System Reference Design

020.10.20.00.00-0001-REP-B-SYSTEM_REFERENCE_DESIGN

Status: **RELEASED**

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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).

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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.

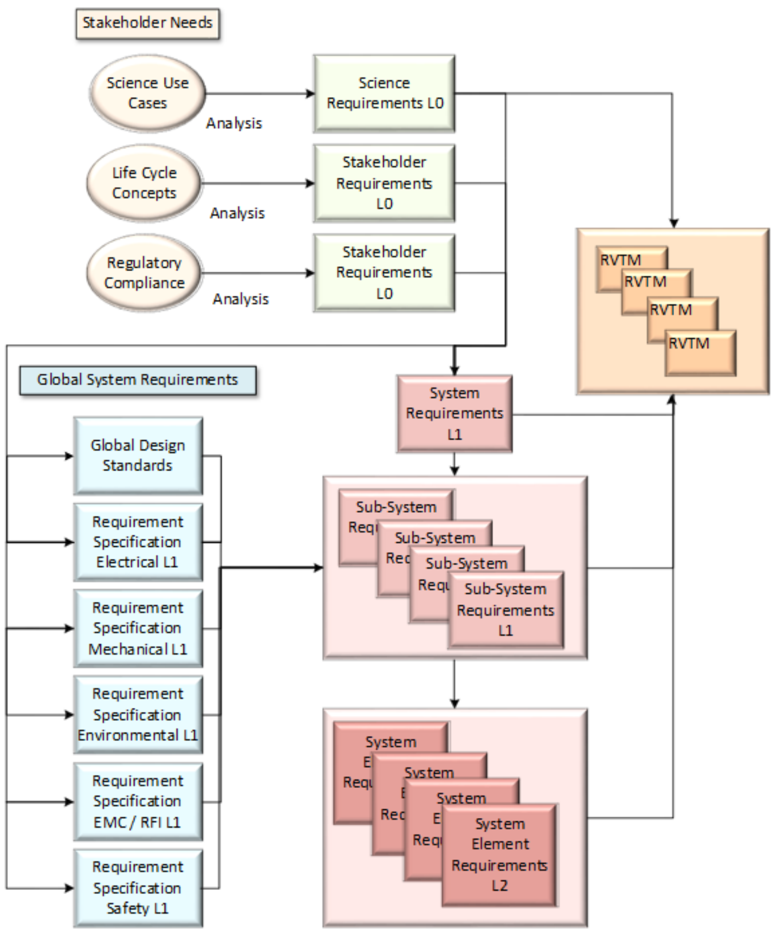

Figure 1 - Relationship between L0 science requirements, L1 system requirements, and associated specifications. [AD06]

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).

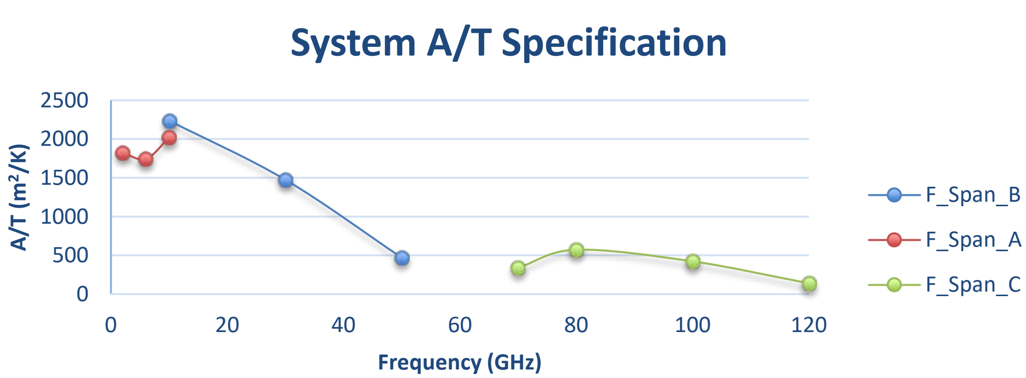

Figure 2 - System A/T specification in m²/K. (SYS1001)

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).

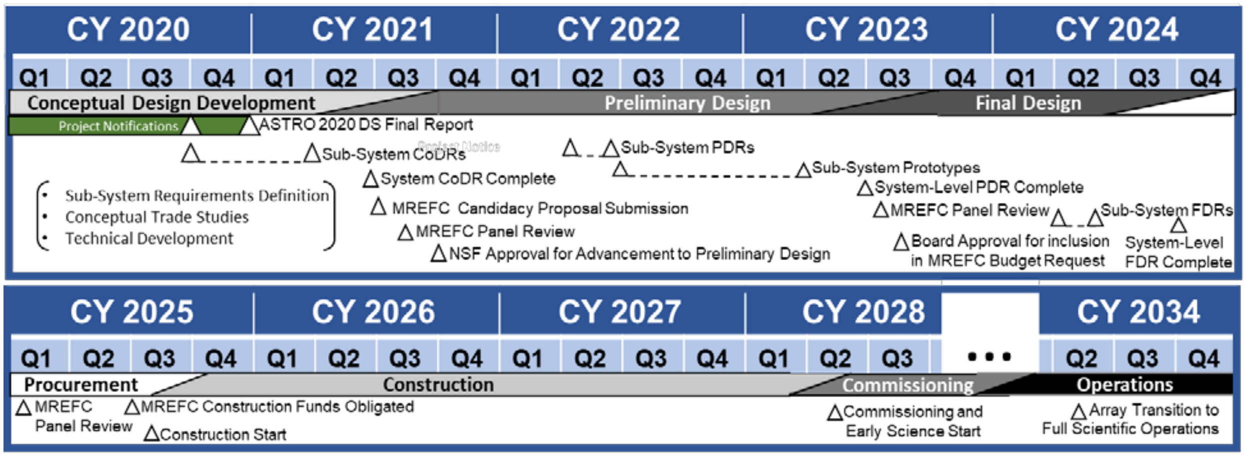

Figure 3 - Preliminary roadmap through design (conceptual, preliminary, final) to construction and operations. Major milestones are shown, such-as sub-system and system-level reviews, and interactions with the NSF MREFC process.

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.

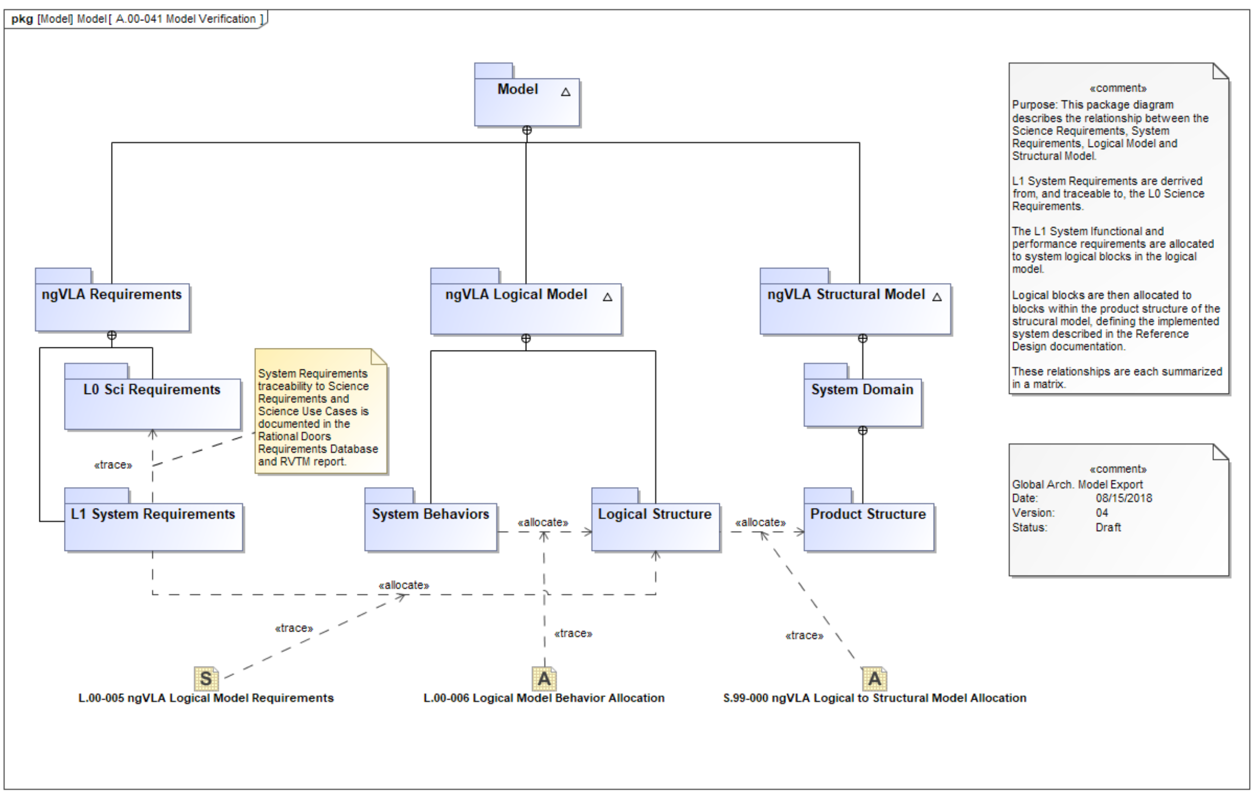

Figure 4 - System architecture model hierarchy and verification strategy. Traceabilty from L0 Science Requirements to L1 System Requirements is captured in the RVTM [AD07]. Requirements and functional behaviors are allocated to blocks in the logical model, and summarized in a Satisfy and Allocate matrix. 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.

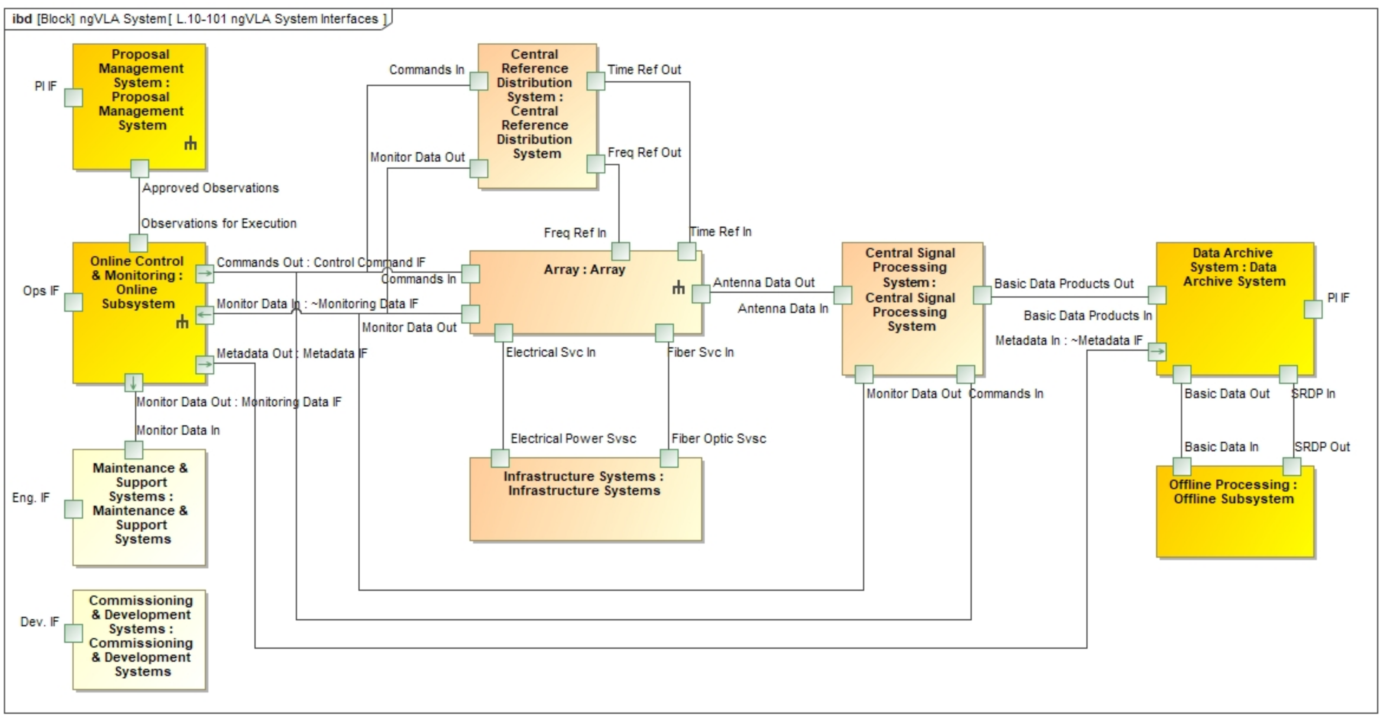

Figure 5 – The high-level ngVLA System Architecture. All deliverables within the facility are sub-components of the identified 10 systems, with major interfaces (IFs) to principal investigators, operations, and engineering shown. [AD09]

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.

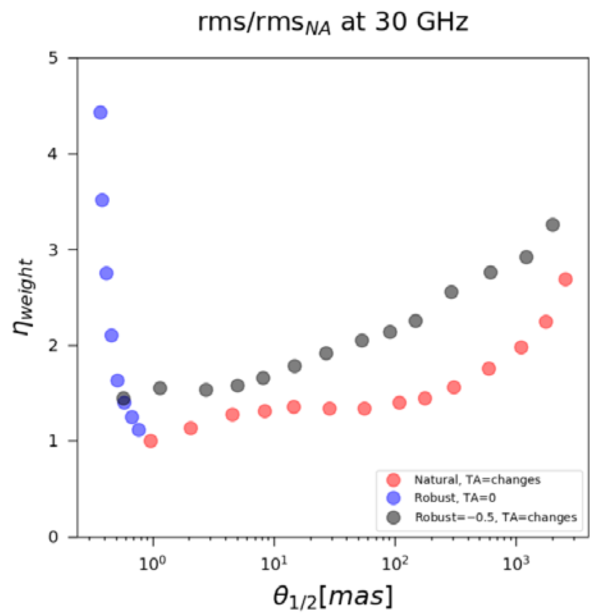

Figure 6 - Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz. The noise has been scaled relative to that of the naturally weighted image (σ_{NA}). The red symbols correspond to use of a (*u,v*) taper and natural weights, and the blue 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]

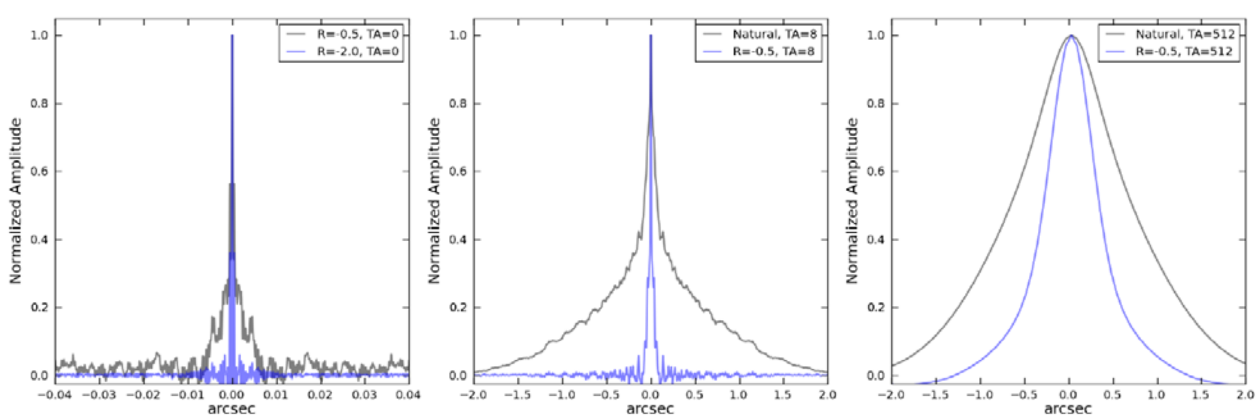

Figure 7 - Simulated 30 GHz PSFs over a range of resolutions show the effect of different imaging weights (TA: (*u,v*) taper in mas, R: Briggs robust parameter). The PSFs are a selection of the data presented in Figure 6: left panel (blue circles), central and right panels (gray and red circles). These 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.

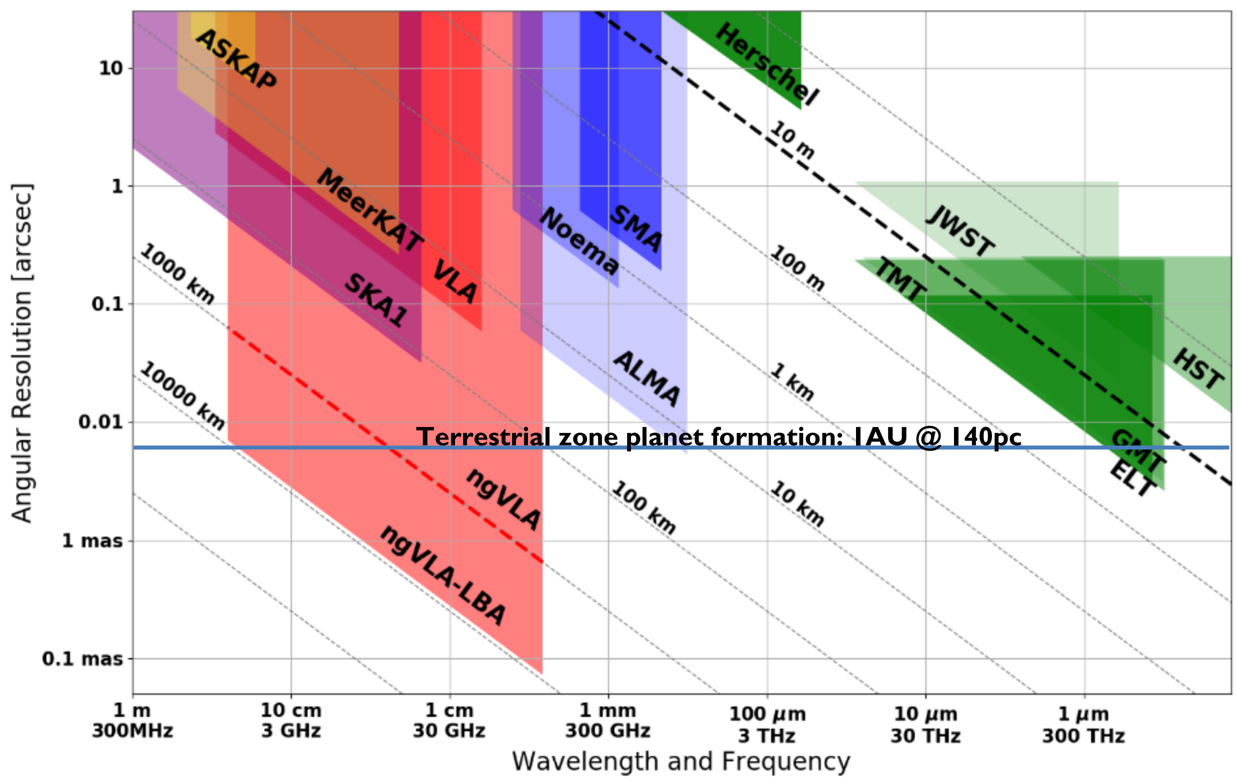

Figure 8 - Spatial resolution versus frequency set by ngVLA maximum baselines as compared to that of other existing and planned facilities.

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.

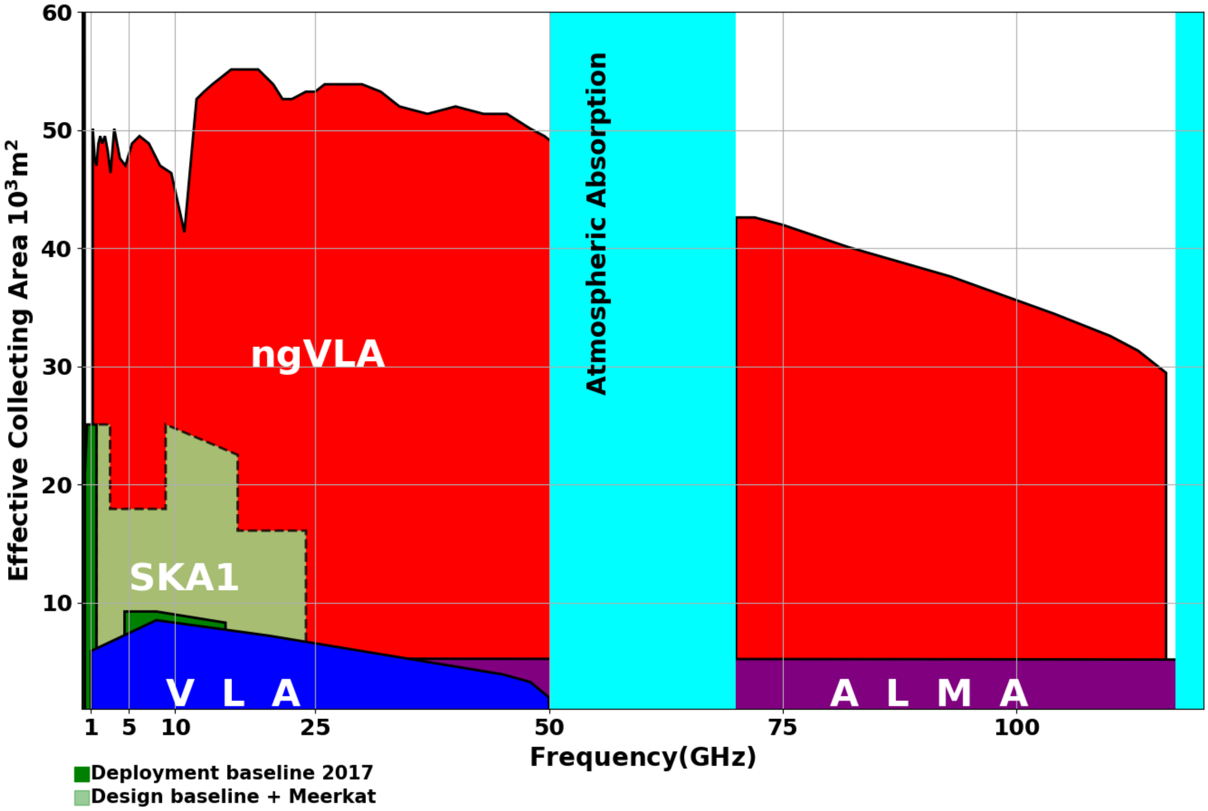

Figure 9 - Effective collecting area versus frequency for ngVLA as compared to that for other existing or planned facilities. Note that lower and higher frequencies are not shown (e.g., SKA-1 will extend to below 100 MHz and ALMA extends up to about a THz). Both the SKA-1 deployment baseline (dark green)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

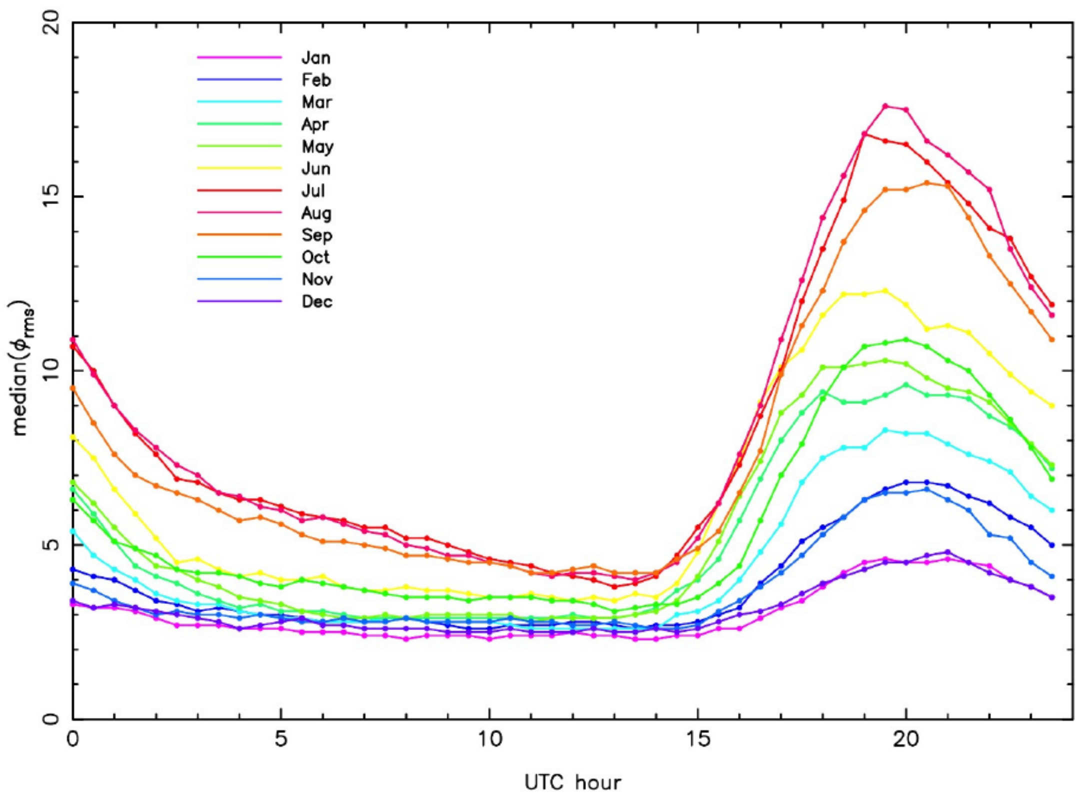

Figure 10 - The median rms phase measured with the atmospheric phase monitor at the VLA (300 m E-W baseline, 11.7 GHz beacon), from 1995 to 2017. Measurements are calculated over a ten-minute period after subtracting any linear trend. Different months are plotted as different colors, as shown in the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

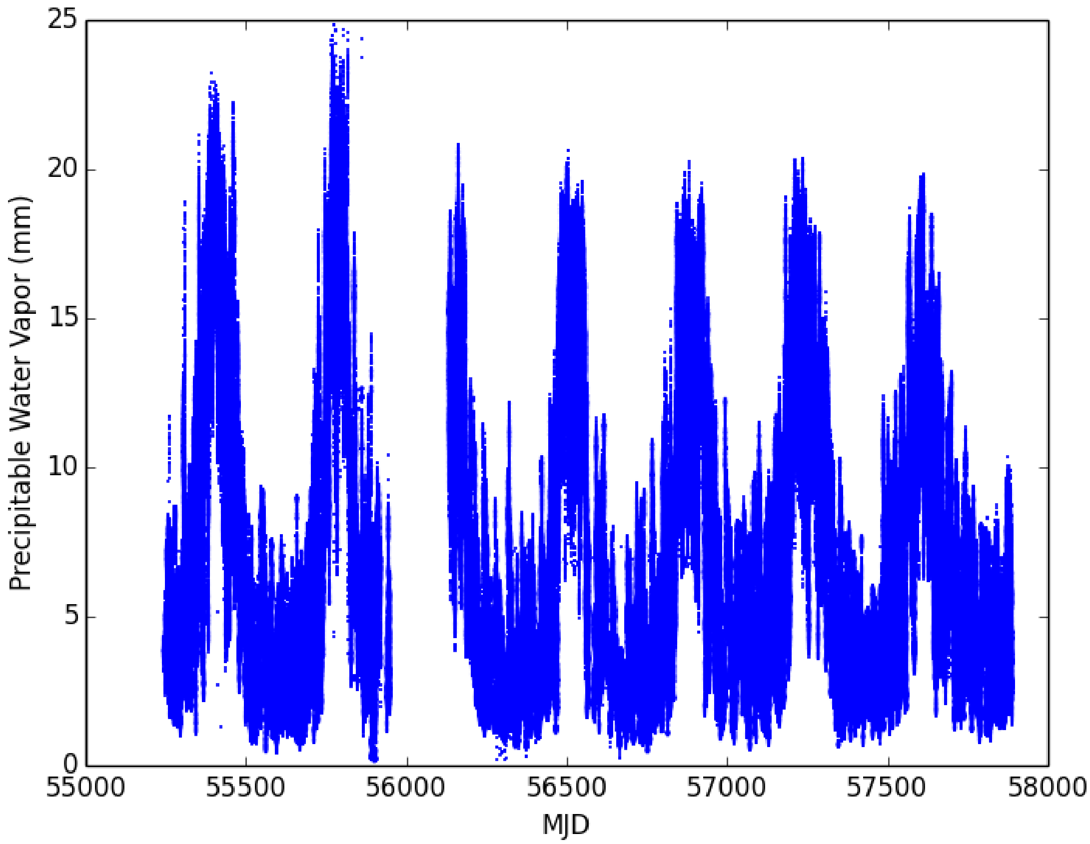

Figure 11 - PWV at the VLA site, estimated using surface weather measurements, from 2010 to 2017. Note that a PWV of 6 mm produces an opacity of less than 7% at 90 GHz.

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).

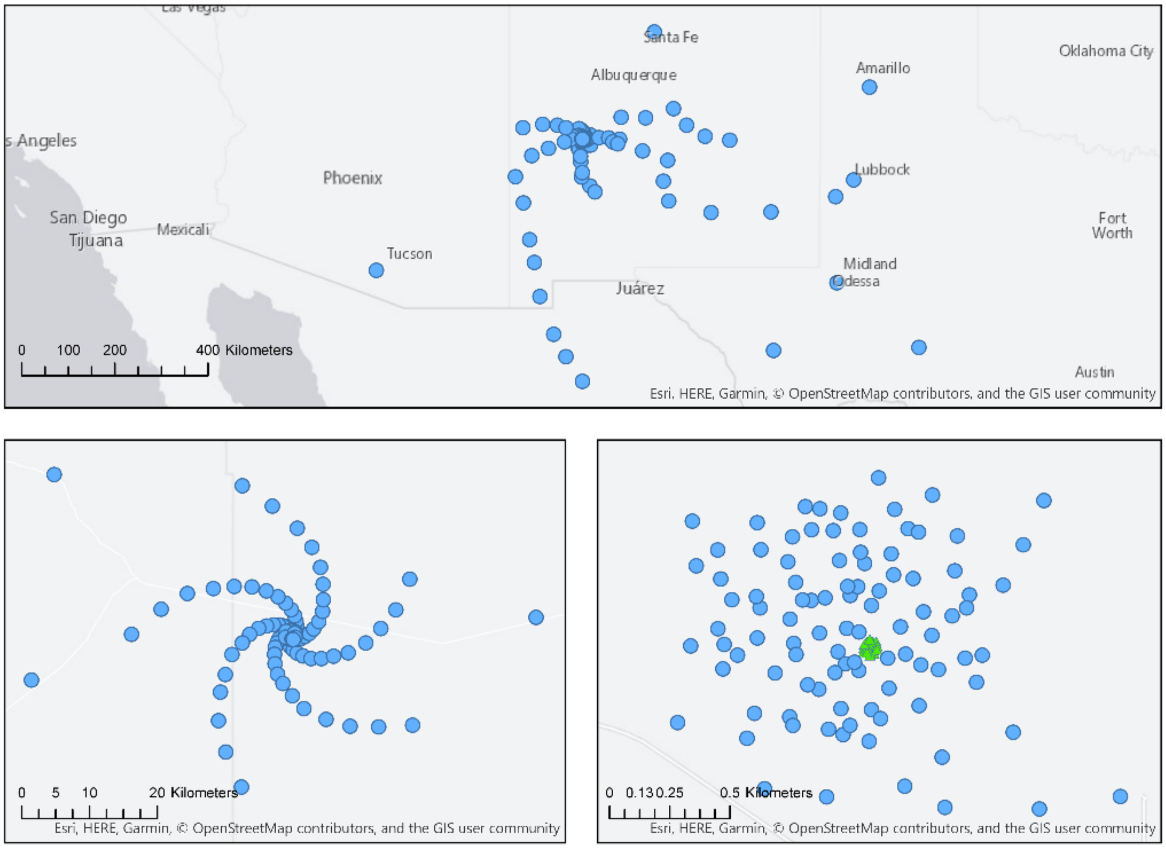

Figure 12 - Top: ngVLA Main Array Configuration Rev. B (Spiral-214). The antenna positions are still notional, but are representative for performance quantification and cost estimation. Bottom left: Zoom view of the Plains of San Agustin. Bottom right: Zoom view of the compact core. SBA antennas are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

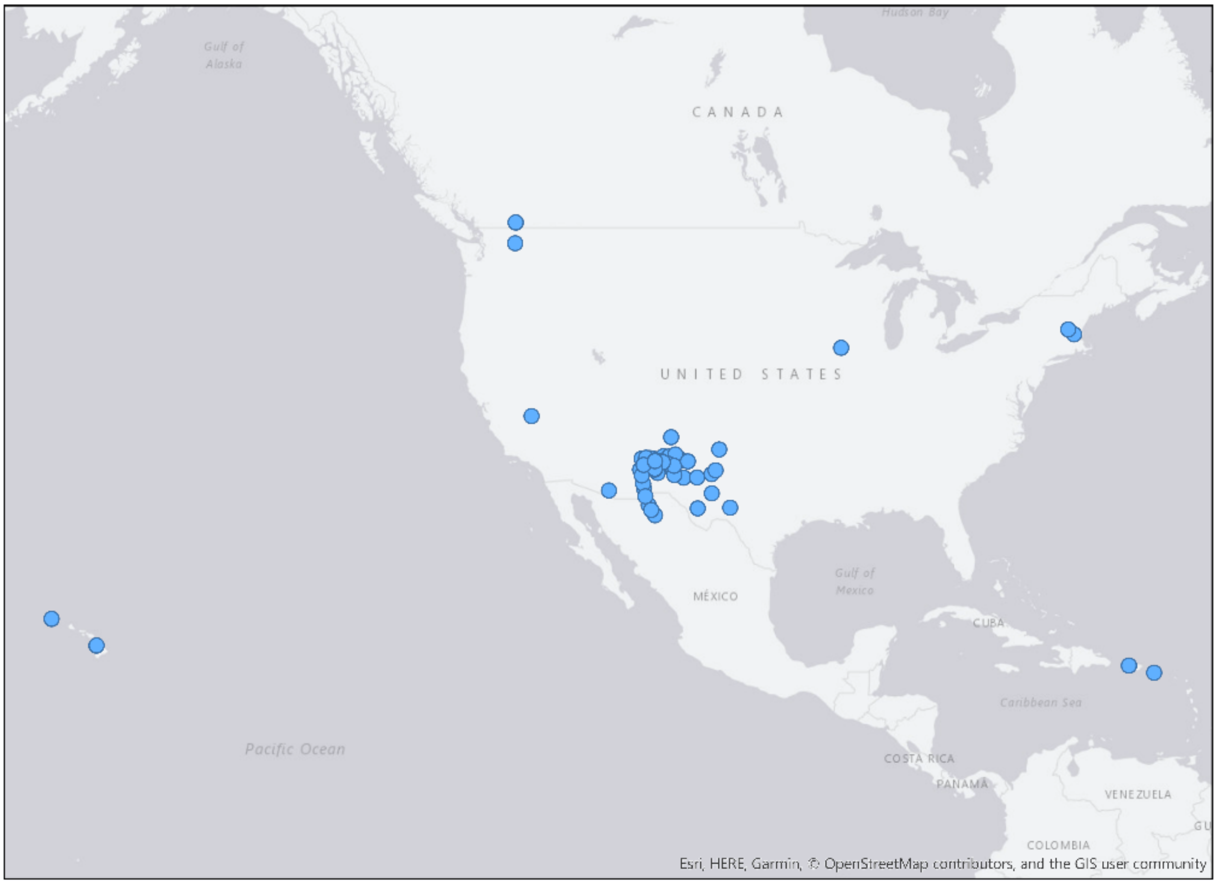

Figure 13 - View of Main Array and Long Baseline Array stations. Multiple antennas are located at each LBA site.

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].

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[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).

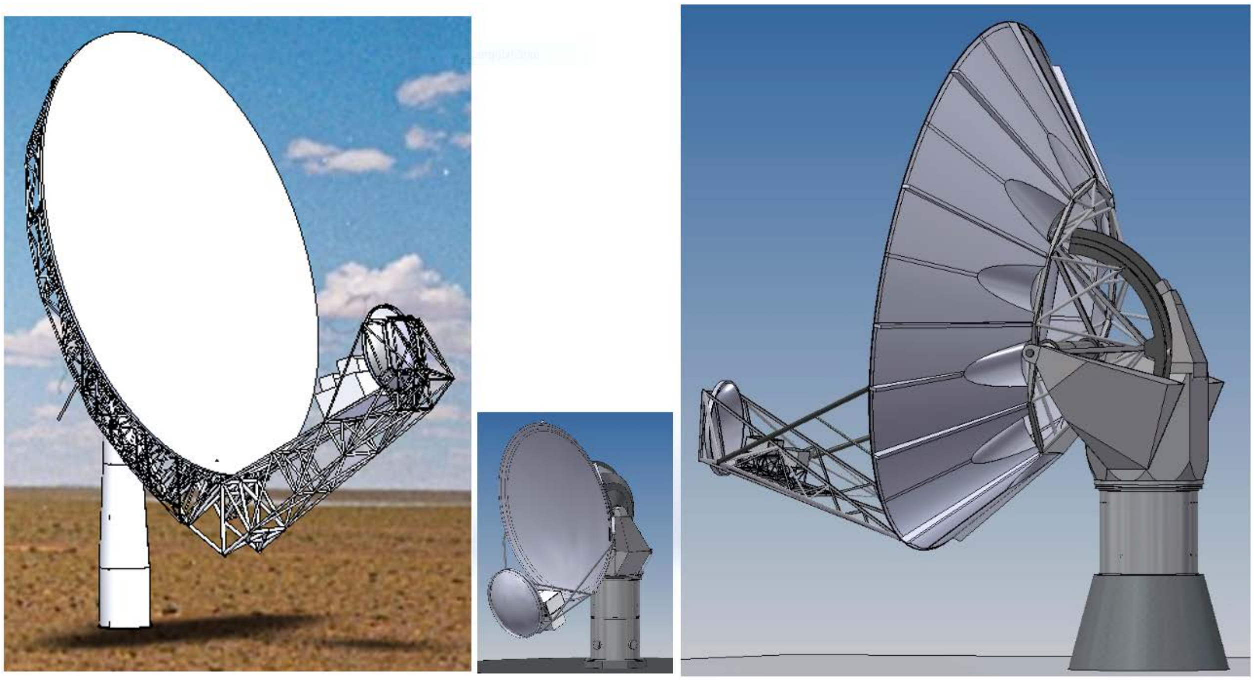

Figure 14 - Left: ngVLA 18-meter antenna design concept prepared by GDMS. Right: 18m antenna concept prepared by NRC. Center: 6m short spacing array antenna concept prepared by NRC.

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.

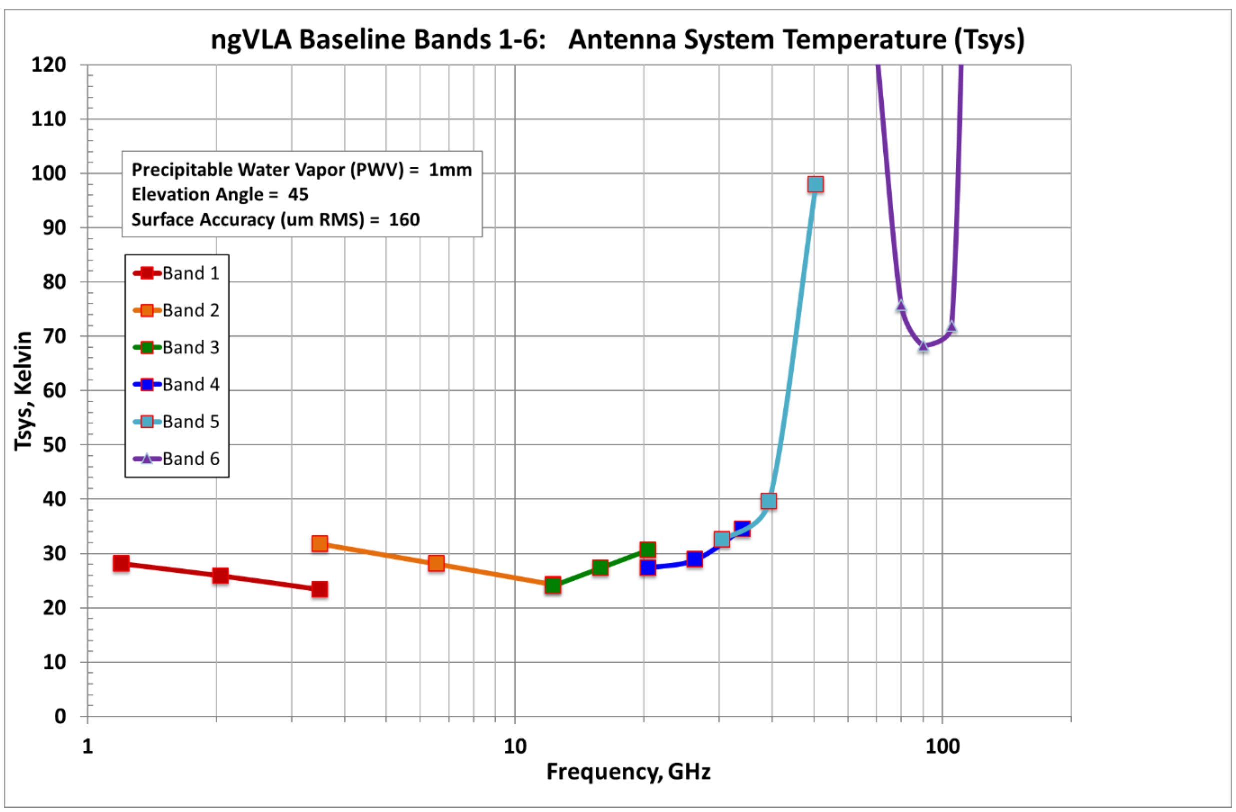

Figure 15 - System temperature for the ngVLA 6-band receiver configuration.

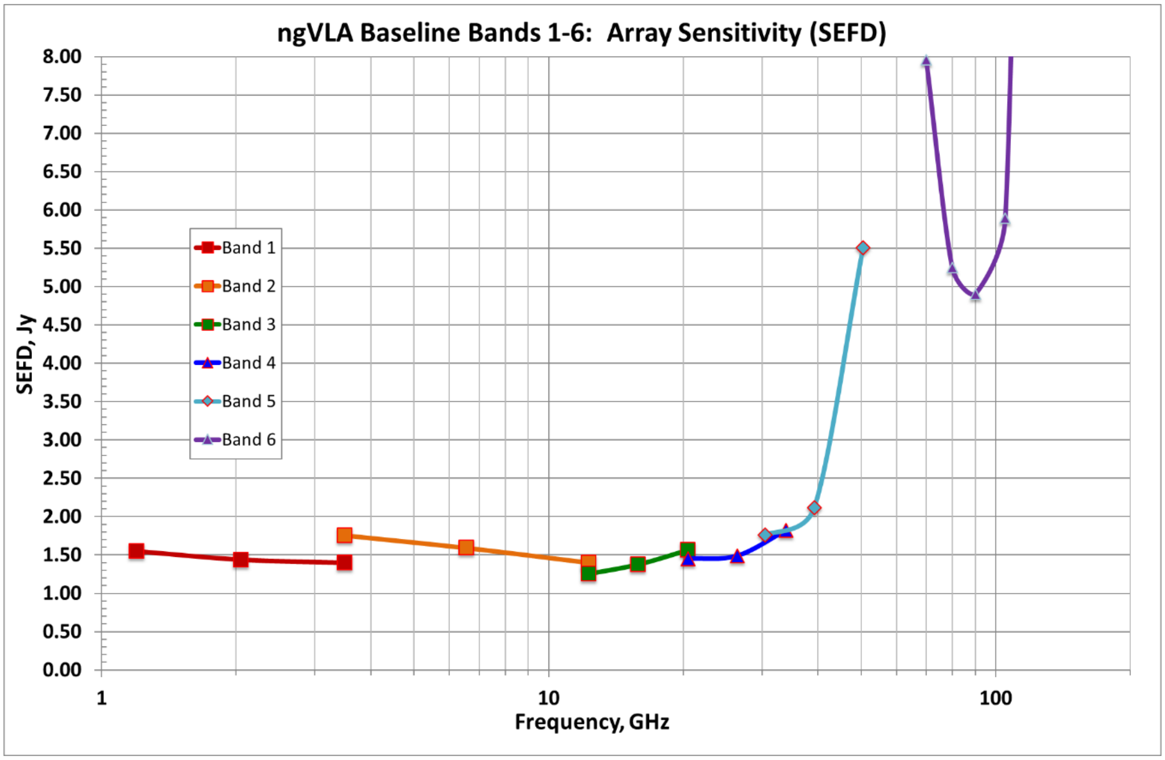

Figure 16 - System SEFD for the full 263 element array (244 @ 18 m, 19 @ 6 m).

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.

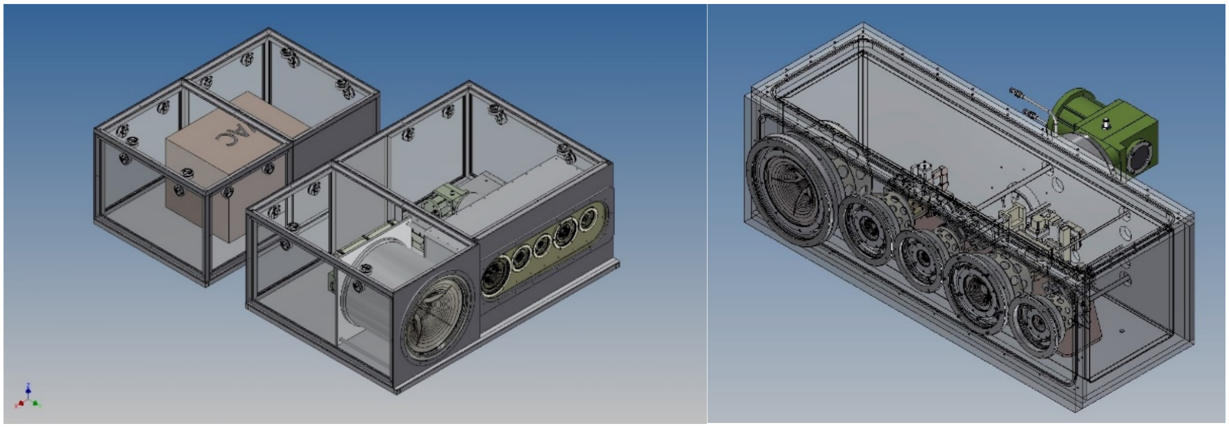

Figure 17 - Left: Front End component packaging at the secondary antenna focus. Band selection and focus are achieved with a dual-axis translation stage. Integrated receiver packages are located in close proximity to cryostats, minimizing the analog signal path length (Section 7.4.3). Right: Bands 2-6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

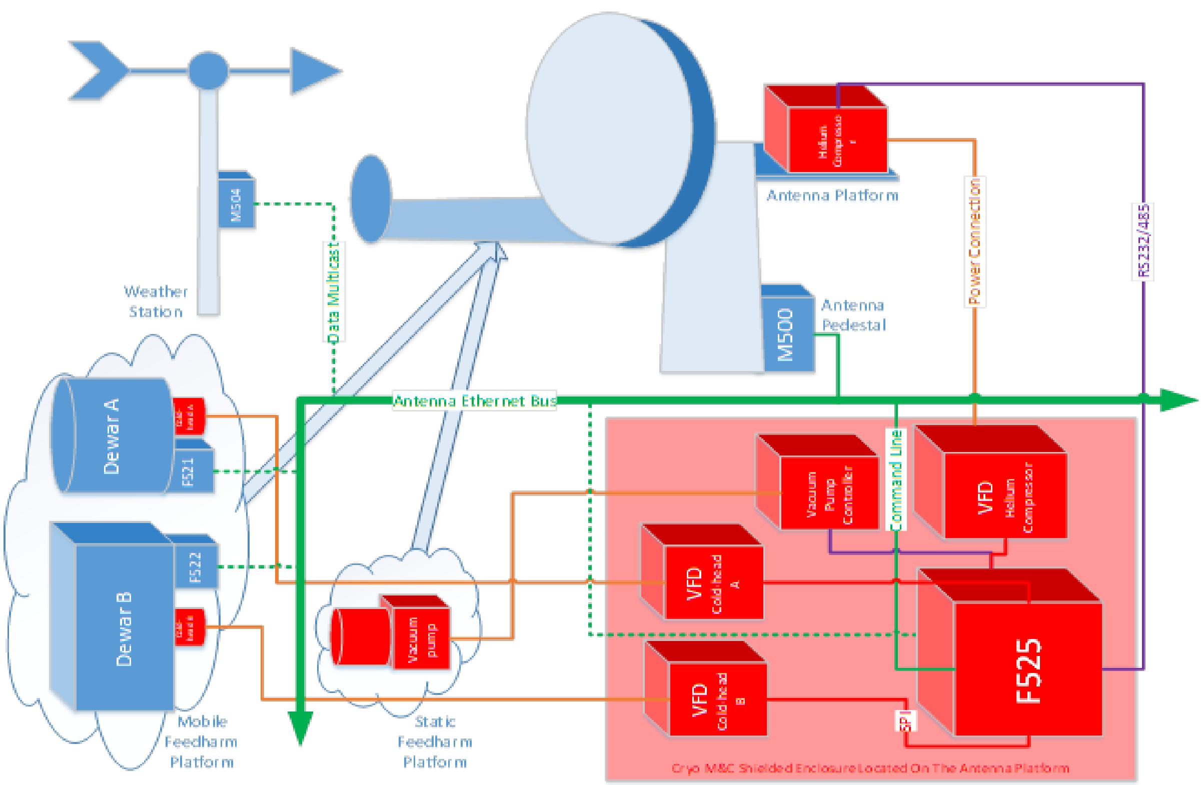

Figure 18 - Cryogenic system interfaces within the antenna. Cryogenic components are shown in red, with interfacing components in blue [AD25].

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.

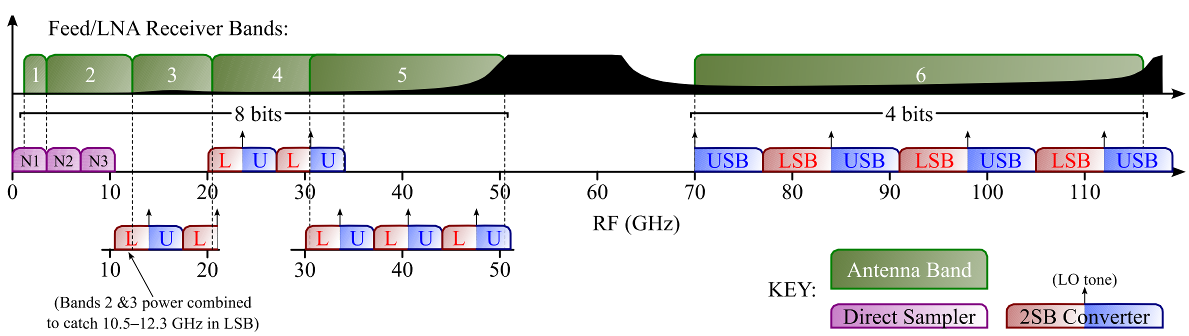

Figure 19 - Present sampling concept employing integrated receiver technology for both direct and dual sideband converter/samplers. Nyquist zones 1 through 3 are direct sampled single-sideband at 8 bits. From 10 GHz to 50 GHz the system uses single-stage down conversion to baseband and IQ sampling at 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.

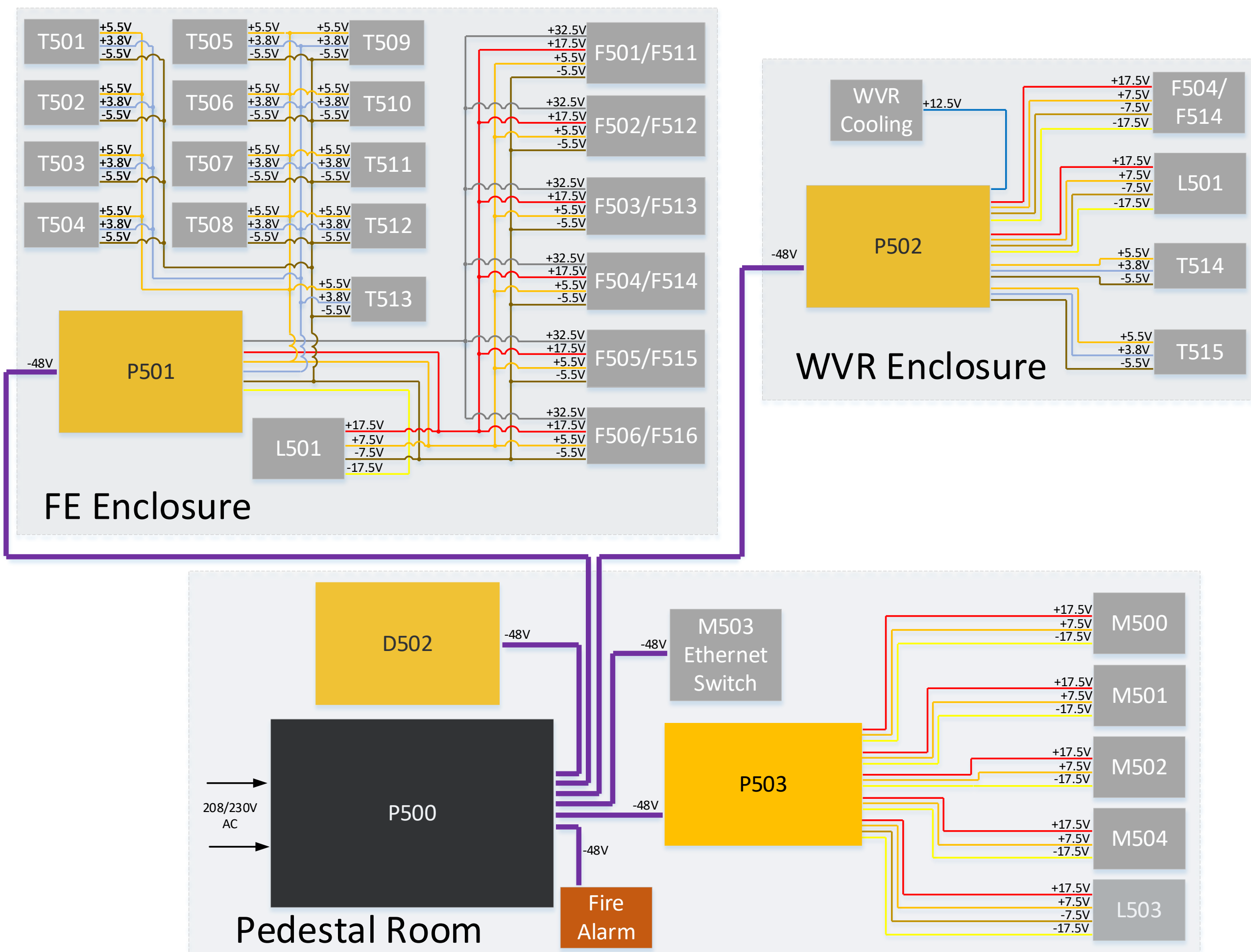

Figure 20 - Block diagram of the DC power supply system.

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.

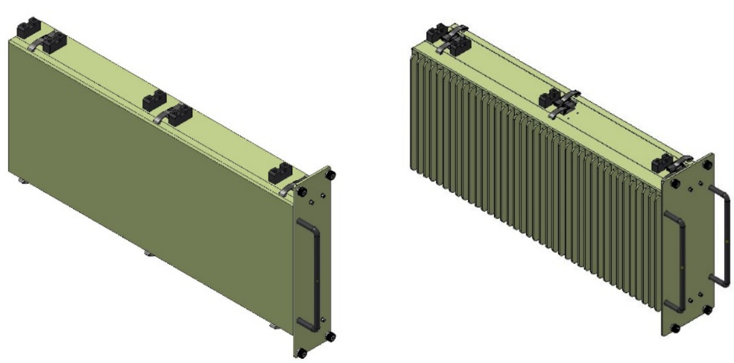

Figure 21 - Series 100 (left) and 300 (right, with heatsink) ARCS Module housings employed in the reference design.

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.

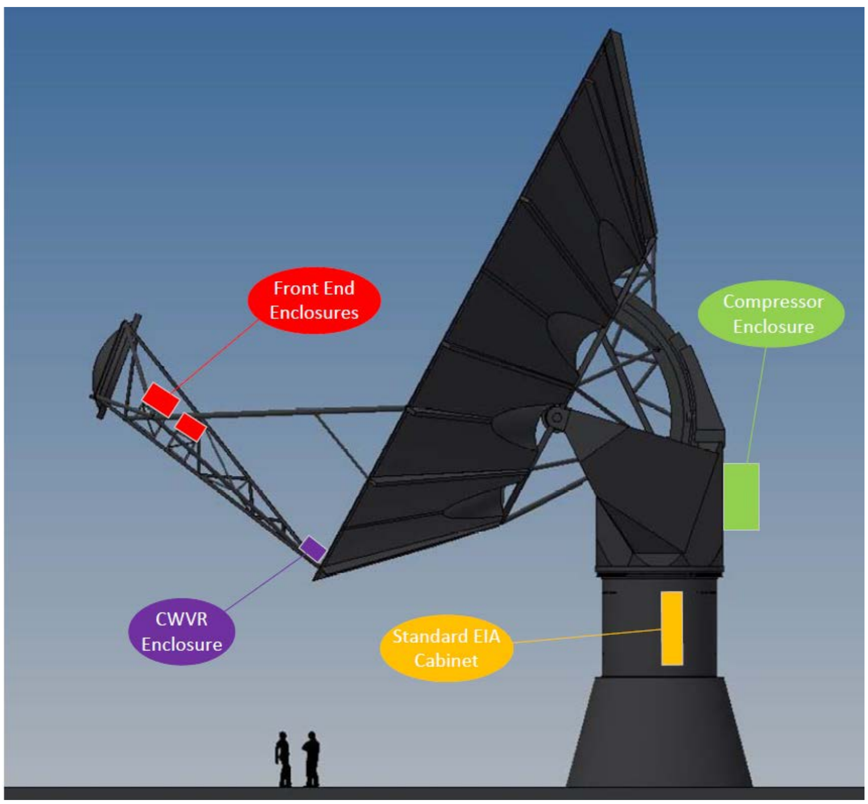

Figure 22 - Location of the thermally regulated enclosures and environmental control system hardware. The NRC 18m antenna is shown as reference.

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.

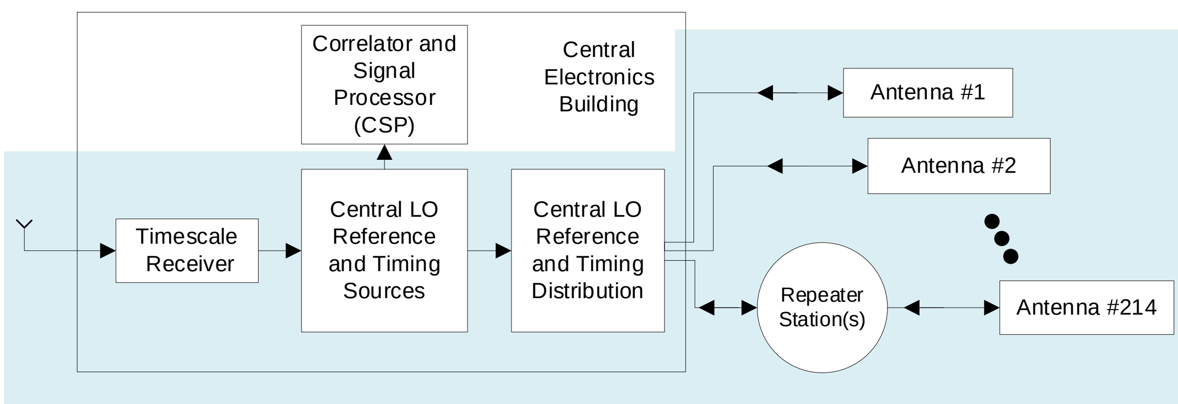

Figure 23 - Block diagram of main array LO Reference and Timing system parts (shaded in blue).

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.

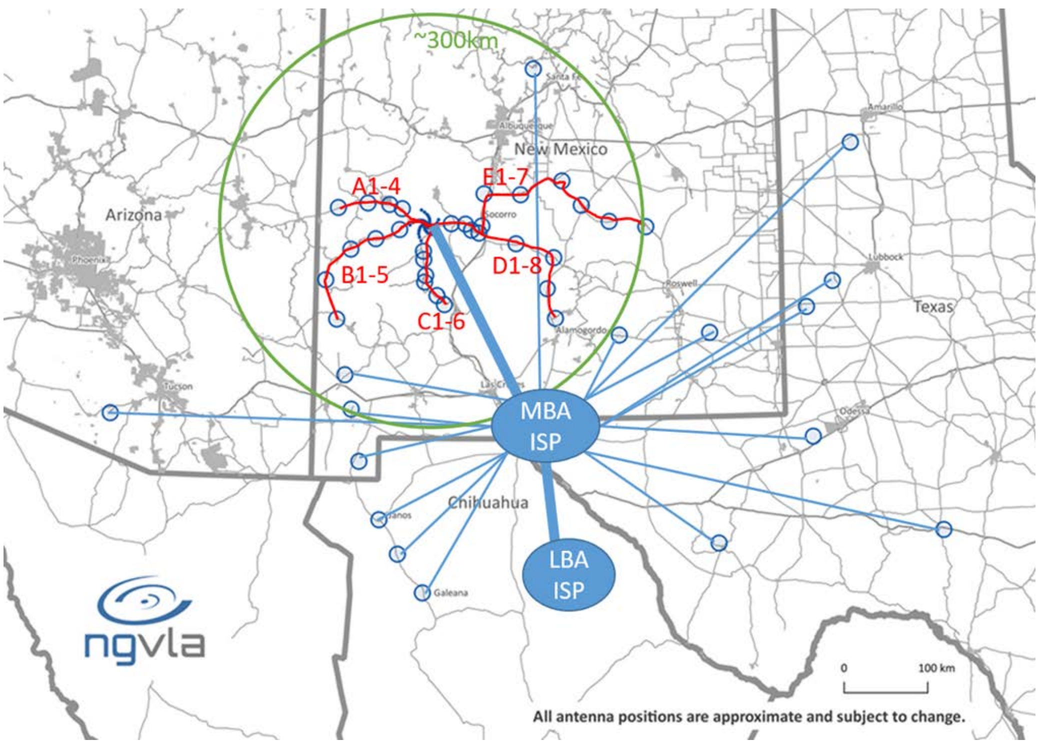

Figure 24 - Data transmission network topology. Antennas within the core and spiral arms are direct point-to-point connections over ngVLA operated fiber. Mid-baseline stations within ~300km are connected over dedicated fiber links with repeater infrastructure hosed at each antenna station. Service points 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.

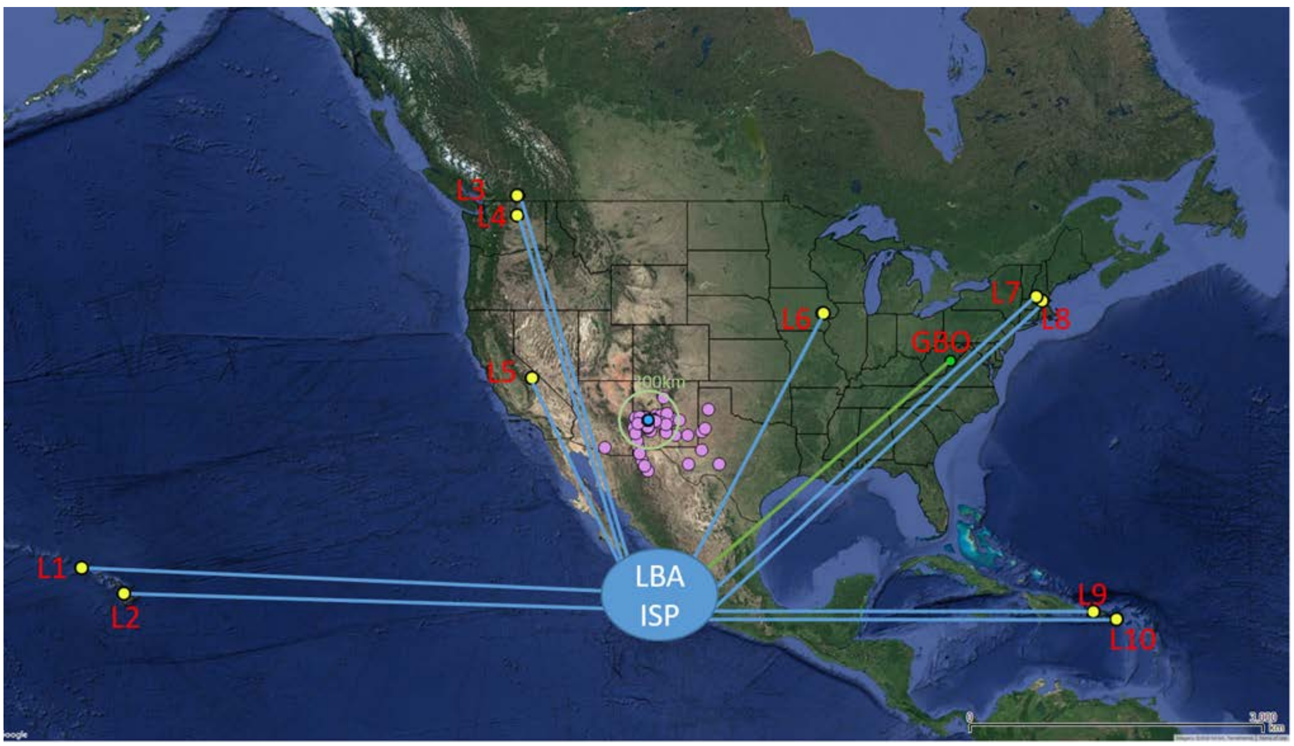

Figure 25 - ngVLA LBA ISP data links. LBA sites are shown in yellow and the GBO site is in green. The ngVLA core and main array are in blue and purple, respectively. A total of 30 antennas are included in the LBA configuration (see Section 7.1) and share links from the ten sites.

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.

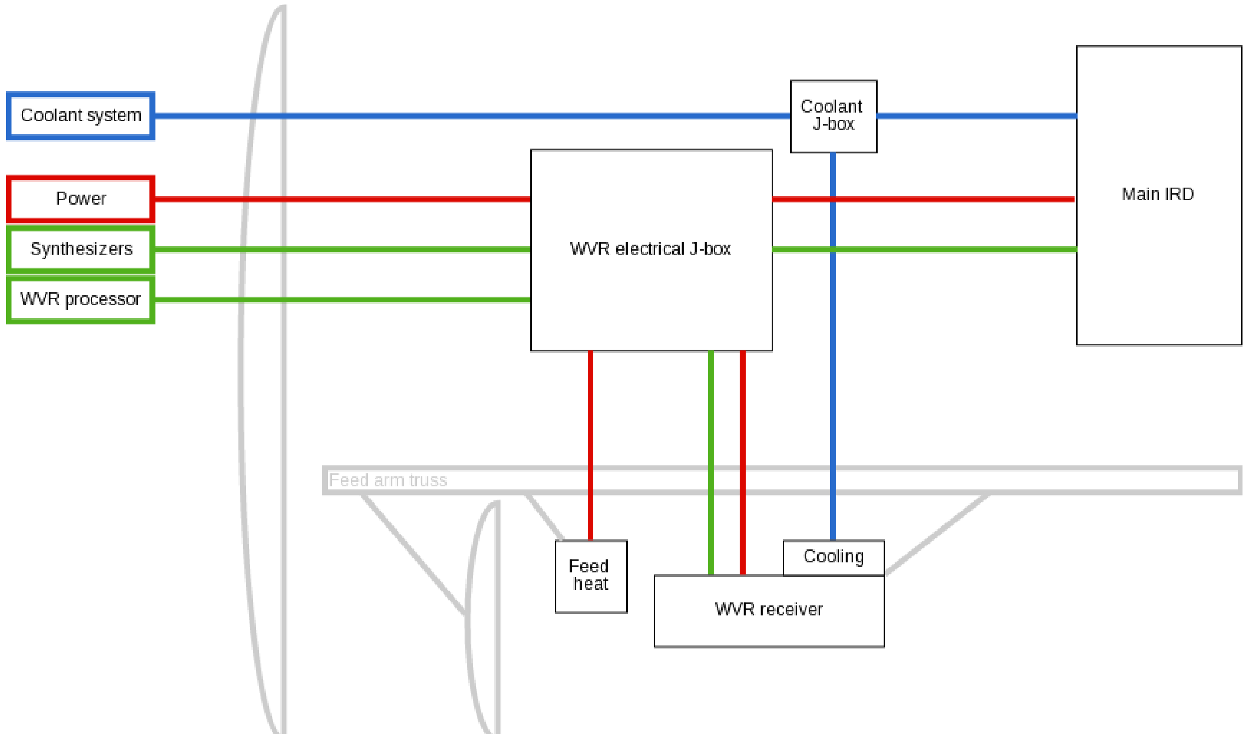

Figure 26 - WVR system block diagram and interfaces.

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.

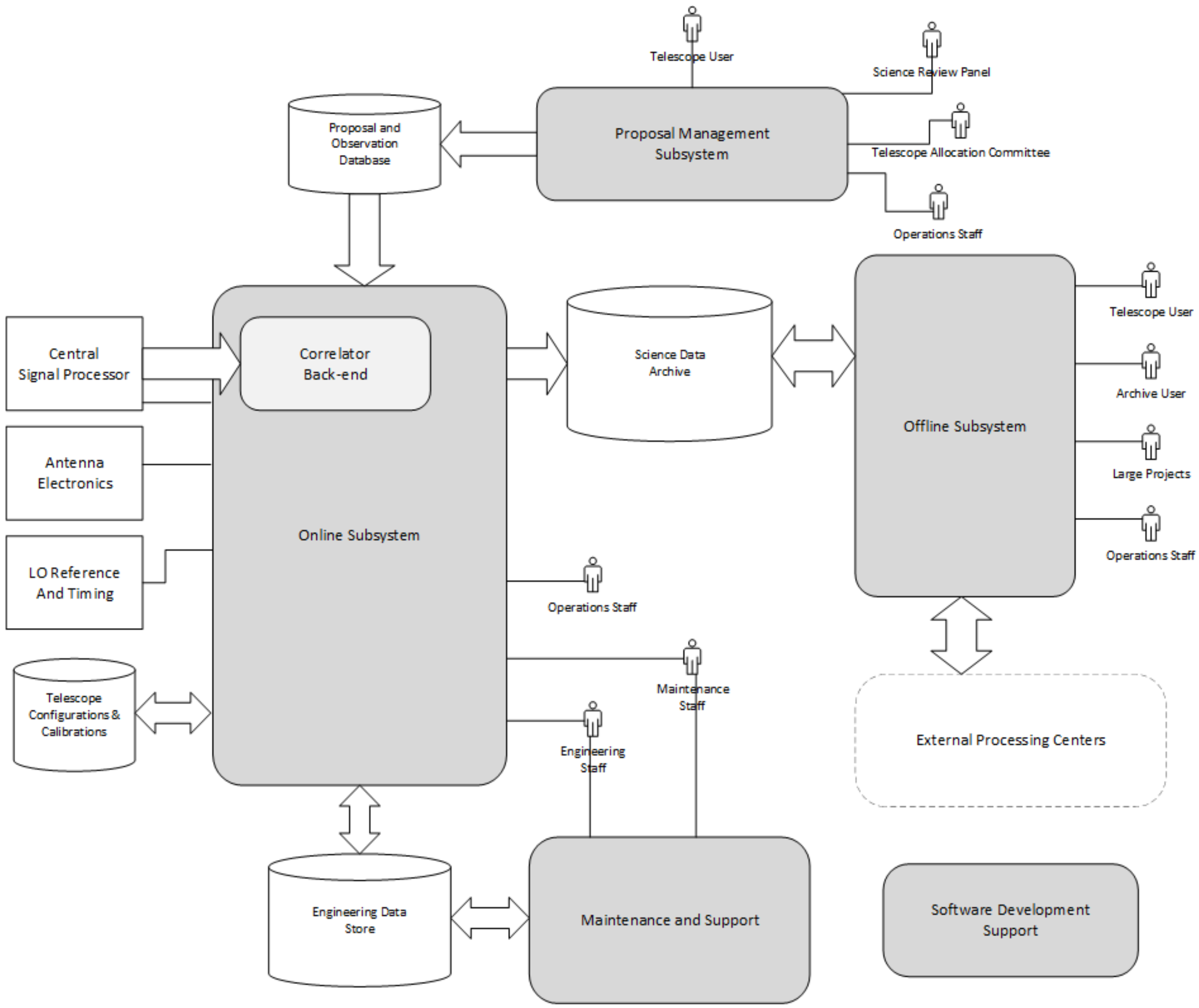

Figure 27 - General Computing and Software architecture, with major subsystems shown as gray boxes. Also shown are interfaces and dataflows between the subsystems, data stores, main actors, and other external system elements. [AD43]

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.

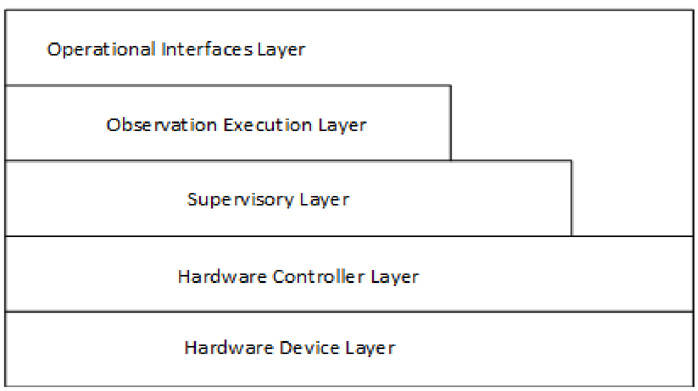

Figure 28 - ngVLA Monitor and Control architecture layers. [AD44]

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.

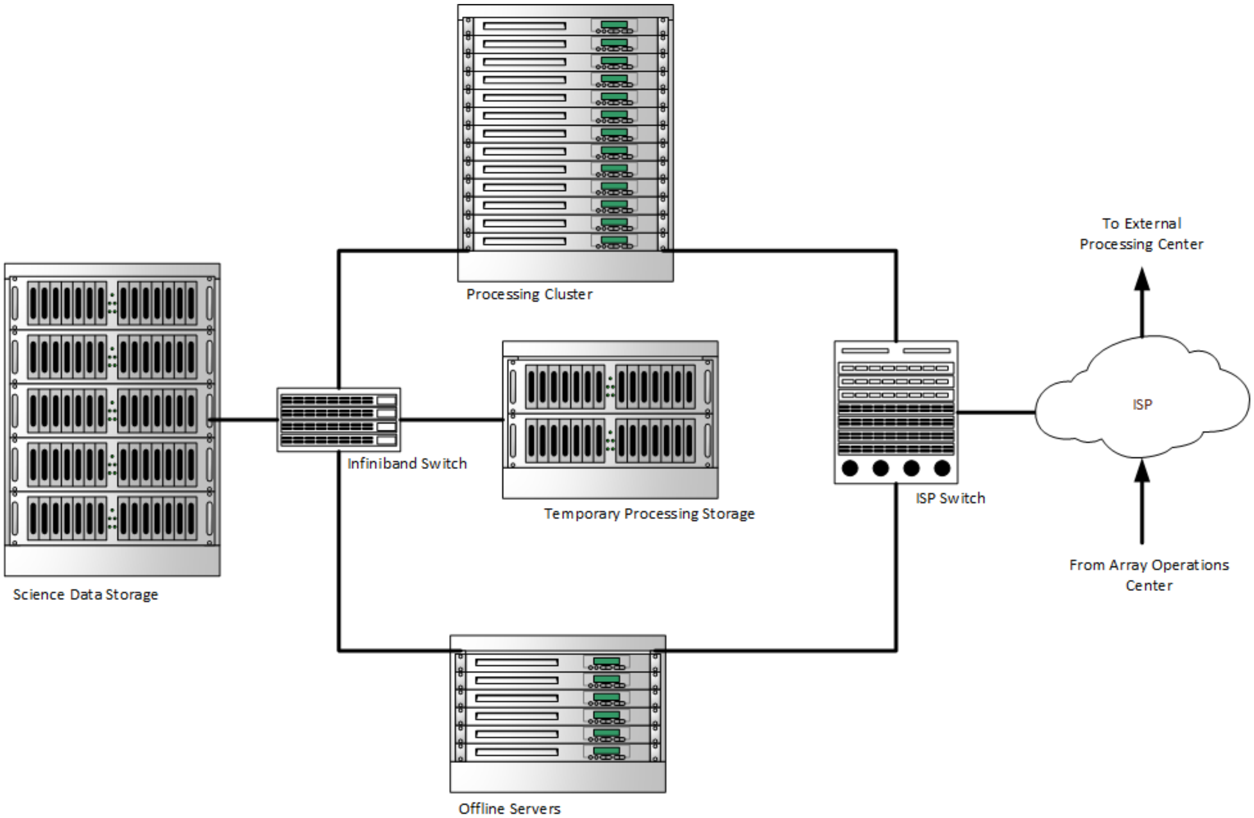

Figure 29 - Offline sub-system physical architecture.

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.

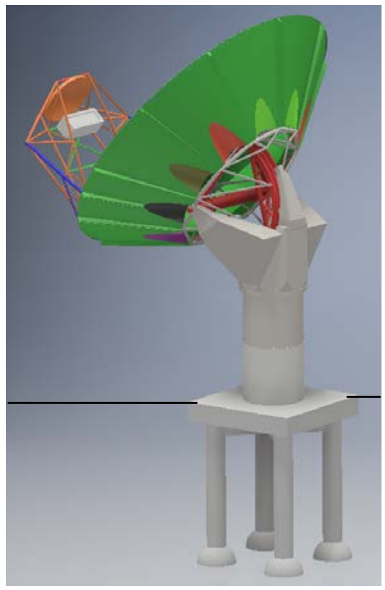

Figure 30 - Foundation design used for costing. The slab below the antenna is at ground level, with concrete caissons extending below grade.

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.

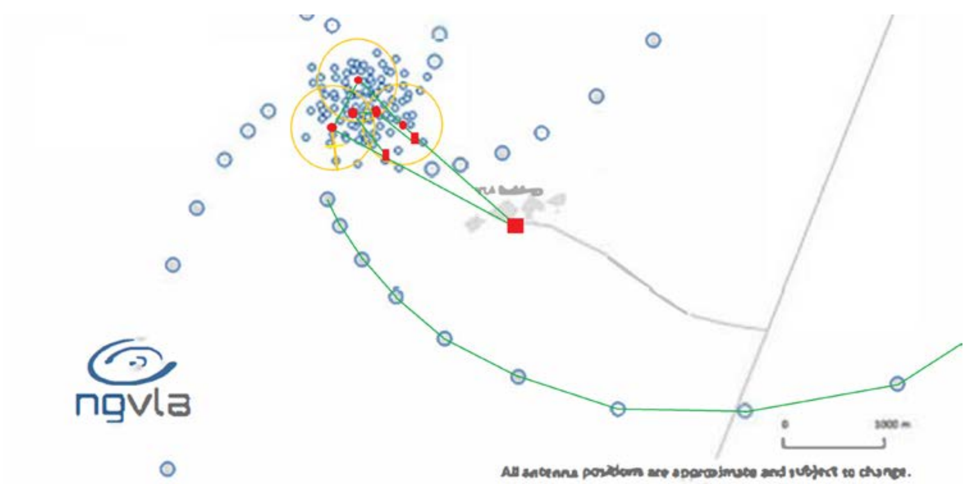

Figure 31 - Example locations of the backup power plant and switchgear locations (red) and utility trenching along arms (green).

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