fitting in the CASA tclean task.

To account for the sensitivity change due to use of imaging weights (relative to the naturally weighted rms σ_{NA}), we adopted an efficiency factor η_{weight} such that expected image rms after weighting is $\eta_{weight}\ \sigma_{NA}$.

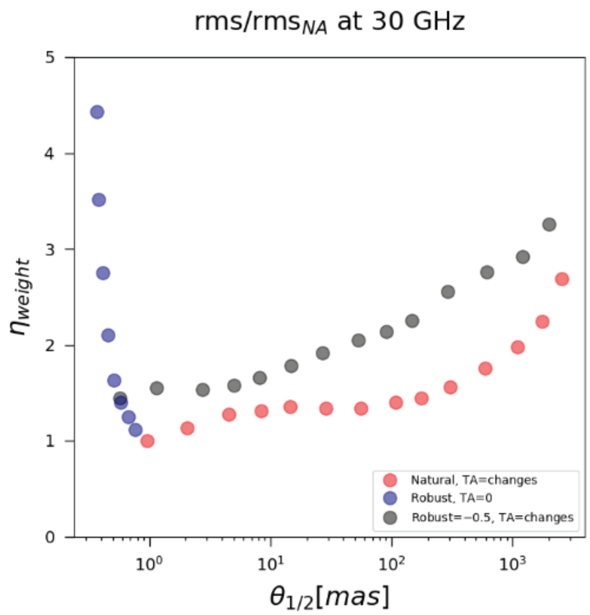

Figure 6 - Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz using the 244 antenna array configuration. The noise has been scaled relative to that of the naturally weighted image (rms_{NA}). The red symbols correspond to use of a uv-taper and natural weights, and the blue symbols to Briggs robust weighting without a taper. The gray symbols are for Briggs robust = –0.5 and a varying uv-taper, which has a large effect on beam quality (see Figure 7).

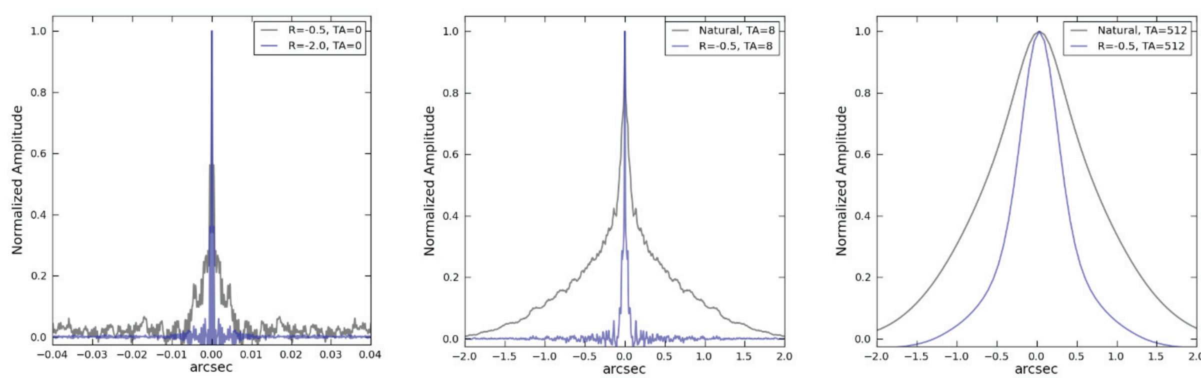

Figure 7 - Simulated 30 GHz PSFs for the present ngVLA reference array over a range of resolutions, showing the effect of different imaging weights (TA: uv-taper in mas, R: Briggs robust parameter). The PSFs are a selection of the data presented in Figure 6. These examples illustrate how combinations of robustness and tapering allow for a beam of much higher quality, meaning, greatly reduced beam skirts, but at the expense of sensitivity (see Figure 6).

We emphasize that the current study is preliminary, with weighting schemes that are adequate to perform some of the Key Science programs defined to date, such as imaging protoplanetary disks on scales down to 1 AU (Memos 13, 41), CO in high redshift galaxies (Memos 13, 41), and radio continuum deep fields (Memos 30, 35). A more in-depth study of imaging performance and sensitivity versus spatial resolution is in progress, including a wider exploration of the parameter space of imaging algorithms. The results will be presented in the Imaging Performance Reference Document in 2019.

4.6 Practical Considerations for Antenna Locations

Antenna locations, in particular for the antennas outside the Plains, incorporate the practical considerations of land access, roads, power, fiber, interference environment, safety, and security. Where possible, antennas have been placed on public land. Public land areas were chosen that are contiguous with nearby primary roads to allow convenient utility access and that are large enough to place the antenna some distance from the road to reduce the impact of radio frequency interference (RFI). Because public land comprises a minority of the current VLA site, antennas on the Plains of San Agustin were placed primarily on land of the same ownership as that of VLA antennas.

Though roads are significant sources of RFI, antennas have generally been placed within 1 km of existing primary roads to allow easier access to both utilities and service vehicles. Some access roads may require surface enhancement and improved drainage management. Sites were selected for several geographic features. In general, antenna sites are shielded by distance or terrain from easily identifiable RFI emitters such as urban centers, airports, radar installations, and large transmitter towers. Most antenna lines of sight are within ten degrees of the horizon. Sites were chosen to be outside visible flood boundaries and wetlands. Sites with provision for non-bedrock anchoring were selected over nearby bedrock-only candidates. While much of the array is sited in and near the seismically active Rio Grande rift zone, some effort was made to avoid sites affected by fault features visible in satellite imagery.

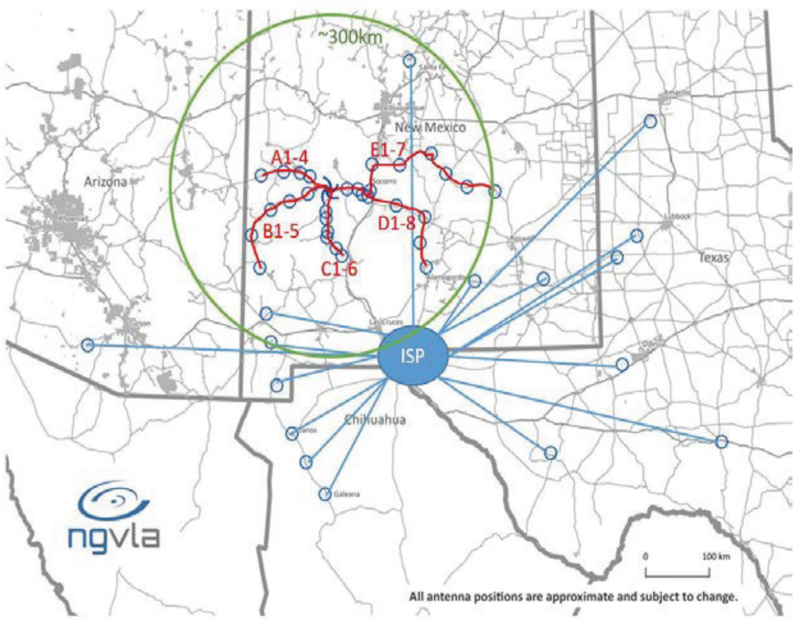

Figure 8 - Model of the proposed fiber architecture for the inner array (<300 km). The wiring scheme for the dark fiber (shown in red) is arranged in five arms (A to E; number scheme increases from the inner to the outer end of the arm). This arrangement will allow for good LO timing, minimizing transmission costs and framing overhead (see Long Haul Fiber Report, Doc No. 020.60.00.00.00-0002).

For outlying antennas, proximity to primary roads allows access to fiber optic lines and power (Figure 8). For antennas on the Plains of San Agustin, utilities can be provided from those at the VLA site. The spiral form for arms was chosen for the Plains antennas not only for imaging performance but also for convenient emplacement of utilities. Each spiral arm can host utility trenches and access roads. Designs for electrical infrastructure provide power distribution systems that are redundant along each arm so that preventive maintenance (PM) or faults need not significantly affect UV coverage.

The arms are centered about 1 km northwest of the VLA array center to reduce physical conflict between a still-operational VLA and ngVLA during ngVLA construction, and to reduce RFI effects between the instruments. For the randomly-sited antennas in the array core, a suitable set of access roads and utilities distribution will be planned, with attention to graceful degradation of performance for PM and faults.

4.7 Future Work and Optimization

The Array Configuration Reference Design is expected to go through additional iterations based on further testing and feedback. One current consideration is how to improve the snapshot uv-coverage when using the longest baselines. A new configuration has been explored in ngVLA Memo #49 which involves moving the 46 outer antennas of the main interferometric array to be configured in a 5 arm spiral within the same maximum baseline of Rev. B (i.e. ~1000 km).

This proposed configuration offers a better snapshot UV coverage than Rev. B while maintaining or improving upon the long-track UV coverage. Further study is also required to optimize the location of the antennas to carefully take into consideration factors such as high frequency observations (e.g., atmospheric conditions), physical infrastructure and the difference in costs with respect of Rev. B.

Remaining work will also include

- Defining PSF imaging metric: Memo with simulations and metrics in preparation for early 2019.
- Imaging simulations of the performance of the SBA and the LBA for their Key Science Programs.
- Multi-scale weighting scheme: new algorithms for optimizing recovered information as a function of angular scale on complex celestial objects, for a multi-scale configuration such as that of the ngVLA. Experimental and ongoing.
- Multi-frequency synthesis simulations: current simulations are based on a single channel.
- Finding a better fit for the "efficiency" weight (eta_weight in Figure 7, right) applied to the rms; model currently uses interpolations.
- Integrating fiber and utility data.

5 Appendix

5.1 Abbreviations & Acronyms

Acronym	Description
AD	Applicable Document
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NSF	National Science Foundation
RD	Reference Document
RF	Radio Frequency
SBA	Short Baseline Array
TBD	To Be Determined
TP	Total Power
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer