ngvla

Next Generation Very Large Array

SYSTEM REFERENCE DESIGN

Volume 3:
Central Systems,
Computing & Infrastructure

Preface

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

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

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

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

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

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

Robert J. Selina
ngVLA Project Engineer
August, 2019

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

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

Volume III

Preface

R. Selina

Part VII: Central Electronics

Local Oscillator Reference and Timing: Preliminary Technical Requirements
020.35.00.00.00-0001-REQ-A
W. Shillue

Local Oscillator Reference and Timing: Design Description
020.35.00.00.00-0002-DSN-A
W. Shillue

Central Signal Processor: Preliminary Technical Requirements
020.40.00.00.00-0001-REQ-A
O. Ojeda, R. Lacasse, R. Selina, B. Carlson, M. Rupen, and M. Pleasance

Central Signal Processor: Preliminary Reference Design
020.40.00.00.00-0002-DSN-A
O. Ojeda

Trident Correlator-Beamformer for the ngVLA: Preliminary Design Specification
TR-DS-000001
B. Carlson and M. Pleasance

Part VIII: Computing and Software Systems

Computing and Software: Preliminary Requirements
020.50.00.00.01-0001-REQ-A
R. Hiriart

Computing and Software Architecture: Reference Design
020.50.00.00.01-0002-REP-A
R. Hiriart, J. Robnett, and M. Pokorny

Monitor and Control System: Reference Design Concept
020.50.25.00.00-0002-DSN-A
R. Hiriart

Monitor and Control Hardware Interface Layer: Preliminary Technical Requirements
020.30.45.00.00-0002-REQ-A
W. Koski and J. Baca

Monitor and Control Hardware Interface Layer: Reference Design Description
020.30.45.00.00-0004-DSN-A
W. Koski and J. Baca

Part IX: Array Infrastructure

Long Haul Fiber Workgroup: Preliminary Report
020.60.00.00.00-0002-REP-A
D. Halstead, D. Hart, A. Erickson, W. Shillue, and R. Selina

Reference Study: ngVLA Buildings and Infrastructure
020.60.00.00.01-0002-REP-A
M. Romero, K. Baker, C. Langley, et al.

Land Acquisition and Regulatory Compliance: Scope and Requirements
020.70.00.00.00-0001-REQ-A
J. Bolyard

Appendix

Product Tree
020.10.10.05.00-0001-LIS-A
R. Selina and R. Treacy

Project Lexicon and Acronyms
020.10.10.10.00-0005-LIS-A
R. Treacy and S. Leff

Local Oscillator Reference and Timing: Preliminary Technical Requirements

020.35.00.00.00-0001-REQ-A-LOCAL_OSCILLATOR_REF_TIMING_TECH_REQS

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02	2018-9-30	B. Shillue	All	Incorporation of Long Baseline Array Requirements Incorporate reviewer edits
03	2018-11-16	B. Shillue	All	Minor edits after Internal Review
04	2019-04-23	B. Shillue	3.4,6,5	Small changes to sections 3.4.6 and 5, other minor edits
05	2019-06-04	B. Shillue	3.4.2, 3.4.3, 4.2.2, 4.2.3, 4.3.1	Changed detail of reqts -0260, -0300 and added -0251
A	2019-07-26	A. Lear	All	Incorporated minor edits from R. Selina & M. McKinnon; prepared PDF for signatures & release

Table of Contents

1 Introduction 3
1.1 Purpose 3
1.2 Scope 3
2 Related Documents & Drawings 3
2.1 Applicable Documents 3
2.2 Reference Documents 3
3 Overview 4
3.1 Document Outline 4
3.2 Project Background 4
3.3 General LO Reference and Timing Description 4
3.4 Summary of LO Reference and Timing Requirements 7
3.4.1 General Requirements 7
3.4.2 LO and Digitizer Frequency Requirement 8
3.4.3 LO Reference and Timing Phase Stability and Accuracy 8
3.4.4 Design and Engineering Requirements 9
3.4.5 Reliability and Lifetime Requirements 9
3.4.6 Interface Requirements 10
4 Functional and Performance Requirements 12
4.1 General Requirements 12
4.1.1 Number of Antennas 12
4.1.2 Maximum Fiber Length 13
4.1.3 Number of Subarrays 13
4.1.4 Phase Preservation 13
4.1.5 Band Switching 13
4.1.6 Phase Calibration Efficiency 14
4.1.7 Compact Core 14
4.2 LO and Digitizer Frequency Requirements 14
4.2.1 Required Nominal LO Frequencies 14
4.2.2 Frequency Offset 15
4.2.3 Number of Simultaneous LOs 15
4.2.4 Incoherent Spurious 15
4.2.5 Sampler Offset 15
4.3 LO and Digitizer Phase Stability and Accuracy 15
4.3.1 Phase Drift 15
4.3.2 Phase Noise or Jitter 16
4.3.3 Timing Accuracy 16
4.3.4 VLBI Phase 16
4.4 Design and Engineering Requirements 16
4.5 Reliability and Lifetime 17
5 Interface Requirements 18
5.1 Interface to Monitor and Control 18
5.2 Interface to Central Electronics Building 18
5.3 Interface to Central Signal Processor 18
5.4 Interface to Site 18
5.5 Interface to Antenna Pedestal 18

5.6 Interface to Front End Enclosure 19
5.6.1 LO Power Level 19
5.6.2 LO Spurious Level 19
6 Environmental Requirements 22
7 RFI and EMC Requirements 22
8 Appendix 23
8.1 System Requirements 23

1 Introduction

1.1 Purpose

This document aims to present a *preliminary* set of technical requirements for the ngVLA Local Oscillator (LO) Reference and Timing (LRT) work element.

1.2 Scope

This document includes descriptions of requirements that will be enforced at an interface with some other part of the Next Generation Very Large Array (ngVLA), and this description will later be superseded by a formal interface control document. This document does not detail the design, planning, test and measurement, or performance verification of the LO Reference and Timing. This document may be superseded in the future after breaking the present extent of the LO Reference and Timing into two or more subsystems, and remapping the requirements accordingly.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this requirements document.

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	V3, 5/10/2018
AD02	System Environmental Specification	020.10.15.10.00-0001-SPE, v7, 2018-10-08
AD03	ngVLA System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ, v3, 2018-05-09
AD04	Inclusion of the "Long Baseline Major Option" into the ngVLA Baseline Design	020.05.60.01.01-0002-ECO, v0.05, 2018-08-02

2.2 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev/Doc. No.
RD01	A Next Generation Very Large Array	http://adsabs.harvard.edu/abs/2017arXiv171109921M
RD02	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK, 2018-04-27
RD03	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK, 2018-04-27
RD04	ngVLA memo 43 (B. Mason, R. Selina, A. Erickson, E. Murphy)	V3, 2018-04-18
RD05	ngVLA Configuration rev B 4/24/2018	http://ngvla.nrao.edu/page/tools
RD06	ngVLA CSP Preliminary Technical Specifications	020.40.00.00.00-0001-SPE, 2018-03-23, v5
RD07	Integrated Receivers and Downconverters: Preliminary Technical Requirements	020.30.15.00.00-0001-REQ-05, 2018-05-03, v0.5

3 Overview

3.1 Document Outline

This document presents the technical requirements of the ngVLA LO Reference and Timing work element.

3.2 Project Background

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will include a main array of approximately 214 reflector antennas each of 18 meters diameter [RD01], a Short Baseline array (SBA) with 19 6m antennas [RD04], and a Long Baseline Array (LBA) with 30 additional 18m antennas on very long baselines [AD04].

3.3 General LO Reference and Timing Description

The ngVLA is a synthesis array of very wide extent. The extent of the array is a primary driver of the design and performance requirements of the LO Reference and Timing, and is thus presented here in some detail. Figure 1 shows the preliminary configuration of the array for the area close to the central core. This shows an area about 8 km × 6 km with 94 antennas. Figure 2 zooms out to show the entire main array in an area of approximately 800 x 600 km. This contains 214 18m antenna stations and 19 6m antennas. Requirements for the LO Reference and Timing include coherence, stability, and timing and are applicable between antenna stations and between the antenna stations and the array center. Figure 3 shows the configuration of the antennas in the LBA.

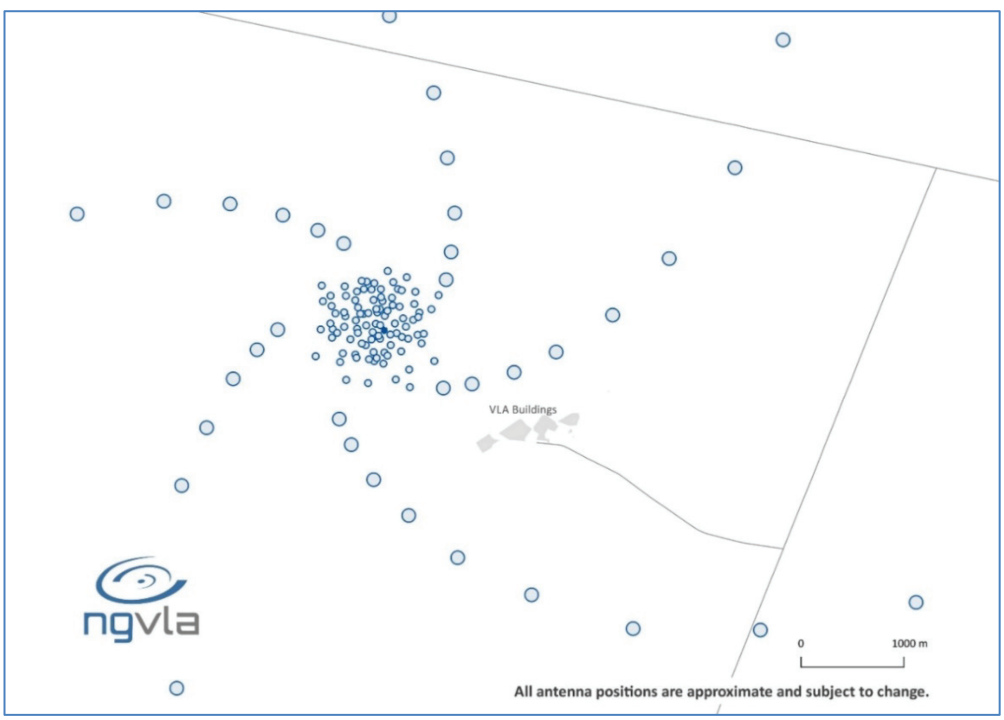

Figure 1 - A preliminary (rev B, Apr 2018) configuration map for only the antennas included in the core. Note that the symbol sizes in the core have been scaled down for visibility. All antennas in the main array including the core are 18m, except for the short baseline array antennas.

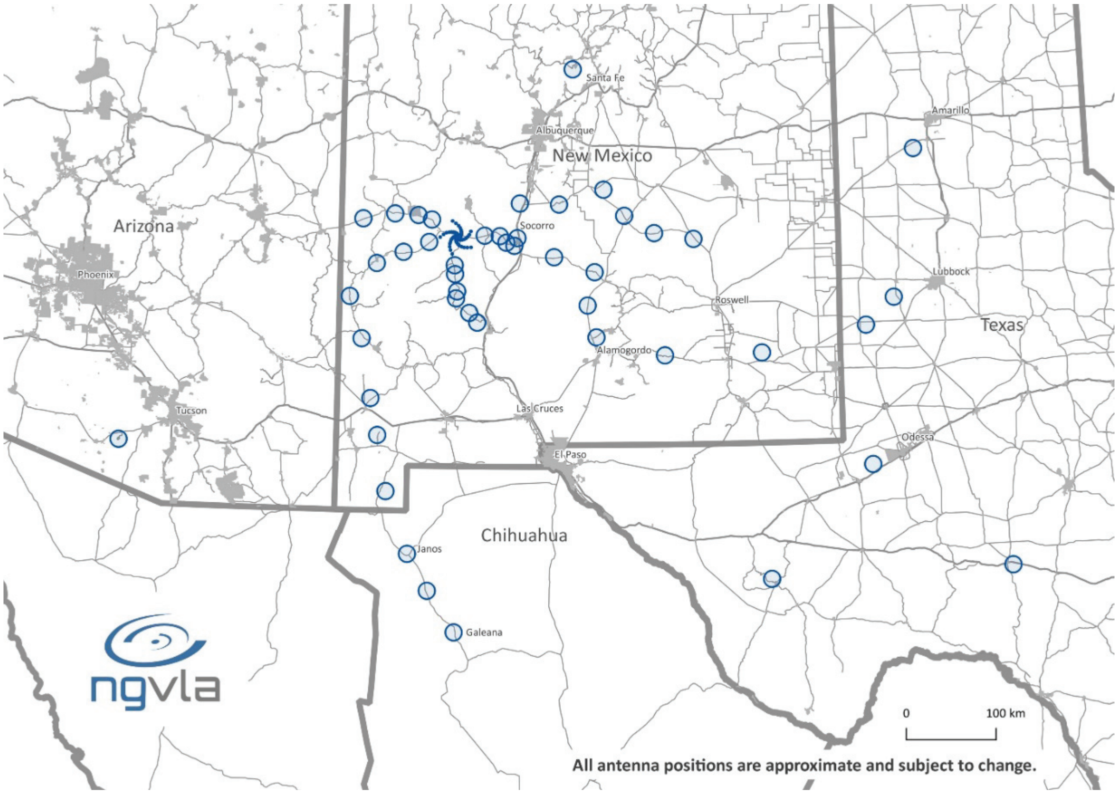

Figure 2 - A preliminary configuration map for all 214+19 antennas included in the main array.

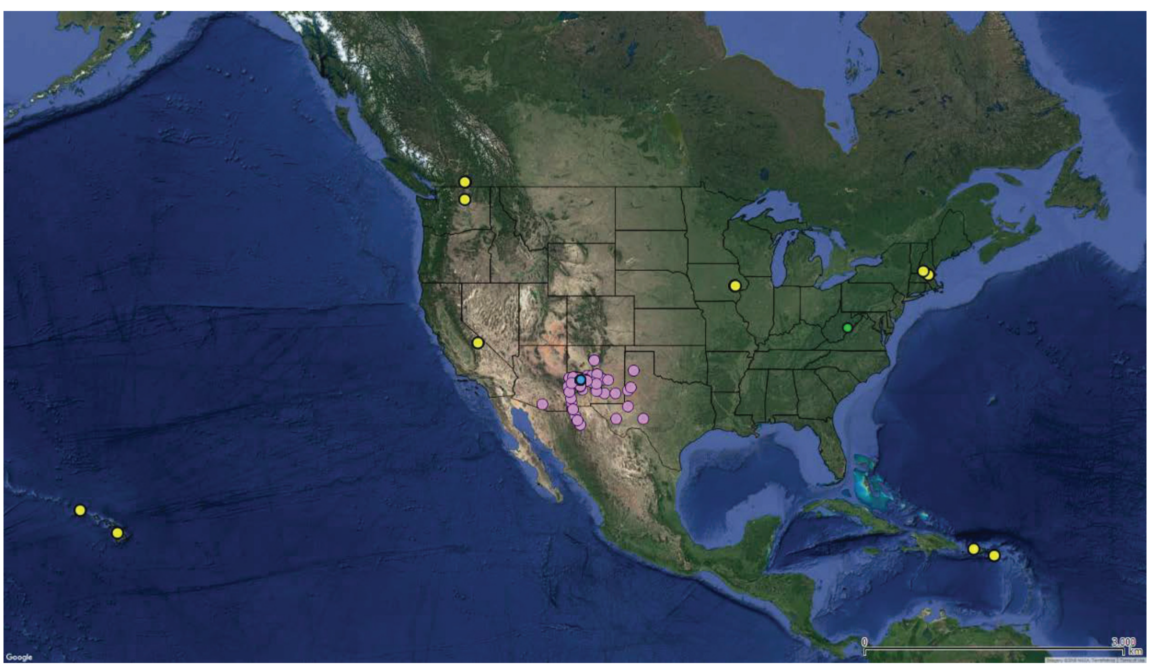

Figure 3 - ngVLA LBA Sites shown in yellow. GBT site shown in green. ngVLA core and main array in blue and purple respectively. 30 antennas are included in the LBA configuration, distributed per Table 1.

Antenna Qty	Location	Possible Site Notes	Distance from Array Center (km)
3	Puerto Rico	Arecibo Observatory.	4370
3	St. Croix	Existing VLBA site.	4580
3	Kauai, Hawaii	Kokee Park Geophysical Observatory.	5260
3	Hawaii, Hawaii	New site.	5000
2	Hancock, NH	Existing VLBA site.	3200
3	Westford, MA	Haystack Observatory.	3240
2	Brewster, WA	Existing VLBA site.	1870
3	Penticton, BC	Dominion Radio Astrophysical Observatory	1990
4	North Liberty, IA	Existing VLBA site.	1610
4	Owens Valley, CA	Existing VLBA site.	1056

Table 1 - List of LBA sites.

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 (CSP). The block diagram shown in Figure 4 illustrates the major functional blocks of the LO Reference and Timing. The references are generated and synchronized in the central building, and a frequency reference and timing signal are provided to the CSP. The references are then distributed with all necessary amplification, buffering, splitting, etc., and the required signals are transmitted to each antenna. This is a much generalized functional diagram, and the following assumptions and caveats are made:

- Central LO Reference and Timing instrumentation are assumed to be in the same central building as the CSP, but no further assumptions are made as to whether the equipment is in the same room, same racks, sharing floor space, ventilation, power, etc.
- Only LO Reference and Timing functions are shown. The data backhaul is expected to have a similar arrangement and possibly share fibers or ducts. Power and monitor and control functions are also not shown.
- Connection to each antenna station is shown as bidirectional which indicates that some form of bidirectional connection is anticipated in order to accomplish the phase synchronization and absolute timing.
- A single repeater station is shown, but additional repeater stations may be needed for signal regeneration or amplification from the most distant antenna stations. No assumptions is made as to whether the repeaters are in standalone equipment huts or co-located with antenna stations.
- The transmission medium is not indicated but is assumed to be optical fiber.
- A spoke-and-wheel connection arrangement is shown, although it is in principle possible to connect antenna stations by daisy-chain or some intermediate arrangement.
- All stations are shown connected to the central building. However, it is possible that some far out stations will standalone with respect to the reference and timing generation, using local hydrogen maser and Global Navigation Satellite System (GNSS) equipment, for instance.

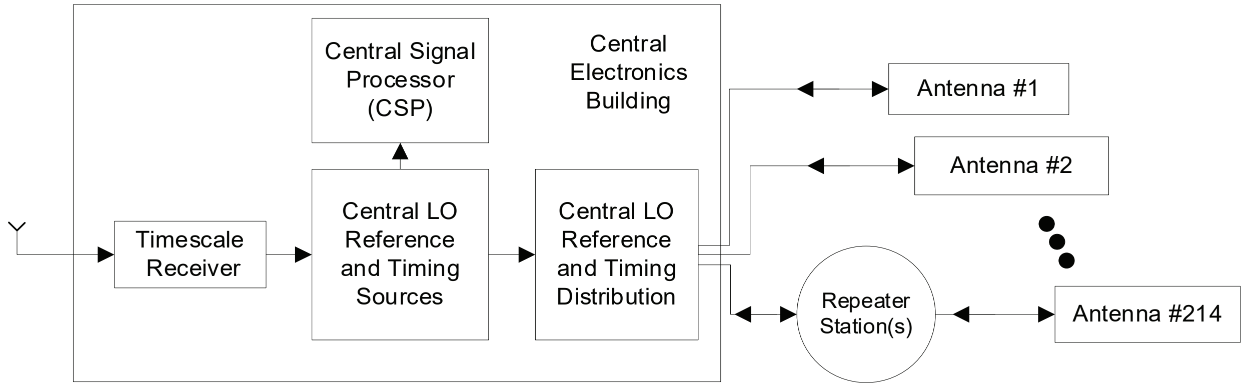

Figure 4 - Block diagram of LO reference and timing.

3.4 *Summary of LO Reference and Timing Requirements*

Table 2 provides a summary of the major LO Reference and Timing requirements in order to provide the reader with a high-level view of the desired system and for quick reference. Full requirement descriptions can be found in Sections 4 through Section 7. Should there be a conflict between the requirements listed in Section 3 and the descriptions in later sections, the latter shall take precedence.

3.4.1 General Requirements

General System Requirements		
Parameter	**Summary of Requirement**	**Reference**
Maximum number of antennas	LO to support NGVLA final configuration with maximum number of antennas as needed. The most recent plan was for a total of 263 antennas	LRT-0010
Maximum fiber length	1,000 km. More distant LBA antennas could connect by fiber if feasible	LRT-0020
Number of sub-arrays	≥ 10	LRT-0030
Phase Preservation	Electronic phase is preserved when adding and/or subtracting an element from a sub-array	LRT-0040
Band Switching Time	< 2 seconds	LRT-0050
Phase Calibration Efficiency	Phase calibration overheads shall not exceed 100% of on-source time for observations at 116 GHz when operating in the precision operating conditions.	LRT-0060
Compact Core	The system shall include a compact core. Approximately 40% of the array collecting area shall be located within 1.25km of the array vertex.	LRT-0070

Table 2 - General system requirements.

3.4.2 LO and Digitizer Frequency Requirement

Parameter	Summary of Requirement		Reference
Required Nominal LO Frequencies	156.25 MHz Sampler Reference	156.25 MHz	LRT-0080
	156.25 MHz Sampler Reference	156.25 MHz	LRT-0090
	Band 2H/3L 2SB LO	14.0 GHz	LRT-0100
	Band 3H 2SB LO	21.0 GHz	LRT-0110
	Band 4 2SB LO1	23.6 GHz	LRT-0120
	Band 4 2SB LO2	30.6 GHz	LRT-0130
	Band 5 A1/B1 2SB LO1	33.6 GHz	LRT-0140
	Band 5 A2/B2 2SB LO2	40.6 GHz	LRT-0150
	Band 5 A3/B3 2SB LO3	47.6 GHz	LRT-0160
	Band 6 A1/B1 2SB LO1	70 GHz	LRT-0170
	Band 6 A2/B2 2SB LO2	84 GHz	LRT-0180
	Band 6 A3/B3 2SB LO3	98 GHz	LRT-0190
	Band 6 A4/B4 2SB LO4	112 GHz	LRT-0200
	WVR LO1	18 GHz	LRT-0210
	WVR LO2	21 GHz	LRT-0220
	WVR LO3	24 GHz	LRT-0230
	WVR LO4	27 GHz	LRT-0240
Frequency Offset	All Local Oscillator bands	+ or –2 GHz	LRT-0250
Fine Frequency Offset	All bands, all antennas	5 MHz increments	LRT-0251
Simultaneous LOs	Three		LRT-0260
Self-Generated Spurious Signal Power Level	Self-generated signals shall not exceed –43dB relative to system noise level on cold sky over 1 MHz bandwidth.		LRT-0270
Sampler Offset	The provision of frequency offsets and/or sampler clock offsets at the antenna level is highly desired to provide additional attenuation of spurious signals.		LRT-0280

Note: For LO frequency requirements, there is requirement flow down from Science to Systems to choice of frequency bands and receiver downconverter implementation. Since these are all upstream decisions, the LO frequencies could change in the future. The present requirements devolve from a design with a single, nominally fixed LO per band. To that can be added a frequency offset so that sky coverage at the nominal LO frequency is possible.

3.4.3 LO Reference and Timing Phase Stability and Accuracy

Parameter	Summary of Requirement	Reference
Phase Drift	LO <84 fsec rms over 300 sec Digitizer <42 fsec rms over 300 sec	LRT-0300
Phase Noise or Jitter	LO <76 fsec Digitizer <76 fsec	LRT-0310
Timing Accuracy	Timestamp accuracy <10 nsec, applicable at the central signal processor	LRT-0320
Unambiguous Phase	Return to Phase after tuning change to LO or digitizer clock	LRT-0330

3.4.4 Design and Engineering Requirements

Parameter	Summary of Requirement	Reference
Fixed Analog Tunings	Minimize analog tunings.	LRT-0340
Modularization	The LO Reference and Timing distribution electronics and assemblies shall be modularized into Line Replaceable Units (LRUs) to facilitate maintenance.	LRT-0350
Sub-system Self-Monitoring	LO Reference and Timing systems shall be self-monitoring and prohibit actions likely to cause damage.	LRT-0360
Network Hardening	LO Reference and Timing systems should be built to withstand expected hack attempts. Should only respond to commands from authorized sources.	LRT-0370
Cost Optimization	LO Reference and Timing system shall be designed to minimize total life-cycle costs over the projected design life.	LRT-0380

3.4.5 Reliability and Lifetime Requirements

Parameter	Summary of Requirement	Reference
Antenna Maintenance Interval	Central LO, LO Reference and Timing distribution shall be designed with a preventative maintenance interval of no less than four years.	LRT-0390
LRU MTBF	Portions of the LO Reference and Timing distribution that are located at an antenna shall contribute to an overall antenna MTBF according to a budgeted allocation, such that the number of antenna failures is less than 50% of the array elements per year.	LRT-0400
Antenna System Availability	Portions of the LO Reference and Timing distribution that are located at an antenna shall contribute by MTBF allocation to an overall minimum 90% availability for all antenna systems combined.	LRT-0410
Centralized LO Availability	Portions of the LO reference timing and distribution that are centrally located shall contribute by MTBF allocation to an overall minimum 95% availability.	LRT-0420
Design Life	The LO Reference and Timing system shall be designed for an expected operational life of 20 years.	LRT-0430

3.4.6 Interface Requirements

A preliminary list of interface requirements follows. These interface requirements have been developed with reference to ***preliminary*** designs for the Front End electronics, pedestal electronics, and Central Signal Processor.

3.4.6.1 Interface to Monitor and Control

LO Reference and Timing instrumentation shall be designed to include an interface to the monitor and control system so that status, alarms, and long term health of the LRUs can be assessed. The details of these interfaces shall be developed into a complete set of interface control documents (ICDs).

3.4.6.2 Interface to Central Electronics Building

Interface	Interface Summary	ICD Reference
Interface to the Central Electronics Building	3-Phase 208V power	ICD-CentralBldg-LRT-0010
	Backup Power	ICD-CentralBldg-LRT-0020
	Air Flow Requirement	ICD-CentralBldg-LRT-0030
	Temperature Regulation	ICD-CentralBldg-LRT-0040
	Floor Space Requirement	ICD-CentralBldg-LRT-0050
	Shielding Requirement	ICD-CentralBldg-LRT-0060
	Fiber Optic Entry/exit	ICD-CentralBldg-LRT-0070
	RF Signal Entry/exit	ICD-CentralBldg-LRT-0080
	Lightning Protection	ICD-CentralBldg-LRT-0090

3.4.6.3 Interface to Central Signal Processor

Interface	Interface Summary	ICD Reference
Interface to Central Signal Processor	100-MHz reference 1-PPS reference	ICD-CSP-LRT-0010 ICD-CSP-LRT-0020

3.4.6.4 Interface to Site

Interface	Interface Summary	ICD Reference
Interface to Site	Fiber Specification - VLA Site Fiber Specification - Offsite Repeater Shelter Locations and Specification	ICD-Site-LRT-0010 ICD-Site-LRT-0020 ICD-Site-LRT-0030

3.4.6.5 Interface to Antenna Pedestal

In general, LO reference and timing will be distributed to each antenna station. A primary interface will be to the antenna pedestal. It is envisaged that the pedestal will contain electronics and signal processing with timing requirements. A preliminary block diagram of electronics contained in the pedestal enclosure is given in [RD02]. The functionality of the LO reference and time will require specific and detailed interfaces with each of these elements: (a) the Site/Network connector, (b) DBE/DTS subsystem, (c) Front End connector, and (d) Antenna Pedestal. The details of thee interfaces shall include electrical, mechanical, and environmental requirements.

Interface	Interface Summary	ICD Reference
Interface to the Site/Network Connector	Fiber Interface between Site/Network multi-fiber-connector (MFC) and LRT	ICD-NMFC-LRT-0010
Interface to DBE/DTS	Signal Interface between DBE/DTS (Timecode) and LRT	ICD-DBE/DTS-LRT-0010
	Cable/connector Interface between DBE/DTS (Timecode) and LRT	ICD-DBE/DTS-LRT-0020
Interface to Front End connector	Signal Interface between Front End multi-fiber connector (FEMFC) and LRT	ICD-FEMFC-LRT-0010
	Cable/connector Interface between Front End multi-fiber connector (FEMFC) and LRT	ICD-FEMFC-LRT-0020
Interface to Antenna Pedestal	Power supply interface to LRT	ICD-PED-LRT-0010
	Pedestal mechanical interface to LRT rack	ICD-PED-LRT-0020
	Pedestal thermal environment interface to LRT	ICD-PED-LRT-0030

3.4.6.6 Interface to Front End Enclosure

Interface	Interface Summary	ICD Reference
Interface to Front End Enclosure	LO Power Level	ICD-FES-LRT-0010
	LO Spurious Level	ICD-FES-LRT-0020
	LO Frequency Range	ICD-FES-LRT-0030
	LO Phase Noise	ICD-FES-LRT-0040
	LO physical interface	ICD-FES-LRT-0050
	Digitizer Clock interface	ICD-FES-LRT-0050
Interface to Water Vapor Radiometers	LO Reference and Timing Interface to Water Vapor Radiometer: Local Oscillators	ICD-WVR-LRT-0010
	LO Reference and Timing Interface to Water Vapor Radiometer: Digitizer Clock(s)	ICD-WVR-LRT-0020

There will be critical LO and digitizer signals distributed to the Front End and downconverters, i.e. the Front End system. A preliminary block diagram of electronics contained in the front end enclosure is given in [RD 02]. The functionality of the LO reference and time will require specific and detailed interfaces for each of these elements: (a) the LO signal to the Front End (b) digitizer signals to the Front End (c) LO signal to the water Vapor Radiometers, and (d) digitizer signals to the Water Vapor Radiometers. The details of thee interfaces shall include electrical, mechanical, and environmental requirements. The following abbreviations are used:

- FES = SA501 Front End System
- WVR = SA502 Water Vapor Radiometer

Important Note: The LO Reference and Timing Interface to the Front End system and the Water Vapor Radiometer system must meet the phase stability and jitter requirements listed above, and must additionally contain a flow down of pertinent signal quality requirements necessary to meet system level requirements for Gain Stability (SYS-1601, -1602, -1603) and system temperature (SYS-1604, SYS-1605).

4 Functional and Performance Requirements

4.1 General Requirements

Table 3 summarizes the array configuration in terms of number of antennas and distance from array center.

	Number of Antennas		Antenna diameter	Distance from Array Center
Main array				
Central Cluster	94		18m	0–1 km
Spiral Arms	74		18m	1–30 km
Long Arms	46		18m	30–1000 km
Main array total		214		
Small Baseline Array	19		6m	0.1 km
Long Baseline array	30		18m	1050–5300 km
Total		263		

Table 3 - Summary of array configuration: Number of antennas and distance from array center.

4.1.1 Number of Antennas

Parameter	Req. #	Value	Traceability
Maximum number of antennas	LRT-0100	The LRT shall support as many antennas as required for the NGVLA design. Table 3 shows 263 at this time, consisting of 214 antennas in the main array [RD01], 19 additional 6m small baseline array antennas [RD04], and 30 antennas in the long baseline option [AD04].	N/A

There is no higher-level requirement for the number of antennas in [AD01], although a baseline of 214 18m and 19 6m have been referenced in [RD01] and [RD04]. Additionally, in August of 2018 a change request was approved to include 30 additional 18m antennas on long baselines [AD04].

A preliminary configuration for the 214 18m array can be found in [RD05]. It consist of 94 antennas within a 1-km radius (the "core"), additional 74 antennas forming a spiral within a 30-km radius (the "plains array"), and additional 46 antennas ("three arm distant spiral") extending to distances of hundreds of km from the core.

For purposes of design to meet these requirements, there may be differences in the design, operations, and/or maintenance of the equipment for these three sections of the array, although it is highly desirable from a user or software standpoint that any differences are not visible.

4.1.2 Maximum Fiber Length

Parameter	Req. #	Value	Traceability
Maximum fiber length	LRT-0020	1000 km	SYS1301

This flows down from the systems requirement for maximum baseline length of greater than 650 km with 1000 km desirable. However, baseline length refers to distance between two antennas, and in an array with a centrally located reference and timing generation the straight line distance to the furthest antenna is always less than the maximum baseline. For practical reasons, fiber to antennas must be run along roadways and this generally means fiber lengths are configuration-dependent. The most recent configuration set forth [RD05] will have a maximum fiber length of approximately 1000 km. For LBA, it is assumed that the LO is not centrally generated although this would be allowed if it were technically practical.

4.1.3 Number of Subarrays

Parameter	Req. #	Value	Traceability
Number of subarrays	LRT-0030	≥10	SYS0601

If the central LO and timing signals are distributed so that each antenna receives one or more fixed frequency references that do not ever change, then this requirement only implies that each antenna can independently select a band, or LO frequency. In that case the number of subarrays that the LO Reference and Timing could support is equal to the number of antennas.

If the synthesis of LO frequencies is done in the central building, and frequencies are generated, tuned or synthesized before being distributed to an antenna, then this requirement may imply a significant increase in the flexibility and complexity of the central LO distribution. For instance, it would be necessary to have at least ten independent frequency synthesis hardware sets that could be mapped arbitrarily to antennas.

4.1.4 Phase Preservation

Parameter	Req. #	Value	Traceability
Phase preservation	LRT-0040	Electronic phase is preserved when adding and/or subtracting an element from a sub-array.	SYS0602

Note: The adding or subtracting of an element from a subarray can be done in software and in general requires a reconfiguration of the antenna (repointing, selecting a new band, etc.). This shall be done without affecting other elements. Additionally, it may be desirable to change the configuration of an antenna (specifically the LO frequency) and then return again to the original LO frequency. In this case the phase and timing should also be preserved.

4.1.5 Band Switching

Parameter	Req. #	Value	Traceability
Band Switching Time	LRT-0050	< 2 seconds	SYS0908

The system-level requirement is for band switching between receiver bands, which must take place within 20 seconds. The requirement of two seconds is set forth here arbitrarily so that the LO and digitizer frequency switching is much faster than the receiving band. It should be a design goal to make this switching time as fast as practical.

4.1.6 Phase Calibration Efficiency

Parameter	Req. #	Value	Traceability
Phase calibration efficiency	LRT-0060	Phase calibration overheads shall not exceed 100% of on-source time for observations at 116 GHz when operating in precision operating conditions.	SYS-1068

This does not impact the LO and timing directly. The main effect of this requirement may be to increase the length of time on source between phase calibrations. This needs to be factored in when setting the requirement and design for the LO and timing stabilities on longer timescales. Additionally, any overhead due to the electronics (i.e. band switching, settling time, etc.) that could be part of a calibration cycle should be minimized.

4.1.7 Compact Core

Parameter	Req. #	Value	Traceability
Compact Core	LRT-0070	The system shall include a compact core. Approximately 40% of the array collecting area shall be located within 1.25 km of the array vertex.	SYS1305

This requirement flows directly from the system requirement. It is noted in these requirements in case the compact core LO Reference and Distribution for some reason has a different implementation, power budget, or number of fiber links, etc. The LO Reference and Timing stability for antennas in the compact core could, for instance, be implemented so that

- there is no active correction, and phase stability is sufficient over the short distance;
- a correction is needed but with less dynamic range than the longer links; or
- a correction is needed but can be implemented in a simpler, less expensive way for the compact core.

4.2 LO and Digitizer Frequency Requirements

4.2.1 Required Nominal LO Frequencies

Parameter	Req. #	Value	Traceability
Required Nominal LO Frequencies	LRT-0080–LRT-0230	See Table 3	SYS0801 SYS0803 SYS0804 SYS0805 SYS0806 SYS0901 SYS0902

The set of required LO and digitizer frequencies can be traced at a high level to the systems requirements referenced here, but the specific set of frequency and bands devolves from [RD03] and [RD07]. Insofar as this represents a preliminary or reference design, the frequency plan may be subject to change to accommodate changes of these designs. The LO Reference and Timing design should be able to provide a set of fixed frequency LOs but not be constrained by the particular values, i.e. a *flexible* design is desired.

4.2.2 Frequency Offset

Parameter	Req. #	Value	Traceability
Coarse Frequency Offset	LRT-0250	+ or – 2 GHz	SYS0806
Fine Frequency Offset	LRT-0251	+ or – 5 MHz in 10 kHz increments	SYS2105

To remove gaps in frequency coverage, a fixed frequency offset to the nominal LO frequency of ±2 GHz is required. See also [RD07].

4.2.3 Number of Simultaneous LOs

Parameter	Req. #	Value	Traceability
Number of simultaneous LOs	LRT-0260	Three	SYS0903, SYS0905

If the central LO and timing signals are fixed frequency, then this requirement only implies that each antenna can independently select receiving band(s), or LO frequencies.

If the synthesis, or some part of the synthesis, of LO frequencies is done in the central building, then this requirement implies a significant increase in the flexibility and complexity of the LO distribution.

4.2.4 Incoherent Spurious

Parameter	Req. #	Value	Traceability
Self-Generated Spurious	LRT-0270	< –43dB relative to the system noise level on cold sky over a 1MHz bandwidth.	SYS2104

4.2.5 Sampler Offset

Parameter	Req. #	Value	Traceability
Sampler Offset	LRT-0280	TBD	SYS2105

If the central LO and timing signals are fixed frequency, then this requirement only implies that each antenna can independently select a band, or LO frequency.

If the synthesis of LO frequencies is done in the central building, then this requirement implies a significant increase in the flexibility and complexity of the LO distribution.

4.3 LO and Digitizer Phase Stability and Accuracy

4.3.1 Phase Drift

Parameter	Req. #	Value	Traceability
Phase Drift	LRT-0300	LO <84 fsec rms over 300 sec in time Digitizer <42 fsec rms over 300 sec in time	SYS1501

Table 3 of [AD01] lists phase drift contributions of 42 fsec each from five sources: antenna structure, first LO, Digitizer, Antenna round-trip phase system, and LO distribution system. The output of the LO in the front end enclosure represents contributions from all of these except for the antenna structure. Therefore the RSS rms phase drift allowable for the LO is $\sqrt{4 * 42^2} = 84$ fsec. If either the LO distribution or the antenna distribution is done open-loop, then the requirement must be met after corrections are applied.

The digitizer requirement is 42 fsec, which refers "effective" delay added at the maximum LO frequency of 112 GHz, or 0.03 radians applied at the digitizer frequency.

4.3.2 Phase Noise or Jitter

Parameter	Req. #	Value	Traceability
Phase Noise	LRT-0310	LO <76 fsec Digitizer <76 fsec	SYS1502

The LO phase noise shall be measured from a 1 Hz offset frequency to the highest significant frequency where jitter is contributing, ~1–10 MHz. The jitter is again applicable at the highest LO frequency, 112 GHz, so 0.05 radians at the digitizer frequency. For instance, at a digitizer clock frequency of 7 GHz, this is 1.2 psec jitter.

4.3.3 Timing Accuracy

Parameter	Req. #	Value	Traceability
Timing Accuracy	LRT-0320	Timestamp accuracy <10 nsec, for periods from 30 min to 10 yr	SYS2002

From [AD01]:

- Timestamps are referenced to international time standard, i.e. UTC.
- 10 nsec accuracy implies tightly constrained connection to UTC by some means (i.e. GNSS, two way satellite, direct fiber connection).
- 10 nsec accuracy at 30-minute timescale is 5e-12 stability; at 10-yr it is 3.2e-17 stability.
- Corrections may be retroactive, i.e. not in real time.

4.3.4 VLBI Phase

Parameter	Req. #	Value	Traceability
Unambiguous Phase	LRT-0330	Return to Phase after tuning change to LO or digitizer clock.	SYS0502

4.4 Design and Engineering Requirements

The following requirements on the design of the LO Reference and Timing are presented as direct flowdown from the systems requirements [AD01].

Parameter	Req. #	Value	Traceability
Fixed Analog Tunings	LRT-0340	Minimize analog tunings.	SYS0906
Modularization	LRT-0350	The LO reference timing and distribution electronics and assemblies shall be modularized into Line Replaceable Units (LRUs) to facilitate maintenance.	SYS2403
Sub-System Self-Monitoring	LRT-0360	The LO Reference and Timing LRUs shall measure, report, and monitor a set of parameters that permit status determination and may help predict or respond to failures.	SYS2701

Parameter	Req. #	Value	Traceability
Network Hardening	LRT-0370	LO Reference and Timing systems should be built to withstand expected hack attempts. Should only respond to commands from authorized sources.	SYS2702
Cost Optimization	LRT-0380	LO Reference and Timing system shall be designed to minimize total life-cycle costs over the projected design life.	SYS2704

4.5 Reliability and Lifetime

The following requirements for design of LO Reference and Timing are presented as direct flow down from the systems requirements [AD01]. Development of a design that meets the functional requirements must prioritize highly reliable components and assemblies and be designed for extended lifetime.

Parameter	Req. #	Value	Traceability
Antenna Maintenance Interval	LRT-0390	Central LO, LO Reference and Timing distribution shall be designed with a preventative maintenance interval of no less than four years.	SYS2401
LRU MTBF	LRT-0400	Portions of the LO reference timing and distribution that are located at an antenna shall contribute to an overall antenna MTBF according to a budgeted allocation, such that the number of antenna failures is less than 50% of the array elements per year.	SYS2402
Antenna System Availability	LRT-0410	Portions of the LO reference timing and distribution that are located at an antenna shall contribute by MTBF allocation to an overall minimum 90% availability for all antenna systems combined.	SYS2901
Centralized LO Availability	LRT-0420	Portions of the LO reference timing and distribution that are centrally located shall contribute by MTBF allocation to an overall minimum 95% availability.	SYS2602
Design Life	LRT-0430	The LO Reference and Timing system shall be designed for an expected operational life of 20 years.	SYS2703

5 Interface Requirements

Interface requirements shall be developed as the design progresses and shall include detailed electronic, mechanical, thermal, environmental definitions wherever two subsystems meet. The details of the interface shall be developed in detail and agreed by the design and administrative authorities of the respective subsystems, in the form of an interface control document (ICD).

The interfaces governed by these control documents shall include but not be limited to the interface between LO Reference and Timing and

- Monitor and Control
- Central Electronics Building
- Central Signal Processor
- Site
- Antenna Pedestal
- Front End Enclosure

Important interfaces between elements within LO Reference and Timing may be governed by internal ICDs.

Note: Sections 5.1–5.6 are placeholders for expanded and detailed interface requirements which are mainly not yet developed. These sections will eventually include expanded detail corresponding to the condensed summary interface requirements listed in Sections 3.4.6.1–3.4.6.6. Future versions of this document may include only links to the formal interface control documents in these sections.

5.1 Interface to Monitor and Control

TBD

5.2 Interface to Central Electronics Building

TBD

5.3 Interface to Central Signal Processor

TBD

5.4 Interface to Site

TBD

5.5 Interface to Antenna Pedestal

TBD

5.6 Interface to Front End Enclosure

5.6.1 LO Power Level

Parameter	Req. #	Value	Traceability
Front End IRD module LO Power Level interface requirement	ICD-FES-LRT-0010	LO power level	[RD07]

The estimated LO power requirements for each of the integrated receiver/downconverter modules is listed in Table 4.

Band Designation	Nominal Frequency	Minimum Power Level (dBm)
Band 2H/3L 2SB LO	14.0 GHz	13
Band 3H 2SB LO	21.0 GHz	13
Band 4 2SB LO1	23.6 GHz	13
Band 4 2SB LO2	30.6 GHz	13
Band 5 A1/B1 2SB LO1	33.6 GHz	13
Band 5 A2/B2 2SB LO2	40.6 GHz	13
Band 5 A3/B3 2SB LO3	47.6 GHz	13
Band 6 A1/B1 2SB LO1	70 GHz	13
Band 6 A2/B2 2SB LO2	84 GHz	13
Band 6 A3/B3 2SB LO3	98 GHz	13
Band 6 A4/B4 2SB LO4	112 GHz	13

Table 4 - LO Power Level interface requirement with Front End IRD modules

5.6.2 LO Spurious Level

Parameter	Req. #	Value	Traceability
Front End IRD module LO spurious level interface requirement	ICD-FES-LRT-0010	LO spurious <–140 dBc (see discussion below)	LRT0270 SYS2104

The following details the initial estimate of the system sensitivity to spurious at the interface between the LO and the RF mixer input in the integrated downconverter module.

The ngVLA system requirement SYS2104 limits self-generated spurious signal power to –43 dB relative to the noise floor in a 1 MHz bandwidth. In order to translate this into a spurious signal spec for the LO, we must determine the noise power level at the mixer and compare it against the required LO pump power.

The integrated downconverter modules will employ step attenuators, preferably in the RF signal path before the mixer. These will be adjusted such that the total power input to the samplers is nearly optimal. This corresponds to a root-mean-square voltage swing of

$$\sigma = \begin{cases} \frac{3}{16} FSR & N = 4\,bits \\ \frac{16}{256} FSR & N = 8\,bits \end{cases}$$

where *FSR* is the full-scale range of the sampler (typically about 1 V). In the 4-bit case, an rms of three sampler thresholds (or LSBs) is close to optimum quantization efficiency. In the 8-bit case, the rms of 16 LSBs implied above is less than optimal for quantization efficiency, but the penalty is negligible and this level buys a great deal of headroom for high dynamic range signals, a very typical compromise for radio astronomy receivers. These translate to noise power as follows:

$$P_{ADC} = \frac{\sigma^2}{R_{ADC}} = \begin{cases} 352\ \mu W & N = 4\ bits \\ 39\ \mu W & N = 8\ bits \end{cases} = \begin{cases} -4.5\ dBm & N = 4\ bits \\ -14.1\ dBm & N = 8\ bits \end{cases}$$

where R_{ADC} = 100 Ω, typically. Given that the IF bandwidth per digitized channel (I or Q) is 7 GHz in 4-bit mode, and 3.5 GHz in 8-bit mode, this corresponds to a power spectral density of

$$S_{ADC} = \frac{P_{ADC}}{BW_{I/Q}} = \begin{cases} -43\ dBm/MHz & N = 4\ bits \\ -49.5\ dBm/MHz & N = 8\ bits \end{cases}$$

The signal path in the IRD modules is still under development, and will vary from band to band, but a typical number for the IF gain would be 45 dB, and 10 dB for the mixer conversion loss. This would make the expected power spectral density at the input to the mixer to be

$$S_{mix} = S_{ADC} - 35\ dB = \begin{cases} -78\ dBm/MHz & N = 4\ bits \\ -84.5\ dBm/MHz & N = 8\ bits \end{cases}$$

There are two ways for an LO spur to get into the IF. The first is by mixing action, for which we expect the worst-case (most efficient) conversion is the same as an RF input. The second is by direct port-to-port leakage. We assume that the mixer's LO-to-IF isolation is higher than its conversion loss, so that the first mechanism dominates. This means that the spurious level spec can be applied to the above power spectral density directly,

$$P_{spur} < S_{mix} - 43 = \begin{cases} -121\ dBm & N = 4\ bits \\ -127.5\ dBm & N = 8\ bits \end{cases}$$

Taking the weaker of these two (8-bit mode), and comparing to an LO power requirement of +13 dBm, this means spurs within the IF range of the LO carrier (or within the baseband, to account for direct leakage) must be less than –140.5 dBc. Spurs outside of this range can be assumed rejected by the anti-aliasing filters, which are specified to have 55 dB attenuation after a 20% guard-band. We may thus estimate a mask as follows (Figure 5):

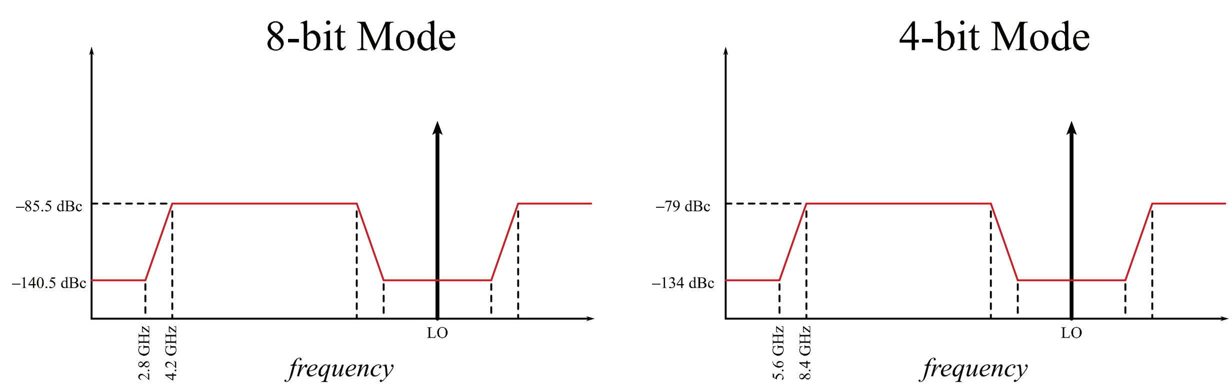

Figure 5 – Spurious signal level specification for 8-bit (left) and 4-bit (right) IRD modules.

This represents a difficult requirement with very low spurious. Future investigation of this requirement will include:

1. Accounting for added noise in the gain stages after the mixer (just the gain). This is likely to be less than ~1 percent, otherwise the IF stages would substantially impact the sensitivity of the receiver.
2. Account for LO noise (or in this case, sideband spur) suppression due to the mixer being balanced. Assuming the mixer is single balanced (very likely), suppression could be 15-20 dB. That will only help in the IF range around the LO, though, outside of that the hybrid will not provide the correct phase shifts.
3. For the spectrum further out than the IF limit, IF components other than just the anti-aliasing filters will be rolling off. This could give another 10–20 dB suppression.

These factors could provide (in the future) ~20 dB easing of the preliminary requirement.

6 Environmental Requirements

LO Reference and Timing equipment may be located in or exposed to one or more of the following environments:

- Storage
- Transportation
- Central Electronics Building
- Repeater Shelter
- Antenna Pedestal
- Front End Enclosure
- Exposed Location on Antenna
- Outdoors at VLA Site
- Outdoor Offsite

Several of these environments have been defined in the ngVLA Environmental Specifications [AD02], although most of the equipment is expected to be indoors with some temperature control and protection from the elements. These environments have not been defined yet. The LO Reference and Timing LRUs should be designed for robust performance in the expected environments, and as the design and the project progresses, the specific environmental requirements shall be specified in the applicable ICDs.

7 RFI and EMC Requirements

LO Reference and Timing LRUs shall meet the RFI and EMC requirements set forth in [AD03]. The methodology presented in [AD03] shall be used to develop RFI/EMC emission limits that may be specific to the LRU or its location.

8 Appendix

8.1 System Requirements

A subset of the system technical requirements filtered for requirements that directly or indirectly impact the LO Reference and Timing requirements are listed in Table 5. These are taken from [AD01].

Parameter	Req. #	Value	Comment
General System Requirements			
Sub-Array Capabilities	SYS0601	System shall be divisible into a minimum of 10 sub-arrays for operation, calibration and maintenance purposes. It is a goal that all functional capabilities listed above should be available in a sub-array.	Features of the centrally located LO Reference and Timing that depend on LO and digitizer frequency must be appropriately switched or multiplexed (no impact if central LO Reference and Timing is "sky frequency agnostic").
Phase Preservation	SYS0602	It shall be possible to preserve electronic phase when adding and/or subtracting an element from a sub-array.	
Band Switching Time	SYS0908	Switching between any receiver bands shall be achievable within 20 seconds. Goal of 10 seconds.	Impact only if there is a slow tuning element in the LO and timing.
Phase Calibration Efficiency	SYS1068	Phase calibration overheads shall not exceed 100% of on-source time for observations at 116 GHz when operating in the precision operating conditions.	Secondary impact only. Choice of calibration cycle time may impact LO round trip timing requirement or design choice.
Longest Baseline	SYS1301	The longest baseline between antennas shall be greater than 650km. It is a goal to have baselines longer than 1000km.	LO Reference and Timing accuracy and power levels must meet requirements over maximum distances with appropriate power and noise budgeting.
Compact Core	SYS1305	The system shall include a compact core. Approximately 40% of the array collecting area shall be located within 1.25km of the array vertex.	Possible design impact if cost-performance optimization dictates two-tiered design: one for close-in antennas and one for far-out antennas.
System Requirements Impacting LO and Digitizer Frequency			
System Frequency Range	SYS0801	System frequency range shall cover the 1.2 to 50 GHz and 70–116 GHz windows.	LO frequencies must cover this band as needed after design choices are made for RF band breakdowns.
Freq. Span A:	SYS0803	1.2–8 GHz	
Freq. Span B:	SYS0804	8–50 GHz	

Freq. Span C:	SYS0805	70–116 GHz	
Continuity of Frequency Coverage	SYS0806	There shall be no gaps in frequency coverage within each frequency span (A, B, C) listed above. It is a goal that any band edges shall include 1% overlap.	LO and sampler design and frequency plan must meet this requirement. For instance, frequency offsetting capability of the LO could fill in baseband frequency gaps.
Front End Bandwidth Ratio	SYS0901	A minimum bandwidth ratio of 1.5:1 is required, with a 4:1 goal over Frequency Span A.	Possible impact to LO tunability (though early design emphasizes fixed LO with wideband digitizers).
Instantaneous Digitized Bandwidth	SYS0902	It is desirable for the system to digitize the full bandwidth of each receiver band.	Possible impact if multiple simultaneous LOs needed for a band.
Total Instantaneous Processed Bandwidth	SYS0903	The system shall transmit and process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	
Frequency Tunability	SYS0905	It shall be possible to select discontinuous sub-bands for transmission and processing. i.e. transmitting both the top and bottom of the 70–116 GHz band.	
Self-Generated Spurious Signal Power Level	SYS2104	Self-generated signals shall not exceed -43dB relative to the system noise level on cold sky over a 1 MHz bandwidth.	May require LO or sampler offsetting.
Frequency or Clock Offsets	SYS2105	The provision of frequency offsets and/or sampler clock offsets at the antenna level is highly desired to provide additional attenuation of spurious signals.	
System Requirements Impacting LO Reference and Timing Phase Stability and Accuracy			
Delay/Phase Variations Magnitude	SYS1501	The delay variations caused by the instrument should be smaller than those caused by the natural environment for at least 90% of the time. These natural limits are those imposed by the residual delay fluctuations of the troposphere after all available corrections (e.g., fast switching, WVR, etc.) have been applied.	See also [AD01] Table 1 for allocations of phase drift.
SNR Loss to Delay/Phase Variations	SYS1502	The instrumental delay/phase noise should not degrade overall system SNR by more than 1%.	See also [AD01] Table 1 for allocations of phase noise/jitter.
Phase Noise Specification	SYS1503	< 132 fsec.	Flows down from SYS1502
Phase Drift Specification	SYS1504	< 95 fsec over 300 sec, goal over 1000 sec.	Flows down from SYS1501.

Temporal Accuracy	SYS2002	Data time-stamps shall be accurate to better than 20 usec.	Note: may be changed to 10 nsec, goal of 1 nsec.
VLBI Capabilities	SYS0502	It is desirable, but not required, to interface with network-connected VLBI stations as real-time correlated elements of the ngVLA.	VLBA Integration/ngVLB Option.
System Requirements Impacting LO Reference and Timing Amplitude Stability			
Gain Stability for Total Power Measurements	SYS1601	System dG/G post-calibration shall not exceed 10^{-3} over a 20-minute period. Goal to not exceed 10^{-4}. (TBC)	LO amplitude stability must be stable over time, temperature, and antenna orientation.
Gain Stability for Interferometric Observations	SYS1602	System dG/G post-calibration shall not exceed 10^{-4} over a 20-minute period. (TBC)	
Gain Variations with Antenna Pointing Angle	SYS1603	T_{REC} shall vary by no more than 0.1% over 1 hr in the precision operating conditions defined in AD09.	
System Temperature Stability over Time	SYS1604	T_{REC} shall vary by no more than 0.1% over 1 hr in the precision operating conditions defined in AD09.	
System Temperature Variations with Antenna Pointing Angle	SYS1605	T_{SPILL} and T_{REC} shall vary by no more than 1.5K combined, over the full range of antenna elevation in the precision operating conditions defined in AD09.	
System Requirements on Design and Engineering			
Shielding & Emission Limits	SYS2106	Shall comply with [AD03].	Governs RFI emission limits from LRUs, shielding practice for amplifiers, oscillators, displays, and digital equipment.
Fixed Analog Tunings	SYS0906	While supporting the Frequency Tunability requirement, the analog system setup options shall be minimized to facilitate calibration from catalog values.	Design requirement.
Antenna Maintenance Interval	SYS2401	The antenna, antenna electronics, and array infrastructure shall be designed with a preventative maintenance interval of no less than four years.	Flows down to reliability and maintenance requirements.
Antenna MTBF	SYS2402	The antenna, antenna electronics and array infrastructure shall be designed with an expected number of failures to be less than 25% of the array elements per year.	Reliability requirement.

Modularization	SYS2403	The system shall be modularized into Line Replaceable Units (LRUs) to facilitate maintenance.	Design requirement.
Antenna System Availability	SYS2901	Minimum 90% availability for all antenna systems combined. Availability is defined as time available for science operations, excluding scheduled and unscheduled maintenance downtime.	Flows down to reliability and maintenance requirements.
Centralized Systems Availability	SYS2602	For all centralized systems (LO distribution, correlator, etc.) that are required for data collection, system availability shall be no less than 95%. See definition of availability above.	Flows down to reliability and maintenance requirements.
Sub-system self-monitoring	SYS2701	All subsystems to monitor system health and prohibit actions likely to cause damage.	Flows down to monitor and control requirement.
Network Hardening	SYS2702	System should be built to withstand expected hack attempts. Should only respond to commands from authorized sources.	Interface requirement.
Design Life	SYS2703	The system shall be designed for an expected operational life of 20 years.	Design Lifetime requirement.
Cost Optimization	SYS2704	The system shall be designed to minimize total life-cycle costs over the projected design life.	Design requirement.

Table 5 - System requirements.

Local Oscillator Reference and Timing Design Description

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Status: **RELEASED**

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3	2018-09-30	B. Shillue	All	Inclusion of Long Baseline Array
4	2018-11-16	B. Shillue	All	Post-Internal Review Updates: • All sections – minor edits • New Section 8.2 added "Antenna Time and Frequency Design Approach" • Sections 8.4, 8.5, and 8.6 extensively modified so that the LO frequency plan matches the Front End and IRD frequency plan.
5	2019-05-30	R. Selina	2.1, 3.1, 4.3, 6.1	Minor edits for release.
A	2019-07-26	A. Lear	All	Incorporated edits by R. Selina & M. McKinnon; prepared PDF for signatures and release.

Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
2 Related Documents and Drawings 6
2.1 Applicable Documents 6
2.2 Reference Documents 6
3 Subsystem Overview 8
3.1 Array Expanse 8
3.2 Top Level Description: LO Timing and Reference 12
3.3 Design Assumptions and Drivers 13
4 LO Reference and Timing Requirements 14
4.1 Key Requirements 14
4.2 Number of Antennas 14
4.3 Phase Drift 14
4.4 Phase Noise 15
4.5 Spurious Level and LO Noise Level 15
4.6 Flexible Subarrays 15
4.7 Number of Simultaneous LOs 16
5 Central Time and Frequency Reference 17
5.1 Central LO Reference and Timing Overview and Block Diagram 17
5.2 Central LO Reference and Timing Components 18
5.3 Central LO Reference and Timing Interfaces with other Subsystems 18
6 Time and Frequency Reference Distribution 19
6.1 Frequency Synchronization - Background 19
6.1.1 ALMA System 19
6.1.2 EVLA System 19
6.1.3 SKA System 20
6.1.4 SKA-low 20
6.1.5 SKA-mid 20
6.1.6 Comparison of SKA-mid and SKA-low 20
6.1.7 Other Examples of Remote Frequency Dissemination 20
6.1.8 Phase Correction Dynamic Range 21
6.2 Time and Frequency Reference Distribution Overview 21
6.3 Time and Frequency Reference Distribution Block Diagrams 22
6.3.1 Round-Trip Phase Transmitter 24
6.3.2 Bidirectional Repeaters 24
6.3.3 LO Receiver Module 26
6.4 LO Reference and Timing Distribution Components 26
6.5 LO Reference and Timing Distribution Interfaces with Other Subsystems 27
7 Antenna Time and Frequency System 28
7.1 Antenna Time and Frequency Reference Interfaces and Block Diagram 28
7.2 Antenna Time and Frequency Reference Design Approach 29
7.3 Reference Receiver, Generator, Distribution Module 29
7.4 LO Reference and Sample Clock Generator module 29
7.5 LO Frequency Plan 30

7.6 Local Oscillator Modules 31
7.7 Standalone Antenna Station 34
7.8 Antenna Time and Frequency Reference Components 35
7.9 Antenna Time and Frequency Reference Interfaces with Other Subsystems 35
8 Appendix 36
8.1 Abbreviations and Acronyms 36

1 Introduction

1.1 Purpose

This document provides a description for the Local Oscillator (LO) Reference and Timing subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the entire design of the LO Reference and Timing subsystem, as part of the ngVLA Reference Design. It includes the subsystem's design, how it functions, and interfaces with the necessary hardware and software systems.

It does not include specific technical requirements or budgetary information.

The document is arranged as follows:

- Section 4: Overview
- Section 5: Requirements
- Section 6: Central Time and Frequency Reference Generation
- Section 7: Time and Frequency Reference Distribution
- Section 8: Antenna Time and Frequency System

The functions and set of hardware described in each of Sections 6, 7, and 8 represent possible future separable ngVLA work elements in that each could in principle be developed, tested, and delivered separately.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev / Doc. No.
AD01	ngVLA LO Reference and Timing: Preliminary Technical Requirements	020.35.00.00.00-0001-REQ
AD02	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Inclusion of the "Long Baseline Major Option" into the ngVLA Baseline Design	020.05.60.01.01-0002-ECO
AD04	ngVLA Environmental Specification	020.10.15.10.00-0001-SPE
AD05	ngVLA System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ

2.2 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev / Doc. No.
RD01	ngVLA Configuration rev B 4/24/2018	http://ngvla.nrao.edu/page/tools
RD02	The ngVLA Short Baseline Array	ngVLA memo #43
RD03	High-stability transfer of an optical frequency over long fiber-optic links	Williams, Paul A., William C. Swann, and Nathan R. Newbury. *JOSA B* 25, no. 8 (2008): 1284–1293.
RD04	Frequency Stability and Coherence Loss in Radio Astronomy Interferometers Application to the SKA	Alachkar, Wilkinson, Grainge. *Journal of Astronomical Instrumentation* 7, no. 01 (2018): 1850001.
RD05	Frequency stability review	Greenhall, C. A. (1987), NASA TDA Progress Report 42-88
RD06	Applications of control precision timing control for radioastronomy maintaining femtosecond synchronization in the Atacama large millimeter array	Cliche, J.-F., and Bill Shillue. *IEEE control systems* 26, no. 1 (2006): 19-26
RD07	A high-precision tunable millimeter-wave photonic LO reference for the ALMA telescope	Shillue, et al. *Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International*, pp. 1–4. IEEE, 2013.
RD08	System Overview and Integration - Hardware	J.Jackson, S. Durand, EVLA Project Book, Chapter 3, Nov 25, 2009 (NRAO Internal document)
RD09	LO/ IF Systems	T.Cotter, EVLA Project Book, Chapter 6: LO/IF Systems (NRAO Internal document)
RD10	Operational Performance of the EVLA Round-Trip Phase System	S. Durand, T. Cotter, EVLA Memo #44, 7/30/2002
RD11	Phase Coherence of the EVLA Radio Telescope	S. Durand, J. Jackson, K. Morris, EVLA Memo #105

Ref. No.	Document Title	Rev / Doc. No.
RD12	A Robust Fiber-based Frequency Synchronization System Immune to Dramatic Temperature Fluctuation	Zhu, Wang, et al, *Chinese Optics Letters* 16, no. 1 (2018): 010605.
RD13	The Mid-Frequency Square Kilometre Array Phase Synchronisation System	Schediwy, et al, *arXiv preprint arXiv: 1805.11455* (2018).
RD14	A Coherent Fiber Link for Very Long Baseline Interferometry	Clivati et al., *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control* 62, no. 11 (2015): 1907–1912.
RD15	Fiber Optic Delivery of Time and Frequency to VLBI Station	Krehlik et al, Astronomy and Astrophysics, 603, A48 (2017).
RD16	Ultrastable long-distance fibre-optic time transfer: active compensation over a wide range of delays	Przemysław Krehlik *et al* 2015 *Metrologia* 52–82
RD17	Long-distance telecom-fiber transfer of a radio-frequency reference for radio astronomy	He, Baldwin, Orr, Warrington, Wouters, Luiten, Mirtschin et al. *Optica* 5, no. 2 (2018): 138–146.
RD18	High resolution frequency standard dissemination via optical fiber metropolitan network	Narbonneau et al, *Review of Scientific Instruments* 77, no. 6 (2006): 064701.
RD19	High-resolution microwave frequency dissemination on an 86-km urban optical link	Lopez et al, *Applied Physics B* 98, no. 4 (2010): 723–727.
RD20	Signal processing aspects of the sample clock frequency offset scheme for the SKA1 mid telescope array	Carlson, Brent, and Thushara Gunaratne, *(URSI GASS)*, 2017
RD21	Long Haul Fiber Workgroup Preliminary Report	020.60.00.00.00-0002-REP, Version 03: 2018-10-08
RD22	Antenna Electronics Pedestal Enclosure Block Diagram	20.30.00.00.00-0003-BLK, NGVLA_Antenna_Block_Diagram Ped_Enclosure_2018-04-27v02.vsdx
RD23	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK, NGVLA_Antenna_Block_Diagram_FE Enclosure_2018-05-09v03.vsdx
RD24	ngVLA Integrated Receivers and Downconverters: Preliminary Technical Specifications/Requirements	020.30.15.00.00-0001-REQ-05, v0.5, 2018-05-03

3 Subsystem Overview

3.1 Array Expanse

The ngVLA is a nominally 263-element synthesis array of very wide extent, with 244 antenna stations of 18m diameter and 19 6m antennas [RD01]. The extent of the array is a primary driver of the design and performance requirements of the LO Reference and Timing, and thus a brief description is included below.

Figure 1 shows the preliminary configuration of the array for the area close to the central core. In addition to the central core area the first antennas in the five spiral arms are shown. The central core contains 94 antennas which covers an area approximately 1km in diameter. Thus 44% of the antennas in the main array are in a close central cluster, and the fiber optic connection to these antennas should all be fairly short, in the range 0-5 km. Additionally, there are an additional array of 19 smaller antennas (nominally 6 m) comprising the short baseline array (SBA), which will all be outfitted with instrumentation identical to the main array [RD02]. (Note: The short baseline array also includes four 18m total power antennas but these four antennas are part of the 94 in the original central core main array). Thus, the total number of antenna stations in the central core is 113.

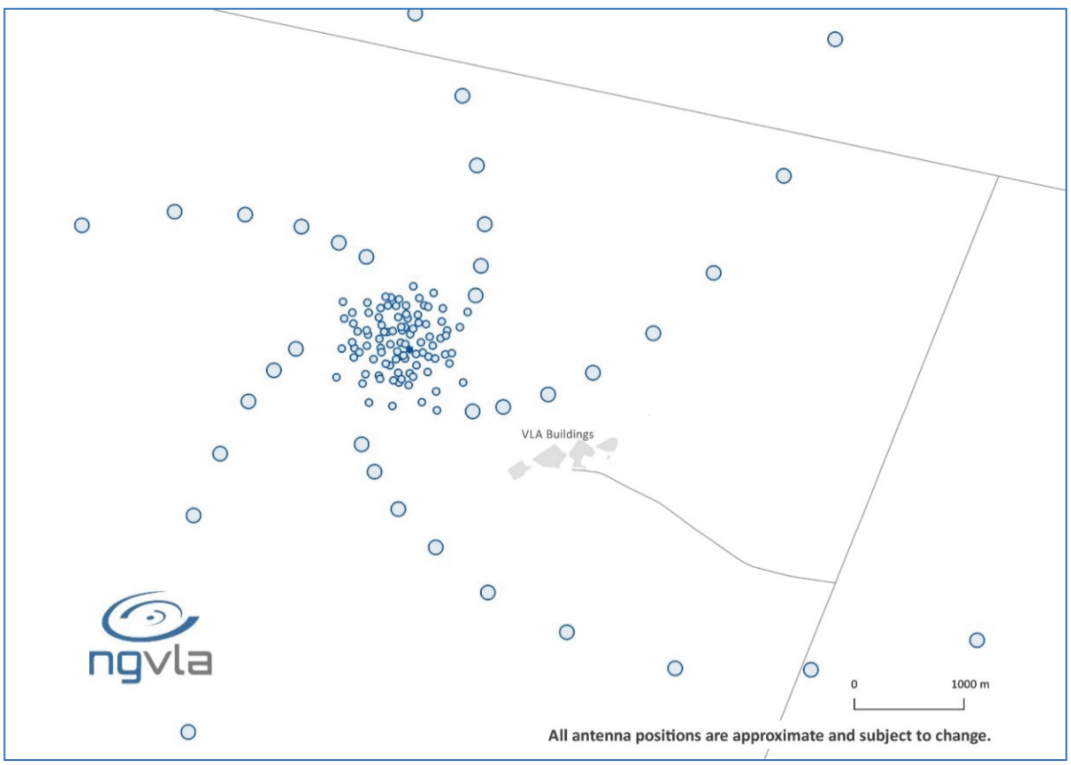

Figure 1 - A preliminary (rev B, Apr 2018) configuration map for only the antennas included in the core. Note that the symbol sizes in the core have been scaled down for visibility. All antennas in the main array including the core are 18 m diameter. However, there are additionally 19 6 m antennas of the Small Baseline Array in a small area at the array center.

Figure 2 shows an area about 60 km east-west by 40 km north-south. These five spiral arms contain an additional 74 antennas. The distance along the spiral arms from the center of the array is about 25–30 km. Together with the central cluster, 78% or 168 out of 214 18m antennas of the main array are included.

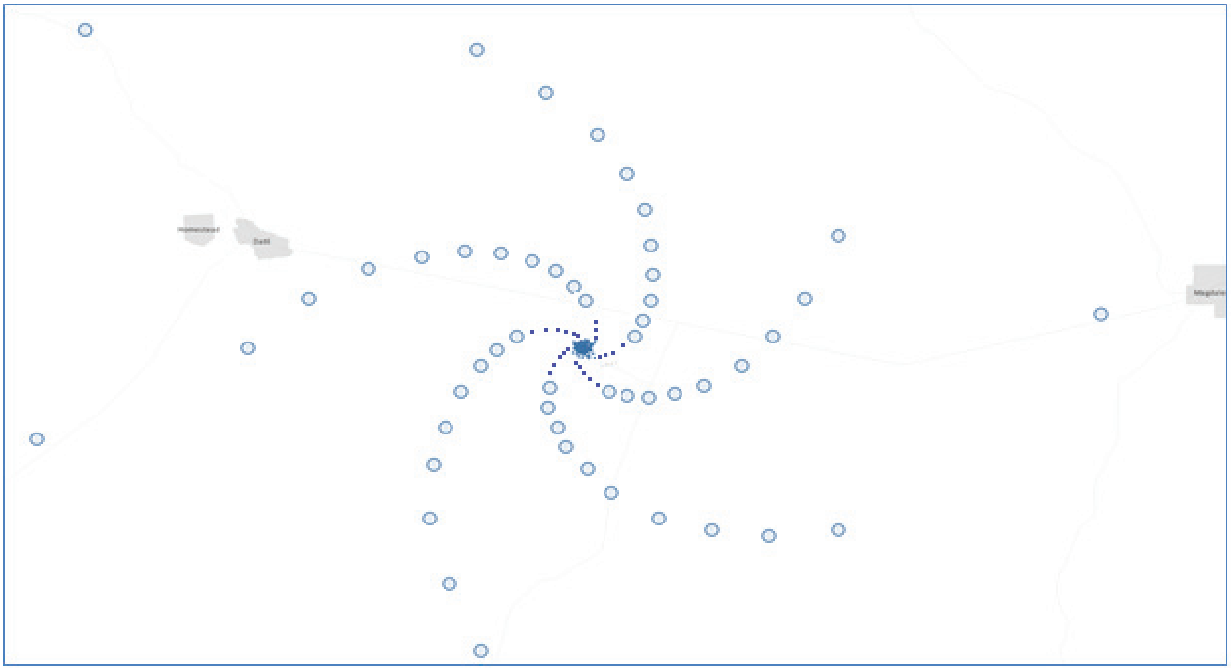

Figure 2 - Central cluster plus five spiral arms. The spiral arms contain 74 18 m antennas. The figure shows approximately 60 km east-west and 40 km north-south. The distance along the spiral arms is approximately 25 to 30 km.

Figure 3 shows the entire main array covering a large span of the Southwestern US. The maximum distance to outlying antennas along roadways is approximately 800 km. There are 46 18 m antennas in this area beyond the central core and spiral arms. These additional 46 antennas have been termed the “Mid-Baseline” Antennas [RD21].

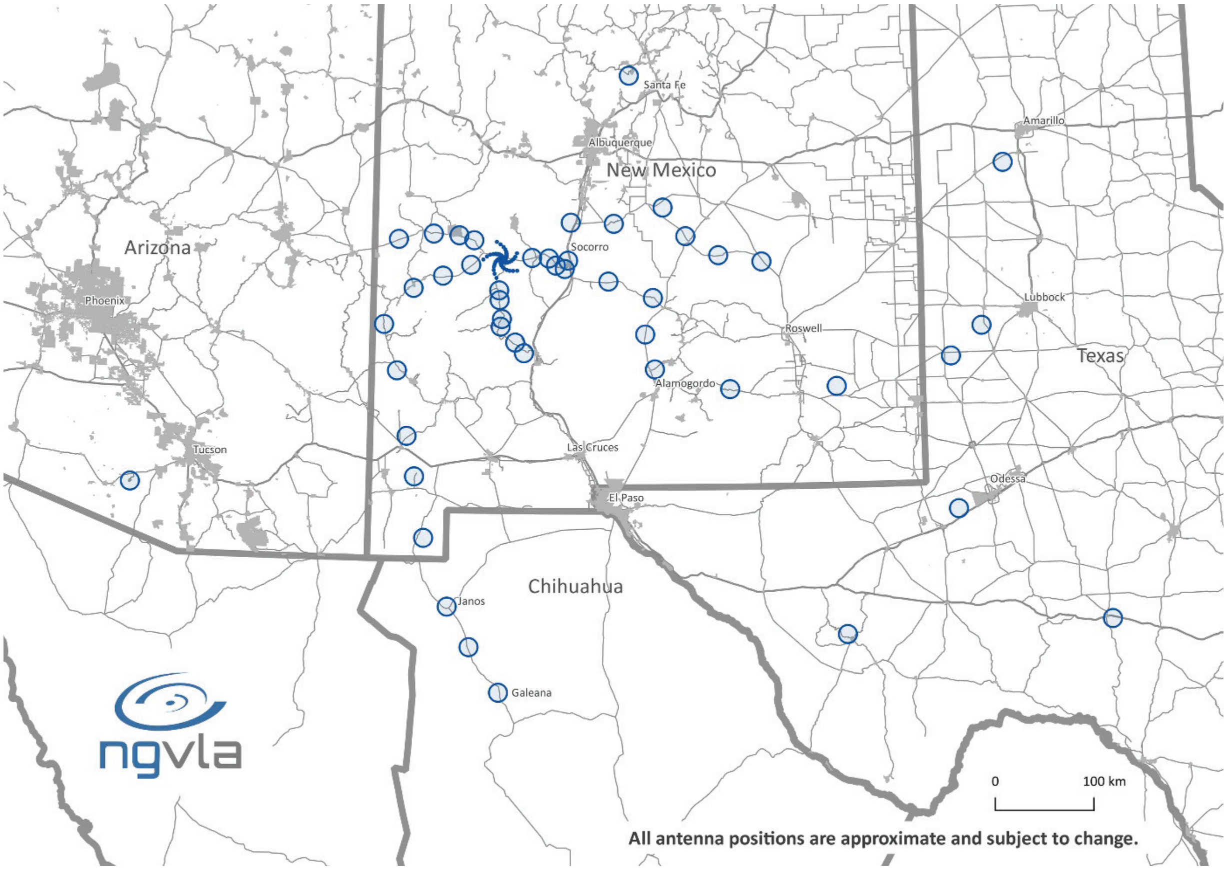

Figure 3 - A preliminary configuration map for the 214 18 m antennas included in the main array.

The final part of the ngVLA configuration is the Long Baseline Array (LBA), consisting of 30 18 m antennas grouped into ten remote stations [AD03]. These antennas nominally must meet the same requirements as the antennas in the main array, but due to the distances involved, the provision of timing and LO to these antennas is expected to be handled differently than those in the main array.

The geographic distribution of the ten remote station sites is shown in Figure 4. The list of sites, number of antennas, and distance from the array center is tabulated in Table 1. An overall summary of the number, type, and location of the ngVLA antennas is shown in Table 2.

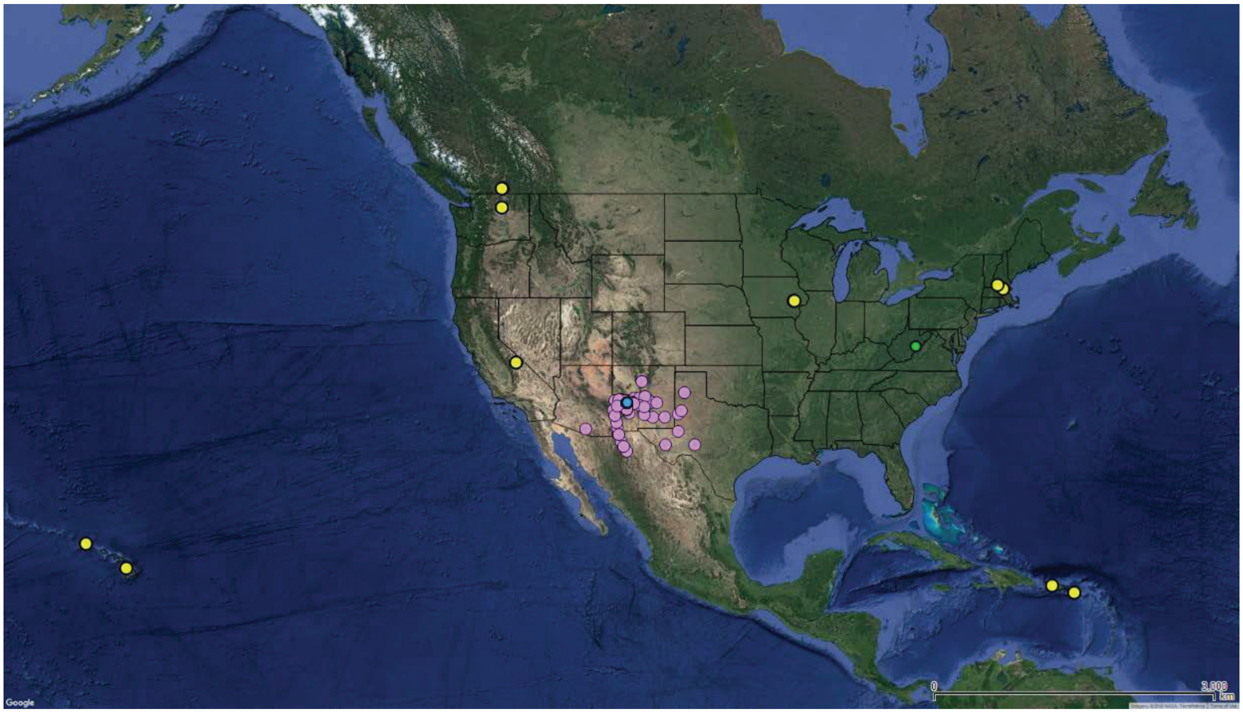

Figure 4 - ngVLA LBA sites shown in yellow. GBT site shown in green. ngVLA core and main array in blue and purple, respectively. 30 antennas are included in the LBA configuration, distributed per Table 1 below.

Antenna Qty	Location	Possible Site Notes	Distance from Array Center (km)
3	Puerto Rico	Arecibo Observatory.	4370
3	St. Croix	Existing VLBA site.	4580
3	Kauai, Hawaii	Kokee Park Geophysical Observatory.	5260
3	Hawaii, Hawaii	New site.	5000
2	Hancock, NH	Existing VLBA site.	3200
3	Westford, MA	Haystack Observatory.	3240
2	Brewster, WA	Existing VLBA site.	1870
3	Penticton, BC	Dominion Radio Astrophysical Observatory.	1990
4	North Liberty, IA	Existing VLBA site.	1610
4	Owens Valley, CA	Existing VLBA site.	1056

Table 1 - List of antenna station sites in the Long Baseline Array (LBA).

	Number of Antennas		Antenna diameter	Distance from Array Center
Main Array				
Central Cluster	94		18 m	0–1 km
Spiral Arms	74		18 m	1–30 km
Mid-Baseline Arms	46		18 m	30–1000 km
Main Array total		214		
Small Baseline Array	19		6 m	0.1 km
Long Baseline Array	30		18 m	1050–5300 km
Total		263		

Table 2 - Summary of sub-arrays, number and size of antennas, and distance from array center.

3.2 *Top Level Description: LO Timing and Reference*

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 (CSP). The block diagram shown in Figure 5 illustrates the major functional blocks of the LO Reference and Timing. 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. Since this is a much generalized functional diagram, the following assumptions and caveats are made:

- Central LO Reference and Timing are assumed to be in the same central building as the CSP, but no further assumptions are made as to whether the equipment is in the same room, same racks, sharing floor space, ventilation, power, etc.
- Only LO Reference and Timing functions are shown. The data backhaul is expected to have a similar arrangement and possibly share fibers or ducts. Power and monitor and control functions are also not shown.
- Connection to each antenna station is shown as bidirectional, which indicates that some form of bidirectional connection is anticipated to accomplish the phase synchronization and absolute timing.
- A single repeater station is shown, but additional repeater stations may be needed for signal regeneration or amplification especially the most distant antenna stations.
- The transmission medium is not indicated but is assumed to be single-mode SiO_2-based optical fiber.
- A spoke-and-wheel connection arrangement is shown, although it is in principle possible to connect antenna stations by daisy-chain or some intermediate arrangement.
- All stations are shown connected to the central building. However, it is possible that some far out stations, and for long baseline array (LBA) stations, standalone LO Reference and Timing generation (using local hydrogen maser and GPS equipment, for instance) will be used.

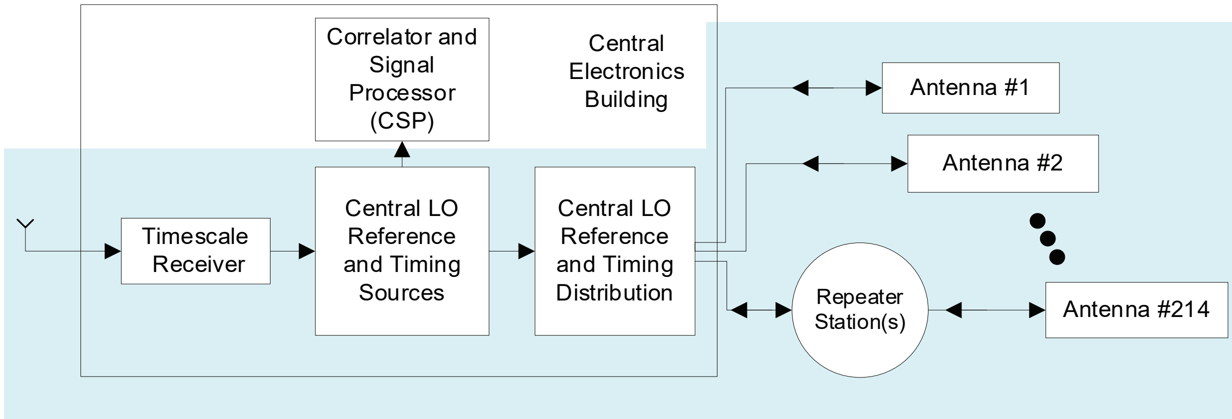

Figure 5 - Block Diagram of LO Reference and Timing: LO Reference and Timing parts are shaded.

3.3 Design Assumptions and Drivers

The following assumptions are reflected in this reference design:

- The design discussed in this document supports the main array of 214 antennas, the SBA of 19 antennas, and the 30 antennas of the LBA.
- It is assumed that the central core, SBA, and spiral arms are connected to the central building by trenched fiber installed and owned by the project.
- Precise timing to nsec level is needed at CSP but not antenna stations.
- PPS timing is distributed by fiber to antenna stations with direct fiber connections.
- PPS timing by GNSS at stations is connected to commercial network.
- Phase drift requirement is still being studied. Performance of most distant antennas should achieve stability at least as stable as a hydrogen maser if most stringent requirement is not met.
- A single, identical design for all antenna stations is desirable but not necessary, especially if substantial cost savings result from adopting different designs. (For instance, far-out antennas may use a different design that near-in antennas.)

4 LO Reference and Timing Requirements

4.1 Key Requirements

Table 2 shows a subset of general system requirements that most directly drive the design.

Parameter	Summary of Requirement	Reference
Maximum Number of Antennas	LO to support NGVLA final configuration with maximum number of antennas as needed. The most recent plan is for 263 antennas total.	LRT-0010
Maximum Fiber Length	1,000 km. More distant LBA antennas could connect by fiber if feasible.	LRT-0020
Number of Sub-Arrays	≥10	LRT-0030
Phase Preservation	Electronic phase is preserved when adding and/or subtracting an element from a sub-array.	LRT-0040
Phase Drift	LO <84 fsec rms over 300 sec in time Digitizer <42 fsec rms over 300 sec in time	LRT-0300
Phase Noise or Jitter	LO < 76fsec Digitizer < 76fsec	LRT-0310
Timing Accuracy	Timestamp accuracy <10 nsec	LRT-0320
Unambiguous Phase	Return to Phase after tuning change to LO or digitizer clock.	LRT-0330
Self-Generated Spurious	<–43dB relative to the system noise level on cold sky over a 1 MHz bandwidth.	LRT-0270
Number of Simultaneous LOs	Three	LRT-0260

Table 3 - Critical LO reference and timing requirements.

4.2 Number of Antennas

The number of antennas is not strictly limited by the design. In general, the design will consist of centrally located references that are split N-ways and distributed to each antenna. Thus increasing or decreasing antenna number is handled by changing the split network and does not represent significant difficulty to change or redesign. It is worth noting that with the current plan for 263 antennas, and with at least 30 of those likely to be "remote" with no central fiber connection, this central distribution can be handled with a very convenient 256-way split.

4.3 Phase Drift

The phase drift has been derived from a consideration of the atmospheric stability and the desire for the electronics systems to not limit the array coherence or drift in a significant way beyond the pre-existing atmospheric effects [AD02]. The specification of 84 fsec for the local oscillator is equal to 0.06 radians (3.4 deg) of phase at 112 GHz. The most distant antennas are expected to be as far as 1000 km. A round-trip phase servo at this distance is bandwidth limited to 1/(4*tau), where tau is the one-way travel time of ~5 msec (at 1000 km), for a maximum bandwidth of 50 Hz [RD03].

At this early stage of the ngVLA project definition there is still some uncertainty about the availability and condition of the optical fiber trunk to the remote stations. However, it is likely that the existing fiber infrastructure will consist of long runs of above ground fiber, and thus the fiber will be exposed to wind, motion, and temperature to a much greater degree than a typical buried fiber. This in turn increases the open loop rms phase accumulated in the fiber, and because the amount of phase correction that can be applied by a servo with finite loop bandwidth is limited, the ultimate frequency stability on overhead fiber will be worse than for more protected fiber.

In [RD04], relations are developed for various noise processes that affect Allan Variance and telescope coherence. It is useful to consider the 84 fsec phase drift requirement at 300 sec, where the required Allan deviation is approximately 84e-15/300 = 2.8e-17. At that level, if the Allan Variance is comprised of either white phase noise (1/tau response) or white frequency noise (1/root(tau) response), the astronomical coherence loss is negligible.

The level at which the coherence would degrade by 1% is significantly higher, about 6e-14, which is closer to what is typical for a hydrogen maser. The temporary conclusion to draw from this is: the 84 fsec rms delay drift requirement allows the array to be stable compared to the atmosphere almost all the time, enabling high dynamic range imaging, but it may be tighter than what is minimally required for effective typical synthesis imaging, even at 116 GHz. With that in mind, and 84 fsec as the preliminary requirement, the following discussion recommends a reference design for ngVLA.

Recent discussions of the phase drift specification within ngVLA indicate that the specification is likely to undergo further refinement. In particular:

- The 84 fsec requirement could at least double to ~160 fsec over 100 sec, or 1.6e-15 Allan deviation.
- The specification could include a further allowance of linear drift of less than 2.5 psec over 300-sec intervals. Linear phase has no effect on the Allan deviation.

4.4 Phase Noise

The strict phase noise requirements are met by transmission of a single reference frequency with very low phase noise to all antennas. At the antenna the reference is used to phase lock a fixed frequency dielectric-resonator-oscillator (DRO), which in turn is used to lock a microwave oscillator, also with very low phase noise.

There is one oscillator per IRD module. The phase-lock loop bandwidths are chosen so that the IRD module LO composite phase noise is minimized. Separately, a digitizer reference is developed from the same low-phase noise transmitted reference, and also distributed to the IRD module as the ADC clock.

4.5 Spurious Level and LO Noise Level

As detailed in [AD01], the local oscillator requirement is to provide a local oscillator for each IRD module in the front end and WVR. The LO must be relatively high power (+13 dBm), low phase-noise, and having low spurious levels. A couple of key design decisions are where to generate the unique LO frequency, and what is the highest frequency to transmit over the fiber.

The requirement LRT-0390 for spurious level below –140 dBc may eliminate the possibility of generating the highest LO frequencies in either the central station or the pedestal, transmitting directly to the IRD modules by fiber, and then producing the LO by direct photo-conversion. Most commercially available photodetectors cannot generate sufficient LO power, and even if the photodetector were followed by an amplifier, the noise processes in the fiber link would prevent meeting the spurious requirement. For this reason, the design incorporates a phase-locked oscillator for each IRD module.

4.6 Flexible Subarrays

Many options for the antenna-based frequency synthesis are affected by the requirement that any antenna can be placed in any subarray. Requirement LRT-0030 [AD01] requires a minimum capability of ten subarrays, but it is further assumed that these subarrays can be arbitrary groupings of antennas. This weighs against the possibility of transmitting a tunable frequency reference from the central building to the antenna stations.

With a tunable reference, certain additional antenna-based tuning mechanisms for the LO could be avoided. With the flexible subarray requirement, the use of a tunable reference could only be implemented at the expense of greatly increased complexity (additional hardware and switching fabric) at the central building. For this reason, a fixed frequency reference between the central building and the antenna stations was chosen.

4.7 Number of Simultaneous LOs

Only one band will be used in observing at a time. However, within a band it is required that three LOs be simultaneously available to take maximum advantage of the correlator bandwidth. The design accounts for this requirement by making the reference frequency available at the antenna to all IRD modules simultaneously.

5 Central Time and Frequency Reference

As detailed in [AD01], each antenna must be supplied with local oscillator and digitizer clocks that have low phase noise and jitter, and that have low phase drift relative to the system clock. Thus, references generated centrally must be distributed to the antennas with synchronous frequency and phase. Additionally, there is a requirement for distribution of time, relative to an international time standard.

5.1 Central LO Reference and Timing Overview and Block Diagram

Figure 6 shows a block diagram of the central timing. A hydrogen maser provides the reference timescale for the entire array for its accuracy from 1 sec to approximately 10^4 seconds. At timescales greater than 10^4, time and frequency will be provided by an advanced global navigation satellite systems (GNSS) receiver, likely Global Positioning System (GPS).

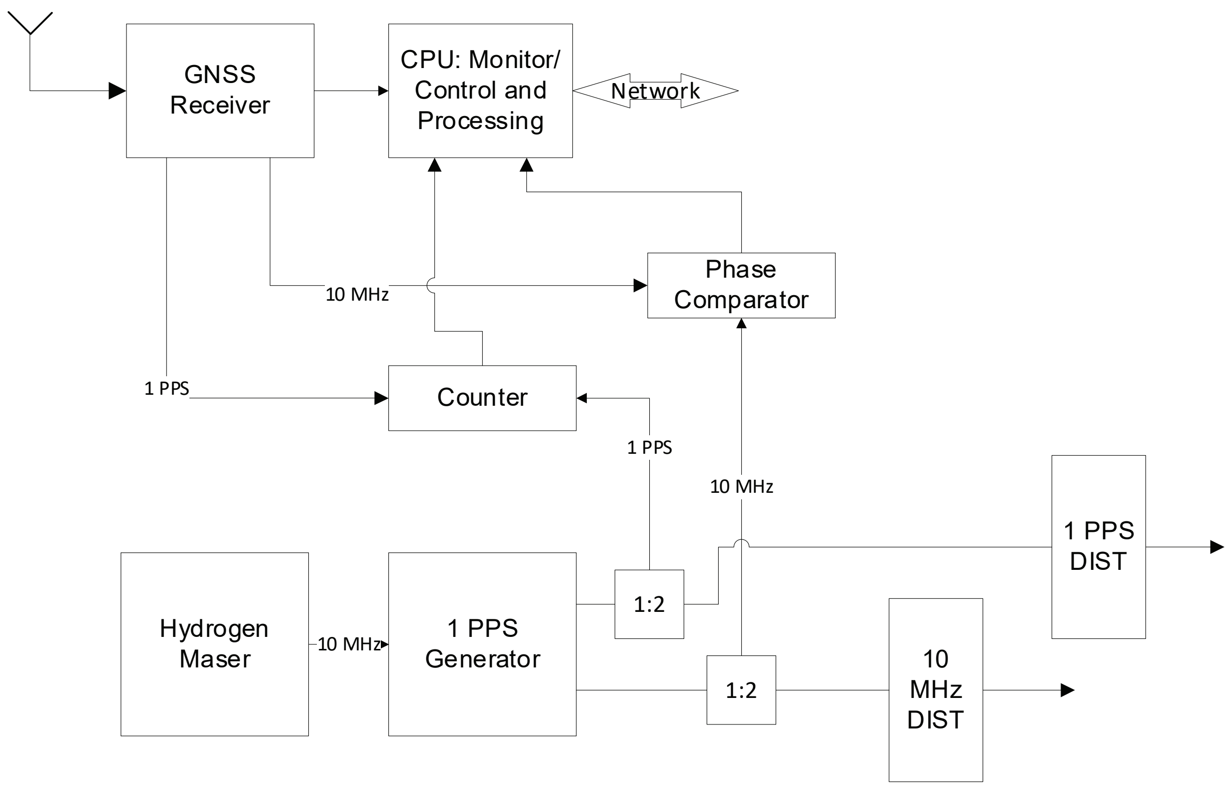

Figure 6 - Block diagram of central timing.

This is a preliminary diagram, as some details of the timing requirements are still unresolved, and interfaces have not yet been defined. It is possible that installed hot spares for critical items like the hydrogen maser will be needed. The function of the central timing is to provide the long term frequency and timing reference (10 MHz and 1 PPS) for the array. The GNSS receiver provides long term 10 MHz and 1 PPS, and these are compared to the maser outputs and logged, with data being available for post corrections. The 10 MHz and 1 PPS distributions assemblies will have as many outputs as needed, and must be high-quality buffer amplifiers with low phase drift or added noise.

5.2 Central LO Reference and Timing Components

The central timing will reside in the array central building. Because of the environmental sensitivity of the hydrogen maser and the thermal stability needed for the critical frequency and timing references, the environmental/building interface will be important feature of the design. Rack space, air flow, building and room access, vibration levels, and temperature control must be defined as part of the ICD to the building.

The hydrogen maser has exceptional frequency stability, as defined by the Allan deviation [RD05], in the range 1 to 10^4 seconds. Typical values are as shown in Table 3.

Tau (seconds)	Allan deviation
1	2e-13
10	2e-14
100	5e-15
1000	2e-15
1e4	2e-15

Table 4 - Typical Allan deviation of hydrogen maser.

5.3 Central LO Reference and Timing Interfaces with other Subsystems

Major interfaces with Building, Central Signal Processor, and Monitor and Control are not yet defined. CSP requires 100 MHz and 1 PPS. Power levels, cable and connector definitions, etc., are TBD.

6 Time and Frequency Reference Distribution

The LO Reference and Timing distribution and synchronization includes the challenging requirement to synchronize all of the ngVLA antennas, including the most distant ~800–1000 km, to within a stability level such that the array will operate with good visibility and coherence at 112 GHz.

ALMA, EVLA, and SKA are obvious and useful data points for ngVLA. Each array has a unique method for achieving array coherence and visibility by frequency synchronization. Each of these is discussed briefly below.

6.1 Frequency Synchronization - Background

6.1.1 ALMA System

ALMA has a tighter LO specification than EVLA (or any prior radio synthesis array), and used special techniques for achieving the required stability. For ALMA, the first LO was required to have maximum RMS phase noise of 53 fsec, and RMS phase drift of 18 fsec. The phase noise was achieved by use of low phase noise crystal oscillator references, a low-phase noise microwave reference common to all antennas, a tightly phase locked dual-laser system for generating the LO reference up to 122 GHz, a YIG-oscillator–warm-multiplier assembly at the antenna as a cleanup oscillator, and finally a cold multiplier to reach the highest millimeter wave frequency bands.

To achieve ultra-low phase drift, a round-trip correction system was implemented based on a stabilized single-frequency laser. The fiber length was stabilized with fiber stretchers, and a polarization stability calibration and passive thermal stabilization were added to further improve the performance [RD06, RD07]. The performance of the LO frequency drift stability in terms of Allan deviation was 1e-16 at 100 seconds.

For a number of reasons, the ALMA system is not practical for ngVLA:

- ALMA fiber distance was only 15 km. The master laser stability supplies a secondary phase drift proportional to the residual drift of the laser. Additionally, the master laser short-term coherence would need to be improved to use on longer baselines.
- The fiber stretcher range was only 5 mm, which would be insufficient for ngVLA.
- The use of longer baselines for ngVLA would imply longer round-trip travel time, and thus smaller loop bandwidth. It would not be possible to lock the loop well while using an optical interferometer.
- Issues with polarization stability would be exacerbated.
- Most importantly, the cost of the ALMA implementation on a per-antenna basis would be prohibitive for the ngVLA.

6.1.2 EVLA System

The EVLA System uses a centrally generated and distributed reference at 512 MHz, a round-trip phase measured at low bandwidth and open-loop as a phase accumulated on the same 512 MHz carrier, with the outgoing and returned signal on separate fibers. At the antenna, the reference is multiplied up in microwave synthesizer PLLs to supply first and second LOs [RD08, RD09]. Phase drift is 2.8 psec per hour [RD10]. Phase noise of the first LO is approximately 300 fsec [RD11].

The ngVLA will need more phase drift and phase noise accuracy than the EVLA for the LO. Additionally, the antenna stations are spread over a much greater geographic area and for the furthest stations will likely traverse sections of overhead fiber. On the other hand, the use of nominally fixed frequency LOs for ngVLA is a simplification compared to EVLA, for which the LOs were required to have significantly more tuning flexibility.

6.1.3 SKA System

The SKA as currently funded consists of SKA-low (Australia) and SKA-mid (South Africa). For these arrays, separate systems have been adopted for use in long-distance frequency synchronization. These are interesting from the point of view of ngVLA reference design development because:

- The SKA has longer fiber optic distances between the central building and the most remote antennas than ALMA or EVLA (~175 km for SKA-mid).
- The SKA intends to use overhead fiber links, and the systems that have been developed have sufficient dynamic range and phase correction bandwidth to cope with this.
- The SKA engaged in a down select to these techniques after considering many other techniques.

6.1.4 SKA-low

The SKA-low solution uses a technique called phase conjugation, sending a laser at a reference frequency (~2 GHz) to the remote station, and a second laser sent back on the same fiber at ~1 GHz. The techniques uses a servo in the remote station to equalize the phase of the 2 GHz signal which has traveled one-way versus the 1 GHz signal which has traveled the round trip. [RD12].

6.1.5 SKA-mid

The SKA-mid solution uses a technique in which a (relatively high) 8 GHz microwave frequency reference is encoded as a difference frequency on optical fiber using a single-sideband modulation of a highly coherent laser. At the antenna the lightwave is slightly frequency-shifted and reflected by a Faraday mirror. The round-trip phase correction employs an acousto-optic modulator (fiber frequency shifter) device that closes the phase-loop by use of a low-frequency (40 MHz) voltage-controlled oscillator [RD13].

6.1.6 Comparison of SKA-mid and SKA-low

Both techniques meet the SKA specification guaranteeing less than 2% coherence loss at the maximum 12 GHz LO frequency. A typical Allan deviation for the SKA-low system at 100 sec is 2e-13, and for SKA-mid is 4e-15 (Note: SKA-low result of 5e-15 was scaled by $(L2/L1)^{1.5}$ = $(175\ km/40\ km)^{1.5}$ = 9.2). The SKA-mid appears to be better suited to higher frequency reference transmission, and although reference transmission stabilization schemes all have different limiting factors in ultimate performance, a system with say, 0.2 rad rms phase stability at 8 GHz is better than a system with 0.2 rad stability at 1 GHz, for generation of radio astronomy high frequency local oscillators.

Despite this, it is not straightforward comparing one system to another. The SKA-low system has some simplicity in terms of availability and expense of components. The SKA-mid system has advantage in simplicity of the antenna station receiver.

6.1.7 Other Examples of Remote Frequency Dissemination

A few other systems with similar features to the ngVLA frequency distribution are described below:

1. Medici Radio Telescope, part of the European VLBI network [RD14]: Uses optical comb referenced to a hydrogen maser at the INRIM Institute to send via 550-km fiber link to the Medici radio telescope, with phase stabilization by means of acousto-optic modulation. Stability at 10–14 at 1 sec, and 2*10–15 at 100 sec was achieved. This solution used optical frequency combs which are an expensive approach to the hardware implementation.
2. Remote synchronization of the Torun VLBI station in Poland to an atomic clock through 350 km of fiber over the "OPTIME" Polish fiber optic network [RD15]. Stability at 2*10–13 at 1 sec, and

7*10–15 at 100 sec was achieved [RD16]. This system uses an integrated circuit to perform delay compensation to the stabilized 10 MHz and synchronizes both time and frequency.

3. A collaboration between CSIRO and several university and institutes in Australia conducted a demonstration test of VLBI with remote H-maser using an 80 MHz RF-over-fiber round trip phase correction. The experiment used telecom fiber of the Australian Academic Research Network (AARN) carrying data traffic, with bidirectional amplifiers added en route to boost the RF tone as needed. This test also measured the transmitted phase stability at the loopback length of 310 km, with stability of 10–13 at 1 sec, and 10–14 at 100 sec [RD17].
4. Researchers at University of Paris and Paris Observatory have conducted RF frequency synchronization over 86 km and 186 km links, using both an electronic and an optoelectronic phase compensation technique. Their studies revealed that to achieve very low phase drift results, special measures may be needed such as polarization scrambling and dispersion compensation. The best result achieved <10–16 at 100 sec [RD18, RD19].

In addition to these systems that have already been designed, deployed, and tested, there is an additional, very recent technique described by Carlson and Gunaratne [RD20] in which a "tracer" LO is sent from each antenna station to the central site, where offsets are tracked and corrected. This technique could theoretically be implemented within the already planned digital back end and correlator-beamformer hardware. Because this is a new and unproven technique it has not been considered for the reference design but could offer cost advantage if it is adopted at a later date.

6.1.8 Phase Correction Dynamic Range

From EVLA memo #105, "Phase Coherence of the EVLA Radio Telescope" [RD11], the round trip phase measurement was about 160 psec peak-to-peak over a day. Despite somewhat longer maximum fiber length, we can expect the ngVLA to have similar delay for the central core and spiral arms where well-buried fiber at 30–50 km is expected. Much of the diurnal effect is from fiber runs on the antennas and in the central building.

For ALMA, fiber stretchers were used as real-time phase compensators which had a range of about 20 psec and which was required to maintain phase compensation under the worst case temperature changes over a one-hour period. It might be feasible to use this technique for ngVLA but the use of stretchers has limited dynamic range and undesirable second order effects like polarization and loss changes. For the long haul fibers, there could be hundreds of km of fiber exposed diurnally to many tens of degrees temperature change, which could result in ~500 nsec of phase drift. Thus, for the central core and spiral arms, it would be desirable to have ~1 nsec of instantaneous dynamic range for phase correction, and ~1 usec of dynamic range for the long haul stations. This implies the use of electronic phase shifts or optical frequency shifts instead of optical delays.

6.2 Time and Frequency Reference Distribution Overview

For the ngVLA reference design, the SKA-mid-like approach has been adopted for the following reasons:

- High frequency reference transmission leading to low Allan deviation and high coherence.
- Simplest receiver configuration, which is advantageous for ngVLA operations.
- Small offsets to the frequency, if needed, can be applied centrally with no additional antenna station complexity.
- Large dynamic range of the phase correction

6.3 *Time and Frequency Reference Distribution Block Diagrams*

As discussed previously the SKA-mid frequency synchronization was based on a dual frequency transmission. In addition, the round-trip phase lock loop requires an IF reference. As shown in Figure 7, there is a Laser Source module (LRU) which contains a high-coherence laser and a means for generating a second wavelength at a fixed separation from the original laser. Thus, the output contains two wavelengths that are both highly coherent, with a fixed separation determined by a microwave source.

For the ngVLA this is envisaged as a fixed frequency (7 GHz), so the microwave source could be a phase-locked single frequency oscillator. A 100 MHz VCXO is locked to the 10 MHz reference to provide both a frequency reference for the Central Signal Processor (CSP) and a clock for a direct digital synthesizer that will be embedded in each transmitter module. Each of the elements shown in Figure 7 is needed just once for the entire ngVLA array.

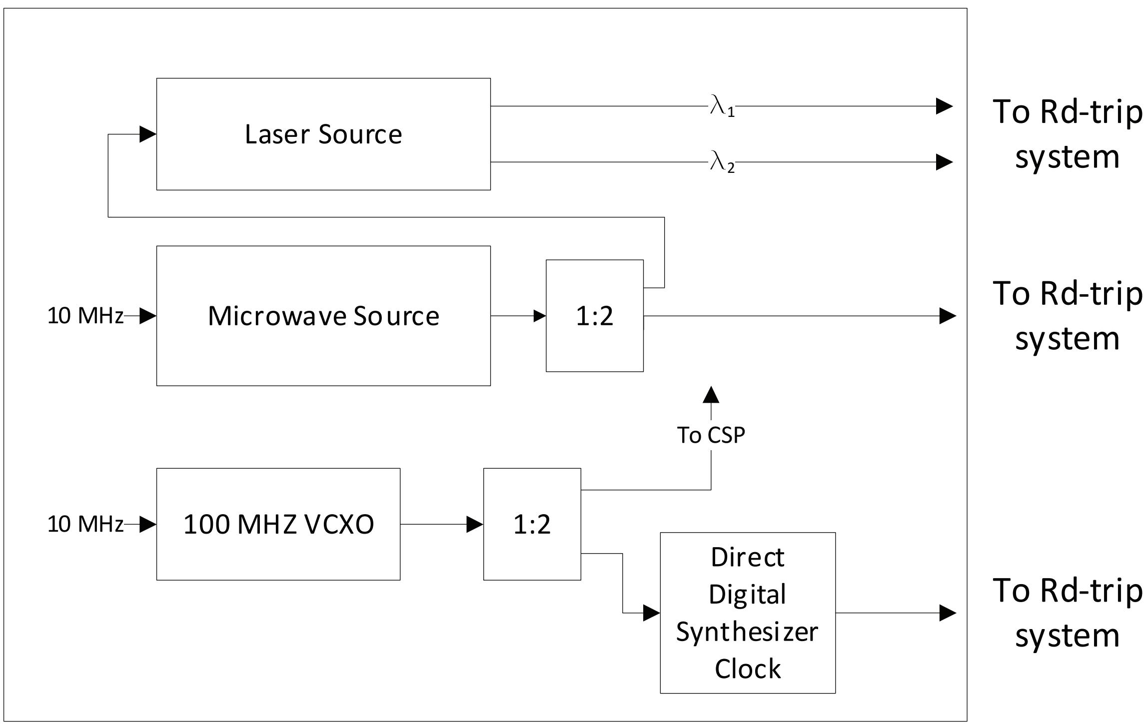

Figure 7 - Block diagram of central reference and timing sources.

Following this, each source shown (laser source, microwave source, and DDS clock) as well as the system 1 PPS is distributed 256 ways, sufficient to supply one per transmitter module, or one per each ngVLA antenna station. This is indicated in Figure 8.

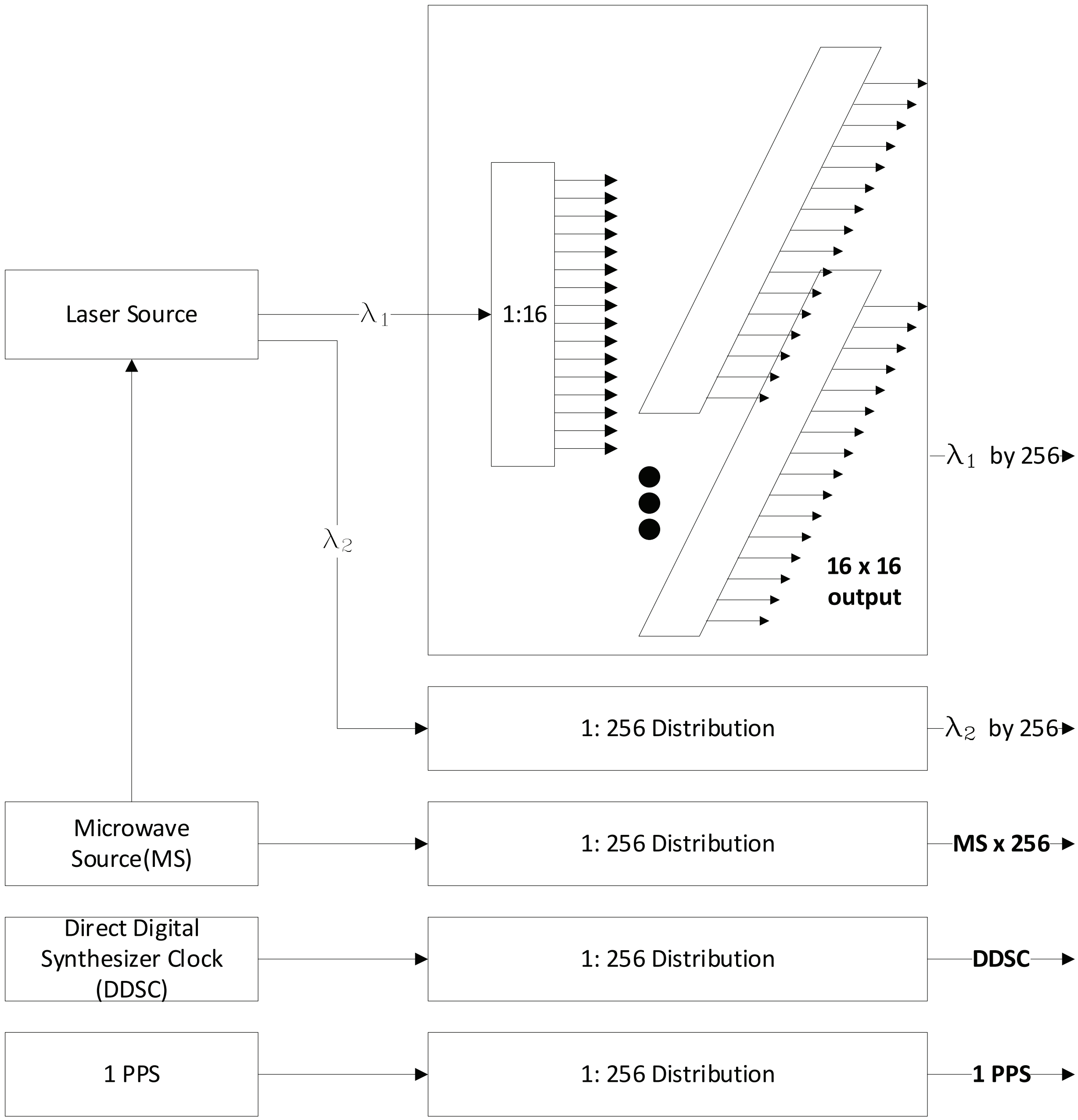

Figure 8 - Detail of reference clock and timing distribution (256-way).

Following the distribution of these signals, the output fibers and cables are crossed from a 5 x 256 grouping to a 256 x 5 grouping. Each set of five inputs (two optical fibers, two RF, and the 1 PPS) then goes to a (round-trip) transmitter module.

The simplified block diagram for the round-trip system is shown in Figure 9. This consists of a transmitter and receiver module at either end of each link (in the central building and antenna station), and additional bidirectional amplifier or repeater stages spaced at approximately every 80 km for the approximately 20% of antennas that are on long baselines.

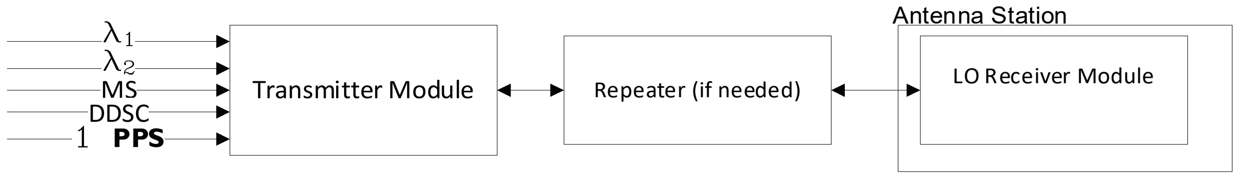

Figure 9 - Simplest view of round-trip circuit.

6.3.1 Round-Trip Phase Transmitter

A block diagram of the transmitter module, repeater, and receiver module are shown in Figure 10, Figure 11, and Figure 12. The transmitter module is shown in Figure 10, with the two laser difference frequency input on the left, and output on a single fiber on the right. The output two-laser difference frequency is equal to the original microwave source frequency plus an additional offset supplied by an acousto-optic modulator acting on wavelength λ_2. The output goes by optical fiber to each remote antenna, where it is frequency shifted (by a different amount), and reflected back completing the round-trip. The frequency shifted local and round-trip signals are then combined and photodetected. The detected signals can then be processed electronically and a phase-lock loop completing the phase correction by driving the λ_2 acousto-optic modulator (AOM). The "loop servo" shown in Figure 10 includes frequency mixing at both the microwave source frequency (7 GHz) and a low frequency offset mixer to apply the DDS offset which can be unique to each antenna. The loop error voltage drives a voltage-controlled oscillator which in turn drives the AOM. More detail describing a similar system designed for SKA-mid is in [RD13].

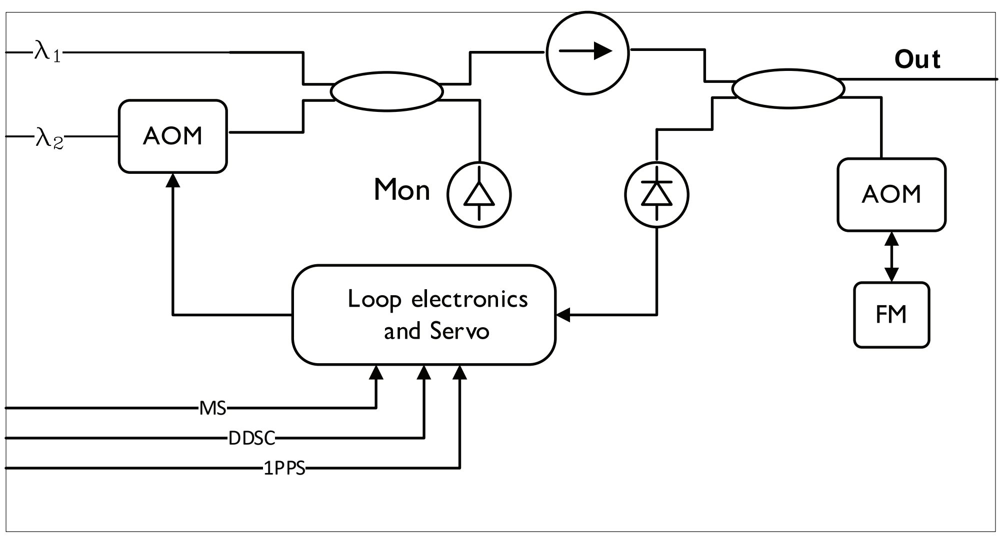

Figure 10 - Detail of round-trip transmitter module.

6.3.2 Bidirectional Repeaters

Repeater stations are needed to allow for boosting the fiber signal which suffers attenuation of about 10 dB per 50 km. Similar systems have employed signal regeneration at approximately 80 km intervals. These consist of a bidirectional amplifier, which can either be two erbium-doped fiber amplifier (EDFAs) sandwiched between directional diplexing circulators, or a single EDFA with the input and output isolators removed. The advantage of the latter is that it keeps the round-trip path intact on a single fiber. The disadvantage is that there is no isolation from reflection. The bidirectional isolator-less regenerative EDFA amplifier should thus be built with good practice for low reflection, and gain kept to ~20 dB to avoid multiple reflections that can induce self-lasing.

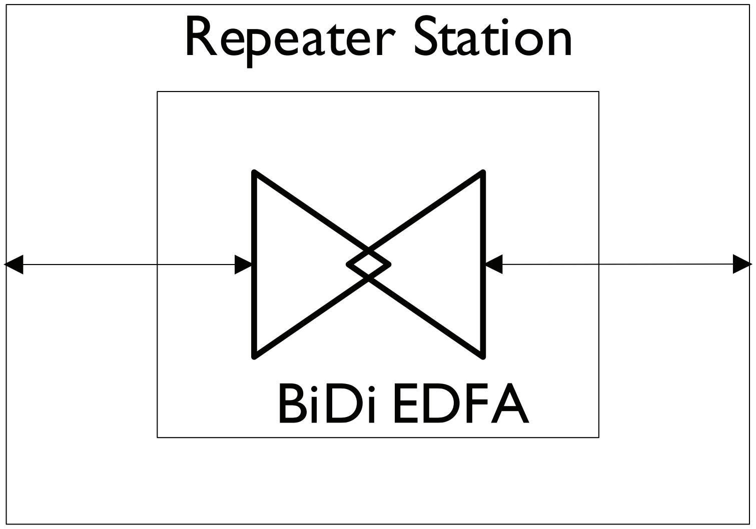

Figure 11 - Detail of bidirectional amplifier hut and repeater hut.

Note that for a plurality of the ngVLA antennas, it is not anticipated that there will be a need for a bidirectional repeater. All of the central cluster, small baseline array antennas, and spiral arms are on fiber trunks with length less than ~30 km. Further, for the long baseline antennas there is not likely a need since the fiber distances are so great, and it would be difficult to achieve all of the following:

1. acquire bandwidth on commercial fiber,
2. permission for bypassing of network switches, and
3. install special bidirectional repeaters on the long links.

Therefore, these repeaters are only applicable for antennas on the Mid Baseline Arms that are connected by fiber to the central building. A preliminary ngVLA Fiber Workgroup report [RD21] shows the layout of these Mid-Baseline stations stretching across mid-Southern New Mexico, eastern Texas, northern Mexico, and one station in Arizona. After initial review by the fiber work group, a strawman design was arrived at with 30 connected antenna stations and 16 standalone stations. For the 30 connected mid-baseline stations, the trunks branch out from the center of the array in several directions as shown in Figure 3.

It is anticipated that there will be a need for at least eleven repeater stations, and that the most practical location for these will be co-located with an antenna station. In that way, power and right-of-way are already accounted for, and there is no increase in the number of maintenance locations. The issue of housing the repeaters will depend on space available in the antenna pedestal versus the additional expense of a separate outdoor enclosure. The number of bidi-EDFAs that will need to be housed depends on the number of antenna stations further down the line on any particular branch. For the branch heading toward Socorro, the maximum number needed given the strawman assumptions is eleven. This would take approximately 6RU high standard rack width equipment not including the power supply.

6.3.3 LO Receiver Module

The receiver module is shown in Figure 12. The optical components already described include the AOM, faraday mirror (FM), and photodetector. This is followed by a phase-locked oscillator that forms the basis of the antenna-based local oscillator discussed in Section 8.

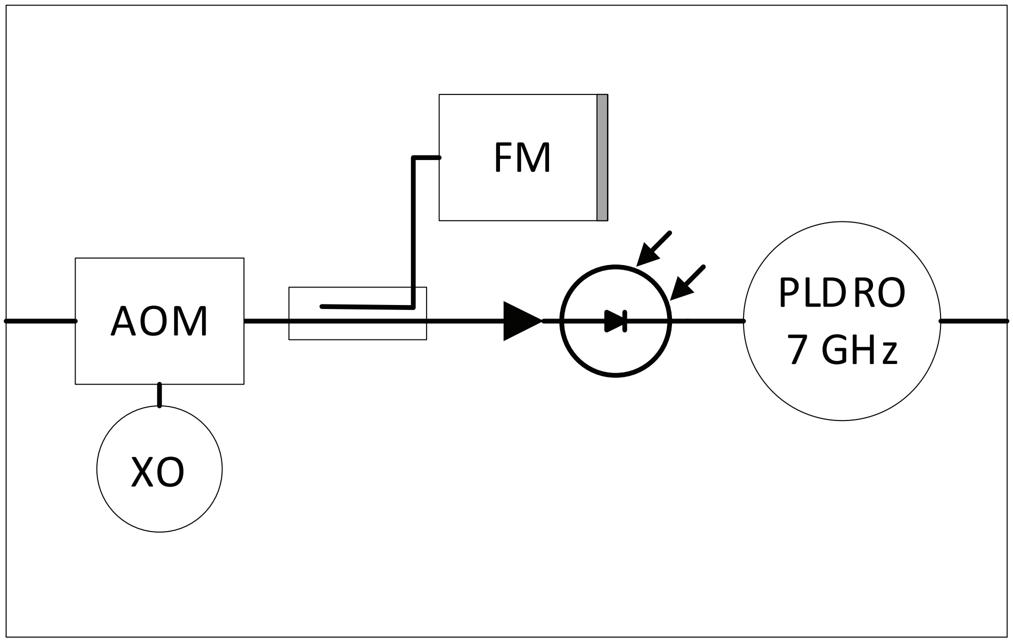

Figure 12 - LO receiver module (antenna).

This module will ideally be located very close to the front end so that there is minimal phase drift of the 7 GHz LO reference output. The packaging will depend on the location and interface with the front end and IRD modules.

6.4 LO Reference and Timing Distribution Components

The following major components are part of the LO Reference and Timing Distribution.

Laser Source: The laser itself is very specialized in that it must be highly coherent. This implies a laser with a very narrow linewidth, but needing no special provision for wavelength stability beyond a reasonably stable temperature environment. The laser is a source for the entire array and thus needs exceptional reliability and hot spare capability. In addition to the laser, there is also a dual wavelength generation function which is required to provide the second optical wavelength at a fixed (7 GHz) offset from the first. This can be provided by an optical modulator which is designed for both single-sideband operation and bias stability.

Microwave Source: The microwave source is a fixed frequency oscillator which is phase referenced to the 10 MHz coming from the maser. The advantage of having a single source for the entire array for frequency generation up to 7 GHz is that any phase drift in the multiplier phase-lock is common to all antennas. This source requires very low phase noise.

100 MHz VCXO: Needed for providing a reference to the Central Signal Processor, and to the round-trip phase transmitter module offset DDS assemblies.

DDS Clock: This is embedded in the transmitter module and provides a small offset to each antenna LO.

Acousto-optic modulators (AOMs): these are fiber optic devices that contain an acoustically sensitive crystal, that are used to provide a single sideband frequency shift to the lightwave passing through the crystal. Where they are used bi-directionally the frequency shift is double.

Faraday Mirror: These devices reflect the input wave in orthogonal polarization to the input. They are inexpensive and reliable.

6.5 LO Reference and Timing Distribution Interfaces with Other Subsystems

Major interfaces exist between the LO Reference and Timing Distribution and:

- Central Signal Processor (frequency references)
- Central Building (space requirement, thermal and air flow, power, etc.)
- Site: fiber infrastructure, repeater station requirements
- Antenna Pedestal: fiber connection, pedestal environment, rack air flow
- Antenna Electronics: interface with power supplies, equipment racks, and digital backend (DBE)
- Monitor and Control

7 Antenna Time and Frequency System

This section details the reference design for the antenna-located portion of the LO Reference and Timing Design. This will include all major interfaces, a discussion of the technical requirement drivers, any relevant design rationales or priorities, and references to relevant prior work.

7.1 Antenna Time and Frequency Reference Interfaces and Block Diagram

Figure 13 shows the LO Reference and Timing elements located at the antenna. The discussion and presentation that follows will detail what specific elements comprise the Antenna Time and Frequency design elements which are shown in red. The diagram does not indicate location specifically, but the following assumptions are made about the location:

- The trunk fiber must interface with the antenna pedestal, for example termination of the cable in a dust and weather protected connector panel
- The DBE/DTS module is located in the antenna pedestal.
- The Front End system and the Water Vapor Radiometer (WVR) are located on the antenna feed arm, with the Front End at the secondary focus and the WVR adjacent to the main reflector.
- The LO output must be placed as close as possible to the Front End/IRD and WVR for reasons of phase drift and to minimize cable loss.
- The LO output will ideally be highly mechanically integrated with the IRD modules

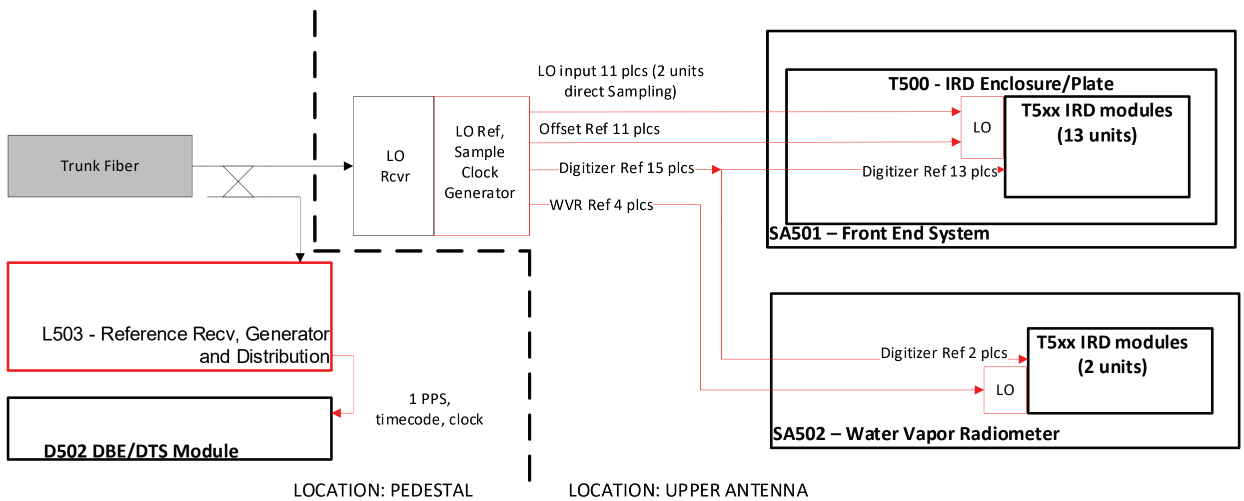

Figure 13 - Antenna time and frequency components (marked in red) and showing interfaces with Front End and DBE/DTS.

Note that the reference signal coming from the trunk fiber is split, and routed both to

1. the pedestal to supply timing for the Digital Backend (DBE) system, and
2. the upper antenna LO Receiver module to supply LO and digitizer references to the Front End.

The LO receiver output at 7 GHz (with small offsets for digitizer clock offset) goes directly to the LO reference sample clock generator module. There is no reason that these modules cannot be combined into one module, except that the LO receiver is part of the Time and Frequency Distribution, and the LO reference sample clock generator module is part of the Antenna Time and Frequency system. Therefore if they are combined physically (which may be desirable for maintenance) then there may need to be some allowance for separate work elements to work together on the integrated module test and deliverable.

7.2 Antenna Time and Frequency Reference Design Approach

In general the design philosophy for the LO include (but are not limited to) the following:

- The LOs are nominally fixed in frequency.
- Each LO is associated with an Integrated Receiver/Downconverter and Digitizer (IRD) module.
- The LO frequency sent via fiber should be at a high frequency for advantageous phase stability, but not so high that polarization mode dispersion becomes an issue, and not so high that frequency synthesis of the required LOs becomes too complex.
- The required LO frequencies depend on the ngVLA band definition, band edges, and the IRD module bandwidth and bit depth.
- The LO frequency synthesis plan should be adaptable so that if these band definitions were to change, the impact on the LO redesign is minimal.
- The frequency synthesis plan must allow for a fixed step of ~1–2 GHz from the nominal LO frequency so that sky frequencies at the nominal LO frequency value are able to be observed.
- The LO frequency synthesis should be designed for cost optimization and packaged for close integration with the IRD modules and Front End.
- Due to the low allowable output spurious, and the very wide RF bands, the LO frequency synthesis shall be designed with this in mind. In particular, integer PLLs may be preferable to non-integer PLLs.

7.3 Reference Receiver, Generator, Distribution Module

The L503 Reference Receiver Generation, and distribution module is taken in part from [RD22], but with the LO Reference photodetector functionality removed. This reduced assembly is shown in Figure 14.

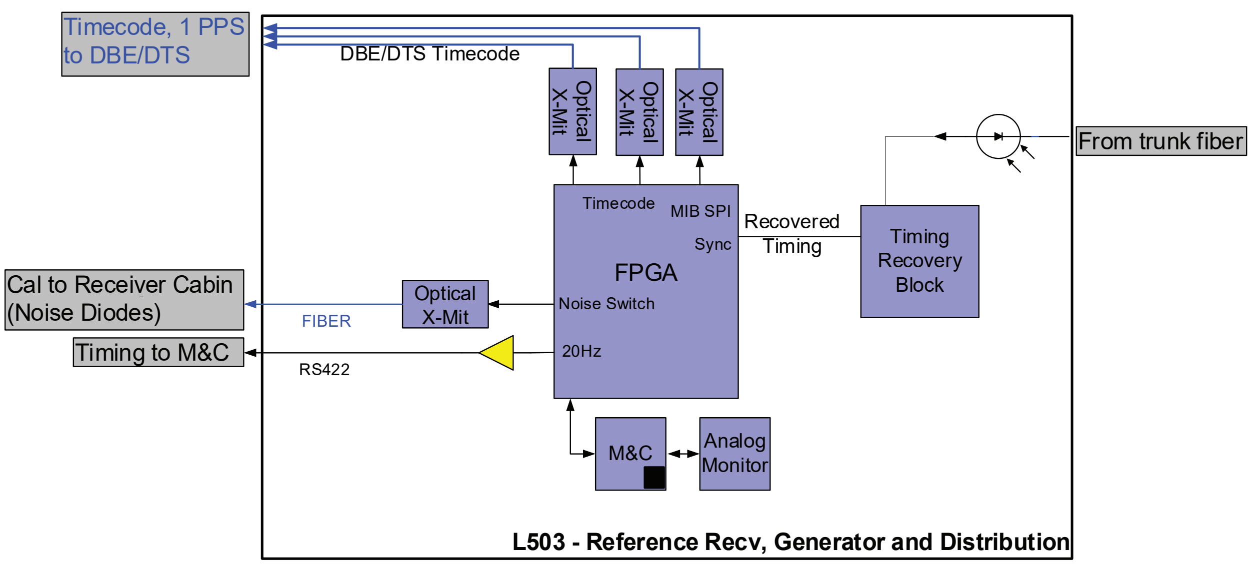

Figure 14 - Reference receiver, generator, and distribution.

7.4 LO Reference and Sample Clock Generator module

The LO Reference and Sample Clock Generator module is shown in Figure 15. This module consists of generation and distribution of the LO reference, a digitizer reference, and any offset references. The LO reference is the 7 GHz, amplified and distributed to as many IRD downconverter modules as needed (currently 11). The digitizer reference is a digital 156.25 MHz signal that can be synthesized from the 7 GHz by a divide by 224, and multiply by 5. The final reference is an offset frequency for the LO. In the LO frequency plan presented in the next section, this offset is not utilized. Nevertheless, it has been kept in the reference design to allow for the possibility of using a second reference frequency for either frequency shifting or offset harmonic frequency locking.

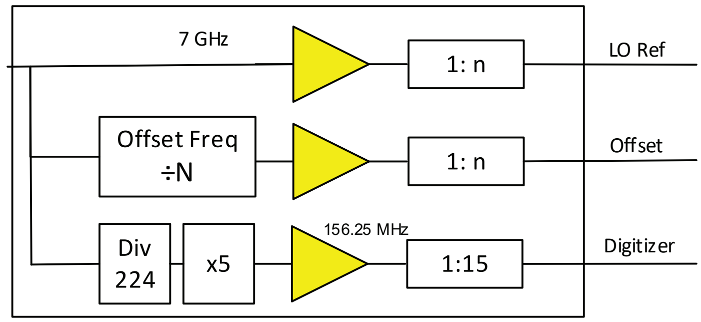

Figure 15 - LO reference and sample clock generator.

7.5 LO Frequency Plan

The RF and LO frequency plan shown in Table 4 is consistent with the frequency plan detailed in [RD24].

Band	RF low	RF hi	Nominal LO Frequency	VCO Frequency (GHz)	Reference Divider, R	RF Divider, N	Phase Detector Frequency (MHz)	M_1	M_2	Actual LO Frequency (GHz)
3	10.5	17.5	14 GHz	14	1	2	7000	1	1	14
	17.5	21	21 GHz	21	1	3	7000	1	1	21
4	20.1	27.1	23.6 GHz	23.6	35	118	200	1	1	23.6
	27.1	34.1	30.6 GHz	15.297	27	59	259.26	2	1	30.59
5	30.1	37.1	33.6 GHz	16.8	5	24	700	2	1	33.6
	37.1	44.1	40.6 GHz	20.3	5	29	700	2	1	40.6
	44.1	51.1	47.6 GHz	23.8	5	17	1400	2	1	47.6
6	70	77	70 GHz	17.5	2	5	3500	2	2	70
	77	91	84 GHz	21	2	6	3500	2	2	84
	91	105	98 GHz	24.5	2	7	3500	2	2	98
	105	119	112 GHz	28	2	8	3500	2	2	112
WVR1	24	27.5	24 GHz	24	7	24	1000	1	1	24
	27	30.5	27 GHz	27	7	27	1000	1	1	27
WVR2	18	21.5	18 GHz	18	7	18	1000	1	1	18
	21	24.5	21 GHz	21	7	21	1000	1	1	21

Table 5 - Proposed LO and RF plan for ngVLA.

The last column shows a set of LO frequencies that must be made available to the IRD modules. Requirements for these LOs are also detailed in [AD01], requirements LRT-0100 to LRT-0240. The LO has a challenging spurious signal level specification of <–140 dBc and a presumed LO power level requirement of +13 dBm. (See [AD01], section 5.6. These performance measures will be incorporated in an ICD with Front End-IRD at a later date.)

As detailed in Section 7.1 and Section 7.4, the recovered LO frequency is nominally 7 GHz. It should be noted that this was chosen because it was a convenient subharmonic, or close to it, for the proposed nominal LO frequencies shown in Table 5.

Band	RF low	RF hi	Nominal LO Frequency	VCO Frequency (GHz)	Reference Divider, R	RF Divider, N	Phase Detector Frequency (MHz)	M_1	M_2	Actual LO Frequency (GHz)
3	10.5	17.5	14 GHz	14	1	2	7000	1	1	14
	17.5	21	21 GHz	21	1	3	7000	1	1	21
4	20.1	27.1	23.6 GHz	23.6	35	118	200	1	1	23.6
	27.1	34.1	30.6 GHz	15.297	27	59	259.26	2	1	30.59
5	30.1	37.1	33.6 GHz	16.8	5	24	700	2	1	33.6
	37.1	44.1	40.6 GHz	20.3	5	29	700	2	1	40.6
	44.1	51.1	47.6 GHz	23.8	5	17	1400	2	1	47.6
6	70	77	70 GHz	17.5	2	5	3500	2	2	70
	77	91	84 GHz	21	2	6	3500	2	2	84
	91	105	98 GHz	24.5	2	7	3500	2	2	98
	105	119	112 GHz	28	2	8	3500	2	2	112
WVR1	24	27.5	24 GHz	24	7	24	1000	1	1	24
	27	30.5	27 GHz	27	7	27	1000	1	1	27
WVR2	18	21.5	18 GHz	18	7	18	1000	1	1	18
	21	24.5	21 GHz	21	7	21	1000	1	1	21

Table 6 - Parametric values for LO source modules (if M1 or M2 = 1, no multiplier is needed).

Note that:

- Bands 1 and 2 use direct sampling and therefore require no local oscillator, just a digitizer reference.
- Band 3 requires LO at 14 and 21 GHz, which are direct multiples of the 7 GHz reference.
- Band 6 requires LO at 70, 84, 98, and 112 GHz, which are direct multiples of the 7 GHz reference.
- For Bands 4 and 5, there are offsets from the nearest 7 GHz harmonic of +2.6 GHz or –1.4 GHz.
- For the Water Vapor Radiometer, the required LO frequencies are 18, 21, 24, and 27 GHz.

The design for these requirements is detailed in the next section.

7.6 Local Oscillator Modules

The Local Oscillator Modules will ideally be located so that either a coaxial or waveguide output connection can be made directly from the LO module output to the IRD module input. The LO module may have three inputs: (1) nominal 7 GHz reference, (2) Digitizer reference, and (3) an optional offset reference. The implementation of the local oscillator for the IRD modules is shown schematically in Figure 16. (Note: in this implementation, the offset frequency is not used.) For each IRD module there is a source module consisting of a voltage-controlled oscillator (VCO) and a phase-lock-loop (PLL), and a multiplication and/or amplification stage.

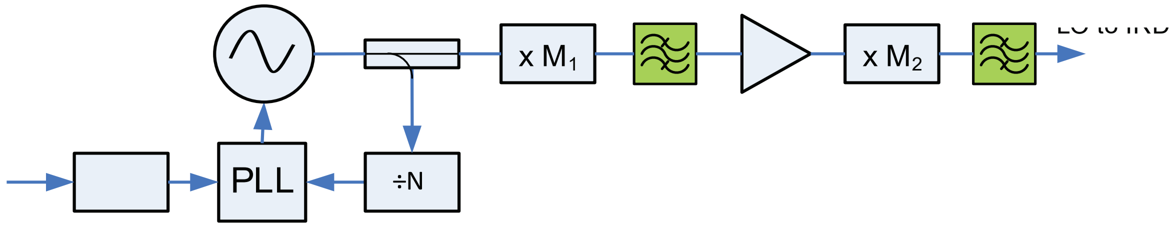

Figure 16 - LO source module generalized schematic.

Using this schematic design, the following table details the parametric values needed to realize the frequency plan given in Table 5. The design is based on the availability of modern integrated circuit PLLs and dividers with integer divide ratios up to 127 and phase detector maximum frequency up to 8 GHz. The divider ratio is kept low where the frequency plan allows. A notable exception is Band 4 in which there is no convenient low-multiple relation between the 7 GHz reference and the 23.6 GHz and 30.6 GHz LO frequencies.

[AD01] (ngVLA LO Reference and Timing Requirements) includes a requirement that each LO be able to be offset in frequency by 2 GHz to remove gaps in the frequency coverage at the nominal LO frequencies. As an example of how this can be accomplished, a frequency design is shown in Table 6 with frequency shifts in the positive direction from the nominal LO frequency in amounts varying from 900 MHz to 2 GHz. This assumes that both the references and RF dividers are programmable with 7 bits each, using for example a part like Microsemi PDF1K.

Band	RF low	RF hi	Nominal LO Frequency	Shifted VCO Frequency (GHz)	Reference Divider, R	RF Divider, N	Phase Detector Frequency (MHz)	M_1	M_2	Shifted LO Frequency (GHz)	Amount of Shift from Nominal (GHz)
3	10.5	17.5	14 GHz	15	7	15	1000	1	1	15	1
	17.5	21	21 GHz	22	7	22	1000	1	1	22	1
4	20.1	27.1	23.6 GHz	24.6	35	123	200	1	1	24.6	1
	27.1	34.1	30.6 GHz	15.75	4	9	1750	2	1	31.5	0.907
5	30.1	37.1	33.6 GHz	17.5	2	5	3500	2	1	35	1.4
	37.1	44.1	40.6 GHz	21	2	6	3500	2	1	42	1.4
	44.1	51.1	47.6 GHz	24.5	2	7	3500	2	1	49	1.4
6	70	77	70 GHz	18	7	18	1000	2	2	72	2
	77	91	84 GHz	21.5	14	43	500	2	2	86	2
	91	105	98 GHz	25	7	25	1000	2	2	100	2
	105	119	112 GHz	28.5	14	57	500	2	2	114	2
WVR1	24	27.5	24 GHz	25	7	25	1000	1	1	25	1
	27	30.5	27 GHz	28	7	28	1000	1	1	28	1
WVR2	18	21.5	18 GHz	19	7	19	1000	1	1	19	1
	21	24.5	21 GHz	22	7	22	1000	1	1	22	1

Table 7 - Shifted frequency plan.

If it were necessary, it would be possible to leave the reference divider unchanged when the LO frequency is shifted, although in some cases it would be necessary to use a lower phase detector frequency so the step shift is not too large. The set of LO modules for ngVLA Bands 3, 4, 5 and 6 are shown in Figure 17 and Figure 18. The LO modules shown in Figure 17 and Figure 18 are shown in context of the rest of the ngVLA Antenna Electronics in [RD23]. Note that the LO design for the Water Vapor Radiometer is not specifically detailed here but would be similar to the Band 3 implementation.

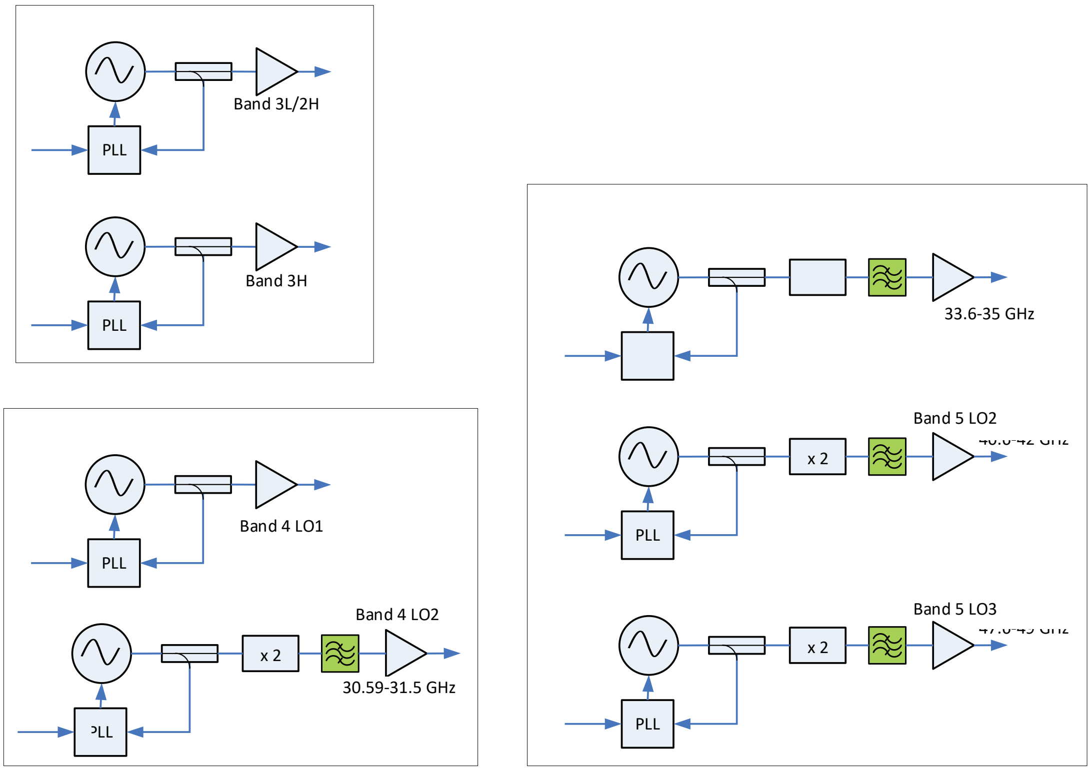

Figure 17 - Implementation of LO for IRD modules for ngVLA Bands 3, 4, and 5.

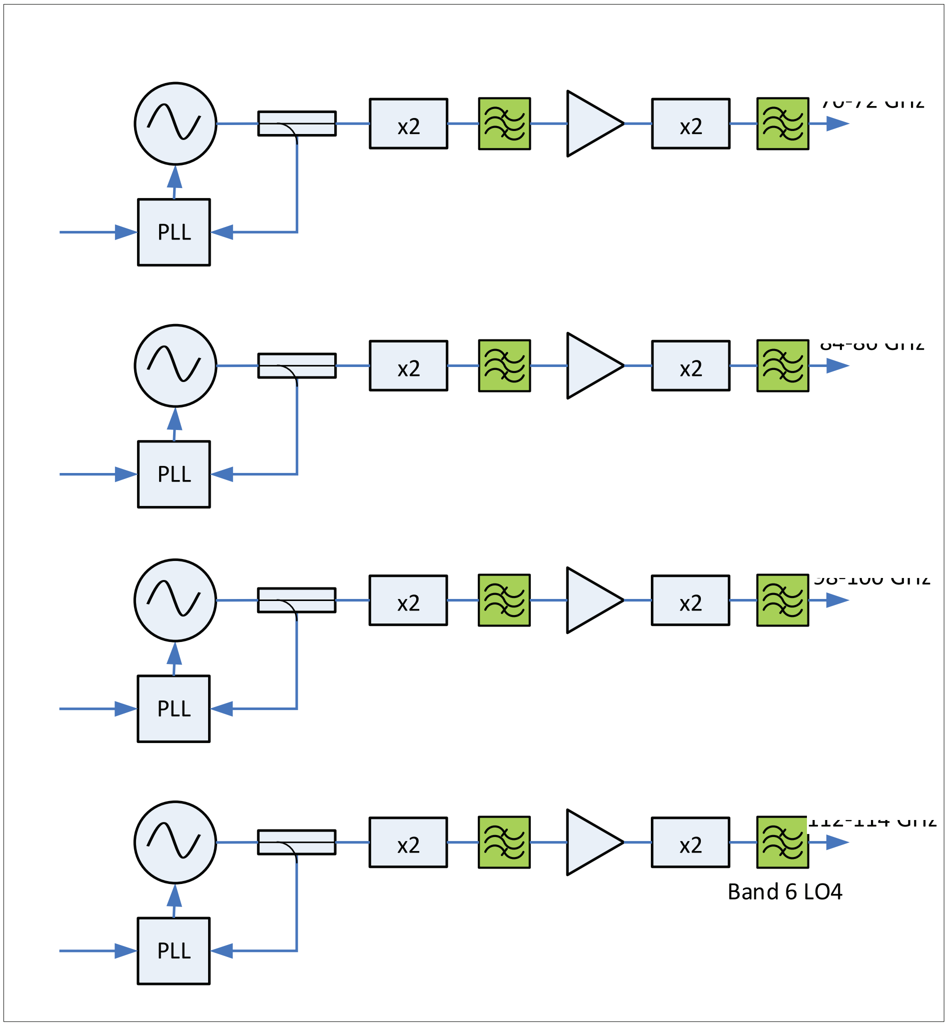

Figure 18 - LO modules for ngVLA Band 6.

7.7 Standalone Antenna Station

For antenna stations that are at distances beyond which accurate round-trip phase correction is possible, or for which the direct connection by dark or bandwidth leased fiber is not possible, the antenna station must be standalone in terms of the provision of accurate local oscillator, timing, and reference frequencies. For these stations:

- A hydrogen maser will be provided to ensure accurate time intervals between 1 sec and 10^4 sec.
- The maser will have a very low phase noise 10 MHz crystal for short-term phase noise.
- There will be a local GPS receiver to supply timing accuracy beyond 10^4 sec.
- Phase and timing differences between 10 MHz and 1 PPS, GPS vs maser will be recorded.
- The 7 GHz LO reference, DDS offset (if required), and digitizer reference will be derived from the maser 10 MHz.
- A simplified round-trip phase correction can be implemented (if needed) for the antenna LO cable.
- The LO source configuration at the IRD modules will not be changed.
- Only the pedestal configuration should be affected, nothing changes on the moving structure.

7.8 Antenna Time and Frequency Reference Components

LO source modules: The modules shown in Figure 17 are critical to the ngVLA performance. They need to provide a tight, low phase noise locking to the 7 GHz reference, and then develop LO power and harmonics as necessary to provide the LO for the IRD modules. It is anticipated that these modules are the primary cost driver for the Antenna Time and Frequency system, so they also need to be cost efficient, manufacturable, and highly reliable.

Recent advanced development of ASIC-based voltage-controlled oscillators with integrated PLLs and very low-phase-noise by Analog Devices are possible solutions for these LO source modules. These devices offer significant potential cost savings but must be verified against ngVLA LO requirements, especially spurious and harmonics. YIG oscillators and hybrid PLL designs offer proven high performance but with higher cost, size, and power.

7.9 Antenna Time and Frequency Reference Interfaces with Other Subsystems

Major interfaces are with the Front End, Water Vapor Radiometer, Antenna Pedestal, Digital Backend, and Monitor and Control.

8 Appendix

8.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter Array
AOM	Acousto-Optic Modulator
ASIC	Application Specific Integrated Circuit
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSP	Central Signal Processor
DBE	Digital Back End
DDS	Direct Digital Synthesizer
DTS	Digital Transmission System
EDFA	Erbium Doped Fiber Amplifier
EMC	Electromagnetic Coupling
EVLA	Extended Very Large array
FM	Faraday Mirror
FPGA	Field Programmable Gate Array
GNSS	Global Navigation Satellite Service
GPS	Global Positioning System
ICD	Interface Control Document
IF	Intermediate Frequency
INRIM	Istituto Nazionale di Ricerca Metrologica
IRD	Integrated Receiver/Downconverter and Digitizer
LBA	Long Baseline Array
LO	Local Oscillator
LRT	LO Reference and Timing
LRU	Line Replaceable Unit
M&C, M/C	Monitor and Control
NSF	National Science Foundation
PLDRO	Phase Locked Dielectric Resonator Oscillator
PLL	Phase Locked Loop
PPS	Pulse per Second
RD	Reference Document
RF	Radio Frequency
RFI	Radio Frequency Interference
SBA	Small Baseline Array
SKA	Square Kilometre Array
TBD	To Be Determined
VCXO	Voltage Controlled Crystal Oscillator
VLA	Jansky Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer
YIG	Yttrium-Iron-Garnet

Central Signal Processor: Preliminary Technical Requirements

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02	2017-12-06	O. Ojeda	3.3, 3.4	Elaboration of high-level requirements.
03	2017-12-28	R. Selina	3, Appendix	Added Reference Observing Program (Appendix). Updated N_{chan}, etc. Broadened from correlator to central signal processor. Reorganized specs in section 3 to add clarity.
04	2018-03-19	O. Ojeda	1 thru 4	Revamped to adopt NRC's FSA.
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Table of Contents

1 Introduction 6
1.1 Purpose 6
1.2 Scope 6
2 Related Documents and Drawings 7
2.1 Applicable Documents 7
2.2 Reference Documents 7
2.3 Terminology 8
3 Overview of the Central Signal Processor Technical Requirements 9
3.1 Document Outline 9
3.2 General Central Signal Processor Description 9
3.3 Summary of CSP Functional Requirements 10
3.3.1 General Functional Specifications 10
3.3.2 Synthesis Imaging Observing Mode Requirements 11
3.3.3 Pulsar Timing Observing Modes Requirements 11
3.3.4 Offline Pulsar Search Observing Mode Requirements 11
3.3.5 VLBI Observing Mode Requirements 12
3.3.6 Interface Requirements 12
4 Central Signal Processor Functional and Performance Requirements.. 13
4.1 General Functional Specifications 13
4.1.1 Connected Antennas 13
4.1.2 Processed Bandwidth and Simultaneous Observing Modes 13
4.1.3 Signal to Noise Ratio Efficiency 14
4.1.4 Delay Compensation 15
4.1.5 Spectral Performance 16
4.1.6 Sideband Separation 17
4.1.7 RFI Mitigation 17
4.1.8 Sub-Array Requirements 17
4.2 Synthesis Imaging Observing Mode 17
4.2.1 Definition 17
4.2.2 Temporal and Spectral Resolutions 18
4.2.3 Mosaics and On-the-Fly Mapping 19
4.3 Pulsar Timing Observing Modes 20
4.3.1 Definition 20
4.3.2 Sub-Arrays and Number of Beams 20
4.3.3 Polarization Calibration 22
4.3.4 Supporting Visibilities 22
4.3.5 Pulsar Timing Accuracy 22
4.3.6 Coherent Dedispersion 22
4.3.7 Folding Performance 23
4.4 Offline Pulsar Search Observing Mode 23
4.4.1 Definition 23
4.4.2 Sub-Arrays and Number of Beams 23
4.4.3 Polarization Calibration 24
4.4.4 Supporting Visibilities 24
4.5 Very Long Baseline Interferometry Observing Mode 25
4.5.1 Definition 25

4.5.2 Sub-Arrays and Number of Beams 25
4.5.3 Supporting Visibilities 25
4.5.4 Polarization Calibration 25
4.5.5 VLBI Channelizer 25
4.7 Spurious Signals/Radio Frequency Interference Generation 26
4.8 Environmental Conditions 26
4.8.1 Normal Operating Conditions 26
4.8.2 Lightning Protection Requirements 26
4.8.3 Seismic Protection Requirements 27
4.8.4 Site Elevation 27
4.9 Maintenance and Reliability Requirements 27
4.10 Monitor and Control Requirements 27
4.11 Lifecycle Requirements 28
5 Interface Requirements 29
5.1 Interface to the Data Transmission System 29
5.2 Interface to the Archive 29
5.3 Interface to the Fiber Optic Transmission System 29
5.4 Interface to the Central Electronics Building 30
5.4.1 Electrical Infrastructure 30
5.4.2 HVAC 30
5.4.3 RFI Mitigation 30
5.4.4 Fire Safety 30
5.5 Interface to the Time & Frequency Reference Distribution System 30
5.6 Interface to the Monitor and Control System 30
6 Safety 31
6.1 General 31
6.2 Safety Design Requirements 31
6.2.1 Fire Safety 31
6.2.2 Mechanical Safety 31
6.2.3 Electrical Safety 31
6.2.4 Handling, Transport, and Storage Safety 31
6.2.5 Toxic Substances 31
6.2.6 Confined Space 31
7 Requirements for Design 32
7.1 Analyses and Design Requirements 32
7.1.1 Reliability, Availability, Maintainability, Analysis 32
7.2 Electromagnetic Compatibility Requirements 32
7.3 Materials, Parts and Processes 32
7.3.1 Fasteners 32
7.3.2 Paints 32
7.3.3 Surface Treatment 32
7.3.4 Rodent Protection 32
7.3.5 Name Plates and Product Marking 32
7.3.6 Labels 33
8 Documentation Requirements 33
8.1 Technical Documentation 33
8.2 Software and Software Documentation 33
9 Verification and Quality Assurance 34

10 Key Performance Parameters 36
11 Appendix 37
11.1 Abbreviations and Acronyms 37
11.2 Maintenance Definitions 39
11.2.1 Maintenance Approach 39
11.2.2 Periodic Preventive Maintenance 39
11.3 Reference Observing Program 40

1 Introduction

1.1 Purpose

This document aims to present a *preliminary* set of technical requirements for the ngVLA Central Signal Processor (CSP).

These requirements flow down from the preliminary ngVLA System Requirements [AD01], which in turn flow-down from the preliminary ngVLA Science Requirements [AD02]. The Science goals elaborated by the Science Advisory Council (SAC) and Science Working Groups (SWGs) have been captured in a series of draft use cases described by the Reference Observing Program in the ngVLA Quantitative eXchange Model [AD03]. A preliminary analysis of these use cases, and the flow down recursively to the science, system and sub-system requirements, is reflected in these documents.

NRAO desires a cost-effective and flexible solution for the CSP. The optimization for value requires flexibility in key requirements until the cost and technical impact of the parameters are understood. These requirements are therefore considered *preliminary*, until refined through feedback with the CSP designer.

1.2 Scope

The scope of this document is the ngVLA central signal processor element. This consists of sub-elements, among which there are a correlator and beamformer (CBF) and a Pulsar Engine (PE). The sub-element required to configure, monitor, and control the CSP is not included in this preliminary requirements specification, as it is not deemed to be a cost driver or risk item. Supporting HVAC and electrical infrastructure is outside the scope of this specification, though coarse interface requirements have been defined. RFI shielding of the electronics is also outside the scope of the CSP element.

This specification establishes the ngVLA CSP performance, functional, design, and test requirements.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this technical specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this technical specification, the content of this technical specification shall be considered as a superseding requirement.

Ref. No.	Document Title	Rev / Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ V3, 5/10/2018
AD02	ngVLA Science Requirements	020.10.15.00.00-0001-REQ V13, 4/4/2018
AD03	ngVLA Quantitative eXchange Model	Version 3.13, 8/8/2018.
AD04	Inclusion of the "Long Baseline Major Option" into the ngVLA Baseline Design	020.05.60.01.01-0002-ECO V0.05, 8/2/2018
AD05	ngVLA Time-Domain Correlator Considerations	P. Demorest, S. Ransom, 1/5/2018
AD06	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD07	Protection Against Electric Shock – Common Aspects for Installation and Equipment	IEC 61140:2016
AD08	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD09	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
AD10	Military Handbook, Reliability Prediction of Electronic Equipment	MIL-HDBK-217F
AD11	Non-Electronic Parts Reliability Data	NPRD-95
AD12	Electromagnetic Compatibility	IEC 61000-3-5

2.2 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev / Doc. No.
RD01	TRIDENT Correlator-Beamformer for the ngVLA Preliminary Design Specification	Rev. C, TR-DS-000001
RD02	A Next Generation Very Large Array	Murphy, E. (2017). Proc. IAU, 13(S336), 426-432
RD03	An Integrated Receiver Concept for the ngVLA	ngVLA Memo No. 29
RD04	Initial Imaging Tests of the Spiral Configuration	ngVLA Memo No. 41
RD05	Pulsar Timing Array Requirements for the ngVLA	ngVLA Memo No. 42
RD06	Discovery of Three Pulsars From a Galactic Center Pulsar Population	doi:10.1088/0004-637X/702/2/L177
RD07	Understanding Massive Star Formation through Maser Imaging	Hunter, Todd R., et al. (2018) arXiv:1806.06981
RD08	Interferometry and Synthesis in Radio Astronomy	https://link.springer.com/book/10.1007/978-3-319-44431-4
RD09	USGS Coterminous US Seismic Hazard Map – PGA 2% in 50 Years	ftp://hazards.cr.usgs.gov/web/nshm/conterminous/2014/2014pga2pct.pdf

2.3 Terminology

For a correct interpretation of this document, it is important to provide clear definitions of some terms, which are identified by capital letters. The following table gathers these terms and their definitions.

Term	Definition
Digitized Wideband Signal	The digital signal received from each of the antennas in the (sub-)array that is available at the CSP input.
Function Mode	Each of the modes in which one Frequency Slice Processor can operate. It applies only to the CBF sub-system of the CSP, which is based on NRC's FSA [RD01]. A tentative list of FSP Function Modes is • Correlation • VLBI • Pulsar–TrueDelay–4beam • Pulsar–TrueDelay–10beam • Pulsar–PhaseDelay–100beam
Observation	An instance of the ngVLA operation that involves one sub-array and one Observing Mode.
Observing Mode	Each of the modes in which the CSP can be configured for each Observation independently. The different Observing Modes are • Synthesis Imaging • Sparse Pulsar Timing • Offline Pulsar Search • VLBI
Reference Observing Program (ROP)	A collection of reference use cases which are gathered in [AD03] and in Section 12.
Spectral Window	The band of frequencies extracted from the Digitized Wideband Signal to be processed in one Observation.
Zoom Window	In the Synthesis Imaging Observing Mode, a band of frequencies within a Spectral Window with smaller channel bandwidth.

3 Overview of the Central Signal Processor Technical Requirements

3.1 Document Outline

This document presents the technical specifications of the ngVLA CSP element. These parameters determine the overall form and performance of the CSP. Traceability of these specifications to those specified by [AD01] or [AD02] is indicated when applicable.

The functional and performance specifications, along with detailed explanatory notes, are found in Section 4. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirements and should guide the verification procedures.

In many cases, the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. In this way, the required analysis and trade-space available is apparent to scientists and engineers who will guide the evolution of the ngVLA CSP concept.

Requirements pertinent to interfacing systems are described in Section 5. Initial requirements are noted by interface, along with identified parameters for Interface Control Documents (ICDs) that will fully define the interfaces as the design progresses.

Safety requirements applicable to both the design phase and the functional CSP are described in Section 6. Additional requirements for the design phase are described in Section 7. Documentation requirements for both technical design documentation and software are provided in Section 8.

Requirements for the Verification and Test, from the conceptual design through to prototype, are described in Section 9.

Section 10 identifies Key Performance Parameters (KPP) that should be estimated and monitored throughout the design phase. These are metrics to assist in the trade-off analysis of various concepts, and help identify and resolve tensions between requirements as the design progresses.

3.2 General Central Signal Processor Description

The CSP ingests the voltage streams digitized and packetized by the digital backend at the antennas, and transmitted via the data transmission system, and produces a number of low-level data products to be ingested by the archive.

In addition to cross-correlation and auto-correlation capabilities, the CSP will support further capabilities required of modern telescopes to enable VLBI and time-domain science. Specifically, the CSP must operate in at least four different Observing Modes depending on the required data product:

- **Synthesis Imaging**: The CSP computes all spectral auto- and cross-correlation functions, including cross-polarizations within a sub-array.
- **(Dense/Sparse) Pulsar Timing**: The CSP generates an average pulse profile per frequency channel per beam. Timing information must be implicit or explicitly preserved along with the profiles. There are two Pulsar Timing Observing Modes: Sparse and Dense. The difference between them is the number of average pulse profiles that are generated per sub-array. Each of these two Observing Modes finds application for sparse or dense pulsar populations in the sky, which lead to different beamforming requirements.
- **Offline Pulsar Search**: In this Observing Mode the CSP outputs all four Stokes parameters at a given time-frequency resolution. In order to minimize telescope observation time, multiple simultaneous

beams are generated and subsequently stored for offline processing. It is anticipated that an "Online" Pulsar Search Observing Mode might be developed in future for commensal serendipitous searches.

- **VLBI**: Additionally, this VLBI Observing Mode is thought to operate the ngVLA as a single VLBI station within a larger network. Within this mode, several beam-channels can be generated and the resulting voltage stream stored in one of the VLBI standard formats.

These Observing Modes reveal the need for some sub-elements: a correlator, a beamformer, and a pulsar engine (to compute pulsar profiles). The correlator and the beamformer are most efficiently implemented as an integrated sub-element. Therefore, the CSP is composed of a Correlator and Beamformer (CBF) and a Pulsar Engine (PE), besides other ancillary sub-elements that will be dealt with in the future (currently out of the scope of this document). The CSP is not responsible for calibration of the beamformer, and when applicable, supporting visibilities generated with this purpose are processed outside the CSP.

NRC's architecture designated the Frequency Slice Architecture (FSA) is currently under consideration for implementation of the CBF. An ngVLA CBF reference design based on this architecture is described in detail in [RD01]. In the FSA, the CBF splits the wideband input streams into narrower oversampled signals, known as Frequency Slices. These Frequency Slices are processed by independent Frequency Slice Processors (FSPs). Each FSP has the capacity to process any one selectable Frequency Slice, for all antennas in the array, or portion thereof for any sub-array (unless otherwise stated). Additionally, each FSP may be configured to operate in any one FSP Function Mode.

The CSP will support multiple simultaneous sub-arrays. A key requirement for the CSP is the degree of simultaneity supported both within a sub-array and across all sub-arrays. By means of NRC's FSA, an FSP processes one select Frequency Slice in one Function Mode. In general, one Function Mode serves to only one Observing Mode (although this is not mandatory). Therefore, the number of FSPs operating in one Function Mode will determine the maximum bandwidth that any sub-array can devote to the associated Observing Mode.

3.3 Summary of CSP Functional Requirements

The following table provides a summary of the major CSP requirements in order to provide the reader with a high-level view of the desired system and for quick reference. Full requirement descriptions can be found in Sections 4 through 8. Should there be a conflict between the requirements listed here and the descriptions in those sections, the latter shall take precedence.

3.3.1 General Functional Specifications

Parameter	Summary of Requirement	Reference Reqs.
Maximum Number of Antennas	263 antennas	CSP0111
Maximum Bandwidth per Observation	20 GHz per polarization	CSP0121
Spectral Window Bandwidth Selection	200 MHz	CSP0122
Spectral Window Tuning Step	4 MHz	CSP0123
Maximum Aggregate Bandwidth (Simultaneous Observing Modes)	28 GHz, per polarization	CSP0124
Discontinuous Spectral Windows	Supported. Sub-bands narrower than 1 GHz	CSP0125
Minimum Efficiency	98.6%	CSP0131
Maximum Data Transport Delay	250 ms (any antenna to the central facility)	CSP0141
Maximum Array Diameter	10,000 km	CSP0142
Phase-Center Location	Within the smallest circle encompassing the sub-array	CSP0143

Parameter	**Summary of Requirement**	**Reference Reqs.**
Packet-Loss Tolerance	Supported	CSP0144
Spectral Leakage	–50 dB (total power, broadband input)	CSP0151
Channel Flatness	0.37 dB (peak to peak)	CSP0152
Channel Gain Correction	Supported	CSP0153
Number of Sub-Arrays	≥10	CSP0181
Sub-Array Independence	Fully supported	CSP0182

3.3.2 Synthesis Imaging Observing Mode Requirements

Parameter	**Summary of Requirement**	**Reference Reqs.**
Channel Bandwidth	1 kHz to 7.2 MHz	CSP0221
Number of Channels	750,000	CSP0222
Zoom Capabilities	Supported	CSP0223
Zoom Window Tuning Step	Non-zoomed channel bandwidth	CSP0224
Integration Time	2 ms to 10 s	CSP0225
Number of Simultaneous Phase Reference Positions	≥10	CSP0231
Maximum Slew Rate	2.5 arcmin per second	CSP0232

3.3.3 Pulsar Timing Observing Modes Requirements

Parameter	**Summary of Requirement**	**Reference Reqs.**
Number of Beams	10, full array	CSP0321
Number of Sub-Arrays (Outer)	1	CSP0322
Number of Sub-Arrays (Non-Core)	1 to 3	CSP0323
Number of Sub-Arrays (Full Array)	1 to 5	CSP0324
Polarization Calibration	–13 dB (cross-polarization)	CSP0331
Pulsar Timing Accuracy	≤ 2% RMS error increase	CSP0611
Dedispersion Measure Range	0–4,000 pc cm^{-3}	CSP0621
Pulse Period Range	1 ms–30 s	CSP0631
Number of Bins	2,048	CSP0632
Folding Integration Time	1–10 s	CSP0633

3.3.4 Offline Pulsar Search Observing Mode Requirements

Parameter	**Summary of Requirement**	**Reference Reqs.**
Number of Beams	10	CSP0421
Maximum Offset from Boresight	0.5"	CSP0422
Number of Antennas	168	CSP0423
Maximum Sub-Array Diameter	30 km	CSP0424
Polarization Calibration	–13 dB (cross-polarization)	CSP0431

3.3.5 VLBI Observing Mode Requirements

Parameter	**Summary of Requirement**	**Reference Reqs.**
Number of Beams	3	CSP0521
Number of Sub-Arrays	3, full array	CSP0522
Polarization Calibration	–13 dB (cross-polarization)	CSP0541
Beam-Channel Tuning Resolution	2 kHz	CSP0552
Beam-Channel Sampling Rate	2, 4, 8, …, 256, 448 MS/s	CSP0553
Beam-Channel Format	VDIF	CSP0554

3.3.6 Interface Requirements

Parameter	**Summary of Requirement**	**Reference Reqs.**
Interface to DTS	6 inputs at ≥80 Gbps	CSP2101 CSP2102 CSP2103
Interface to the Archive	150 outputs at 40 Gbps	CSP2201 CSP2202
Interface to Time & Frequency Reference Distribution System	100 MHz reference 1 PPS reference	CSP2501 CSP2502

4 Central Signal Processor Functional and Performance Requirements

These requirements apply to a properly functioning system, for an **RFI-free input** and under the normal operating environmental conditions defined in Section 4.6.1, unless otherwise stated.

4.1 General Functional Specifications

The requirements in this Section apply to **all CSP Observing Modes**.

4.1.1 Connected Antennas

Parameter	Req. #	Value	Traceability
Maximum Number of Antennas	CSP0111	The CSP shall support inputs from at least 263 dual-polarization antennas.	

The current array configuration concept clearly defines a 263-antenna ngVLA, arranged as 214 antennas for the main array, 19 antennas for the SBA (Short Baseline Array), and 30 antennas for the LBA (Long Baseline Array). No spare inputs have been required. Rather, a modular scalable design is preferred.

A preliminary configuration for the 214 18m main array can be found in [RD04]. It consists of 94 antennas within a 1-km radius (the "core"), an additional 74 antennas forming a spiral within a 30-km radius (the "spiral"), and an additional 46 antennas extending to distances of hundreds of km from the core.

4.1.2 Processed Bandwidth and Simultaneous Observing Modes

Refer to Section 2.3 for a definition of "Observation" and Spectral Window.

Parameter	Req. #	Value	Traceability
Maximum Bandwidth per Observation	CSP0121	The CSP shall support a maximum bandwidth per Observation of at least 20 GHz per polarization.	SYS0903

This requirement is intended to specify the maximum bandwidth that will be required by a single Observation. If needed, all CSP resources can be devoted to that single Observation. Thus, the CSP designer is free to trade off bandwidth when the CSP operates simultaneously in more than one Observing Mode. Additionally, the maximum number of frequency channels might limit the maximum bandwidth achievable at the finest frequency resolution as well. A bandwidth of at least 20 GHz is only required for the Synthesis Imaging use cases of the ROP. Beamforming Observing Modes will not need this amount of bandwidth (the maximum bandwidth found in the ROP is 8.8 GHz for any beamforming mode) as all use cases operate at the lower frequency bands. However, processing 20 GHz of bandwidth in Pulsar Timing Observing Mode might be desirable in future [AD01], and hence a scalable design as well.

Parameter	Req. #	Value	Traceability
Spectral Window Bandwidth Selection	CSP0122	The CSP shall select the bandwidth of an Observation's Spectral Window in steps less than or equal to 200 MHz and independently from other simultaneous Observations.	SYS0905 SYS0907

The CSP has to adjust the bandwidth of the Spectral Window so that the number of channels can be adjusted according to the Observation needs. This is intended to help controlling the output data rate.

System Requirements [AD01] specify a coarsest sub-band granularity of 1 GHz, with a goal of 200 MHz.

Parameter	Req. #	Value	Traceability
Spectral Window Tuning Step	CSP0123	The CSP shall tune the Spectral Window in steps less than or equal to 4 MHz.	

The goal here is to minimize the number of CSP sub-bands that a frequency band of interest extends across. Note that the receiver LO frequency is slightly tunable and could perform this task. Nonetheless, in some cases it might be preferable doing it digitally. The specified tuning step, 4 MHz, translates to steps of 4,000 channels at their narrowest bandwidth of 1 kHz.

Parameter	Req. #	Value	Traceability
Maximum Aggregate Bandwidth (Simultaneous Observing Modes)	CSP0124	The CSP shall support a maximum aggregate bandwidth of at least 28.8 GHz per polarization across different Observing Modes running simultaneously.	SCI0010

SCI0010 requires all sub-arrays to operate at their full specification. Achieving that goal with NRC's FSA would lead to an FSP part able to process 80-GHz bandwidth (20-GHz of bandwidth in each Observing Mode), or at least 44 GHz (20 GHz in Synthesis Imaging plus 8 GHz for each of the three beamforming Observing Modes). This would result in excessive cost and power dissipation, although it is fundamentally possible.

The justification for the value of 28.8 GHz derives from the relaxation of the requirement to at least support 20-GHz bandwidth in Synthesis Imaging Observing Mode, in addition to 8.8-GHz bandwidth in one of the beamforming Observing Modes (e.g., for simultaneous pulsar timing using full Band 2).

Parameter	Req. #	Value	Traceability
Discontinuous Spectral Windows	CSP0125	The CSP shall support discontinuous Spectral Windows, as far as the maximum aggregate bandwidth is not exceeded. This capability allows selecting which sub-bands are transmitted and/or processed, whose bandwidth cannot be greater than 1 GHz.	SYS0905 SYS0907

The current version of System Requirements [AD01] includes the capability to select any sub-band within the digitized spectral bandwidth, specifically the capability to process the top and bottom of ngVLA Band 6 (70–116 GHz). The required granularity is 1 GHz, with a 200-MHz goal.

4.1.3 Signal to Noise Ratio Efficiency

Parameter	Req. #	Value	Traceability
Minimum Efficiency	CSP0131	The SNR at the output of the CSP shall be at least 98.6% of what could be ideally obtained for the same input signal.	SYS1033

This accounts for sensitivity losses due to diverse non-ideal operations such as quantization, non-ideal filtering and decimation, etc. It also includes any inaccuracies the CSP may incur, such as in delay tracking or phase-delay beamforming. Sensitivity losses not attributable to the CSP are not included, e.g., due to inaccurate beamforming coefficients, which are computed externally to the CSP. As a reference, 4-bit quantization efficiency is better than 98.8%, so this requirement should be feasible.

The required efficiency is obtained by distributing equal weight to the ADC, the Digital Back-End (DBE), and the CSP, in order to satisfy the digital system efficiency required by SYS1033 in [AD01], which is 96%. No significant loss is expected after the CSP. This allows (close to ideal) 4-bit quantization both at the ADC and the DBE.

A detailed SNR efficiency budget should be developed in future versions to guarantee satisfaction of this requirement. This document requires 99.9% efficiency for each individual operation at the CSP that may incur an SNR loss. Up to 14 independent operations can be carried out successively at that efficiency level before violating the overall CSP requirement.

4.1.4 Delay Compensation

Parameter	Req. #	Value	Traceability
Maximum Data Transport Delay	CSP0141	The CSP shall compensate for instrumental delay differences between antennas up to at least 250 ms.	

This accounts for data transport delays mainly. The value has been taken from [AD04] for up to approximately 5,000-km data links. Once the data transport system is defined, this requirement should be revisited.

Parameter	Req. #	Value	Traceability
Maximum Array Diameter	CSP0142	The CSP shall compensate for geometric and atmospheric delays for pairwise distance between antennas of up to 10,000 km.	

The maximum geometric delay in 10,000-km [RD02] baselines is 3.3 ms, which is small compared to estimated data transport delays.

Parameter	Req. #	Value	Traceability
Phase-Center Location	CSP0143	The CSP shall locate the phase center of each sub-array anywhere within the smallest circle encompassing the sub-array.	SYS0602

SYS0602 requires phase stability regardless of sub-array elements, which can be obtained by providing a phase-center location independent of the sub-array configuration.

Parameter	Req. #	Value	Traceability
Packet-Loss Tolerance	CSP0144	The CSP shall be tolerant of packet loss in communication of data from the antennas.	

This capability is required by [AD04]. By "tolerant" it is understood that the CSP will operate at its full specification (within what would be theoretically feasible) under any kind of packet loss in the data transport system.

4.1.5 Spectral Performance

Parameter	**Req. #**	**Value**	**Traceability**
Spectral Leakage	CSP0151	For a spectrally flat input, the total leaked power from all spectral components spaced more than half the channel spacing away from the center frequency of one channel output, shall be at least 50 dB less than the power from the spectral components within the passband of that same channel output.	SCI0115

This applies to all CSP data products: visibilities, pulse profiles, Stokes parameters and VLBI channels[1]. The channel passband is defined by the half-power points, which must be located at half the channel spacing from the center frequency due to channel flatness requirements when averaging adjacent channels. This requirement is achieved through a combination of both a sharp transition band and high stopband attenuation.

Parameter	**Req. #**	**Value**	**Traceability**
Channel Flatness	CSP0152	The peak-to-peak ripple within the central 80% of the passband of any channel output shall be less than 0.37 dB.	SYS1033 SYS1701 SYS1702 SYS1703

This requirement applies to all CSP data products: visibilities, pulse profiles, Stokes parameters and VLBI channels. It also applies to channels produced by channel averaging or zooming modes. As a result, the channel edge response must be controlled as well. Channels require approximately –3 dB gain at their edges to ensure approximately uniform response across channels.

As the value provided in SYS1702, ±1.5 dB, accounts mainly for analog signal processing, the value in this requirement has been obtained by imposing a 99.9% SNR efficiency due to a non-flat channel for a spectrally flat input signal. The approximate maximum ripple can be computed as:

$$R = 5\log_{10}\left(\frac{1+2\eta\sqrt{1-\eta^2}}{2\eta^2-1}\right)\ \mathrm{dB}$$

where η is the desired SNR efficiency. For $\eta = 0.999$, the maximum ripple becomes ±0.19 dB. This is more stringent than what is obtained by assuming a sinusoidal ripple [RD08]:

$$R = 20\log_{10}\left(1+\sqrt{\frac{2\eta^2-1-\eta\sqrt{3\eta^2-2}}{1-\eta^2}}\right)\ \mathrm{dB}$$

which results in ±0.27 dB.

[1] It would be desirable to develop separate requirements for each Observing Mode, as the spectral dynamic range is only specified for observing emission lines.

Parameter	Req. #	Value	Traceability
Channel Gain Correction	CSP0153	The CSP shall output all overall channel gains for any input.	SYS1701 SYS1702 SYS1703

In practice, the full bandwidth flatness is not critical as long as it is corrected by subsequent processing, which is the motivation for requiring outputting the channel gains. In fact, it is beneficial to allow variable channel gains for processing colored (spectrally non-flat) inputs optimally.

However, channel flatness requirements across spectrally averaged channels impose some constraints on the individual channel gains.

The CSP need not correct its output for the channel gains, but shall provide the means to do it. Future versions shall include the required accuracy.

4.1.6 Sideband Separation

Because of the DBE adapter between the ADC and the CSP, it is not clear at this moment that both sidebands will be made available to the CSP, preventing it from applying any digital sideband separation technique other than in the proximity of the sub-band containing IF zero. Future versions of this document shall specify the required rejection ratio, and which sub-bands must be processed.

4.1.7 RFI Mitigation

RFI detection performance shall be specified through a collection of use cases as a result of an ngVLA RFI study. The RFI detectors generate a flag-bit signal in sync with the data stream. This signal may or may not be used by subsequent signal processing blocks to prevent processing concurrent data.

System requirement SYS0702 specifies that the CSP shall provide the archive of all information necessary to generate flagging tables. These tables should be readily generated from the channel quality measure.

4.1.8 Sub-Array Requirements

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays	CSP0181	The CSP shall support at least 10 sub-arrays operating simultaneously.	SYS0601
Sub-Array Independence	CSP0182	The CSP shall support independent sub-array configuration.	SCI0010

Refer to the discussion under aggregate bandwidth requirement CSP0124 for full compliance with SCI0010.

4.2 Synthesis Imaging Observing Mode

All requirements in this section apply only to the Synthesis Imaging Observing Mode.

4.2.1 Definition

When operating in the Synthesis Imaging Observing Mode, the CSP computes all auto and cross-correlation products (or visibilities) between the antenna inputs within a sub-array.

A sub-array is defined as any arbitrary set of antennas, including the set of all antennas. However, it is not clear yet whether heterogeneous sub-arrays will be required.

4.2.2 Temporal and Spectral Resolutions

Parameter	Req. #	Value	Traceability
Channel Bandwidth	CSP0221	The channel bandwidth shall be selectable within the range from 1 kHz to 7.2 MHz in steps less than or equal to one octave.	SYS1401

Except for Zoom Windows (see CSP0223 and Section 2.3), the channel bandwidth is the same across the entire processed bandwidth. One octave seems a sufficiently fine step to cover the channel bandwidth range.

The maximum channel bandwidth is obtained from the Reference Observing Program in Section 12; while the minimum bandwidth from SYS1401, i.e., 1 kHz/channel. There is a desired goal (SYS1401) of reaching a minimum of 400 Hz/channel.

The ratio between maximum and minimum bandwidths is 7,200. This can be achieved, for instance, through zoom factors up to 128 and channel averaging factors up to 60 channels, with a native channel bandwidth of 128 kHz. Relaxing the required channel averaging factors could lead to prohibitive output data rates.

Parameter	Req. #	Value	Traceability
Number of Channels	CSP0222	The CSP shall compute and output visibilities for up to 750,000 frequency channels at all frequency resolutions.	SYS1402

This is (coarsely) the minimum number of channels needed to comply with the Reference Observing Program in Section 12. This requirement is subject to not exceeding the maximum bandwidth. Considering the maximum bandwidth limit (20 GHz), only channel bandwidths smaller than 26.7 kHz can exceed the maximum number of channels.

Parameter	Req. #	Value	Traceability
Zoom Capabilities	CSP0223	Within each sub-band, the CSP shall be able to generate one or more nonoverlapping Zoom Windows with finer (than non-zoomed) spectral resolution. The bandwidth of each Zoom Window shall be independently selectable in steps of 1,000 channels or less.	KSG3-006

This requirement enables a zoom feature within a more coarsely channelized observation. This capability has been dropped in current Science and System Requirements, but seems still part of ngVLA Key Science Goal 3.

A use case used as a reference for the definition of this requirement is [RD07]. The total number of Zoom Windows is not specified by higher-level requirements. However, it is understood that this number must be limited in practice. As no Zoom Window is included in the Reference Observing Program (see Section 12), [RD07] has been used as a reference instead. This zoom feature is not intended as a way of exceeding the maximum number of channels, which the CSP is required to satisfy across the entire Spectral Window, including any number of Zoom Windows it might contain.

Trading observation bandwidth off in order to satisfy this requirement is deemed an affordable compromise. For example, a sub-band can be processed twice at two different resolution, which forces another sub-band not to be processed.

Parameter	Req. #	Value	Traceability
Zoom Window Tuning Step	CSP0224	The CSP shall tune each Zoom Window with a tuning step less than or equal to the non-zoomed channel bandwidth.	

It is assumed that the CSP correlator will have the capability to select what frequency channels are zoomed, what is the rationale behind the chosen tuning step.

Parameter	Req. #	Value	Traceability
Integration Time	CSP0225	The CSP shall support visibility integration times ranging from 2 ms to 10 s, configurable in steps smaller than or equal to one octave.	SYS2001

There is a trade-off between the maximum integration time and maximum baseline length, which is limited by circumferential smearing. In order to keep the smearing low, a rule of thumb is to keep the integration time well below [RD08]:

$$\left(\omega_e D_\lambda \theta_f\right)^{-1}$$

where ω_e is the Earth's rotation angular velocity, D_λ is the baseline length in wavelength units, and θ_f is the angular size of the sky image. For the 18m main array, the maximum image size is approximately 1,000 km/18 m $\approx$ 60,000 synthesized beams.

This would lead to a conservative minimum integration time equal to 10% of the above expression, which would result in 20 ms. For the LBA, this value would be 10 times smaller, that is, 2 ms. However, the image sizes in the use cases of the Reference Observing Program are significantly smaller than 60,000 beams, so this requirement needs further revision as the LBA use cases have not been developed yet.

For the maximum integration time, it can be chosen so that the circumferential smearing and radial smearing effects are similar [RD08]. Then, the worst-case radial smearing (2.5-MHz channel bandwidth at 1.2 GHz) allows integration times on the order of 30 s long. However, a maximum integration time of 10 s is deemed long enough to sufficiently decrease the output data rate. Further integration, when needed, can be carried out external to the CSP. Note that the maximum raw visibility data rate at 10 s integration times, for the main array and maximum number of channels, is 55 GB/s at single precision.

Additionally, it can be deduced that shorter integration times will be likely constrained by the archive data rate in practice, and might be only achievable using sub-arrays or a reduced number of channels.

In Section 12, it is shown that the maximum output data rate required by the Reference Observing Program is at least 80 GB/s, which results from use cases with integration times much shorter than 10 s. Thus, increasing the integration time beyond 5 s would not reduce the maximum output data rate that must be supported.

4.2.3 Mosaics and On-the-Fly Mapping

Parameter	Req. #	Value	Traceability
Number of Simultaneous Phase Reference Positions	CSP0231	The CSP shall support up to at least 10 different phase reference positions (in the sky) in Synthesis Imaging Observation Mode.	

This requirement has been demanded in [AD04] in support of the LBA.

Parameter	Req. #	Value	Traceability
Maximum Slew Rate	CSP0232	The CSP shall support OTF mapping with full operational capability at slew rates up to 2.5 arcmin per second.	SCI0106

This requirement has been obtained from SCI0106 [AD02].

4.3 Pulsar Timing Observing Modes

All requirements in this section apply only to the CSP operating in both Sparse and Dense Pulsar Timing Observing Modes, unless otherwise stated.

4.3.1 Definition

Through the Pulsar Timing Observing Modes, the CSP computes a given number of "beams" at the CBF, which are further processed by the PE. The standard data products of this Observing Mode are pulsar profiles.

The difference between Sparse and Dense Pulsar Timing Observing Modes resides in the number of beams per sub-array that need to be generated. The purpose of the Dense Mode is to maximize the number of beams per sub-array, even at the cost of other observation parameters. It is intended for telescope time optimization in those cases where multiple pulsars fall within the antenna HPBW. On the contrary, the Sparse Pulsar Timing Observing Mode is aimed at those cases where a single pulsar is within the field of view. Then, the compromises made in the Dense Pulsar Timing Observing Mode to increase the number of beams are no longer required.

Currently, only the Sparse Pulsar Timing Observing Mode is required, although a future implementation of its "Dense" version is anticipated.

The additional processing performed at the PE that shall be supported includes

- Coherent dedispersion: Performed at each beam-channel to correct for propagation through the dispersive medium.
- Channel stitching: Several contiguous beam-channels are combined together to generate a wider beam-channel.
- Conversion to Stokes parameters.
- Folding: Using a time-variant pulse period model, the Stokes parameters are accumulated at each pulse phase bin.

Although the standard result is the pulse profile, certain flexibility in the selection of the CSP data product is desirable.

4.3.2 Sub-Arrays and Number of Beams

Parameter	Req. #	Value	Traceability
Number of Beams	CSP0321	In Dense Pulsar Timing Observing Mode, the CSP shall support at least 10 different beams using the full array. Only one beam per sub-array is required in Sparse Pulsar Timing Observing Mode.	SYS0203

This requirement is in support of timing pulsars located in the Galactic Center (see Section 12). A goal of 50 beams is desired for globular clusters [AD05], but this is not currently required.

According to the Reference Observing Program, the required maximum bandwidth per beam is 8.8 GHz (full bandwidth of Band 2).

Note that at least one additional beam might be desired to facilitate the beamformer calibration while minimizing overheads.

Current FSP Function Modes are limited either in array diameter (phase-delay modes), number of beams, or number of antennas (true-delay) [RD01]. As a result, none of the FSP Function Modes can generate 10 beams for the full array. The decision on which FSP Function Mode is more suitable has to be done on a per Observation basis, depending on the required field of view, number of beams, sub-array configuration and ratio between bandwidth and number of available FSPs.

Although the ngVLA is a flexible sub-array oriented telescope, the following sub-array requirements is a non-exclusive list of explicit use cases that must be supported within Pulsar Timing Observing Mode as a guidance for the CSP designer (only in case general requirement CSP0181 cannot be met).

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays (Outer)	CSP0322	In Pulsar Timing Observing Modes, the CSP shall support 1 sub-array made of the 46 outer antennas.	SYS0203 SYS0601

This capability enables Pulsar Timing Observations using the outer (main-array) antennas, which run simultaneously and independent of other Observation(s) using the spiral and core. More than one sub-array might be useful in low-sensitivity Observations (it is assumed that a 40-antenna sub-array will offer a sensitivity similar to the Robert C. Byrd Green Bank Telescope [RD05]).

Note that both Sparse and Dense Pulsar Timing Observing Modes shall be available for this "outer" sub-array. Thus, maximization of the number of beams in the Dense Pulsar Timing Observing Mode leads to a true-delay beamforming mode constrained in the number of antennas.

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays (Non-Core)	CSP0323	In Pulsar Timing Observing Modes, the CSP shall support up to 3 sub-arrays when only the 120 non-core antennas are used.	SYS0203 SYS0601

The non-core antennas are the antennas located outside the ngVLA core, that is, the outer ones and those located at the 30-km radius spiral. This capability enables pulsar-timing Observations using the non-core antennas, simultaneous with other Observation(s) that use the core antennas only. More than three sub-arrays would be useful in low-sensitivity Observations.

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays (Full Array)	CSP0324	In Pulsar Timing Observing Modes, the CSP shall support up to 5 sub-arrays for the full array.	SYS0203 SYS0601

This capability enables pulsar-timing observations when the 18-m main array is fully devoted to it. Support for more than five sub-arrays might not be required due to the associated sensitivity penalty [AD05]. However, satisfying the general requirement to support ten sub-arrays (CSP0181) might be desirable to optimize telescope time in low-sensitivity Observations. Conversely, a "full-array" true-delay FSP Function Mode could be desirable for high-sensitivity Observations.

4.3.3 Polarization Calibration

Parameter	Req. #	Value	Traceability
Polarization Calibration	CSP0331	The CSP shall apply calibration coefficients such that each cross-polarization beamformed pattern is at least 13 dB lower than its respective co-polarization pattern beam (within the main beam FWHM).	

This requirement is a placeholder for future versions of this document. The polarization calibration level required by [RD05] is at least 5% (–13 dB). This requirement shall be revisited after definition of cross-polarization antenna requirements.

4.3.4 Supporting Visibilities

It is a goal that the CSP shall compute and output ancillary visibilities for one select beam aimed at a calibrator. Such visibilities can be used for real-time calibration of the beamformer. Real-time calibration capabilities have been identified as most likely required by both [AD05] and [RD05]. Calibration based in simultaneous supporting visibilities should contribute towards SYS1061 objective, minimization of calibration overheads.

Computation of the beamforming coefficients shall be carried out externally to the CSP.

This real-time calibration concept is at an early stage. Future studies should define, for instance, the likelihood of finding suitable calibrators within the HPBW of the antenna, the minimum set of correlation products needed for an effective calibration, how fast beamforming coefficients need to be updated, etc. Moreover, visibility channel bandwidths and integration times might need to be restricted with respect to Synthesis Imaging Mode in order to support simultaneity within the same Observing Mode.

4.3.5 Pulsar Timing Accuracy

Parameter	Req. #	Value	Traceability
Pulsar Timing Accuracy	CSP0611	The CSP shall not increase the best achievable timing RMS error by more than 2% with respect to an ideal processor.	

CSP SNR loss, finite time resolution of the overall dedispersed beam-channel response, as well as the folding process incur a loss of pulsar timing accuracy. When computing the error increase, the ideal processor is constrained to the same beam-channel and pulse profile sampling times as the CSP.

4.3.6 Coherent Dedispersion

Parameter	Req. #	Value	Traceability
Dispersion Measure Range	CSP0621	The CSP shall support dispersion measures ranging from 0 to 4,000 pc cm^{-3}.	

Pulsars at the Galactic Center are expected to exhibit DM ≥ 1,500 pc cm^{-3} and even double this value [RD06]. Since these are only estimates, some margin has been added to the maximum value.

In practice, the complexity of implementing a dedispersion filter for a given DM is a function of the radio frequency. In addition, Observations requiring high DM values are more likely to be carried out at high frequencies. Thus, it might be desirable to set an upper DM limit as a function of frequency.

CSP channel flatness requirements apply to the output of the dedispersed beam-channel.

4.3.7 Folding Performance

Parameter	Req. #	Value	Traceability
Pulse Period Range	CSP0631	The CSP shall support pulse periods ranging from 1 ms to 30 s.	

The required pulse period range has been defined in [AD05].

Parameter	Req. #	Value	Traceability
Number of Bins	CSP0632	The CSP shall support up to 2,048 time bins per period.	

The required number of beams has been defined in [AD05].

Parameter	Req. #	Value	Traceability
Folding Integration Time	CSP0633	The CSP shall support folding a variable number of periods such that the integration time can be selected at least within the range from 1 to 10 seconds.	

The upper limit allows dumps every 10 s for millisecond pulsars, as required by [AD05].

4.4 Offline Pulsar Search Observing Mode

All requirements in this Section apply only to the CSP operating in Offline Pulsar Search Observing Mode.

4.4.1 Definition

Through the Offline Pulsar Search Observing Mode, the CSP computes a number of beam-channels, which are then detected (Stokes parameters) and incoherently integrated as required to achieve the selected time-frequency resolution. The CBF generates the beam-channels, which are further processed by the PE. In principle, the minimum frequency resolution is given by the CBF, hence avoiding further channelization at the pulsar engine. This mode is mainly intended for targeted pulsar searches, although it could be used for pulsar timing as well (e.g., globular clusters). The greater number of beams is achieved by phase-delay beamforming, which demands less computational resources per beam. This comes at the cost of maximum baseline length and/or pointing offset, maximum channel bandwidth, and perhaps other desired features such as simultaneous supporting visibilities.

4.4.2 Sub-Arrays and Number of Beams

Parameter	Req. #	Value	Traceability
Number of Beams	CSP0421	The CSP shall generate up to 10 beams, each up to 8.8 GHz wide.	SYS0203

For the Galactic Center search, the goal is to cover a circular area (solid angle) of about 1" diameter at 20 GHz [AD05]. Assuming a circular 0.1" FWHM beam for 30-km baselines at this frequency, at least 91 beams are necessary to cover the targeted area through hexagonal packing. However, the Reference Observing Program (Section 12) explicitly specifies only ten beams for this use case, which is the main driver of CSP0421. The ROP also determines 8.2 GHz of bandwidth for this use case, but the required bandwidth per beam has been increased in anticipation of future use of this Observation Mode in Band 2.

In any case, given the high relative bandwidth under consideration, the number of beams required might vary across the bandwidth depending on the specific frequency band observed and the beamforming strategy. The output data rate of the Galactic Center search (13 GB/s) is smaller than what is required by the Synthesis Imaging Observing Mode.

Parameter	Req. #	Value	Traceability
Maximum Offset from Boresight	CSP0422	The CSP shall support beam steering offsets up to 0.5" from boresight.	

This requirement arises from KSG4 [AD02] to cover a solid angle up to 0.5" off the Galactic Center [AD05]. The boresight (or phase reference direction) is the only one for which delay is truly compensated, while narrowband phase-delay approximations are used to generate beams towards offset directions.

The following sub-array requirements must be supported within the Offline Pulsar Search Observing Mode as a guidance for the CSP designer (only in case general requirement CSP0181 cannot be met).

Parameter	Req. #	Value	Traceability
Number of Antennas	CSP0423	The CSP shall support one pre-determined sub-array composed of up to 168 antennas.	
Maximum Sub-Array Diameter	CSP0424	The CSP shall support a sub-array diameter up to 30 km long in Offline Pulsar Search Observing Mode.	

Both requirements originate from the need to support the sub-array composed of the core and the spiral. This sub-array provides a good trade-off between sensitivity (78.5%) and covered solid angle for a given number of beams [AD05].

4.4.3 Polarization Calibration

Parameter	Req. #	Value	Traceability
Polarization Calibration	CSP0431	The CSP shall apply calibration coefficients such that each cross-polarization beamformed pattern is at least 13 dB lower than its respective co-polarization pattern beam (within the main beam).	SYS1901

This requirement is a placeholder for future versions of this document. The polarization calibration level required by [RD05] is at least 5% (–13 dB). This requirement shall be revisited after definition of cross-polarization antenna requirements.

Note that the polarization purity requirement SYS1901 demands a post-calibration cross-polarization leakage at least 60 dB smaller than the co-polarization component. However, this requirement does not seem necessary in Pulsar Search Observing Mode and requires further consideration.

4.4.4 Supporting Visibilities

Refer to Section 4.3.4 for an explanation of the role of the CSP in real-time calibration of the beamformer.

Some of the phase-delay beamforming FSP Function Modes developed by NRC allow simultaneous supporting visibilities for a reduced number of beams (16 beams). Those FSP Function Modes might result an interesting option for Observations where real-time calibration is desired.

4.5 Very Long Baseline Interferometry Observing Mode

All requirements in this Section apply only to the CSP operating in VLBI Observing Mode.

4.5.1 Definition

In VBLI Observing Mode, the CSP generates a number of VLBI beam-channels. Each one is a select portion of the spectrum of one wideband beam. In addition, the CSP formats each beam-channel according to a standard VLBI format before outputting the beam-channels voltage stream. Supporting visibilities could be generated from an additional beam pointed at a calibrator.

4.5.2 Sub-Arrays and Number of Beams

Parameter	Req. #	Value	Traceability
Number of Beams	CSP0521	The CSP shall support at least 3 beams in VLBI Observing Mode, each up to 20 GHz wide.	SYS0501

System requirement SYS0501 requires three beams with a goal of five beams. The current VLBI FSP Function Mode of NRC's design allows up to four beams per frequency slice processor. Therefore, five beams can only be obtained by trading bandwidth per beam off. Note that a requirement of 20 GHz bandwidth per beam is much bigger than other VLBI sites' current capabilities. The maximum output data rate, 480 Gbps at 2-bit quantization, is smaller than CSP's output interface limit.

Parameter	Req. #	Value	Traceability
Sub-Arrays	CSP0522	The CSP shall support at least 3 sub-arrays simultaneously operating in VLBI mode, including the full array.	SYS0501

This is understood from VLBI Functional Requirements in the System Requirements document [AD01].

4.5.3 Supporting Visibilities

The considerations made in Section 4.3.4 for Pulsar Timing Observing Modes are equally valid here.

4.5.4 Polarization Calibration

Parameter	Req. #	Value	Traceability
Polarization Calibration	CSP0541	The CSP shall apply calibration coefficients such that each cross-polarization beamformed pattern is at least 13 dB lower than its respective co-polarization pattern beam (within the main beam).	

This requirement follows the same rationale as in Pulsar Timing Observing Mode.

4.5.5 VLBI Channelizer

Parameter	Req. #	Value	Traceability
Number of VLBI Beam-Channels	CSP0551	The CSP shall support at least 4 beam-channels within the same sub-band.	

In some use cases, the band of interest can be narrowband and closely spaced so that they all fit within a single sub-band. This requirement specifies how many of these frequency bands can be individually recorded before having to record the entire sub-band. This requirement assumes a sub-band bandwidth on the order of a few hundreds of MHz.

Parameter	Req. #	Value	Traceability
Beam-Channel Tuning Resolution	CSP0552	The CSP shall independently tune each VLBI beam-channel in steps less than or equal to 2 kHz.	

This resolution guarantees at least 99.9% (SNR) efficiency due to passband mismatch for 1-MHz channel bandwidth.

Parameter	Req. #	Value	Traceability
Beam-Channel Sampling Rate	CSP0553	The CSP shall support all VLBI-standard sampling rates from 2 MS/s to 256 MS/s, and 448 MS/s.	

Standard VLBI sampling rates, expressed in MHz, take values of a power of two. It is not so important the channel bandwidth as the total aggregate bandwidth, so the main driver should be to cover as much aggregate spectrum as possible. The maximum aggregate bandwidth equals the beam bandwidth in CSP0521. However, in current NRC's FSA, the maximum channel bandwidth equals the Frequency Slice bandwidth, which is not a VLBI standard. Thus, all VLBI-standard sampling rates up to twice the Frequency Slice bandwidth, in addition to twice the Frequency Slice bandwidth itself, shall be supported.

Parameter	Req. #	Value	Traceability
Beam-Channel Format	CSP0554	The CSP shall support at least VLBI-standard VDIF format.	

Multiple formats might be added in future.

4.7 Spurious Signals/Radio Frequency Interference Generation

There is no current specification on the spurious signal level of the CSP electronics. Shielding will be provided at the room level by the central electronics building. However, designs that emit less RFI, and therefore require lower levels of shielding, are preferable.

4.8 Environmental Conditions

4.8.1 Normal Operating Conditions

The environmental conditions will comply with the specifications set forth by the infrastructure requirements. It is assumed that the central electronics building HVAC system will maintain such conditions when in normal operation. The adoption of a water cooling system for the CSP is under study. In the event of an HVAC malfunction, the CSP should self-protect and shut down to prevent equipment damage or fire.

4.8.2 Lightning Protection Requirements

Since the CSP electronics will be located within a shielded and grounded room, with only filtered copper connections penetrating that boundary, the shielded room is expected to meet all requirements for lightning protection, for both electronics systems and personnel.

4.8.3 Seismic Protection Requirements

Parameter	Req. #	Value	Traceability
Seismic Protection	CSP0831	The CSP packaging and anchoring to the building shall be designed to withstand a low probability earthquake with up to 0.2g peak acceleration in either the vertical or the horizontal axis.	

Low probability has been defined as a 2% probability of an event exceeding this magnitude over a 50-year period, consistent with data available from the USGS Seismic Hazard Model [RD09].

4.8.4 Site Elevation

Parameter	Req. #	Value	Traceability
Altitude Range	CSP0841	The CSP shall be designed for operation at an altitude of 2200 m.	

This requirement is most applicable to the thermal design of the system.

4.9 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Availability	CSP0901	Under Normal Operating Conditions, the CSP shall be available for science operations 95% of the time, excluding scheduled and unscheduled maintenance downtime.	SYS2602

The maintenance and reliability requirements are in support of high-level requirements that limit the total operating cost of the array. Monitor points or sensors should be included in the MTBF/MTTR analysis, but sensors and other components that can be reasonably deemed to be ancillary to operation may be removed from the determination of compliance with the MTBF requirement. “Failure” will be defined as a condition which places the system outside of its performance specifications or into an unsafe state, requiring repair.

4.10 Monitor and Control Requirements

Parameter	Req. #	Value	Traceability
Self-Monitoring	CSP1001	The CSP shall measure, report and monitor a set of parameters that allow for determination of its status and may help predict or respond to failures.	SYS2601

The expectation with self-monitoring is that the CSP control system expose lower level sensors to the monitor and control system when queried. The cadence of access is flexible, and is not expected at high rates (typical access might be on second to minute scales). Any high-cadence monitoring should generally be internal to the CSP control system with a summary output on the interface.

Other features of the M&C interface are to be specified in the Monitor and Control ICD.

4.11 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	CSP1101	The CSP shall be designed to be operated and supported for a period of 20 years.	SYS2701
Lifecycle Optimization	CSP1102	The CSP design shall minimize its life-cycle cost for 20 years of operation.	SYS2702

Lifecycle costs include manufacturing, transportation, construction/assembly, operation, and decommissioning.

5 Interface Requirements

This section provides information about the interfaces of the CSP. Interface Control Documents (ICDs) are required between the correlator and all connecting systems. In many cases, specifications for the interfaces are not yet available, but the broad scope of the ICD can be defined.

Some interfaces are highly dependent on architecture, in which case the NRC's FSA has been assumed.

These interfaces shall be developed and documented by the CSP Designer, and approved by the ngVLA Project Office, as part of the correlator conceptual design effort, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface to the Data Transmission System

Parameter	Req. #	Value	Traceability
Total Number of Inputs	CSP2101	6 per antenna	
Input Data Rate	CSP2102	Up to 80 Gbps	
Maximum Input Bandwidth and Number of Bits per Sample	CSP2103	10 GHz at 8 (4+4) bits/sample 5 GHz at 16 (8+8) bits/sample	

The CSP will admit six inputs per antenna from the DTS, each at up to 80 Gbps. Polarization pairs from each antenna may be multiplexed through a single input or use independent inputs. It is expected that the CSP is arranged in three equal parts, each part processing two inputs. Then, the input bandwidth per polarization is either 10 GHz with 4-bit quantization or 5 GHz using 8-bit quantization.

Each input consists of a sequence of complex numbers representing the equivalent baseband signal of a 5-GHz bandwidth portion of the radio frequency spectrum, except for the lowest 5-GHz portions, which are directly sampled in one Nyquist zone. Each sample consists of 16 bits, 8 bits for each of the real and imaginary parts. Note that even though the ADC may use 4 bits per sample in some cases, the adapter between the ADC and the CSP might increase the number of bits at the CSP input in order to satisfy efficiency requirements in [AD01]. The total data rate per input is 80 Gbps, and the total input data rate is 480 Gbps per antenna.

It is assumed that the DBE/DTS system will convert from the ADC format to the CSP format, and most likely perform the sub-band selection.

5.2 Interface to the Archive

Parameter	Req. #	Value	Traceability
Total Number of Outputs	CSP2201	150 (one per FSP)	
Data Rate per Output	CSP2202	40 Gbps	

40 Gbps per FSP can allocate the maximum per-FSP data rates required by the ROP (Section 12). An output switch fabric is required as the overall maximum output data rate from the entire CSP is only about 80 GB/s.

5.3 Interface to the Fiber Optic Transmission System

The incoming and outgoing signals are considered part of the interface to the data transmission system and archive respectively. The communications interface to the CSP shall be considered part of the monitor and control system interface.

5.4 Interface to the Central Electronics Building

5.4.1 Electrical Infrastructure

- 3-phase, 208V, 60 Hz power will be provided to the CSP room. Service size is under study.
- Building will provide UPS capability.
- Building will be responsible for protecting CSP from brownout conditions where one or two phases of the distribution system are lost. Any shunt trip device shall be remotely resettable, and shall have a programmable automatic reset sequence.
- Building will provide lightning protection.

The ICD should describe both the mechanical and electrical specifications of the electrical interfaces. Circuit sizing and load estimates should also be described.

5.4.2 HVAC

- Building will provide the HVAC system. Size, plenum temperature, temperature stability, and some other requirements are under study.
- Direct Contact Liquid Cooling is the preferred cooling option for efficiency, lifetime and maturity of COTS supporting technology.

5.4.3 RFI Mitigation

- Building will provide a shielded room, with attenuation dependent on the correlator electronics emissions.

5.4.4 Fire Safety

- Building will provide a fire suppression system.
- Any interlocks or similar devices should be described here.

5.5 Interface to the Time & Frequency Reference Distribution System

Parameter	Req. #	Value	Traceability
Clock reference	CSP2501	100 MHz	
Time reference	CSP2502	1 PPS	

A 100 MHz reference signal will be required to generate clock signals internally. A 1 PPS signal in sync with the 100 MHz reference will be required to solve clock ambiguity within 1-s intervals. Timestamps will be distributed along with data input.

5.6 Interface to the Monitor and Control System

The Local Control System (LCS) will govern the local control of the CSP, processing higher-level commands into lower level commands suitable for configuring the correlator electronics. In all cases, no action or inaction of the monitor and control system can cause incorrect or dangerous conditions in the covered hardware. In addition, the LCS shall provide monitor data defining the current condition of key monitor points that describe the overall health and status of the correlator.

The physical interface between the LCS and M&C system shall be multimode fiber using TCP/IP over Ethernet.

6 Safety

6.1 General

Parameter	Req. #	Value	Traceability
Code Compliance	CSP6001	The design shall comply with all relevant federal and State of New Mexico building codes.	
Safety of Personnel	CSP6002	The design shall allow the Observatory to comply with all relevant federal and state occupational health and safety regulations for personnel servicing the correlator.	

6.2 Safety Design Requirements

6.2.1 Fire Safety

The fire safety requirements of the CSP and its component elements shall comply with their relevant international or US product standard.

6.2.2 Mechanical Safety

The mechanical safety requirements of the CSP shall comply with their relevant international or US product standard.

6.2.3 Electrical Safety

Electrical equipment installed on the CSP shall comply with their relevant international or US product standard.

Electrical installations and equipment shall be specifically built and/or derated in order to safely perform their intended functions under the applicable environmental conditions. Insulation shall be coordinated in conformity with IEC 60664 [AD08] while taking into account the altitude of up to 2500 m above sea level.

6.2.4 Handling, Transport, and Storage Safety

The design of the CSP shall incorporate all means necessary to preclude or limit hazards to personnel and equipment during assembly, disassembly, test, and operation.

6.2.5 Toxic Substances

No use of toxic substance (asbestos, formaldehyde, lead, etc.) and of their derivatives shall be permitted in the CSP. Any insulation materials and paint specifications shall be reviewed by ngVLA.

6.2.6 Confined Space

Considerations of confined space in the sense of [AD09] shall be taken into account in the design where applicable.

7 Requirements for Design

7.1 *Analyses and Design Requirements*

7.1.1 Reliability, Availability, Maintainability, Analysis

A Reliability, Availability, Maintainability analysis shall be performed to locate weak design points and determine whether the design meets the Maintenance and Reliability requirements. ngVLA suggests to apply the Parts Count Method for predicting system reliability as described in [AD10], but the designer may propose to use other methods. For non-electronic parts, the values of [AD11] may be used, or data from manufacturers or other databases may be used. Another, more time consuming (and considered more accurate) method, the Parts Stress Analysis Prediction, is also described in [AD10] and may be used if results of the Parts Count Method do not comply with the Maintenance and Reliability requirements.

The ngVLA CSP will operate at an elevation of 2200m above sea level, where temperature and pressure might decrease the Mean Time Between Failures (MTBF) relative to that at low elevations. These conditions shall be taken into specific account in the reliability prediction by using the environmental factor given in [AD10]. The analysis shall result in estimates of the MTBF, the Mean Time to Repair (MTTR), assuming that any scheduled preventive maintenance is performed.

7.2 *Electromagnetic Compatibility Requirements*

The ngVLA CSP element shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility).

7.3 *Materials, Parts and Processes*

7.3.1 Fasteners

All fasteners shall be metric except those that are on off-the-shelf units. The use of standard metric cross-sections for construction materials is preferred but not required.

7.3.2 Paints

Any painted coatings shall be chosen to last at least 20 years without repainting.

7.3.3 Surface Treatment

Any unpainted surfaces shall be treated against corrosion.

7.3.4 Rodent Protection

The correlator room shall be assumed a rodent-free zone, and no specific protection measures will be required.

7.3.5 Name Plates and Product Marking

As a general rule, the main parts and all exchangeable units shall be equipped with nameplates which are visible after installation of the part/unit and which contain the following information:

- Part/unit name
- Drawing number including revision
- Serial number
- Manufacturing month and year
- Name of manufacturer

Alternatively, a system of marking based on barcodes or similar system may be used upon approval by ngVLA.

For Line Replaceable Units (LRU, See Section 11.2), it is highly desirable that the serial number of the LRU be ascertainable over the monitor and control interface (See Section 5.6)

7.3.6 Labels

All cables and switches, junction boxes, sensors, and similar equipment shall be labeled.

8 Documentation Requirements

8.1 Technical Documentation

All documentation related to the CSP shall meet the following requirements:

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use metric units.
- Layouts of electronic circuits and printed circuit boards shall also be provided in electronically readable form. The ngVLA preferred formats are Altium Designer files for electronic circuit diagrams and printed circuit board layouts.
- The electronic document formats are Microsoft Word and Adobe PDF.
- The preferred CAD system used is AutoDesk Inventor and/or AutoCAD.

Any deviation from the above shall be agreed to by the ngVLA Project Office.

8.2 Software and Software Documentation

The CSP software (including so-called firmware) and any other specially developed software, are deliverables. The software shall be delivered in source and object form, together with all procedures and tests necessary for compilation, installation, testing, upgrades and maintenance.

- Software must be tagged with suitable version numbers that allow identification (also on-line remotely) of a Release.
- User manuals of software developed under this specification and of any other commercial software used (controllers embedded software, special tools, etc.) shall be provided.
- Software maintenance and installation upgrade documentation shall be provided.
- Full Test and Acceptance procedures shall be documented.

Software upgrades shall allow deployment and commissioning on a sub-array basis.

9 Verification and Quality Assurance

The design may be verified to meet the requirements by design (D), analysis (A) inspection (I), a factory acceptance test (FAT) or a site acceptance test (SAT). The definitions of each are given below.

Verification by Design: The performance shall be demonstrated by a proper design, which may be checked by the ngVLA project office during the design phase by review of the design documentation.

Verification by Analysis: The fulfillment of the specified performance shall be demonstrated by appropriate analysis (hand calculations, finite element analysis, thermal modeling, etc.), which will be checked by the ngVLA project office during the design phase.

Verification by Inspection: The compliance of the developed item is determined by a simple inspection or measurement.

Verification by Factory Acceptance Test: The compliance of the developed item / assembly / unit with the specified performance shall be demonstrated by tests. A FAT is performed w/o integration with interfacing systems.

Verification by Site Acceptance Test: The compliance of the developed item / assembly / unit with the specified performance shall be demonstrated by tests. SAT is performed on-site with the equipment as installed.

Multiple verification methods are allowed. The following table summarizes the expected verification method for each requirement.

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
	General					
CSP0111	Maximum Number of Antennas	*				
CSP0121	Maximum Bandwidth per Observation	*				
CSP0122	Spectral Window Bandwidth Selection	*				
CSP0123	Spectral Window Tuning Step	*				
CSP0124	Maximum Aggregate Bandwidth	*				
CSP0125	Discontinuous Spectral Windows	*				
CSP0131	Minimum Efficiency		*		*	
CSP0141	Maximum Data Transport Delay	*				
CSP0142	Maximum Array Diameter	*				
CSP0143	Phase-Center Location	*				
CSP0144	Packet-Loss Tolerance	*			*	
CSP0151	Spectral Leakage		*			
CSP0152	Channel Flatness		*			
CSP0153	Channel Gain Correction	*				
CSP0181	Number of Sub-Arrays	*				
CSP0182	Sub-Array Independence	*			*	*
	Synthesis Imaging					
CSP0221	Channel Bandwidth	*				
CSP0222	Number of Channels	*				
CSP0223	Zoom Capabilities	*				
CSP0224	Zoom Window Tuning Step	*				
CSP0225	Integration Time	*				

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
CSP0231	Number of Simultaneous Phase Reference Positions	*			*	*
CSP0232	Maximum Slew Rate	*			*	*
	Pulsar Timing					
CSP0321	Number of Beams	*				
CSP0322	Number of Sub-Arrays (Outer)	*				
CSP0323	Number of Sub-Arrays (Non-Core)	*				
CSP0324	Number of Sub-Arrays (Full Array)	*				
CSP0331	Polarization Calibration	*			*	*
CSP0611	Pulsar Timing Accuracy	*			*	*
CSP0621	Dispersion Measure Range	*				
CSP0631	Pulse Period Range	*				
CSP0632	Number of Bins	*				
CSP0633	Folding Integration Time	*				
	Offline Pulsar Search					
CSP0421	Number of Beams	*				
CSP0422	Maximum Offset from Boresight	*	*			*
CSP0423	Number of Antennas	*				
CSP0424	Maximum Sub-Array Diameter	*				
CSP0431	Polarization Calibration	*			*	*
	VLBI					
CSP0521	Number of Beams	*				
CSP0522	Sub-Arrays	*				
CSP0541	Polarization Calibration	*			*	*
CSP0551	Number of VLBI Beam-Channels	*			*	*
CSP0552	Beam-Channel Tuning Resolution	*				
CSP0553	Beam-Channel Sampling Rate	*				
CSP0554	Beam-Channel Format					
	Environmental					
CSP0831	Seismic Protection	*				
CSP0841	Altitude Range	*				*
	Maintenance					
CSP0901	Mean Time Between Failures	*				
	M&C					
CSP1001	Self-Monitoring	*			*	*
	Lifecycle					
CSP1101	Design Life	*				
CSP1102	Lifecycle Optimization		*			
	Safety					
CSP6001	Code Compliance	*		*		
CSP6002	Safety of Personnel	*		*		

Table 1 - Expected requirements verification method.

10 Key Performance Parameters

This section provides key performance parameters that the designer should estimate and that NRAO should monitor NRAO throughout the project design phase. These parameters strongly influence the eventual effectiveness of the facility, and are useful high-level metrics for trade-off decisions.

These parameters are of higher importance to NRAO. Improved performance above the requirement is desirable on these parameters. The impact on system-level performance is discussed in Section 4.

The technical requirements are generally specified as *minimum* values. This gives the designer some latitude in optimization for a balanced design. Understanding the CSP's anticipated performance (not just its specified minimum) on these parameters is valuable for system-level analysis and performance estimation.

These parameters may also be useful for determining the relative priority of the requirements documented in Section 4 and can assist in the required analysis should tensions be identified between requirements or reductions in capability be required to fit within cost constraints.

The Key Performance Parameters identified for monitoring are described in Table 2. Note that the order in the table reflects the order in the document, and is not indicative of relative importance or priority.

Key Performance Parameter	Req. #
Maximum bandwidth per Observation	CSP0121
Maximum aggregate bandwidth	CSP0124
Sub-array independence	CSP0182
Zoom capabilities	CSP0223
Number of simultaneous phase reference positions	CSP0231
Number of beams	CSP0321 CSP0421 CSP0521
Mean Time Between Failures	CSP0901
Interface to the archive	CSP2201 CSP2202

Table 2 - Key performance parameters for monitoring during design.

11 Appendix

11.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ADC	Analog to Digital Converter
CBF	Correlator and Beamformer
CCU	Correlator Control Unit
CDR	Critical Design Review
CoDR	Conceptual Design Review
CPC	Cross-Polarization Correction
CSP	Central Signal Processor
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
DBE	Digital Back End
DFT	Digital Fourier Transform
DTS	Data Transmission System
EIRP	Equivalent Isotropic Radiated Power
EM	Electro-Magnetic
EMC	Electro-Magnetic Compatibility
EMP	Electro-Magnetic Pulse
FAT	Factory Acceptance Test
FDR	Final Design Review
FEA	Finite Element Analysis
FOV	Field of View
FSA	Frequency Slice Architecture
FSP	Frequency Slice Processor
FWHM	Full Width Half Max
HPBW	Half Power Beam Width
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
KSG	Key Science Goal
LBA	Long Baseline Array
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LO	Local Oscillator
LRU	Line Replaceable Unit
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
ngVLA	Next Generation VLA
NRC	National Research Council Canada
OTF	On-The-Fly
PDB	Phase-Delay Beamforming
PE	Pulsar Engine

Acronym	Description
PPS	Pulse Per Second
PTB	Pulsar Timing Beamforming
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
ROP	Reference Observing Program
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SAT	Site Acceptance Test
SBA	Short Baseline Array
SCFO	Sample Clock Frequency Offset
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
VCC	Very Coarse Channelizer
VDIF	VLBI Data Interchange Format
VLA	Jansky Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry

11.2 Maintenance Definitions

11.2.1 Maintenance Approach

Required maintenance tasks shall be minimized.

Maintenance shall be mainly performed at assembly and subassembly level by exchange of Line Replaceable Units (LRUs). LRUs are defined as units which can be easily exchanged (without extensive calibration, of sufficient low mass and dimension for easiness of handling, etc.) by maintenance staff of technician level.

LRU exchange shall be possible by 2 trained people within 4 working hours. It is desirable that LRU replacement be possible using only standard tools identified in a CSP maintenance manual.

A systematic procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

LRUs shall be defined by the CSP designer, depending on the design. The LRUs will be maintained by the ngVLA project (with or without industrial support).

11.2.2 Periodic Preventive Maintenance

Preventive maintenance may be performed at planned intervals in order to maintain the correlator operational and within its specified performance. Any required preventive maintenance should be documented in the Maintenance Manual.

11.3 Reference Observing Program

Name	Science Use Fraction	Science Use Cases Field of View (arcsec)	PSF FWHM (mas)	Dynamic Range	Center Frequency	Bandwidth	Science Channel Width	Maximum Dump Time
KSG1 Driving Cont Band 6 eg Taurus disk	0.03	5.0	10	1.00E+03	100.0 GHz	FULL	120.0 MHz	1
KSG1 Driving Cont Band 4 eg Taurus disk	0.03	5.0	10	1.00E+03	27.3 GHz	FULL	120.0 MHz	2
KSG2 Driving Line Band 5 eg Sgr B2(N)	0.03	60.0	100	1.00E+03	40.5 GHz	4.0 GHz	13.5 kHz	1
KSG2 Driving Line Band 4 eg Sgr B2(N)	0.03	60.0	100	1.00E+03	27.3 GHz	4.0 GHz	9.1 kHz	2
KSG2 Driving Line Band 3 eg Sgr B2(N)	0.03	60.0	100	1.00E+03	16.4 GHz	4.0 GHz	5.5 kHz	2
KSG3 Driving Line Band 5 eg COSMOS	0.03	FULL	1000	1.00E+02	40.5 GHz	FULL	675.0 kHz	1
KSG3 Driving Line Band 4 eg COSMOS	0.03	FULL	1000	1.00E+02	27.3 GHz	FULL	455.0 kHz	2
KSG3 Driving Line Band 3 eg COSMOS	0.03	FULL	1000	1.00E+02	16.4 GHz	FULL	273.3 kHz	2
KSG3 Driving Line Band 6 eg Spiderweb galaxy	0.03	5.0	100	1.00E+03	72.0 GHz	240.0 MHz	7.2 MHz	1
KSG3 Driving Line Band 5 eg Spiderweb galaxy	0.03	5.0	100	1.00E+03	36.0 GHz	120.0 MHz	3.6 MHz	1
KSG3 Driving Line Band 4 eg Spiderweb galaxy	0.03	5.0	100	1.00E+03	27.7 GHz	92.3 MHz	2.8 MHz	2
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	FULL	100	1.00E+03	112.5 GHz	6.0 GHz	375.0 kHz	1
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	FULL	100	1.00E+03	89.0 GHz	6.0 GHz	296.7 kHz	1
KSG3 Driving Line Band 1 eg M81 Group	0.03	FULL	1000	1.00E+03	1.4 GHz	7.0 MHz	4.7 kHz	2
KSG3 Driving Line Band 1 eg M81 Group	0.03	FULL	60000	1.00E+03	1.4 GHz	7.0 MHz	4.7 kHz	2
KSG5 Driving Cont Band 1 OTF Find LIGO event	0.03	FULL	1000	5.00E+03	2.4 GHz	FULL	2.0 MHz	0.5
KSG5 Driving Cont Band 4 OTF Find LISA event	0.03	FULL	1000	5.00E+03	27.3 GHz	FULL	5.0 MHz	0.5
KSG5+4 Driving Cont Band 2 OTF Find BHs+Possib	0.03	FULL	1000	5.00E+03	7.9 GHz	FULL	5.0 MHz	0.5
KSG5 Driving Cont eg Band 2 Followup from OTF	0.03	1.0	10	5.00E+03	7.9 GHz	FULL	120.0 MHz	2
KSG5 Driving Cont Band 2 Find SMBH binaries in V	0.03	2.5	10	5.00E+03	7.9 GHz	FULL	120.0 MHz	2
KSG3 Supporting Cont Band 6 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	93.0 GHz	FULL	5.0 MHz	1
KSG3 Supporting Cont Band 5 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	40.5 GHz	FULL	5.0 MHz	1
KSG3 Supporting Cont Band 4 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	27.3 GHz	FULL	5.0 MHz	2
KSG3 Supporting Cont Band 3 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	16.4 GHz	FULL	5.0 MHz	2
KSG3 Supporting Cont Band 2 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	7.9 GHz	FULL	5.0 MHz	2
KSG5 Driving Cont Band 1 PTA timing 5 subs 1 PSF	0.03	0.1	10	1.00E+02	2.4 GHz	FULL	500.0 kHz	2
KSG4 Driving Cont Band 3 GalCen search 1 sub 10	0.03	0.1	10	1.00E+02	16.4 GHz	FULL	1.0 MHz	0.0001
KSG4 Driving Cont Band 3 GalCen timing 1 sub 10	0.03	0.1	10	1.00E+02	16.4 GHz	FULL	1.0 MHz	2
KSG5 Driving Cont Band 2 PTA timing 5 subs 1 PSF	0.03	0.1	10	1.00E+02	7.9 GHz	FULL	500.0 kHz	2

Name	Use Fraction	FOV Imaged	Image Linear	Validation Band	Actual Bandwidth	Maximum Channel	N Chan	Visibility Dump Time (s)	Core	Mid	Stations	N Antenna	Nbaseline	N Facets
KSG1 Driving Cont Band 6 eg Taurus disk	0.03	5.0	1500	Band 6	20.0 GHz	2.5 MHz	7902	0.39	Yes	Yes	Yes	215	23,005	1
KSG1 Driving Cont Band 4 eg Taurus disk	0.03	5.0	1500	Band 4	13.5 GHz	576.6 kHz	23415	0.39	Yes	Yes	Yes	215	23,005	1
KSG2 Driving Line Band 5 eg Sgr B2(N)	0.03	60.0	1800	Band 5	4.0 GHz	13.5 kHz	296297	1.00	Yes	Yes	No	155	11,935	1
KSG2 Driving Line Band 4 eg Sgr B2(N)	0.03	60.0	1800	Band 4	4.0 GHz	9.1 kHz	439561	2.00	Yes	Yes	No	155	11,935	1
KSG2 Driving Line Band 3 eg Sgr B2(N)	0.03	60.0	1800	Band 3	4.0 GHz	5.5 kHz	727273	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 5 eg COSMOS	0.03	114.9	345	Band 5*	20.0 GHz	675.0 kHz	29630	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 4 eg COSMOS	0.03	170.5	512	Band 4*	13.5 GHz	455.0 kHz	29671	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 3 eg COSMOS	0.03	284.9	855	Band 3	8.2 GHz	273.3 kHz	30004	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 6 eg Spiderweb galaxy	0.03	5.0	150	Band 6	240.0 MHz	7.2 MHz	34	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 5 eg Spiderweb galaxy	0.03	5.0	150	Band 5	120.0 MHz	3.6 MHz	34	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 4 eg Spiderweb galaxy	0.03	5.0	150	Band 4	92.3 MHz	2.8 MHz	34	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	32.0	960	Band 6	6.0 GHz	375.0 kHz	16000	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	40.7	1222	Band 6	6.0 GHz	296.7 kHz	20223	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 1 eg M81 Group	0.03	2473.8	7421	Band 1	7.0 MHz	4.7 kHz	1480	2.00	Yes	Yes	No	155	11,935	30
KSG3 Driving Line Band 1 eg M81 Group	0.03	2473.8	124	Band 1	7.0 MHz	4.7 kHz	1480	2.00	Yes	No	No	77	2,926	1
KSG5 Driving Cont Band 1 OTF Find LIGO event	0.03	2920.1	8760	Band 1	2.3 GHz	216.0 kHz	10649	0.50	Yes	Yes	No	155	11,935	42
KSG5 Driving Cont Band 4 OTF Find LISA event	0.03	170.5	512	Band 4*	13.5 GHz	3.7 MHz	3650	0.50	Yes	Yes	No	155	11,935	1
KSG5+4 Driving Cont Band 2 OTF Find BHs+Possib	0.03	1001.2	3003	Band 2	8.8 GHz	630.0 kHz	13969	0.50	Yes	Yes	No	155	11,935	5
KSG5 Driving Cont eg Band 2 Followup from OTF	0.03	1.0	300	Band 2	8.8 GHz	98.4 kHz	89397	0.39	Yes	Yes	Yes	215	23,005	1
KSG5 Driving Cont Band 2 Find SMBH binaries in \	0.03	2.5	750	Band 2	8.8 GHz	98.4 kHz	89397	0.39	Yes	Yes	Yes	215	23,005	1
KSG3 Supporting Cont Band 6 eg Virgo Cluster	0.03	42.2	127	Band 6	20.0 GHz	5.0 MHz	4000	1.00	Yes	No	No	77	2,926	1
KSG3 Supporting Cont Band 5 eg Virgo Cluster	0.03	114.9	345	Band 5*	20.0 GHz	5.0 MHz	4000	1.00	Yes	Yes	No	155	11,935	1
KSG3 Supporting Cont Band 4 eg Virgo Cluster	0.03	170.5	512	Band 4*	13.5 GHz	3.7 MHz	3650	2.00	Yes	Yes	No	155	11,935	1
KSG3 Supporting Cont Band 3 eg Virgo Cluster	0.03	284.9	855	Band 3	8.2 GHz	2.2 MHz	3704	2.00	Yes	Yes	No	155	11,935	1
KSG3 Supporting Cont Band 2 eg Virgo Cluster	0.03	1001.2	3003	Band 2	8.8 GHz	630.0 kHz	13969	2.00	Yes	Yes	No	155	11,935	5
KSG5 Driving Cont Band 1 PTA timing 5 subs 1 PSF	0.03	0.1	30	Band 1*	2.3 GHz	35.2 kHz	65423	0.39	Yes	Yes	Yes	215	23,005	1
KSG4 Driving Cont Band 3 GalCen search 1 sub 10	0.03	0.1	30	Band 3	8.2 GHz	345.9 kHz	23704	0.00	Yes	Yes	Yes	215	23,005	1
KSG4 Driving Cont Band 3 GalCen timing 1 sub 10	0.03	0.1	30	Band 3	8.2 GHz	345.9 kHz	23704	0.39	Yes	Yes	Yes	215	23,005	1
KSG5 Driving Cont Band 2 PTA timing 5 subs 1 PSF	0.03	0.1	30	Band 2	8.8 GHz	98.4 kHz	89397	0.39	Yes	Yes	Yes	215	23,005	1

Correlation Use Cases

	Criterion 1						Criterion 2					
Name	**Number of Channels**	**Visibility Dump Time (s)**	**Number of Baselines**	**CSP Data Rate (GB/s)**	**FSP Number of Channels**	**FSP Data Rate (GB/s)**	**Number of Channels**	**Visibility Dump Time (s)**	**Number of Baselines**	**CSP Data Rate (GB/s)**	**FSP Number of Channels**	**FSP Data Rate (GB/s)**
KSG1 Driving Cont Band 6 eg Taurus disk	7,902	0.386	23,005	7.54	80	0.08	8,507	1.000	23,005	3.13	80	0.03
KSG1 Driving Cont Band 4 eg Taurus disk	23,415	0.386	23,005	22.35	347	0.33	5,742	2.000	23,005	1.06	347	0.06
KSG2 Driving Line Band 5 eg Sgr B2(N)	296,297	1.000	11,935	56.58	14,815	2.83	296,297	1.000	14,196	67.30	14,815	3.37
KSG2 Driving Line Band 4 eg Sgr B2(N)	439,561	2.000	11,935	41.97	16,384	1.56	439,561	2.000	14,196	49.92	16,384	1.86
KSG2 Driving Line Band 3 eg Sgr B2(N)	727,273	2.000	11,935	69.44	16,384	1.56	727,273	2.000	14,196	82.59	16,384	1.86
KSG3 Driving Line Band 5 eg COSMOS	29,630	1.000	11,935	5.66	297	0.06	29,630	1.000	14,196	6.73	297	0.07
KSG3 Driving Line Band 4 eg COSMOS	29,671	2.000	11,935	2.83	440	0.04	29,671	2.000	14,196	3.37	440	0.05
KSG3 Driving Line Band 3 eg COSMOS	30,004	2.000	11,935	2.86	732	0.07	30,004	2.000	14,196	3.41	732	0.08
KSG3 Driving Line Band 6 eg Spiderweb galaxy	34	1.000	11,935	0.01	28	0.01	34	1.000	14,196	0.01	28	0.01
KSG3 Driving Line Band 5 eg Spiderweb galaxy	34	1.000	11,935	0.01	56	0.01	34	1.000	14,196	0.01	56	0.01
KSG3 Driving Line Band 4 eg Spiderweb galaxy	34	2.000	11,935	0.00	72	0.01	33	2.000	14,196	0.00	72	0.01
KSG3 Driving Line Band 6 eg Virgo Cluster	16,000	1.000	11,935	3.06	534	0.10	16,000	1.000	14,196	3.63	534	0.12
KSG3 Driving Line Band 6 eg Virgo Cluster	20,223	1.000	11,935	3.86	675	0.13	20,223	1.000	14,196	4.59	675	0.15
KSG3 Driving Line Band 1 eg Virgo Cluster	1,480	2.000	11,935	0.14	16,384	1.56	1,490	1.162	14,196	0.29	16,384	3.20
KSG3 Driving Line Band 1 eg M81 Group	1,480	2.000	2,926	0.03	16,384	0.38	1,490	2.000	4,465	0.05	16,384	0.59
KSG5 Driving Cont Band 1 OTF Find LIGO event	10,649	2.000	11,935	1.02	926	0.09	15,581	0.984	14,196	3.60	926	0.21
KSG5 Driving Cont Band 4 OTF Find LISA event	3,650	2.000	11,935	0.35	55	0.01	5,340	2.000	14,196	0.61	55	0.01
KSG5 Driving Cont Band 2 OTF Find BHs for Tom	13,969	2.000	11,935	1.33	318	0.03	20,439	2.000	14,196	2.32	318	0.04
KSG5 Driving Cont eg Band 2 Followup from OTF	89,397	0.386	23,005	85.32	2,033	1.94	749	2.000	23,005	0.14	2,033	0.37
KSG5 Driving Cont Band 2 Find SMBH binaries in VLASS	89,397	0.386	23,005	85.32	2,033	1.94	1,872	2.000	23,005	0.34	2,033	0.37
KSG3 Supporting Cont Band 6 eg Virgo Cluster	4,000	1.000	2,926	0.19	40	0.00	4,000	1.000	4,465	0.29	40	0.00
KSG3 Supporting Cont Band 5 eg Virgo Cluster	4,000	1.000	11,935	0.76	40	0.01	5,332	1.000	14,196	1.21	40	0.01
KSG3 Supporting Cont Band 4 eg Virgo Cluster	3,650	2.000	11,935	0.35	55	0.01	5,340	2.000	14,196	0.61	55	0.01
KSG3 Supporting Cont Band 3 eg Virgo Cluster	3,704	2.000	11,935	0.35	91	0.01	5,420	2.000	14,196	0.62	91	0.01
KSG3 Supporting Cont Band 2 eg Virgo Cluster	13,969	2.000	11,935	1.33	318	0.03	20,439	2.000	14,196	2.32	318	0.04

Bytes per visibility	4	(16b+16b)
Polarization products	4	

Beamforming Use Cases

Name	**Number of Channels**	**Visibility Dump Time (s)**	**Beam-Phase bin Product**	**CSP Data Rate (GB/s)**	**FSP Number of Channels**	**FSP Data Rate (GB/s)**
KSG5 Driving Cont Band 1 PTA timing 5 subs 1 PSF each	4,600	2.00	10,240	0.38	400.00	0.03
KSG4 Driving Cont Band 3 GC search 1 sub 10 PSFs	8,200	0.00010	10	13.12	200.00	0.32
KSG4 Driving Cont Band 3 GC timing 1 sub 10 PSFs	8,200	2.00	20,480	1.34	200.00	0.03
KSG5 Driving Cont Band 2 PTA timing 5 subs 1 PSF each	17,600	2.00	10,240	1.44	400.00	0.03

Bytes per polarization product	4	32
Polarization products	4	

Central Signal Processor: Preliminary Reference Design

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2	2018-09-27	O. Ojeda	All	Update for ngVLA Reference Design Review. Incorporates feedback from Reference Design Workshop. CBF part based on TR-DS-000001, Rev. D.
3	2018-11-08	O. Ojeda	All	Minor adjustments for the Internal Review.
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Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 4
3 Central Signal Processor Overview 5
4 Central Signal Processor Design 7
4.1 Design Criteria 7
4.2 Simplified Central Signal Processor Overview 7
4.3 Correlator and Beamformer Reference Design 8
4.3.1 The Correlator and Beamformer Signal Processing Architecture 10
4.3.2 The Correlator and Beamformer Physical Architecture 14
4.4 The Pulsar Engine Reference Design 17
4.4.1 The Pulsar Engine Signal Processing Architecture 18
4.4.2 The Pulsar Engine Physical Architecture 19
4.5 Interfaces with Other Subsystems 24
4.5.1 Interface with the Digital Back End 24
4.5.2 Interface with the CSP Back End 24
4.5.3 Interface with the Monitor and Control Subsystem 24
4.5.4 Interface with the Timing and LO Reference Subsystems 24
4.5.5 Interface with the Central Electronics Building 24
5 Appendix 25
5.1 Abbreviations and Acronyms 25

1 Introduction

1.1 Purpose

This document describes the Central Signal Processor (CSP) subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design Workshop/Review documentation package.

1.2 Scope

This document covers the preliminary design of the ngVLA CSP, as part of the ngVLA Reference Design. It includes CSP design, how it functions, and its interfaces with the necessary hardware and software systems. It does not include specific technical requirements or budgetary information.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA CSP Preliminary Requirements	020.40.00.00.00-0001-REQ Version 9
AD02	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-SPE Version 3
AD03	ngVLA Science Requirements	020.10.15.00-0001-REQ Version 13

2.2 Reference Documents

This text references the following documents:

Reference No.	Document Title	Rev/Doc. No.
RD01	TRIDENT Correlator-Beamformer for the ngVLA: Preliminary Design Specification	TR-DS-000001 Revision 1
RD02	ngVLA CSP Cost Estimate	020.40.00.00.00-0003-BUD Version 2
RD03	Handbook of Pulsar Astronomy	Lorimer and Kramer, 2005

3 Central Signal Processor Overview

The CSP ingests the voltage streams digitized 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 a high-performance computing system known as the CSP Back End (CBE).

In addition to cross-correlation and auto-correlation capabilities, the CSP will support further capabilities required of modern telescopes to enable VLBI and time-domain science. Specifically, the CSP operates in up to five different Observing Modes (OM) depending on the desired data product:

- **Synthesis Imaging**: The CSP computes all spectral auto- and cross-correlation functions, including cross-polarizations within a sub-array. Spectral resolution and time averaging are independently configured for each sub-band (enabling zoom windows) and across sub-arrays.
- **(Sparse/Dense) Pulsar Timing**: The CSP generates an average pulse profile per frequency channel per beam. Timing information must be implicit or explicitly preserved along with the profiles. There are two Pulsar Timing OMs: Sparse and Dense. The difference between them is the number of beams that are generated per sub-array. Each of these two OMs finds application for sparse or dense pulsar populations in the sky, which lead to different beamforming requirements.
- **Offline Pulsar Search**: In this OM, the CSP outputs all four Stokes parameters at a given time-frequency resolution. To minimize telescope observation time, a great number of simultaneous beams are generated and subsequently stored for offline processing (without prejudice to an eventual implementation of an Online Pulsar Search OM).
- **VLBI**: Additionally, this VLBI Observing Mode is thought to operate the ngVLA as a single VLBI station within a larger network. Within this mode, several beam-channels can be generated and the resulting voltage stream is stored in one of the VLBI standard formats.

All key science goals (KSGs) require Synthesis Imaging mode as identified in [AD02]. Sparse Pulsar Timing is the standard mode used for observing and timing pulsars, which is required by KSG5. Dense Pulsar Timing allows observing up to ten different pulsars at once, optimizing telescope time.

For example, the Reference Observing Program foresees a use case aimed at timing ten pulsars around the Galactic Center. Although this can be done less efficiently through other Observing Modes[1], the cost of developing an additional Observing Mode is estimated around $2 million, or 1.5% of the total cost [RD01], which will be clearly paid off in terms of operation cost through telescope time savings. The Pulsar Search mode is required for KSG4 and KSG5, to search for pulsars as well as detecting Fast Radio Bursts (FRBs) and hence enabling time domain science. And finally, the VLBI mode is a requirement for KSG5 [AD03].

These observing modes reveal the need for some sub-elements: A correlator, a beamformer, and a pulsar engine to compute pulsar profiles. The correlator and the beamformer are most efficiently implemented as an integrated sub-element. Therefore, the CSP is composed of a Correlator and Beamformer (CBF) and a Pulsar Engine (PE), besides other ancillary sub-elements that will be dealt with in subsequent design reviews (such as the Local Monitor and Control sub-element). The CSP is not responsible for calibration

[1] For example, generating ten beams within a single sub-array, as required by SCI0008, can be done through the Sparse Pulsar Timing mode. However, since the corresponding CBF Function Mode can only generate four beams while in this mode, three times the hardware resources would be needed. Ten beams could also be generated through the CBF mode associated with the Pulsar Search Observing Mode, but it only provides limited field-of-view coverage depending on the sub-array diameter. The Dense Pulsar Timing mode provides full coverage for a limited set of antennas (i.e. 144 antennas). More details can be found in [RD01].

of the beamformer and, when applicable, supporting visibilities generated with this purpose are processed outside the CSP.

The Frequency Slice Architecture (FSA), developed by NRC, is currently under consideration for implementation of the CBF. In the FSA, the CBF splits the wideband input streams into narrower oversampled signals, known as Frequency Slices. This task is accomplished on a per antenna basis at the CBF sub-elements known as Very Coarse Channelizers (VCCs). Then, a set of independent Frequency Slice Processors (FSPs) process those Frequency Slices. Each FSP has the capacity to process any one selectable Frequency Slice, for all antennas in the array. When sub-arrays are used, each FSP processes one Frequency Slice for all the sub-arrays in the array. Additionally, each FSP may be configured to operate in any one FSP Function Mode (FM). The relationship between the CSP's Observing Modes and the FSP's Function Modes [RD01] are anticipated to be bijective, although final FMs might evolve during development.

The CSP will support multiple independent simultaneous sub-arrays. A key requirement for the CSP is the degree of simultaneity supported both within a sub-array and across all sub-arrays. By means of NRC's FSA, all sub-arrays operating in the same Function Mode are processed by the same hardware while still being independently configured.

Assuming the anticipated correspondence between FMs and OMs, the number of FSPs operating in one Function Mode will determine the maximum bandwidth that any sub-array can devote to its associated Observing Mode. One exception will be FSP Function Modes with a limited number of antennas. Once the antenna limit is exceeded, the number of FSPs devoted to these Function Modes must be distributed between sub-arrays as well.

In Pulsar OMs, the CBF delivers the generated "beam-channels" to the Pulsar Engine for further processing. Therefore, the PE is an integral part of the CSP along with the CBF. The purpose of the PE is to generate some of the CSP data products, such as pulse profiles, which the CBF does not compute. Nevertheless, the CBF channelizes each beamformed signal into beam-channels, prior to its transmission to the PE.

The PE performs a sequence of signal processing functions necessary to obtain the desired data product. The anticipated set of PE functionalities include:

- coherent de-dispersion,
- channel stitching,
- detection or Stokes parameter computation, and
- folding.

The specific set of PE tasks carried out is selectable and configured as a function of the desired data products. Nonetheless, the main data products in pulsar timing OMs are (de-dispersed) average pulse profiles on a per beam-channel basis, while the PE is expected to compute Stokes parameters only (no de-dispersion or folding threads) while in the Offline Pulsar Search OM.

The PE will deliver the generated data products to the CBE (CSP Back End) through the same interface as the CBF. The reference PE architecture partitions the PE in a way that is compatible with the CBF architecture, i.e. one computing node per FSP. Therefore, when a PE node is generating data products, its associated FSP is not, as it is operating in one of the pulsar OMs.

4 Central Signal Processor Design

4.1 Design Criteria

The design of the CSP pursues the minimization of total lifecycle costs over the projected design life, in accordance with SYS2702 [AD02]. Contrary to most of the other subsystems, the challenge here is not just to satisfy CSP requirements but to do it in the most cost-efficient way, as the CSP can be realized using many different technological solutions and architectures. For the purpose of this reference design, such efficiency is defined in terms of total lifecycle cost. Also, a low-risk approach is taken considering only already available technologies instead of using predictions about future solutions.

Different technological solutions have been assessed independently for the CBF and the PE. A research collaboration has been established between NRAO and NRC to develop a reference design for the CBF component. The CBF reference design leverages NRC's large expertise, as they are the same team behind both the VLA correlator and the SKA-Mid CBF. As a result, the CBF reference design is based on the same technological solution as SKA-Mid, which has been scaled and adapted to the ngVLA requirements. A detailed description of the CBF reference design can be found in [RD01].

As regards the PE, its architecture can be partitioned in a technology agnostic way, so that both technology and system architecture become independent. The different technologies assessed for the PE are Graphical Processing Units (GPUs) and Field-Programmable Gate Arrays (FPGAs). The first have been coarsely evaluated in several of their different flavors, (i.e. general purpose GPUs, system-on-chip (SoC) technologies (namely, NVIDIA's Tegra SoC), and GPU-based server solutions).

FPGA implementations have been studied considering two approaches. The first uses on-chip Block Random Access Memory (BRAM), and the second employs second-generation High Bandwidth Memory (HBM2). Similar best results are offered by different technologies, with some degree of uncertainty in total cost estimates. This prevents us from making a final choice without further experimental investigation. Consequently, several candidate technologies are proposed for the reference design.

4.2 Simplified Central Signal Processor Overview

The simplified architecture of the CSP is presented in Figure 1, which clearly identifies the two main CSP components, namely the CBF and the PE. In addition, at least a third component will control the CSP local Monitor and Control (M&C). However, the M&C sub-element is out of the scope of the current costing exercise, as it is deemed too small in size and complexity to become a design driver.

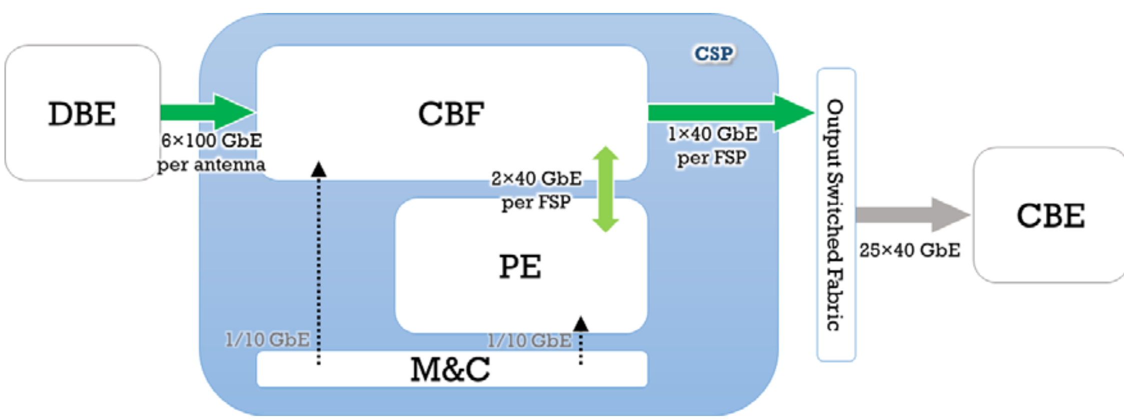

Figure 1 - Simplified block diagram of ngVLA central signal processor.

Digitized voltage streams from the stations are received at the Digital Back End (DBE), which conditions it to the CSP input (the CSP subsystem interfaces are defined in Section 4.5). The DBE performs at least two functions: formatting the data to the CSP input and routing the data to the proper CBF section (as seen next, the CBF is a trine of smaller CBFs, hence is codenamed "Trident").

The DBE may perform additional functions, such as splitting the bandwidth into sub-bands, selection and transmission of the sub-bands to be processed, coarse digital sideband separation, etc. Some of these tasks are redundant with the CBF functionality described herein, specifically the VCC. Nonetheless, a fully functional CBF reference design is preferred for a conservative cost estimate, hence allowing further system optimization in the future.

In the following, it will be assumed all voltage data streams are received at the CBF, which splits them into coarse channels of the same bandwidth known as Frequency Slice (FS). One FS per antenna, corresponding to the same sky frequency within a sub-array, is sent to every Frequency Slice Processor (FSP) to be processed in one selectable Function Mode (FM).

Those FSPs which operate in Synthesis Imaging or VLBI modes generate the final data products that are delivered through a switched fabric to the CSP Back-End (CBE). On the other hand, FSPs operating in Pulsar Timing modes deliver the beamformed data to the PE for further processing. Then, it is the PE that delivers the final data products. Finally, still under consideration, it is anticipated that the FSPs will output the final data products when operating Offline Pulsar Search modes as well.

4.3 Correlator and Beamformer Reference Design

The CBF ingests the voltage streams, digitized and packetized by the antennas, transmitted via the data transmission system, and possibly pre-processed by the DBE subsystem. The CBF produces a number of low-level data products to be ingested by the CBE (the "Science Data Processor" or "Archive" in [RD01]). The CBF is also responsible for beamforming all sub-arrays, and delivering the result to either the PE or the VLBI back-end (presumably located at the CBE) depending on the Observation Mode.

Figure 2 depicts the so-called "Trident" CBF architecture [RD01]. The Trident architecture partitions the CBF into three independent smaller CBFs, each based on the FSA and capable of processing up to 10 GHz of dual-polarization bandwidth. In the Trident CBF jargon, each of these three components is referred to as trident. The CBF reference design describes a digital correlator-beamformer system based on FPGA technology that meets the science requirements of the ngVLA synthesis radio telescope, specifically, processing 28 GHz of aggregate bandwidth per polarization from 263 antennas [AD01].

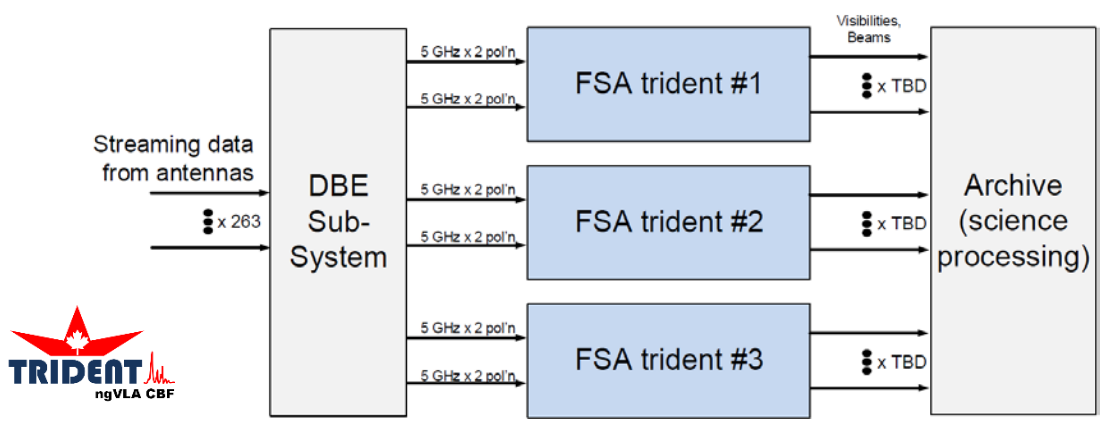

Figure 2. Simplified block diagram of the Trident CBF [RD01].

The reference design uses the Frequency Slice Architecture (FSA) developed by NRC, which aims to optimize cost by reducing the processing hardware requirements while increasing modularity. Incredible flexibility is provided by delivering many independent Frequency Slice Processors (FSPs), which can be allocated to continuum, spectral line (zoom), or beamforming work, depending on the needs of an observation. Some examples of such flexibility are the following:

- **Example 1**: 20 GHz for Synthesis Imaging plus 10 GHz for Pulsar Timing
  - Sub-array 1: Synthesis Imaging
    - 10 GHz of continuum bandwidth at 5-km/s resolution in FSPs 1–50
    - 20 zoom windows at 0.1 km/s resolution in FSPs 51–71
  - Sub-array 2: Synthesis Imaging
    - 20 GHz of continuum bandwidth at 10-km/s resolution in FSPs 1–100
  - Sub-array 3: Pulsar Timing
    - 1 beam 10 GHz wide in FSPs 101–150
  - Sub-array 4: Pulsar Timing
    - 1 beam 5 GHz wide in FSPs 101–125
  - Sub-array 5: Pulsar Timing
    - 1 beam 5 GHz wide in FSPs 126–150
  - Sub-array 6: Pulsar Timing
    - 2 beams 10 GHz wide in FSPs 101–150
- **Example 2**: 20 GHz for Synthesis Imaging with zoom windows and Commensal Pulsar Search
  - Sub-array 1: Synthesis Imaging
    - 20 GHz of continuum bandwidth at 5 km/s resolution in FSPs 1–100
  - Sub-array 2: Synthesis Imaging
    - 14 GHz of continuum bandwidth at 5 km/s resolution in FSPs 1–70
    - 10 zoom windows at 0.1 km/s resolution in FSPs 71–80
  - Sub-array 2: Commensal Pulsar Search
    - 10 beams 10 GHz wide of commensal Pulsar Search in FSPs 101–150

As determined by requirements, at least ten independent sub-arrays can be operating simultaneously, although this number could be increased as needed.

Note that sub-array use cases are still under development. As detailed in [RD01], the cost of the Trident CBF is mainly dominated by hardware cost. It represents approximately $100 million dollars, or about 78% of the total cost. Therefore, future efforts should be aimed at hardware optimization. As regards the requirements impact on the cost, hardware costs in this reference design are roughly proportional to the product of number of antennas and aggregate bandwidth. These are the two key parameters to consider for any cost optimization.

The reference design implements an FSA CBF using NRC's TALON technology currently under development for the Square Kilometer Array Mid Frequency Telescope Correlator/Beamformer. The TALON technology is fiber-connected Intel Stratix 10 FPGA based signal processing boards in 2U (air-cooled) or 1U (liquid-cooled) rack mount server boxes.

While ngVLA will use future FPGA technology still in development, the reference design represents a low-risk solution using currently available technology that can be accurately costed. Cost, power consumption, and rack space requirements can be extrapolated to future technology nodes based on industry projections.

4.3.1 The Correlator and Beamformer Signal Processing Architecture

Figure 3 outlines the CBF signal processing architecture, which is based on NRC-developed Frequency Slice Architecture (FSA). The FSA splits the CBF into two parts. The VCC part provides band-specific signal progressing to channelize wideband input streams into a number of narrower oversampled Frequency Slices (FS).

The bandwidth of an FS is common for all bands making subsequent processing band-agnostic. Each FS can be routed to one or more configurable Frequency Slice Processors (FSP) in the FSP part. The DBE is responsible for routing the needed input signal to its corresponding trident according to the current configuration of the FSP part. Each FSP can be programmed to operate in one of the five Observing Modes described above and can perform that function for any number of sub-arrays in different bands.

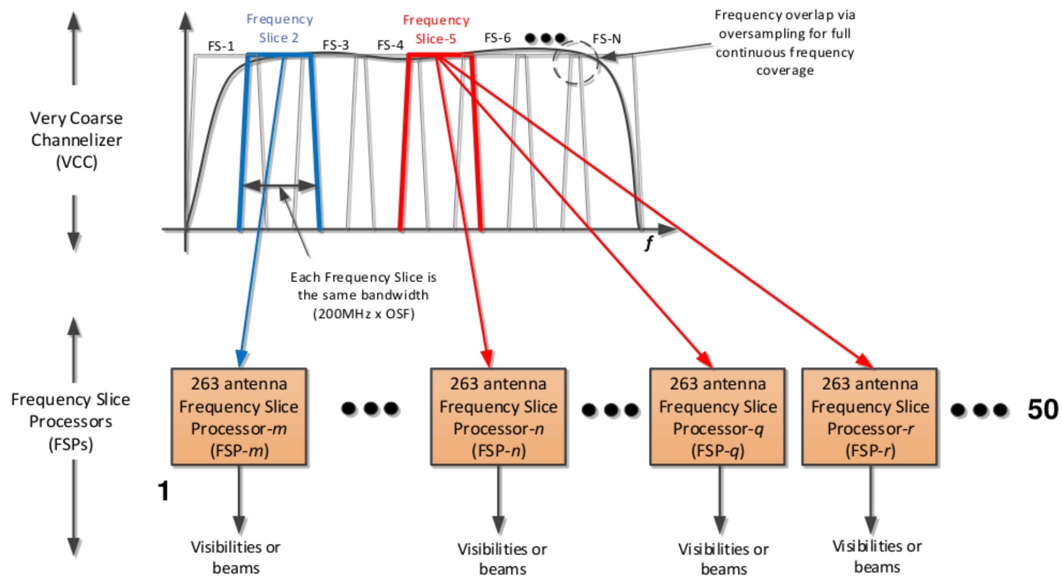

Figure 3 - The Trident CBF signal processing architecture is based on NRC-developed Frequency Slice Architecture. The figure represents the signal processing diagram for each trident [RD01].

Note that the same portion of the spectrum can be processed simultaneously for one sub-array at two different tridents when it is processed in two different Observing Modes (e.g., in commensal observations). This is possible thanks to the routing capabilities at the DBE. The total number of FSPs dictates the aggregate bandwidth that can be processed simultaneously, but distribution of bandwidth across Observing Modes can vary by observation.

This optimizes the amount of processing hardware required while providing the flexibility to assign processing resources to normal fine-channel imaging, zoom imaging, or beamforming. The modular approach and clear division between the VCC part and FSP part allows implementation of future upgrades (such as new receivers or Observing Modes) with minimal impact to existing functionality.

4.3.1.1 Very Coarse Channelizer Functionality

One VCC part of each trident processes up to 10 GHz of dual-polarization bandwidth for all the antennas in the array and generates the FSs to be further processed in the FSPs. All functions performed at the VCC part are OM-independent, and the main ones are

- Coarse channelization of input data streams into Frequency Slices (for those stations whose DBE has not already carried out this task);
- Fine frequency tuning for optimal FSP utilization (in the same case as above);
- Coarse (or bulk) wideband delay tracking;
- Radio Frequency Interference (RFI) flagging both at the input and the FS streams; and
- Routing any selectable Frequency Slice to any of the (50) FSPs within the trident.

The role of the VCC might vary significantly for the ngVLA with respect to [RD01]. The reason is that selecting the Spectral Windows efficiently from the 14-GHz samples utilized by the receivers requires implementing sub-band channelization at the DBE. This is also the case for digital sideband separation. If this is finally confirmed, the hardware employed at the VCC will be significantly reduced, as well as its associated cost.

The coarse channelization at the VCCs is performed through an oversampling polyphase filterbank. This determines the Frequency Slice bandwidth such that each FS is at optimal bandwidth and sample rate for downstream direct-sample-rate FPGA processing, eliminating the complexities of a corner-turner before the next stage [RD01]. Figure 4 shows one example of its planned channel response.

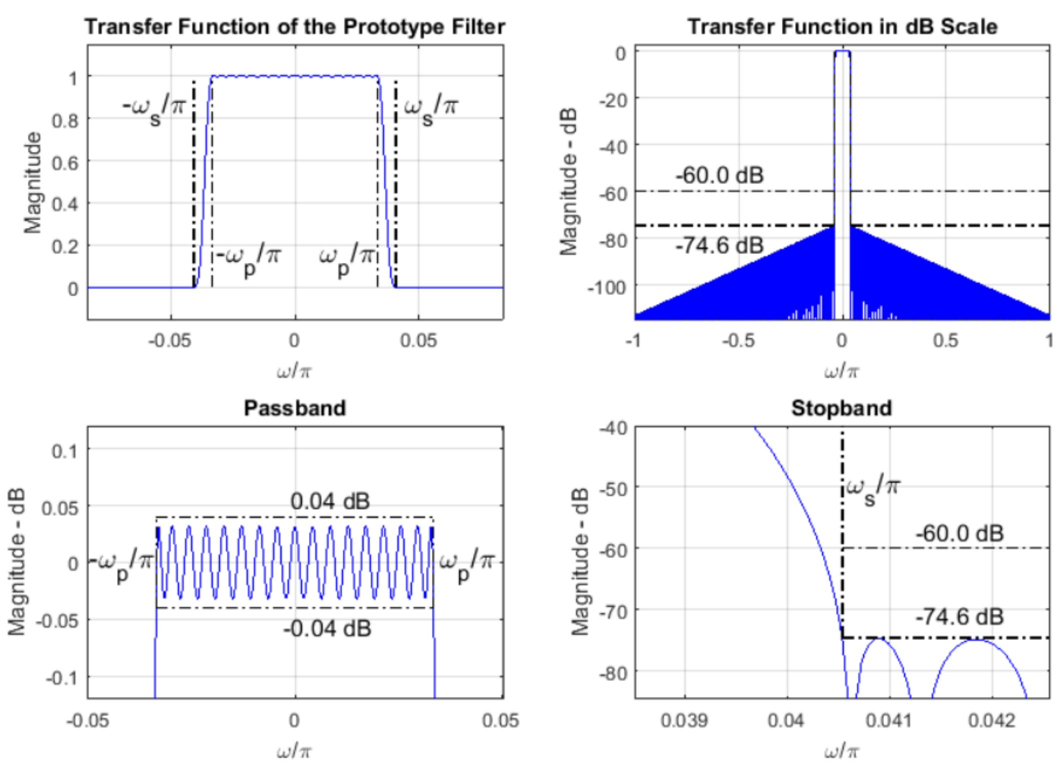

Figure 4 - Example VCC channelizer output channel [RD01]. Upper left: zoomed-in linear magnitude response. Lower left: zoomed-in magnitude response dB. Upper right: magnitude response dB. Lower right: zoomed-in magnitude response transition band dB. Not shown is that the phase response is linear across the passband.

Regarding RFI flagging, potential implementation candidates include pre-correlation techniques such as spectral kurtosis or the simple short-term/long-term power ratio detector shown in [RD01]. Furthermore, other signal processing techniques, such as Sample Clock Frequency Offset, inherently exhibit RFI mitigation capabilities. This also applies to RFI mitigation techniques anticipated for the FSP.

4.3.1.2 Frequency Slice Processor Functionality

The FSP part processes one selected (dual-polarization) FS per antenna for all antennas in one configurable Observation Mode. This part is sized according to total instantaneous bandwidth to be processed, aggregated across all Observation Modes. For 28 GHz of aggregate bandwidth, 140 FSPs are needed; Trident CBF tripartite symmetry leads to 150 FSPs in all. A single FSP can be seen as a smaller configurable (FX) correlator or beamformer able to process 200 MHz of bandwidth (one FS) for all antennas in the array. Many FSP main tasks, listed below, depend on the current OM. More details can be found in [RD01].

- Synthesis imaging:
  - Fine delay tracking
  - Spectral zooming
  - 'FX' correlation
  - Spectral averaging
  - RFI flagging both at the zoom window and the correlation resolutions
- Sparse Pulsar Timing:
  - True-time delay beamforming
  - Up to four beams per sub-array (26 beams across all sub-arrays)
  - Full primary beam coverage for unlimited aperture diameter
  - Fine channelization (~MHz resolution)
  - Wideband antenna polarization correction per beam
  - Supporting visibilities for simultaneous calibration beam
  - RFI flagging at the supporting visibilities' resolution
- Offline Pulsar Search:
  - Phase-delay beamforming
    - At least ten beams per sub-array
    - Trade-off: Aperture diameter vs. Offset from boresight
  - Fine channelization (~MHz resolution)
  - RFI flagging at the fine channel resolution
  - Narrowband antenna polarization correction per beam
- VLBI:
  - True-time delay beamforming
    - Up to four beams per sub-array (26 beams across all sub-arrays)
    - Full primary beam coverage for unlimited aperture diameter
  - No fine channelization, but recording multiple VLBI-standard frequency channels per beam is possible
  - Wideband antenna polarization correction per beam
  - Supporting visibilities for simultaneous calibration beam
  - RFI flagging at the supporting visibilities' resolution
  - VLBI-standard data formatting

The FSP functionality for Dense Pulsar Timing can be adjusted between those of Sparse Pulsar Timing and Offline Pulsar Search Modes depending on factors such as the required number of beams desired, the sub-array diameter, or the required primary beam coverage.

Figure 5 (next page) shows a simplified signal flow of the Trident CBF.

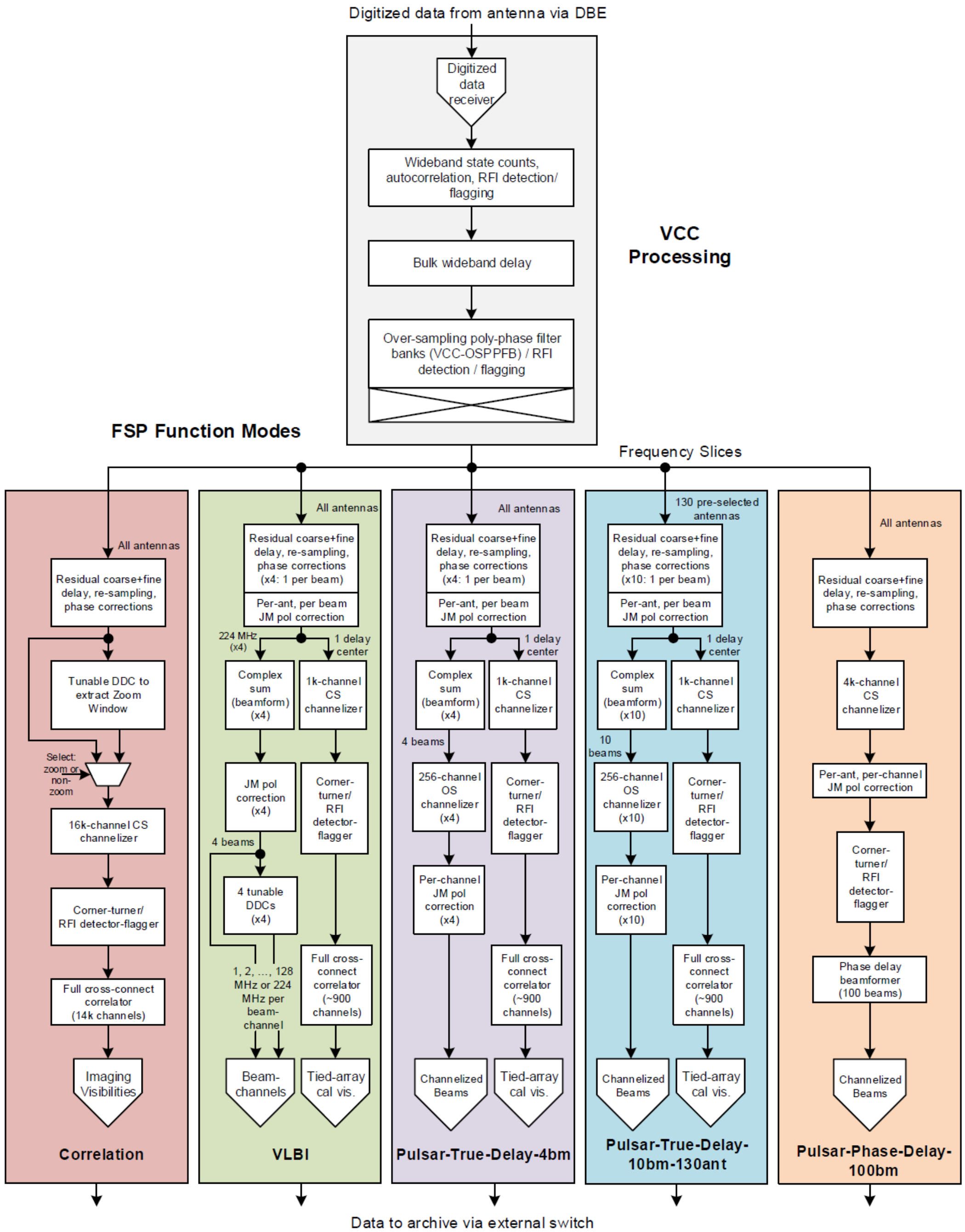

Figure 5 - Trident-CBF simplified signal flow diagram [RD01].

4.3.1.2.1 Delay Tracking and Fringe Rotation

Digital delay tracking is carried out in two steps: a coarse (bulk) correction at the VCC, and a fine correction at the FSP [RD01]. The bulk coarse delay correction at the VCC is not fundamental; it rather simplifies delay tracking by adjusting for the bulk of the delay correction every so often (10+ seconds) using high-capacity external DDR4 RAM. This leaves only the small number of residual coarse samples at the FS sample rate and the very fine delay to be corrected in the FSP FPGAs.

The restriction is that for any particular antenna, all delay tracking centers on the sky must be somewhat constrained, normally within the HPBW of the antenna. This means that one would not be able to form a boresight beam and a beam with a large offset from it such as through a sidelobe, since the residual coarse delay in the FSP FPGA would exceed capacity (depending on distance to the array phase center).

Contrary to the bulk delay correction applied at the VCC, the fine delay tracking achieved at the FSP is implemented through a re-sampling block that employs a first-order delay model [RD01]. The combination of re-sampling to a different sample rate and very-fine-delay tracking provides for virtually perfect very-fine-delay tracking with no discernible delay-tracking effects: since re-sampling is constantly and rapidly sweeping through many steps (typically 1024 or 2048) between +/–0.5 samples, the average of the filter re-sampler response is the average of the transfer function of the very-fine-delay tracking response. Further details and performance results can be found in [RD01].

The re-sampling block at the FSP also performs a complex phase-rotation/mixing operation, to apply any required phase corrections to the data prior to further channelization, correlation, and beamforming. Generation of spurious signals is minimized by means of dithering [RD01].

4.3.2 The Correlator and Beamformer Physical Architecture

The Trident CBF for ngVLA is implemented as a trine of identical, independent, 10-GHz dual-polarization components known as "tridents" (see Figure 2). The physical architecture for each of these components is sketched in Figure 6[2]. Voltage data is received by each component from the DBE matrix switch via 100GbE communication links.

Assuming 4-bit quantization, 10 GHz of bandwidth per polarization fits comfortably with the link capacity. For compatibility with the lower frequency bands, 5 GHz of bandwidth per polarization is also possible with 8-bit quantization. Additionally, compatibility with multiple sub-band input formats and/or finer quantization for reduced input bandwidth can be developed as needed, especially if a coarse channelizer is finally implemented at the DBE.

Each of the three tridents contains one VCC part and one FSP part. The VCC part contains one FPGA[3] for each antenna and performs very coarse channelization to generate up to 50 dual-polarization Frequency Slices (FSs), for a 10-GHz input. The 286 FPGAs in the VCC part are grouped in sets of 11, which along with passive interconnection hardware, is referred to as VCC unit. Therefore, there are 26 VCC units in each trident to accommodate for all 263 ngVLA antennas plus 23 spare inputs.

Tighter arrangements might be possible and shall be studied in future, such as 24 VCC units with 11 antennas each, or 22 VCC units with 12 antennas each. The feasibility of an increase in the number of antennas processed per FSP FPGA, from 10 antennas to 11 or 12, respectively, has not been proven for the current technology node, although it might be the preferred option in future designs.

Each antenna data stream is sliced into 50 FSs, hence 50 FSPs are needed to process all of them at once. As a result, the FSP part of each Trident component is made of 50 FSPs. Each FSP in turn consists of 26 FPGAs, one per VCC unit, plus additional interconnection hardware. Each of the 26 FPGAs connects to one of the 26 VCC units in the VCC part. The FSP hardware is referred to as an FSP unit, so that one FSP consists of one FSP unit.

[2] The figure actually shows the number of units for a 260-antenna design (26 × 10). Final numbers for a 286-antenna design (26 × 11) can be found in [RD01].

[3] Obviously, there is more hardware around each FPGA. The term FPGA as used in this document includes all that hardware associated to FPGA as well. A brief description of such hardware can be found below, or in [RD01] in more detail, namely the TALON-DX board developed at NRC.

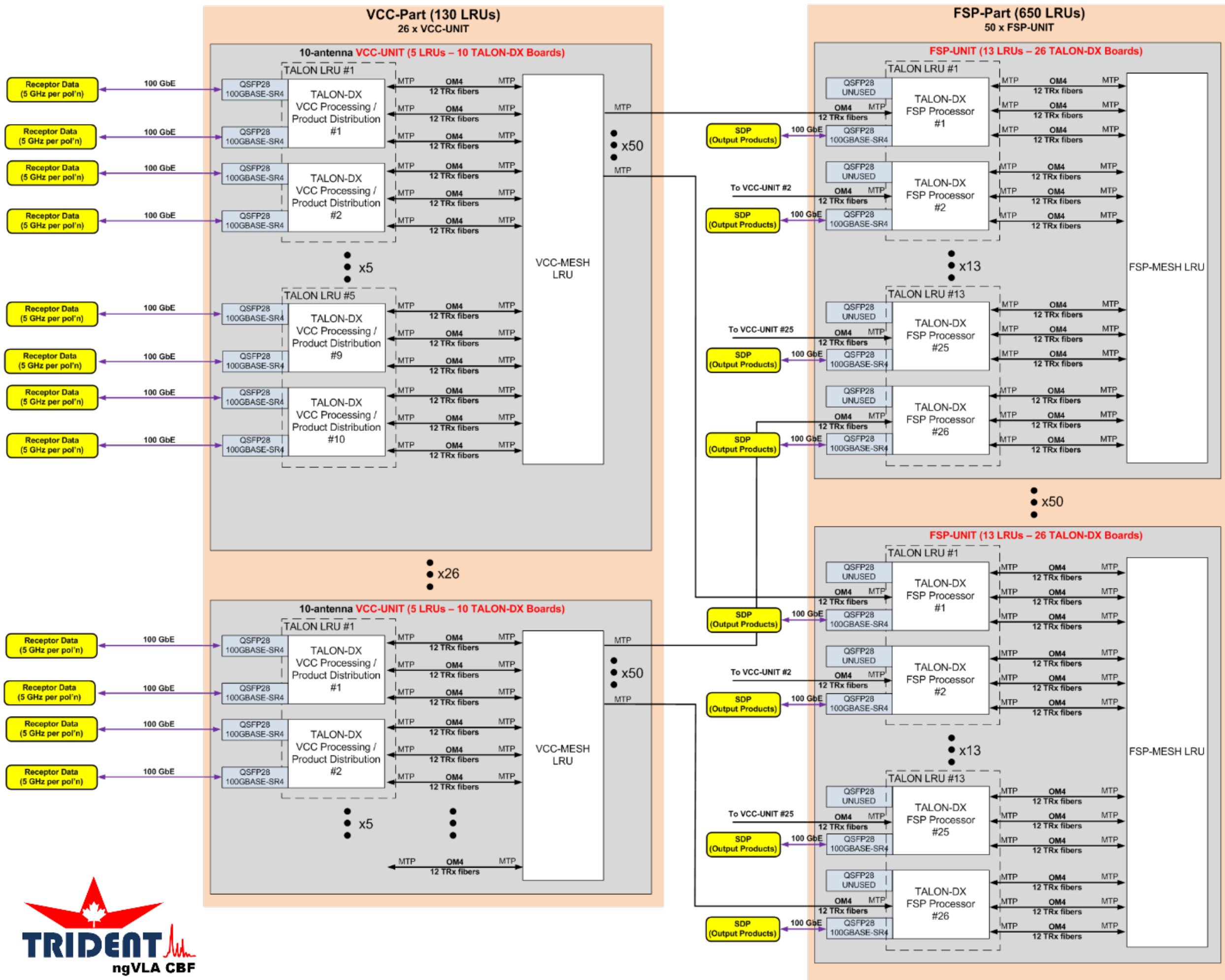

Figure 6 - Physical architecture for one of the three Trident CBF 10-GHz dual-polarization tridents [RD01].

For every trident, the connection between one VCC unit and all 50 FSP units in the FSP part is done by a separate LRU (Line Replaceable Unit) of the VCC unit referred to VCC-Mesh, using a passive optical circuit. For every antenna, any Frequency Slice can be directed to one or more FSPs in the FSP part. Data from one VCC unit towards one FSP are grouped together at the VCC-Mesh and sent to its corresponding FPGA within that FSP through one single 12-fiber MPO (MTP®) cable.

The FPGA technology node used in this design allows up to 64 high-speed serial interfaces for each FPGA high-bandwidth connection. Whereas eight of these interfaces have been used for 2 x 100GbE I/O interfaces, each FPGA of the VCC part could be connected to up to 56 FSPs (i.e. 11.2 GHz of bandwidth). This technology limit is one of the reasons behind the tripartite Trident CBF architecture, and as a result the architecture must be revamped for future technology nodes.

As said, the FSP part (of each trident) contains 50 FSP units, which can each be configured to perform one of the five Observing Modes. An FSP unit contains 26 FPGAs and one passive optical circuit in an LRU designated FSP-Mesh. This network mesh provides 26-Gb/s communication links between every pair of FPGAs within the FSP unit. Each FSP FPGA receives ten inputs to the FSP unit (grouped in one single 12-

fiber MPO cable) with one Frequency Slice each from the ten antennas processed in one VCC unit. This provides a total input capacity for 260 antennas into an FSP unit.

In general, the processing in each FSP FPGA is achieved in two stages. First, per-antenna processing is performed on each of the ten antennas received by one FSP FPGA. Data is then distributed to the other FSP FPGAs based on bandwidth or beams via the FSP-Mesh, so that each FPGA gets a portion of the data for all antennas for correlation or beamforming.

In addition to their internal connection through the FSP-Mesh and the connection to their respective VCC unit, each FPGA in the FSP unit has available at least one 25GbE (or 100GbE) interface to output the data products generated. As a result, there are 26 of these interfaces per FSP unit, 1,300 per FSP part, which amounts to 3,900 outputs for the entire CBF towards the CBE.

Both VCC and FSP FPGAs are based on the same hardware, namely the TALON-DX board whose simplified block diagram is shown in Figure 7. Two TALON-DX boards make one TALON LRU. Each trident is physically composed of 26 VCC units and 50 FSP units. In total, this amounts to 806 × 1U (water-cooled) TALON LRUs, with each LRU containing the two TALON-DX boards, plus support equipment (power supplies, liquid cooling plates, fans, etc.) [RD01].

Each TALON-DX board contains one Intel Stratix 10 FPGA (SX family device equipped with an embedded quad-core ARM A53 processor), two QSFP28 cages for 100GbE interfaces, 54 high-speed optical SERDES via five FCI Leap mid-board optical modules and four DDR4 DIMM modules. A picture of both a TALON-DX prototype and a 2U (air-cooled) TALON LRU can be seen in Figure 8.

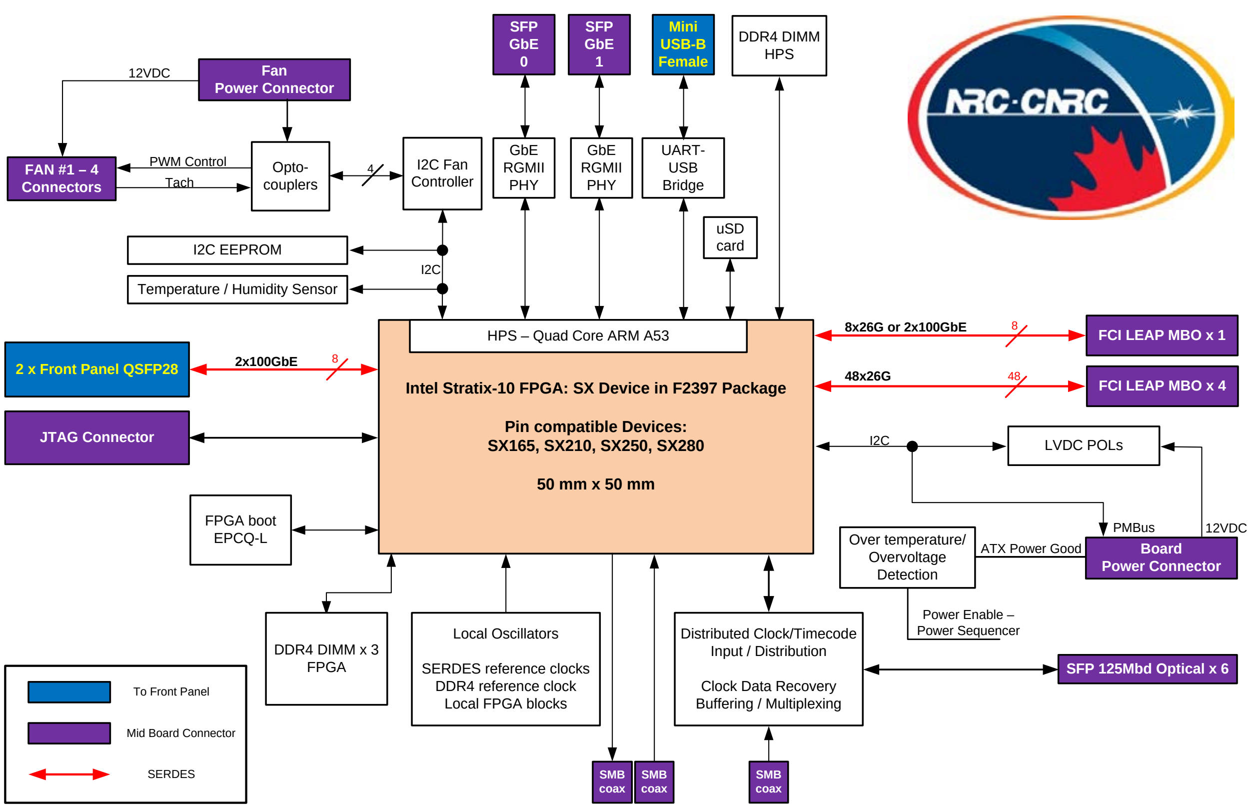

Figure 7 - Simplified block diagram of a TALON-DX board [RD01].

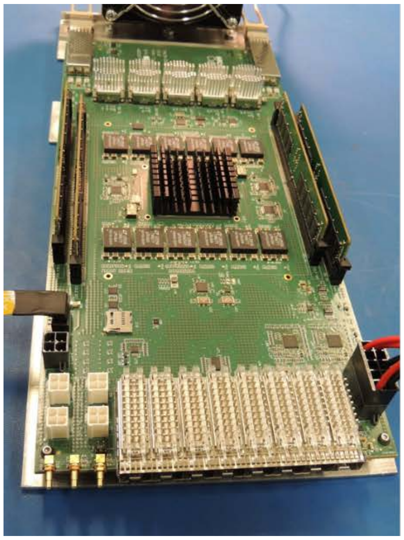
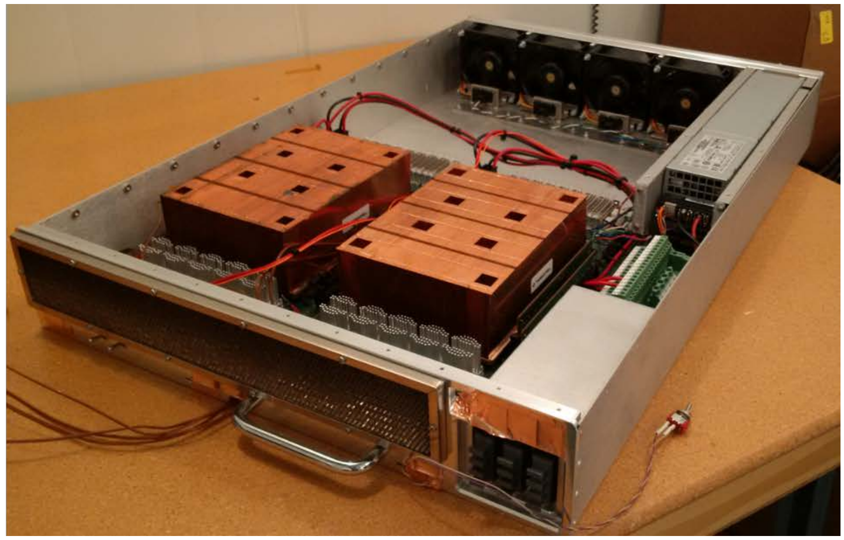

Figure 8 - Prototype TALON-DX board (left) and prototype 2U TALON LRU (right) [RD01].

Each trident requires 26 racks where the different LRUs are installed [RD01]. Spare FSP units can be installed within the available space for improved reliability and availability of the system. In addition to the 78 racks required for the three tridents, one or two additional racks for central monitor and control servers need to be installed. The estimated power consumption per rack is about 20 kW, while the targeted racks allow up to 40 kW of heat dissipation.

Overall, the entire ngVLA Trident CBF will require 80 racks and 2,418 TALON LRUs, and its estimated power consumption (not including cooling infrastructure) is approximately 1,500 kW. Projections of future technology nodes suggests this number could decrease to 80% or even 60% [RD01].

4.4 The Pulsar Engine Reference Design

The Pulsar Engine is a sub-element of the ngVLA Central Signal Processor (CSP) whose purpose is to generate some of the CSP data products, such as pulse profiles, that the CBF does not compute. Until recently, systems performing similar tasks lacked the computing power to operate in real-time except for a meager beam-bandwidth product.

The situation has changed thanks to the fast evolution of GPU computing power and power efficiency, which has put them at the core of every state-of-the-art supercomputing design in recent years. For example, both SKA pulsar search and timing engines are based on GPUs. Nevertheless, FPGAs too have increased their on-chip memory bandwidth substantially enough to rival GPU performance thanks to their lower power versus bandwidth ratio.

The input to the PE are the “beam-channels” generated by the fine channelizer at the CBF when the CSP operates either in Pulsar Timing or Pulsar Search Observing Modes.

As described above, the CBF can compute the desired beam-channels at any of its 150 FSPs, which results in a maximum bandwidth per beam of 30 GHz. However, it has been decided that the Pulsar Engine will have application only in the lower three frequency bands of operation of ngVLA, that is, under ~20 GHz. The maximum beam bandwidth (restricted to one ngVLA band) is 8.8 GHz, in Band 2.

The PE has been designed to digest up to 88 GHz of beam-bandwidth product, as the minimum number of beams required to satisfy ngVLA science goals is ten beams [AD03]. Thanks to its fully scalable architecture, the PE can be upgraded in the future as needed.

Once it has computed the desired data products, the PE delivers them to the CBE. For Offline Pulsar Search OM, the PE has the capability of computing full Stokes parameters at the required time-frequency resolution. However, this task is most efficiently carried out at the CBF, which also relaxes the required PE output data rate. Consequently, the PE only operates in either Sparse or Dense Pulsar Timing OMs.

The PE provides the same functionality for both OMs, as their different requirements affect only the beamformer. The PE can generate pulsar profiles at any phase, time, and spectral resolution values within the specified margins. Also, despite not being considered for the moment, the PE could be upgraded in future to include a "Real-Time" Pulsar Search mode.

Thanks to the fully scalable architecture based on independent computing nodes, the PE can be sized to meet virtually any point at the beam-bandwidth vs. cost curve. For the purpose of this design, a maximum beam-bandwidth product of 88 GHz per polarization is considered, resulting from ten beams, 8.8 GHz wide each.

4.4.1 The Pulsar Engine Signal Processing Architecture

Architecturally, the PE is composed of a set of computing nodes, each node processing a reduced amount of beam-bandwidth product. Since the PE input connects to the FSP-part of the CBF, it makes sense to partition the PE so that each computing node processes the beam-bandwidth product that one FSP can generate, that is, 2 GHz per polarization or ten beams 200 MHz wide each per FSP. This architecture is shown in Figure 9.

Note that ten beams per FSP cannot be generated by one single FSP in Sparse Pulsar Timing, but instead up to three FSPs per Frequency Slice would be needed. Additionally, since in principle one computing node is directly connected to one FSP, an external switching network would be required as well. This capability has not been included in the design, as the Dense Pulsar Timing Observing Mode overcomes these limitations.

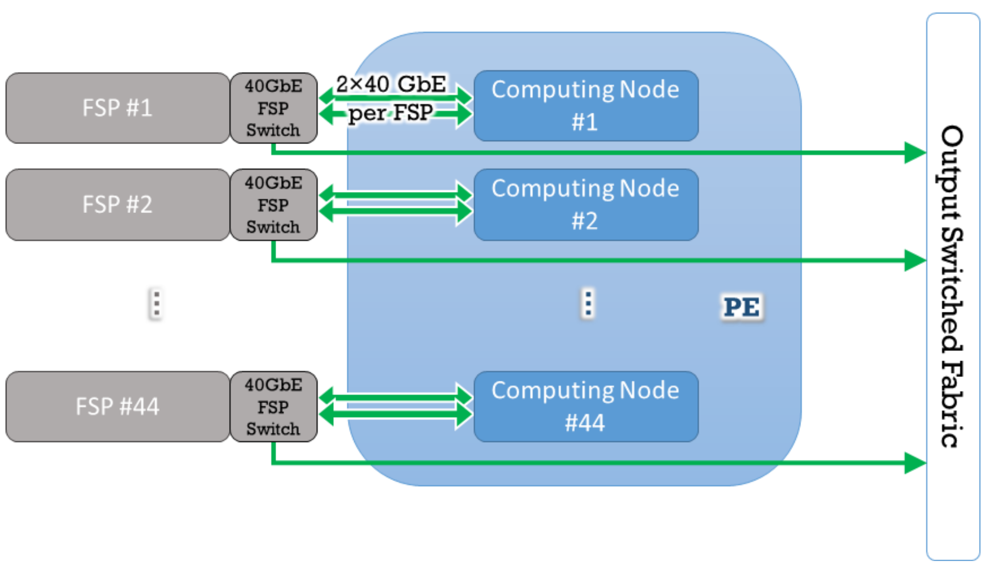

Figure 9 - Simplified block diagram of the Pulsar Engine architecture. In this design, only 44 FSPs are enough to satisfy the beamforming bandwidth requirements, and hence connected to the PE.

As stated, one Frequency Slice Processor (FSP) can generate up to ten beams of 200 MHz bandwidth each, or a beam-bandwidth product of 2 GHz per polarization. Assuming 16 bits per sample (complex, 8 bits for real and imaginary parts each), the total incoming throughput (64 Gbps) can be received through 2 x 40GbE interfaces. This allows employing the same switched fabric used to multiplex the outgoing traffic from the FSP FPGAs. Furthermore, there is still enough room for allocating the PE output data towards the CBE, and even additional meta-information, such as that required for RFI flagging at the PE.

At the PE, the CBF receives each beam already channelized. Then the PE performs a sequence of signal processing functions necessary to obtain the desired data product, nominally average pulsar profiles. The set of operations carried out by the PE include

- coherent de-dispersion,
- channel stitching,
- Stokes parameter computation, and
- time folding.

For greater flexibility, the specific set of PE functionalities carried out is selectable and configured as a function of the desired data product. Nonetheless, the main data products are (de-dispersed) average pulse profiles on a per-beam-channel basis. Additional operations related to RFI mitigation can be performed, but defining the specific RFI mitigation technique employed is the goal of ongoing study.

4.4.2 The Pulsar Engine Physical Architecture

The computing nodes composing the PE can be implemented in many different technologies. Section 5.2 gathers a comparison table with a coarse estimate of the total lifecycle costs of several candidate technologies. According to the CSP design criteria, the most efficient candidates have been selected for further description.

At first sight, achieving real-time operation of the PE is a matter of meeting two requirements: I/O throughput and computational power. However, analyzing the algorithmic implementation of the required signal processing tasks reveals that the main design driver is memory bandwidth. As a result, all three conditions must be satisfied to obtain a fully functional design.

The highest ranked technology of the comparison table is an FPGA implementation based on extensive use of BRAM memory. The reason is this memory is distributed on a chip and can be read massively in parellel, achieving the highest memory bandwidth.

The second-best option is based on recently released NVIDIA Xavier SoC module. This option is less expensive to build than the previous one. However, its increased power consumption as compared to FPGAs makes it more costly in the long term than FPGAs. This result has been obtained for a sustained electricity rate of 0.15 $/kWh, which is an optimistic forecast if, most likely, commodity prices increase in future. Therefore, the power consumption is expected to weight more in favor of FPGAs, in reality.

It is worth mentioning the third best ranked technology is based on general-purpose GPUs, which are even more inexpensive to build than the design based upon the SoC module. Once again, the higher power consumption makes this option less attractive over the entire lifecycle.

4.4.2.1 Pulsar Engine Design Based on FPGA

After some analysis, the most promising technology to implement the PE computing nodes is the one based on the FPGA making extensive use of BRAM. The amount of on-chip memory has increased exponentially with each FPGA generation. External memory solutions, such as DDR4, are not as efficient because of their limited memory bandwidth. The latest on-chip memory technology, HBM2, provides much more memory capacity than BRAM. However, this increase is obtained at the cost of memory bandwidth, which is the critical design parameter.

The most demanding PE tasks, in terms of memory, are coherent de-dispersion and channel stitching. These two tasks are more efficiently implemented by means of the FFT algorithm. From the CSP requirements [AD01], it can be obtained than the longest (radix-2) FFT to be implemented is a 2^{16}-point FFT. In single precision, one FFT would require at least 512 kB of memory.

If the beam-channel bandwidth is narrower than what is needed to achieve the required time resolution, the PE must perform a channel stitching process to increase this bandwidth. However, this can be done along with de-dispersion filtering. This results in a potentially smaller length of the first FFT, as the number of de-dispersion filter taps decreases with beam-channel bandwidth. The procedure required to stitch several narrowband channels is well known, and the computational power is smaller when channel stitching is required (because the beam-channel bandwidth is narrower, hence the de-dispersion filter is shorter).

Filtering requires implementing two FFTs or, more accurately, one FFT and one inverse FFT. Assuming two FFT input samples are processed for every input sample, similar to the overlap-save filtering algorithm, the total memory size required by a dual-polarization data stream is the number of FFT stages times 2 MB. Fitting the memory needed to process all ten beams generated by one FSP is feasible in the latest FGPAs.

Considering two-stage FFTs, total memory reserved for implementing FFTs is 40 MB (10 x 4 MB). Considering additional memory must be reserved to implement functions other than FFTs, this amount of memory is beyond state-of-the-art FPGAs. Fortunately, this requirement can be halved by making the FFT algorithm run at twice the real-time speed so that one FFT can process, for example, one polarization in half the required time and the other polarization in the second half of the interval). This leads to logic speeds around 400 MHz, which, although challenging, are routinely achieved with modern FPGAs.

The strength of FPGA technology is the huge I/O bandwidth available. For example, for a beam-bandwidth product of 2 GHz (10 beams, 200 MHz bandwidth each), 2x 40GbE interfaces (or a single 100GbE) are required. As Figure 10 (next page) shows, a single modern FPGA can handle much more I/O bandwidth than that.

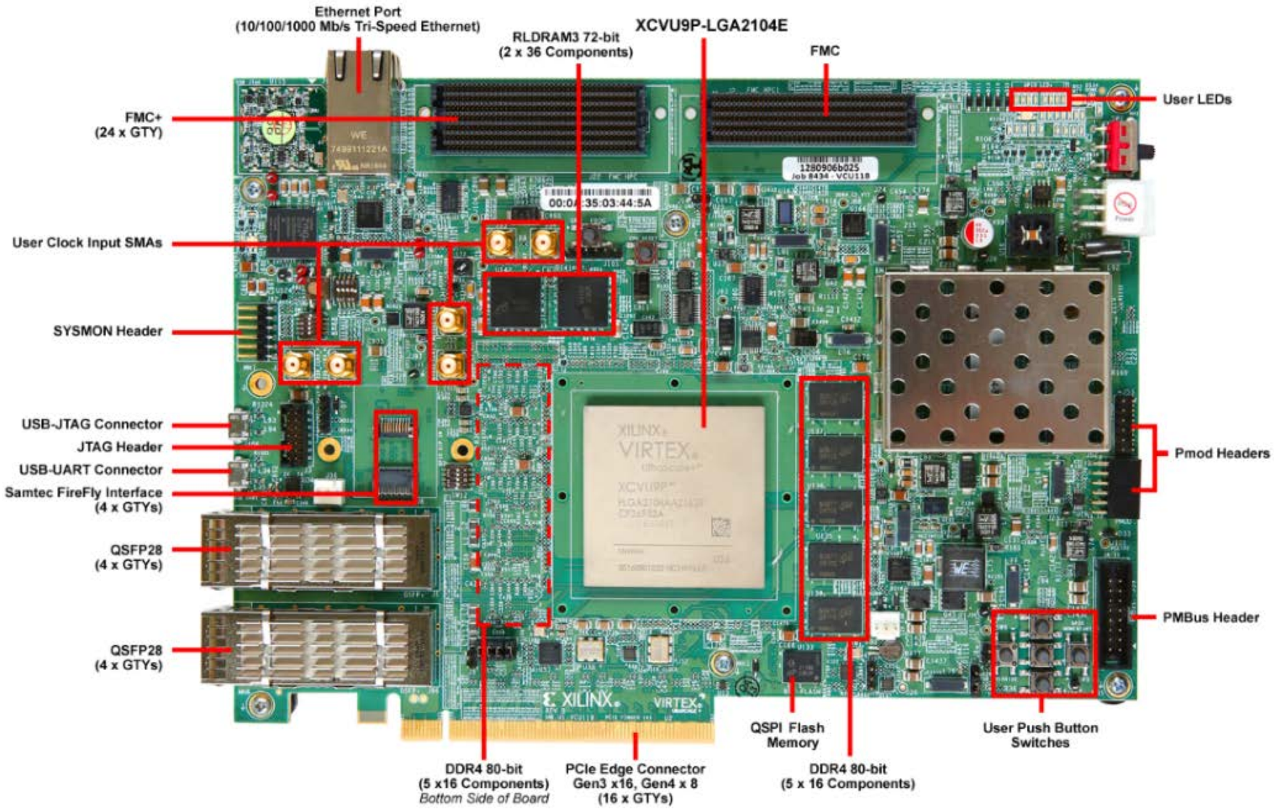

Figure 10 - Xilinx VCU118 evaluation board including an XCVU9P FPGA with 300+ Mb of BRAM. The prospective PE computing node will include a second FPGA chip and will not require the PCI Express nor the FMC interfaces. The theoretical I/O bandwidth of the XCVU9P is almost 4 Tb/s full duplex.

Finally, the computational power of the latest FPGAs seems enough for the complexity of the signal processing tasks (filtering, detection, accumulation, etc.). For example, let us assume a beam-channel bandwidth of 2 MHz. Since the intra-channel dispersion is bigger for smaller RF frequencies, the worst case for ngVLA corresponds to its minimum RF frequency, which is 1.2 GHz. The time difference at the highest DM required (4,000 $cm^{-3}pc$) and this frequency becomes [RD03]:

$$\Delta t \simeq 4.15 \times 10^6 \text{ ms} \times (f_1^{-2} - f_2^{-2}) \times \text{DM} = 38.33 \text{ ms}$$

Thus, a de-dispersion filter of at least 16,770 taps is required. Whereas FFT libraries are most efficient for radix-2 algorithm, the required FFT length for such a long filter is 2^{16} points. As a result, the total number of FFT-butterfly operations per input sample is 16. Since the number of floating-point operations per second (FLOPS) per (radix-2) FFT-butterfly is ten, 160 FLOPS/sample are required.

This result does not consider simplifications thanks to trivial twiddle factors that reduce the number of operations. Then, the pre-computed frequency transform of the de-dispersion is applied. Since the FFT length is twice the number of new input samples, two complex multiplications must be computed per input sample, resulting in additional six FLOPS/sample. Then, an inverse FFT must be performed on the filtered data, which adds 160 FLOPS/sample to the filtering process.

Again, further simplifications in the IFFT computation and the overlap-save method are possible. Obviating those, the overall number of operations for the de-dispersion filtering process results in 326 FLOPS/sample.

After coherent de-dispersion, pulse profiles are computed by accumulation of Stokes parameters as a function of the pulse phase. Computation and accumulation of Stokes parameters takes 18 FLOPS per polarization pair of samples, or 9 FLOPS/sample. In total, a minimum of 335 FLOPS/sample are required for computing average pulse profiles.

Considering now the input beam-bandwidth product, 2 GHz per polarization, and an oversampling factor for the CBF channelizer of 8/7, the required computational power is approximately 1.5 TFLOPS. The theoretical computational power of last generation FPGAs is several times this requirement, which should be achievable.

4.4.2.2 Pulsar Engine Design Based on SoC

In a long-life memory-bandwidth constrained application, it is not surprising that SoC devices become a well performing option. These "embedded" GPUs provide a memory bandwidth similar to high-performance GPUs, while trading computational power for a reduced power consumption.

This specific PE design solution proposed is based on the NVIDIA Jetson Xavier module, shown in Figure 11. In terms of memory bandwidth, this SoC provides up to 137 GB/s access through a 256-bit bus to 16 GB of LPDDR4 memory. Since the memory required to perform one 2^{16}-point FFT exceeds the cache size of NVIDIA's Volta architecture, a two-stage FFT algorithm is considered for the de-dispersion filter.

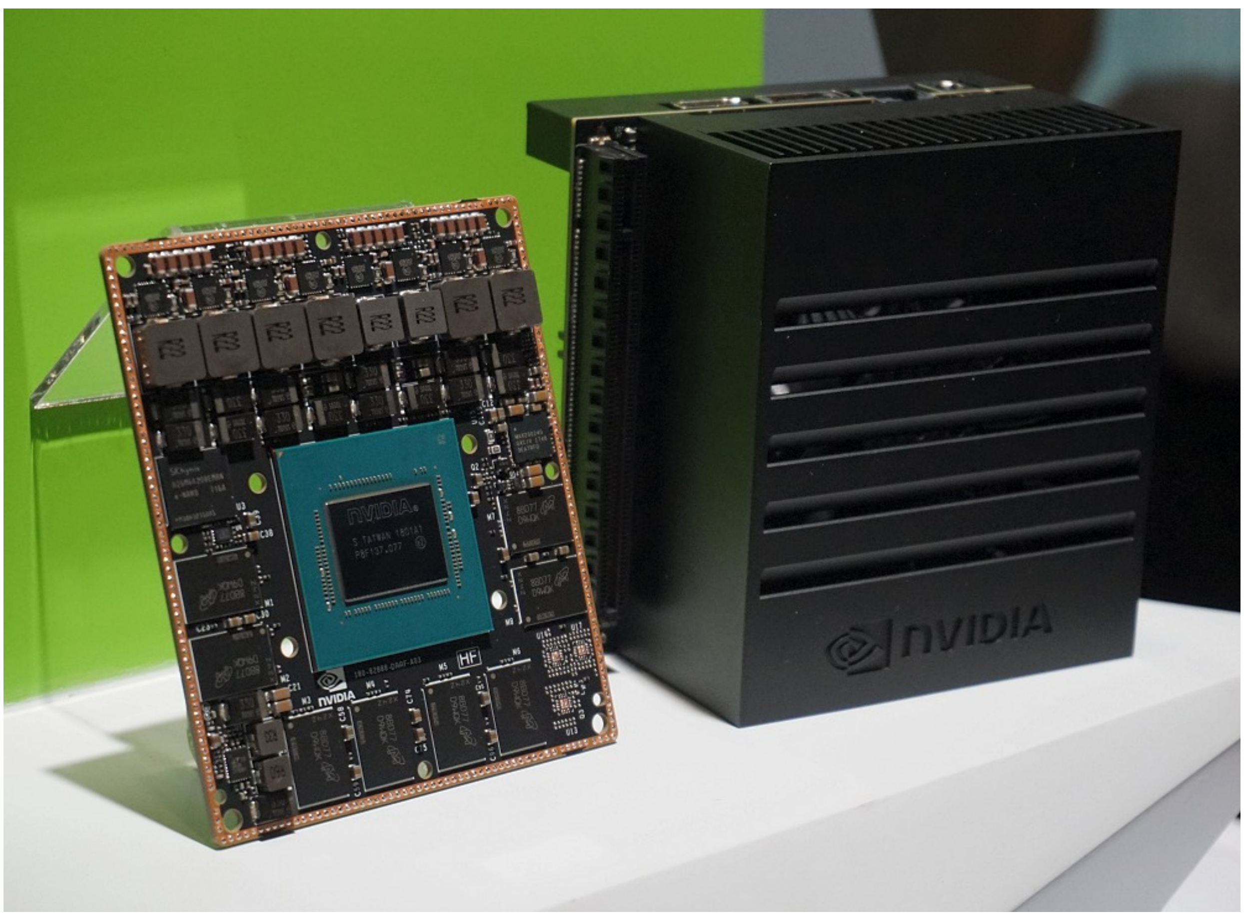

Figure 11 - NVIDIA's Jetson Xavier SoC module (left) and the Jetson Xavier development kit (right).

In one single precision implementation, the number of bytes read from memory for every polarization pair input sample are at least 228 bytes per input pair[4]. Thus, to process a dual-polarization 200-MHz beam, with an 8/7 oversampling factor in the channelizer, the required memory bandwidth is at least 45.6 GB/s. As a result, one Jetson Xavier has the memory bandwidth to potentially process three beams.

As regards the I/O bandwidth, the fastest input interface available is PCI express Gen4, x8, which can allocate up to 15.75 GB/s. Even at 64 bits per input sample (complex, single precision), three dual-polarization 200-MHz beams, oversampled with an 8/7 factor, would only take 5.5 GB/s. Thus, memory bandwidth is a more critical parameter.

Similar results can be found in terms of computational power. With a 512-core Volta GPU, the Jetson Xavier SoC has a peak performance of 1.3 TFLOPS, enough to process at least five times what is required by the de-dispersion filter at 2-MHz channelization, 8/7 oversampling factor, and the input beam-bandwidth product. This should provide enough room as peak performance could hardly be achieved in practice.

Other GPU-based systems, namely the UTMOST beamformer and the CHIME X-engine, achieve a computing efficiency of about 55% and 82%, respectively. For that reason, this design exercise assumes a conservative computing efficiency around 20%.

Finally, Figure 12 shows a simplified layout for the described SoC-based PE computing node. In this first estimate, the entire 4-GHz beam-bandwidth product (2 GHz per polarization) generated from one FSP is distributed over four SoCs so that each SoC processes 2.5 beams (note that the 200-MHz beams are received split into beam-channels, which are then distributed). A mid-range FPGA is required to convert I/O data streams from 40GbE to PCI Express 4.0, and vice versa. The FPGA has enough connectivity to add external memory for I/O buffering if needed.

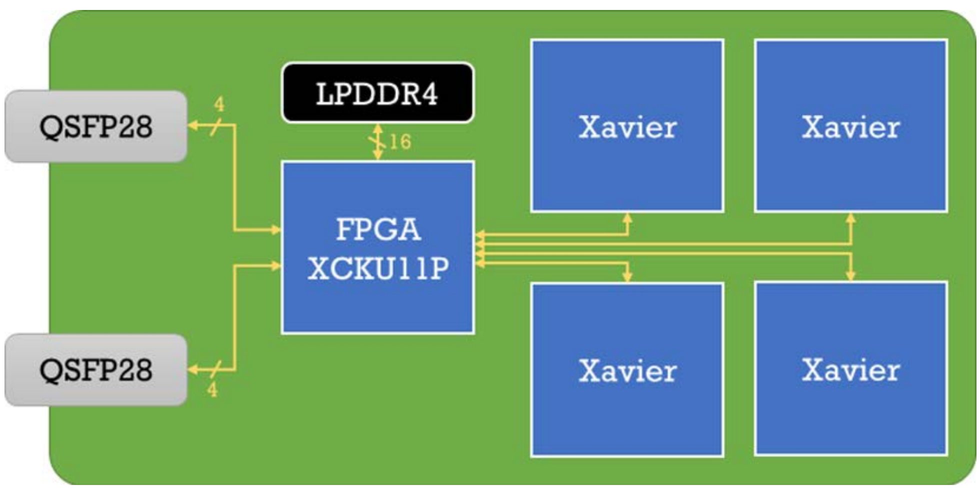

Figure 12 - Simplified layout of a PE computing node (one LRU) based on NVIDIA's Jetson Xavier SoC.

The generated data products can be output through the 1GbE interfaces available at each SoC or, as the preferred option, through the input interface whenever there is enough bandwidth to do so, as all communication links are bidirectional. Figure 12 represents one computing node implemented as a single LRU, which can be made to fit within the CBF racks.

[4] This can be broken down as follows: 4 bytes for the integer to float conversion, 32 bytes for each stage of the FFT, 64 bytes for the multiplication with the filter coefficients, 32 bytes for each stage of the inverse FFT, and 32 bytes for the Stokes parameter computation and accumulation.

4.5 Interfaces with Other Subsystems

Definition of interfaces with other subsystems is at an early stage, and most of this section is TBD. The CSP interfaces the following subsystems: the DBE, the CBE, the M&C subsystem, the Timing subsystem, the LO Reference subsystem, and the Central Electronics Building.

4.5.1 Interface with the Digital Back End

The CSP has 6 x 100GbE inputs per antenna (two inputs per trident) from the DBE (1,716 inputs for the full array) that connect directly to the CBF. Using 4-bit quantization, each input carries either 10-GHz single-polarization or 5-GHz dual-polarization data; 8-bit quantization is allowed for 5-GHz single-polarization data. It is assumed that the DBE/DTS system will convert from the ADC format to the CSP format.

4.5.2 Interface with the CSP Back End

The amount of data the CSP can generate and deliver at full specification is orders of magnitude above what the CBE can handle. Sizing the CBE for the worst case has a huge impact on cost, and it is not required in the use cases identified in the Reference Observing Program [AD01]. As a result, this interface has been designed to accommodate the worst case in said Program: an aggregate bandwidth of 85 GB/s.

The aggregation of data at the CSP is made through internal 10GbE to 40GbE switches which connect to every FSP LRU (10GbE), a PE LRU when applicable (40GbE), and the external output switched network (40GbE). In the Reference Observing Program, the worst-case single-FSP bandwidth fits tightly within 3 x 10GbE interfaces, but a 40GbE output per FSP relaxes requirements and simplifies the output cabling. However, scaling this figure to 150 FSPs results in an aggregate bandwidth four times that required. Therefore, an external output switched network is needed for aggregating the output data from at least six FSPs together into the 25 x 40GbE CBE input interface.

4.5.3 Interface with the Monitor and Control Subsystem

This design assumes a local M&C component within the CSP, which is not included in this design because it is a small component in terms of estimated cost and power. This component will govern local CSP control and serves as the sole interface to the M&C subsystem, processing higher-level commands into lower level commands suitable for configuring the CSP electronics. In addition, the local M&C shall provide monitor data defining the current condition of key monitor points that describe the overall health and status of the correlator. Some general notions about this subsystem can be found in [RD01].

4.5.4 Interface with the Timing and LO Reference Subsystems

Input data is expected to arrive timestamped. This is a requirement to support packet loss at the data transport system. A 100-MHz reference will be required to generate clock signals internally. A 1-PPS signal in sync with such reference will be required to solve clock ambiguity within 1 second intervals.

4.5.5 Interface with the Central Electronics Building

All CSP connections to the electrical infrastructure use three-phase, 208 V, 60 Hz power, which will be provided to the CSP room. The service size is about 2 MW. The design assumes the building will provide UPS capability, lightning and brownout protection, and a HVAC system. Direct Contact Liquid Cooling is the preferred cooling option for efficiency, lifetime, and maturity of COTS supporting technology. Further details can be found in [RD01].

This design assumes the building will provide a shielded room, with attenuation dependent on the correlator electronics emissions. It also assumes the building will provide a fire suppression system.

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
BRAM	Block Random Access Memory
CBE	CSP Back End
CBF	Correlator and BeamFormer
COTS	Commercial off-the-Shelf
CSP	Central Signal Processor
DBE	Digital Back End
DDR4	(RAM) Double Data Rate, 4th generation
FFT	Fast Fourier Transform
FLOPS	FLoating-point OPerations per Second
FM	(FSP) Function Mode
FMC	FPGA Mezzanine Card
FPGA	Field-Programmable Gate Array
FRB	Fast Radio Burst
FS	(CBF) Frequency Slice
FSA	(CBF) Frequency Slice Architecture
FSP	(CBF) Frequency Slice Processor
Gb/s	Gigabit per second
GPU	Graphical Processing Unit
HBM2	High Bandwidth Memory, 2nd generation
HVAC	Heating, Ventilation, and Air Conditioning
I/O	Input/Output
KSG	Key Science Goal
LCS	Local Control System
LPDDR4	(RAM) Low Power DDR4
LRU	Line Replaceable Unit
M&C	Monitor and Control
MPO	Multi-fiber Push On
NRC	National Research Council (Canada)
OM	(CSP) Observing Mode
PCI	Peripheral Component Interconnect
PE	Pulsar Engine
PPS	(1-PPS) Pulse Per Second
RAM	Random Access Memory
RD	Reference Document
RFI	Radio Frequency Interference
SKA	Square Kilometre Array
SoC	System on Chip
UPS	Uninterruptible Power Supply
VCC	(CBF) Very Coarse Channelizer
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry

5.2 Comparison Table of Candidate Technologies for the Pulsar Engine

Platform	GFLOPS SP	GFLOPS DP	Cost	Watts	GFLOPS/$ SP	GFLOPS/W SP	GFLOPS/$ DP	GFLOPS/W DP	Chip codename	GB/s	MB/s/$	2-MHz Channels	Beams	Input Gbps	CUDA	MHz/$	Units per FSP	Units	kW	20yr @ 15 ¢/kWh	HW Cost	Total	Rank
NVIDIA DGX-1	141,600	62,400	210,000	3,500	0.7	40.5	0.3	17.8	V100	7,200	34	-	10	64.0	7.0	0.010	1	44	154	4,049,892	9,240,000	13,289,892	**20**
NVIDIA Tesla V100 SXM2	15,700	7,800	10,000	300	1.6	52.3	0.8	26.0	V100	900	90	1,000	10	64.0	7.0	0.200	1	44	13	347,134	440,000	787,134	**8**
NVIDIA Jetson Xavier	1,300		1,000	50	1.3	26.0	-	-	GV10B?	137	137	262	3	16.0	7.0	0.500	4	176	9	231,422	176,000	407,422	**2**
NVIDIA Tegra X2 (Parker)	665		**800**	20	0.8	33.3	-	-	GP10B	60	75	114	1	7.1	6.2	0.278	9	396	8	208,280	316,800	525,080	**3**
NVIDIA Tegra X1	512		550	20	0.9	25.6	-	-	GM20B	26	47	49	0	3.0	5.3	0.173	21	924	18	485,987	508,200	994,187	**16**
NVIDIA Titan V	14,000	7,000	4,600	350	3.0	40.0	1.5	20.0	GV100-400	653	142	1,000	10	64.0	7.0	0.435	1	44	15	404,989	202,400	607,389	**4**
NVIDIA GTX 1180	*13,000*		*1,700*	*300*	*7.6*	*43.3*	*-*	*-*	*GT104*	*512*	*301*	*982*	*5*	*32.0*		*0.588*	*2*	*88*	*26*	*694,267*	*149,600*	*843,867*	*11*
GeForce GTX 1080 Ti	11,300		1,700	350	6.6	32.3	-	-	GP102-350	484	285	928	5	32.0	6.1	0.588	2	88	31	809,978	149,600	959,578	**14**
GeForce GTX 1080	9,000		1,100	280	8.2	32.1	-	-	GP104-4x0	320	291	614	5	32.0	6.1	0.909	2	88	25	647,983	96,800	744,783	**7**
GeForce GTX 1070	6,500		783	250	8.3	26.0	-	-	GP104-200	256	327	491	3	21.3	6.1	0.851	3	132	33	867,834	103,400	971,234	**15**
GeForce GTX 1060 3GB	3,935		500	220	7.9	17.9	-	-	GP106-300	192	384	368	3	21.3	6.1	1.333	3	132	29	763,694	66,000	829,694	**10**
GeForce GTX 1050	1,862	58	277	175	6.7	10.6	0.2	0.3	GP107-300	112	405	214	2	12.8	6.1	1.446	5	220	39	1,012,473	60,867	1,073,340	**17**
GeForce GTX 980 Ti	5,632	176	1,650	350	3.4	16.1	0.1	0.5	GM200	336	204	644	5	32.0	5.2	0.606	2	88	31	809,978	145,200	955,178	**13**
AMD FirePro W9100	5,240	2,620	2,400	260	2.2	20.2	1.1	10.1		320	133	614	5	32.0		0.417	2	88	23	601,698	211,200	812,898	**9**
Radeon R9 290X	5,632	704	1,050	250	5.4	22.5	0.7	2.8		320	305	614	5	32.0		0.952	2	88	22	578,556	92,400	670,956	**5**
Radeon R7 260X	1,971	123	283	115	7.0	17.1	0.4	1.1		104	368	199	2	10.7		1.178	6	264	30	798,407	74,674	873,082	**12**
9 beams per HBM2-FPGA	27,565		11,000	50	2.5	551.3	-	-	XCVU37P	460	42	882	5	32.0		0.091	2	88	4	115,711	968,000	1,083,711	**18**
10 beams (210 Mb UltraRAM)	49,000		7,700	40	6	1,225	-	-	XCVU9P	-	-	-	10	64.0		0.260	1	44	2	46,284	338,800	385,084	**1**
9 beams (290 Mb UltraRAM)	49,000		70,000	40	1	1,225	-	-	XCVU13P	-	-	-	9	57.6		0.026	2	88	4	92,569	6,160,000	6,252,569	**19**
HCM (120GB/s)			2,000	50			-	-	XCKU035	120	60	230	2	12.8		0.200	5	220	11	289,278	440,000	729,278	**6**

TRIDENT-CBF

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E	2018-09-18	DRAFT for final review. Flesh out some sections including thermal performance, use latest TALON-DX pricing from Mike. Fill in future power and cost estimates.	B. Carlson
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Table of Contents

1 Introduction 10
2 Applicable and Reference Documents 12
2.1 Applicable Documents 12
2.2 Reference Documents 12
3 System Overview 14
4 System Requirements 20
4.1 Functional Requirements 20
4.2 Interface Requirements 27
4.3 Control and Monitor Requirements 29
4.4 Performance Requirements 29
4.5 Environmental Requirements 31
4.6 Reliability and Maintenance Requirements 32
4.7 Other Requirements 33
5 System Architecture 35
5.1 Simplified Overview 35
5.2 Signal Processing Architecture 37
5.2.1 VCC-part Processing 37
5.2.2 FSP-Part Processing 38
5.2.2.1 Re-Sampler (and delay/phase tracker) 38
5.2.2.2 Tunable DDC 39
5.2.2.3 16k Critically-sampled Imaging Channelizer 41
5.2.2.4 1k Critically-sampled “simultaneous visibilities” Channelizer 41
5.2.2.5 256-pnt Oversampling Channelizer Response 43
5.2.2.6 RFI Detector-Flagger 43
5.2.2.7 Other Signal Processing Blocks 44
5.3 Physical Architecture 45
5.3.1 VCC-UNIT 45
5.3.2 FSP-UNIT 48
5.3.3 TALON LRU 51
5.3.4 Passive Fiber Meshes (VCC-MESH, FSP-MESH) 52

5.3.5 Timecode Distribution 54
5.3.6 Hardware Packaging and Installation 54
5.4 Software/Control and Monitor Architecture 56
6 Technologies 57
6.1 TALON-DX Board and TALON LRU 57
6.2 Passive Fiber Meshes 60
6.3 Direct Contact Liquid Cooling (DCLC) 60
6.4 Other Rack Components 62
7 Performance 63
7.1 Signal Processing 63
7.2 Thermal 67
8 Reliability, Availability, Maintainability 70
8.1 Reliability 70
8.2 Availability 70
8.3 Maintainability 70
9 Environmental 72
10 Safety 73
11 Manufacturing and Procurement Plan 74
12 Testing and Deployment Plan 75
13 Development, Construction, and Operational Cost 76

List of Figures

Figure 3-1 Overview block diagram of the Trident-CBF system. 14
Figure 3-2 Fundamental data flow of each FSA trident. 15
Figure 3-3 FSA Frequency Slice processing diagram for each trident. 16
Figure 3-4 Trident-CBF simplified signal flow diagram. 19
Figure 5-1 Simplified block diagram of each trident in Trident-CBF. 36
Figure 5-2 Example VCC-OSPPFB output channel (from SKA Mid.CBF, Band 5). (Upper-left: zoomed-in linear magnitude response; lower-left: zoomed-in magnitude response dB; upper-right: magnitude

response dB; lower-right zoomed-in magnitude response transition band dB.) Not shown is that the phase response is linear (0) across the passband. 38

Figure 5-3 Effective average transfer function of the re-sampler/delay-tracker. 39

Figure 5-4 Tunable DDC efficient implementation block diagram. 40

Figure 5-5 Zoom Window tunable DDC output for a FS/32 width. 40

Figure 5-6 16k imaging channelizer response. 41

Figure 5-7 End-to-end channel response of the Zoom Window signal chain after application of channel gain correction factors. 42

Figure 5-8 Channel response of the 1k channelizer for simultaneous visibilities with beamforming. 42

Figure 5-9 RFI detector-flagger. 43

Figure 5-10 Post-correlation, high time-resolution RFI detector-flagger. 44

Figure 5-11 Simplified diagram of the VCC-UNIT. 45

Figure 5-12 VCC-UNIT internal connectivity to TALON-DX boards and the VCC-MESH. 46

Figure 5-13 VCC-MESH LRU connectivity. 47

Figure 5-14 FSP-UNIT simplified block diagram. 48

Figure 5-15 FSP-UNIT internal connectivity to TALON-DX boards and the VCC-UNIT(s). 49

Figure 5-16 FSP-MESH internal connectivity between TALON-DX boards. Although the FSP-UNIT can ingest up to 286 inputs, correlation and beamforming is only provided for the required 263. 50

Figure 5-17 Rendering of the 2U air-cooled 19” rack-mount TALON LRU for SKA Mid.CBF. The 1U DCLC LRU would be ½ the height. Note that this LRU has no front-rail mounting ears because of fiber routing space limitations; instead, it is mounted on custom slide rails in a 19” rack, and quick-lock secured to the rack at the back 52

Figure 5-18 Molex FlexPlane optical circuit—a passive optical cross-connect. 53

Figure 5-19 Leviton 5R1UD-S12 1U optical circuit enclosure. 53

Figure 5-20 Trident-CBF notional 42U 19” server rack population. If required, a 48U server rack could be used since there is no spare space available. 55

Figure 6-1 TALON-DX board simplified block diagram. 57

Figure 6-2 TALON-DX board layout diagram. The location of a stacked-fin heatsink for air cooling is indicated; for DCLC, a liquid cooling plate would be used instead, allowing for a 1U packaging height. 58

Figure 6-3 TALON-DX prototype board under test. 59

Figure 6-4 2U air-cooled TALON LRU prototype under test. The large orange boxes are copper stacked-fin heatsinks for air cooling. These would be replaced by liquid cooling plates for a liquid-cooled 1U DCLC design. 60

Figure 6-5 CoolT DCLC cold plate example showing the interior micro-fins for heat exchanging. For a DCLC TALON-DX, a customized plate like this would cover the FPGA, MBOs, and LVDC power supplies. 61

Figure 6-6 View looking down the stainless-steel manifold, located at the rear of the rack. The manifold provides the interface between the cold plate attached to the FPGA (etc.) and the CHx40 heat exchanger. The manifold has a supply and return side, providing 2 hoses to each TALON-DX board (i.e. 4 per LRU). 61

Figure 6-7 CoolIT CHx40 liquid-to-liquid heat exchanger. Dual 1+1 redundant circulating pumps are located in this unit. If a failure is detected, all of the LRUs in the rack must be powered down, but with dry quick connect/disconnects, this unit can be quickly replaced. It also has an Ethernet network connection to allow its status to be continuously monitored. 62

Figure 7-1 End-to-end imaging correlation result with a strong in-FS RFI tone (at 30 dB power relative to the total noise power into an 8-bit digitizer) in the Frequency Slice. Here, the green trace is the quantized (Q) cross-correlation result (i.e. representative of the actual implementation) with ~99% correlation efficiency, per-channel gain/ripple corrections applied, and showing over 100 dB of SFDR (U=floating point/un-quantized model) with some RFI amplitude reduction due to earth-rotation phase wrapping. Note that in this plot the edges of the FS are near the center, and there is a deliberate uncorrelated portion of the FS from channel index ~8500 to ~13500. 63

Figure 7-2 Auto-correlation and cross-correlation noise spectra for digitizer input signals containing a single tone of power 20 dB (top), 30 dB (middle) and 40 dB (bottom) without (left) and with (right) scrambling (dithering) in the Re-Sampler phase/delay correction. 64

Figure 7-3 Sensitivity across the sampled (channelized) bandwidth for phase-delay beamforming ("realizable"=quantized realized signal processing chain). Here for SKA1 Mid.CBF, the bandwidth is ~330 MHz and the aperture is 20 km, with one antenna on either side of it. For the ngVLA this corresponds to a ~40 km aperture, a 220 MHz FS bandwidth, and less beam offset from boresight due to the narrower primary beam of the ngVLA antenna. The ripple across the band is uncorrected and due to the VCC-OSPPFB response (see Figure 5-2). 65

Figure 7-4 Sensitivity of true-delay beamformed real output for 2 antennas across the FS sampled bandwidth of 224 MHz, shifted by ~10 MHz in frequency (hence the asymmetry of the incoherent regions). Here, +/- frequencies of the spectrum of the FS are shown and ripple is due to the VCC-OSPPFB. The apparent >100% sensitivity is due to a modelling anomaly in the sensitivity calculation relative to a single antenna receiving the same signal. 66

Figure 7-5 Sensitivity of a true-delay 128 MHz VLBI beam-channel output. The signal is real and aliasing occurs at the band edges (noted with dashed vertical lines) due to the beam-channel tunable DDC finite transition bands. Ripple is due to the VCC-OSPPFB response. 67

Figure 7-6 Cooling capacity curves for the CoolIT CHx40. Trident-CBF is expected to require 20 kW of cooling capacity per rack which, at a facility water temperature of 40 ^{o}C, requires a flow rate of ~40 L/min. The CHx40's power consumption is ~120W. 68

Figure 7-7 CHx80 cooling capacity curves. The CHx80's power consumption is ~625W. 69

Figure 13-1 Trident-CBF cost summary, based on the SKA1 Mid.CBF cost model, 2018 dollars. This is for 6 TALON LRUs per VCC-UNIT, 24 VCC-UNITs, and 13 TALON LRUs per FSP-UNIT. 77

Figure 13-2 Trident-CBF cost summary (2018 dollars) for the 5 TALON LRUs per VCC-UNIT, 28 VCC-UNITs, and 14 TALON LRUs per FSP-UNIT option mentioned as a note to Figure 5-1. 77

List of Tables

Table 2-1 Applicable Documents 12
Table 2-2 Reference Documents 12
Table 3-1 Trident-CBF FSP beamforming Function Modes 18
Table 4-1 Trident-CBF functional requirements 20
Table 4-2 Trident-CBF interface requirements 27
Table 4-3 Trident-CBF control and monitor requirements 29
Table 4-4 Trident-CBF performance requirements 29
Table 4-5 Trident-CBF environmental requirements 31
Table 4-6 Trident-CBF reliability requirements 32
Table 4-7 Trident-CBF other requirements 33

Definitions, Acronyms, and Abbreviations

ADC – Analog to Digital Converter.

CBF – Correlator and Beamformer.

COTS – Commercial Off-the-Shelf.

CSP – Central Signal Processor.

DCLC – Direct Contact Liquid Cooling.

DDC – Digital Down Converter.

DDR – Double Data Rate.

EMI – Electro-Magnetic Interference.

EVLA – Expanded Very Large Array.

FinFET – "Fin" Field Effect Transistor. Also known as "Tri-gate" or "3D silicon".

FPGA – Field Programmable Gate Array.

FS – Frequency Slice.

FSA – Frequency Slice Architecture.

FSP – Frequency Slice Processor.

HBM – High Bandwidth Memory.

HPBW – Half Power Beam Width.

HPS – Hard Processor System.

JM – Jones Matrix.

LRU – Line-Replaceable Unit.

M&C – Monitor and Control.

MBO – Mid-Board Optics.

MT/s – Mega Transfers per second.

MTBF – Mean Time Between Failures.

MTP – Brand of fiber connector containing x12 fibers.

ngVLA – Next Generation Very Large Array.

NRE – Non-Recurring Engineering (costs).

OSPPFB – Oversampling Poly-Phase Filterbank.

QSFP28 – Quad Small Form factor Pluggable, 28 Gbps/line (4 lines).

PDU – Power Distribution Unit.

RFI – Radio Frequency Interference.

SCFO – Sample Clock Frequency Offset.

SERDES – Serializer/Deserializer.

SFP – Small Form-actor Pluggable.

SKA1 Mid – Square Kilometer Array phase 1 Mid-frequency telescope array.

TALON – Name of the CBF for SKA1 Mid, “SKA1 Mid.CBF”.

TALON-DX – Name of the FPGA PCB assembly for SKA1 Mid CBF, providing the function/performance/cost basis for Trident-CBF.

TBC – To Be Confirmed.

TBD – To Be Defined.

Trident-CBF – The name of the proposed system described in this document.

VCC – Very Coarse Channelizer. The name of the one major processing step in the FSA.

VDIF – VLBI Data Interchange Format.

VLBI – Very Long Baseline Interferometry.

WIDAR – Wideband Interferometric Digital Architecture.

1 Introduction

This design specification defines the requirements, presents the design, and estimates the cost and power of a "Trident" correlator and beamformer ("Trident-CBF") system for the ngVLA. Key aspects of this system are as follows:

- Employs the NRC Frequency Slice Architecture (FSA), developed for the SKA1 Mid telescope array CBF (Mid.CBF), to provide a scalable high-performance system that meets and in many cases far exceeds ngVLA requirements, including 30 GHz/pol of bandwidth processing. Some corner-case requirements aren't technically met, but in practise, significant hardware savings are realized while providing considerable observing flexibility, compared with a design that strictly meets the corner cases (e.g. see TCBF-0007 in Table 4-1 on p.21).
- Poly-phase FX correlation for superior spectral performance, including ~80 dB of channel-to-channel isolation, seamless linear channel spacing across the digitized input bandwidth, tunable zoom window selection, and post-correlation channel averaging.
- Phase-delay beamforming for large numbers of beams on a ~40 km diameter restricted array aperture. True-delay beamforming for fewer beams to allow for an unlimited aperture for maximum tied-array output sensitivity.
- With antenna incoherent clocking [RD1] or SCFO (Sample Clock Frequency Offset sampling), spectral confinement of RFI, decorrelation of all digitizer clock frequency-dependent artefacts including those from interleaved sampling, and virtually unlimited SFDR[1] (Spurious Free Dynamic Range).
- Virtually 100% correlation and beamforming efficiency to facilitate maximum telescope sensitivity, even in an extreme RFI environment.
- Delay and phase tracking are performed virtually perfectly with no need for post-correlation or post-beamforming corrections.
- Beamforming Jones Matrix corrections for application of offset parabola polarization corrections.
- VLBI tied-array outputs in VLBI-standard VDIF format.
- Costed for 263 antenna, 30 GHz/pol capability but with fundamental physical architectural capable of handling up to 484 antennas with unlimited bandwidth in 10 GHz/pol swatches.
- Huge output bandwidth capability; an output switch, not included in this costing, is required to ingest and route these data to the archive.
- DCLC (Direct Contact Liquid Cooling) for maximum reliability and minimum total power use.

The estimated cost of the Trident-CBF system, using c. 2018 technology (Intel 14 nm FinFET FPGAs) is ~$130 M USD (2021 FPGA costs, 2018 dollars, see Section 13), including NRE and contingency. Power is estimated at ~1.5 MW. Considerable development has gone into these estimates largely leveraging the approximately 60 person-years of pre-construction effort for the SKA1 Mid.CBF system.

[1] Provided the antenna digitizer doesn't saturate.

If constructed in the ~2025 timeframe, the cost could reduce to a range of $108M to $121M (2018 dollars), based on FPGA cost multiplier factors of 0.5 and 0.8 and 900-1200 kW of power consumption based on power savings projections from Intel's FinFET devices available at that time.

2 Applicable and Reference Documents

2.1 Applicable Documents

The following documents at their indicated revision form part of this document to the extent specified herein.

Table 2-1 Applicable Documents

Ref No	Document/Drawing Number	Document Title	Issue Number
AD1	020.40.00.00.00-0001-SPE	ngVLA Central Signal Processor: Preliminary Technical Specifications, 09/10/2018.	08
AD2			

2.2 Reference Documents

The following documents provide useful reference information associated with this document. These documents are to be used for information only. Changes to the date and/or revision number do not make this document out of date.

Table 2-2 Reference Documents

Ref No	Document/Drawing Number	Document Title	Issue Number
RD1		Carlson, B.R., Incoherent clocking in coherent radio interferometers, *IEE Electronics Letters* (2018), 54 (14):909.	
RD2		Carlson, B., Gunaratne, T., Signal processing aspects of the sample clock frequency offset scheme for the SKA1 mid telescope array, 32nd URSI GASS, Montreal, 19-26 August 2017.	
RD3	SKA-TEL-CSP-00000069 311-000000-007	SKA1 CSP Mid Array Correlator and Central Beamformer Sub-element Signal Processing MATLAB Model (EB-7), 2018-08-16.	4
RD4		The TANGO Control System Manual	9.2

		http://ftp.esrf.fr/pub/cs/tango/tango_92.pdf	
RD5	SKA-TEL-CSP-00000066 311-000000-003	SKA1 CSP Mid Correlator and Beamformer Sub-element Detailed Design Document (EB-4a), 2018-07-26	2

3 System Overview

An overview block diagram of the Trident-CBF system is shown in Figure 3-1:

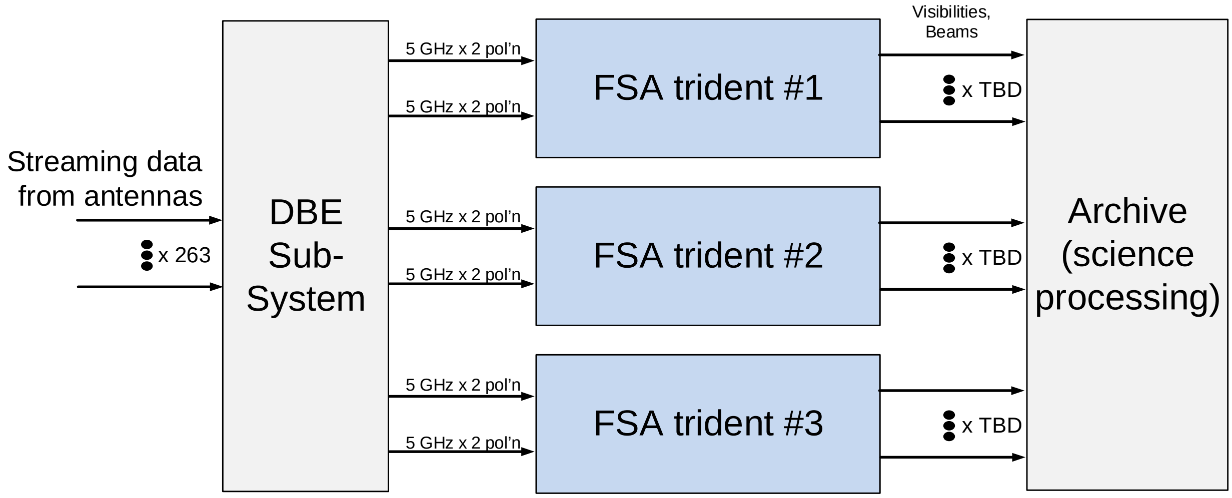

Figure 3-1 Overview block diagram of the Trident-CBF system.

In this architecture, three identical FSA tridents[2] are provided, each having 10 GHz/pol of ingest and correlation/beamforming processing capacity. The output from each trident feeds the archive via an external switch (not shown in the figure).

The fundamental data flow of *each* FSA trident is illustrated in Figure 3-2, with an associated Frequency Slice (FS) processing diagram shown in Figure 3-3. In these figures:

- The 10 GHz/pol (i.e. @ 4+4b sampling; 5 GHz/pol @ 8+8b sampling, with a separate FPGA bitstream for each such sampling mode) of ingest bandwidth is divided, via VCCs (Very Coarse Channelizers, one for each antenna), into up to 50 x 200 MHz (of processed bandwidth[3]) FSs, oversampled to 220 MHz of sampled bandwidth. Each FS is oversampled and overlaps with adjacent slices such that correlation and beamforming output data, when concatenated in frequency, are seamless across the input digitized bandwidths[4] with no undue anomalies in amplitude, phase, or sensitivity at the overlap boundaries. The VCCs additionally contain bulk coarse delay tracking[5] corrections, allowing each FSP to perform delay and phase corrections suited to its needs.

---

[2] Note that a "trident" refers to an individual 1/3rd of the entire system. "Trident-CBF" is the name of the entire system consisting of all 3 tridents.
[3] Processed bandwidth is defined as bandwidth, however processed, that is science-quality and delivered to the archive.
[4] The "digitized bandwidth" refers to the raw bandwidth out of a physical ADC digitizer, i.e. the antenna digitizers. When the term "sampled bandwidth" is used, it is similar but is the output from an entirely logic/digital process.
[5] Steps of many samples, updated relatively infrequently, using bulk memory external to the FPGA. By doing so, active coarse delay tracking in the FSPs is performed on-chip, greatly simplifying implementation and maximally distributing external memory bandwidth needs across VCCs and FSPs.

- Via a switch built into each VCC, each FS may be routed to any FSP (Frequency Slice Processor) within its trident, including routing the same FS to multiple FSPs, or not processing select FSs at all. This affords considerable flexibility in how bandwidth is processed.
- Each FSP performs one "Function Mode" (correlation and various beamforming modes) for all sub-arrays processed in the FSP. The Function Mode configuration of each FSP is independent of all other FSPs.
- Output correlation and beamformed data products from the FSPs are routed to the archive via an external switch.

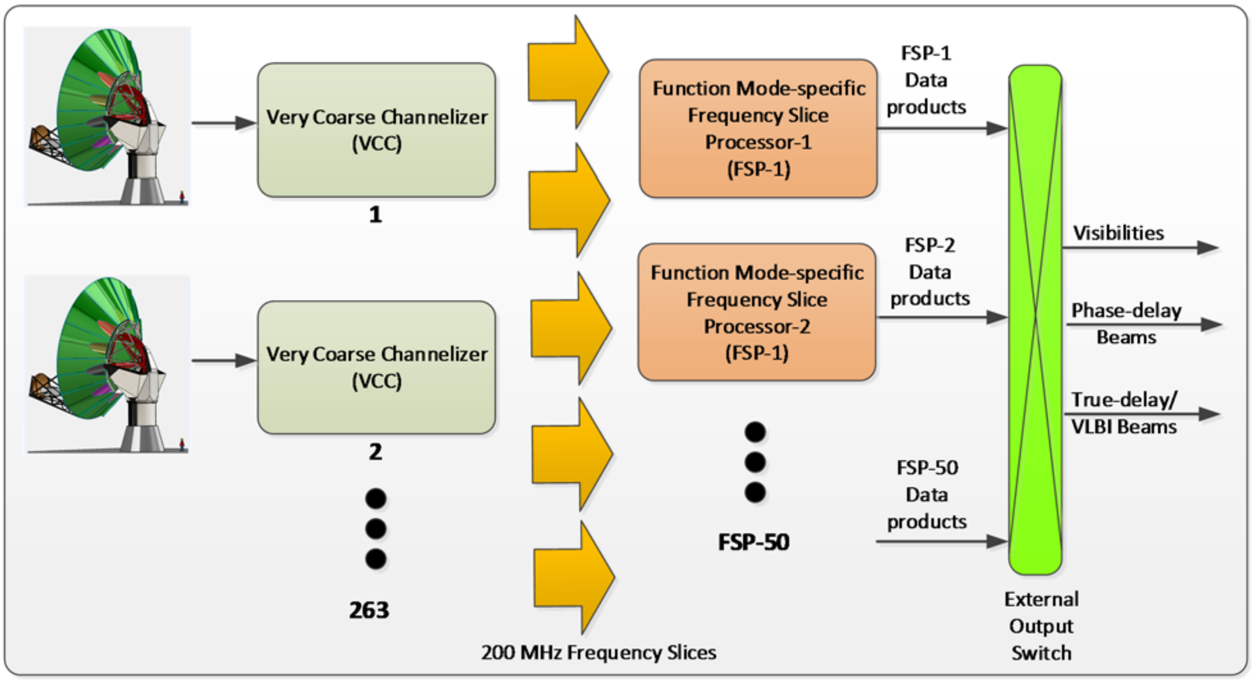

Figure 3-2 Fundamental data flow of each FSA trident.

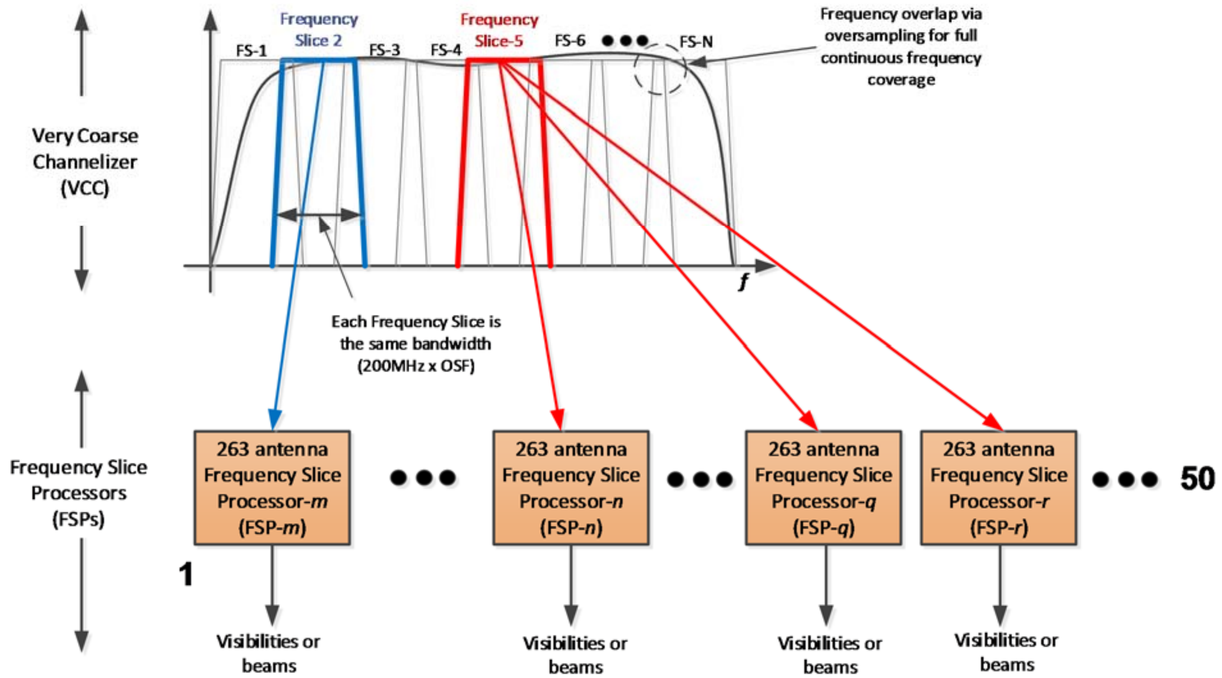

Figure 3-3 FSA Frequency Slice processing diagram for each trident.

Each FSP can be (FPGA-bitstream) independently configured to operate in exactly one "Function Mode", where these Function Modes have been specifically designed to meet ngVLA requirements [AD1], when the requisite FSPs are configured accordingly to meet required ngVLA Observing Modes [AD1]. ngVLA Trident-CBF Function Modes are briefly described below:

- **Correlation.** In this Function Mode, each sub-array performs normal channel resolution or zoom resolution cross-correlation including auto-correlation. At normal channel resolution, 16k channels across the FS sampled bandwidth of ~220 MHz are provided; at zoom resolution, for tunable filter sampled bandwidths of 220 MHz/2, /4, …, /64, the same number of channels are provided, thereby providing much higher spectral resolution. In both cases, post-correlation channel averaging can be used to reduce the delivered spectral channel resolution and therefore visibility output transport bandwidth.
- **VLBI.** In this Function Mode, Jones Matrix corrections are applied per antenna, followed by true-delay beamforming to form up to 4 dual-polarization beams with independent delay centers on the sky (within the beam of the antenna), each beam including any number of ngVLA antennas[6], with simultaneous correlation of 1k channel visibilities[7] for tied-array calibration solutions. After beamforming, Jones Matrix polarization corrections are applied to each beam, followed by tunable digital filters that can be used to select specific parts of the FS to ultimately be output as VLBI "beam-channels" at VLBI standard data rates in VDIF format to the archive.

[6] i.e. no beamforming aperture size restrictions.
[7] Note, with its own 1k critically sampled channelizer per antenna followed by correlation. i.e. visibilities are developed prior to beamforming for all antennas in the beamforming array.

- **Pulsar-True-Delay-4beam.** This is similar to the VLBI Function Mode except that after beamforming a 256-channel (up to 4k) oversampling channelizer is available on each beam with per-channel Jones Matrix corrections applied. Simultaneous correlation of 1k channel visibilities is also provided.
- **Pulsar-True-Delay-10beam-144ant.** Same as Pulsar-True-Delay-4beam, except 10 beams are produced from a pre-selected (hardwired -- i.e. specific antenna inputs into Trident-CBF) set of up to 144 antennas. Here, the number of antennas that can be beamformed is reduced to be able to increase the number of beams. Simultaneous correlation of 1k channel visibilities is also provided.
- **Pulsar-Phase-Delay-100beam.** Here, phase-delay beamforming is performed to produce a large number of beams very efficiently. As a consequence, the beamforming aperture diameter for any sub-array, to obtain required efficiency of each beam within the antenna primary beam, is restricted to ~40 km. Beamforming is performed on any number of antennas as long as the aperture diameter restriction is not exceeded. If beam offsets from boresight[8] are more restricted, the beamforming aperture can be increased accordingly. Here, no simultaneous correlation of 1k channel visibilities is performed in the FSP, relying on other FSPs being configured to provide correlation capability to develop tied-array calibration solutions.

Table 3-1 contains a list of all of the key capabilities of FSP beamforming Function Modes.

Figure 3-4 is a simplified overview signal flow diagram showing VCC processing and all of the Trident-CBF Function Modes. All processing is dual polarization. Note that each of the 3 tridents in the system:

- Provides processing for 10 GHz/pol of bandwidth.
- Provides 50 FSPs, each of which can be independently configured for each Function Mode.

[8] The main true-delay tracking delay center on the sky, typically in the center of the antenna primary beam.

Table 3-1 Trident-CBF FSP beamforming Function Modes

FSP Function Mode	Beam Steering	Aperture diameter	Beam offset from boresight	Nant	Beamforming Channelizer	Nbeams	JM per FS?	JM per ant?	JM per ch?	JM per bm?	Post-BF Channelizer	Post-BF JM?	Visibility Channelizer	Correlated vis per FS	Notes
VLBI	True-delay	no limit	Full antenna main BW	256	N/A	4/subarray (26 total)	Y	Y	N/A	Y	Multiple independently tunable DDCs, 1 for each beam-channel	Y: per-224 MHz beam	1k-CS on 1 beam	1k (across the 224 MHz OS FS)	Beam-channel output bandwidths of 1, 2, 4, 8, 16, 32, 64, 128, or 224 MHz.
Pulsar-True-Delay-4bm	True-delay	no limit	Full antenna main BW	256	N/A	4/subarray (26 total)	Y	Y	N/A	Y	256 OS	Y: per-OSchan	1k-CS on 1 beam	1k (across the ~220 MHz OS FS)	Post-beamforming channelizer could be any radix-2 up to perhaps 4k (bitstream compile-time-defined).
Pulsar-True-Delay-10bm-144ant	True-delay	no limit	Full antenna main BW	144	N/A	10/subarray (26 total)	Y	Y	N/A	Y	256 OS	Y: per-OSchan	1k-CS on 1 beam	1k (across the ~220 MHz OS FS)	144 antennas, selected from 2 broad pre-defined hardwired sub-arrays, with, for each group of 11 ants, 6 of 11 antenna selection. Post-BF channelizer could be any radix-2 to up
Pulsar-Phase-Delay-100bm	Phase-delay	40 km	Within antenna HPBW	BF-aperture limited	4k-CS	~100 tot	N	Y	Y	N	N/A	N	none	none	>40 km aperture possible: inversely proportional to beam offset from boresight. Simultaneous visibilities possible if only 10 beams are required.

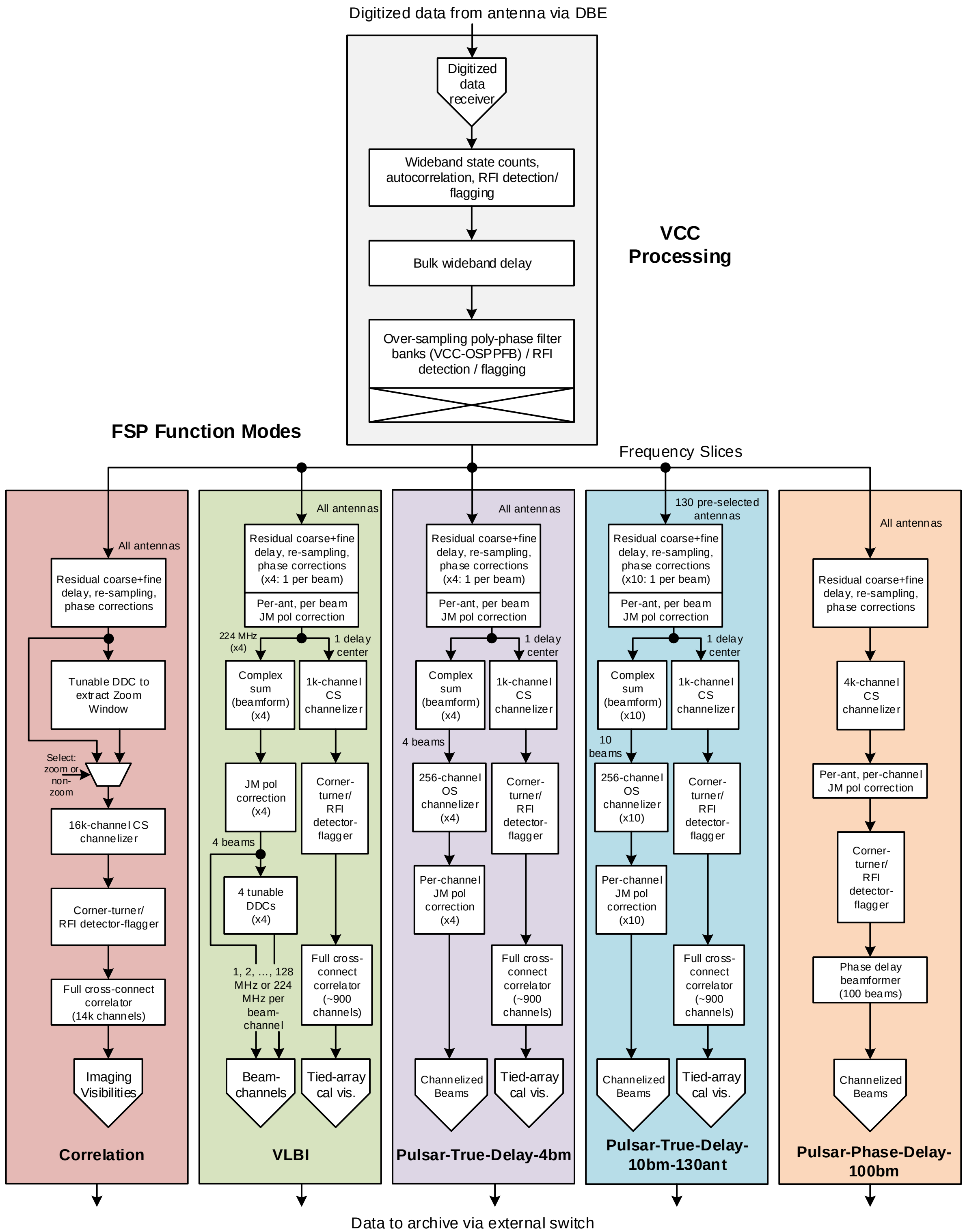

Figure 3-4 Trident-CBF simplified signal flow diagram.

4 System Requirements

This section develops requirements for the Trident-CBF system, with traceability to requirements as defined in [AD1]. Requirements are specifically defined in terms of the Trident-CBF FSA architecture outlined in Section 3, with further physical details in Section 5.3.

4.1 Functional Requirements

Table 4-1 Trident-CBF functional requirements

Trident-Req#	Requirement	Traceability [AD1]	Compliance/Comments
General			
TCBF-0001	There shall be 3 tridents in Trident-CBF, each of which ingests and processes 10 GHz/pol of single-sideband digitized data from each of at least 263 antennas via the DBE.	CSP0111 CSP0121 CSP0124 CSP0161	Compliant.
TCBF-0002	Trident-CBF shall configure its processing resources such that: • Data from each antenna digitizer is divided into multiple identical Frequency Slices whose collective contiguous processed bandwidth covers the entire digitized bandwidth and, • The processed bandwidth of each Frequency Slice is 200 MHz +/-2 MHz.	CSP0121 CSP0124 CSP0122 CSP0123 CSP0125	Compliant. Note on CSP0123: The intent in the requirement for 4 MHz tuning steps seems to be to provide contiguous bandwidth coverage across the full input digitized bandwidth.
TCBF-0003	Each trident of Trident-CBF shall contain 50 FSPs, each FSP processes any select Frequency Slice for each sub-array independently, and each FSP is independently configurable under software control to any of the following Function Modes: • Correlation, • VLBI, • Pulsar-True-Delay-4bm, • Pulsar-True-Delay-10bm-144ant or, • Pulsar-Phase-Delay-100bm	CSP0121 CSP0124	Compliant.

TCBF-0004	The maximum data transport delay from any antenna to Trident-CBF shall be 250 msec.	CSP0141	Compliant. The bulk delay in the VCC is implemented with external DDR4 RAM with more than sufficient capacity.
TCBF-0005	Trident-CBF shall provide processing for a maximum ngVLA array diameter of 10,000 km.	CSP0142	Compliant. The bulk delay in the VCC is implemented with external DDR4 RAM with more than sufficient capacity.
TCBF-0006	The phase-center, for any sub-array, shall be within the smallest circle encompassing the sub-array.	CSP0143	Compliant.
TCBF-0007	Trident-CBF shall provide sub-arraying capability, for at least 10 independent simultaneous sub-arrays in each FSP for any Function Mode.	CSP0181 CSP0322 CSP0323 CSP0324	Partially compliant. Sub-arraying is independent in each FSP, for the configured Function Mode. The corner-case of each sub-array performing a different Observing Mode, each for the maximum aggregate bandwidth, cannot be met.
TCBF-0008	Trident-CBF shall automatically detect and flag RFI in time and frequency, at each frequency resolution available through each signal flow.	CSP0171 CSP0172	Compliant.
TCBF-0009	For all output correlation and beamforming data products, as appropriate, Trident-CBF shall calculate, and provide on request via monitor and control channels, all internally-determined and calculated gain correction factors to be applied in post-processing.	CSP0153	Compliant.
Function Mode: Correlation (for synthesis imaging)			
TCBF-0101	The normal (non-zoom) Correlation Function Mode shall provide:	CSP0222 CSP0221	Partially compliant.

	• 14,000 to 15,000 critically-sampled channels across the Frequency Slice processed bandwidth. • Post-correlation channel averaging factors of at least 2, 3, 4, 6, and 8. • Linearly-spaced channels, with or without channel averaging, across the processed bandwidth of the Frequency Slice and any number of adjacent Frequency Slices sourcing from the same digitizer. • Per-visibility integration times ranging from 2 msec to 10 sec, at least in steps of the minimum integration time, and such that integration times across all FSPs, across all tridents, that are part of the same sub-array are synchronized in time. • A phase-reference position on the sky (a.k.a the boresight delay center), which is within the antenna primary beam HPBW and independent of any other FSP.	CSP0225 CSP0231	14k to 15k channels provides a channel bandwidth of 14.2 kHz to 13.3 kHz. Channel averaging of 8 provides 114 kHz channel resolution; wider channels (likely) must be produced external to Trident-CBF. Larger channel averaging factors require further investigation. Linear channels across multiple adjacent Frequency Slices is not specifically in [AD1], however it is implied by CSP0222. Without the re-sampling function, it would be unwieldy or impossible to do so in a 2-stage oversampling poly-phase filterbank.
TCBF-0102	Correlation Function Mode, when correlating Zoom Windows, shall provide: • At least 1 tunable Zoom Window per antenna, with a tuning resolution of at least 10 kHz anywhere in the Frequency Slice processed bandwidth. • Zoom Window processed bandwidths of /2, /4, /8, /16, /32, /64 of a Frequency Slice processed bandwidth. • Number of channels, channel averaging, integration times, and independent phase-reference position identical to non-zoom visibilities. Linear channel	CSP0221 CSP0222 CSP0223 CSP0224 CSP0231	Compliant down to a channel width of 220 Hz (without averaging).

	spacing applies only to channels within the Zoom Window.		
TCBF-0103	In Correlation Function Mode, each sub-array in an FSP shall be independently configurable to be correlating zoom *or* non-zoom visibilities; if zoom, then each sub-array must have a single Zoom Window processed bandwidth, not dependent on any other sub-array's zoom or non-zoom configuration.	CSP0181	
Function Mode: VLBI			
TCBF-0201	In VLBI Function Mode, each FSP shall form at least 4 beams per-sub-array, on at least 1 VLBI sub-array, and each beam: • Has a contiguous, non-channelized, processed bandwidth of a Frequency Slice. • Is independently steerable to delay center on the sky anywhere within the HPBW of the antenna primary beam. • Can be formed from any select ngVLA antennas of any beamforming aperture within the sub-array.	CSP0521 CSP0522	Compliant. At least 10 simultaneous sub-arrays are possible, each one producing 4 beams, each beam independently steerable per sub-array.
TCBF-0202	In VLBI Function Mode, simultaneous with beamforming in each VLBI sub-array each FSP shall: • Produce 900 to 1000 supporting visibilities for at least 1 beam (i.e. delay center), across the Frequency Slice processed bandwidth. • Have a per-visibility integration times in the range of 20 msec to 5 sec, synchronized in time within each sub-array across all FSPs and tridents.	CSP0531 CSP0532 CSP0533	Compliant. [AD1] is TBD on CSP0532 and CSP0533; these are achievable values.
TCBF-0203	In VLBI Function Mode, the following Jones Matrix (JM) beam polarization corrections shall be applied:	CSP0541	Compliant. CSP0541 is TBD in [AD1].

	• Prior to beamforming, per-antenna, per-beam, on the Frequency Slice sampled bandwidth. • Post-beamforming, per-beam on the Frequency Slice sampled bandwidth (TBC)		
TCBF-0204	In VLBI Function Mode, at least 4+1 beam-channels shall be produced per sub-array with: • 4 beam-channels having at least 2 kHz tuning resolution anywhere within the Frequency Slice sampled bandwidth (of 224 MHz), with bandwidths of 1 MHz x 2^n (n=0, 1, …, 7). • 1 beam-channel fixed at the Frequency Slice sampled bandwidth of 224 MHz. • Real output. • Nyquist output sample rates. • Independently settable 2-bit, 4-bit, 8-bit, or 16-bit word size per beam-channel. • VDIF formatted output.	CSP0551 CSP0552 CSP0553 CSP0554	Compliant. In [AD1] the number of beam-channels output is TBD. The Trident-CBF design can provide up to an aggregate of 104+26 beam-channels per FSP.
Function Mode: Pulsar-True-Delay-4bm			
TCBF-0301	In Pulsar-True-Delay-4bm Function Mode each FSP shall produce at least 4 true delay beams arbitrarily allocated to any sub-array, and each beam: • Has a contiguous, non-channelized, processed bandwidth of a Frequency Slice. • Is independently steerable to delay center on the sky anywhere within the HPBW of the antenna primary beam. • Can be formed from any select ngVLA antennas of any beamforming aperture within the sub-array.	CSP0321 CSP0121 CSP0324 CSP0611	Partially compliant. Multiple FSPs allocated to the same Frequency Slices are required. The total beams x bandwidth product is 4 beams/FSP x 50 FSPs x 200 MHz/FS = 40 GHz. Thus, 50 beams at 0.8 GHz/beam can be formed. This is for the full array, any number of ngVLA antennas, any aperture size

	• Post-beamforming, before output, channelized to at least 128 oversampled channels across the Frequency Slice sampled bandwidth.		
TCBF-0302	In Pulsar-True-Delay-4bm Function Mode, the following Jones Matrix (JM) beam polarization corrections shall be applied: • Prior to beamforming, per-antenna, per-beam, on the Frequency Slice sampled bandwidth. • Post-beamforming, per-beam on each output oversampled channel independently.	CSP0331	Compliant.
TCBF-0303	In Pulsar-True-Delay-4bm Function Mode, simultaneous with beamforming in each Pulsar-True-Delay-4bm sub-array each FSP shall: • Produce 900 to 1000 supporting visibilities for at least 1 beam (i.e. delay center), across the Frequency Slice processed bandwidth. • Have a per-visibility integration times in the range of 20 msec to 5 sec, synchronized in time within each sub-array across all FSPs and tridents.	CSP0341	Compliant.
Function Mode: Pulsar-True-Delay-10bm-144ant			
TCBF-0401	In Pulsar-True-Delay-10bm-144ant Function Mode each FSP shall produce at least 10 true delay beams pre-allocated to a select 144 antennas, and each beam: • Has a contiguous, non-channelized, processed bandwidth of a Frequency Slice. • Is independently steerable to delay center on the sky anywhere within the HPBW of the antenna primary beam.	CSP0321 CSP0121 CSP0423 CSP0611	Partially compliant. CSP0423 requires 168 antennas but only 144 are believed possible. Multiple FSPs allocated to the same Frequency Slices are required. The total beams x bandwidth product is 10 beams/FSP x 50 FSPs x 200 MHz/FS =

	• Can be formed from any of the pre-selected ngVLA antennas of any beamforming aperture within the sub-array. • Post-beamforming, before output, channelized to at least 128 oversampled channels across the Frequency Slice sampled bandwidth.		100 GHz. Thus, 50 beams at 2 GHz/beam can be formed. The current design/resource utilization indicates that only 130 pre-selected antennas can provide this capability (CSP0423 requires 168).
TCBF-0402	In Pulsar-True-Delay-10bm-144ant Function Mode, the following Jones Matrix (JM) beam polarization corrections shall be applied: • Prior to beamforming, per-antenna, per-beam, on the Frequency Slice sampled bandwidth. • Post-beamforming, per-beam on each output oversampled channel independently.	CSP0331	Compliant.
TCBF-0403	In Pulsar-True-Delay-10bm-144ant Function Mode, simultaneous with beamforming in each Pulsar-True-Delay-10bm-144ant sub-array each FSP shall: • Produce 900 to 1000 supporting visibilities for at least 1 beam (i.e. delay center), across the Frequency Slice processed bandwidth. • Have a per-visibility integration times in the range of 20 msec to 5 sec, synchronized in time within each sub-array across all FSPs and tridents.	CSP0341	Compliant.
Function Mode: Pulsar-Phase-Delay-100bm			
TCBF-0501	In Pulsar-Phase-Delay-100bm Function Mode each FSP shall produce at least 100 phase-delay beams, and each beam: • Has a contiguous processed bandwidth of a Frequency Slice.	CSP0421 CSP0422 CSP0423 CSP0424 CSP0121	Compliant. This exceeds the CSP0421 requirement of 10 beams; if only 10 beams are produced, then

	• Is independently steerable to delay center on the sky anywhere within the HPBW of the antenna primary beam. • Can be formed from any up to 168 antennas with a beamforming aperture diameter of up to 30 km. • Channelized to 4096 critically-sampled channels across the Frequency Slice sampled bandwidth.		simultaneous supporting visibilities are possible.
TCBF-0502	In Pulsar-Phase-Delay-100bm Function Mode, the following Jones Matrix (JM) beam polarization corrections shall be applied: • Prior to beamforming, per-antenna, per-channel.	CSP0431	Compliant.

4.2 Interface Requirements

Table 4-2 Trident-CBF interface requirements

Trident-Req#	Requirement	Traceability [AD1]	Compliance/Comments
TCBF-1001	Each trident of Trident-CBF shall interface to each of 263 antennas as either: • 10 GHz/polarization at 4+4b complex per sample or, • 5 GHz/polarization at 8+8b complex per sample.	CSP0111 CSP2101 CSP2102 CSP2103	Compliant.
TCBF-1009	Trident-CBF shall automatically recover and require no on-sky calibration in the event of a packet loss or loss of link on any or all antenna data ingest pipelines.	CSP0144	Compliant. This requires that the ingest data includes an embedded 1PPS marker with a pre-determined and unchanging number of

			samples between 1PPS markers, which could be different for each antenna (i.e. to support SCFO sampling), and that synchronous counting/timing occurs in the antenna even though the antenna-CBF link sample data link has packet loss or has dropped.
TCBF-1002	Each of the 150 FSPs in Trident-CBF shall provide a data product output bandwidth of at least 40 Gbps.	CSP2201 CSP2202	Partially compliant. Trident-CBF require a 27 x 10/40G Ethernet switch for each FSP, which is currently not costed.
TCBF-1003	Trident-CBF shall receive and synchronize all operations to a 100 MHz and 1-PPS reference. Note: all antenna sampled inputs are frequency-synchronous with these references.	Section 3.4.6	Compliant.
TCBF-1004	Trident-CBF control and monitor interface shall be multi-mode fiber using TCP/IP over Ethernet.	Section 5.6	Compliant.
TCBF-1005	Trident-CBF shall provide an electrical power interface to 3-phase, 208 VAC (delta), 60 Hz power.	Section 5.4.1	Compliance expected.
TCBF-1006	Trident-CBF shall be water-based liquid cooled and the interface for such cooling shall be: • Per-rack water source and return at TBD L/s at a source temperature of TBD C per rack. • Fittings sizes TBD.	Section 5.4.2	Compliant.
TCBF-1007	Trident-CBF racks shall be standard 19" racks, each with maximum dimensions of 24" W x 42" D x 42U high.	TBD (trace to infrastructure ICD)	Compliant.

TCBF-1008	The complete Trident-CBF installation shall consist of TBD 19" racks.	TBD (trace to infrastructure ICD)	

4.3 Control and Monitor Requirements

Table 4-3 Trident-CBF control and monitor requirements

Trident-Req#	Requirement	Traceability [AD1]	Compliance/Comments
TCBF-1101	Trident-CBF shall monitor and report a set of parameters that allow for determination of its status.	CSP1001	Compliant.
TCBF-1102	Trident-CBF shall monitor and detect 99.9% of communications faults whilst operationally available.	CSP1001	Compliant.
TCBF-1103	Trident-CBF shall perform in-situ off-line (i.e. not operationally available) tests on a per-antenna and per-FSP basis to detect processing faults with 99.9% probability of detection.	CSP1001	Compliant. The idea here is to roll testing across the system so as to not have to take the entire system down to run such tests.

4.4 Performance Requirements

Table 4-4 Trident-CBF performance requirements

Trident-Req#	Requirement	Traceability [AD1]	Compliance/Comments
TCBF-1201	In FSP Correlation Function Mode normal and zoom visibilities shall: • Have a -3 dB +/-0.01 dB channel edge amplitude.	CSP0151 CSP0152 CSP0153 CSP0131	Compliance expected. Further analysis required to verify that CSP0151 -50 dB leakage is met.

	• Be monotonically decreasing in any region above -60 dB from the channel edge to the next adjacent channel center frequency. • Have an amplitude of -80 dB or better thereafter (i.e. reject band). • Have a post-gain factor correction amplitude that varies at most by +/-0.01 dB across the processed bandwidth across all Frequency Slice of a digitized bandwidth. • Provide at least 98.6% correlation efficiency where there is no more than 10% RFI power present in any particular channel.		
TCBF-1202	In FSP VLBI Function Mode simultaneously-produced visibilities shall: • Have visibility channel response: maximum +/-0.1 dB amplitude and +/-0.01 radian phase passband (channel edge-to-edge) ripple; -3 dB +/-0.2 dB channel edge amplitude; monotonically decreasing amplitude from the channel edge to the adjacent channel far edge; at least -60 dB reject-band amplitude anywhere greater than the 1 channel width away from the channel edge. • Have at least 98.6% correlation efficiency when in-channel RFI power is <10%.	CSP0131 CSP0151 CSP0152	Partially compliant. CSP0151: -50 dB total power leakage probably not achievable (requires more logic+memory), TBC.
TCBF-1203	Trident-CBF shall apply wavefront delay model corrections such that the coherence loss resulting from such corrections is <0.1%.	CSP0131	Compliant.
TCBF-1204	Trident-CBF shall apply wavefront phase model corrections such that the	CSP0131	Compliant.

	coherence loss resulting from such corrections is <0.1%.		
TCBF-1205	Trident-CBF shall apply delay and phase model corrections such that there is no discernable correlated phase or amplitude closure anomalies on any integration time scale above the expected noise.	TBD (missing requirement)	Compliant.
TCBF-1206	Trident-CBF shall apply delay and phase model corrections on true delay beams such that there is no discernible phase or amplitude variation due to such application over the expected noise.	TBD (missing requirement)	Compliant.

4.5 Environmental Requirements

Table 4-5 Trident-CBF environmental requirements

Trident-Req#	Requirement	Traceability [AD1]	Compliance/Comments
TCBF-1301	The operating ambient temperature for Trident-CBF shall be in the range of 20 C to 30 C with a maximum rate of change of temperature of TBD C/Hr and humidity of TBD % relative.	CSP0811 CSP0812 CSP0813	Compliance expected. DCLC largely buffers electronics' dT/dt against room ambient temperature changes.
TCBF-1302	Trident-CBF shall self-protect and shutdown if a destructive over-temperature condition is reached.	Section 4.8.1	Compliant.
TCBF-1303	Trident-CBF packaging and installation shall be designed to survive, with no permanent damage, an earthquake event of up to 1 per year with up to 0.2 g peak acceleration in either the vertical or horizontal axis.	CSP0831	Compliance expected.

TCBF-1304	Trident-CBF shall operate up to an altitude of 2200 m above sea level.	CSP0841	Compliance expected.
TCBF-1305	The electrical power quality provided to Trident-CBF shall be such that Trident-CBF need not itself provide any battery backup or dirty power conditioning other than normally provided in COTS server AC-DC power supplies.	Section 5.4.1	Compliant.
TCBF-1306	At least 90% of Trident-CBF power shall be removed using water cooling.	TBD (trace to infrastructure ICD)	Compliance expected. This allows the water and air-cooling systems' requirements to be determined.
TCBF-1307	Each LRU in Trident-CBF shall, as a minimum, meet FCC Part 15, Sub-part J, Class A radiated and conducted emissions standards.	Section 5.4.3 Section 8.2	Compliant. Reasonable EMI design measures required.
TCBF-1308	The Trident-CBF installation shall comply with all relevant federal and State of New Mexico building and electrical codes.	CSP6001 CSP6002	Compliant. Assume meeting UL and U.S./Canada electrical codes is sufficient.

4.6 Reliability and Maintenance Requirements

Table 4-6 Trident-CBF reliability requirements

Trident-Req#	**Requirement**	**Traceability** [AD1]	**Compliance/Comments**
TCBF-1401	Trident-CBF shall have an inherent availability (Ai) of at least 99.9% while Operationally Capable. Note: Trident-CBF is Operationally Capable when it can produce 99% of required data products using at least 99% of the antennas.	CSP0901	Compliance TBD. Further analysis is required, but these numbers are based on a single TALON LRU failure.

4.7 Other Requirements

Table 4-7 Trident-CBF other requirements

Trident-Req#	**Requirement**	**Traceability** [AD1]	**Compliance/Comments**
TCBF-1501	Trident-CBF shall have a design-lifetime of at least 20 years.	CSP1101	Compliance expected.
TCBF-1502	The design of Trident-CBF shall minimize its life-cycle cost for 20 years of operation.	CSP1102	Non-compliant. Fundamentally impossible to do this; “minimal” is achievable, but beyond the current work scope to determine.
TCBF-1503	All materials used in the Trident-CBF installation shall be RoHS-compliant.	Section 7.2.5	Compliance expected.
TCBF-1504	All fasteners in Trident-CBF, with the exception of those in COTS units, shall be metric.	Section 8.3.1	Compliant.
TCBF-1505	Any painted coatings in Trident-CBF shall last without degradation for at least 20 years.	Section 8.3.2	Compliant.
TCBF-1506	Any unpainted surfaces in Trident-CBF shall be treated against corrosion and to provide necessary function for at least 20 years.	Section 8.3.3	Compliant.
TCBF-1507	All LRUs in Trident-CBF shall be equipped with nameplates which are visible after installation and contain the following information: • Name and model number. • Revision. • Serial number.	Section 8.3.5	Partially compliant. “Drawing number including revision” seems like an impossible requirement to meet since many such drawings could apply.

	• Manufacturing month and year. • Name of manufacturer.		Instead suggest "Name and model number".

5 System Architecture

5.1 Simplified Overview

A simplified block diagram of *each* of the 3 tridents in Trident-CBF is shown in Figure 5-1. In this diagram:

- The "TALON LRU" is used for all signal processing functions in the VCC-part and the FSP-part. It contains 2 large FPGAs and substantial fiber I/O on 2 TALON-DX boards. Each LRU is identical: it is loaded with firmware and software needed to perform VCC or FSP functions, depending on where it is installed. See Section 6.1 for further information on the TALON LRU.
- A "VCC-UNIT" consists of 6 TALON LRUs and provides 10 GHz/pol (5 GHz/pol @ 8+8b/sample) VCC-part processing for 11 antennas (only one TALON-DX board of one of the LRUs is used). A VCC-UNIT is a convenient grouping of antennas for the purposes of VCC-UNIT-internal passive fiber routing via the "VCC-MESH" LRU, wherein each of 50 12-fiber MTP output connectors contains one Frequency Slice for 11 antennas. The VCC-UNIT grouping places no restrictions on sub-arraying or FS selection for any of the 11 antennas.
- Each "FSP-UNIT" consists 13 TALON LRUs, providing the required processing capacity for up to 286 antennas (263 is the requirement[9]). Each FPGA (of 26) in the FSP-UNIT accepts a FS from 11 antennas, providing the required processing for the configured Function Mode according to Figure 3-4. Within the FSP-UNIT the "FSP-MESH" LRU internal passive-fiber interconnect provides all mesh connectivity needed to cross-connect the data for correlation and beamforming. Each FSP-UNIT's FPGA outputs its data via its own 10/40G connector to the archive, consolidated into a single 40G output for the FSP-UNIT via a COTS 40G 27-port switch (not costed, but not a significant cost).
- The "VCC-FSP Passive Fiber Interconnect" block shown is not a separate block from the VCC-UNITs. It is the above-described VCC-MESH passive-fiber interconnects incorporated into each one. Thus, there is only point-to-point cabling from the VCC-UNITs to the FSP-UNITs. Each VCC-UNIT 12-fiber MTP output, consisting of one FS from each of 11 antennas, routes to exactly one FSP-UNIT MTP bulkhead input. In total, for a 263 antenna system, in *each* trident there are 50 (FSPs) x 26 (MTP 12-fiber cables per FSP) = 1300 12-fiber MTP cables.

[9] 286-antenna ingest input, but only 263 antenna correlation and beamforming capability. The number of VCC-UNITs can be reduced to 24 to provide 24x11=264-antenna ingest.

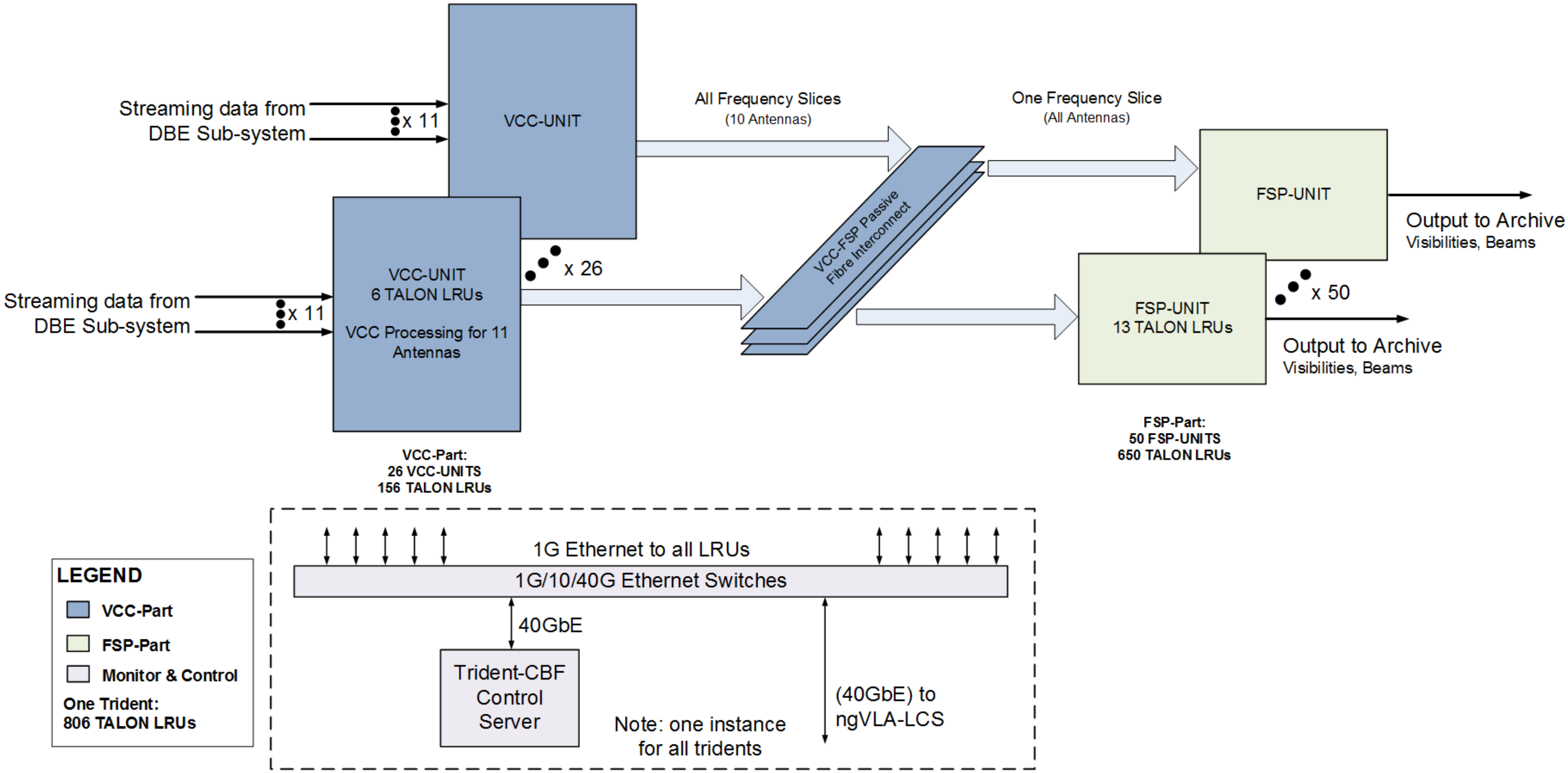

Figure 5-1 Simplified block diagram of each trident in Trident-CBF[10].

[10] 26 VCC-UNITs are shown, but this could be reduced to 24 to reduce cost and provide 24x11=264 antenna capacity, meeting the 263 antenna requirement. Another alternative if more FSP FPGAs are required for correlation/beamforming processing, is to keep each VCC-UNIT at 10 antennas and increase the number of FPGAs in each FSP to 28, providing up to 280 antenna capacity. In this case, there are 28 VCC-UNITs and each FSP-UNIT contains 14 TALON LRUs.

5.2 Signal Processing Architecture

The signal processing architecture is essentially a two-stage process, where the first stage is executed in the VCC-part and the second stage, specific to each FSP Function Mode, is executed in the FSP-part. This architecture allows separation of Band-specific signal processing (in the VCC-part) from Band-agnostic signal processing (in the FSP-part), which finds significant utility in the SKA1 Mid telescope with 6 different Bands, many of them with different sample rates, for which the FSA was developed. The utility of this architecture for ngVLA is allowing for ingest of either 5 GHz/polarization 8+8b samples or 10 GHz/polarization 4+4b samples, as well as considerable flexibility in how Trident-CBF resources are allocated to the signal processing tasks required for any given set of simultaneous observations, with the ability to optimize design for specific processing tasks with no disruption to other tasks (i.e. each FSP Function Mode design can be unique although many share the same signal processing block designs).

This section provides an overview description, rationale, and survey of the key signal processing blocks within the simplified signal processing flow of Figure 3-4.

5.2.1 VCC-part Processing

The first stage in the VCC consists of bulk coarse delay followed by an oversampling coarse poly-phase filterbank to produce the 200 MHz FSs.

The bulk coarse delay correction here is not fundamental, but rather simplifies delay tracking by adjusting/compensating for the bulk of the delay correction[11] every so often (10+ seconds) using high-capacity external DDR4 RAM, leaving only the small (O(10^3-to-10^4), TBC) number of residual coarse samples at the FS sample rate and the very fine delay, to be corrected in the FSP in the FSP FPGAs. The restriction is that for any particular antenna, all delay tracking centers on the sky must be somewhat constrained, normally within the HPBW of the antenna. This means that one would not be able to form a boresight beam and a beam with a large offset from it such as through a sidelobe, since the residual coarse delay in the FSP FPGA would exceed capacity (depending on distance to the array phase center).

The oversampling coarse poly-phase filterbank (VCC-OSPPFB) and FS bandwidth is chosen such that each FS is at a bandwidth and sample rate that is optimal for downstream direct-sample-rate FPGA processing, eliminating the complexities of a corner-turner before the next stage. For Trident-CBF, a 200 MHz bandwidth, oversampled to ~220 MHz is chosen, requiring an FPGA clock rate of ~450 MHz, something that is a reasonable performance target for the TALON-DX technology node. As FPGA performance increases, the FS bandwidth could be increased accordingly, although this is not thought to be cost-effective within the assumed ~2025 construction timeframe of Trident-CBF.

An example VCC-OSPPFB channel response, extracted from [RD3] is shown in Figure 5-2. In this case (for SKA1 Mid.CBF), the input sample stream is real, sampled at ~6 Gs/s, and the VCC-OSPPFB is a 30-channel 10/9 oversampling filterbank. For Trident-CBF, with 5 Gs/s complex (5 GHz digitized bandwidth) in, a different oversampling factor and some adjustment of the FS bandwidth will be needed, TBD.

[11] Encompassing wavefront as well as signal transmission delay from the antennas to Trident-CBF.

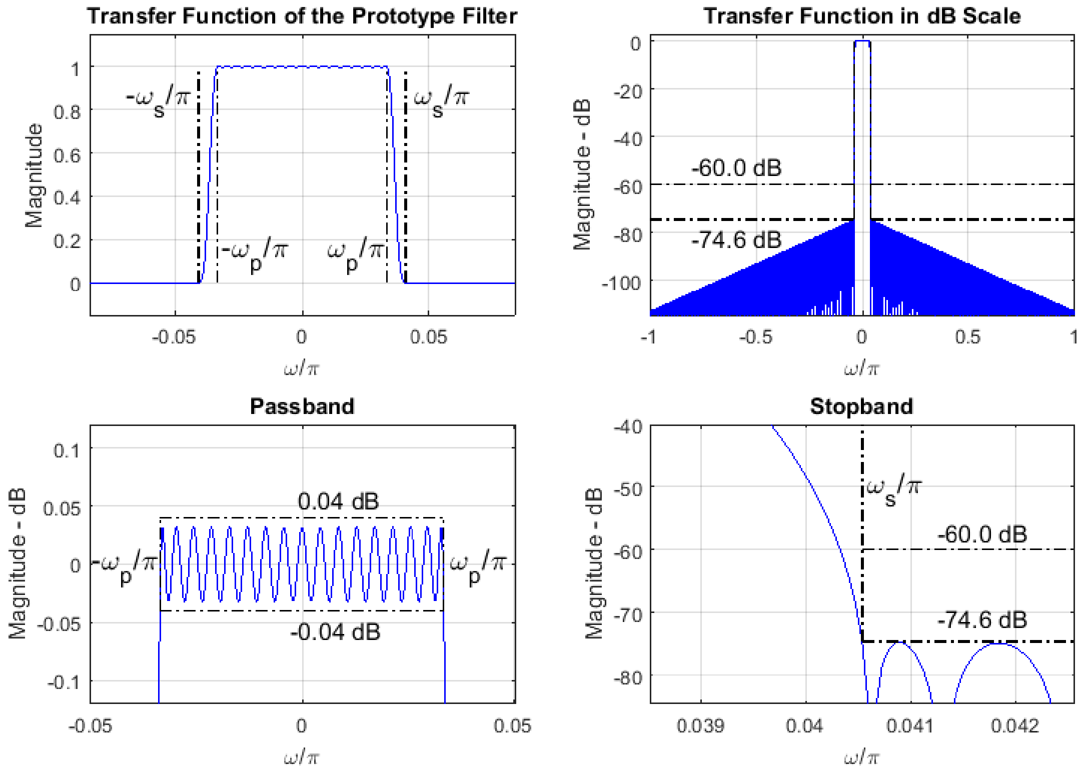

Figure 5-2 Example VCC-OSPPFB output channel (from SKA Mid.CBF, Band 5). (Upper-left: zoomed-in linear magnitude response; lower-left: zoomed-in magnitude response dB; upper-right: magnitude response dB; lower-right zoomed-in magnitude response transition band dB.) Not shown is that the phase response is linear (0) across the passband.

After the VCC-OSPPFB, as indicated in Figure 3-4, there is a circuit switch (internal to the FPGA) that allows any FS to be directed to any of the 50 outputs. This provides the system with considerable flexibility in allocating FSP resources to FSs.

5.2.2 FSP-Part Processing

Processing in each FSP is specific to the particular Function Mode that is currently configured (see Figure 3-4). However, there are some common components, and some insight into the operation and performance of each is provided in the following sub-sections.

5.2.2.1 Re-Sampler (and delay/phase tracker)

The Re-Sampler block performs the following functions:

- Performs residual coarse delay tracking correction (left over after bulk delay in the VCC-part), at the FS sampled rate. This is performed using on-FPGA memory, at the FS sample rate.
- Digitally re-sampling of the data from the raw Frequency Slice sample rate to the sample-rate conducive to providing linearly-spaced channels (requiring a post-re-sampling frequency shift) across multiple adjacent FSs and at channel sample rates that are conducive to distributed correlation and channel-averaging. As well, if the ngVLA employs SCFO sampling or incoherent

clocking, this re-sampler is essential to sample the data to a common rate prior to correlation and/or beamforming.

- Part and parcel with re-sampling is very-fine-delay tracking. Since re-sampling is a delay operation, then very-fine-delay tracking is simply a delay-model-varying offset into the Re-Sampler block.

The combination of re-sampling to a different sample rate and very-fine-delay tracking provides for virtually perfect very-fine-delay tracking with no discernible delay-tracking effects: since re-sampling is constantly and rapidly sweeping through many steps (typically 1024 or 2048) between +/-0.5 samples, the average of the filter re-sampler response is the average of the transfer function of the very-fine-delay tracking response. This is extracted from [RD3] and shown in Figure 5-3:

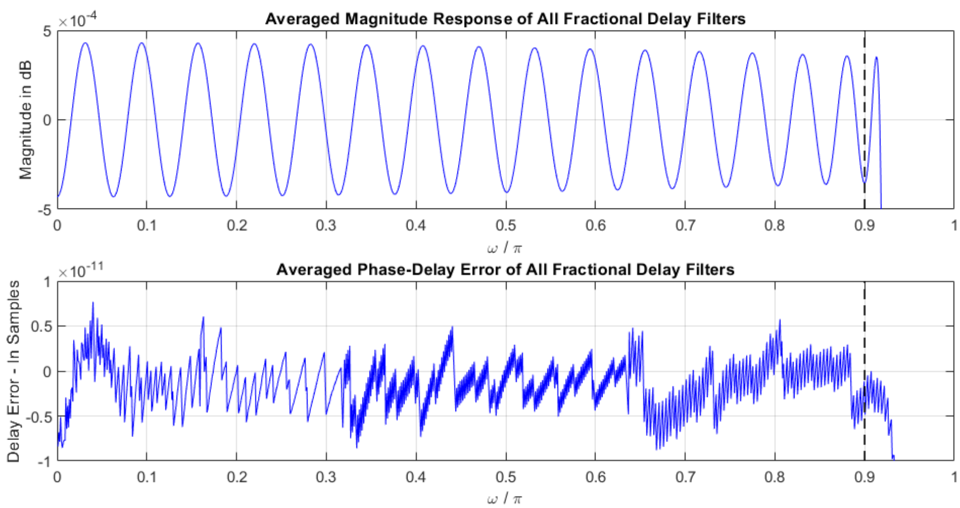

Figure 5-3 Effective average transfer function of the re-sampler/delay-tracker.

Furthermore, since there are a finite number of fine delay steps between +/-0.5 samples in the re-sampler, this imposes a sawtooth delay error waveform that is the magnitude of one step, e.g. 1/1024 samples for 1024 steps. This sawtooth modulates the input spectrum and produces a splatter of copies of the input spectrum. However, this effect is highly mitigated by scrambling the LSBit of the fractional delay so that the sawtooth modulation is turned into random noise. Results presented in [RD3] and Figure 7-2 show that all splatter products are gone and spread into low-level uncorrelated white noise.

The Re-Sampler block also performs a complex phase-rotation/mixing operation, to apply any required phase corrections to the data prior to further channelization, correlation, and beamforming. As above, such a mixing operation isn't perfect, even with 18-bit operations, and so scrambling the LSBit of phase before the required sin/cos LUT (look up table) turns splatter products that could correlate into uncorrelated white noise [RD3].

5.2.2.2 Tunable DDC

A tunable DDC (Digital Down Converter) is used for Zoom Window selection and VLBI beam-channel extraction from the 224 MHz beam. It is a complex decimating FIR filter, with a frequency shift to allow for Zoom Window tuning. A memory-efficient implementation from [RD3] is shown in Figure 5-4, and a typical response (/32 Zoom Window is shown in Figure 5-5).

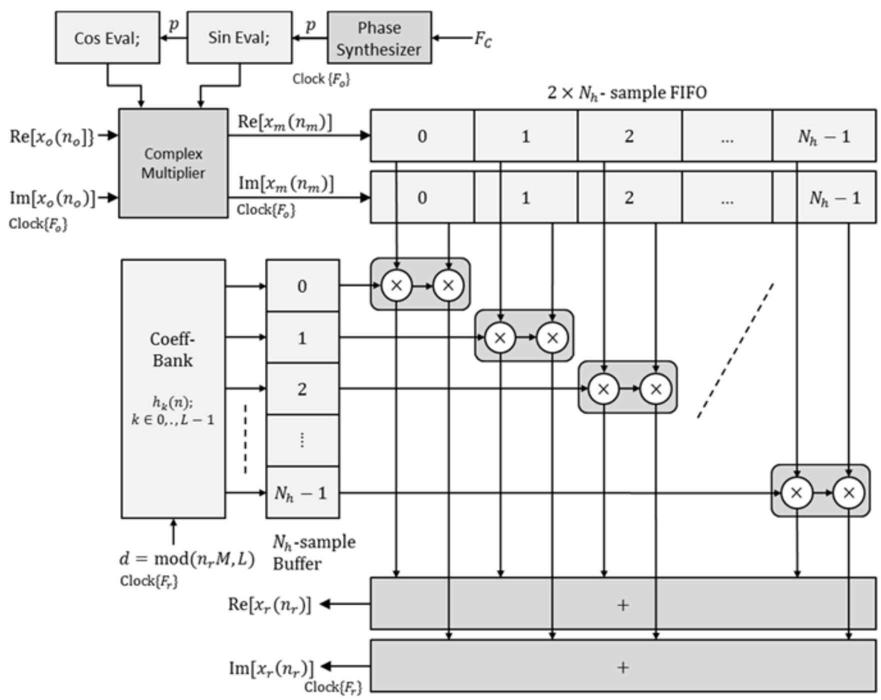

Figure 5-4 Tunable DDC efficient implementation block diagram.

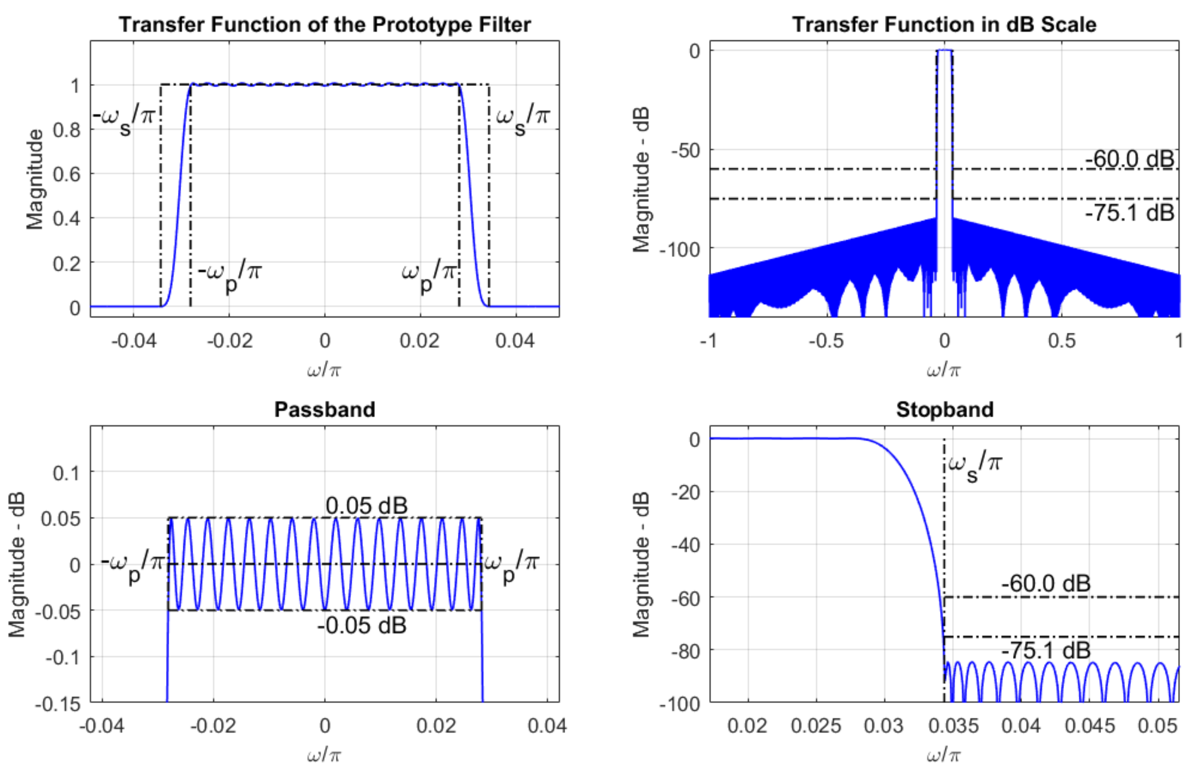

Figure 5-5 Zoom Window tunable DDC output for a FS/32 width.

5.2.2.3 16k Critically-sampled Imaging Channelizer

The imaging channelizer in the Correlation Function Mode, identical for zoom and normal (non-zoom) is crucial for providing required spectral resolution and channel-to-channel isolation. The channelizer filter response, extracted from [RD3], is shown in Figure 5-6.

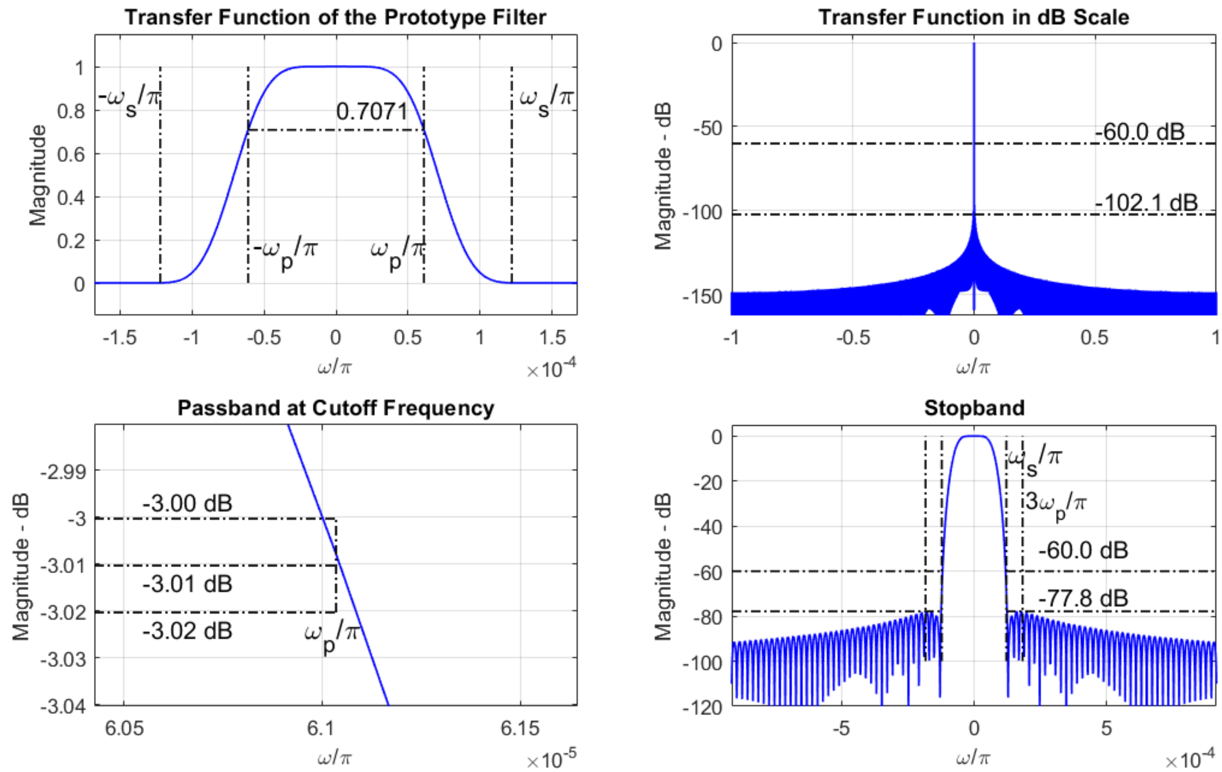

Figure 5-6 16k imaging channelizer response.

The total output channel response, of course, includes the effects of the VCC-OSPPFB, the Re-Sampler, the tunable DDC (for zoom), and the 16k channelizer. Such an end-to-end response, after application of per-channel gain corrections (provided by Trident-CBF to ngVLA-LCS) extracted from [RD3] is shown in Figure 5-7.

5.2.2.4 1k Critically-sampled "simultaneous visibilities" Channelizer

Several Function Modes require simultaneous correlation of ~1k visibilities in the FSP. The channel response of this channelizer, taken from [RD3], is shown in Figure 5-8.

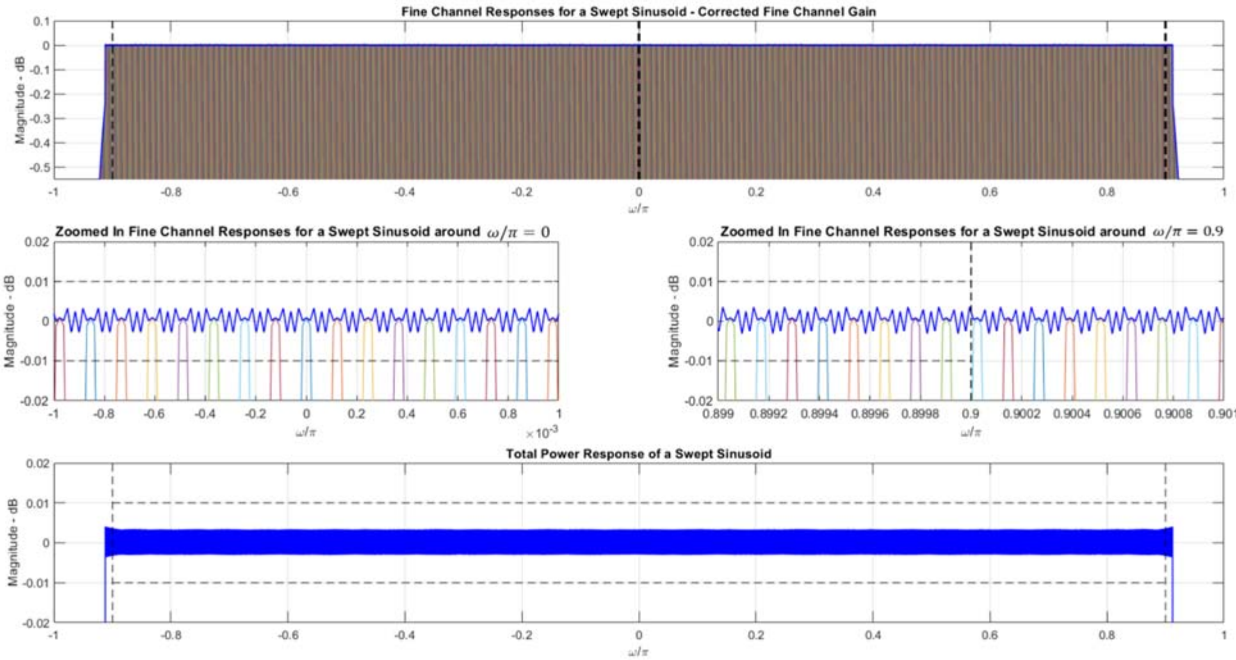

Figure 5-7 End-to-end channel response of the Zoom Window signal chain after application of channel gain correction factors.

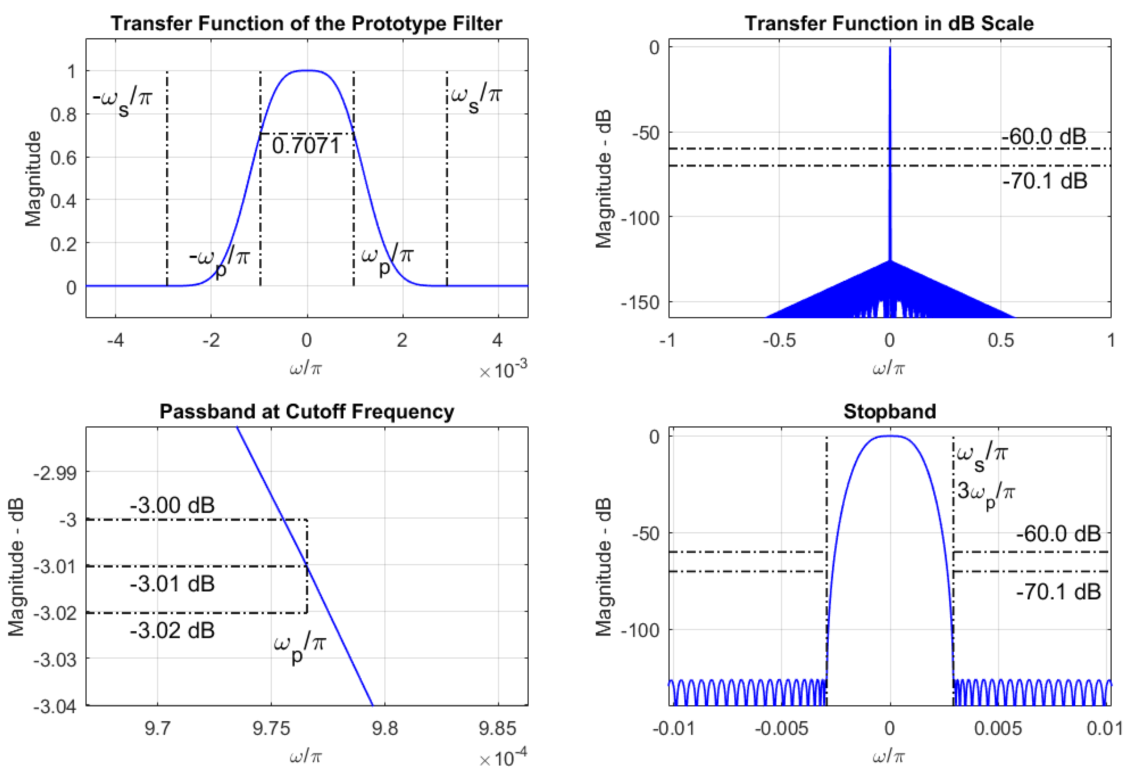

Figure 5-8 Channel response of the 1k channelizer for simultaneous visibilities with beamforming.

5.2.2.5 256-pnt Oversampling Channelizer Response

The response of the 256-pnt oversampling channelizer, performed post-beamforming to allow for fine-frequency Jones Matrix polarization corrections is something of a free parameter since it is not a cost/power driver. Typically, though, the response would be of a similar nature to that shown in Figure 5-2 or better.

5.2.2.6 RFI Detector-Flagger

The RFI detector-flagger, present at each accessible[12] channel resolution in each signal processing flow is extracted from [RD3] and shown in Figure 5-9. This block is a "gear-box" that can be configured ngVLA-LCS to detect and flag RFI with the desired effects.

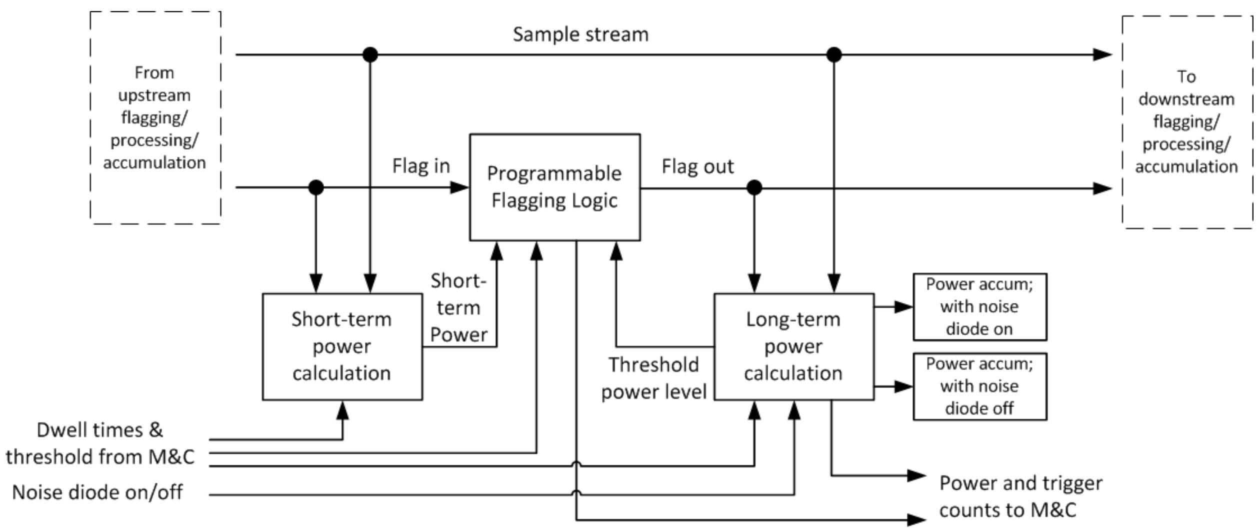

Figure 5-9 RFI detector-flagger.

Furthermore, built into the correlator gear-box is a higher time-resolution post-correlation RFI detector-flagger, if desired. This gear-box is shown in Figure 5-10.

[12] i.e. at the output of a filterbank and not, for example, internal to an FFT.

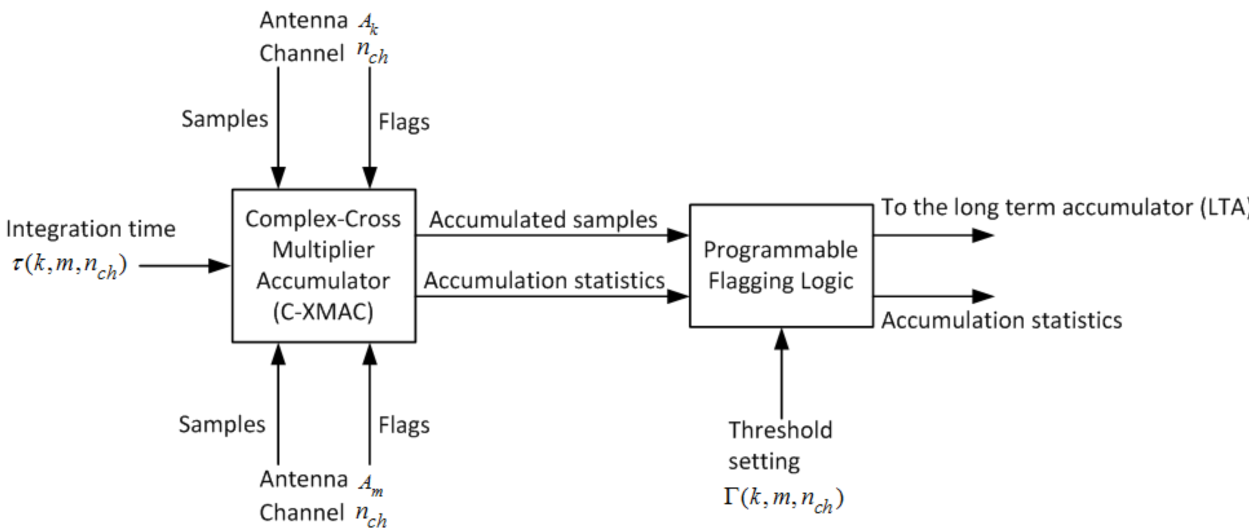

Figure 5-10 Post-correlation, high time-resolution RFI detector-flagger.

5.2.2.7 Other Signal Processing Blocks

The other signal processing blocks—correlation, phase-delay beamforming, Jones Matrix polarization corrections—occur in the FSPs and are straightforward operations with details not included here, rather see [RD5].

Correlation and beamforming are largely data management tasks with the key approaches described below:

- Correlation:
  - Full cross-connect design: time-multiplexed acquisition of all baselines for a portion of the channels in each FSP FPGA. This means that all timing must be synchronized for all sub-arrays within an FSP. Thus, there is a "kernel" integration time, and all sub-array integration times are an integer multiple of it.
  - Zoom and non-zoom handled simultaneously in different sub-arrays in the same FSP since zoom channel sample rates are integer divisions of non-zoom channel sample rates.
  - Separate designs, but same basic approach, for the 16k imaging correlator and the 1k correlator for visibilities in support beamforming. Both correlators perform 6+6b correlation. In the SKA1 Mid.CBF, 19503 baselines are correlated with 9+9b samples @ 744 channels per FSP FPGA (for imaging). In Trident-CBF, 34716 baselines @ ~570 channels per FSP FPGA must be processed and therefore Nbits/sample is reduced to 6+6b (which packs into an 18-bit multiplier, the key multiplier unit size in the FPGA), which should likely accommodate the increased number of baselines (TBC). Alternatively, more FPGAs could be deployed per FSP as noted for Figure 5-1.
  - Corner-turner integrated into the correlator design, after the mesh cross-connect.
- True-delay beamforming:

- o The bulk of the beamforming task is performed with per-antenna, per-beam true-delay steering in the Re-Sampler blocks. After that, beamforming is a summing operation, with final beam sums and other post-beam operations performed after the mesh.
- Phase-delay beamforming:
  - o Similar to correlation, after meshing, each FPGA in the FSP performs phase-delay corrections relative to boresight (set by Re-Sampler trued delay) for all antennas and a subset of the 4k channels for all 100 beams.

5.3 Physical Architecture

A simplified overview of the physical architecture of Trident-CBF was shown in Figure 5-1. This section delves into more detail of the key blocks, notably the VCC-UNIT, the FSP-UNIT, further details on the key LRUs, and hardware packaging and installation.

5.3.1 VCC-UNIT

A simplified diagram of the VCC-UNIT, and there are 26 such units in each trident of the system, is shown in Figure 5-11. Each TALON LRU consists of two TALON-DX boards[13], and each board contains a large high-performance Intel Stratix-10 FPGA. Each such FPGA performs the VCC-part processing (bulk coarse delay, VCC-OSPPFB, FS switch) for 2, dual-polarization sampled data streams.

Data is output from the FPGA onto fiber, each fiber containing one select Frequency Slice. Fibers for all FPGAs are passively cross-connected in the “VCC-MESH” optical circuit such that the output fibers are now arranged in MTP connectors ready for point-to-point connection to the 50 FSPs.

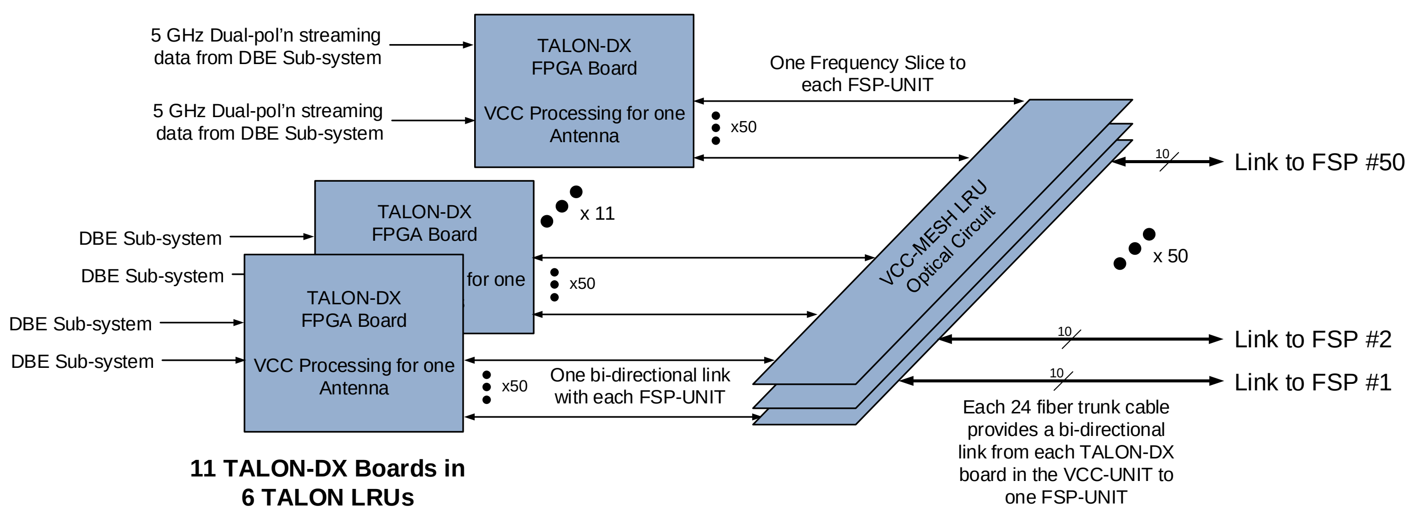

Figure 5-11 Simplified diagram of the VCC-UNIT.

A more detailed look at VCC-UNIT connectivity is shown in Figure 5-12. In this figure:

[13] Since only 11 TALON-DX boards are required, one LRU could contain only one board. However, doing so would break the uniformity of there being one TALON LRU, used everywhere.

- All connections to ngVLA antennas via the DBE are made using 100GBASE-SR4 fiber-optic modules plugged into the TALON-DX board dual QSFP28 cages via the TALON LRU front panel.
- All connections to the VCC-MESH are via the TALON-DX board's FCI LEAP 12 x 26G fiber Mid-Board Optical modules (MBOs), also via the TALON LRU front panel. Each TALON-DX has 5 of these: 4 contain 12 TRx fibers each and 1 contains dual 100G capability (i.e. using only 8 TRx fibers). All-tolled, including the QSFP28 cages, there are 64 x 26G transceiver channels connecting to the FPGA.
- The VCC-MESH LRU is a 1U-packaged box with MTP bulkhead connectors on the front and back panels, and an internal fiber passive cross-connect—specific to the needs of the VCC-UNIT and hidden from access—on the inside. The connectivity of this mesh is shown in Figure 5-13; refer to Section 5.3.4 for details of this COTS passive fiber mesh technology.
- Although the diagram shows bi-directional connectivity through the VCC-MESH, only the outgoing direction contains data, namely Frequency Slices en-route to the FSP-UNITs.

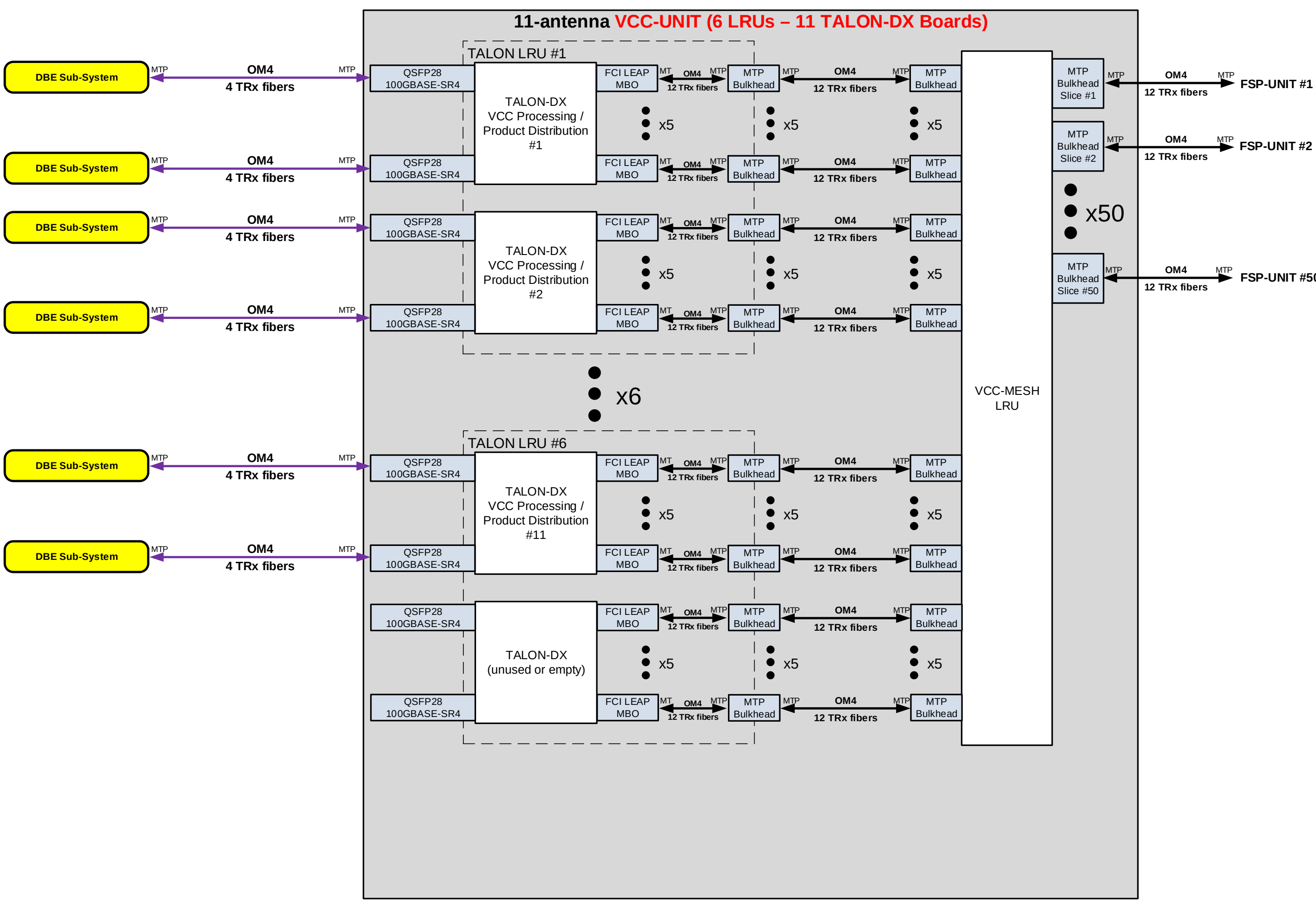

Figure 5-12 VCC-UNIT internal connectivity to TALON-DX boards and the VCC-MESH.

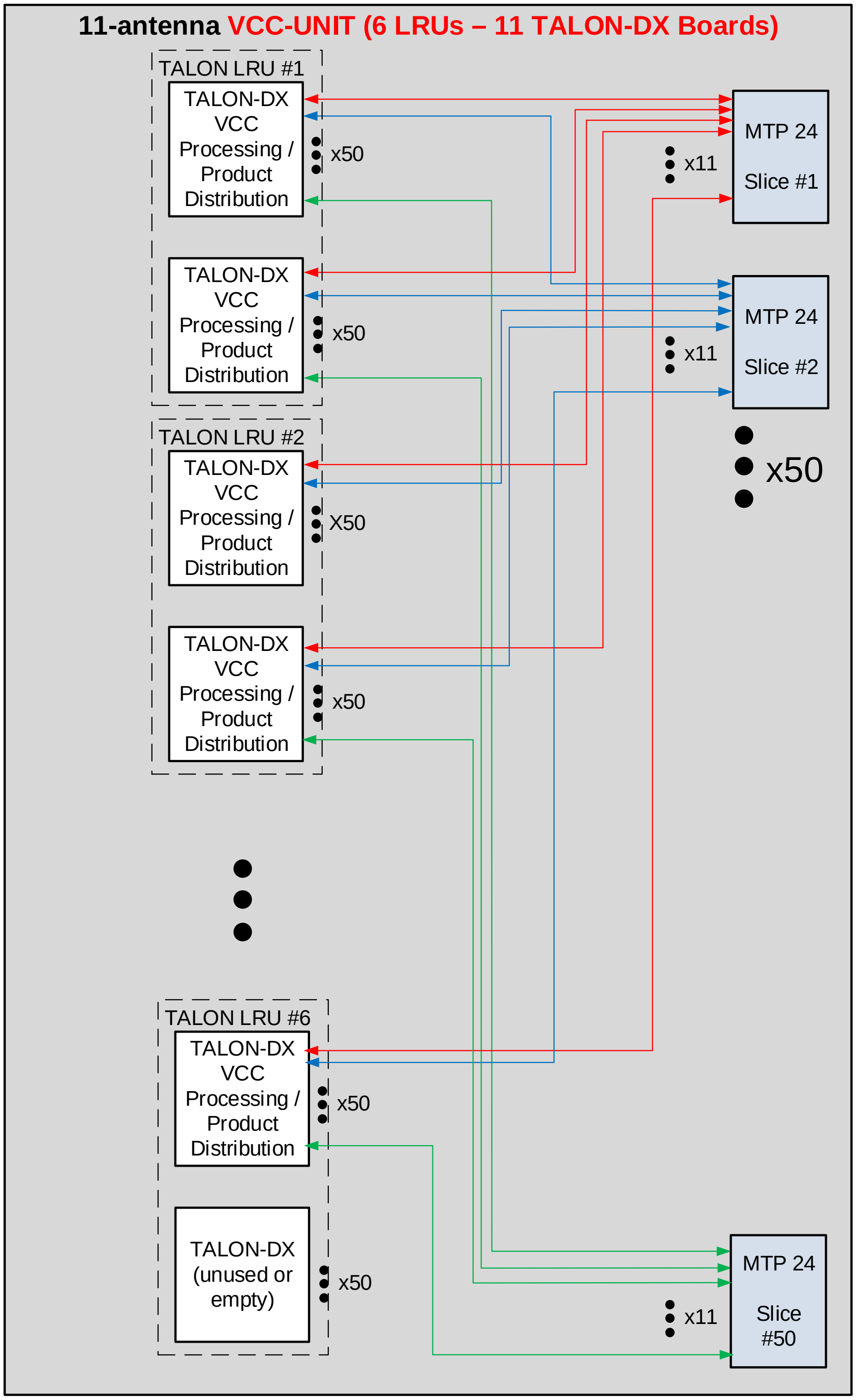

Figure 5-13 VCC-MESH LRU connectivity.

5.3.2 FSP-UNIT

Each FSP-UNIT in each trident is identical. It consists of 13 TALON LRUs (and therefore 26 TALON-DX boards), with direct plug-in inputs from VCC-UNITs (i.e. antenna data in), and a passive fiber FSP-MESH to provide the final mesh connections to organize the data back into the TALON-DX FPGAs for correlation and beamforming. A simplified diagram of the VCC-UNIT is shown in Figure 5-14:

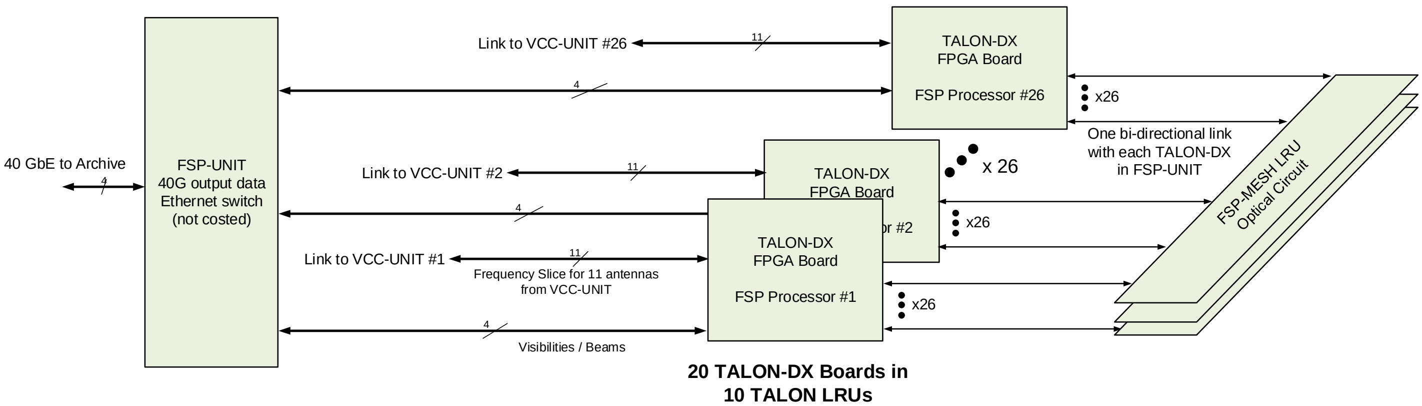

Figure 5-14 FSP-UNIT simplified block diagram.

A more detailed look at FSP-UNIT connectivity is shown in Figure 5-15. In this figure:

- All meshing cross-connectivity is provided by the FSP-MESH LRU, shown in Figure 5-16. As with the VCC-MESH, it is a 1U passive box with MTP bulkheads on the front panel and all fiber cross-connect details hidden internally. Thus, to the installer/maintainer, all connections here (and indeed the entire system) are via MTP fiber cables and connectors.
- Only one of the 40G QSFP28 cages[14] per TALON-DX board is used to output data to a COTS 40G Ethernet switch (not costed), which consolidates data for transmission via as single 40G link to the archive. There is much more bandwidth if needed.
- Although bi-directional connections are shown to VCC-UNITs, Frequency Slice data is only flowing into the FSP-UNIT.

[14] These cages support 100G-BASE-xR4 modules, plug compatible with 40GBASE-xR4.

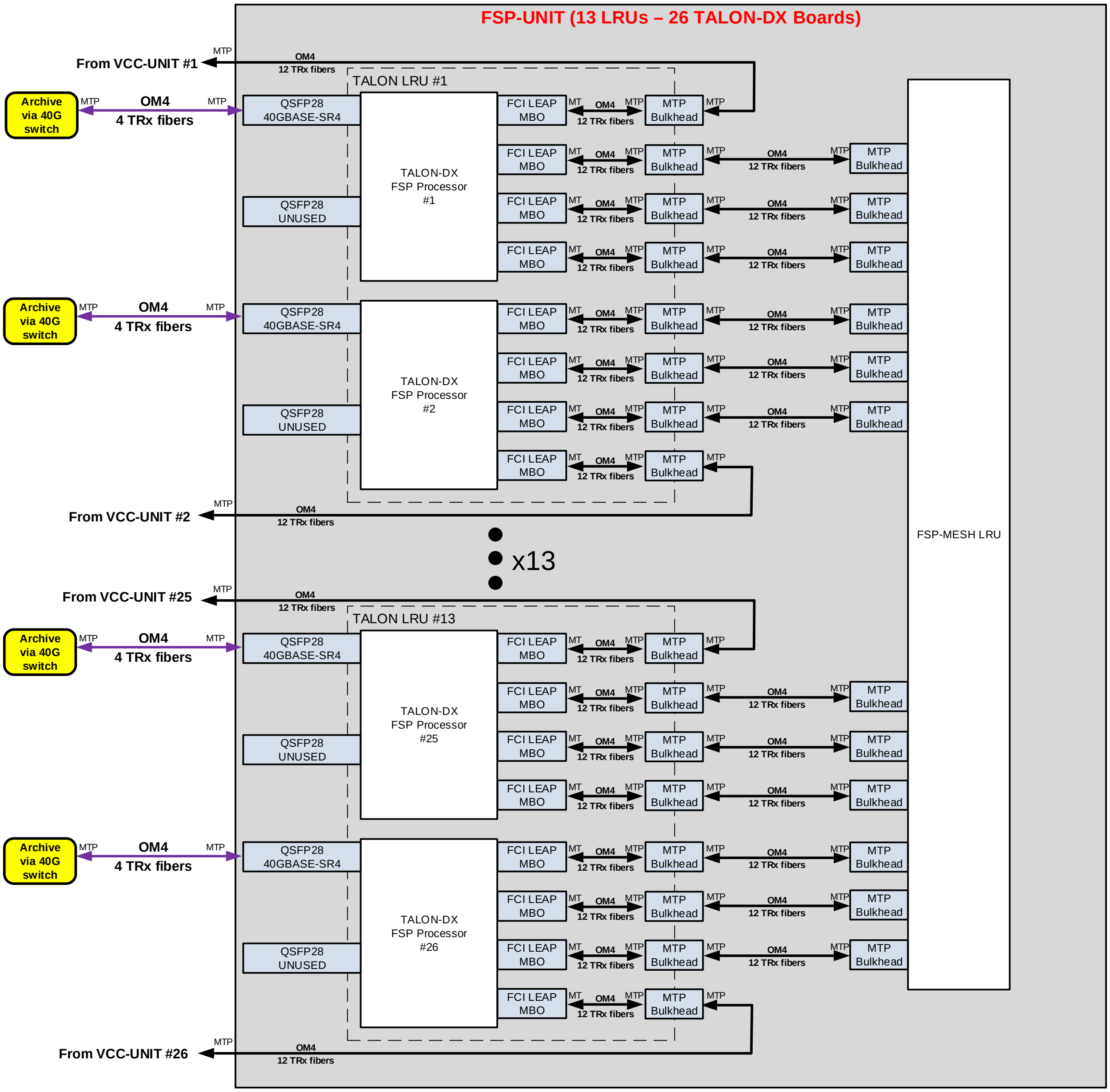

Figure 5-15 FSP-UNIT internal connectivity to TALON-DX boards and the VCC-UNIT(s).

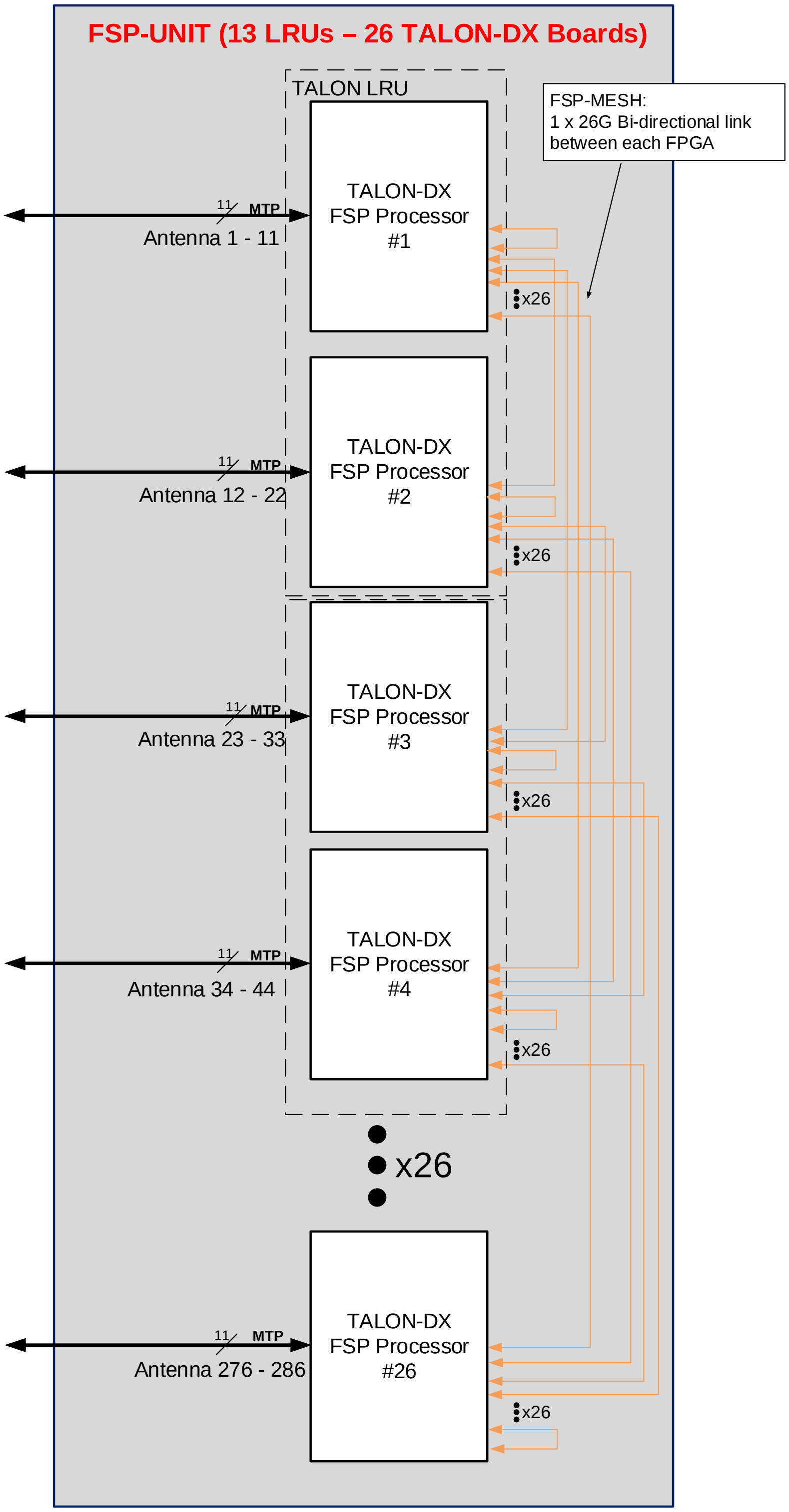

Figure 5-16 FSP-MESH internal connectivity between TALON-DX boards. Although the FSP-UNIT can ingest up to 286 inputs, correlation and beamforming is only provided for the required 263.

5.3.3 TALON LRU

The TALON LRU, containing two independent TALON-DX boards, performs all signal processing functions. There is one LRU, loaded with firmware (FPGA code) and software, which is able to take on VCC or FSP processing tasks depending on where it is located in the system and how it is configured.

This LRU design is based on extensive design and prototyping work done for the SKA1 Mid.CBF system. In that system, air-cooling is a requirement, and so the design of the LRU (enclosure, fans, heat sink) is for air cooling, but the basic design of the board and internal layout was built to be transportable to DCLC (Direct Contact Liquid Cooling)[15].

Each TALON-DX board is independent and has the following key capabilities:

- Intel SX280 Stratix-10 14 nm FinFET FPGA. This device has ~11k 18-bit multipliers and extensive logic and on-chip memory operating typically and comfortably at 500 MHz, and 64 x 26G SERDES transceiver channels—all of which are available as I/O. The device also contains an on-chip HPS (Hard Processing System) based on a quad-core ARM A53 CPU.
- 5 FCI LEAP Mid Board Optical (MBO) modules connecting to FPGA SERDES; 4 contain 12 transmit/receive SERDES at up to 26G each; 1 contains 8 transmit/receiver SERDES connecting to FPGA 2x100G Ethernet cores—they may be used for 100G Ethernet, or individual SERDES channels. The number of fiber I/O places a limit on the number of FPGAs in the FSP, and therefore the number of antennas. At 11 antennas per FPGA, the limit is (3 x 12 fibers + 1 x 8 fibers + 1 x 4 fibers [100G cage]) x 11 = 528 antennas.
- 2 x QSFP28 cages, each supporting COTS plug-in 100G (or 40G) fiber transceivers and connecting to the other 2x100G Ethernet cores in the FPGA.
- 4 x 72-bit, 2400 MT/s DDR4 DIMM modules. Three of these are accessible to the FPGA fabric (two of which may be as large as 256 GB each), one is accessible to the HPS cores.
- 100 Mbps fiber module I/O via 6 SFP cages including Clock Data Recovery (CDR) PLLs for Timecode distribution across the system. Timecode is a 100 MHz encoded clock containing the 1PSS and 32-bit 1 second timestamp.
- Dual 1 Gb/s Ethernet I/O for M&C, via SFP cages.
- High-capacity micro-SD card to hold FPGA bitstreams and HPS software.

The TALON LRU is powered by dual 1+1 redundant COTS 800 W AC-DC hot-pluggable power supply, providing each TALON-DX board with its +12 VDC mains supply. If desired, a plug-compatible power supply is available with 48 VDC mains supply. In the 1U DCLC design, 1+1 redundancy of this power supply is likely not possible due to height constraints.

A rendering of the air-cooled 2U TALON LRU for the SKA1 Mid.CBF is shown in Figure 5-17. The 100G QSFP28 cages are located along the bottom, with the MTP optical breakouts (for MBOs and Timecode) in a consolidated bulkhead on the right side. A DCLC 1U LRU is similar, but without the need for such a large air-flow cross-section, and clearly with some re-arrangement of the MTP optical bulkheads. See

[15] Indeed, the initial concept for the LRU was to use DCLC, but the infrastructure in the South African SKA1 Mid facility cannot support it.

Section 6.1 for further detailed technical and prototyping information on this 2U air-cooled LRU for SKA1 Mid.CBF.

Figure 5-17 Rendering of the 2U air-cooled 19" rack-mount TALON LRU for SKA Mid.CBF. The 1U DCLC LRU would be ½ the height. Note that this LRU has no front-rail mounting ears because of fiber routing space limitations; instead, it is mounted on custom slide rails in a 19" rack, and quick-lock secured to the rack at the back

5.3.4 Passive Fiber Meshes (VCC-MESH, FSP-MESH)

The passive fiber meshes in the VCC-UNITs and FSP-UNITs provide all of the necessary fiber cross-connect routing for the system. These are based on the Molex FlexPlane optical circuit, shown in Figure 5-18, packaged in a COTS 1U LRU and broken-out into MTP bulkhead connectors, as shown in Figure 5-19.

The required optical cross-connects for the VCC-UNIT (Figure 5-13) and FSP-UNIT (Figure 5-15) are custom, but procured—turn-key—through a COTS procurement process. All of the complex cross-connect details are contained and hiding in these mesh LRUs, leaving system installation and maintenance dealing only with point-to-point MTP-MTP connections within and across racks in the system.

An additional "TC-MESH" for Timecode distribution is also required, but not discussed in detail here.

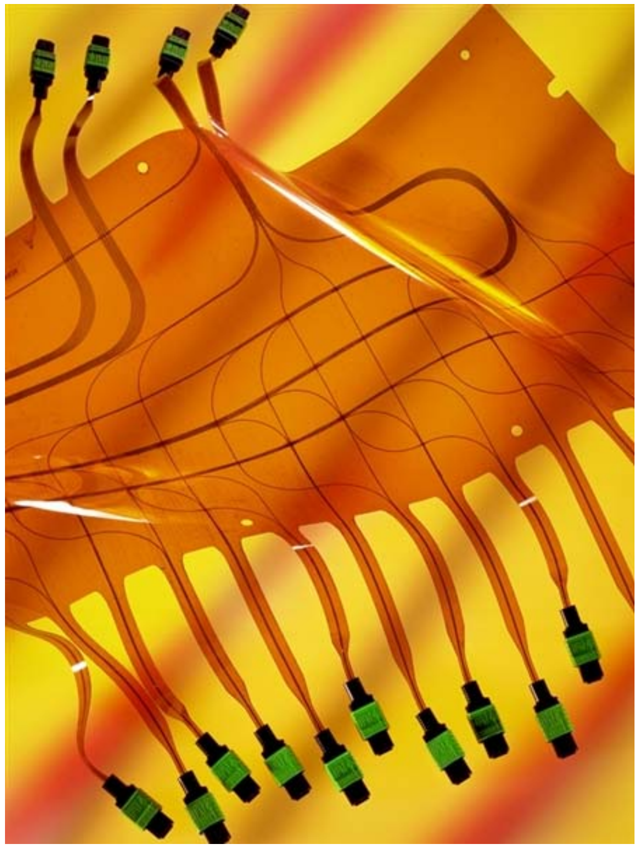

Figure 5-18 Molex FlexPlane optical circuit—a passive optical cross-connect.

Figure 5-19 Leviton 5R1UD-S12 1U optical circuit enclosure.

5.3.5 Timecode Distribution

An identical approach to timing and synchronization across the Trident-CBF system is taken as for SKA1 Mid.CBF (details found in [RD5]), itself derived from a similar approach used in the EVLA WIDAR correlator. Here, a single Timecode fiber signal, derived from the 100 MHz and 1PPS reference input and therefore synchronized to the ngVLA timing reference, is distributed to all TALON-DX boards in the system using a hierarchical approach, each trident separately and identically. Distribution components include the 6 Timecode fiber receivers/repeaters in each TALON-DX board and a TC-MESH optical circuit LRU contained in each rack.

The Timecode signal is a 100 Mbaud signal formatted as follows:

<pre-amble><1PPS mark> **<32-bit 1 sec count><32-bit msg><CRC-8>** <pre-amble>…

The bold 32-bit fields including the CRC-8 are scrambled with a known scramble code whose sequence starts at the 1PPS mark, to ensure DC-balance and that the receiver Clock Data Recovery (CDR) unit in the TALON-DX board doesn't see long strings of 1's or 0's. An example sequence is:

…10101010_0_00110001110101010101…_010101011100101001…_01011001_01010101…,

with the second 0 in the first double-0 of the sequence being the <1PPS mark>. Further work is required to develop the exact Timecode distribution design for Trident-CBF; SKA1 Mid.CBF distributes Timecode to a total of 27 racks—therefore a similar design, for each trident independently[16], is applicable.

5.3.6 Hardware Packaging and Installation

The entire Trident-CBF system is contained in COTS 19" server racks. Each such rack, with a notional population shown in Figure 5-20, contains:

- Two FSP-UNITs requiring 15U each. 13U are required for the TALON DCLC LRUs, 1U for FSP-MESH optical circuit LRU, and 1U for the 40G Ethernet output switch.
- One VCC-UNIT requiring 7U. 6U for the 6 TALON DCLC LRUs providing 11 antenna, single-trident, processing capability, and 1U for the VCC-MESH optical circuit.
- 1U for the TC-MESH optical circuit for Timecode distribution in the rack.
- 2U for a COTS 10G/1G Ethernet switches for monitor and control into the TALON-DX FPGA HPS processors.
- 2U for the COTS CoolIT CHx40, 40 kW[17] heat exchanger (https://www.coolitsystems.com/coolant-distribution-units/). Estimated power dissipation of each TALON LRU, based on extensive prototyping testing for SKA1 Mid.CBF, is ~600 W; with 32 TALON LRUs (with one TALON-DX board missing or powered off), the heat exchanger must handle ~19.3 kW.

[16] But still with cross-trident synchronization to meet requirements for data product timestamping synchronization.
[17] At 30 C supply water temperature.

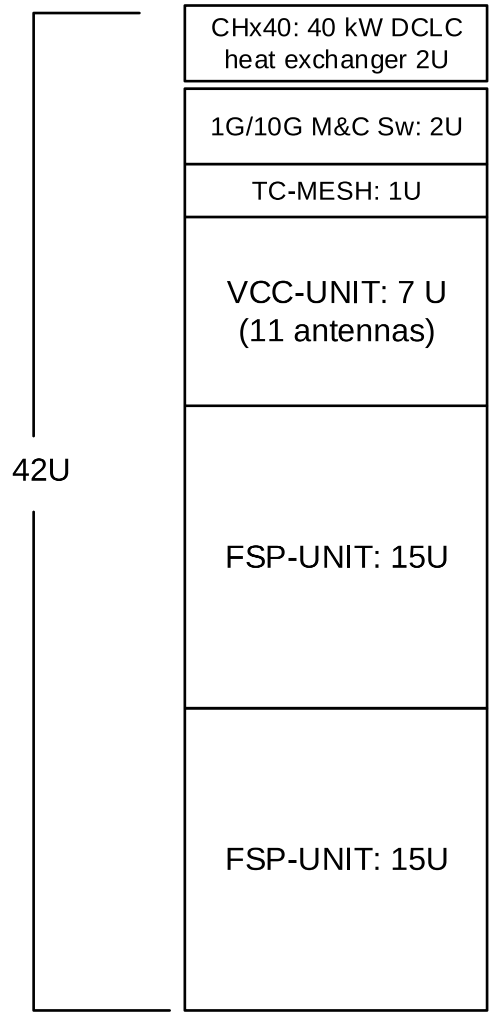

Figure 5-20 Trident-CBF notional 42U 19" server rack population. If required, a 48U server rack could be used since there is no spare space available.

- At the rear, and AC-AC COTS Power Distribution Unit, as well as a DCLC manifold to provide connectivity between the CHx40 unit and the DCLC heat exchangers on the TALON-DX boards.

For *each* trident, with 50 FSPs and 263 antennas, 26 such racks are required, with 24 such racks containing only the VCC-UNIT and potentially a redundant FSP, if desired.

The total number of racks for all 3 tridents is therefore 78, plus 1 or 2 air-cooled racks for central monitor and control and networking. Thus, space for 80 racks, 78 at ~19.3 kW and 2 at ≤ ~10 kW is required for a Trident-CBF based on this generation of technology. See Section 13 for forecasting of power and space to ~2025 technology.

See Section 6.4 for further details on rack technology.

5.4 Software/Control and Monitor Architecture

Details of the software/M&C architecture for Trident-CBF are TBD, however, such details have been worked out extensively for the SKA1 Mid.CBF design. A summary of key aspects is as follows:

- The TANGO software communications and abstraction infrastructure [RD4] is used throughout, including on the TALON-DX FPGA HPS processors.
- Hard real-time embedded processing, such as delay and phase tracking model updates in the FPGA fabric, occurs in the TALON-DX FPGA HPS processors.
- Firmware IP blocks in the FPGA connect to the HPS processors via a standard bus (Avalon or AXI). All such IP blocks' read/write/control registers are accessed by software running on the HPS processors, by the Trident-CBF Control Server, and indeed any network node with available access, via device drivers that are "TANGO devices".
- The FPGAs' ability for "partial bitstream re-configuration" is used extensively:
  - The FPGA I/O ring and HPS processors are always active. This means that M&C intelligence, high-speed serial connectivity, and Timecode connectivity across the system is always maintained.
  - When a new FSP Function Mode is configured, only the internal partial reconfiguration region of the FPGA is bitstream-configured. This approach means minimal time to change Function Modes, typically a few seconds. Similarly for the VCC FPGA 10 GHz/pol 4+4b or 5 GHz/pl 8+8b configurations.
- The HPS processors run real-time Linux. Boot time from the micro-SD card is a few seconds, and the processors are always active independent of FPGA bitstream.
- The central Trident-CBF Control Server translates high-level configuration commands from the ngVLA-LCS to internal VCC-UNIT and FSP-UNIT M&C, via the 10G/1G Ethernet network provided.

Whilst the above M&C approach is used for SKA1 Mid.CBF, for Trident-CBF any standardized M&C infrastructure required by the ngVLA may be used, simply requiring the same hierarchy of processing.

6 Technologies

6.1 TALON-DX Board and TALON LRU

A simplified block diagram of the TALON-DX board is shown in Figure 6-1, with a layout diagram shown in Figure 6-2. The key capabilities of this board are described in Section 5.3.3.

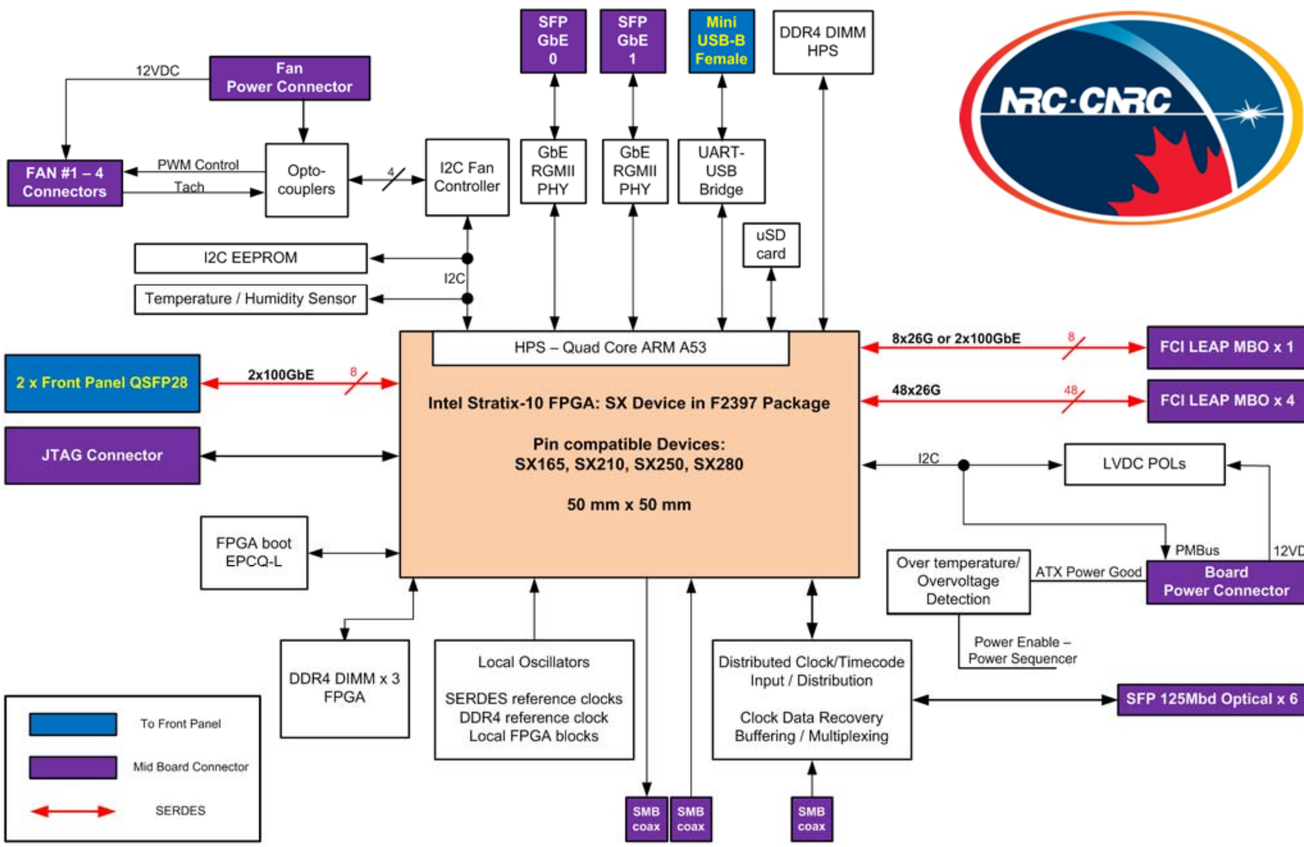

Figure 6-1 TALON-DX board simplified block diagram.

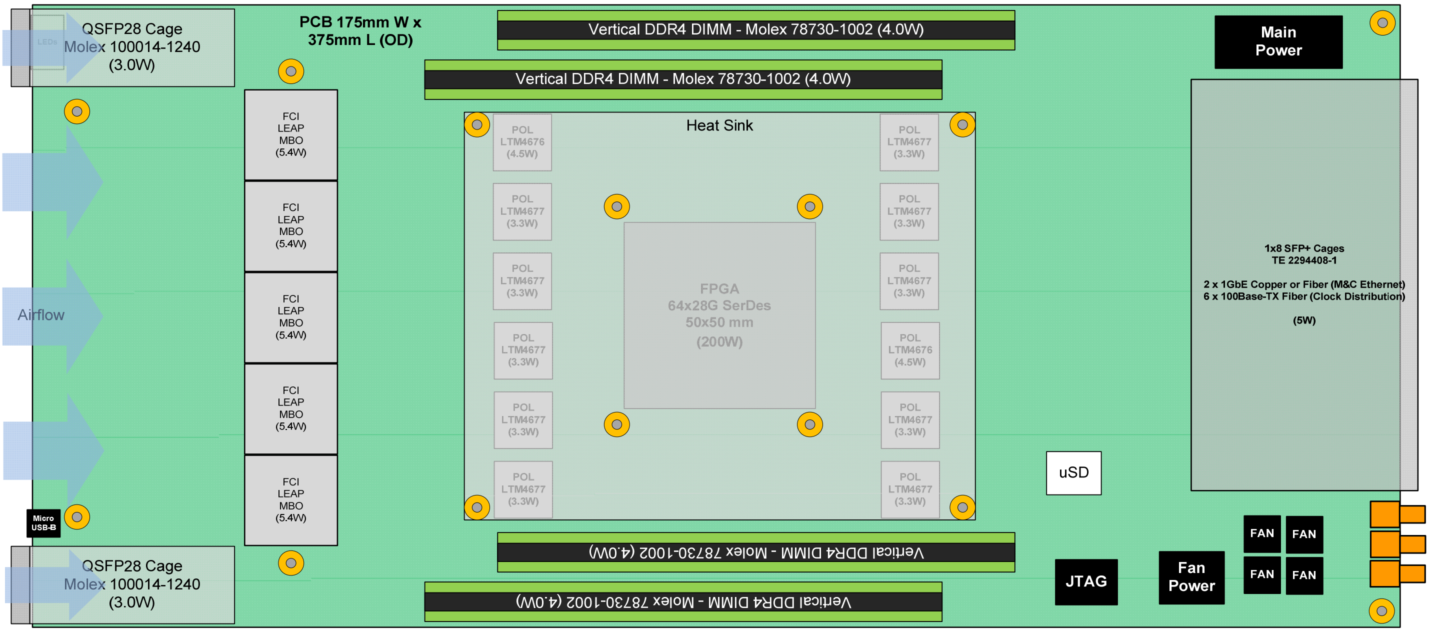

Figure 6-2 TALON-DX board layout diagram. The location of a stacked-fin heatsink for air cooling is indicated; for DCLC, a liquid cooling plate would be used instead, allowing for a 1U packaging height.

As mentioned previously, significant development and prototyping of this board, including HPS processor boot/software development, has been done for SKA1 Mid.CBF and all of the key risks (SERDES 26G performance, DDR4 2400 MT/s performance) have been retired, using engineering prototypes of the FPGA. As of this writing (Sept. 2018) the NRC team is gearing up for procurement of several more prototypes of the 2nd spin of the board to include bug fixes and updates for the board to be used for SKA1 Mid antenna post-digitization signal processing (digital sub-band selection). Also, more extensive performance and margin testing will be performed on these models.

The following figures contain photos of the TALON-DX board and LRU prototypes.

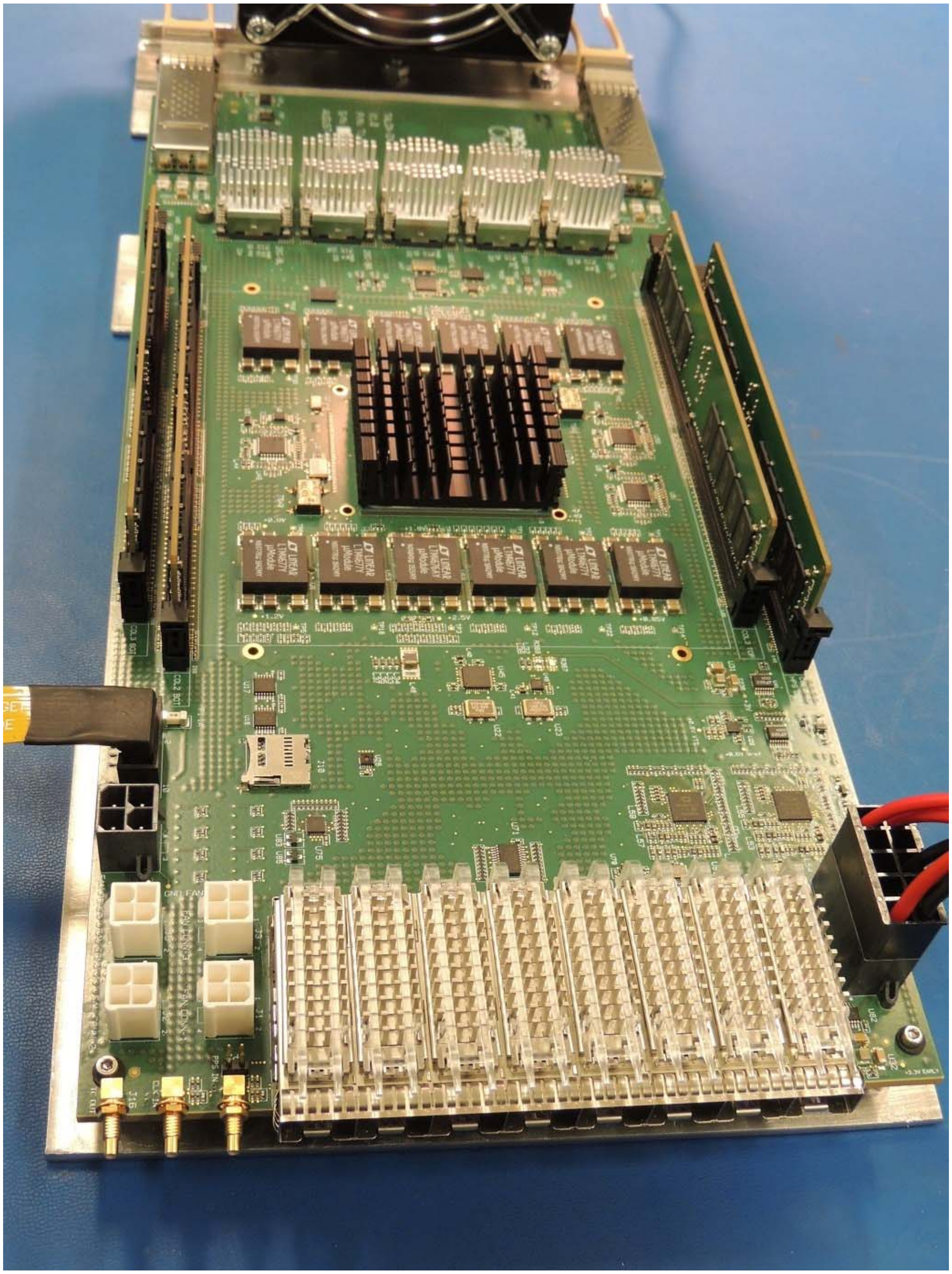

Figure 6-3 TALON-DX prototype board under test.

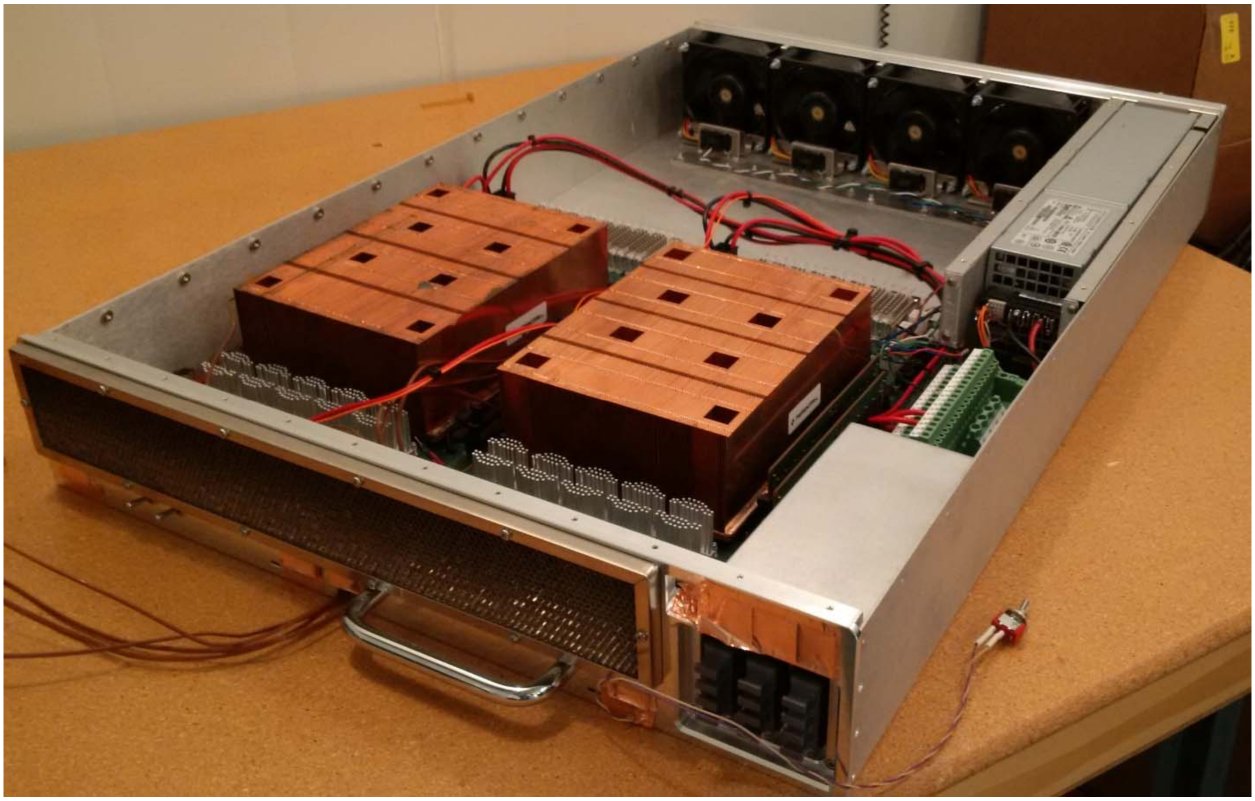

Figure 6-4 2U air-cooled TALON LRU prototype under test. The large orange boxes are copper stacked-fin heatsinks for air cooling. These would be replaced by liquid cooling plates for a liquid-cooled 1U DCLC design.

6.2 Passive Fiber Meshes

See Section 5.3.4.

6.3 Direct Contact Liquid Cooling (DCLC)

There are several flavours of liquid cooling solutions used throughout the industry. In DCLC, a cooling plate—through which cooling water-based fluid circulates—is thermally attached to the main heat generating devices on the board. For the TALON LRU, this means thermal attachment to the FPGA, MBOs, and LVDC power supplies. Thermal attachment to the DDR4 DIMMs is possible, but instead could be a small amount of air cooling—provided by ~2 1U fans at the rear of the LRU, TBC.

A leading player in the design, manufacture, and deployment of DCLC solutions is CoolIT (https://www.coolitsystems.com/). This manufacturer provides custom liquid cooling plate designs and associated COTS components. These include the passive cold plate, rack manifold, and top-of-rack liquid-to-liquid heat exchanger between the rack liquid loop and the facility liquid loop (the latter dumping heat to the outside via a liquid-to-air heat exchanger (radiator). Photos of key components in a DCLC solution are shown in the following figures.

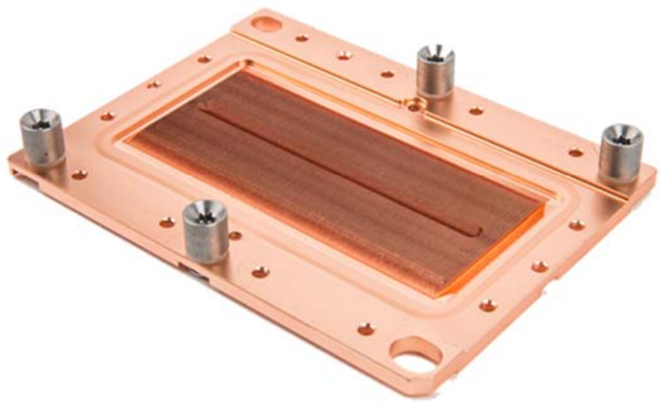

Figure 6-5 CoolT DCLC cold plate example showing the interior micro-fins for heat exchanging. For a DCLC TALON-DX, a customized plate like this would cover the FPGA, MBOs, and LVDC power supplies.

Figure 6-6 View looking down the stainless-steel manifold, located at the rear of the rack. The manifold provides the interface between the cold plate attached to the FPGA (etc.) and the CHx40 heat exchanger. The manifold has a supply and return side, providing 2 hoses to each TALON-DX board (i.e. 4 per LRU).

Figure 6-7 CoolIT CHx40 liquid-to-liquid heat exchanger. Dual 1+1 redundant circulating pumps are located in this unit. If a failure is detected, all of the LRUs in the rack must be powered down, but with dry quick connect/disconnects, this unit can be quickly replaced. It also has an Ethernet network connection to allow its status to be continuously monitored.

The CoolIT solution is very robust and is used extensively throughout the industry, including the CHIME GPU correlator, located at the NRC-Penticton site. All liquid connections, including the CHx40 connections to the rack manifolds and the (overhead) facility liquid lines, are via dry quick-connect/disconnect lines. Nevertheless, each TALON LRU will contain humidity/water sensors to detect leaks (CoolIT also has an integrated solution to detect manifold and other leaks) to take mitigating action if a leak is detected. As well, a welded screened room to house Trident-CBF is highly recommended so that a major leak won't cause catastrophic room failure.

6.4 Other Rack Components

Each of the Trident-CBF racks is a COTS 19" rack with the TALON LRUs, optical circuit LRUs, Ethernet switches, and DCLC components installed. Additionally, each rack contains a COTS AC-AC Power Distribution Unit (PDU), located at the back of the rack. The PDU is Ethernet-controllable to monitor power and control each output; a switch in the Trident-CBF Control Server rack would provide access to each of these PDUs.

7 Performance

7.1 Signal Processing

Extensive performance modelling and testing of the SKA1 Mid.CBF signal processing chains have been undertaken, with results presented in [RD3]. Since the Trident-CBF signal processing chains are based on this design, then these results are directly relevant, with key excerpts presented in the following figures.

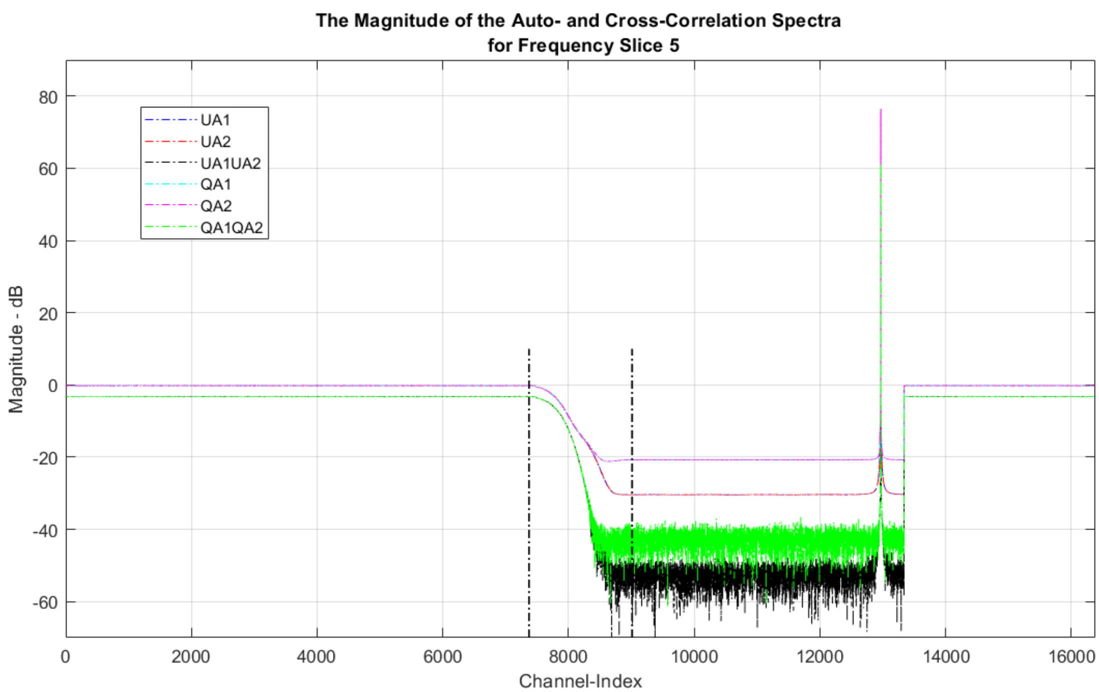

Figure 7-1 End-to-end imaging correlation result with a strong in-FS RFI tone (at 30 dB power relative to the total noise power into an 8-bit digitizer) in the Frequency Slice. Here, the green trace is the quantized (Q) cross-correlation result (i.e. representative of the actual implementation) with ~99% correlation efficiency, per-channel gain/ripple corrections applied, and showing over 100 dB of SFDR (U=floating point/un-quantized model) with some RFI amplitude reduction due to earth-rotation phase wrapping. Note that in this plot the edges of the FS are near the center, and there is a deliberate uncorrelated portion of the FS from channel index ~8500 to ~13500.

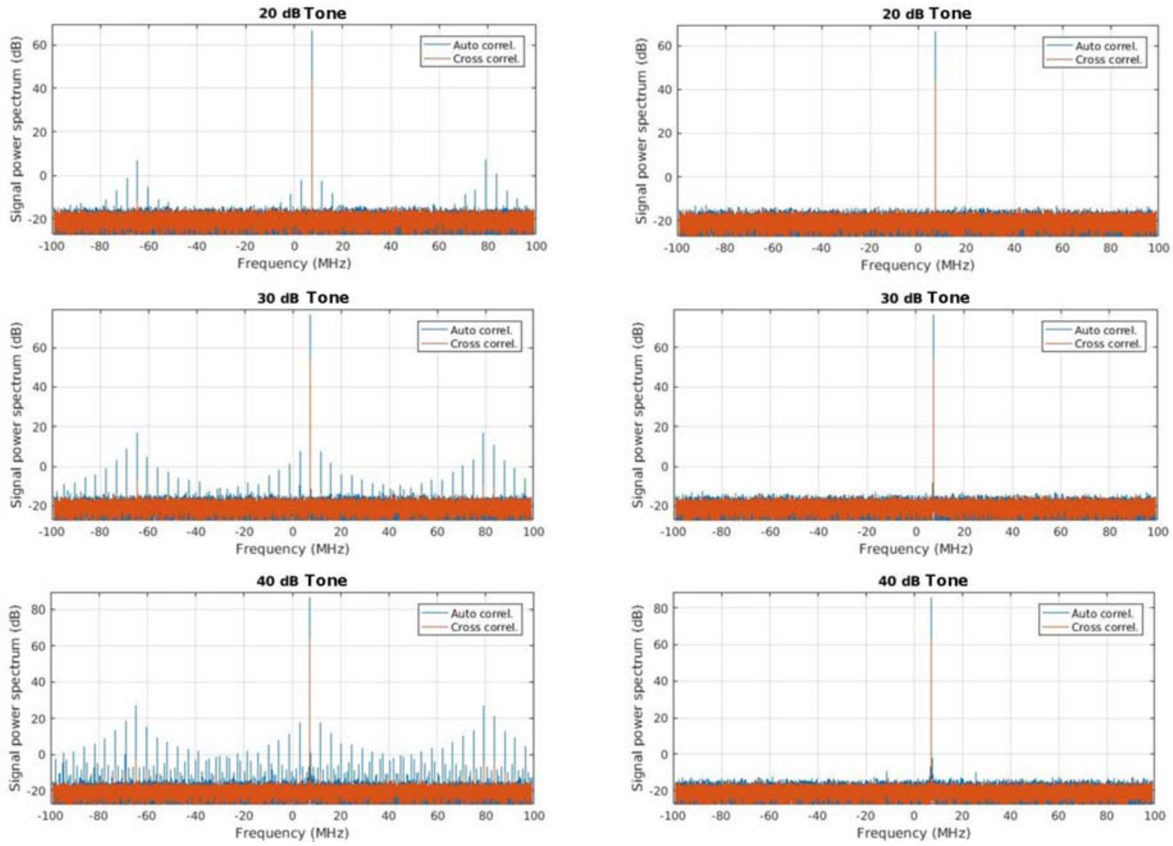

Figure 7-2 Auto-correlation and cross-correlation noise spectra for digitizer input signals containing a single tone of power 20 dB (top), 30 dB (middle) and 40 dB (bottom) without (left) and with (right) scrambling (dithering) in the Re-Sampler phase/delay correction.

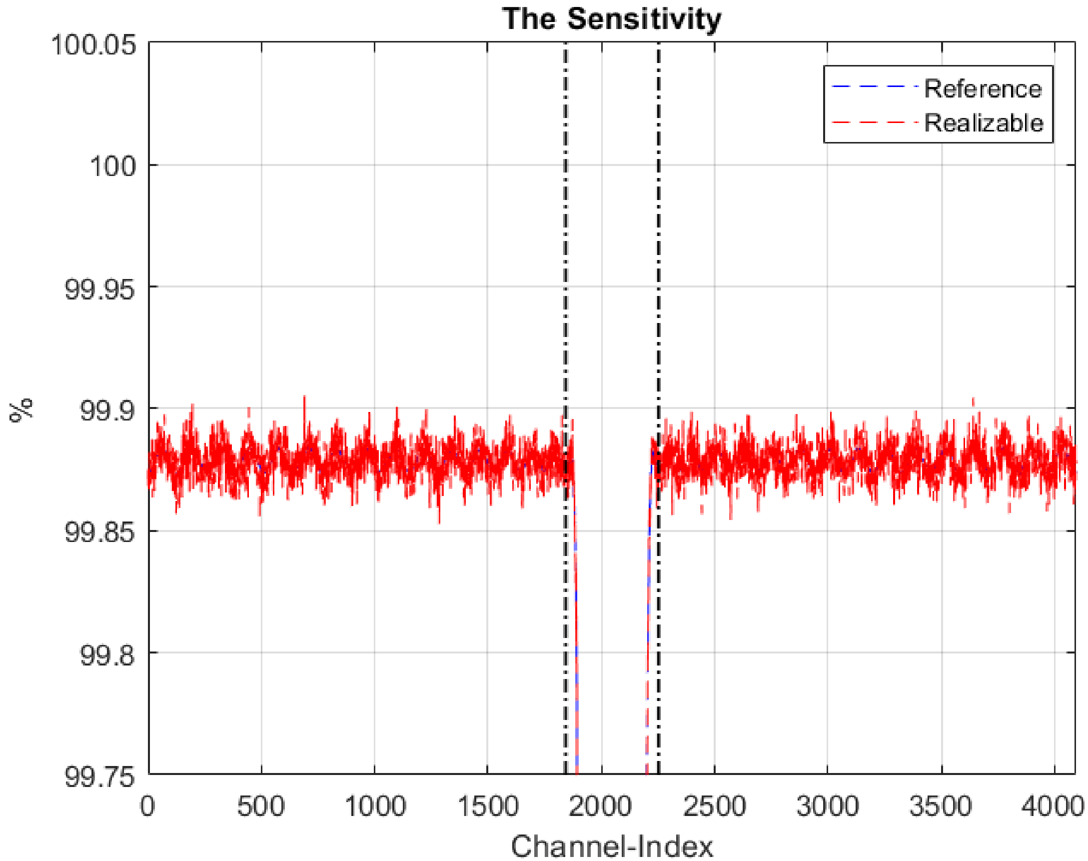

Figure 7-3 Sensitivity across the sampled (channelized) bandwidth for phase-delay beamforming ("realizable"=quantized realized signal processing chain). Here for SKA1 Mid.CBF, the bandwidth is ~330 MHz and the aperture is 20 km, with one antenna on either side of it. For the ngVLA this corresponds to a ~40 km aperture, a 220 MHz FS bandwidth, and less beam offset from boresight due to the narrower primary beam of the ngVLA antenna. The ripple across the band is uncorrected and due to the VCC-OSPPFB response (see Figure 5-2).

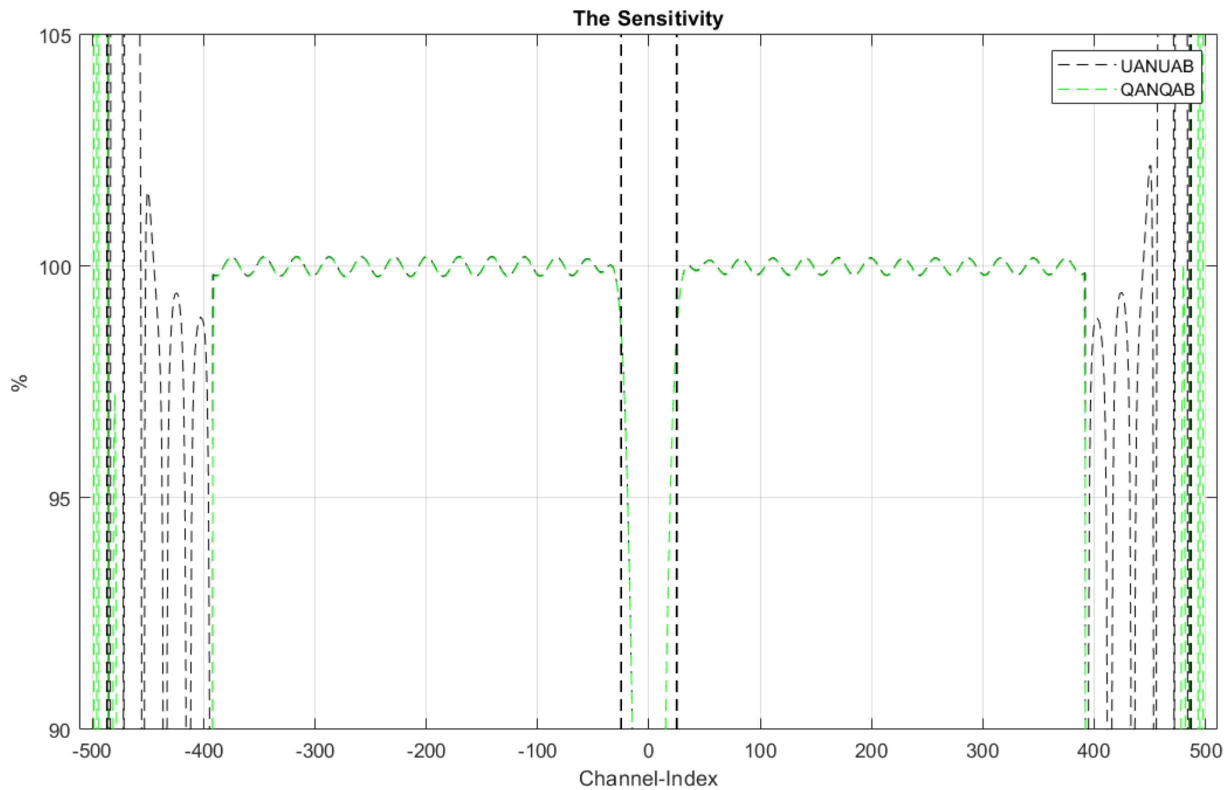

Figure 7-4 Sensitivity of true-delay beamformed real output for 2 antennas across the FS sampled bandwidth of 224 MHz, shifted by ~10 MHz in frequency (hence the asymmetry of the incoherent regions). Here, +/- frequencies of the spectrum of the FS are shown and ripple is due to the VCC-OSPPFB. The apparent >100% sensitivity is due to a modelling anomaly in the sensitivity calculation relative to a single antenna receiving the same signal.

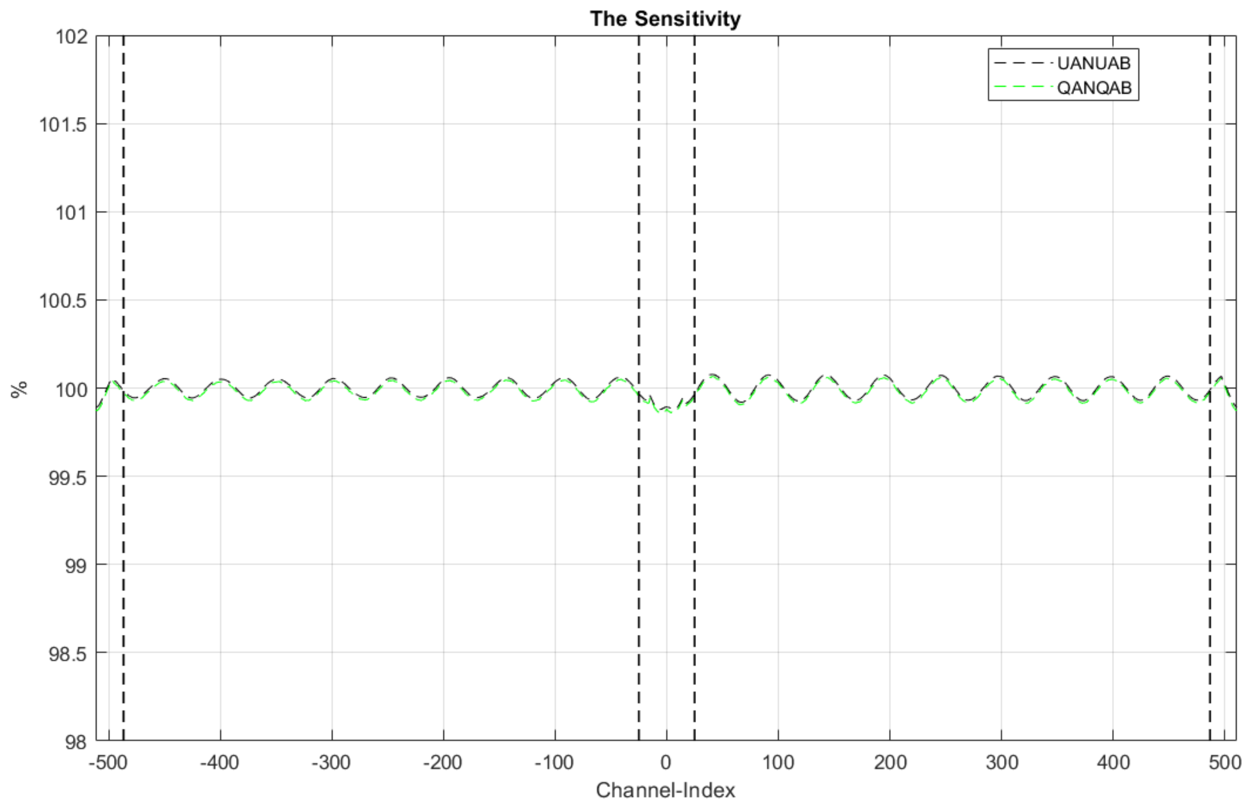

Figure 7-5 Sensitivity of a true-delay 128 MHz VLBI beam-channel output. The signal is real and aliasing occurs at the band edges (noted with dashed vertical lines) due to the beam-channel tunable DDC finite transition bands. Ripple is due to the VCC-OSPPFB response.

7.2 Thermal

Extensive thermal modelling of the air-cooled TALON-LRU for SKA1 Mid.CBF has been performed and it has been found that acceptable thermal operation at the expected power up to Tamb=27 ^{o}C is obtained.

However, for Trident-CBF with DCLC, thermal performance is much better since a) only ~20 kW/rack needs to be cooled, easily within the capacity of the CHx40 heat exchanger and b) DCLC heat transfer is much more efficient than air. The CHx40 operates with facility water supply temperatures in the range 2-45 ^{o}C with a cooling capacity of 40 kW at 30 ^{o}C supply water temperature. Cooling capacity curves for the CHx40 are shown in Figure 7-6:

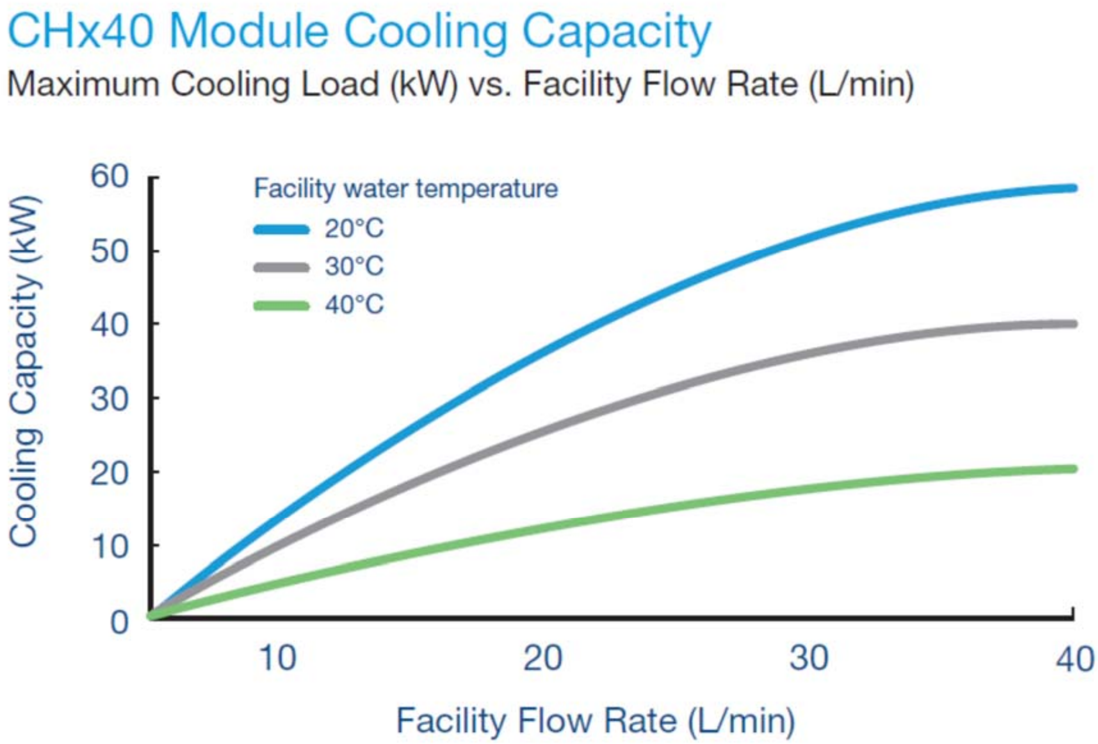

Figure 7-6 Cooling capacity curves for the CoolIT CHx40. Trident-CBF is expected to require 20 kW of cooling capacity per rack which, at a facility water temperature of 40 ^{o}C, requires a flow rate of ~40 L/min. The CHx40's power consumption is ~120W.

If the CHx40 turns out to not have sufficient capability, the CHx80, with up to 80 kW of cooling capacity can be used instead. It requires 4U of rack space and its cooling capacity curves are shown in Figure 7-7:

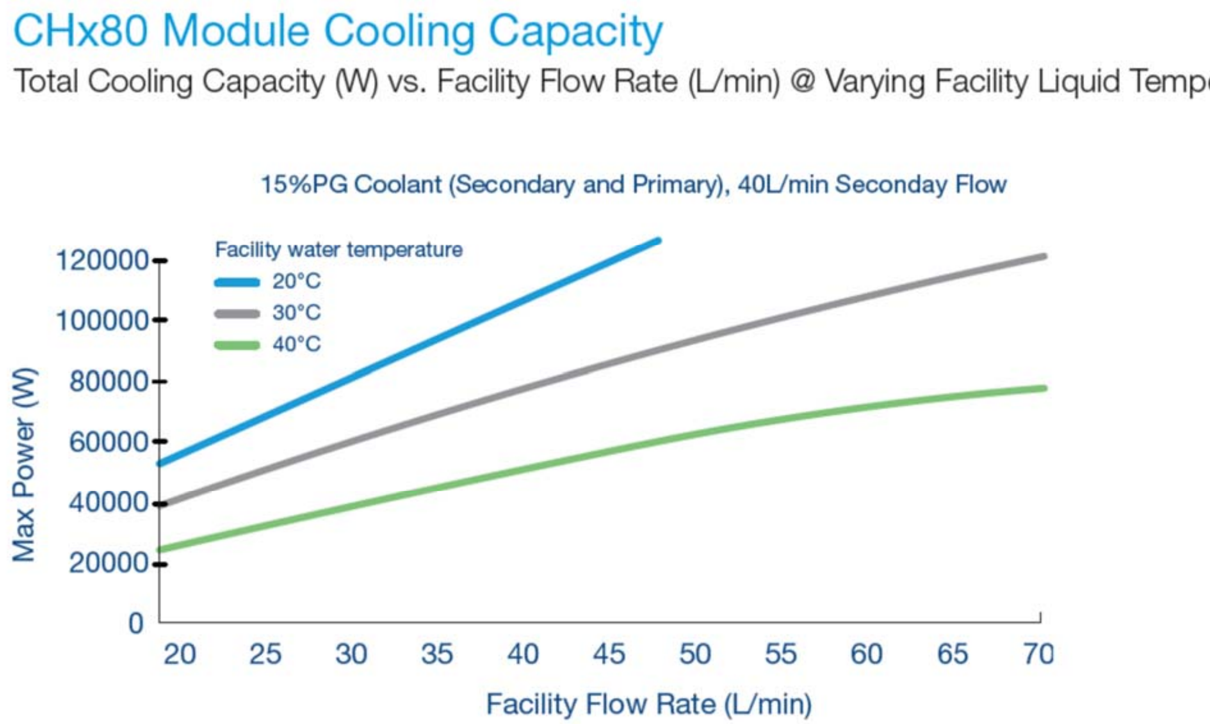

Figure 7-7 CHx80 cooling capacity curves. The CHx80's power consumption is ~625W.

8 Reliability, Availability, Maintainability

8.1 Reliability

From SKA1 Mid.CBF studies reported in [RD5], the MTBF of the TALON-DX assembled board, calculated using the parts-count method according MIL-HDBK-217FN2 is 5 years. In practise, MIL-217 is very conservative and an MTBF of at least 10 years is more likely.

8.2 Availability

Availability requirement TCBF-1401 is met assuming a single TALON LRU fails at any given time. As well, the Intel Stratix-10 FPGAs on the TALON-DX boards contain integral single SEU detection and correction and multiple SEU detection. Given the size of the devices, the number in the system, and the VLA-site 7000 foot location, SEUs due to cosmic rays will occur on a regular basis, sometimes needing FPGA bitstream reboots to correct.

8.3 Maintainability

All of the following items are hot-swap replaceable:

- TALON LRUs. There is one LRU type, loaded with hardware, firmware, and software to take on the required function (VCC or FSP), depending on where it is located. The LRU contains on-board high-capacity non-volatile memory that holds all firmware (FPGA bitstreams) and software—updates to these are pushed-out to the LRUs over the monitor and control network. TALON LRUs have dry quick connect/disconnect DCLC cooling lines at the rear-of-rack manifold (Figure 6-6).
- AC-DC power supply in the TALON LRU. This can be replaced without removing the TALON LRU from the rack.
- VCC-MESH, FSP-MESH, and TC-MESH. These are passive LRUs so shouldn't fail. Removing/replacing the VCC or FSP-MESH boxes necessarily takes down an entire VCC-UNIT, and therefore 11 antennas for one trident, or FSP-UNIT.
- Rack COTS Ethernet switches.

The following items are replaceable, but doing so requires powering-down the rack they are in.

- CoolIT CHx40 top-of-rack heat exchanger. This 2U module has dry quick connect/disconnect fittings. Replacement is very quick, typically ~0.5 hrs or so. This unit has internal 1+1 redundant circulating pumps and network monitoring and so normally it is possible to replace a unit before it fails.
- Rack AC PDU.

As with the EVLA WIDAR correlator, all communications paths between TALON LRUs are continuously tested with embedded error checking, however, off-line tests need to be performed periodically to ensure FPGA-internal calculations are correct. In the Trident-CBF system it is not necessary to take the entire system off-line to do so, FSP-UNITs can be tested individually, as can select portions of VCC-UNITs (doing so takes off-line one or more antennas of a trident).

9 Environmental

The Trident-CBF system is design to be located in a clean, ground-benign, office environment. Since DCLC cooling is employed there should be little to no dust build-up in TALON LRUs, however a dust contamination environment similar to the EVLA WIDAR correlator should be assumed.

With DCLC, there is always the possibility of a liquid cooling leak. The rack local loop (from the TALON LRUs to the manifold, to the CHx40) holds several liters of water and is at relatively low pressure. However, the main liquid loop (CHx40s in all racks to the external heat exchanger), is much higher volume flow and pressure water. In any case, a room construction that would withstand a leak of many 10s of liters of water is prudent, e.g. if in an EMI screened room, welded rather than bolted construction.

Since TALON LRUs, and in fact all equipment in Trident-CBF, are enclosed in individual 19" rack-mount boxes, no special room ESD protection measures are required.

Total estimated power consumption of the Trident-CBF system, implemented using TALON-DX Stratix-10 technology is ~1.5 MW (Section 5.3.6).

10 Safety

All equipment, including the TALON LRU, meet industry standards for electrical safety. The TALON LRU uses a COTS hot-pluggable AC-DC power supply, which is certified to all relevant safety standards.

11 Manufacturing and Procurement Plan

All Trident-CBF PBS items are COTS or COTS-specified, except the TALON LRU. However, for it, a COTS procurement model is applicable as follows:

- The TALON-DX board/assembly manufacturer is tooled-up by the developer to build the board, but also to assemble the entire LRU, load it with firmware and software, and run tests to verify that is operates according to specification. The manufacturer also is tooled and capable of supporting a full RFQ, quote, purchase order, deliver, and defect/repair RMA cycle, complete with standard and extended warranty support.
- For each deployment milestone, required COTS and TALON LRU items are purchased. TALON LRUs are purchased in a COTS-manner from the manufacturer through a normal procurement cycle.

12 Testing and Deployment Plan

This plan will be based on ngVLA project-driven testing and deployment methods and milestones, TBD.

13 Development, Construction, and Operational Cost

The total cost of Trident-CBF is based on the very-well developed SKA1 Mid.CBF cost model, with the following points of note:

- TALON-DX assembled board pricing is based on CY2021production in 2018 dollars and includes actual vendor quotes for all aspects of it, including manufacturing.
- TALON LRU pricing includes production costs of the all components, assembly, and testing. Even though Trident-CBF uses DCLC, the cost of this is judged to be approximately the same as air cooling. Same for rack components.
- TALON LRU pricing is for the volume of SKA1 Mid.CBF (359 LRUs + spares), whereas Trident-CBF contains ~2382 LRUs[18], thus LRU pricing for Trident-CBF is somewhat conservative.
- Although Trident-CBF has some different FPGA firmware blocks, it is largely the same as for SKA1 Mid.CBF. Thus, it is judged that overall the NRE of Trident-CBF will be approximately the same as SKA1 Mid.CBF.
- The complete SKA1 Mid.CBF NRE (including management, system engineering, testing, and deployment) is included in the cost, i.e. it is not assumed that Trident-CBF NRE can be reduced because much of the work has already been done.

Based on these points, the SKA1 Mid.CBF cost model was updated to increase the number of TALON LRUs, optical cables, mesh boxes, Ethernet switches, racks etc. to that required for Trident-CBF. A summary of the results are shown in Figure 13-1 and Figure 13-2. Based on FPGA cost multiplier factors of 0.5 and 0.8 for future 2025 technology, the procurement and production cost of ~$91.8M[19], could reduce to ~$73M-$84M, for a total cost of ~$108M-$121M respectively (2018 dollars).

From Section 5.3.6, total Trident-CBF power, not including cooling infrastructure, is ~1.5 MW. However, this is for 14 nm FinFET 2018 technology. Based on forecasts from Intel, in ~2025 power per operation should be 0.6 to 0.8 of this, and so total system power could be in the 900-1200 kW range.

[18] For the 6 TALON LRU per VCC-UNIT and 13 TALON LRU per FSP-UNIT case. All TALON LRUs in the VCC-UNITs are fully populated with TALON-DX boards. Some cost could be shaved by having an LRU with only one TALON-DX board.

[19] The most significant costs are the FPGAs in the TALON LRU.

WBS Category Definition	WBS Category	Labour PDs									Total PDs	Labour PD%	Labour Cost	Non-Labour Cost	Travel Cost	Contingency	TOTAL COST
		PM:Sr	PM:Int	Eng:Sr	Eng:Int	Eng:Jr	Sci:Sr	Sci:Int	Con	Admin							
		$1,100	$900	$1,000	$900	$750	$1,050	$850	$950	$500							
Management	MGT	825	0	660	550	0	0	0	209	825	3069	16.0%	$2,673,550	$0	$261,000	$293,455	$3,228,005
System Engineering	SE	0	0	917	766	0	0	0	0	0	1683	8.8%	$1,606,367	$0	$220,400	$182,677	$2,009,443
Product Design	PD	0	0	0	0	0	0	0	0	0	0	0.0%	$0	$0	$0	$0	$0
Hardware Development	HW	0	0	0	606	0	0	0	0	0	606	3.2%	$545,738	$449,893	$69,600	$228,319	$1,293,550
Firmware Development	FW	0	0	0	4937	0	0	0	0	0	4937	25.8%	$4,443,683	$360,000	$208,800	$1,282,535	$6,295,018
Software Development	SW	0	0	0	3986	0	0	0	0	0	3986	20.8%	$3,587,704	$240,000	$139,200	$731,197	$4,698,101
Sub-System Integration Infrastructure	SII	0	0	88	461	0	0	0	0	0	549	2.9%	$502,975	$291,668	$34,400	$118,332	$947,376
Integration & Test (a.k.a. Development Testing)	I&T	0	0	193	1348	0	0	99	0	0	1639	8.6%	$1,489,400	$0	$413,800	$420,456	$2,323,656
Acceptance Test for Verification	AT	0	0	88	807	0	0	0	0	0	895	4.7%	$814,000	$116,006	$116,000	$83,680	$1,129,686
Shipping and Installation	S&I	0	0	0	128	0	0	0	0	293	422	2.2%	$262,167	$160,000	$60,200	$42,589	$524,956
Procurement and Production Hardware Cost	PHW	0	110	0	0	231	0	0	0	110	451	2.4%	$327,250	$91,763,078	$46,400	$9,205,200	$101,341,928
Warranty	WTY	41	6	102	692	12	0	5	10	61	929	4.8%	$828,392	$4,669,032	$83,710	$631,618	$6,212,752
TOTALS		**866**	**116**	**2047**	**14282**	**243**	**0**	**104**	**219**	**1290**	**19166**	**100.0%**	**$17,081,224**	**$98,049,677**	**$1,653,510**	**$13,220,059**	**$130,004,469**

Figure 13-1 Trident-CBF cost summary, based on the SKA1 Mid.CBF cost model, 2018 dollars. This is for 6 TALON LRUs per VCC-UNIT, 24 VCC-UNITs, and 13 TALON LRUs per FSP-UNIT.

WBS Category Definition	WBS Category	Labour PDs									Total PDs	Labour PD%	Labour Cost	Non-Labour Cost	Travel Cost	Contingency	TOTAL COST
		PM:Sr	PM:Int	Eng:Sr	Eng:Int	Eng:Jr	Sci:Sr	Sci:Int	Con	Admin							
		$1,100	$900	$1,000	$900	$750	$1,050	$850	$950	$500							
Management	MGT	825	0	660	550	0	0	0	209	825	3069	16.0%	$2,673,550	$0	$261,000	$293,455	$3,228,005
System Engineering	SE	0	0	917	766	0	0	0	0	0	1683	8.8%	$1,606,367	$0	$220,400	$182,677	$2,009,443
Product Design	PD	0	0	0	0	0	0	0	0	0	0	0.0%	$0	$0	$0	$0	$0
Hardware Development	HW	0	0	0	606	0	0	0	0	0	606	3.2%	$545,738	$449,893	$69,600	$228,319	$1,293,550
Firmware Development	FW	0	0	0	4937	0	0	0	0	0	4937	25.8%	$4,443,683	$360,000	$208,800	$1,282,535	$6,295,018
Software Development	SW	0	0	0	3986	0	0	0	0	0	3986	20.8%	$3,587,704	$240,000	$139,200	$731,197	$4,698,101
Sub-System Integration Infrastructure	SII	0	0	88	461	0	0	0	0	0	549	2.9%	$502,975	$291,668	$34,400	$118,332	$947,376
Integration & Test (a.k.a. Development Testing)	I&T	0	0	193	1348	0	0	99	0	0	1639	8.6%	$1,489,400	$0	$413,800	$420,456	$2,323,656
Acceptance Test for Verification	AT	0	0	88	807	0	0	0	0	0	895	4.7%	$814,000	$116,006	$116,000	$83,680	$1,129,686
Shipping and Installation	S&I	0	0	0	128	0	0	0	0	293	422	2.2%	$262,167	$160,000	$60,200	$42,589	$524,956
Procurement and Production Hardware Cost	PHW	0	110	0	0	231	0	0	0	110	451	2.4%	$327,250	$96,647,568	$46,400	$9,693,649	$106,714,867
Warranty	WTY	41	6	102	692	12	0	5	10	61	929	4.8%	$828,392	$4,913,257	$83,710	$656,040	$6,481,399
TOTALS		**866**	**116**	**2047**	**14282**	**243**	**0**	**104**	**219**	**1290**	**19166**	**100.0%**	**$17,081,224**	**$103,178,392**	**$1,653,510**	**$13,732,930**	**$135,646,056**

Figure 13-2 Trident-CBF cost summary (2018 dollars) for the 5 TALON LRUs per VCC-UNIT, 28 VCC-UNITs, and 14 TALON LRUs per FSP-UNIT option mentioned as a note to Figure 5-1.

Computing and Software: Preliminary Requirements

020.50.00.00.01-0001-REQ-A-COMPUTING_SOFTWARE_PRELIM_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
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APPROVALS	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.30 07:44:16 -06'00'	Electronics Division, NRAO	2019-07-30
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.30 10:32:34 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-30

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.30 10:32:48 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-30

Change Record

Version	Date	Author	Notes/Changes
01	2018-04-09	Hiriart	Initial draft
02	2019-07-19	Hiriart	Updated for reference design.
03	2019-07-22	Selina	Minor updates for release.
A	2019-07-30	Lear	Prepared PDF for signatures and release.

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents 5
2.1 Applicable Documents 5
2.2 Reference Documents 5
3 Proposal Management Requirements 5
4 Online Subsystem Requirements 6
4.1 Scheduling Requirements 6
4.2 Observation Control Requirements 6
4.3 Observing Mode Requirements 8
4.4 Calibration Requirements 8
4.5 Configuration Requirements 9
4.6 Data Product Requirements 9
4.7 Interface Requirements 10
4.8 Monitoring and Control Requirements 10
5 Offline Subsystem Requirements 12
6 Maintenance and Support Subsystem Requirements 13
7 Development Operations Requirements 13

1 Introduction

1.1 Purpose

This document defines L2 requirements for the elements belonging to the ngVLA Computing and Software system. The main inputs for the derivation of these requirements are the ngVLA Science Requirements [AD01], the ngVLA System Requirements [AD02], and the ngVLA Operations Concept [AD03]. The requirements defined in this document are preliminary, and will be completed and refined as the project advances to more detailed design stages.

1.2 Scope

The scope of this document is the system elements belonging to the ngVLA Computing and Software subsystem. Following the Computing and Software architecture [RD01], this document has been structured in sections that classify requirements according to the following areas:

- **Proposal Management:** Requirements related to the process of proposal submission, evaluation, time allocation and the generation of observing instructions (scheduling blocks).
- **Online Subsystem:** Requirements related to the execution of telescope observations, up to the point where raw data is stored persistently into the Science Archive.
- **Offline Subsystem:** Requirements related to all the post-observation operations performed on the collected science data.
- **Maintenance and Support:** Requirements related to the system elements that provide support for engineering and maintenance activities.
- **Development Operations:** Requirements related to system elements that support software development activities.

The requirements defined for the Online Subsystem include the Monitoring & Control requirements, with the exception of requirements pertaining to the hardware interface between Computing & Software and the antenna electronics systems, the Module Interface Board (MIB). These requirements are defined in [RD02].

2 Related Documents

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev / Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	System Requirements	020.10.15.10.00-0003-SPE
AD03	Operations Concept	020.10.05.00.00-0002-PLA

2.2 Reference Documents

The following documents are referenced within this text.

Ref. No.	Document Title	Rev / Doc. No.
RD01	Computing & Software Architecture: Reference Design	020.50.00.00.01-002-REP
RD02	Monitor and Control Hardware Interface Layer: Preliminary Technical Requirements	020.30.45.00.00-0002-REQ

3 Proposal Management Requirements

Parameter	Req. #	Value	Traceability
NRAO Proposal System Integration	CSW0075	The ngVLA Proposal Management Subsystem shall be integrated with the NRAO Proposal Management System, which currently supports the VLA, GBT, and VLBA telescopes, and supports the proposal submission, review, and time allocation use cases.	SYS2201, STK2502
ngVLA Resources Model	CSW0076	The Proposal Management Subsystem shall incorporate the ngVLA Resource Model.	SYS2221
Sub-Array Management Support	CSW0077	The ngVLA Resource Model shall incorporate the necessary data elements to support sub-array management.	SYS2302
Post-Processing Support	CSW0078	The ngVLA Resource Model shall incorporate the necessary data elements to support automatic post-processing, for the supported Standard Observing Modes.	SYS0703, SYS0721, STK0800
Expert Mode Support	CSW0079	The ngVLA Proposal Management Subsystem shall support expert modes, allowing the specification of non-standard instrument configurations and data processing.	
Scheduling Block Generation	CSW0080	The ngVLA Proposal Management Subsystem shall generate observing instructions (scheduling blocks) from the information entered in the submitted proposals.	SYS2222

4 Online Subsystem Requirements

4.1 Scheduling Requirements

Parameter	Req. #	Value	Traceability
Automatic Scheduling Block Selection	CSW0070	The Online Subsystem shall dynamically select the Scheduling Block to be executed in a sub-array, based on a pool of candidate Scheduling Blocks, and the current conditions of the sub-array and its environment, including the weather conditions.	SYS2302
Manual Scheduling Block Selection	CSW0071	The Online Subsystem shall provide an interface for the Operator to select the Scheduling Block to be executed in a sub-array.	SYS2223
VLBI Observations	CSW0072	The Online Subsystem shall provide an interface to execute VLBI observations in a sub-array. A VLBI observation shall be specified in VEX format, and the system shall provide a way to synchronize the observation with other participating observatories.	SYS0006
Observation Execution Abortion	CSW0073	The Online Subsystem shall provide a way for the Array Operator to abort a running observation in a sub-array. The observations running in other sub-arrays shall not be affected by this abort operation.	SYS2224, SYS3004, STK0902
Manual Sub-Array Management	CSW0074	The Online Subsystem shall provide an interface for the Array Operator to create and destroy sub-arrays.	SYS2302

4.2 Observation Control Requirements

Parameter	Req. #	Value	Traceability
Antenna Pointing	CSW0048	The Online Subsystem shall control the pointing of antennas belonging to a sub-array during an observation. The subsystem shall allow to partition the sub-array in portions that point to different directions (this is necessary for calibration observations such as interferometric pointing and sky holography).	
Online Antenna Pointing Calibration	CSW0049	The Online Subsystem shall compute pointing calibration coefficients from the data acquired in pointing scans and apply these coefficients on subsequent antenna movements.	SYS2303
Delay Tracking	CSW0050	The Online Subsystem shall command the sub-array electronic systems to perform delay tracking during an observation.	
Frequency Tuning	CSW0051	The Online Subsystem shall command the sub-array electronic system to down-convert and process the specified observation frequency range(s).	SYS0801, SYS0806

Parameter	Req. #	Value	Traceability
Doppler Tracking	CSW0052	The Online Subsystem shall shift the observing frequency to account for Doppler effects. This function shall be an observation option; i.e. it should be possible to turn this function on or off.	
Signal Path Attenuation	CSW0053	The Online Subsystem shall command the sub-array electronic system to set optimal attenuator gains.	SYS1203
Online Antenna Focus Calibration	CSW0054	The Online Subsystem shall compute focus calibration coefficients from the data acquired in focus scans and apply these coefficients on subsequent antenna sub-reflector settings.	
CSP Antenna Input Distribution	CSW0055	The Online Subsystem shall manage the distribution of antenna inputs into the CSP, mapping antenna streams to CSP tridents, both for the direct-connected antennas and the ISP-connected antennas.	
Unconnected Antennas Data Transmission	CSW0056	The Online Subsystem shall manage the data transmission for the ISP-connected antennas, starting and stopping the transmission of data packets from the antennas.	
Fringe Rotation	CSW0057	The Online Subsystem shall issue the necessary commands to the sub-array electronic system to perform fringe rotation during an observation.	
LO Offsetting	CSW0058	The Online Subsystem shall command the sub-array electronic systems to perform LO offsetting.	
Timing Synchronization	CSW0059	The Online Subsystem shall command the sub-array electronic systems so their local clocks are synchronized in time.	
Return to Phase	CSW0060	The Online Subsystem shall issue the necessary commands to the sub-array electronic systems to return to phase; i.e. when returning to a given frequency after observing in a different frequency the visibility phase should be as if the system had been observing in the first frequency all the time.	
Beam-forming weights	CSW0061	The Online Subsystem shall compute beam-forming weights and pass them to the CSP during an observation.	

4.3 Observing Mode Requirements

Parameter	Req. #	Value	Traceability
Continuum Interferometry Observing Mode	CSW0062	The Online Subsystem shall support the Continuum Interferometry Observing Mode.	SYS0002
Spectral Line Interferometry Observing Mode	CSW0063	The Online Subsystem shall support the Spectral Line Interferometry Observing Mode.	SYS0002
Total Power Observing Mode	CSW0064	The Online Subsystem shall support the Total Power Observing Mode.	SYS0007
Pulsar Timing Observing Mode	CSW0065	The Online Subsystem shall support the Pulsar Timing Observing Mode.	SYS0004
Pulsar Search Observing Mode	CSW0066	The Online Subsystem shall support the Pulsar Search Observing Mode.	SYS0005
Very Long Baseline Interferometry Observing Mode	CSW0067	The Online Subsystem shall support the Very Long Baseline Interferometry Observing Mode.	SYS0006, SYS0201, SYS0203
On-the-Fly Mosaicking Observing Mode	CSW0068	The Online Subsystem shall support the On-the-Fly Mosaicking Observing Mode.	SYS0008
Solar Observing Mode	CSW0069	The Online Subsystem shall support the Solar Observing Mode.	SYS0009

4.4 Calibration Requirements

Parameter	Req. #	Value	Traceability
Array Calibration Tools	CSW0016	The Online Subsystem shall provide tools to compute calibration models, store them, and apply them into the system.	SYS1063
Amplitude Calibration	CSW0017	The Online Subsystem shall compute complex amplitude calibration tables and include them in the output data product.	SYS1068
Flux Calibration	CSW0018	The Online Subsystem shall compute flux calibration tables and include them in the output data product.	SYS1064, SYS1801, SYS4801
Bandpass Calibration	CSW0019	The Online Subsystem shall compute bandpass calibration tables and include them in the output data product.	SYS1066
Polarization Calibration	CSW0020	The Online Subsystem shall compute polarization calibration tables and include them in the output data product.	SYS1065, SYS1901
Pointing Calibration	CSW0021	The Online Subsystem shall compute pointing calibration tables and include them in the output data product.	
Focus Calibration	CSW0022	The Online Subsystem shall compute focus calibration tables and include them in the output data product.	

Parameter	Req. #	Value	Traceability
Delay Calibration	CSW0023	The Online Subsystem shall compute delay calibration tables and include them in the output data product.	
WVR Calibration	CSW0024	The Online Subsystem shall compute WVR calibration tables and include them in the output data product.	
Offline Calibration Tools	CSW0025	The Online Subsystem shall provide tools to calculate the calibration tables generated during an observation (amplitude, flux, bandpass, polarization, pointing, focus, delay, and WVR) offline from saved datasets.	

4.5 Configuration Requirements

Parameter	Req. #	Value	Traceability
Persistent Configuration Data	CSW0026	The Online Subsystem shall persistently store system configuration data. This configuration data includes the array center position, the antenna locations, the cable and electronic delay model, alarm thresholds, and other parameters. Configuration data shall be kept under version control.	SYS2406, STK1300
System Reconfiguration	CSW0027	The Online Subsystem shall allow an Operator to change configuration parameters and apply these changes in the affected systems automatically.	STK1704

4.6 Data Product Requirements

Parameter	Req. #	Value	Traceability
Visibility Data Format	CSW0028	The Online Subsystem shall output visibility data in the same format as required for processing (calibration and imaging).	SYS0701, SYS0702
Pulsar Timing Profile Data Format	CSW0029	The Online Subsystem shall output pulsar timing profile data in PSRFITS format.	SYS0741
Offline Pulsar Search Data Format	CSW0030	The Online Subsystem shall output offline pulsar search data in PSRFITS format.	SYS0742
VLBI Data Format	CSW0031	The Online Subsystem shall output VLBI data in VDIF format.	

4.7 Interface Requirements

Parameter	Req. #	Value	Traceability
Antenna Electronics M&C Interface	CSW0032	The Online Subsystem shall interface with the antenna electronic systems for M&C through the MIB boards, using the Ethernet protocol.	
LO Reference M&C Interface	CSW0033	The Online Subsystem shall interface with the LO Reference equipment for M&C using the Ethernet protocol.	
Time Synchronization M&C Interface	CSW0034	The Online Subsystem shall interface with the Time Synchronization equipment for M&C using the Ethernet protocol.	
CSP M&C Interface	CSW0035	The Online Subsystem shall interface with the CSP for M&C using the Ethernet protocol.	
CSP Output Interface	CSW0036	The Online Subsystem shall interface with the CSP to receive its output using the Ethernet protocol.	
Operations Interface	CSW0037	The Online Subsystem shall provide an interface for array operations.	SYS2407, SYS2305, SYS2306, SYS2307, SYS2223, STK1703
Engineering Support Interface	CSW0038	The Online Subsystem shall provide an interface for engineering support.	SYS2407
Quality Assurance Interface	CSW0039	The Online Subsystem shall provide an interface for observation quality assurance.	

4.8 Monitoring and Control Requirements

Parameter	Req. #	Value	Traceability
Autonomous Operations	CSW0040	The Monitor and Control systems shall initialize and configure themselves and their connected elements to become operationally ready autonomously. Monitoring shall start as soon as possible, also autonomously.	STK1506
Line Replaceable Unit Serial Number	CSW0041	Each Line Replaceable Unit (LRU) shall be identified by a unique serial number.	SYS2403
Ethernet M&C Protocol	CSW0042	The Monitoring and Control protocol shall be based on Ethernet.	
Automatic Reconfiguration	CSW0043	The system shall detect when an LRU has been replaced and reconfigure itself automatically.	STK1506
Low-Level Access to MIB Boards	CSW0044	The system shall provide low-level access to the MIB boards in order to support effective troubleshooting operations.	
Self-Diagnostic Operations	CSW0045	The system shall incorporate self-diagnostic operations.	SYS2405

Parameter	Req. #	Value	Traceability
Safety-Critical Operations	CSW0046	The Monitor and Control system shall not be responsible for safety-critical operations involving possible damage to personnel and equipment.	SYS2700
Oscilloscope Function	CSW0047	The system shall provide an oscilloscope function, which allows sampling a monitor point with high frequency for an interval of time. The system shall provide the capability to trigger this function both manually and automatically.	

5 Offline Subsystem Requirements

Parameter	Req. #	Value	Traceability
Visibility Data Rate	CSW0006	The Offline Subsystem shall support an input data rate for interferometric data of 6,714.5 GVis per hour, 7.46 GB/s in average, with a peak of 119,342 GVis per hour, 132.6 GB/s. This is estimated to require 322.9 PFLOPs/s of processing.	SYS0752
Pulsar Timing Data Rate	CSW0007	The Offline Subsystem shall support an input data rate for pulsar timing data of 130MB/s.	SYS0301, SYS0302, SYS0303, SYS0304, SYS0305, SYS0306, SYS0307
Pulsar Search Data Rate	CSW0008	The Offline Subsystem shall support an input data rate for pulsar search data of 820 MB/s.	SYS0401, SYS0402, SYS0403, SYS0404, SYS0405
Synthesis Imaging Performance	CSW0009	The Offline Subsystem shall be able to calibrate and produce imaging data products from interferometric data with a throughput that matches or exceeds the input data rate (CSW0006).	SYS1062, SYS0752
Pipeline Reliability	CSW0010	The Offline Subsystem shall tolerate failure of 10% (TBC) of computing nodes and associated storage involved in a pipeline execution without losing data computed so far.	SYS0752
SRDP Integration	CSW0011	The ngVLA Offline Subsystem shall be based on the architecture developed by the SRDP project.	STK2500
External Processing	CSW0012	The Offline Subsystem shall support the capability of using external (i.e. non-Observatory) computing resources in order to support Large and Legacy scale projects.	
Visibility Processing Software Package	CSW0013	The Offline Subsystem shall provide a software package for visibility processing.	STK1202
Data Analysis Software Package	CSW0014	The Offline Subsystem shall provide a software package for data analysis.	SYS0761, SYS2201, STK1201
Reprocessing capacity	CSW0015	The Offline Subsystem shall incorporate enough processing capacity to service reprocessing requests. Total capacity shall be 1.5 times the processing power necessary to generate the standard data products.	SYS0736, SYS0734

6 Maintenance and Support Subsystem Requirements

Parameter	Req. #	Value	Traceability
Concurrent Software Versions	CSW0003	It shall be possible to run multiple software versions in all systems with multiple instances concurrently, for testing and commissioning purposes.	STK1501, STK1402
Automatic Maintenance Scheduler	CSW0004	The system shall continuously analyze the array status, automatically generate maintenance activity tickets, and maintain the maintenance schedule.	SYS2405, STK1700
Autonomous Antennas	CSW0005	The system shall include a supervisory system for controlling the antennas, evaluating its performance, calibrating the antennas, and solving routine problems.	SYS2304, STK1506, STK1704

7 Development Operations Requirements

Parameter	Req. #	Value	Traceability
Simulation Support	CSW0001	The ngVLA development infrastructure shall incorporate telescope simulation capabilities in order to support development, testing, integration, and verification activities.	
Consistent Deployment	CSW0002	The ngVLA development infrastructure shall keep all the necessary artifacts to deploy a consistent system under version control. This includes the source code, configuration data for both software and hardware, and external libraries.	

Computing & Software Architecture: Reference Design

020.50.00.00.01-0002-REP-A-COMPUTING_SOFTWARE_ARCHITECTURE_REF_DSN

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Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
2 Related Documents 5
2.1 Applicable Documents 5
2.2 Reference Documents 5
3 General Architecture 6
3.1 Subsystems 6
3.2 Data Stores 7
3.3 System Actors 8
4 Proposal Management Subsystem 10
4.1 Subsystem Function: Proposal Submission 10
4.2 Subsystem Function: Proposal Evaluation 10
4.3 Subsystem Function: Telescope Time Allocation 10
4.4 Subsystem Function: Scheduling Block Generation 10
4.5 Subsystem Function: Scheduling Block Definition 10
4.6 Subsystem Function: Security 11
4.7 Interfaces and Dataflows 11
4.7.1 Proposal Submission Tool Interfaces 11
4.7.2 Proposal Handling Tool Interfaces 11
4.7.3 Proposal Builder Tool Interfaces 11
4.7.4 Observation Preparation Tool Interfaces 11
5 Online Subsystem 12
5.1 Subsystem Function: Scheduling Block Selection 12
5.2 Subsystem Function: Sub-Array Management 13
5.3 Subsystem Function: Telescope System Configuration 13
5.4 Subsystem Function: Array System Calibration 13
5.5 Subsystem Function: Observation Control 14
5.5.1 Antenna Control Functions 15
5.5.2 Antenna Data Transmission Functions 16
5.5.3 Central Signal Processor Control Functions 17
5.5.4 Correlator Back End Processing Functions 17
5.5.5 Array Observation Control Functions 18
5.6 Subsystem Function: Archive Ingestion 19
5.7 Subsystem Function: Metadata Capture 19
5.8 Subsystem Function: Online Calibration 19
5.9 Subsystem Function: Online Quality Assurance 20
5.10 Subsystem Function: Operator Shift Logging 20
5.11 Subsystem Function: Monitoring 20
5.12 Subsystem Function: Error Handling 20
5.13 Subsystem Function: Security 20
5.14 Interfaces and Dataflows 20
5.14.1 Scheduling Module Interfaces 22
5.14.2 Operation Module Interfaces 22
5.14.3 Observation Module Interfaces 23

5.14.4 Antenna Supervisory Control Module Interfaces ... 23
5.14.5 LO and Timing Supervisory Control Module Interface ... 23
5.14.6 CSP Supervisory Control Module Interfaces ... 23
5.14.7 Metadata Capture Module Interfaces ... 23
5.14.8 Configuration Module Interfaces ... 24
5.14.9 Quick-Look Module Interfaces ... 24
5.14.10 Calibration Module Interfaces ... 24
5.14.11 Monitoring Module Interfaces ... 24
5.14.12 Data Streams ... 24
5.14.13 Controller Board Interfaces ... 25
5.15 Physical Architecture ... 25
6 Offline Subsystem ... 28
6.1 Subsystem Function: Raw Data Calibration ... 29
6.2 Subsystem Function: Imaging Product Generation ... 30
6.3 Subsystem Function: Source Catalog Product Generation ... 30
6.4 Subsystem Function: Project Tracking ... 30
6.5 Subsystem Function: Data Product Discovery ... 31
6.6 Subsystem Function: Data Product Retrieval ... 31
6.7 Subsystem Function: Data Product On-Demand Post-Processing ... 31
6.8 Subsystem Function: Data Product Analysis ... 31
6.9 Subsystem Function: Security ... 31
6.10 Interfaces and Data Flows ... 31
6.10.1 Science Archive Interfaces ... 32
6.10.2 Observatory Interfaces ... 32
6.10.3 Data Processing Management Interfaces ... 33
6.10.4 Processing Resource Interfaces ... 33
6.10.5 Data Processing Pipeline Interfaces ... 33
6.11 Quality Assurance Interfaces ... 33
6.12 Data Analysis Package Interfaces ... 33
6.13 Data Streams ... 33
6.14 Physical Architecture ... 34
6.14.1 Data Reduction Performance Requirements ... 35
7 Maintenance and Support Subsystem ... 39
7.1 Subsystem Function: Preventive Maintenance Analysis ... 39
7.2 Subsystem Function: Maintenance Schedule Management ... 39
7.3 Subsystem Function: Inventory Management ... 39
7.4 Subsystem Function: Troubleshooting Support ... 39
7.5 Subsystem Function: Security ... 39
7.6 Interfaces and Dataflows ... 39
7.7 Physical Architecture ... 40
8 Development Support Subsystem ... 40
8.1 Physical Architecture ... 40
9 Appendix ... 41
9.1 Abbreviations and Acronyms ... 41

1 Introduction

1.1 Purpose

This document describes the computing and software architecture for the ngVLA reference design. The architecture is defined by decomposing systems functions progressively in higher levels of detail, and defining the necessary structural elements and interfaces accordingly. First, the system structure is partitioned into subsystems based on high-level system functions. Next, the subsystems are broken down into modules, and the high-level functions are decomposed into subsystem functions. The functionality required by these functions is allocated between the modules, along with the necessary interfaces.

The physical architecture, i.e. the computing and networking equipment necessary to implement the required functions, is defined for each subsystem. This architecture will be refined in subsequent iterations during the project's Conceptual Design phase. Modules will be decomposed into software components, and their requirements and interfaces will be defined in detail.

1.2 Scope

This document covers all computing and software systems required for ngVLA as specified in the reference system design [AD04]. The detail provided in this document has been defined to the level necessary to enable the process of estimating development and construction costs. This document avoids the definition of design features when these do not significantly impact the cost or constrain the design.

2 Related Documents

2.1 Applicable Documents

The following documents may not be directly referenced herein but provide necessary context and requirements applicable to this architecture.

Ref. No.	Document Title	Rev / Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	System Requirements	020.10.15.10.00-0003-SPE
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	ngVLA System Reference Design	020.10.20.00.00-0001-REP
AD05	SRDP System Concept	530-SRDP-014-MGMT
AD06	M&C Reference Design Concept	020.50.25.00.00-0002-DSN
AD07	Reference Observing Program	020.10.15.05.10-0001-REP

2.2 Reference Documents

The following documents are referenced within this text or provide supporting context.

Ref. No.	Document Title	Rev / Doc. No.
RD01	Digital Back End & Data Transmission System: Reference Design	020.30.25.00.00-0002-DSN
RD02	LO Reference and Timing: Reference Design	020.35.00.00.00-0002-DSN
RD03	Central Signal Processor: Reference Design	020.40.00.00.00-0002-DSN

3 General Architecture

In general, all functions under the Computing and Software IPT fall in the following main categories:

1. Manage the proposal submission process and schedule observations.
2. Perform observations.
3. Monitor telescope status and support maintenance activities.
4. Generate derived data products.
5. Provide access to data products.
6. Support commissioning, development, and other operational activities.

The expected data rates for raw data (average 7.46 GB/s, peak of ~132 GB/s for the most stringent use cases; Table 3) are high but expected to be technically manageable and economically feasible in 2035, given recent advances in computing and storage systems. For perspective, this is 1,000 times the current VLA data rate but roughly 10,000 times less than the SKA (expected to be several Petabytes per second). Differently from SKA, for ngVLA it will be possible to store the raw data and decouple data acquisition/correlation from generation of calibration and imaging products. Consequently, the system architecture has been decomposed structurally into five major subsystems and four data stores, as shown in Figure 1 (next page).

3.1 Subsystems

The subsystems that define this architecture are detailed in Figure 1 and include the following:

- **Proposal Management Subsystem:** This subsystem receives proposal submissions from PIs and provides software to support review, scoring, and allocation in observing sessions. It also provides software to simulate several weather scenarios and how they affect the schedule of observations on several timescales. Proposals accepted for observation are transformed into one or more scheduling blocks. This process transforms the proposal's science requirements into the technical configurations necessary to perform the observation with the telescope.
- **Online Subsystem:** The online subsystem selects scheduling blocks and executes them in a sub-array. It coordinates all operations necessary to perform observations, resulting in archived science data. The system reads configurations and calibrations from the telescope configuration database and applies them in the corresponding telescope systems. It continuously monitors the state of the telescope, saving the monitoring data and alarms in the Engineering database. This database also includes integrated logs generated by all software components as they perform their operations.
- **Offline Subsystem:** This subsystem is responsible for all post-observation operations performed on the collected science data, including the generation of derived data products, support for quality assurance activities, and the provision of interfaces to search for and retrieve data products.
- **Maintenance and Support Subsystem:** This subsystem incorporates several modules that support engineering diagnostic and maintenance activities.
- **Development Operations Subsystem:** This subsystem integrates common software components and provides supporting infrastructure for simulation and testing.

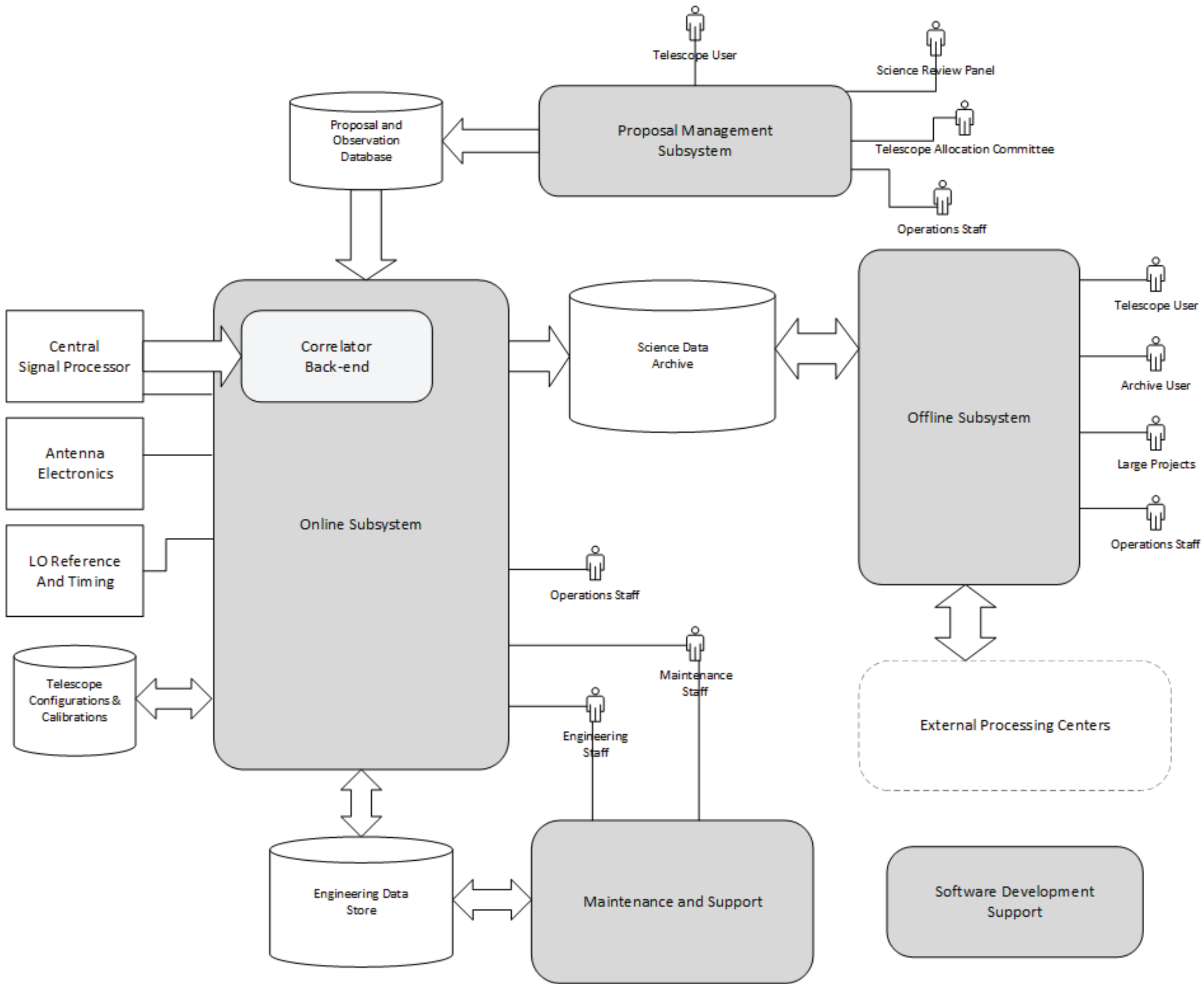

Figure 1 - General architecture for ngVLA. The major subsystems are shown as gray boxes. Also shown are the interfaces and data flows between subsystems, data stores, main actors, and other external system elements.

3.2 Data Stores

The data stores shown in Figure 1 are logical and are deployed into physical storage systems and databases depending on their requirements. They may be consolidated if necessary. 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:** The science data includes visibility files, calibration tables, images, catalogs, and their associated metadata.
- **Engineering Data Store:** This mainly includes monitoring data, alarms, and system logs.

3.3 System Actors

Figure 1 also shows the main system actors, which include:

- **Telescope Users:** These users enter the system through a well-defined proposal process. The Observatory has well established processes for adjudicating proposals' relative merits and allocating telescope time based on this process. Telescope users design observations to address specific scientific questions and envision the data products that will allow them to address these concerns.
- **Archive Users:** Archive users enter the system through the archive interface and may be anonymous. These users seek to reuse existing data (and products) to answer scientific questions, which may be unrelated to the initial science case.
- **Large Projects:** These projects can be both telescope and archive based, and represent a limited number of significant investments on the part of both the PI and the Observatory.
- **Operations Staff:** This category primarily comprises data analysts, telescope operators, scientific staff, and any other NRAO staff with functional effort allocated to supporting observatory operations.
- **Maintenance Staff:** These NRAO staff members are responsible for the preventive and corrective maintenance activities of the array.
- **Engineering Staff:** NRAO Engineering Division staff members support array operations, maintenance, and development activities.
- **Science Review Panel:** This panel of scientists evaluates and scores proposal according to their scientific merit.
- **Telescope Allocation Committee:** This committee is responsible for ranking proposals and allocating the available observing time among the accepted proposals. This committee incorporates the chair of each Science Review Panel.

Table 1 shows system function allocations to subsystems and their decomposition in subsystem functions.

System Function	Allocated Subsystems	Subsystem Functions
1. Manage proposal submission process and schedule observations	Proposal Management Subsystem	Proposal Submission Proposal Evaluation Telescope Time Allocation Scheduling Block Generation Scheduling Block Definition
2. Perform observations	Online Subsystem	Scheduling Block Selection Sub-Array Management Telescope System Configuration Array System Calibration Observation Control Archive Ingestion Metadata Capture Online Calibration Online Quality Assurance Operator Shift Logging
3. Monitor telescope status and support maintenance activities	Online Subsystem	Monitoring Error Handling
	Maintenance & Support Subsystem	Engineering Data Analysis Preventive Maintenance Management Inventory Management

System Function	Allocated Subsystems	Subsystem Functions
4. Generate derived data products	Offline Subsystem	Raw Data Calibration Imaging Product Generation Source Catalog Product Generation
5. Provide access to data products	Offline Subsystem	Project Tracking Data Product Discovery Data Product Retrieval Data Product On-Demand Post-Processing Data Product Analysis
6. Support commissioning, development. and other operational activities	Development Operations Subsystem	E.g., offline development and testing of new observing modes.
	(Entire system)	E.g., operations reporting, testing.

Table 1 - Allocation of system functions in subsystems.

Supporting integration and verification, commissioning, and development activities may require provision of special paths and extended APIs across the system. For example, running observations from scheduling blocks generated from proposal information imposes unnecessary overhead on these activities. Commanding the array directly from observation scripts is preferred.

It is also usually required to provide low-level access to hardware interfaces, while normal observations use higher-level science-oriented interfaces. These concerns will not be introduced as separate functions but rather as architectural features across the system.

In addition to the subsystem functions defined above, each subsystem must implement an adequate level of security. This is defined as an additional function, which will be specified in more detail during the Conceptual Design phase of the project.

The following sections describe each subsystem in detail.

4 Proposal Management Subsystem

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 lets Telescope Users 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.

These applications require several modifications for ngVLA. Some of these modifications are general and can be introduced before the ngVLA starts its construction phase. 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). Another change that may be necessary is the introduction of grouping structures similar to ALMA *ObsUnitSet* and *ScienceGoal*.

4.1 Subsystem Function: Proposal Submission

This process allows a Telescope User to create and submit a Proposal requesting ngVLA observing time. This function is allocated in the PST.

4.2 Subsystem Function: Proposal Evaluation

This process allows the Science Review Panel members to score each proposal. This function is allocated in the PST.

4.3 Subsystem Function: Telescope Time Allocation

This is the process through which the Telescope Allocation Committee assigns telescope time to each accepted proposal. This function is allocated in the PHT.

4.4 Subsystem Function: Scheduling Block Generation

This function refers to the generation of Scheduling Blocks from the Proposal. It is allocated in the PBT.

4.5 Subsystem Function: Scheduling Block Definition

This function allows the creation, modification, or deletion of Scheduling Blocks, and it is allocated in the OPT. Manual creation of Scheduling Blocks is necessary to support Integration & Verification and Commissioning activities.

4.6 Subsystem Function: Security

This function refers to the implementation of strategies and countermeasures to deal with internal and external security threats.

4.7 Interfaces and Dataflows

4.7.1 Proposal Submission Tool Interfaces

- **Telescope User UI:** Through this user interface (UI), Telescope Users define, validate, and submit proposals.
- **Science Review Panel UI:** The Science Review Panel uses this interface to score proposals.
- **Operations Staff Interface UI:** This interface lets Operations Staff manage the proposal process. Constructed around other interfaces in this module, it provides extended privileges and capabilities.
- **Proposal Submission Tool Interface:** This is a REST interface used by the UIs in this module.

4.7.2 Proposal Handling Tool Interfaces

- **Telescope Allocation Committee UI:** This interface allows the TAC to manage the telescope allocation time process.
- **Proposal Handling Tool Interface:** This is a REST interface used by the UIs in this module.

4.7.3 Proposal Builder Tool Interfaces

- **Operation Staff UI:** The Operations Staff generates scheduling blocks from the proposal using this interface.
- **Proposal Builder Interface:** This is a REST interface used by the UIs in this module.

4.7.4 Observation Preparation Tool Interfaces

- **Telescope User UI:** The Telescope User uses this to review and edit scheduling blocks and associated structures.
- **Operations Staff Interface UI:** This interface lets Operations Staff manage scheduling blocks and associated structures. It is usually constructed around other interfaces in this module but provides extended privileges and capabilities.
- **Observation Preparation Tool Interface:** This is a REST interface used by the UIs in this module.

5 Online Subsystem

The Online Subsystem 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.

The next sections describe the subsystem functions.

5.1 Subsystem Function: Scheduling Block Selection

This function permits selecting one or more Scheduling Blocks for execution in a specific sub-array execution queue. It is allocated entirely in the Schedule module. It provides three operation modes:

1. Manual mode: The operator manually selects the Scheduling Block to be executed.
2. Advisory mode: The system presents a selection of recommended Scheduling Blocks to be executed, but the operator must manually insert them into the execution queue.
3. Fully automatic: The system selects automatically the Scheduling Blocks to be executed.

The first manual mode requires querying the pool of "observable" Scheduling Blocks and presenting the set of attributes that the operator needs to perform a selection. The advisory and fully automatic modes require the current weather data and usually perform a short-term weather prediction to decide the next Scheduling Block to observe.

For VLBI observations, VEX files will be converted into Scheduling Blocks. These Scheduling Blocks must be executed at a precise time along with other observatories, so their handling in the execution queue have special requirements.

5.2 Subsystem Function: Sub-Array Management

This function refers to the allocation of disjointed sets of antennas in sub-arrays. It is implemented as an interaction of the Array Operator, the Scheduling module, and the Observation module. The Operator decides how the telescope antennas should be partitioned in sub-arrays, and creates sub-arrays by means of a UI in the Scheduling module, which in turn invokes functions in the Observation module for allocating hardware resources to the sub-array and configuring it.

An input for the sub-array allocation algorithm is the availability of antenna capabilities. For example, some antennas will have all bands available, but others could have only some in an operational state. Although some of the information can be retrieved directly from the online system status, it may be necessary to retrieve data from the maintenance database to have a complete picture of each antenna's availability.

Allocating a set of antennas in a sub-array involves several operations in the systems electronics:

1. The Local Oscillator reference and central timing signal generators need to be controlled for each sub-array. Each antenna LO reference is independently tunable, so this function mostly involves setting the required values of each LO reference for each scan.
2. The data transmitted from the antennas to the central signal processor (CSP) is routed to two of three CSP Tridents. This distribution operation is managed by the software, and involves issuing control commands to the digital backend (DBE) and the CSP. These operations may be different for the direct-connected antennas and the antennas connected through the public network.
3. Configure the CSP. This involves configuring the very coarse channelizers (VCCs), mapping the VCCs to common array frequency slice processors (FSPs), and configuring the FSPs.
4. Configure the data transmission between the CSP and CBE, and the CBE resources to process the sub-array data stream from the CSP.

5.3 Subsystem Function: Telescope System Configuration

The telescope systems (electronic, computing, and software) require a set of configuration data that is loaded during the system initialization. This data includes attenuator values, antenna positions, delay models, high/low alarm thresholds, software version information, etc. This data is kept in the Telescope Configuration database, under version control. This subsystem function includes both the provision of interfaces to maintain this data and procedures for retrieving and loading data on corresponding devices.

For hardware devices, this data will be loaded by the Supervisory Layer if the Telescope Configuration database can be accessed. If not, the devices will load default values from internal memory. The system should support updating and loading configuration data with minimal re-initializations.

5.4 Subsystem Function: Array System Calibration

This function refers to the acquisition of array calibration data. This includes measurement of

1. the antenna positions,
2. the delays in fiber optic cables and electronics,
3. the antenna pointing coefficients,
4. the antenna focus coefficients, and
5. the antenna surface deviations.

These measurements involve the execution of specialized procedures and observations. The acquired data will be stored in the Configuration database, along with the time the measurement was performed. After QA, this data is applied on the system and is then available to be read and loaded on the required hardware and software systems.

Note that this is not the only calibration function in the system. Calibration data are also acquired during an observation (usually by observing calibrator sources of the required characteristics), and calibration tables are derived during post-processing. These are described separately.

5.5 Subsystem Function: Observation Control

This section describes how the system issues control commands to perform astronomical observations. The system must support the following observing modes:

1. Continuum interferometry
2. Spectral line interferometry
3. Total Power (auto-correlation products)
4. Pulsar Timing (phased sum mode)
5. Pulsar Search (phased sum mode)
6. Very Long Baseline Interferometry (phased sum mode)
7. On-the-Fly Mosaicking
8. Solar Observing

An observing mode is defined as a way of using sub-array resources to meet a specific science objective. Although observation parameters (number of spectral channels, integration time, field of view, etc.) vary, all science use cases fall in one of the above categories.

An observation is divided in time intervals called *scans*, which have associated *intents*. The intent differentiates scans performed for the purpose of calibration from those performed over the astronomical objects of scientific interest. The observing mode concept also encompasses the calibration strategies that define the required duration and frequency of the calibration scans.

In practice, observing modes require high modifiability and are typically developed and maintained by scientific staff. Because of this, observing modes are implemented in scripting languages (e.g., Python). The execution of an observation script calls an API that exposes high-level functions of the telescope system. These functions encapsulate the technical complexities of controlling the telescope hardware, incorporating timing and concurrency considerations. The ngVLA system will follow a similar architecture. The scripted observing mode and high-level system API will be implemented in the Observation module.

The execution of an observing mode script in the Observation module results in several commands directed to components in the Supervisory layer. These commands include the timestamp of execution, calculated sometime in the future to allow for propagation and processing delays. The supervisory components execute the commands, which in turn results in several operations sent to the Controller boards. The Observation module waits for response messages from the Supervisory components, acknowledging reception of the command, start of the execution, and end of the execution. The Observation module waits for these messages with a timeout, and follows error procedures in case of failures or missing responses. This typically involves sending flagging commands to the Metadata Capture module or aborting the observation in case of critical problems.

Because of the timing unpredictability in the transmission of commands sent to remote station antennas, several commands will be aggregated in a single message, encompassing a larger time interval. This mode of operation is similar to the execution of VLBI observations, where a script for the entire observation is generated and executed in isolation by each station.

Controlling and observation functions can be classified by the scope of involved subsystems. The following sections describe functions specific for Antenna Electronics, Data Transmission, CSP, and correlator Back End systems, and functions encompassing more than one subsystem, i.e. array observation functions.

5.5.1 Antenna Control Functions

The control software must perform the following functions with antenna electronics.

5.5.1.1 Antenna Pointing

For each scan, the antennas are pointed to a point in the sky. As the antennas have alt-azimuth mounts, their movement is controlled by the Antenna Control Unit (ACU) in horizon coordinates (azimuth and elevation). The sky coordinates, on the other hand, are specified in celestial coordinate systems such as equatorial (right ascension and declination) or galactic coordinates. The supervisor software will perform the necessary transformations and command the ACU. These commands form a data stream when the antennas track a sky position as the Earth rotates.

The ACU incorporates a pointing model consisting of several coefficients to account for antenna deformations and other effects. The software uses a calibration program (e.g. TPOINT) to calculate these coefficients from data gathered by special pointing scans. The pointing model includes a static or main model, loaded from the Configuration Database; and an auxiliary or secondary model consisting of coefficient offsets determined by the calibration software from pointing scans and loaded into the ACU before the next scan.

Besides pointing the telescope to fixed positions in the sky, the software should support variable objects or Ephemeris (usually planets and satellites). A list of Ephemeris objects will be supported.

The antenna pointing data are included in the observation metadata recorded by the Metadata Capture module. Because this pointing data includes both the commanded coordinates and the coordinates where the antenna was actually pointed (read from the axis encoders), the pointing data needs to be retrieved from the ACU by the Antenna Control Supervisor module—which is local to the ACU—and sent to the Metadata Capture module to be included in the Science Data Model (SDM) tables.

5.5.1.2 Frequency Tuning

Configuring a sub-array to receive a selected range of frequencies involves setting up the LO frequency to the specified value. Besides this, other functions (fringe rotation and LO offsetting) require passing the LO frequencies to the CSP. This function will be performed by the Control and Correlator modules.

The central LO system distributes the LO signal to all the antennas. This is a 7 GHz reference signal shifted differently for each antenna by an offset frequency. This reference frequency is used at each antenna to synthesize the final down-conversion frequency used in the IRD. Therefore, the software system is required to set the antenna-dependent LO offset frequencies in the central LO system, and perform band-selection and spectral window selection in the antenna electronics.

Each antenna sends a total bandwidth of 20 GHz to the CSP, channelized in 200 MHz spectral windows. The band is selected by controlling the IRD input that will be processed in the DBE. Channelization is performed in the DBE.

5.5.1.3 Doppler Tracking

Because of the relative velocity of a source with respect to the telescope antennas, the observed frequency will appear shifted by a Doppler offset. The system will have the capability to calculate the frequency offsets at the beginning of an observation and apply them when tuning the frequency in the electronics, when necessary.

The Proposal Management subsystem will convert the specified user frequencies, which the PI can specify in different reference frameworks, to a common framework (e.g., the center of the solar system).

5.5.1.4 Signal Path Attenuator Management

This function involves determining and setting gain values in the attenuators installed in the signal path. The values are typically calculated from measurements of the total power, from where the attenuations are determined in such a way to optimize the output power for the antenna digitizer statistics. The sampling of the total power and setting of the gains are exposed as high-level observing script functions.

5.5.1.5 On-the-Fly Mosaicking

In this particular way of observing, an extended area of the sky is observed by moving the antennas continuously in sky coordinates. This mode is usually more efficient than forming mosaics by combining static observations of a spaced grid in the sky, a mode known as “pointed mosaics”. The accurate recording of the antenna pointing positions is necessary for synthesizing images in post-processing. This mode imposes constraints in the delay correction.

5.5.1.6 Sideband Separation

After LO mixing in the IRD module, the signal received from the sky is transformed into an IQ pair that contains both upper and lower sidebands. The sidebands are separated digitally in the DBE and the FSP. Frequencies far from the LO frequency are separated in the DBE using coarse frequency resolution, while frequencies close to the LO are separated in the FSP with high spectral resolution. The data is transmitted from the antennas as a set of IQ pairs, both for the frequencies already separated and those not yet separated.

The software is required to store a set of sideband separation coefficients in the Configuration Database. These coefficients will be loaded in the DBE and FSP before execution of an observation.

5.5.1.7 Cryogenic Management

This function refers to the control and monitoring of the Front End cryostats. This function may incorporate a power saving mode.

5.5.1.8 Band Power Management

This function refers to controlling Front End bands powered up during an observation. To save power, not all available bands may be powered up at the same time.

5.5.1.9 Digitizer Offset Correction

The digitizer clock in the antennas is generated from the LO reference signal. However, as this signal includes an offset, the generated signal does not have the correct frequency and must be corrected in the DBE.

5.5.2 Antenna Data Transmission Functions

It is assumed that the data transmission from the connected antennas to the CSP is largely automatic and does not require active control, besides normal monitoring, during an observation. They are assumed to be transmitting continuously to the CSP. On the other hand, the long-haul antennas will transmit data through the public network only while observing. Therefore, the Execution module will need to issue commands to start and stop the data packet transmissions.

5.5.3 Central Signal Processor Control Functions

The CSP can be configured to work in the following observing modes for each sub-array:

- Synthesis Imaging
- (Sparse/Dense) Pulsar Timing
- Offline Pulsar Search
- VLBI

The observing modes defined at the beginning of this section are mapped into one of these correlator observing modes. The CSP observing modes differ from the observation observing modes in that the latter incorporate concerns that do not affect the CSP, such as differences in calibration strategies or antenna movement patterns.

The CSP is further divided in the Correlator and Beamformer (CBF), the Pulsar Engine (PE), and a Monitoring and Control Module that receives control and monitoring commands from the CSP Supervisor server. The CBF is further divided in the VCC-part, which divides received spectra into frequency slices, and the FSP-part, which processes each frequency slice. The computing resources allocated in the CBF and PE must be configured for each sub-array and scan during an observation. The commands necessary to accomplish this are TBD but at a minimum must include a spectral configuration data structure, directing how the spectra should be divided in slices, and how each one should be processed.

For Pulsar modes, which involve simultaneous observation of several beams inside the antenna primary beam, the CSP Supervisor computer will compute beam-forming weights and pass them on to the CSP. The CSP will also receive the necessary data for delay compensation, fringe tracking, and LO offsetting.

The data from each FSP will be directed to a computer node in the correlator backend. The details of this interface are TBD but will probably involve passing the receiving computer node IP addresses to the CSP.

5.5.4 Correlator Back End Processing Functions

The Correlator Back End (CBE) receives data for the low-level products generated in the CSP and produces the final (raw) data products. Depending on the observing modes, the final data products are:

- Visibility data stored in a format compatible with the interfaces used by data processing systems (currently the Measurement Set (MS or Multi-MS) format)
- Pulsar Timing Profiles in PSRFITS format
- Offline Pulsar Search data in PSRFITS format
- VLBI data recorded in VDIF format

The CBE may also generate additional files to store auxiliary data.

The CBE collaborates with the Metadata Capture module. While the Metadata Capture module gathers observation metadata, the CBE processes binary data, performing operations such as band-stitching, averaging, and formatting. In general, all data necessary to form a binary file should be routed to the same CBE computer node, but depending on the processing requirements, other load balancing strategies could be implemented. CBE operations will most probably be parallelized with MPI and MPI-IO, following a design similar to the VLA.

5.5.5 Array Observation Control Functions

5.5.5.1 Delay Tracking

To avoid loss of coherence and sensitivity, signals from each antenna must be in-phase before computing correlation products. This is accomplished by introducing a delay in the signal path for each antenna. The Control module will calculate the delays periodically in advance and send them to the Correlator Supervisor computer, which will compute a polynomial fitting for each time interval and apply it in the CSP. All delay compensations will be applied in the CSP.

5.5.5.2 Fringe Rotation

As the delay compensation is applied after the received signal has been down-converted in frequency, a fringe term appears in the correlator output. This effect can be compensated by introducing a rotating phase in the local oscillator signal or by removing it in the correlator. For ngVLA this operation will be performed in the CSP. The Control module sends the delay commands to the CSP along with LO frequencies.

5.5.5.3 LO Offsetting

To suppress spurious signals and other effects (such as frequency aliasing in the CSP frequency slicing), a distinct offset is introduced in the LO signal for each antenna and is removed before correlation in the CSP. The Control module incorporates these LO offsets when tuning the receiver frequencies and sends them to the CSP.

5.5.5.4 Timing Synchronization

An observation depends on application of several operations at precise, absolute times. Electronic controller cards will be time-synchronized with the Supervisor server by means of NTP. An NTP server will run in the Supervisor server, which will receive the 1 PPS and timing signals from the Reference Receiver module (L503). These signals permit assigning an absolute time (from the central GNSS module) to each edge of the 1 PPS signal. The system will use UT as the time standard across software systems. In addition, the controller cards will receive a 20 Hz clock signal from the L503 module.

The central LO and timing system will be replicated in remote centers connected with the ISP-connected antennas. To account for the communications unpredictability to remote station antennas, it is assumed that the packets containing the digitized samples of the received signal at each antenna will be timestamped. This operation is performed in the DBE, which receives the 1 PPS and timing signals, without involvement of control software.

There are two central time references: a Maser and a GNSS timing system. The former is more stable for relatively short spans of time ($<10^4$ s), while the latter provides a better long-term time reference. Both systems output 1 PPS and 10 MHz clocks. These are compared and their relative error is logged. The system is not required to apply a dynamic phase correction on the maser. Corrections are applied offline.

The central timing equipment will be replicated in remote centers that will provide time synchronization signals for the long-haul, ISP-connected antennas.

5.5.5.5 RFI Excision

This function is implemented in different stages: at the antenna-based voltage streams; after correlation either in the CSP or the CBE; or after formatting and storage in the post-processing systems. As the interface between CSP and CBE has been scoped to support the data rates shown in Table 3, any RFI excision operation that involves high time resolution visibilities will need to be implemented in the CSP.

This function also requires the development of an RFI monitoring database, which will be integrated with the Configuration Database.

5.5.5.6 Return to Phase

This system function refers to the avoidance of phase jumps when switching frequencies during an observation. All the LO mixing operations performed in the signal path need to be considered, returning the phase to the value it would have had if the frequency wouldn't have been changed. Besides the LO signal transmitted to the antennas for down-conversion, it is necessary to control the phase introduced in the digital LO mixing in the correlator. Returning to phase is necessary to be able to jointly calibrate scans observed at different times, without bracketing them with additional phase calibration scans.

5.6 Subsystem Function: Archive Ingestion

As an observation proceeds, the Correlator Back End and the Metadata Capturer write the raw data products in a staging storage area. The system ingests these files into the Science Archive, which is assumed to be collocated with the data processing cluster, in the Science Operations and Data Center. As the data arrives, a process collects the metadata and stores it in the Archive Metadata Database. The raw data files are stored into the permanent Science Data storage.

In order to avoid unnecessary copy operations, the reception staging area in the Science Operations and Data Center will be the cache space used by the processing cluster. As the data is saved directly in the format required by the data reduction software, it is immediately available for the calibration pipeline.

Pulsar timing and search data is assumed to be ingested into the archive as well. Storing the data into disk-based VLBI data systems such as Mark 6, to be sent to other observatories is not a requirement, although spare capacity will be allocated in the CBE switch (see Section 5.15) to allow the connection of the necessary equipment in the future, if necessary.

5.7 Subsystem Function: Metadata Capture

During the execution of an observation, several software modules send metadata structures to the Metadata Capture module, which parses them and writes the Measurement Set sub-tables (the MS Main table is written by the Correlator Back-end). For the non-visibility data products, the Metadata Capture module fulfills a similar function.

5.8 Subsystem Function: Online Calibration

As the observation is executed, the Calibration module receives messages from the Metadata Capture module announcing the availability of calibration scans to be processed. The Calibration module reads the corresponding scans from the raw data files and computes the calibration tables, which are sent back to the Metadata Capture component to be integrated into the metadata tables (or alternatively they are written directly to disk by the Calibration module).

In some cases, the calibration results are loaded into the Online Subsystem components to be applied on the instrumentation. This is typically the case of Pointing and Focus models, and when the array data needs to be "phased" (all relative phase differences between the data from different antennas are corrected and the time-series summed up). These calibration models are sent to the Supervisor computers to be applied in the instrumentation.

The system needs to compute and apply the attenuator gains in the antenna. This will be performed by the science script. Functions will be implemented in the script API for measuring the power after pointing the antenna to the desired target and setting other aspects of the instrumentation (frequency tuning, etc.). This measurement is used to calculate the desired attenuator setting for optimizing the output power. Currently the antenna electronics doesn't incorporate square law detectors (like ALMA), but the received power can be measured from the IRD ADC.

5.9 Subsystem Function: Online Quality Assurance

The system provides interfaces for the Science Staff and Operator to assess the quality of the observation while the observation is being executed. This is sometimes referred as QA0. (Regarding observatory quality control functions, QA0 refers to the quality control during the observation; QA1 refers to the quality control of the telescope, including antenna position models, pointing models, etc.; and QA2 refers to quality control functions after post-processing).

5.10 Subsystem Function: Operator Shift Logging

This function refers to the annotation of several events that happen during an operation shift. The system provides an application that automatically annotates events such as sub-array creation or destruction, observation beginning and end, etc., and allows the operator to annotate other relevant information.

5.11 Subsystem Function: Monitoring

This function refers to the acquisition, transmission, archival and use of monitoring data from the telescope hardware and software systems.

5.12 Subsystem Function: Error Handling

This function refers to the detection and handling of system faults and errors.

5.13 Subsystem Function: Security

This function refers to the implementation of strategies and countermeasures to deal with internal and external security threats.

5.14 Interfaces and Dataflows

Figure 2 (next page) and Figure 3 (p. 22) show the main connections and data flows involved in controlling the execution of an observation and monitoring the state of the array, respectively. The diagram shows the control and monitoring modules distributed in the layers specified in the M&C architecture (see [AD06]). These are:

- **Operation Layer:** Operational interfaces for the Array Operations Staff (e.g., Operator and Astronomer-on-Duty).
- **Execution Layer:** Coordinates the execution of observations.
- **Supervisory Control Layer:** Includes real-time computers for controlling the antenna electronics, LO reference, timing and synchronization equipment, and the CSP.
- **Hardware Controller Layer:** Includes the Hardware Controller Boards. These are interface boards between the supervisory computers and electronic equipment, translating Ethernet commands to low-level electronic protocols such as GPIO, SPI, I2C, etc.

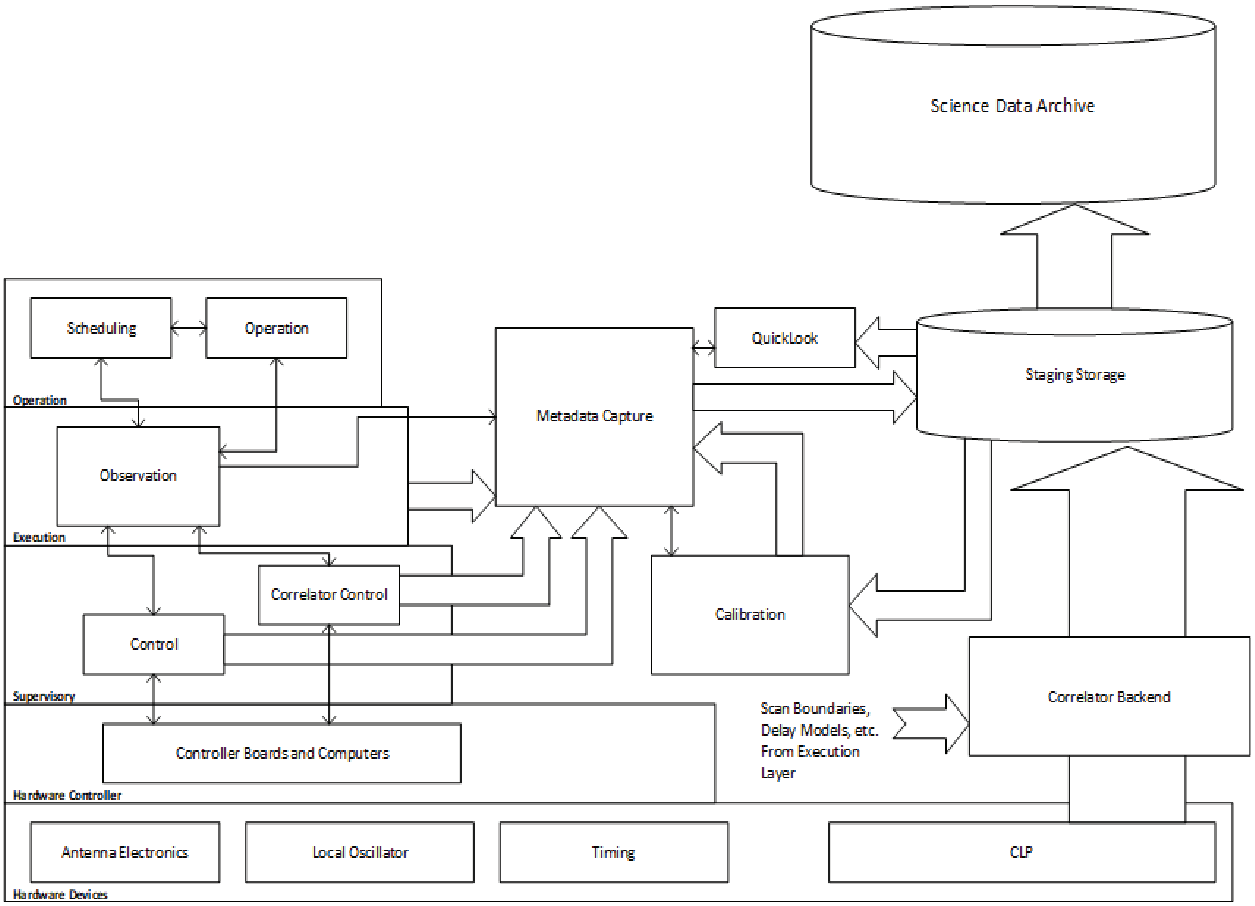

Figure 2 - Online subsystem observation-related data flows. Data streams are shown as wide arrows, while single line arrows denote control paths.

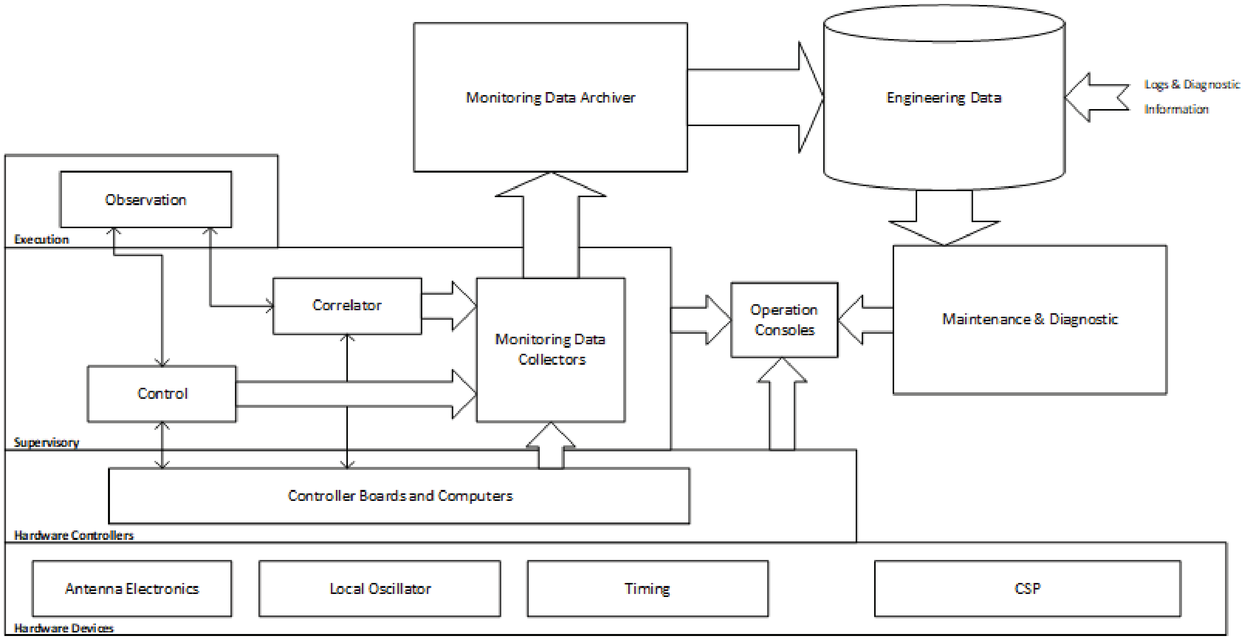

Figure 3 - Online subsystem monitoring-related data flows. Data streams are shown as wide arrows, while single line arrows denote control paths.

5.14.1 Scheduling Module Interfaces

- **Sub-Array Management UI:** This is the user interface that the Operator uses to create, destroy and query sub-arrays, query the list of observable Scheduling Blocks, select them to be executed, and monitor the status of the execution. This interface aggregates information about the status of the antennas, allowing the Operator to visualize the sets of antennas that can be used in specific sub-arrays.
- **Scheduling Block Interface:** This is a software interface that allows one to query the Scheduling Blocks stored in the Proposal Database.
- **Weather Prediction Interface:** This software interface allows one to execute the weather forecasting process, for different time scales. This process uses the weather historic database.

5.14.2 Operation Module Interfaces

- **Alarm & Notifications UI:** This user interface allows the operator to see a list of alarms and other notifications, ordered by priority. The error handling system incorporates logic to detect the root cause of problems, filtering secondary alarms. This interface allows the operator to filter alarms using several criteria, provides documentation about the recovery procedures to follow for known problems, and allows one to acknowledge alarms once they have been dealt with.
- **Logging UI:** This user interface allows the operator to see the system logs, and filter by log priority and other criteria.
- **Hardware Status UI:** This user interface allows the operator to visualize the status of the telescope systems. It allows the operator to browse this information at several levels of detail, through tabular and graphical representations (mimics).
- **Console Interfaces:** This is a low-level console interface that allows the operator to connect to different components of software and hardware (software components, supervisory servers, and controller cards) and issue monitoring and control commands.

5.14.3 Observation Module Interfaces

- **Sub-array Management Interface:** Interface used to create and destroy sub-arrays, and query information about the existing sub-arrays.
- **Observation Interface:** Interface that allows one to start observations and abort observations, passing a Scheduling Block identifier and a time in UT.
- **Observing Mode Interface:** This interface provides a science-oriented API to execute an observation. It is used by standard observation scripts and commissioning scripts.

5.14.4 Antenna Supervisory Control Module Interfaces

- **Antenna Pointing Interface:** Software interface to command the antenna to point in the supported coordinate systems. Includes support for Ephemeris objects.
- **Frequency Tuning Interface:** Software interface to command the antenna electronics to tune to specified observing frequencies. This involves selecting the observing bands in the antenna. (Besides this, frequency tuning involves tuning the LO offset in the LO reference system).
- **Attenuator Control Interface:** Software interface to retrieve and set the value of the IRD attenuator gains.

5.14.5 LO and Timing Supervisory Control Module Interface

- **Local Oscillator Reference Interface:** This interface allows one to control the Local Oscillator reference hardware. An important function in this interface is setting the offsets for each antenna. These offsets carry both the fine tuning and an LO offset that is afterwards removed in the CSP (see LO Offsetting function).
- **Time Synchronization Interface:** This interface allows one to control the timing synchronization hardware.

5.14.6 CSP Supervisory Control Module Interfaces

- **Correlator and Beam-former Interface:** This interface allows one to control the Correlator and Beam-former hardware.
- **Pulsar Engine Interface:** This interface allows one to control the Pulsar Engine hardware.

5.14.7 Metadata Capture Module Interfaces

- **Observation Metadata Interface:** The functions in this interface are called during an observation to transmit observation metadata. These are typically when the observation starts/ends, when a scan start/ends, etc.
- **Pointing Data Interface:** This interface is used to receive the Pointing Data streams from the antennas.
- **Weather Data Interface:** This interface is used to receive the Weather Data streams from the Weather Stations.
- **WVR Data Interface:** This interface is used to receive data from the Water Vapor Radiometer data and store it as an auxiliary table along with the MS tables.
- **Configuration Data Interface:** This interface is used to send the system configuration (e.g., pointing model, focus model, antenna positions, etc.) at the beginning of an observation, and any changes that may have occurred while observing.
- **Flagging Interface:** This interface is used to report flagging commands, usually as a result of a hardware fault during an observation.

- **Calibration Data Interface:** This interface is used to send calibration tables from the Calibration module, to be stored in the MS or as auxiliary tables.

5.14.8 Configuration Module Interfaces

- **Configuration Interface:** This interface is used to set and retrieve configuration data structures.
- **Configuration History Interface:** This interface allows the query of the history of changes applied in the configuration data structures.

5.14.9 Quick-Look Module Interfaces

- **Quick-Look UI:** This user interface allows one to visualize QA0 (observation quality assurance) data as the observation proceeds. This usually consists of plots showing results from the Calibration module.

5.14.10 Calibration Module Interfaces

- **Telescope Calibration Interface UI:** This interface consists of several utilities that read data collected from performing telescope calibration observations, and derive calibration models. The interface allows one to commit the calibration models into the configuration database once they have been validated.
- **Online Calibration Interface:** This is a software interface through which the Calibration Module is notified of the existence of new calibration scans to be processed. The Calibration Module computes calibration tables and sends them to the Metadata Capture Module.

5.14.11 Monitoring Module Interfaces

- **Monitoring Control Interface:** This interface allows one to control what monitor points will be sampled, along with their frequency.

5.14.12 Data Streams

- **Pointing Data Stream:** This data stream contains pointing data from the Antenna Supervisor modules to the Metadata Capture module. The pointing data includes the antenna encoder pointing data.
  Assuming that the need to record pointing data comes from the single dish and OTFM observing modes, a sample rate can be derived from the antenna scan speed requirements and the primary beam width. The scan speed has not been specified yet for ngVLA, but as a reference, the highest RF frequency is equivalent to Band 3 in ALMA, where a sampling rate of 48 ms is used. This results roughly in a 90 KB/s aggregated data rate for all antennas.
- **Delay Model Data Stream:** This data stream contains the delay compensation data, which includes the geometrical delay for all antennas combined with the cable delay and other instrumentation delays. It also includes the addition of a "causality delay" to make the delay compensation for all antennas positive. It is sent from the Observation module to CSP module.
  Although the details may change, a message containing the delay models for all antennas for some interval of time in the future (typically 1 minute) is sent in advance to allow the CSP to receive it and process it before the corresponding antenna data packet arrive.
- **Water Vapor Radiometer Data Stream:** This data stream contains Water Vapor Radiometer data, from the WVR devices to the Calibration module.
- **Weather Data Stream:** This data stream contains weather data, from the weather stations to the Observation Module (weather data is necessary for calculating delays models), to the Metadata Capture Module and to the Calibration Module.

- **Monitoring Data Stream:** This data stream contains monitoring data, from the Monitoring Data Collectors to the Monitoring Archiver. The number of monitor points per antenna for both ALMA and VLA is around 5000. Assuming each monitor value is transmitted in 16 bytes (8 bytes timestamp, 4 bytes identifier, and 4 bytes value) and an average monitoring rate of 1 Hz, this data stream should be around 80 KB/s per antenna and 21 MB/s for all 263 antennas. This data stream will require approximately 0.6 PB of storage per year. In practice, a few years will be kept in an online database, and older data will be stored offline. This is a small fraction of the storage needed for the science data.
- **Alarm and Notification Stream:** This data stream consist of alarms and notifications, broadcasted from the Supervisor modules.
- **CSP Output Data Stream:** This data stream contains low-level science data products, from the CSP to the Correlator Back End.
- **Science Staging Data Stream:** This data stream contains the final science data products, from the Correlator Back End to a disk staging area.
- **Science Archive Ingestion Data Stream:** This data stream transmits the staged science data from the disk staging area in the Array Operations and Repair Center to the Science Operations and Data Center.

5.14.13 Controller Board Interfaces

- **Generic M&C Interface:** This is an interface that all controller boards implement, and includes basic status information, the firmware version, a reset command, and other general operations.
- **Control Interface:** This interface implements the control points for each type of controller board. The execution of control commands can be performed at a specified timestamp in the future, or as soon as possible. A protocol will be defined for issuing commands and receiving return codes.
- **Monitoring Interface:** This interface allows the Data Collectors to collect monitoring data from each one of its connected controller boards.

5.15 Physical Architecture

The Online Subsystem physical architecture is shown in Figure 4 (next page). The logical modules, interfaces, and data streams listed in the previous sections are mapped into the computing, storage and network equipment presented in the diagram.

Antenna data is streamed from the antennas to the CSP. This data stream contains voltage data for two polarizations, channelized in 200 MHz spectral windows to form a total bandwidth of 20 GHz. This data is encoded in 4 bits, resulting in 320 Gbps per antenna (2 polarizations × 40 GHz Nyquist rate × 4 bits/sample).

In terms of the nature of the connections, the antennas are divided in three classes: the directly connected antennas; the antennas connected through commercial dark fiber; and the antennas that will be connected through the public packet switching network. The antenna data is sent in 4 x 100 GbE interfaces to the CSP. The CSP is composed of three Tridents, each capable of processing 2 x100 GbE streams. The software controls how these 200 Gbps data streams are distributed to each Trident.

The CSP produces visibility and pulsar data, which is sent to Correlator Back-end. This system produces the final raw data product in a Staging Storage area, from where it is read by the online computers to be sent to the Science Operations and Data Center through the ISP network. The Correlator Back-end also provides computing resources for the Calibration Module software.

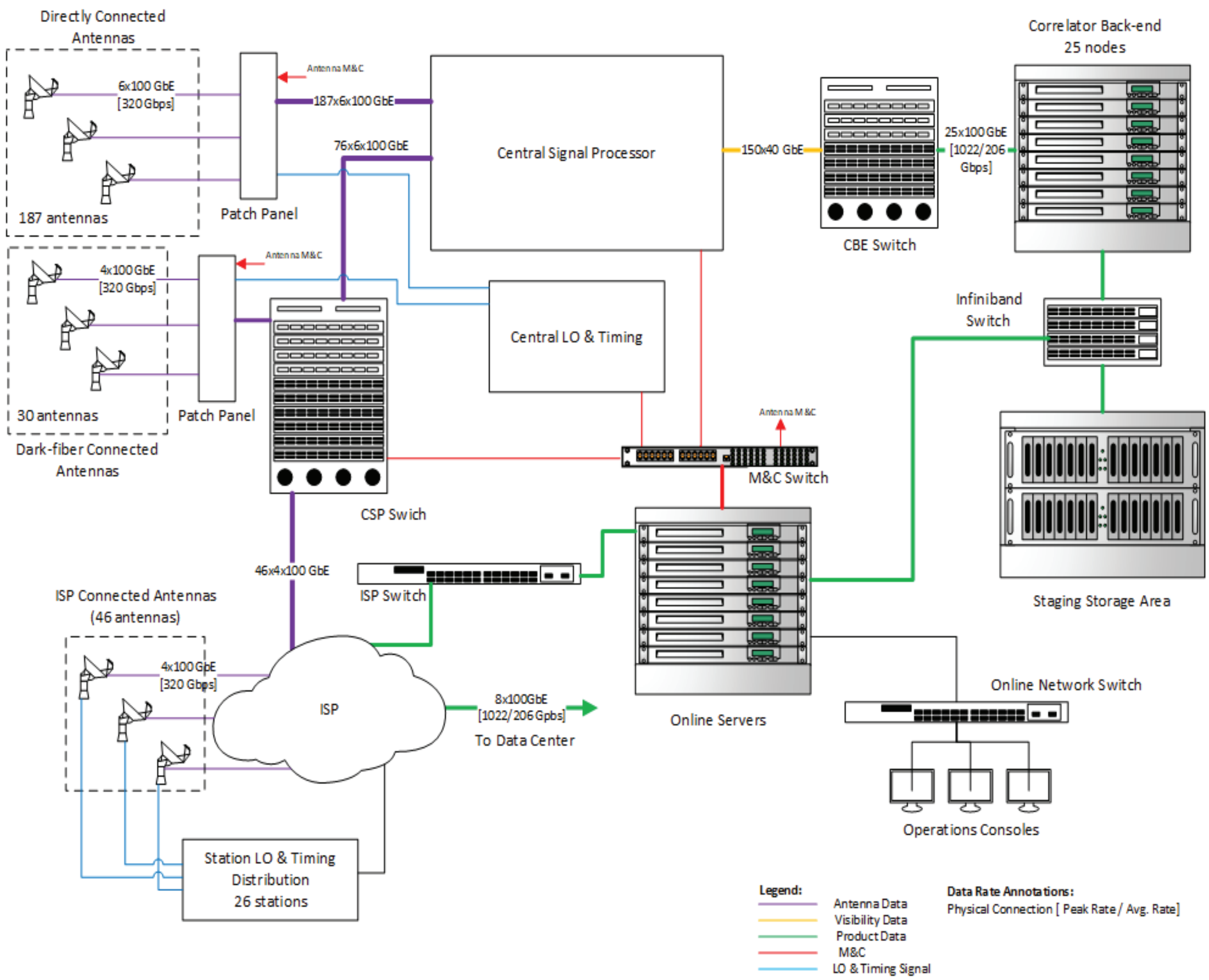

Figure 4 - Online subsystem physical architecture.

The Online Servers rack includes 13 servers, defined in Table 2. It may be possible to decrease the number of physical machines by virtualization.

Name	Quantity	Purpose
General Services Server	1	General purpose. Build and deployment, troubleshooting, etc.
CSP Supervisory Computer	1	Real time computer, controls the CSP.
LO and Timing Supervisory Computer	1	Real time computer, controls the LO reference and timing systems.
Calibration Support Server	1	Executes the Calibration module software.
Observation Execution Server	1	Executes the Observation Executor. It may require real-time capabilities.
Observation Support Server	1	Executes other components belonging to the Observation module, e.g., the Delay Calculation component, Metadata Capturer, etc.
Data Transmission Server	1	Executes software that reads the raw data and transmit it to the Science Operations and Data Center.
Operations Console	3	Operator consoles.
Scheduling Database Server	1	Executes a DBMS system containing the scheduling blocks.
Engineering Database Server	1	Executes a DBMS system for the Engineering Database.
Configuration Database Server	1	Executes a DBMS system for the Configuration Database.
Monitoring Server	1	Executes software from the Monitoring module.

Table 2 - Online servers.

6 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 3 shows the telescope expected data rates. These figures are large enough to make it difficult for end users to 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 [AD05] for additional information about SRDP.

Science Case	Use Fraction	Vis Per Hour	Data Rate	Storage Rate
KSG1 Driving Cont Band 6 eg Taurus disk	8%	73.19 GVis	0.081 GB/s	0.21 PB/Month
KSG1 Driving Cont Band 4 eg Taurus disk	4%	216.28 GVis	0.240 GB/s	0.63 PB/Month
KSG2 Driving Line Band 5 eg Sgr B2(N)	4%	97241.83 GVis	108.046 GB/s	284.14 PB/Month
KSG2 Driving Line Band 4 eg Sgr B2(N)	1%	72129.85 GVis	80.144 GB/s	210.76 PB/Month
KSG2 Driving Line Band 3 eg Sgr B2(N)	1%	119342.01 GVis	132.602 GB/s	348.72 PB/Month
KSG3 Driving Line Band 5 eg COSMOS	4%	5985.35 GVis	6.650 GB/s	17.49 PB/Month
KSG3 Driving Line Band 4 eg COSMOS	1%	2996.82 GVis	3.330 GB/s	8.76 PB/Month
KSG3 Driving Line Band 3 eg COSMOS	1%	3030.45 GVis	3.367 GB/s	8.85 PB/Month
KSG3 Driving Line Band 6 eg Spiderweb galaxy	2%	11.16 GVis	0.012 GB/s	0.03 PB/Month
KSG3 Driving Line Band 5 eg Spiderweb galaxy	1%	11.16 GVis	0.012 GB/s	0.03 PB/Month
KSG3 Driving Line Band 4 eg Spiderweb galaxy	1%	5.58 GVis	0.006 GB/s	0.02 PB/Month
KSG3 Driving Line Band 6 eg Virgo Cluster	7%	3232.05 GVis	3.591 GB/s	9.44 PB/Month
KSG3 Driving Line Band 1 eg M81 Group	10%	149.48 GVis	0.166 GB/s	0.44 PB/Month
KSG3 Driving Line Band 1 eg 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+PossiblePulsars	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
	Average:	6714.55 GVis	7.461 GB/s	19.62 PB/Month

Table 3 - Expected data rates, from science use cases. It is assumed that full polarization is required, and visibilities are stored in half precision (2 bytes per number, 4 bytes per visibility).

The Offline Subsystem is divided into the following modules:

- **Science Archive:** The Science Archive 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 module 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. This includes visualization and processing interfaces, in order to examine large images without having to download them first. It also includes Virtual Observatory compatible 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 such as the Open Science Grid, Amazon Web Services, and XSEDE. Although the exact distribution of local and remote resources is still TBD, the system will probably operate in a hybrid mode where local, dedicated, high-utilization resources handle the reduction of raw data to generate standard data products up to certain capacity, while external resources are used to process jobs that overflow this level.
- **Data Processing Pipelines:** This module includes 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.

The following sections describe the subsystem functions.

6.1 Subsystem Function: Raw Data Calibration

The raw data acquired for Proposals that adhere to the ngVLA standard observing modes will be automatically calibrated. Each execution of a Scheduling Block is defined as an Execution Block. Execution Blocks are calibrated independently. A set of Execution Blocks that are processed together by the imaging pipeline is known as a Program. Calibration is triggered by the Data Processing Management module. If the raw data is still the temporary storage (where it is being left after data transmission), the calibration pipeline is executed immediately; if not, it is retrieved from the Science Archive first.

The calibration pipeline is executed in the processing cluster, removing instrument-dependent effects from the data, producing a set of calibration tables and a calibrated dataset along with QA reports and other auxiliary products. These are analyzed by QA staff by means of the Quality Assurance Interfaces, and if accepted the data products are ingested into the Archive. The calibrated dataset is not stored into the Archive, but the calibration tables are. When necessary, the calibration tables can be applied on the raw data to create a *restored* calibrated dataset.

If the quality of the dataset is deemed insufficient, it can be re-processed (typically after additional flagging) or re-observed. A problem tracking system, part of the Observatory Interfaces module, allows one to communicate and follow-up on problems with the PI.

For visibility data, the pipeline performs calibrations for phase, amplitude, band-pass, flux, polarization, and other standard calibrations. Pulsar data is usually calibrated for flux and polarization.

Currently, the algorithms used to solve the calibration tables are not parallel. Depending on timing results, it may be necessary to investigate parallelization possibilities. In lower frequencies, self-calibration may be needed in order to achieve high dynamic range. This ties calibration performance requirements with the imaging.

6.2 Subsystem Function: Imaging Product Generation

Once all the datasets that belong to the same Imaging Program have been successfully calibrated and accepted by QA, the Data Processing Management module triggers the imaging pipeline. In order to avoid unnecessary copies, the recently calibrated dataset is kept in a cache, from where it is read by the imaging processes.

The imaging process runs the CLEAN algorithm. This algorithm iteratively executes gridding, degridding, FFT and deconvolution operations in a *major cycle*, with the embedded deconvolution operation being iterative itself, executing several *minor cycles* during each major cycle. The gridding operation includes also a convolution operation of the corrected visibility data with a *support function or kernel*, which incorporates corrections for wide field distortions and other effects.

Given the scale of the ngVLA datasets, extensive parallelization and performance improvements on the data reduction software will be needed. This will require algorithm research during the Design & Development phase of the project.

The production of imaging data products follows a workflow similar to calibration. Once the pipeline has finished, the images are examined for quality assurance, and if accepted, they are ingested into the Archive.

6.3 Subsystem Function: Source Catalog Product Generation

Images that have been successfully accepted by QA and ingested into the Archive can be used as input of processes that generate catalogs. These processes scan the images to find sources and extract several properties from them. These tables go through the same quality assurance processes as other data products and are ingested into the Archive.

6.4 Subsystem Function: Project Tracking

This function refers to the provision of interfaces for PIs to track the status of their accepted proposals. This includes the capability of tracking the status of scheduled observations and quality assurance processes for the raw and derived data products.

6.5 Subsystem Function: Data Product Discovery

This function encompass the capability of interacting with the Archive to search its contents, visualize results, save queries or results, and select data products for later use. These capabilities will be provided by the SRDP project.

6.6 Subsystem Function: Data Product Retrieval

This function refers to the capability of retrieving the metadata and binary files of a data product. Several delivery mechanisms will be provided: a password protected URL, a download manager, staging into NRAO processing cluster storage, or external services such as AWS. These capabilities will be provided by the SRDP project.

6.7 Subsystem Function: Data Product On-Demand Post-Processing

Once one or more data products have been selected using the Archive interfaces, they can be used as inputs in data processing pipelines. The system allows one to customize the execution parameters. This capability will be provided by the SRDP project.

6.8 Subsystem Function: Data Product Analysis

The CASA package currently provides tools to enable analysis of resulting science products. The ngVLA project will extend this package with ngVLA specific capabilities.

6.9 Subsystem Function: Security

This function refers to the implementation of strategies and countermeasures to deal with internal and external security threats.

6.10 Interfaces and Data Flows

Figure 5 (next page) shows the offline flow of data from the Array Operations Center to Observatory Interfaces and external processing centers.

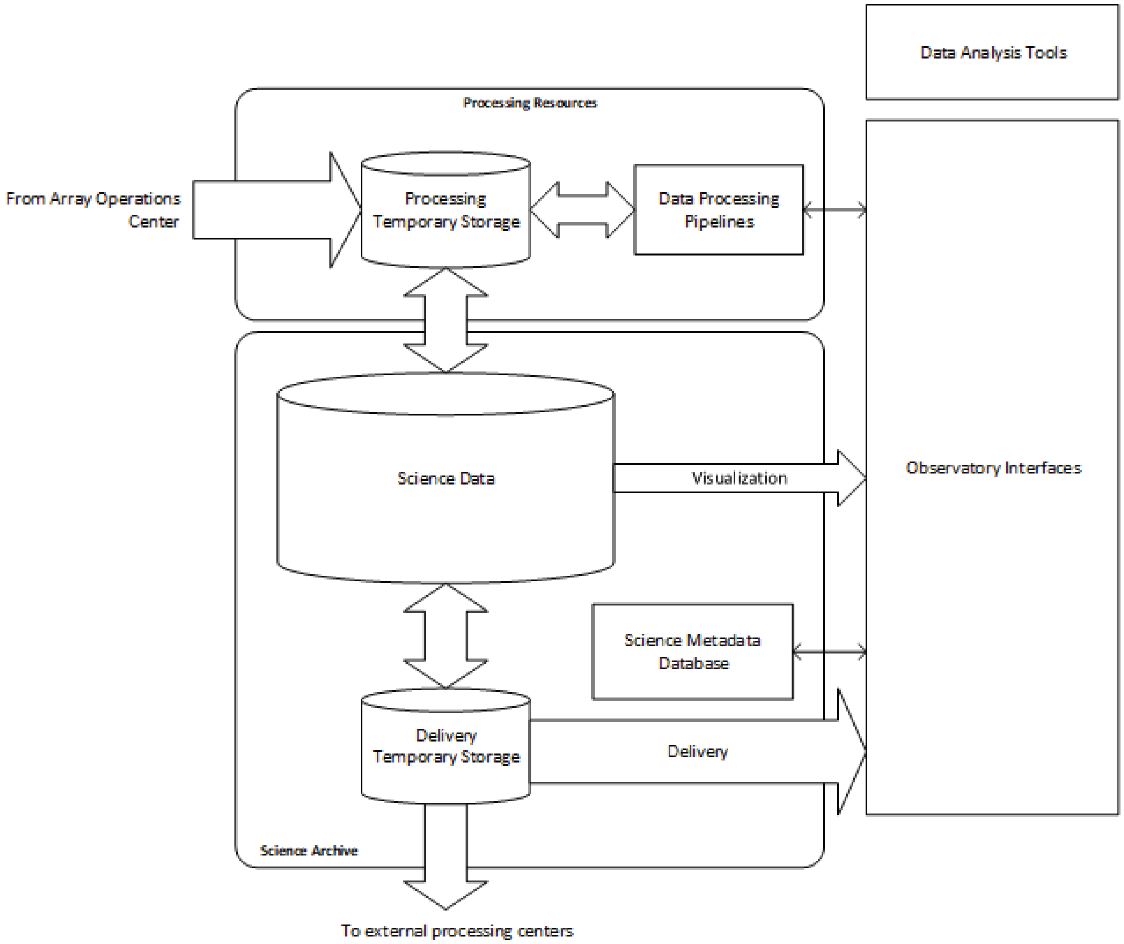

Figure 5 - Offline data flows. Data streams are shown as wide arrows, while single line arrows denote control and query paths.

6.10.1 Science Archive Interfaces

- **Archive Metadata Database Interface:** This interface allows one to submit queries and retrieve results from the Archive Metadata Interface.
- **Archive Storage System Interface:** This interface provides access to the Archive Storage System. It allows one to search and list files, retrieve file metadata, download files, upload files and delete files.
- **User Database Interface:** This interface permits retrieval of information about user accounts.
- **Calibrator Database Interface:** This interface provides access to the Calibrator Database. Lists of calibration sources are maintained in this database, along with their properties and time series.

6.10.2 Observatory Interfaces

- **Archive Web UI:** This Web application allows users to search the Archive contents.
- **Workspace UI:** This Web application lets users access their *workspace*, where they save references to data products and queries, submit post-processing requests, and manage their execution.
- **Helpdesk Interface:** This interface provides access to NRAO Helpdesk, which allows users to submit and follow up problems related with observations and post-processing jobs.
- **Virtual Observatory Interface:** This interface provides VO-compatible services.

6.10.3 Data Processing Management Interfaces

- **Data Processing Management UI:** This interface permits management of automated data processing. It uses the Product and Job interfaces.
- **Product Interface:** This REST interface permits management of product information. It provides methods to create new products, retrieve product information, update the product status, manage dependent products, etc.
- **Job Interface:** This REST interface permits management of product-generation jobs.

6.10.4 Processing Resource Interfaces

- **Processing Resource Management Interface:** This interface permits management of processing resources. It provides a common interface to heterogeneous processing resources (local clusters, external resources such as Amazon Web Services, etc.).

6.10.5 Data Processing Pipeline Interfaces

- **Pipeline Processing Request Interface:** This interface is based on an XML file (PPR.xml) that is parsed by the pipeline. The file contains data elements such as the project information, the PI name, the Measurement Set, etc., and processing instructions about the pipeline tasks that will be executed, along with their parameters.
- **Pipeline Scripting Interface:** The Pipeline Scripting Interface is an API based on the pipeline tasks, which are constructed using CASA tasking infrastructure.
- **Weblog Interface:** The Weblog is one of the products generated by the Pipeline. It consists of a set of generated HTML pages and plots describing several aspects of the generated data products and associated processing.

6.11 Quality Assurance Interfaces

- **Quality Assurance UI:** This Web application allows QA personnel to access job execution information, Weblogs, etc. The application permits introducing comments and performing actions to follow up QA decisions (accept data products, reject data products, submit for re-processing, submit Helpdesk issues, etc.). This UI uses the Quality Assurance Interface.
- **Quality Assurance Interface:** This REST interface permits management of QA information.

6.12 Data Analysis Package Interfaces

- **Plot MS UI:** This is a plotting application for the Measurement Set format.
- **Image Viewer UI:** This application allows viewing and manipulating astronomical images.
- **Data Analysis Task Interface:** This permits defining parameters and executing data analysis tasks.

6.13 Data Streams

- **Archive/Processing Data Stream:** This is the data stream between the temporary storage resources in the Processing Resources and the Archive Storage System. Both local and external processing resources need to be considered.
- **Delivery Data Stream:** This is the data stream between the Archive Storage System and the user, when downloading data products. In practice, the data product will be staged in a delivery storage area, from where it will be streamed to the end user. The staged data product can be the result of

delivery processing tasks such averaging, mosaicking, image cutout, restoration of calibrated MS from calibration tables, etc.

- **Visualization Data Stream:** NRAO is working in an advanced visualization system that will be provided as a browser application, reducing the need to retrieve full image files for viewing. This will originate a data stream between the Archive and the user browser.

6.14 Physical Architecture

Figure 6 shows the Offline Subsystem physical architecture.

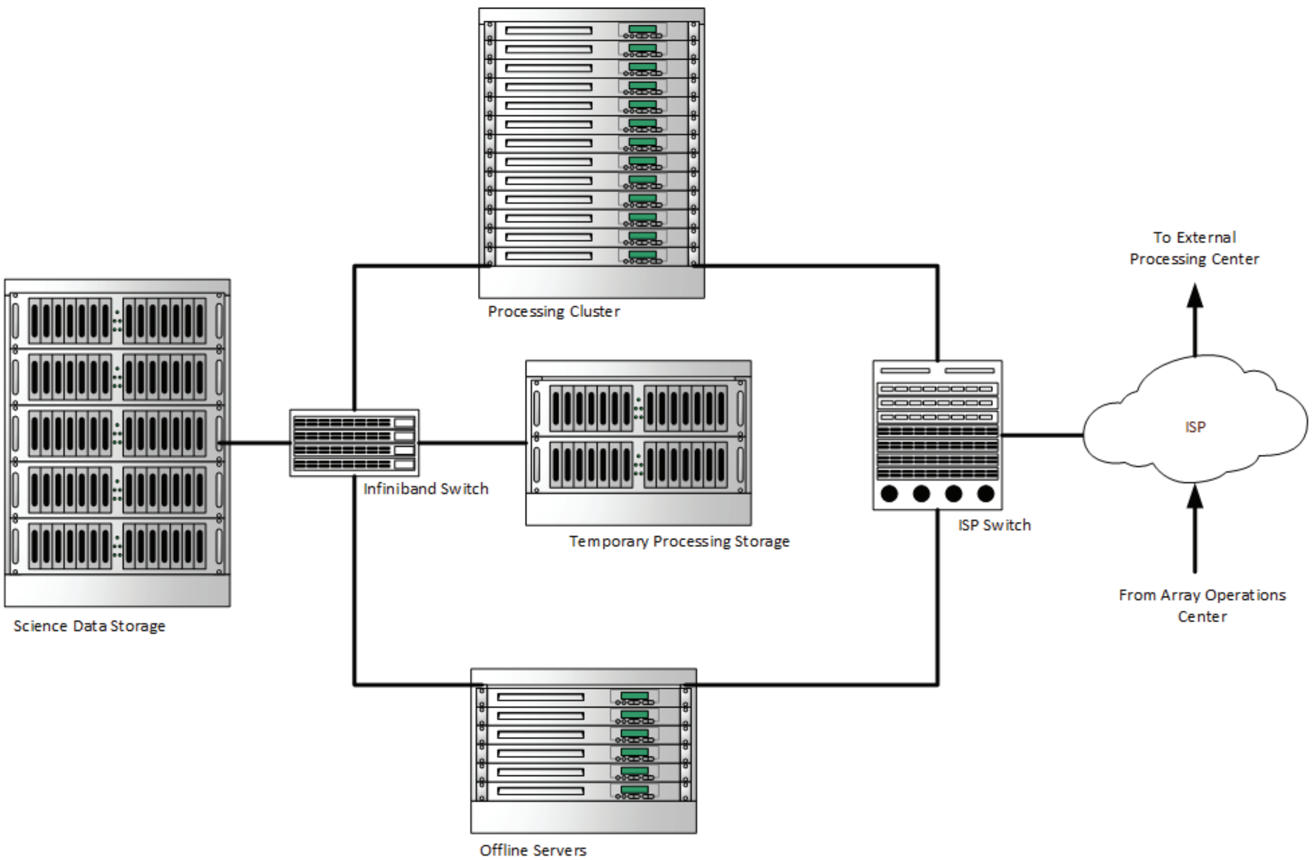

Figure 6 - Offline subsystem physical architecture.

The Offline Servers rack includes nine machines, described in Table 4.

Server Name	Quantity	Description
Archive Services Server	1	Executes services from Science Archive module.
Observatory Interfaces Server	2	Deploys Observatory Interfaces services.
Quality Assurance Support Server	1	Executes QA support software.
General Services Server	1	Supports software maintenance and development.
Metadata Database Server	1	Runs the Metadata Database.
Processing Management Server	1	Executes software from Processing Management module.
Proposal Management Database Server	1	Runs Proposal Management Database.
Proposal Management Server	1	Executes Proposal Management software.

Table 4 - Offline subsystem servers.

6.14.1 Data Reduction Performance Requirements

The main requirement for data processing is the ability of the system to maintain the throughput while reducing (calibrating and imaging) the raw data stream from observations. It is not possible to accumulate observations waiting for processing resources, beyond normal variations. The system is sized to sustain the average throughput, while latency is considered a "floating" variable. This section documents preliminary analyses and measurements for estimating the required system performance.

The computing load for one gridding cycle is

$$CL_{gridding} = \frac{\text{Visibilities}}{\text{second}} \cdot \frac{\text{FLOPs}}{\text{Visibility}}$$

The number of FLOPs per visibility depends on the size of the convolution kernel used during gridding, which varies depending on the algorithm used (W-projection, A-projection, etc.)

It is assumed that the total number of operations involved in reducing a dataset is proportional to $CL_{gridding}$:

$$CL = k \cdot CL_{gridding}$$

The factor k includes the repetition gridding /degridding in each major cycle, the deconvolution operations performed in each minor cycle, the effect of multi-term and multi-scale algorithms, and the operations performed in calibration tasks.

We define the observed performance of a single core (or more generally a "processor," as the system is likely to include accelerator hardware) as:

$$CP^{(obs,sc)} = \frac{\text{FLOPs}}{\text{Execution time for a single core}}$$

measured by executing test runs with simulated datasets and applying scaling laws.

Similarly, the observed performance on a parallel system is

$$CP^{(obs,par)} = \frac{\text{FLOPs}}{\text{Exec. time for parallel system}}$$

$$= CP^{(obs,sc)} \cdot \frac{\text{Execution time for single core}}{\text{Execution time for parallel system}}$$

$$= CP^{(obs,sc)} \cdot Sp(N_c)$$

The speedup $Sp(N_c)$ can be modeled from Amdahl's Law, and measured by observing how the execution time scales as the number of cores increases.

The observed core performance differs from the nominal core performance by the core efficiency ε_c factor:

$$CP^{(obs,sc)} = \varepsilon_c CP^{(sc)}$$

The nominal performance is the peak figure reported in the processor specifications. Achieving it would require keeping the processor busy only doing floating point operations, using SIMD instructions.

Matching the required computing load with the parallel system throughput:

$$CL = \varepsilon_c CP^{(sc)} Sp(N_c)$$

Multiplying and dividing by the number of core N_c, and defining the parallelization efficiency as $\varepsilon_p = Sp(N_c)/N_c$, the ratio of the real speedup and the ideal speedup, we obtain

$$CL = CP^{(sc)} N_c \varepsilon_c \varepsilon_p$$

The single-core performance times the number of cores is the quantity that is usually reported as the "system performance" of an HPC system. Naming this quantity $SP = CP^{(sc)} N_c$, the required system performance can be expressed as

$$SP = \frac{k CL_{gridding}}{\varepsilon_c \varepsilon_p}$$

The parameters used on this estimation are shown in Table 5, the algorithmic requirements for each science case can be found in Table 6), and Table 7 (next page) shows the estimated system performance for each science case.

Parameter	Value	Notes
Base Convolution Kernel Size	7	Prolate spheroidal. Linear size, i.e. the kernel matrix dimensions are 7x7.
Primary Beam Kernel Size	8	Linear size. When A-proj is used, this kernel is convolved with the base kernel to produce the final convolution kernel.
W-projection Kernel Size	100	Linear size. When W-proj is used, this kernel is convolved with the base kernel to produce the final convolution kernel.
Ionospheric Corr. Kernel Size	8	Linear size. When this alg. is used, this kernel is convolved with the base kernel to produce the final convolution kernel.
Gridding to Full Expansion Factor	25.0	Base case for estimating k.
Multi-Scale Factor	1.2	Multiplies k when multi-scale is used.
Multi-Term Factor	3.0	Multiplies k when multi-term is used.

Parameter	Value	Notes
Base FLOPs/Visibility	3900	Preliminary measurement for base case. It is scaled with the combined kernel size when other algorithms are used.
Core Efficiency	0.1	ε_c. From preliminary measurements.
Parallelization Efficiency	0.9	ε_p. Educated guess. This parameter needs to be measured (there is no currently software available that allows this measurement).
Arithmetic Intensity for Gridding	170 FLOPs/byte	Preliminary measurements for gridding.

Table 5 - Parameters used for estimating the required computing performance for reducing ngVLA observations.

Science Case	w-proj	PB correction	Ionospheric Correction	Multi-scale	Multi-term
KSG1 Driving Cont. Band 6 e.g. Taurus disk	No	No	No	Yes	Yes
KSG1 Driving Cont. Band 4 e.g. Taurus disk	No	No	No	Yes	No
KSG2 Driving Line Band 5 e.g. Sgr B2(N)	No	Yes	No	Yes	No
KSG2 Driving Line Band 4 e.g. Sgr B2(N)	No	Yes	No	Yes	No
KSG2 Driving Line Band 3 e.g. Sgr B2(N)	No	Yes	No	Yes	No
KSG3 Driving Line Band 5 e.g. COSMOS	No	Yes	No	Yes	No
KSG3 Driving Line Band 4 e.g. COSMOS	No	Yes	No	Yes	No
KSG3 Driving Line Band 3 e.g. COSMOS	No	Yes	No	Yes	No
KSG3 Driving Line Band 6 e.g. Spiderweb galaxy	No	Yes	No	Yes	No
KSG3 Driving Line Band 5 e.g. Spiderweb galaxy	No	Yes	No	Yes	No
KSG3 Driving Line Band 4 e.g. Spiderweb galaxy	No	Yes	No	Yes	No
KSG3 Driving Line Band 6 e.g. Virgo Cluster	No	Yes	No	Yes	No
KSG3 Driving Line Band 1 e.g. M81 Group	Yes	Yes	Yes	Yes	No
KSG3 Driving Line Band 1 e.g. M81 Group	No	Yes	Yes	Yes	No
KSG5 Driving Cont. Band 1 OTF Find LIGO event	Yes	Yes	Yes	Yes	Yes
KSG5 Driving Cont. Band 4 OTF Find LISA event	No	Yes	No	Yes	Yes
KSG5+4 Driving Cont. Band 2 OTF Find BHs + Possible Pulsars	Yes	Yes	No	Yes	Yes
KSG5 Driving Cont. Band 3 Gw170817@200Mpc	No	No	No	Yes	Yes

Table 6 - Algorithmic requirements for each science case.

Science Case	Use Fraction	Required System Perf.
KSG1 Driving Cont. Band 6 e.g. Taurus disk	8%	0.079 PFLOPs/s
KSG1 Driving Cont. Band 4 e.g. Taurus disk	4%	0.078 PFLOPs/s
KSG2 Driving Line Band 5 e.g. Sgr. B2(N)	4%	412.782 PFLOPs/s
KSG2 Driving Line Band 4 e.g. Sgr. B2(N)	1%	306.184 PFLOPs/s
KSG2 Driving Line Band 3 e.g. Sgr. B2(N)	1%	506.595 PFLOPs/s
KSG3 Driving Line Band 5 e.g. COSMOS	4%	25.407 PFLOPs/s
KSG3 Driving Line Band 4 e.g. COSMOS	1%	12.721 PFLOPs/s
KSG3 Driving Line Band 3 e.g. COSMOS	1%	12.864 PFLOPs/s
KSG3 Driving Line Band 6 e.g. Spiderweb galaxy	2%	0.047 PFLOPs/s
KSG3 Driving Line Band 5 e.g. Spiderweb galaxy	1%	0.047 PFLOPs/s
KSG3 Driving Line Band 4 e.g. Spiderweb galaxy	1%	0.024 PFLOPs/s
KSG3 Driving Line Band 6 e.g. Virgo Cluster	7%	13.720 PFLOPs/s
KSG3 Driving Line Band 1 e.g. M81 Group	10%	24.130 PFLOPs/s
KSG3 Driving Line Band 1 e.g. M81 Group	12%	0.055 PFLOPs/s
KSG5 Driving Cont. Band 1 OTF Find LIGO event	7%	3558.202 PFLOPs/s
KSG5 Driving Cont. Band 4 OTF Find LISA event	7%	13.891 PFLOPs/s
KSG5+4 Driving Cont. Band 2 OTF Find BHs + Possible Pulsars	8%	783.613 PFLOPs/s
KSG5 Driving Cont. Band 3 Gw170817@200Mpc	23%	0.005 PFLOPs/s
	Average:	322.907 PFLOPs/s

Table 7 - Required system performance for ngVLA data reduction.

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 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.

7.1 Subsystem Function: Preventive Maintenance Analysis

This function refers to the analysis of monitoring data and alarms to detect conditions or trends that can indicate the need to service equipment before actual problems occur. This function is allocated in the CMMS Integration Module.

7.2 Subsystem Function: Maintenance Schedule Management

This function refers to the management of the maintenance schedule. It is allocated in the CMMS system.

7.3 Subsystem Function: Inventory Management

This function refers to the management of the spare parts inventory and is allocated in the CMMS system.

7.4 Subsystem Function: Troubleshooting Support

This function provides support for troubleshooting operations. It is allocated to the Integrated Support Module. This module allows users to search, visualize and correlate data from the Engineering Database.

7.5 Subsystem Function: Security

This function refers to the implementation of strategies and countermeasures to deal with internal and external security threats.

7.6 Interfaces and Dataflows

- **CMMS Interface:** This interface allows Operations staff to access the CMMS functionality.
- **Engineering Support Interface:** This interface, provided by the Integrated Support Module, allows Engineering support staff to access data from the Engineering Database.

7.7 Physical Architecture

Table 8 lists the servers included in this subsystem.

Name	Quantity	Description
Maintenance and Support Server	1	Executes custom software developed in this subsystem.
CMMS Server	1	Executes the CMMS system.
Maintenance Issue Tracking Server	1	Executes the Maintenance Issue Tracking system.

Table 8 - Maintenance and support subsystem servers.

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.

8.1 Physical Architecture

Table 9 lists the servers included in this subsystem.

Name	Quantity	Description
Continuous Integration Server	1	Executes software to manage the continuous integration process (automatic build and test system).
Software Configuration Management Server	1	Executes a software configuration management system.
Software Development Services Server	2	Execute services to support software development (issue tracking and planning, software reviews, documentation, simulators, test databases).
Software Test Server	4	Used by developers to test several versions of the system.

Table 9 - Development support servers.

9 Appendix

9.1 Abbreviations and Acronyms

Acronym	Description
ACU	Antenna Control Unit
ADC	Analog to Digital Converter
API	Application Programming Interface
AWS	Amazon Web Services
CASA	Common Astronomy Software Applications
CBF	Correlator Beamformer
CBE	Correlator Back End
CDP	Central Data Processor
CMMS	Computerized Maintenance Management System
COTS	Commercial Off-The Shelf
CSP	Central Signal Processor
DBE	Digital Back End
DBMS	Database Management System
DTS	Data Transmission System
FE	Front End System
FSP	Frequency Slice Processor
GPIO	General Purpose Input Output
IF	Intermediate Frequency
IPT	Integrated Product Team
IRD	Integrated Downconverter/Digitizer Module
IQ	In-Phase and Quadrature
ISP	Internet Service Provider
KSG	Key Science Goal
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C	Monitor and Control
MPI	Message Passing Interface
MS	Measurement Set
ngVLA	Next Generation VLA
NTP	Network Time Protocol
OPT	Observation Preparation Tool
OTFM	On The Fly Mosaic
PBT	Proposal Builder Tool
PE	Pulsar Engine
PHT	Proposal Handling Tool
PPS	Pulse Per Second
PST	Proposal Submission Tool
QA	Quality Assurance
REST	Representational State Transfer
RFI	Radio Frequency Interference
SDM	Science Data Model

Acronym	Description
SKA	Square Kilometer Array
SPI	Serial Peripheral Interface
SRDP	Science-Ready Data Products
TAC	Telescope Allocation Committee
UI	User Interface
UT	Universal Time
VCC	Very Coarse Channelizer
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry
VO	Virtual Observatory
WVR	Water Vapor Radiometer

Monitor and Control System: Reference Design Concept

020.50.25.00.00-0002-DSN-A-MONITOR_CONTROL_REF_DESIGN_CONCEPT

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Table of Contents

1 Introduction ... 4
1.1 Purpose ... 4
1.2 Scope ... 4
2 Related Documents ... 4
3 General Requirements ... 4
4 Control Architecture ... 6
5 Monitoring Architecture ... 9
6 Error Handling ... 10
7 Time Synchronization ... 11
8 Security ... 11
9 Development and Simulation ... 12
10 Appendix ... 13
10.1 Abbreviations and Acronyms ... 13

1 Introduction

1.1 Purpose

This document describes general concepts and design choices for the ngVLA Monitor and Control (M&C) System as a preliminary step in deriving its system requirements and specifying detailed design.

1.2 Scope

The scope of this document is to analyze how ngVLA requirements shape the design of the M&C system, focusing on design aspects that affect the interfaces between the telescope electronic systems and computing. It considers in particular the operational needs for maintenance and troubleshooting.

The general architecture of the software and computing systems, including the main data flows involved in performing observations and computing derived data products, are described in [AD05], along with other M&C aspects. The supporting design of the electronic interface boards between the computing systems and the telescope electronics is described in [AD01].

2 Related Documents

Ref. No.	Document Title	Rev/Doc. No.
AD01	Monitor & Control System: Hardware Reference Design	020.30.45.00.00-0004-DSN
AD02	Operations Concept	020.10.05.00.00-0002-PLA
AD03	Preliminary System Requirements	020.10.15.10.00-0003-SPE
AD04	ngVLA: System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements	020.10.15.10.00-0002-REQ
AD05	Computing & Software: Reference Design Architecture	020.50.00.00.01-0002-REP

3 General Requirements

Besides the usual functionality expected from a modern control and monitoring system, the main requirement affecting this design is the budget constraint on telescope operations. This document analyzes how this requirement affects the relative priority of system attributes and what strategies can be introduced in the design to achieve the required performance levels. The system must achieve high reliability, maintainability, and usability to decrease operational and maintenance costs. Given the high number of antennas, scalability is also a concern.

Maintenance operations usually are either preventive or corrective. Preventive maintenance seeks to retain the system in an operational or available state by preventing failures. It affects reliability directly. By contrast, corrective maintenance includes all actions to return the system from a failed to an operating or available state. System reliability determines the load of corrective maintenance activities. Thus, the system should support and facilitate scheduling of optimal preventive maintenance activities to increase reliability and decrease the amount of required corrective maintenance and associated down time. At the same time, making the system more maintainable should decrease the cost of both preventive and corrective maintenance.

Array operations costs are correlated with the required number of operators. Their activities can be roughly classified as array coordination, observation execution, array supervision, and failure recovery. Costs can be decreased by automating these activities as much as possible and designing a highly usable system.

The array availability must also be considered. Availability considers both the probability of failures and the time that it takes to recover from them. Given the scale of the ngVLA telescope, there is a relatively high probability of devices failing, compared to currently operating telescopes. The system must be designed to tolerate failures during observations. After recovery, devices and antennas should be reintegrated into the array as efficiently as possible. This is facilitated by designing the system as a composition of decoupled components that can be operated autonomously with a minimum of centralized interactions.

In general, the ngVLA M&C concept is guided by two principles, derived from lessons learned from the EVLA and ALMA:

- The system should be based on autonomous and decoupled components controlling smart devices.
- The system should be organized and managed as a hierarchically connected system.

The first principle worked well for the EVLA, where the M&C system was structured by Module Interface Boards (MIBs) and MIB-like boards and computers which were highly decoupled, connected to the rest of the system by their Ethernet interfaces. They were designed as autonomous components. Once they were powered up, they were functionally operative and ready to receive command messages and send monitoring data. In case of failures, a MIB and its controlled electronics can be powered down, recovered or replaced, and powered up again without affecting the rest of the system.

ALMA was structured as a hierarchy of control components, forming a Distributed Control System (DCS). In general, this architecture handles complexity well, is scalable, improves reliability, and is well suited for a geographically dispersed system. A DCS allows one to distribute the system load on multiple machines and enables the installation of redundancy strategies. It also helps to scale networking loads, as higher level components can receive commands of a higher level of abstraction, which are translated to multiple commands directed to the lower level components. Monitoring can be scaled similarly.

Integral in this architecture was 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 is also necessary in order to develop tools that facilitate the task of gathering all the necessary information needed to effectively troubleshoot problems.

4 Control Architecture

Implementing the principles from Section 3, the ngVLA control system will be structured in five layers, as shown in Figure 1. The bottom Hardware Device layer represents the hardware devices that compose the telescope. The electronics devices will be packaged as Line Replaceable 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 be Controller boards, but they could consist of computers that implement the same interface.

The Ethernet messages received by the Controller boards can be command messages (usually referred as SET messages), or monitoring messages (GET messages) and they need to specify the target device and the specific value inside the device that is being modified or requested (the command or monitor *point*). For SET messages, the command can optionally carry an application timestamp in the future, specifying when the command should be applied. If not present, the command should be applied as soon as possible. The controller sends a response message in return for both the GET and SET messages. It responds with the value and read timestamp for GET messages, and with the application timestamp and a status code for SET messages.

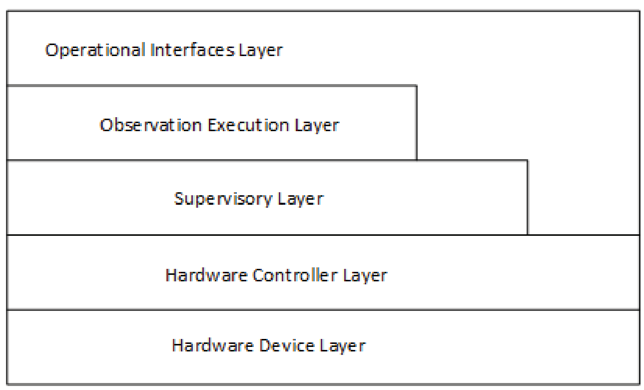

Figure 1 - Control architecture layers. The boundary between the Computing and Software IPT and other hardware IPTs has been defined as the interface between the Supervisory Layer and the H/W Controller Layer.

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 in order 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 frontend, which could then be translated into several commands sent to the controller boards that are 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 that identifies its function in the system, and a role that identifies where it is installed in the system. As an example, each antenna has several IRD modules, each one connected to receive different polarizations and frequency bands.

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 sets of antennas 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 the allocation of real-time requirements, these are divided in hard real-time requirements and soft real-time requirements, the distinction being 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. The allocation of real time requirements in either the Supervisory Layer or the Hardware Controller Layer depends on the scope of the operations involved. If a real-time operation involves more than one device, then its deadline constraints should be imposed in the Supervisory Layer. Otherwise, they should be allocated in the respective Controllers and devices.

So far, no real-time operation has been recognized that would imply real-time requirements in the Supervisory Layer. At the present stage of the project, it may be too early to make a strong decision on this area, but if this assumption holds, it can be stated that the Supervisory and above layers will deal only with soft deadlines, where the outcome of missing them will mostly result in intervals of flagged science data, and hard real-time requirements will be implemented in the Hardware Controller Layer and below. This is consistent with the general principle of constructing the system with smart devices.

Another aspect that will be affected by real-time requirements is the protocol between the Supervisory Layer and the Hardware Controller Layer. Currently, because of its ubiquity in the industry, it seems clear that an Ethernet-based solution is highly preferred. However, it is important to recognize that Ethernet is not a real-time control communication protocol, and it is affected by unpredictable latencies.

Several modifications of the Ethernet protocol have been proposed by the control system industry to address this issue. These are defined in the IEC 61784 standard, organized in profiles depending on their performance indicators (which include delivery time, throughput, and time synchronization accuracy). These protocols modify the protocol stack at different levels, and are classified as “Top of TCP/IP”, “Top of Ethernet”, or “Modified Ethernet”, depending on where they introduce modifications. Examples are Modbus/TCP, Ethernet/IP, TCNet, Profinet CBA, EtherCAT, and Profinet IO.

The decision as to whether these modified protocols are required is tied to the decision of requiring real-time capabilities in the Supervisory Layer. This decision is deferred to the Conceptual Design phase of the project, as it depends on detailed information about the hardware interfaces.

If normal, unmodified Ethernet can be used in the Supervisory/Controller interface, and an interesting possibility would be to select protocols such as HTTP/REST, UPnP, CoAP, MQTT and XMPP for control, monitoring, and discovery. GraphQL, an optimization of REST, is also gaining good traction. These protocols have become popular choices on constructing the "Internet of Things." There are clear advantages on selecting well-known and used protocols: the existence of good quality implementations and a wide pool of available developers. The task of securing the interface is also facilitated, as security is a core requirement for the Internet of Things. As they have been designed to work on public networks, they could be a good choice for controlling and monitoring the long haul antenna stations.

Regarding safety requirements, LRUs (which are composed of 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 monitoring and control system. Otherwise, LRUs are no longer autonomous and pose an operational risk.

5 Monitoring Architecture

The system will periodically sample the current values of a collection of attributes for each device, and will transmit them through a monitoring bus to the subscribed clients. In general, the source of monitoring data will be the hardware controllers, and clients will be distributed in all upper layers in the system. The monitoring bus incorporates publish/subscribe interfaces and allows the definition of multiple channels, allowing the receivers to select the monitoring data of interest, and control filtering options.

Although monitoring data originating from controllers will normally be listened to by clients in the supervisory and upper layers, the system does permit controllers to receive data from other controllers, if necessary.

Higher-level components in the control hierarchy could accumulate, translate, or summarize the monitoring data received from its lower-level components. For example, the antenna supervisory component could send an antenna status event, which would incorporate the status of the antenna devices whose malfunction would trigger data flagging commands. This translation of monitoring events allows one to distribute the processing of the monitoring event to the components that are better capable of interpreting them.

The system should provide interfaces to modify dynamically the parameters that control the capture and processing of monitoring data (the monitoring sampling frequency, the offset and slope to translate from hardware units to system units, etc.). Upon startup, their default values will be loaded from files stored in flash memory in the controllers, but they may be overridden by the supervisor with values read from the Telescope Configuration database. All the configurations defined in the Telescope Configuration database will be kept under version control.

The sampling period for specific monitor points could be shortened for a period of time when a given error or warning condition is detected, with the intention of collecting additional data to aid in debugging. This type of automatic collection of debugging information would be triggered by the Supervisor. This would be similar to an "oscilloscope function" with an automatic trigger. Given the amount of data that this function can potentially generate, the high-rate data will not be sent through the network in the normal monitoring stream, but will be stored in local files in the Supervisor.

The Supervisor will be the place where functions to aid in troubleshooting operations will be implemented. This part of the system will need to be constructed with modifiability in mind, as it is usually the case that the incorporation of logic to debug urgent problems needs to be incorporated as soon as possible. One strategy to achieve the required modifiability could be to introduce this logic at configuration, and not during implementation. This can be achieved by the use of scripted logic, which would be executed when a certain configured condition is detected. These scripts would conform to a safe API, which expose only the functions necessary for this troubleshooting operations.

Given the number or antennas, devices, and monitoring points that the system is required to monitor, scalability is a concern. Scalability needs to be considered both for the data acquisition, which ends with the monitoring data saved in a database, and for the use of this database, which should respond to queries in a reasonable amount of time. The monitoring system can be scaled horizontally by deploying multiple data collection processes, and the application of clustering at the database level.

6 Error Handling

The system must detect and react adequately upon the occurrence of error conditions. The error handling functions will incorporate strategies to improve the system availability, constraining the impact of faults to be as limited as possible. Error handling also plays an important role in improving maintainability, by collecting error information, processing it, and presenting it with the goal of facilitating the task of troubleshooting problems as much as possible.

The system will incorporate one or more messaging channels to propagate detected errors. At the lowest level, error conditions will be detected in the Controller layer. These will be received by their Supervisor, which will apply rules to interpret the received messages. The Supervisor will take reactive actions and will propagate the messages to the upper layers. The messages sent by the Supervisor can aggregate several received messages, perform error analysis, and add additional information. The structure of the error messages will be designed to preserve the original messages while adding information. This is necessary in order to prevent cascading error messages, which can make the identification of the root problem by the operator more difficult.

This pattern of reception, interpretation, encapsulation, and forwarding will be repeated in each layer of the Monitor & Control architecture as error events propagate upwards. Ideally, a single error message should appear in the operator console, clearly specifying the problem and suggesting corrective actions.

In practice, the logic of the error handling system will be based initially on artifacts such as Root Cause Analysis, Fault Mode and Effect Analysis, and other system engineering specifications. As engineering and operations teams develop an understanding of the system, the error handling system will need to incorporate this knowledge in a timely manner. Therefore, it is important to design this part of the system in such a way that it can be easily modified and extended by different groups. After some time, maintenance teams will understand the reasons behind system failures, and operators will become experts on how to recover the system. It is important to define ways for this knowledge to be captured and integrated.

After errors are analyzed by the M&C hierarchy, they will be consumed by a centralized, system-wide error analyzer. This system will apply more extensive algorithms, which can involve not only the instantaneous information collected during the occurrence of the problem, but also data from the monitoring database. The tasks of analyzing the occurrence of an error condition, deducing the root of the problem, and suggesting the course of action is closely related to the task of analyzing monitoring data to predict possible problems, and suggest preventive maintenance actions.

Those two functions could be allocated in the same component, or two different deployments of the same component. This approach is known as Condition-Based Maintenance, which manages maintenance actions based on the condition or state of the elements of a system, applying algorithms for diagnostics (to assess the current condition) and prognostics (to predict the future condition) to increase the effectiveness and decrease the cost of maintenance operations.

7 Time Synchronization

Both the application of commands at the correct time and the timestamping of monitoring data depend on the Supervisory and Controller computers to be synchronized in time. The time synchronization mechanism designed into the system will depend on the precision required in these operations, which are derived from the telescope system requirements.

There are several alternatives: The EVLA relies on the internal clocks of the MIBs and single-board computers, and uses the Network Time Protocol to keep them synchronized. ALMA, on the other hand, locks the real time machines to a timing event coming from a Maser, and sets the absolute time from a GPS. These different schemes (and possibly others) will need to be analyzed and compared against the timing requirements.

For now, the working assumption is that following a synchronization mechanism similar to the EVLA should suffice.

8 Security

The M&C security design will be based on system policies that are yet to be specified. These policies should identify possible vulnerabilities, their probability of occurrence, their impact and the cost of the associated countermeasures. A wide range of possible internal and external threats could affect the M&C system, e.g., intercepting control and monitoring command streams, hacking into the supervisor and controller machines, issuing commands to intentionally corrupt operational databases, etc. The appropriate security level for different parts of the system must be specified before introducing protective measures into the design.

Regarding the antenna deployment, the components belonging to the Supervisor, Controller, and Device layers will be located inside an antenna, while the upper layers will be deployed in the Central Electronics Building. Logical access to antenna networks will be limited via private addressing and filtered to include a designated set of control points. Connections from control points will require an authentication handshake and should support tiered authorization levels for monitor versus control commands.

Monitor & Control communication channels from the Central Building to the Antennas can be uniquely encrypted based on authorization if required. It is less clear whether the communications inside an antenna should be encrypted as well, as accessing these channels would require breaking into the antenna and presumably an alarm system should alert for the intrusion and trigger protective measures. At this time, there is no requirement to encrypt the individual antenna data streams.

Any subsystem which could pose risks to the antenna or human life will have a hardware failsafe to protect against malicious commands.

9 Development and Simulation

The general functionality of an M&C system has much in common with automatic control systems in other industries (e.g., energy, gas, oil, and manufacturing). The project will analyze the suitability of incorporating a third-party framework.

For example, SKA recently selected Tango Controls (http://www.tango-controls.org). ALMA developed the ALMA Common Software (ACS, http://www.eso.org/projects/alma/develop/acs) system, and other telescopes and research facilities have incorporated the Experimental Physics and Industrial Control System (EPICS, https://epics.anl.gov). The use of these frameworks, along with code-generation strategies (it is usually the case that a set of statements must be repeated for each control and monitoring point) can significantly reduce software implementation and maintenance costs.

The project will also develop simulation components early in the development phase in order to facilitate testing and integration activities. Simulation and mocking components will be needed at different levels to test the integration between software components and individual electronic devices, and to test system-level functions.

10 Appendix

10.1 Abbreviations and Acronyms

Acronym	Description
ACS	ALMA Common Software
ALMA	Atacama Large Millimeter-submillimeter Array
CSP	Central Signal Processor
DBE	Digital Back End
DCS	Distributed Control System
DTS	Data Transmission System
EPICS	Experimental Physics and Industrial Control System
EVLA	Expanded Very Large Array (Jansky Very Large Array)
FE	Front End System
GPIO	General Purpose Input Output
GPS	Global Positioning System
IF	Intermediate Frequency
IRD	Integrated Downconverter/Digitizer Module
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C	Monitor and Control
MIB	Module Interface Board
MS	Measurement Set
ngVLA	Next Generation VLA
OPT	Observation Preparation Tool
PBT	Proposal Builder Tool
PHT	Proposal Handling Tool
PST	Proposal Submission Tool
SKA	Square Kilometre Array
TAC	Telescope Allocation Committee
UI	User Interface
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

Monitor and Control Hardware Interface Layer: Preliminary Technical Requirements

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08	2018-11-13	W. Koski	All	Jim Jackson's Block Diagram Alignment
09	2019-04-24	S. Durand	All	Small edits, addressed TBDs
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11	2019-07-23	L. Leyba-Newton	All	Reformatted, added needed requirements, and added clarification/traceability
12	2019-07-24	R. Selina	All	Updated for reference design release
A	2019-07-29	A. Lear	All	Prepared PDF for signatures and release

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 5
3 Overview of the M&C HIL Technical Requirements 5
3.1 Document Outline 5
3.2 General M&C HIL Description 5
4 M&C HIL Functional and Performance Requirements 6
4.1 Functional Requirements 6
4.2 System Monitoring Requirements 7
4.3 Environmental Requirements 7
4.4 Maintenance, Availability, and Reliability Requirements 8
4.5 Lifecycle Requirements 9
4.6 Safety Design Requirements 9
4.7 Electromagnetic Compatibility Requirements 9
5 Documentation Generation and Storage Goals 10
5.1 Technical Documentation 10
5.2 Software and Software Documentation 10
6 Verification and Quality Assurance 11
7 Appendix 13
7.1 Abbreviations and Acronyms 13
7.2 Maintenance Definitions 14
7.2.1 Maintenance Approach 14
7.3 Monitor and Control Maintenance Considerations 14
7.3.1 Introduction 14
7.3.2 Documentation 14
7.3.3 Antenna Recovery 14
7.3.4 Resets: MIB, FPGA, Device Reset and Programming, and Device Power 15
7.3.5 Remote Maintenance Monitoring Instrumentation 15
7.3.6 Reliability Centered Maintenance (Predictive & Preventive Maintenance) 15
7.3.7 Predictive Maintenance 15
7.3.8 Preventive Maintenance 15
7.4 Maintenance Database 16
7.5 Monitor and Control Redundancy 16
7.6 Redundancy Outside of Monitor and Control 16

1 Introduction

1.1 Purpose

This document presents a set of technical requirements for the ngVLA Monitor and Control Hardware Interface Layer (M&C HIL). Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn flow down from the preliminary ngVLA Science Requirements [AD01]. This draft reflects a preliminary analysis of the science use cases and the operations concept, and the flow down recursively to the science, system, and subsystem requirements.

1.2 Scope

The scope of this document is the ngVLA M&C HIL. This consists of the Module Interface Board (MIB), similar to the EVLA Project MIB, and other related M&C HIL sub-boards and line-replaceable units (LRUs). This requirements document establishes the performance, functional, design, and test requirements applicable to the ngVLA M&C HIL.

Because the system touches upon or is part of all equipment in the antenna, sub-buildings, and the central electronics, there will be a high level of collaboration with all other Integrated Product Teams (IPTs) as their requirements will influence the Monitor and Control requirements and vice versa. This document includes interface requirements that need further decomposition in the conceptual design stage.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this technical specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this technical specification, the content of this technical specification shall be considered a superseding requirement.

Ref. No.	Document Title	Rev/Doc. No.
AD01	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD03	System Reference Design	020.10.20.00.00-0001-REP
AD04	System Environmental Specification	020.10.15.10.00-0001-SPE
AD05	System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD06	L0 Safety Requirements	020.10.15.00.00-0004-REQ
AD07	Monitor & Control System: Reference Design Concept	020.50.25.00.00-0002-REQ

2.2 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev/Doc. No.
RD01	Military Handbook, Reliability Prediction of Electronic Equipment	MIL-HDBK-217F
RD02	Non-electronic Parts Reliability Data	NPRD-95
RD03	Electromagnetic Compatibility	IEC 61000-3-5

3 Overview of the M&C HIL Technical Requirements

3.1 Document Outline

The technical requirements of the ngVLA M&C HIL determine the overall form and performance of the M&C HIL. The functional and performance specifications, along with detailed explanatory notes, are found in Section 4. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirements and should guide the verification procedures. In many cases, the notes explain or analyze how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. This makes the required analysis and trade-space available apparent to scientists and engineers who will guide the evolution of the ngVLA M&C HIL concepts. Documentation requirements can be found in Section 5.

Verification and Test requirements, from the conceptual design through to prototype, are described in Section 6. Section 7 (Appendix) contains relevant Monitor and Control maintenance information that informs the requirements of the M&C HIL.

3.2 General M&C HIL Description

The system will consist of an M&C Interface Board (MIB), similar to the EVLA Module Interface Board (MIB), which serves as the core hardware layer interface between the antenna M&C network and devices that need to be monitored and controlled. Additional boards proposed are analog and digital boards to provide flexibility and simplicity when added as part of the user device design. Finally, for M&C itself, antennas will be outfitted with six Line Replaceable Units (LRUs), currently called out as the M500 (Supervisor), M501 (Maintenance), M502 (Five Axis Antenna Control Unit), M503 (Antenna M&C Ethernet Switch), M504 (Weather Station), and M505 (Utility or Environmental). The first four and sixth LRUs are always present on the antennas, while the fifth is for selected remote antennas away from the array core at the VLA site.

The M502 Five Axis controller will likely be provided as part of the antenna contract, but a provision has been left in place for an NRAO-produced unit. Also, the antenna contract may specify use of a NRAO MIB.

The M&C system is an Ethernet fiber-based system that provides a great deal of RFI immunity versus copper connections. Other systems will be utilizing fiber as well throughout the antenna, so the fiber infrastructure will manage the M&C fiber infrastructure as well. Commercial products such as the fiber Ethernet switch are considered a gray area for LRUs. If the switch is easily replaceable by exchanging labeled cables, etc., then it could be considered a LRU. However, if it goes into programming in the field or insertion into a RFI shielded enclosure, it would not be considered a LRU since this would require additional labor at the antenna and a higher-level Tier I support team.

4 M&C HIL Functional and Performance Requirements

These requirements apply to a properly functioning system under operating environmental conditions unless otherwise stated.

4.1 Functional Requirements

Parameter	Req. #	Value	Traceability
Ethernet Interface	MCH0100	The MIB shall provide a high-level Ethernet interface to the M&C system; 1000Base-SX; SFP.	SYS3101
Serial Interface	MCH0101	Device (LRU) driven; CAN, SPI, USB, RS232, RS485, I^2C.	SYS3101
Parallel Interface	MCH0102	Device (LRU) driven; PC104, GPIO.	SYS3101
Device Identification	MCH0103	The MIB shall provide the protocol interfaces to support device identification.	SYS2406, SYS2407, SYS2408, SYS3102, SYS3103
Low-Speed Sampling-Analog	MCH0104	The M&C HIL shall provide analog data to system (screens, archive, etc.); ±10V span; ≥12 bits; <200 kHz.	SYS3101
High-Speed Sampling-Analog	MCH0105	The M&C HIL shall provide the capability of analog data recording, with a high-speed oscilloscope function for remote diagnostics; ±2V span; ≥8 bits; ≥100 MHz.	SYS3105
Digital to Analog Capability	MCH0116	The M&C HIL shall provide a function generator feature for remote and long-term maintenance.	SYS3105
Cross Point Switch-Analog and Digital	MCH0108	The M&C HIL shall provide logic analyzer capabilities for remote & long-term maintenance; inputs/multiple digital paths.	SYS3105
Weather Monitoring: Wind Speed	MCH0109	The M&C HIL shall provide wind speed measurements at each antenna site: W 33 m/s average over 10 min, W ≤40 m/s gust.	SYS2501
Weather Monitoring: Temperture	MCH0110	The M&C HIL shall provide temperature measurements at each antenna site: –20 C ≤T ≤45 C.	SYS2501
Weather Monitoring: Humidity	MCH0111	The M&C HIL shall provide humidity measurements at each antenna site: 0% to 100% RH	SYS2501
Weather Monitoring: Barometric Pressure	MCH0112	The M&C HIL shall provide barometric pressure measurements at each antenna site: 50 to 1100 hPa, ±0.10 hPa.	SYS2501
Weather Monitoring: Precipitation	MCH0113	The M&C HIL shall provide precipitation measurements at each antenna site: 5 cm/hr. over 10 min.	SYSTBD

Parameter	Req. #	Value	Traceability
Safety Weather Monitoring	MCH0114	The M&C HIL shall be designed to have redundant measurements for wind and temperature at each antenna site; ≤1minute periods	SYS2502
Weather Archive	MCH0115	The M&C HIL shall collect and forward, to the archive, weather data from all weather stations at no less than 1-minute periods.	SYS2503

4.2 System Monitoring Requirements

Parameter	Req. #	Value	Traceability
LRU Monitoring	MCH0150	Each LRU shall provide on-board monitoring and diagnostics to determine the health and status of the unit.	SYS3101
LRU Alerts	MCH0151	When an LRU is out of specification, it shall generate a prioritized alert for processing by the operator and maintenance scheduler.	SYS3102
Monitor Archive	MCH0152	Monitor data and alerts shall be archived at variable rates, depending on criticality, for the full life of the instrument. (SYS2801)	SYS3103
Subsystem Monitoring Screens	MCH0153	Engineering consoles shall be provided for all major subsystems.	SYS3104
Fast Read-Out Modes	MCH0154	Fast-read out modes shall be available for remote engineering diagnostics of all LRUs (i.e. an on-board oscilloscope function).	SYS3105

4.3 Environmental Requirements

Parameter	Req. #	Value	Traceability
Temperature-Normal Operating Conditions	MCH0203	The M&C HIL, with environmental conditioning from the Antenna Electronics Environmental Control System, shall have normal operations in the temperature range of: controlled environment (0°C to 60°C) when the system is exposed to the outside environment (–15°C ≤T ≤35°C)	ENV0323
Temperature Rate of Change-Normal Operating Conditions	MCH0204	The M&C HIL, with environmental conditioning from the Antenna Electronics Environmental Control System, shall have normal operations in the temperature rate of change when the system is exposed to the outside environment: 3.6°C/Hr.	ENV0324
Humidity-Normal Operating Conditions	MCH0205	The M&C HIL weather station components that are exposed to the environmental conditions shall be operate in a humidity range of 0% to 100% (non-condensing)	SYSTBD

Parameter	Req. #	Value	Traceability
Altitude-Normal Operating Conditions	MCH0206	The M&C HIL shall be designed to operate at altitudes ranging from sea level to 2500m	ENV0351
Temp-Survivability	MCH0207	The M&C HIL shall survive at a temperature range of $-30°C \leq T \leq 50°C$, non-energized state	ENV0342

4.4 Maintenance, Availability, and Reliability Requirements

Parameter	Req. #	Value	Traceability
Mean Time To Failure	MCH0250	The M&C HIL shall have a MTBF of ≥131,400 Hours	SYS2402
Modulation	MCH0251	The M&C HIL and its subassemblies shall be modularized into Line Replaceable Units (LRUs)	SYS2403
Predictive and Self-Diagnostic Function	MCH0252	The M&C HIL shall provide the required communication interface for antenna system/subsystem to route predictive maintenance and self-diagnosis data.	SYS2405
Configuration Monitoring	MCH0253	The M&C HIL shall provide the required communication interface for antenna system/subsystem to route monitoring and tracking information.	SYS2406
Engineering Console	MCH0254	The M&C HIL shall provide the required communication interface for antenna system/subsystem to route needed information for system status and to assist in real-time diagnosis.	SYS2407
Engineering Database	MCH0255	The M&C HIL shall record monitor data at variable rates for automated use by predictive maintenance programs and for direct inspection by engineers and technicians.	SYS2408
Reliability, Availability, and Maintainability	MCH0400	The M&C HIL shall undergo reliability, availability, and maintainability analysis per MIL-HDBK-217F.	SYS2402

The maintenance and reliability requirements support high-level requirements that limit total array operating cost. Monitor points/sensors should be included in the MTBF/MTTR analysis, but sensors and other components that can be reasonably deemed ancillary to operation may be removed from the determination of compliance with the MTBF requirement. A software failure for which the system can automatically recover is also excluded. "Failure" is defined as a condition that places the system outside of its performance specifications or into an unsafe state, requiring repair. For the M&C HIL, the MTBF must be high as this subsystem is the link between LRUs and the online control system.

A Reliability, Availability, Maintainability analysis shall be performed in order to locate weak design points and to determine whether the design meets the Maintenance and Reliability requirements. The project recommends applying the Parts Count Method for predicting system reliability as described in the MIL-HDBK-217F, but the designer may propose to use other methods. For non-electronic parts, the values of NPRD-95 [AD22] or data from manufacturers or other databases may be used. Another, more time consuming (and considered more accurate) method, the Parts Stress Analysis Prediction, is also described in MIL-HDBK-217F. This may be used if the result of the Parts Count Method does not comply with the Maintenance and Reliability requirements.

ngVLA equipment will typically operate at an elevation of 2200 m above sea level, where temperature and pressure might decrease the MTBF relative to that at low elevations. These conditions shall be taken into specific account in the reliability prediction by using the environmental factor given in MIL-HDBK-217F. The analysis shall result in estimates of the Mean Time to Failures (MTTF) and Mean Time to Repair (MTTR), assuming that any scheduled preventive maintenance is performed.

4.5 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	MCH0300	The M&C HIL shall be designed to be operated and supported for a period of 20 years.	SYS2801
Life Cycle Optimization	MCH0301	The M&C HIL design shall minimize its lifecycle cost for 20 years of operation.	SYS2802

4.6 Safety Design Requirements

Parameter	Req. #	Value	Traceability
Controls for Safe Operations	MCH0350	The M&C HIL shall be designed to allow manual shutoff commands to part of the antenna that are identified as a potential hazard during an emergency and when energized.	SAF0040; SYS2701
Safety Design	MCH0351	The design of the M&C HIL shall incorporate all means necessary to preclude or limit hazards to personnel and equipment during assembly, disassembly, test, and operation.	SAF0042
Subsystem Self-Monitoring	MCH0352	The M&C HIL shall provide the communication interface between the antenna electronic subassemblies and the control center for the purpose system state-of-health monitoring.	SYS2701
IT Security	MCH0353	The M&C HIL shall be designed and operated in accordance with current IT Security best practices as defined by NSF-funded Center for Trustworthy Scientific Infrastructure (https://trustedci.org) and the AUI Cyber Security Policy.	SYS2702

4.7 Electromagnetic Compatibility Requirements

Parameter	Req. #	Value	Traceability
Shielding & Emission Limits	MCH0400	The M&C HIL element shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility).	SYS2106

5 Documentation Generation and Storage Goals

5.1 Technical Documentation

All documentation related to the M&C HIL shall meet the following requirements:

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use metric units.
- Layouts of electronic circuits and printed circuit boards shall also be provided in electronically readable form. The ngVLA preferred formats are Altium Designer files for electronic circuit diagrams and printed circuit board layouts.
- The electronic document formats are Microsoft Word and Adobe PDF.
- The preferred CAD system used is AutoDesk Inventor and/or AutoCAD.

Any deviation from the above shall be agreed to by ngVLA.

5.2 Software and Software Documentation

The M&C HIL software and any other specially developed software are deliverables. The software shall be delivered in source and object form, together with all procedures and tests necessary for compilation, installation, testing, upgrades, and maintenance.

Software must be tagged with suitable version numbers that allow identification (also online remotely) of a release. Software user manuals developed under this specification and for any other commercial software used (controller embedded software, special tools, etc.) shall be provided, along with software maintenance and installation upgrade documentation. Full Test and Acceptance procedures shall be documented.

6 Verification and Quality Assurance

The design may be verified to meet the requirements by design (D), analysis (A), inspection (I), a factory acceptance test (FAT), or a site acceptance test (SAT). The definitions of each are given below.

Verification by Design: The performance shall be demonstrated by a proper design, which may be checked by the ngVLA project office during the design phase by review of the design documentation.

Verification by Analysis: The fulfillment of the specified performance shall be demonstrated by appropriate analysis (hand calculations, finite element analysis, thermal modeling, etc.), which will be checked by the ngVLA project office during the design phase.

Verification by Inspection: The compliance of the developed item is determined by a simple inspection or measurement.

Verification by Factory Acceptance Test: The compliance of the developed item / assembly / unit with the specified performance shall be demonstrated by tests. A FAT is performed without integration with interfacing systems.

Verification by Site Acceptance Test: The compliance of the developed item / assembly / unit with the specified performance shall be demonstrated by tests. SAT is performed on-site with the equipment as installed.

Multiple verification methods are allowed.

The following table summarizes the expected verification method for each requirement.

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
MCH0100	Ethernet Interface	*				
MCH0101	Serial Interface	*				
MCH0102	Parallel Interface	*				
MCH0103	Device Identification					*
MCH0104	Low-Speed Sampling-Analog				*	
MCH0105	High-Speed Sampling-Analog				*	
MCH0106	Digital to Analog Capability				*	
MCH0107	Programmable I/O Bits-Digital				*	
MCH0108	Cross Point Switch-Analog and Digital				*	
MCH0109	Weather Monitoring-Wind Speed				*	
MCH0110	Weather Monitoring-Temp				*	
MCH0111	Weather Monitoring-Humidity				*	
MCH0112	Weather Monitoring-Barometric Pressure				*	
MCH0113	Weather Monitoring-Precipitation				*	
MCH0114	Safety Weather Monitoring				*	
MCH0115	Weather Archive				*	
MCH0150	LRU Monitoring					*
MCH0151	LRU Alerts					*
MCH0152	Monitor Archive					*
MCH0153	Subsystem Monitoring Screens				*	
MCH0154	Fast Read-Out Modes					*

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
MCH0202	Humidity-Precision Operating Conditions				*	
MCH0203	Temperature-Normal Operating Conditions				*	
MCH0204	Temperature Rate of Change-Normal Operating Conditions				*	
MCH0205	Humidity-Normal Operating Conditions				*	
MCH0206	Altitude-Normal Operating Conditions				*	
MCH0207	Temp-Survivability				*	
MCH0250	Mean Time To Failure		*			
MCH0251	Modulation			*		
MCH0252	Predictive and Self-Diagnostic Function					*
MCH0253	Configuration Monitoring					*
MCH0254	Engineering Console					*
MCH0255	Engineering Database					*
MCH0400	Reliability, Availability, and Maintainability		*			
MCH0300	Design Life		*			
MCH0301	Life Cycle Optimization		*			
MCH0350	Controls for Safe Operations					*
MCH0351	Safety Design		*			
MCH0352	Subsystem Self-Monitoring					*
MCH0353	IT Security		*			
MCH0400	Shielding & Emission Limits				*	

Table 1 - Expected requirements verification method.

7 Appendix

7.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
CoDR	Conceptual Design Review
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
EIRP	Equivalent Isotropic Radiated Power
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMP	Electromagnetic Pulse
FDR	Final Design Review
FEA	Finite Element Analysis
FOV	Field of View
FWHM	Full Width Half Max (of Primary Beam Power)
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LO	Local Oscillator
LRU	Line Replaceable Unit
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
ngVLA	Next Generation VLA
PDR	Preliminary Design Review
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares
RTOS	Real-Time Operating System
RTP	Round Trip Phase
SAC	Science Advisory Council
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
VLA	Jansky Very Large Array

7.2 Maintenance Definitions

7.2.1 Maintenance Approach

Required maintenance tasks shall be minimized. Maintenance shall be mainly performed at assembly and subassembly level by exchange of Line Replaceable Units (LRUs). LRUs are defined as units that can be easily exchanged (without extensive calibration, of sufficient low mass and dimension for ease of handling, etc.) by technician-level maintenance staff. LRU exchange shall be possible by two trained people within four working hours. It is desirable that LRU replacement be possible using only standard tools identified in a maintenance manual for the M&C HIL. A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

LRUs shall be defined by the M&C HIL designer, depending on the design. The LRUs will be maintained by the ngVLA project (with or without industrial support).

7.3 Monitor and Control Maintenance Considerations

7.3.1 Introduction

Maintenance for 263 or more ngVLA antennas will be complex especially given the proposed requirement of only a one visit/year for antennas. The maintenance approach to the antenna may impose monitoring and control requirements on the M&C HIL. These broader maintenance considerations are explored in this section.

7.3.2 Documentation

General documentation will be stored at each antenna for network loss. Specific documentation will be stored at each antenna or device for network loss. When a MIB or device is exchanged, all specific information will be either pre-loaded or loaded automatically into the antenna or device. Specifically, this includes any module firmware such as FPGAs updates, and MIB software updates.

7.3.3 Antenna Recovery

Automatic recovery is preferable to restore operation after failure due to external events. Full recovery (cold startup) usually follows a major power event. The antenna is placed into a safe position (stowed). Once communications are reestablished with the operational center, critical observational devices (HVAC, Dewar vacuum, cryogenics, etc.) are powered up based upon last antenna status, then non-critical devices are powered up.

The antenna must next establish timing synchronization to the array. The antenna self-tests at the antenna/device level, and self-testing continues until last antenna statuses match and receivers are operational. Operations staff conduct external/internal visual/aural inspection during self-testing. The antenna joins the calibration array automatically (preferred) or via Operations, and once calibrated it transfers to the observational array automatically (preferred) or via Operations.

Recovery (warm startup) usually follows an antenna temporary protective event such as high winds, extreme cold, etc. The antenna self-tests at the antenna/device level during the event, and after the event Operations staff conduct external/internal visual/aural inspection by operations. The antenna joins the calibration array automatically (preferred) or via Operations, and once antenna calibrated it transfers to the observational array automatically (preferred) or via Operations.

Complex maintenance (yearly checkup) would be full recovery (most likely) or recovery once personnel clears. Simple maintenance (repair) would be recovery (most likely) or full recovery (for critical observation devices) once personnel clears.

7.3.4 Resets: MIB, FPGA, Device Reset and Programming, and Device Power

Each MIB shall be individually resettable and remotely programmable. Device and FPGA program reset shall occur via MIB and/or via MIB reset, if applicable. FPGA and FPGA support memory shall be programmable via MIB. Devices should be capable of being individually remotely powered up or down.

7.3.5 Remote Maintenance Monitoring Instrumentation

- Oscilloscope ≥100 MHz sampling
- Logic analyzer/logic stimulator ≥100 MHz sampling; number of logic probes: TBD.
- Spectrum analyzer: requirements TBD.
- Signal generator: requirements TBD.

7.3.6 Reliability Centered Maintenance (Predictive & Preventive Maintenance)

Reliability centered maintenance (RCM) includes predictive maintenance (AKA condition monitoring) and preventive maintenance. This technique mainly relies upon conditional monitoring that would achieve just-on-time array-wide observing for ngVLA.

7.3.7 Predictive Maintenance

To evaluate equipment condition, predictive maintenance utilizes non-destructive measurement technologies such as infrared, acoustic including ultrasonic and sound level, visual, vibration, and other specific online testing. When the instrumentation feature is not being used by maintenance personnel, it would be processing conditions at the antenna for each device. Coupling these equipment measurements with measurements of observational performance would link antenna astronomical performance to equipment maintenance.

7.3.7.1 Predictive Maintenance Methods

Remote visual inspection provides a cost-efficient primary assessment. Essential information and defaults can be deduced from the external and endoscopic examinations. Good lighting is essential.

Vibration analysis is most productive on high-speed rotating equipment and can be the most expensive and difficult component to analyze. Vibration analysis, when properly done, allows the user to evaluate the condition of equipment to avoid failures.

Acoustical analysis can be done on a sonic or ultrasonic level. Ultrasonic techniques for condition monitoring make it possible to hear friction and stress in rotating machinery, as they produce distinctive sounds in the upper ultrasonic range that can predict deterioration faster than conventional techniques.

Sonic level monitoring is less expensive, but it also has fewer uses than ultrasonic technologies. Sonic technology is useful only on mechanical equipment, while ultrasonic equipment can detect electrical problems and is more flexible and reliable in detecting mechanical problems.

Infrared monitoring and analysis has the widest range of application (from high-speed to low-speed equipment), and is effective for spotting both mechanical and electrical failures and is considered to be a cost-effective technology. Model based condition monitoring for motors involves spectral analysis on the motor's current and voltage signals and then compares the measured parameters to a known and learned model of the motor to diagnose various electrical and mechanical anomalies.

7.3.8 Preventive Maintenance

Preventive maintenance uses average or expected life statistics to predict when maintenance will be required. Any planned preventive maintenance shall be documented in the Maintenance Manual.

7.3.8.1 *Preventive Maintenance Methods*

Oil analysis occurs offline and may require years to become effective. Basically, it can be thought of as used oil analysis and wear particle analysis. Used oil analysis determines the condition of the lubricant itself for both quality and suitability. Wear particle analysis determines the mechanical condition of machine components that are lubricated. Wear particle analysis allows identification of the composition of the solid material present and evaluation of particle type, size, concentration, distribution, and morphology.

Periodic calibration and maintenance would occur annually. An example for periodic calibration is COTS instrumentation such as weather instrumentation that requires yearly calibration to maintain performance specifications. An example for periodic maintenance is yearly lubricant replacement such as oil or grease, which would include sampling for later analysis.

7.4 Maintenance Database

While predictive and preventive maintenance begins with a robust M&C system to provide the best possible information, it ends at a Computerized Maintenance Management System (CMMS). This system would evaluate the status of a particular antenna to the device or object level, then write up a maintenance form for an issue that needs attention as soon as possible or create a punch-list item for the next antenna maintenance visit. The form would include information such as the azimuth, elevation, observation being run, temperatures, visual, aural, the device or object in question, and the detected issue. For the punch-list situation, gathering further information can help correlate the issue with other influencing factors such as antenna position or temperature to point personnel to the probable cause at the antenna or when the device is in for repair.

The importance of the CMMS can be viewed from an extreme thought experiment case: All 263 antennas have 10 random fault conditions at the same time. The CMMS would prioritize each antenna's condition for observational impacts, then provide that information to the operations staff, instead of having 2,630 faults vying for operations staff attention to sort priorities and observational impacts.

7.5 Monitor and Control Redundancy

Redundancy for the ngVLA within the M&C is limited, as having two MIBs in every device is not practical. However, an exception may be the M500 M&C Supervisor module, which can be viewed as equivalent to the VLBA Control Computer. Having two high-level MIBs able to operate the antenna reduces single-point failure. Also, when both MIBs are operational, the operational tasks can be subdivided between them for efficiency. Only when one fails does the other take up the full task load at a lessened efficiency level. This loss of efficiency will not compromise the observation.

7.6 Redundancy Outside of Monitor and Control

The current block diagram does not indicate devices that require redundancy. Therefore, each IPT group designer will have to determine if redundancy is required for their devices and how it can be provided.

Monitor & Control Hardware Interface Layer: Reference Design Description

020.30.45.00.00-0004-DSN-A-MCHIL_REF_DESIGN

Status: **RELEASED**

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Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 5
2.1 Applicable Documents 5
2.2 Reference Documents 5
3 Overview: Monitor and Control Devices by Location 6
3.1 Subsystem Block Diagram 6
3.2 Antenna Front End Enclosure Device Possibilities 8
3.2.1 Front End Interface Devices 8
3.2.2 Local Oscillator Devices 8
3.2.3 IRD Devices 9
3.2.4 Power Supply Devices 9
3.3 Pedestal Enclosure Device Possibilities 9
3.3.1 DBE/DTS Devices 9
3.3.2 Local Oscillator Devices 9
3.3.3 Monitor and Control Devices 9
3.3.4 Power Supply Devices 10
3.4 Interfaces with Other Subsystems 10
4 Appendix 11
4.1 Monitor and Control Amounts and Cost 11
4.2 Interface Boards 12
4.3 Abbreviations and Acronyms 13

1 Introduction

1.1 Purpose

This document provides a description for the Monitor and Control Hardware Interface Layer (M&C HIL) subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the entire design of the M&C HIL subsystem as part of the ngVLA Reference Design. It includes the subsystem's design, how it functions, and interfaces with the necessary hardware and software systems. It does not include specific technical requirements or budgetary information.

This document is to define the design description for the M&C at the hardware layer or level. This document will define the ngVLA project deliverable as an in-house designed Module Interface Board (MIB), similar to the EVLA project MIB. Because the system touches upon or is part of all equipment in the antenna, possible sub-buildings, and the main central control building, there must be a high level of collaboration between all other Integrated Product Teams (IPT) as their requirements will influence the M&C requirements and vice-versa.

In the Appendix, Figure 3 depicts the EVLA MIB and Figure 4 depicts the companion analog to digital board as visual examples.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	ngVLA System Requirements	020.10.15.10.00-0003-REQ
AD03	System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD04	Environmental Specification	020.10.15.10.00-0001-SPE
AD05	System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ

2.2 Reference Documents

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK
RD02	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK

3 Overview: Monitor and Control Devices by Location

The term *device* represents a physical device such as a LRU or other hardware unit that is to be monitored and controlled. A *MIB device* has an internal MIB providing all M&C functions taking place within the device. A *satellite device* type has interface circuitry to which an external MIB device communicates. A *high-level device* has higher requirements, especially for storage and computational power.

An example of a MIB device is the L502 whose MIB is connected to an analog board and a FPGA inside the device. Some examples of satellite devices are the T501 through T513, which linked to the F523 MIB device via serial communications. An example of a high-level device is the M500 Supervisor, which has higher storage and computational capacity necessary to carry out its functions.

3.1 Subsystem Block Diagram

Figure 1 and Figure 2 show the Monitor and Control Subsystem block diagrams for the interface protocol identification and the routing scheme plan.

Two antenna locations contain equipment requiring MIB devices: the Front End Enclosure and the Pedestal Enclosure. Table 1 lists all devices at the Front End location, and ngVLA Document #020.30.00.00.00-0002-BLK [RD01] presents a block diagram of the Front End Enclosure. Table 2 lists all devices at the Pedestal location, and ngVLA Document #020.30.00.00.00-0003-BLK [RD02] presents a block diagram of the Pedestal Enclosure.

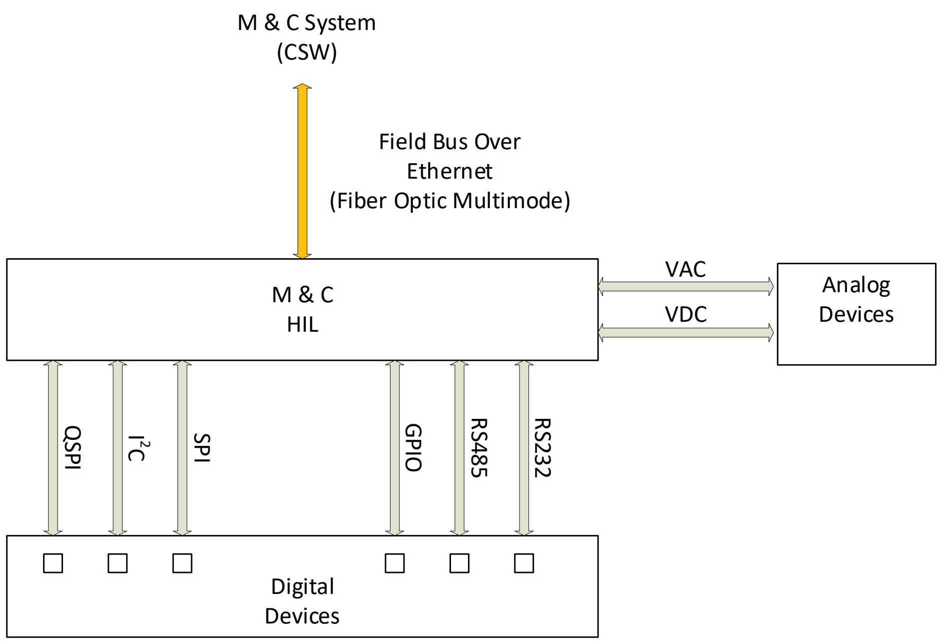

Figure 1 - Monitor & Control system interface protocol plan. The M&C HIL interfaces to analog and digital devices over a wide variety of protocols, while providing a single field bus over Ethernet interface to the M&C software system.

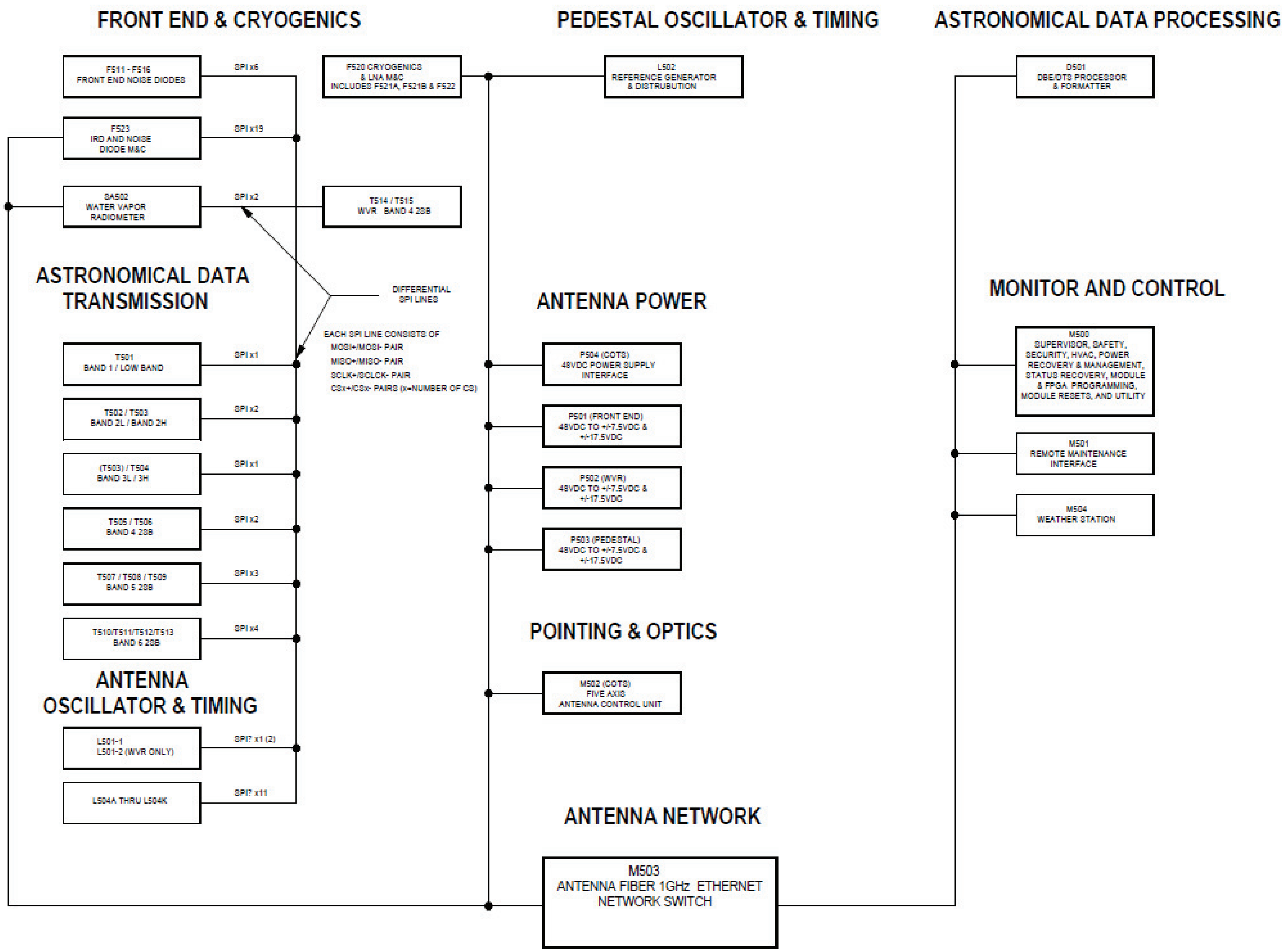

Figure 2 - Monitor & Control system routing scheme diagram for ngVLA reference array at the hardware layer. ngVLA Document #020.30.45.00.00-0001-BLK shows the diagram at full size.

3.2 *Antenna Front End Enclosure Device Possibilities*

Device	Description	Type	Quantity	Notes
F511–F516	Noise Diode	Satellite	6 (SPI)	F523 Satellites
F520	Cryo and LNA M&C	High-Level	1	Satellites out to F521A, F521B, & F522
F521A	Dewar A Cryogenics Driver	Satellite	1	F520 Satellite
F521B	Dewar B Cryogenics Driver	Satellite	1	F520 Satellite
F522	Vacuum Pump Driver	Satellite	1	F520 Satellite
F523	IRD & Noise Diode M&C	MIB	1	Satellites out to F511–F516, L501-1, (L501-2), L504 & T501–T513
L501-1, L501-2	LO Reference & Sample Clock Generator	Satellite	1 (2)	F523 Satellite (L501-2) Only for WVR Antennas
L504-A–K	LO Generators	Satellite	11	F523 Satellite
T501, T502	BAND 1 IRD Device BAND 2 IRD Device	Satellite	2 (SPI)	F523 Satellites
T503	BAND 2/3 IRD Device	Satellite	1 (SPI)	F523 Satellite
T504	BAND 3 IRD Device	Satellite	1 (SPI)	F523 Satellite
T505, T506	BAND 4 IRD Device BAND 4 IRD Device	Satellite	2 (SPI)	F523 Satellites
T507–T509	BAND 5 IRD Device	Satellite	3 (SPI)	F523 Satellites
T510–T513	BAND 6 IRD Device	Satellite	4 (SPI)	F523 Satellites
SA502	Water Vapor Radiometer	MIB	1	Only for WVR Antennas
T514, T515	WVR BAND 4 IRD Device	Satellite	2 (SPI)	Only for WVR Antennas SA502 Satellites
P501	Power Supply	MIB	1	
P502	Power Supply	MIB	1	Only for WVR Antennas

Table 1 - Front End enclosure M&C device list.

3.2.1 Front End Interface Devices

The F520 has a high-level MIB and is responsible for biasing the low noise amplifiers for Bands 1–6. It also has the cryogenic system control for satellite LRUs: Dewar A Cryogenics Driver (F521A), Dewar B Cryogenics Driver (F521B), and Vacuum Pump Driver (F522).

The F523 IRD & Noise Diode M&C LRU monitors and controls IRD LRUs (T501–T513) and Noise Diode LRUs (F511–F516) for Bands 1–6 via 19 SPI interfaces. The L501 (-1,-2) LO Reference & Sample Clock Generators and L504 (-A–K) LO Generators are satellites as well, but their 12 to 13 interfaces have not been established (they will likely be SPI).

The SA502 is similar to the F523 but is only on selected antennas that have the water vapor radiometer (WVR) installed. It contains two SPI interfaces for the IRD LRUs T514 and T515. Its temperature control subsystem keeps IRD LRUs T514 and T515 at a controlled, stable temperature. Note that for the final design there may be a WVR for each antenna, this drives only needing the F523.

3.2.2 Local Oscillator Devices

The L501-1 and L501-2 (only if WVR is installed) are LO Reference and Sample Clock Generators. The L504 (-A–K) LO Generators are satellite LRUs to the F523 LRU.

3.2.3 IRD Devices

The T501 through T513 LRUs and the optional WVR T514 & T515 LRUs sample RF astronomical information at high speed and convert it to the digital stream sent on fiber to the D500. On each T5XX device is a serial peripheral interface (SPI) connected to the F523 or the SA502 on copper differential signal lines. Normally SPI consists of master out/slave in (MOSI), master in/slave out (MISO), serial clock (SCLK), and either none, one, or multiple low true chip select (CS*) lines. For the T501 through T513 alone, this would mean 78 (none), 104 (one), or 208 (multiple assuming five CS* lines) copper connections.

3.2.4 Power Supply Devices

The P501 and P502 power supply devices have a MIB and analog board.

3.3 *Pedestal Enclosure Device Possibilities*

Device	Description	Type	Quantity	Notes
D501	DBE/DTS Device	High-Level	1	
L503	Reference Receiver, Generator, & Distribution Device	MIB	1	
M500	Supervisor Device	High-Level	1	Single point of failure
M501	Maintenance Device	High-Level	1	M500 redundancy?
M502	Five Axis Control Device	High-Level	1	COTS device? MIB added
M503	Ethernet Fiber Switch	High-Level	TBD	COTS device; M&C included
M504	Weather Station Device	MIB	1	For weather station antennas only. Satellites to instruments via RS232
M505	Utility LRU	MIB	1	–48VDC power supply, HVAC, etc.
P503	Pedestal Power Supply	MIB	1	
P504	48VDC Power Supply	MIB	1	COTS device; M&C included

Table 2 - Pedestal Enclosure M&C device list.

3.3.1 DBE/DTS Devices

The D501 DBE/DTS LRU uses a high-level MIB that will monitor and control the Polarization A and B processing devices for astronomical data needs. These include clock recovery & aligner, channelization, RFI, quantization, future digital, internal routing fabric, and Ethernet formatter. The high-level MIB connects to its own FPGA, which in turns provides SPI and JTAG connections for each polarization device. It must store all functional data routing, processing codes, and formats for the various data transmission methodologies.

3.3.2 Local Oscillator Devices

The L503 Reference Receiver & Generator and Distribution LRU has a MIB and analog board that includes a FPGA interface for its functionality.

3.3.3 Monitor and Control Devices

The M500 Supervisor LRU has a high-level MIB and this device has the following functional capabilities beyond the Supervisor role: safety, security, HVAC, power recovery and management, and status recovery. The M500 presents a single-point-of-failure risk, so redundant functionality is desirable.

The M501 Remote Maintenance Interface LRU has a high-level MIB and is a candidate for M500 redundancy, provided the redundancy requirement requires separation. With 263 ngVLA antennas proposed, remote maintenance will be essential to determine issues that affect the array's ability to carry out scientific observations. It may be part of the M&C system as in the original VLA design, with two monitor streams: one used by the operating system, the other devoted to maintenance and under technical staff control. This device would stream complex information to remote users monitoring a situation via oscilloscope, spectrum analyzer, logic analyzer, and signal generator. It could also include visual and aural capabilities to determine unusual sounds and, upon detection, activate a robotic camera (or even a drone) to examine the antenna and transmit information for maintenance, safety, and security.

The M502 Four-Axis Antenna Control Unit (ACU) and focus translation mount (FTM) device has a high-level MIB interface. As this is considered a COTS device provided by the antenna manufacturer, NRAO may have to contractually make the high-level MIB chosen by NRAO identical to the one in this device, otherwise this MIB will be unique.

The M503 Ethernet Switch device is COTS and has a high-level MIB with a unique design. It currently specifies 32 fiber connections to the Ethernet switch at 1 GHz. However, the connections do not account for local maintenance ports for laptops, test equipment, LabVIEW, etc., so 40–48 is a reasonable range for Ethernet switch port connections.

The M504 Weather Station device uses a MIB or high-level MIB to monitor weather conditions at the antenna, especially for remote antennas located distantly from the core. Not every antenna would necessarily have a weather station; rather, antennas would be chosen that could manage an array cluster group. The station sensors would measure temperature, dew point, and barometer, mounted on the dish backside to be level with or higher than the feeds as the antenna tracks, or on a fold-over tower. On the tower would be wind speed and wind direction, making it very light as these instruments add little weight.

The M505 Utility uses a MIB analog board that would monitor Antenna environment and provide environmental controls.

3.3.4 Power Supply Devices

The P503 Power Supply device uses a MIB and analog board.

The P504 has a MIB and analog board to monitor and control the –48V DC power supply subsystem. This COTS device may have a built-in M&C interface, which like the M503 would be unique.

3.4 Interfaces with Other Subsystems

The M&C HIL stands between the network and the subsystem devices. Therefore, the ICD for the network side uses standard Ethernet protocols such as TCP/IP, UDP, ICMP, RDP, 3PC, etc. However, the Ethernet standards do not preclude NRAO from devising their own in-house protocols.

For the sub-system devices, the MIB will provide interfaces such as PC104, 3-Wire SPI, 4-Wire SPI, QSPI, I^2C, GPIO, RS232, RS485, etc. Once the interfaces for the MIB have been determined, the ICD would indicate what is available, while the sub-system ICD will determine interface choice(s) and how it will use them. This includes deviations from best practices and any specialized protocols for message or data transmissions.

4 Appendix

4.1 Monitor and Control Amounts and Cost

The 15-year budget for the M&C HIL (020.30.15.00.00-0003-BUD) bases total cost for the MIB and analog boards on the known NRE and production costs during the EVLA project, adjusted for inflation. The digital card cost was based on the current cost for a similar card that was developed for the EVLA WVR project.

The cost of satellite cards, which may not fall under the purview of M&C, is an estimation. The high-level MIB cost is based upon the Advantech PCM-3365EW-S9A1E, a commercial PC104 board having maximum solid state storage and additional memory added.

LRU costs are based on recent quotations for metalwork machining, combined with the high-level MIB cost above, except for the M504 which assumes usage of the standard MIB combined with a lower quantity requirement of 55 M504s.

4.2 *Interface Boards*

EVLA designs requiring M&C have a main board with an area for the connectors and mounting holes needed to place the analog board and/or the module interface board (Figure 3) upon it. This provides an adaptable system such that if no analog board is needed, the designer installs only the MIB. If needed, the analog board (Figure 4) is installed onto the main board first, then the MIB is placed on the analog board.

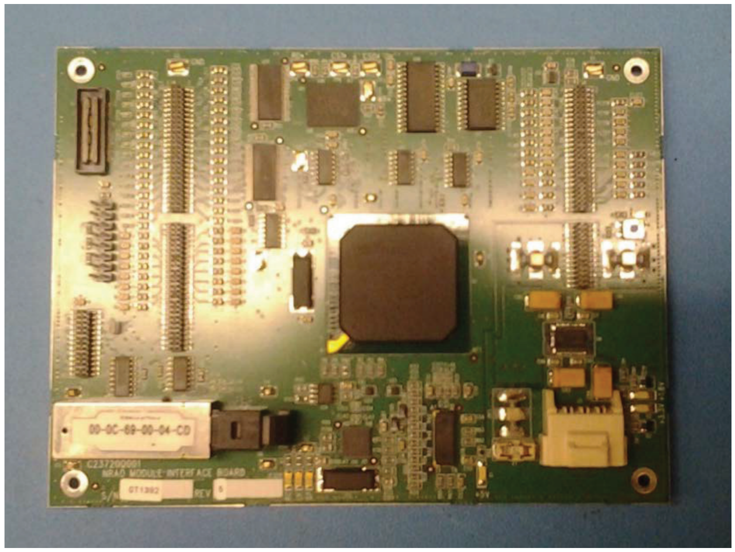

Figure 3 - EVLA module interface board.

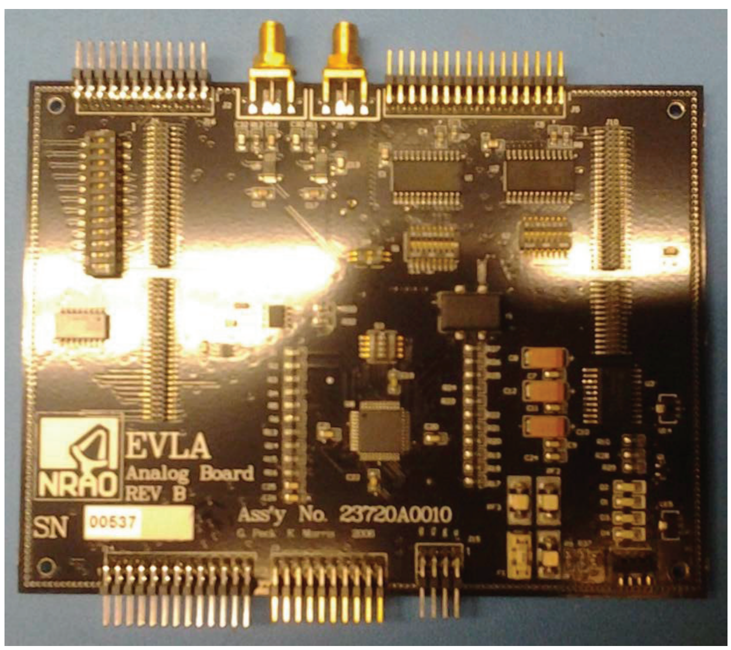

Figure 4 - EVLA analog board.

4.3 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
DBE	Digital Back End
DTS	Data Transmission System
IF	Intermediate Frequency
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C, M/C	Monitor and Control
M&C HIL	Monitor and Control Hardware Interface Layer
MIB	Monitor & Control Interface Board
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NSF	National Science Foundation
PLL	Phase Locked Loop
RD	Reference Document
RF	Radio Frequency
TBD	To Be Determined
VLA	Karl G. Jansky Very Large Array
WVR	Water Vapor Radiometer

Long Haul Fiber Workgroup Preliminary Report

020.60.00.00.00-0002-REP-A-LONG_HAUL_FIBER_WORKGROUP_REPORT

Status: **RELEASED**

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Table of Contents

1 Project Introduction 3
1.1 Scope of this Document 3
1.2 Applicable Documents 3
2 Fiber Workgroup Summary 4
3 Fiber Workgroup Membership 6
4 Design Assumptions 7
5 Recommendations 8
6 Budget Model 9
7 Identified Risks 9
8 Appendix 10
8.1 ngVLA Long Haul Fiber Costing Model 10
8.2 Acronyms and Abbreviations 11

1 Project Introduction

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

The facility will be operated as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products; automated pipelines will calibrate raw data and create higher-level data products (typically image cubes). Data and quality assured data products will be 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 user institutions.

The array signal processing center will reside 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. LBA stations will be located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

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

1.1 Scope of this Document

The ngVLA Long-Haul Fiber Work Group (FWG) was charged with providing a Reference Design for the long-haul fiber and associated connectivity needs of the Mid-Baseline (MB) stations and the Long Baseline Array (LBA). The Mid-Baseline stations refer to all Main Array antennas outside the spiral arm structure on the Plains of San Agustin. This work intersects with several other work packages that are described in [AD02] through [AD09].

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 System Reference Design	020.10.20.00.00-0001-REP
AD02	Array Configuration: Preliminary Requirements	020.23.00.00.00-0001-REQ
AD03	Array Configuration: Reference Design Description	020.23.00.00.00-0002-DSN
AD04	Digital Back End & Data Transmission System: Preliminary Requirements	020.30.25.00.00-0001-REQ
AD05	Digital Back End & Data Transmission System: Reference Design	020.30.25.00.00-0002-DSN
AD06	LO Reference and Timing: Preliminary Requirements	020.35.00.00.00-0001-SPE
AD07	LO Reference and Timing: Reference Design	020.35.00.00.00-0002-DSN
AD08	Computing & Software Systems: Reference Design Architecture	020.50.00.00.01-0002-REP
AD09	Buildings & Array Infrastructure Reference Design Study	020.60.00.00.01-0002-REP

2 Fiber Workgroup Summary

The ngVLA Long-Haul Fiber Work Group (FWG) was charged with providing a Reference Design for the long-haul fiber and associated connectivity needs of the Mid-Baseline (MB) stations and Long Baseline Array (LBA). The current ngVLA design calls for 168 antennas within the core and spiral arms of the Main Array connected with trenched fiber, in addition to the 19 antennas of the Short Baseline Array (SBA). The Mid-Baseline stations are the 46 Main Array antennas beyond the spiral arms on the Plains of San Agustin. An additional 30 antennas will make up the Long Baseline Array, for a total of 263 ngVLA antennas.

The 46 antennas located at the MB stations will extend approximately 800 km from the core. The Working Group identified a 300 km radius from the core as being the maximum extent to which dark fiber would be practical for local oscillator (LO) and timing reference propagation (Figure 1, shown in green). To formulate a construction and operations model, it is proposed that stations within this radius be connected using a daisy-chain architecture for dark fiber connectivity (shown in red). This allows for LO and data signal regeneration since all station links within this radius are less than the 80 km maximum for unrepeated signal propagation.

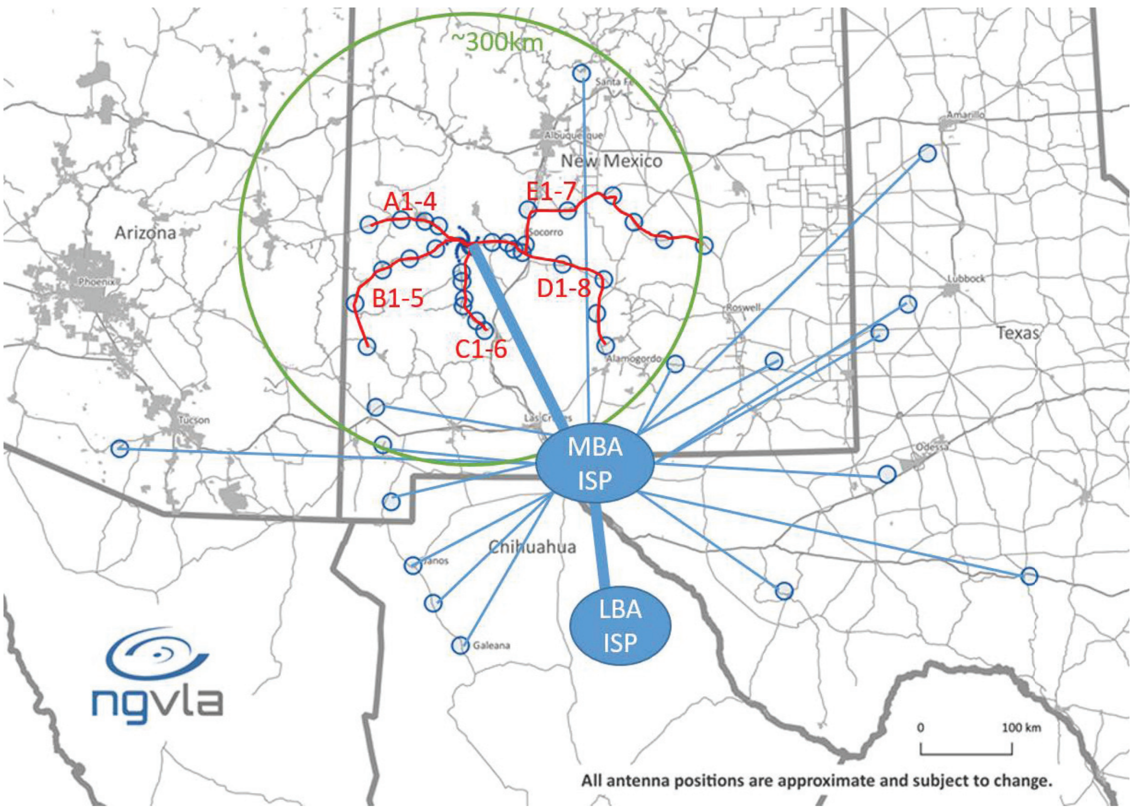

Figure 1 - ngVLA Main Array [AD03]. Approximately 168 antennas are located on the Plains of San Agustin, and 46 antennas are outside the five-spiral-arm configuration.

As Figure 1 shows, stations beyond this radius (currently 16), as well as the 30 antennas associated with the Long Baseline Array (LBA), will be serviced via a strategic partnership with an Internet Service Provider (ISP). LO and timing references for these stations must be provided by local references [AD06, AD07].

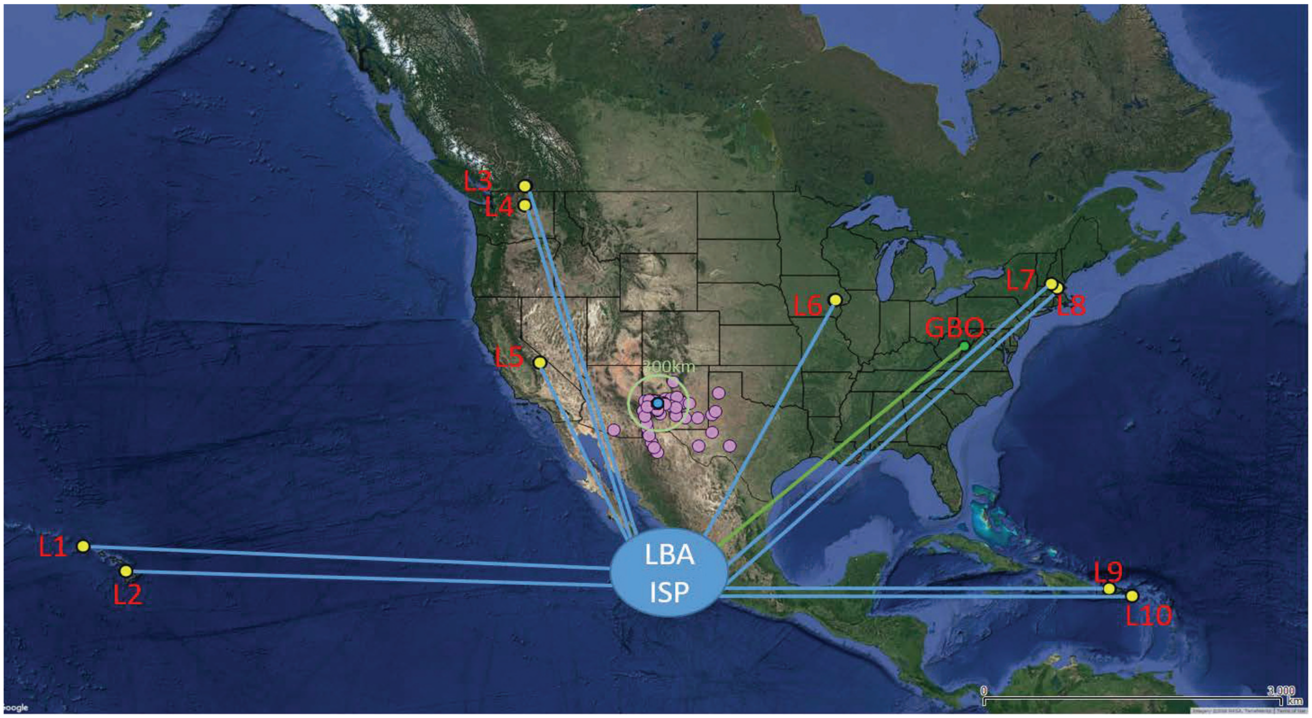

Figure 2 - ngVLA LBA sites are shown in yellow, GBT site in green, and ngVLA SBA and Main Array in blue and purple respectively. The configuration includes 30 LBA antennas, distributed per the table below [AD03].

# of Antennas	Location	Possible Sites
3	Puerto Rico	Arecibo Observatory.
3	St. Croix	Existing VLBA site.
3	Kauai, Hawaii	Kokee Park Geophysical Observatory.
3	Hawaii, Hawaii	New site.
2	Hancock, NH	Existing VLBA site.
3	Westford, MA	Haystack Observatory.
2	Brewster, WA	Existing VLBA site.
3	Penticton, BC	Dominion Radio Astrophysical Observatory.
4	North Liberty, IA	Existing VLBA site.
4	Owens Valley, CA	Existing VLBA site.

Table 1 summarizes the connectivity arrangement envisaged by the Working Group.

Sub-Array	# of Antennas	Antenna Diameter	Trenched Fiber	Commercial Fiber—Dark	ISP	Distance from Array Center
MA: Core	94	18m	94	0	0	0–1 km
MA: Spiral Arms	74	18m	74	0	0	1–30 km
Mid-Baseline	46	18m	0	30	16	30–1000 km
Main Array Total	**214**		**168**	**30**	**16**	
SBA	19	6m	19	0	0	0.1 km
LBA	30	18m	0	0	30	1050–5300 km
ngVLA Total	**263**		**187**	**30**	**46**	

Table 1 - ngVLA configuration by antenna number and type, fiber network connection, and distance from array center.

The ngVLA data rates are substantial, with individual antennas outputting 320 Gbps each. However, *these data rates can be accommodated with present technology*, even over the ISP links. The technical risk associated with this approach is low, with the uncertainty being in the cost estimate and the likely cost scaling that can be expected from today to the start of early science operations in 2028, and full operations by 2035.

3 Fiber Workgroup Membership

The ngVLA FWG membership is selected to provide broad expertise and representation of interests in ngVLA network infrastructure, utility system construction, data transmission, and frequency reference transmission. The number of people serving on the FWG is not set. The FWG is overseen by a chair who is responsible for coordinating the group's activities.

FWG members currently include:

- David Halstead (Chair)
- Viviana Rosero (Array Configuration)
- Alan Erickson (GIS Database)
- Jim Jackson (Data Transmission System)
- Bill Shillue (Time & Frequency Distribution)
- Christophe Jacques (Time & Frequency Distribution)
- Omar Ojeda (Central Signal Processor)
- Kevin Baker (Array Infrastructure)
- Chris Langley (Array Infrastructure)
- Jody Bolyard (Land Acquisition & Reg. Compliance)
- Derek Hart (Lead Network Administrator)

Additional members will be added based on suggestions from the Project Director or the Chair.

Ex-Officio members include:

- Rob Selina (ngVLA Project Engineer)
- Rafael Hiriart (ngVLA Software & Computing IPT Lead)

4 Design Assumptions

The following assumptions are inherent in the proposed design.

- Data will be transmitted over 100 Gbps IPv6 streams employing standard protocols such as UPD (no guarantee of delivery) or TCP (re-transmit of lost packets) depending on data profiles.
- Packet size will be maximized (~64 KB).
- Data streams will be multiplexed via wavelength separation to improve fiber utilization: 800 Gbps is the current norm for an individual long-haul single mode fiber.
- The maximum unrepeated fiber distance for LO timing and 100 Gbps Ethernet is 80 km.
- Dark fiber will be provisioned over 24-strand single-mode fiber using ZX (or equivalent) optics.
- Fiber is trenched for the main array central cluster and spiral arms, and for the small baseline array. For commercial fiber in the mid-baseline array, existing commercial fiber infrastructure will be used where available, either buried or pole strung (usually in place for power distribution).
- Current costs for 10 Gbps network technology will approximate to 100 Gbps technology in eight to ten years (a conservative Moore's Law projection).
- The model assumes that each single-mode fiber strand can carry 800 Gbps of data.
- No replacement funds are allocated beyond warranty maintenance for addressing hardware failure during construction.
- Maximum data rate from any single antenna is 320 Gbps, requiring four 100-Gbps circuits.
- LO reference signals require dark fiber reserved in each bundle for "home-run" strands to the central time source (using passive signal regeneration at every 80 km or less). This requires bidirectional transmission.
- The model includes no LO components other than the fiber.
- Post-correlation data will flow to a national data center for processing and archiving with a maximum data rate of 800 Gbps.
- The correlator has ~250 ms of delay tolerance from station send to receive, which implies that lost or out-of-sequence packets will not be viable.
- The MB station fiber network topology is not provisioned as fiber loops, meaning only a single path exists for any given source. This has the advantage of simplifying the network hardware (no IP routing) but will impact availability (see risks).
- Each of the 30 LBA stations (distributed between 10 sites) will require 320 Gbps of bandwidth per antenna.
- At each step along each chain, the hardware required for repeating the signals from downstream stations will be co-located with that station's network hardware. For some chains, this will result in a substantial footprint of repeating equipment; e.g., Station D1 will be servicing 14 downstream stations. A fiber build path factor was added to the inter-site fiber lengths obtained from GIS data to reflect the actual installed length vs. point-to-point distance available.
- This model does not include correlator network switch hardware costs, as these will be included in the CSP budget.

5 Recommendations

A clear differentiation exists between the stations to which the project can run dark fiber and those for which ISPs providing lit service must be engaged. It is strongly recommended that the dark fiber be owned and managed by a local service provider (for installation and fiber repair) but that the ngVLA provide the lit service electronics to these stations. Typically, stations with dark fiber will have a higher construction cost but lower recurrent operations cost. ISP-serviced stations will require last-mile fiber provisioning, and the monthly recurrent cost (MRC) will be high with unpredictable variability per location depending on installed infrastructure and upstream service partner(s).

It is important that the ngVLA project identify a National Research serving partner for coordinating the provisioning and operations management of infrastructure of this scale; current candidates would, for example, include Internet 2 and ESNet. The current model predicts a total fiber length of ~1,100 km to service the 30 MB stations being provisioned with dark fiber.

The LBA station costs will be weighted toward operations since service providers are reluctant to give access to dark fiber and tend to charge by capacity. Provisioning a low "committed" rate (tens of Gbps) with a much higher "burstable" rate (320 Gbps) may be possible with quality of service and priority of service definitions being useful to align service expectations. The project should define these to be recognizable by ISPs.

ISP contracts based around IRUs (e.g., 10+ year indefeasible right of use) are essential for amortizing the initial cost but will result in higher operating costs. Partnering with ISPs to access NTIA and Federal communications grants should be explored especially for EPSCoR locations (e.g., NM, Hawaii, US Virgin Islands). ISP contracts should assume no access to commodity Internet services. This will simplify the infrastructure and reduce the security overhead at the sites. A separate commodity service (e.g., 10 Mbps) should be provisioned for basic network needs such as M&C connectivity, visiting service technicians, security cameras, and alerts.

Engaging a support partner for operating and supporting the fiber (e.g., American Tower, Crown Castle, or SBA Communications) may prove beneficial since their business model permits distributed communications technology infrastructure support. The project would also benefit from their insight into current wireless communications infrastructure placement.

Identification of "anchor" institutes within individual stations' geographic regions could prove useful in coordinating fiber construction and sponsoring network access operations. VLBA experience has shown that this model works well, but does increase the management overhead overall due to distributed ownership.

6 Budget Model

The model identifies four main costing items:

- dark fiber installation and operation (based on a distance scaling),
- network switch gear purchase and maintenance (in units of 100 Gbps),
- equipment needed for network signal regeneration (LO signal regeneration requirements are tracked elsewhere), and
- ISP lit service costs (in units of 100 Gbps/year)

The current working model (Appendix 8.1) is populated with order of magnitude dollar amounts for proof of concept purposes. The model intends to allow for a defensible Basis of Estimate parameterization.

7 Identified Risks

- Any assumption of "Moore's Law" value scaling is an approximation and may not apply to each technology equally.
- The daisy-chain model assumes a risk from fiber damage and single-path availability that would result in multiple stations being taken off-line in the event of a localized fault along the fiber chain. In the worst case, 15 of the Mid-Baseline stations could be impacted by a single failure.
- The power and cooling needed for signal regeneration (LO and data) must be factored into station design.
- The use of aerial strung fiber may not be appropriate for LO signal distribution over long distances due to thermal fluctuations, but the cost of trenched fiber will be two to three times higher.
- Stations in areas of low population density have the associated challenge that local broadband providers will not have exposure of infrastructure to support a Peta-scale communications initiative.
- The aggregation of ISP data flowing from the 16 MB stations and 30 LBA antennas will be massive and will need a co-location demarcation point.
- The four MB Stations outside of the US (three in Mexico and one in Canada) and Island sites will present unique issues for bandwidth provisioning.
- The ISP-supported stations will often have a local service provider for last-mile access from the site to the backbone infrastructure managed by a national carrier (e.g. Level3/Century Link, Verizon, AT&T). This can result in accountability gaps especially for ownership of intermittent throughput performance issues.

8 Appendix

8.1 ngVLA Long Haul Fiber Costing Model

ngVLA Long Haul Fiber costing model for 46 Mid Baseline Stations and 10 Long Baseline Array sites
October 2018

Parameters						
Build				Operations		
Fiber Build/km	400G Router/ Switch	100Gbps repeater	Fiber Build Path factor (GIS vs. actual)	Fiber strand/km/year	Operating per 100Gbps/year	Annual Maintenance % of purchase
$20,400	$50,000	$2,000	1.20	$500	$72,000	10%

	MBA	LBA	Total
Construction cost:	$26,540,592	$3,224,400	$29,764,992
Annual Operating cost:	$6,809,490	$8,940,000	$15,749,490

Site	Inbound Neighbor	Inbound fiber (km)	100Gbps circuits	Network Hardware	Fiber Build	Operating
A1 (m105)	Core (via m059)	30.0	16	$82,000	$612,000	$38,200
A2 (m78)	A1 (m105)	19.1	12	$74,000	$389,232	$21,710
A3 (m107)	A2 (m78)	31.2	8	$66,000	$636,480	$22,200
A4 (m082)	A3 (m107)	43.0	4	$58,000	$876,384	$16,540
B1 (m107)	Core (via m074)	36.0	20	$90,000	$734,400	$54,000
B2 (m080)	B1 (m106)	36.7	16	$82,000	$749,088	$44,920
B3 (m111)	B2 (m80)	38.8	12	$74,000	$790,704	$36,470
B4 (m81)	B3 (m111)	56.9	8	$66,000	$1,160,352	$35,040
B5 (m108)	B4 (m81)	58.8	4	$58,000	$1,199,520	$20,500
C1 (m109)	Core (via m015)	30.0	24	$98,000	$612,000	$54,800
C2 (m79)	C1 (m109)	11.9	20	$90,000	$242,352	$23,850
C3 (m110)	C2 (m79)	23.3	16	$82,000	$474,912	$31,480
C4 (m092)	C3 (m110)	9.5	12	$74,000	$193,392	$14,510
C5 (m084)	C4 (m092)	26.3	8	$66,000	$536,112	$19,740
C6 (m087)	C5 (m084)	16.8	4	$58,000	$342,720	$10,000
D1 (m093)	Core (via m044)	42.0	60	$170,000	$856,800	$174,500
D2 (m102)	D1 (m093)	20.3	56	$162,000	$413,712	$87,180
D3 (m103)	D2 (m102)	12.2	52	$154,000	$249,696	$55,180
D4 (m104)	D3 (m103)	11.5	48	$146,000	$235,008	$49,160
D5 (m099)	D4 (m104)	55.3	16	$82,000	$1,128,528	$63,520
D6 (m100)	D5 (m099)	57.7	12	$74,000	$1,177,488	$50,690
D7 (m089)	D6 (m100)	45.6	8	$66,000	$930,240	$29,400
D8 (m090)	D7 (m089)	44.3	4	$58,000	$903,312	$16,870
E1 (m094)	D4 (m104)	12.0	28	$106,000	$244,800	$31,600
E2 (m096)	E1 (m094)	46.6	24	$98,000	$949,824	$79,640
E3 (m097)	E2 (m096)	52.3	20	$90,000	$1,067,328	$74,400
E4 (m098)	E3 (m097)	62.5	16	$82,000	$1,275,408	$70,720
E5 (m085)	E4 (m098)	44.6	12	$74,000	$910,656	$40,880
E6 (m091)	E5 (m085)	46.2	8	$66,000	$942,480	$29,700
E7 (m113)	E6 (m091)	53.2	4	$58,000	$1,084,464	$19,090
ISP1		1.0	4	$50,000	$20,400	$293,000
ISP2		1.0	4	$50,000	$20,400	$293,000
ISP3		1.0	4	$50,000	$20,400	$293,000
ISP4		1.0	4	$50,000	$20,400	$293,000
ISP5		1.0	4	$50,000	$20,400	$293,000
ISP6		1.0	4	$50,000	$20,400	$293,000
ISP7		1.0	4	$50,000	$20,400	$293,000
ISP8		1.0	4	$50,000	$20,400	$293,000
ISP9		1.0	4	$50,000	$20,400	$293,000
ISP10		1.0	4	$50,000	$20,400	$293,000
ISP11		1.0	4	$50,000	$20,400	$293,000
ISP12		1.0	4	$50,000	$20,400	$293,000
ISP13		1.0	4	$50,000	$20,400	$293,000
ISP14		1.0	4	$50,000	$20,400	$293,000
ISP15		1.0	4	$50,000	$20,400	$293,000
ISP16		1.0	4	$50,000	$20,400	$293,000
ISP Core (MBA)		1.0	64	$800,000	$20,400	$80,000
LBA1		1.0	8	$100,000	$20,400	$586,000
LBA2		1.0	8	$100,000	$20,400	$586,000
LBA3		1.0	12	$150,000	$20,400	$879,000
LBA4		1.0	12	$150,000	$20,400	$879,000
LBA5		1.0	12	$150,000	$20,400	$879,000
LBA6		1.0	12	$150,000	$20,400	$879,000
LBA7		1.0	12	$150,000	$20,400	$879,000
LBA8		1.0	12	$150,000	$20,400	$879,000
LBA9		1.0	16	$200,000	$20,400	$1,172,000
LBA10		1.0	16	$200,000	$20,400	$1,172,000
ISP Core (LBA)		1.0	120	$1,500,000	$20,400	$150,000
Archive Data Center link		1	10	$50,000	$20,400	$725,000

8.2 Acronyms and Abbreviations

Acronym	Description
AD	Applicable Document
CSP	Central Signal Processor
DB	Data Base
DBE	Digital Back End
DTS	Data Transmission System
EPSCoR	Established Program to Stimulate Competitive Research
FWG	Fiber Working Group
Gbps	Giga-bits per second
GIS	Geographic Information System
IP	Internet Protocol
IPT	Data Transmission System
IRU	Indefeasible Right of Use
ISP	Internet Service Provider
ITU	International Telecommunication Union
LBA	Long Baseline Array
LO	Local Oscillator
MA	Main Array
MB	Mid-Baseline
MRC	Monthly Recurrent Cost
ngVLA	Next Generation Very Large Array
NTIA	National Telecommunications and Information Administration
PI	Principal Investigator
RD	Reference Document
SBA	Short Baseline Array
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
VLBA	Very Long Baseline Array
ZX	1000BASE-ZX, a nonstandard but multivendor term, refers to Gigabit Ethernet using a 1550 nm wavelength to transmit data 70+ km over single-mode fiber.

Reference Study: ngVLA Buildings and Infrastructure

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Table of Contents

1 Introduction ... 3
2 Project Background ... 4
3 Related Documents ... 4
3.1 Applicable Documents ... 4
3.2 Reference Documents ... 4
4 Scope ... 5
5 Operations Infrastructure Concept ... 6
6 Integration and Testing Centers ... 7
6.1 Concept ... 7
6.2 Assembly Centers ... 7
6.2.1 Line 1: Integrated Receiver Package ... 7
6.2.2 Line 2: SA501 ... 7
6.2.3 Line 3: Power Supplies ... 7
6.2.4 Line 4: DBE/DTS, M&C ... 8
6.2.5 Line 5: WVR/Weather Station ... 8
6.2.6 Line 6: LO Generator/RTP ... 8
6.2.7 Line 7: Antenna Component Assembly ... 8
6.2.8 Antenna Integration ... 8
6.2.9 Warehouse ... 8
7 Observatory Building Location Options ... 9
7.1 Option 1: Use Existing JVLA and DSOC Facilities, with Necessary Upgrades ... 10
7.1.1 RFI ... 10
7.1.2 Integration Centers ... 10
7.1.3 Transition Plan ... 10
7.1.4 Travel ... 11
7.1.5 Infrastructure ... 11
7.2 Option 2: Staff Housed Between Socorro, Magdalena, and the ngVLA site ... 11
7.2.1 Socorro (DSOC) ... 11
7.2.2 Magdalena Area ... 11
7.2.3 ngVLA Site ... 12
7.2.4 RFI ... 12
7.2.5 Integration Centers ... 12
7.2.6 Transition Plan ... 12
7.2.7 Travel ... 12
7.3 Option 3: Science/Computer Operations Staff Located in Major Metropolitan Center 13
7.4 Option 4: Remote Support Station Option ... 13
8 Assessment of Current Facilities ... 14
8.1 VLA Buildings and Utility Infrastructure ... 14
8.1.1 Buildings ... 14
8.2 JVLA Antenna Pads ... 15
8.3 Domenici Science Operations Center ... 15
9 Reference Design ... 16
9.1 Site Electrical Infrastructure ... 16
9.1.1 Assumptions ... 16

9.1.2 Goals 16
9.1.3 System Description 16
9.1.4 System Behaviors 19
9.1.5 System Components and Costs 22
9.1.6 Lifecycle Support 22
9.2 Antenna Pads 23
9.2.1 Pad Design 23
9.2.2 Antenna Security Fences 26
9.2.3 Site Geotechnical Surveys 27
9.3 Roads 27
9.4 Buildings 29
9.4.1 Science and Computing/Array Support Center in Major Metropolitan Area 29
9.4.2 New Electronics Repair Facility in Socorro 29
9.4.3 Domenici Science Operations Center 29
9.4.4 New Shops, Warehouse, and Offices Near Magdalena 30
9.4.5 Processor Building at ngVLA Site 30
9.4.6 Heavy Equipment Depot at ngVLA Site 30
9.4.7 Auto and Heavy Equipment Repair Facility at ngVLA Site 30
9.4.8 Remote Support Stations 31
9.4.9 RFI Chamber 31
9.5 Site Support 31
9.5.1 Site Water and Sewer, Trash Removal 31
9.5.2 Fiber Communications 32
9.5.3 Site Communications 32
9.5.4 Trash Transfer Station and Recycling 32
9.5.5 Weather Station Infrastructure 32
10 Alternative Design and Cost Reduction Options 33
10.1 Leverage Existing VLA Buildings and Infrastructure 33
10.2 Power Redundancy for Processor Building and Central Site 33
10.3 Potential Cost Reductions 33
10.3.1 Plains Array Switchgear 33
10.3.2 Generators 33
10.3.3 Above Ground Processor Building 34
10.3.4 Eliminate Remote Support Stations 34
11 Options vs. Cost 34
11.1 Assumed Costs 34
11.2 Building Costs – Options 34
11.3 Building Plan Options 35
12 Recommendation 36
13 Appendix 37
13.1 Abbreviations and Acronyms 37
13.2 VLA Demolition Costs 38
13.3 VLA Demolition Gains 39
13.4 Electrical Staffing 39

1 Introduction

The National Radio Astronomy Observatory (NRAO) is proposing the design and construction of a new astronomical observatory that will operate at centimeter wavelengths. The majority of the Next Generation Very Large Array (ngVLA) antennas will be located in the vicinity of the current Jansky Very Large Array (JVLA), with additional elements located in New Mexico, adjoining states, northern Mexico, and targeted locations throughout the hemisphere.

The ngVLA will ultimately replace the JVLA. A portion of the proposal effort includes an assessment of building and infrastructure needs. Building location recommendations and cost estimates for buildings and infrastructure to support the ngVLA mission is also required. This document will discuss each and, based on the findings, provide a costed reference recommendation for ngVLA buildings and infrastructure. With consideration to

1. the project mission,
2. existing NRAO facilities and utilities that may be leveraged,
3. the ngVLA operations concept [AD01],
4. environmental concerns, and
5. the overall construction cost,

this report recommends that the number of staff permanently stationed close to the antennas be minimized.

To accomplish this, we propose considerable changes from JVLA operations in the location from which support staff operate. Along with the infrastructure and antenna pads needed to support the central antenna group, the central ngVLA site should be outfitted with a new, partially submerged processor building along with another structure or structures to serve as heavy equipment support facilities. Building a new campus located 24 miles east of the array in Magdalena, NM, is recommended to facilitate immediate antenna repair. Employees at this location would be responsible for replacing failing line replaceable units (LRUs), regular maintenance activities and the storage of spare LRUs, and regular preventive array maintenance. Array support staff such as Environment, Safety, and Security (ES&S) would also be located in Magdalena.

Engineers and technicians who perform repairs requiring a higher level of technical expertise are recommended for a new Socorro, NM electronics facility. Although a considerable number of observatory support staff would necessarily remain located at the Domenici Science Operations Center (DSOC) in Socorro, NM, to improve the recruitment and retention of staff and ease travel, scientific, array computing, and observatory support staff could be located in a major metropolitan center.

During construction, several assembly/integration centers are required. This report identifies each and which of these can be repurposed for ngVLA operations support.

2 Project Background

The ngVLA is a project of the NRAO to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 263 reflector antennas, most 18 meters in diameter, operating in a phased or interferometric mode.

The signal processing center and 187 antennas will be located in the vicinity of the current JVLA site, on the Plains of San Agustin, New Mexico. The array will include 46 mid-baseline stations in other locations throughout the state of New Mexico, west Texas, eastern Arizona, and northern Mexico. Thirty long-baseline antennas will be distributed between ten sites, many of which are the present locations used by the Very Large Baseline Array (VLBA).

Operations will be conducted from both the ngVLA Processor Building and the Science Operations Center (DSOC) in Socorro, NM. Scientific and Computing staff may be located in a yet undetermined metropolitan area.

3 Related Documents

3.1 Applicable Documents

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD02	Environmental Specifications	020.10.15.10.00-0001-SPE
AD03	Assessment for Very Large Array Facility – Including Site Infrastructure, Control Building, & Site Buildings	020.60.00.00.01-0002-REP

3.2 Reference Documents

Ref. No.	Document Title	Rev/Doc. No.
RD01	2018 Building Construction Costs with RSMeans Data	ISBN 1946872016
RD02	ngVLA Radio Frequency Interference Forecast	ngVLA Memo #48
RD03	Long Haul Fiber Workgroup Preliminary Report	020.60.00.00.00-0002-REP
RD04	Transition Concept	020.10.05.00.00-0003-PLA
RD05	ngVLA Core and Plains Power Infrastructure	020.60.00.00.01-0003-DWG-A-NGVLA_ONE_LINE

4 Scope

This document includes requirements and costing information for the buildings and support facilities that directly support the ngVLA. The infrastructure located at the ngVLA core, plains, and remote areas will also be addressed.

Several items are not included in the scope of this reference study. Because other efforts to plan for a Visitor Center are taking place through the Education and Public Outreach department, an ngVLA Visitor Center is not included in this study. Costing for the various shop equipment or support vehicles, fiber system components (other than the buried fiber itself), cost of land, and easements are not within scope, nor are long fiber runs not associated with the main site, such as the run between Socorro and the ngVLA site, and cross-country rented fiber. These are addressed in [RD03], ngVLA Long Haul Fiber Workgroup Preliminary Report.

The eventual decommissioning of the JVLA antennas, buildings, and infrastructure is also considered outside the scope of this document, though budgetary estimates are provided in the appendix.

5 Operations Infrastructure Concept

Key aspects of the operations infrastructure concept as described in [AD01], ngVLA Operations Concept, are repeated in this section. The material presented in the most recent version of [AD01] supersedes any material included here.

The operations concept requires specific support infrastructure. Workspace sizing estimates have been developed, though these are preliminary and will be revised and expanded as part of the overall operations plan. To streamline operations and to minimize RFI, it is desirable to limit the number of staff and operating equipment located on-site in lieu of working out of a nearby Maintenance Center, perhaps located in Magdalena, NM. A majority, if not all, of line replaceable units (LRUs) and equipment is expected to be located at the Maintenance Center and its warehouse. This means the array site will have a limited number of depots, garages, and storage buildings.

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

In the following table, a breakdown is given of the type of work done and buildings and equipment needed for various locations of operations effort. It starts with the work to be done at the array and progressively moves further from the array. Continuously operated equipment and buildings are minimized at the site in lieu of a Maintenance Center and Remote Support Stations, while array operations, array maintenance, science operations, and support work are done at various locations further away.

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

6 Integration and Testing Centers

6.1 Concept

Electronic and other components will be directed to one of several integration and test centers, where they will be assembled into LRUs and tested in-house prior to being shipped to the warehouse for inventory and storage. These LRUs will be checked out of the central warehouse by the Antenna Integration and Verification group (AIV) for antenna assembly and acceptance testing.

6.2 Assembly Centers

Table 1 (next page) is self-explanatory. It lists seven integration and test lines, with the basic building requirements. Some of these lines are likely to be housed in the same structure. Of the seven integration lines, the Integrated Receiver Package, SA501, and Antenna Assembly locations are reasonably well understood. An additional facility or facilities for the remaining lines must be identified. It is possible one or more of these lines could be located in a leased structure, and possibly near a metropolitan center. This discussion will continue as the ngVLA construction and integration plan matures.

Center	Location	Size sf	# of Staff	Loading Docks	Clean Room Sq ft	RFI Chamber sf	Stock Room sf	Offices	Video Conf	ESD
Integrated Receiver Package	Charlottesville								accessible	
SA501	Socorro	15,000	15	2	2000	10X15 (2)	1000	5	1	50%
Power Supplies	Socorro	3000	3	1	-	-	1500	1	accessible	-
DBE/DTS, M&C		5000	6	1	1000			3	1	50%
WVR / weather staion		2000	2	1	1000	-	1000	3	accessible	80%
LO generator/ RTP		3000	4	1	3000	10X15 (1)	500	3	1	100%
Antenna Assembly	ngVLA				0	-		3	accessible	-

Table 1 – ngVLA assembly centers and building requirements.

6.2.1 Line 1: Integrated Receiver Package

The Integrated Receiver Package is being designed and developed at the NRAO Central Development Laboratory (CDL) in Charlottesville, Virginia. These assemblies will be manufactured out of house. They will be delivered to the CDL for testing prior to being transported to the SA501 (Front End) integration center in Socorro, NM.

6.2.2 Line 2: SA501

The Front End assembly (SA501) includes two dewars, six feeds, integrated receivers, and other electronics. The assembly and testing of the Front End subsystem requires a center of considerable size and sophistication, with 15,000 sq. ft. of floor space, 2,000 feet of clean room, and a stock room sufficient to collect and store the various components awaiting integration. Located in Socorro, completed and tested assemblies from this center will be transported by NRAO staff to the ngVLA Warehouse, where they will reside until antenna integration. The SA501 center is a prime candidate for re-purposing into an electronics repair lab after construction is complete. This building may be built as AUI/NRAO property, or it may be constructed by a local entity (New Mexico Tech or the City of Socorro) and leased to NRAO.

6.2.3 Line 3: Power Supplies

All power supplies will be ordered out of house. They could be installed into modules by NRAO staff, or this task could be outsourced to a third party. Regardless, they will be tested in Socorro. Upon acceptance, these will be transported to the ngVLA Warehouse for future integration into antennas.

6.2.4 Line 4: DBE/DTS, M&C

The Digital Back-End (DBE), Data Transmission System (DTS), and Monitor and Control (M&C) electronics will be manufactured out of house. Integration of printed circuit boards and other standalone components into LRUs may take place in Line 4, or at an off-site manufacturing house. Each unit will undergo acceptance testing prior to becoming part of the warehouse inventory.

6.2.5 Line 5: WVR/Weather Station

Water Vapor Radiometers (WVR) for each antennas along with approximately 65 weather stations will be manufactured and tested out of house before undergoing in-house acceptance testing.

6.2.6 Line 6: LO Generator/RTP

The Local Oscillator (LO) Generator and Round Trip Phase assemblies will be designed by staff at the NRAO CDL.

6.2.7 Line 7: Antenna Component Assembly

If a composite dish design is adopted by the project, these will likely be fabricated at the VLA site. Possible existing locations, after modifications, include the Antenna Assembly Building, the Transporter Shop, and the Track Building. The backing structure would be joined to the dish at the same location.

6.2.8 Antenna Integration

Assembly of the major antenna components (dish, pedestal, Front Ends, other electronics) will occur at each antenna pad.

6.2.9 Warehouse

Though not an integration center per se, the project warehouse is listed here for completeness. A warehouse sufficient to house components and LRUs during array construction and spares and consumables during operations is recommended to be built in reasonable proximity to the ngVLA. A portion of the warehouse must be climate controlled, as several of the electronic assemblies are susceptible to extreme temperatures.

7 Observatory Building Location Options

The ngVLA project presents the challenge of constructing and operating an array of 263 antennas. To support such a large array, many groups will find it necessary to work closely together. These groups will require substantial work areas/buildings capable of meeting the demands of both constructing and outfitting the array in the early stages and maintaining and servicing the array. The following describes the groups that will need workspace for the ngVLA project.

- **Electronics**: Responsible for outfitting and maintaining all Front End and electronics components in the array. They will need space to build, test and validate, maintain, and service all the components. Additionally, electronic technicians will be responsible for maintaining and servicing electrical aspects on the antenna. The electronics building must house staff and provide office workspace, a testing area, and a production space for ngVLA components.
- **Antenna Technicians**: Responsible for servicing and repairing antenna LRUs and mechanical components. This includes preventive maintenance on the entire array as well as repairing antennas as parts fail.
- **Servo**: Responsible for the antenna movement, including azimuth, elevation, and Front End receiver positioning. The servo group will need space to accommodate array maintenance and service. The servo building must house staff and provide office workspace, a testing area, and a production space for ngVLA components.
- **Cryogenics**: Responsible for the cryogenics systems on all the antennas. Each antenna will have six cryogenically cooled receivers. The cryogenics group must build, outfit, and maintain all the cryogenics systems for the entire array. The cryogenics building must house staff and provide office workspace, a testing area, and a production space for ngVLA components.
- **Computing and Information Services (CIS)**: Responsible for the installation and upkeep of the myriad computing resources necessary to support the ngVLA mission and the local NRAO community. At least a representative group of CIS staff should be located at the DSOC in Socorro.
- **Machine Shop**: Responsible for manufacturing ngVLA components and maintaining the site once it is up and running. Due to the remote location and system uniqueness, an in-house machine shop is required. The machine shop building must house staff and the machine shop area, to include Computer Numerical Control (CNC) and manual machines in support of both construction and maintenance activities for the ngVLA.
- **Auto Shop**: Responsible for maintaining and repairing all vehicles used to run and service the array. Due to the remote location and the heavy and light duty equipment that will be required, an in-house auto shop is required.
- **Grounds**: Responsible for maintaining roads and antenna areas on site. The grounds building must house staff and all equipment needed for antenna array grounds maintenance.
- **Electrical**: Responsible for all site low, medium, and high voltage electrical components. These include utility power distribution, backup generators, and site building and antenna power systems. This group will be responsible for maintaining all the site and building electrical systems, but will not be responsible for any buildings leased from outside entities.
- **HVAC**: Responsible for outfitting and maintaining the Heating, Ventilation, and Air Conditioning (HVAC) units for all array antennas. The group is also responsible for maintaining the HVAC for all site buildings, but not any buildings leased from other entities. Members of this group may be seconded to the support of site water and sewer facilities.
- **ES&S**: Environmental, Safety, and Security personnel are responsible for coordination and implementation of safety and health best practices and to support all staff with regard to all safety and health programs.

7.1 Option 1: Use Existing JVLA and DSOC Facilities, with Necessary Upgrades

This option proposes to upgrade and repurpose the current JVLA site and DSOC facilities to accommodate the ngVLA project. The VLA site infrastructure and buildings will be upgraded and refurbished as necessary to support ngVLA. This would include renovating all site buildings, bringing them up to code and performing necessary upgrades to extend their life to meet that of the ngVLA.

This option would most likely include some new construction to accommodate the scale of the ngVLA as well as facilitate the transition period. The JVLA is expected to operate during the transition period. The current site buildings will be close to 40 years old at the start of ngVLA construction and will have to be upgraded to extend the lifespan no less than an additional 20 years. The control building along with metal workshops will have to be updated to current code in respect to both building structure and ADA and OSHA standards.

Under this option, the personnel located at the ngVLA site will mirror that of the current VLA. The technical services including Machine Shop, HVAC, Electricians, ES&S, Antenna Technicians (Antenna Mechanics, Servo Cryogenics), Warehouse, and the Auto Shop will all be located at the central site. All support vehicles and equipment would be at the central site location.

7.1.1 RFI

Radio Frequency Interference (RFI) is a major concern going forward with ngVLA as more electronic devices are dependent on Bluetooth and Wi-Fi, including vehicles. Locating all the maintenance and repair centers on site would most definitely introduce unwanted RFI. RFI generated close to the central core would have a detrimental impact on the science for the array.

Having a Visitors Center close to the core would also introduce a major RFI risk. Newer vehicles are equipped with Bluetooth, Wi-Fi, and other new technologies such as self-driving capability. These new vehicle technologies would jeopardize the quality of science if these vehicles were positioned near the array center. The visitors themselves also present RFI issues with smartphones and other Bluetooth devices such as smart watches, health monitors, and headphones. The simple fact is that if anyone with any emitting electronic device visits the center core, the science for the duration of their presence would be compromised. RFI and its potential effects on the operation of the ngVLA are explored in [RD02], ngVLA Radio Frequency Interference Forecast.

7.1.2 Integration Centers

Reutilizing the VLA site would require separate integration centers where new antenna components could be stored and assembled. The magnitude of this project would require renting or building large production facilities to accommodate building necessary components to outfit the large number of antennas. The DSOC is not currently capable of supporting a project the size of ngVLA. A production-oriented facility with loading docks and ample workspace will be required. It may be possible to rent space in the Socorro area, but availability may be an issue and will most likely require new construction to meet our needs. After ngVLA construction and antenna outfitting are complete, under this scheme the integration centers would no longer be needed.

7.1.3 Transition Plan

As described in [RD04], ngVLA Transition Concept, the prevailing concept is to keep the current VLA operational until ngVLA is at least partially online. However, the option of re-using the current VLA facility during the transition would be very difficult, if not impossible. If the control building were to be repurposed and used to house the new processor, it would be a wiring and communications nightmare to have both systems running simultaneously. The existing control building would have to be wired for ngVLA power and fiber, while not disturbing the old infrastructure. Furthermore, the control building would have to undergo a tremendous amount of destructive renovations to bring it up to current codes and standards. The building would likely be rendered useless for science during these upgrades.

7.1.4 Travel

The site work structure would mirror that of the current VLA. Employees would arrive to the VLA site as their home work station. The workers would then perform work as required on the array. As with the current VLA operations, buses would run from Socorro and Magdalena to the site. The number of buses would necessarily be increased as the number of employees increases for ngVLA.

7.1.5 Infrastructure

A perceived advantage of reusing the existing site is the ability to reuse, to a degree, the current VLA infrastructure, roads, sewer, buildings, etc. within the current square mile on which the VLA resides.

7.2 Option 2: Staff Housed Between Socorro, Magdalena, and the ngVLA site

To minimize staff at the ngVLA site, it has been proposed to construct an offsite campus close enough to house specific technical services for the array, but far enough away so that RFI would not be a concern.

Magdalena, NM is the ideal location for the second campus. It is located 24 miles from the current VLA and 27 miles from the DSOC. With this concept, the DSOC remains an integral location and will house the Electronics Division along with other observatory support staff. The breakdown for personnel located at each site is provided below.

7.2.1 Socorro (DSOC)

Science, computing, electronics, and administrative support staff will be located in Socorro at the DSOC or possibly a newly constructed building. This model is similar to the current VLA operations that are located at the DSOC. High-level repairs would be sent to Socorro from the ngVLA site. The Electronics Division would make the repairs to Front End and LO/IF modules, then ship them to the Magdalena campus for storage until needed. The Socorro group would be responsible for higher-level repair and testing, while simpler repairs would be done at the Magdalena facility.

Depending on staffing requirements, an addition to the existing DSOC facility or totally new construction may be necessary. This would require a modification to the land agreement with New Mexico Tech if it is decided to expand the DSOC. If science and computing are relocated to another location, the space freed up could be used for more lab space, which may make the current building size adequate. Additionally, if the current VLBA is replaced by ngVLA and the DSOC is not needed to house the VLBA correlator, support staff, and facilities, this area also becomes available for ngVLA operations, support, and overhead staff.

7.2.2 Magdalena Area

Technical services including Cryogenics, Machine Shop, Servo, HVAC, Electricians, ES&S, Antenna Technicians, the main Warehouse, and possibly the Auto Shop would be located in the Magdalena area. Essentially the idea here is to pack up the current VLA model and move it to Magdalena with a few exceptions. The technical staff would be stationed at the Magdalena campus and would perform maintenance and repairs on the antenna components on site. For maintenance or repair that requires an antenna visit, the technicians stationed in Magdalena would travel directly to the affected antenna, without necessarily needing to travel to the central site.

7.2.3 ngVLA Site

In the effort to have a minimum of full-time staff located at the site, only security guards and possibly ES&S representatives will be a constant presence at the ngVLA site. Transient staff including the operator and auto mechanics would only be at the site as required. The main building at the site would be the processor building, which would house the processor and all required on-site computing. This building would be constructed as an RFI-tight building, and possibly underground. It would house a few offices and a conference area to facilitate on-site meetings and support during the transition period.

Generators for site backup power will be at the central site near the processor building. An auto shop would need to be on site to facilitate maintenance and repairs to the site vehicles and equipment, some of which are very large. A vehicle depot housing all maintenance vehicles and heavy equipment would also be located at the central site. As with the current JVLA, an RFI testing chamber could be located at the central site, but could also be built in Magdalena.

Moving the majority of operations off site does not necessarily mean the existing buildings will be demolished. The existing metal buildings, including tech services, warehouse, auto shop/servo building, and track shop may be used as cold storage or remote warehouses, in addition to construction centers for the new antennas. One of these buildings could alternatively be repurposed or expanded to accommodate a new auto shop. The antenna barn can also be used as an auto depot for maintenance vehicles. Buildings that cannot be reused or repurposed would ultimately have to be demolished as part of any planned JVLA decommissioning effort.

7.2.4 RFI

The greatest observing and science benefit of this option would be the elimination of almost all RFI introduced by staff and computing. By removing the maximum personnel from the site, automobile and computer emissions or the risk of a device such as a cell phone being inadvertently left on is greatly reduced, if not altogether eliminated. Technical services requiring electronic equipment would not have to worry about noise created if they are not on site. It would be much more difficult to deal with RFI with the ngVLA center core being so congested with antennas. Per [RD02], reducing RFI must be a priority in the design and construction of the new array.

7.2.5 Integration Centers

The opportunity to have all new construction for the majority of ngVLA support buildings has a built-in advantage for integration centers. The new buildings can be designed to act as integration centers for the ngVLA construction and antenna outfitting, then modified for steady state operations and maintenance. The buildings would be built as production facilities and transition into support facilities as construction ends. The integration centers can be built in Magdalena and later transition into antenna support buildings there as well as Socorro. One could also transition into an electronics support location.

7.2.6 Transition Plan

A transition plan would allow for the JVLA to operate at some level until the ngVLA is up to a minimal operational state. Depending on the determined site of the central core of antennas, the current JVLA building configuration may adversely affect the way power and fiber are routed to the new array.

7.2.7 Travel

The site work structure would somewhat mirror that of the current VLA. Employees would arrive to the Socorro and Magdalena locations as their home work station. Each day the staff in Magdalena would receive assignments and then travel to the main site to perform work as required on the array. As with the current VLA operations, buses or perhaps vans could transport remote staff assigned to the Magdalena campus. From the Magdalena campus, workers would only go to central site if repairs or maintenance are required. Likely they would travel as teams in company vehicles to the equipment depot, where they would transfer to a larger vehicle capable of servicing the antennas.

7.2.7.1 Infrastructure

At the ngVLA site, portions of the existing VLA infrastructure, roads, sewer, buildings, etc., could be reused for the processor building where appropriate. New infrastructure (electrical, communications, water, and sewer) will necessarily be new construction for any production and maintenance facilities built in Magdalena.

7.3 Option 3: Science/Computer Operations Staff Located in Major Metropolitan Center

This option would potentially allow for easier employee recruitment and retention and, if the city were an airline hub, could streamline travel. An office building would be leased in a major metropolitan center. For this reference study, Phoenix, Dallas, and Denver are used as examples. Moving these staff away from Socorro would free up many of the offices at the DSOC. The new space at the DSOC would allow for additional room for overhead staff as well as electronics and engineering offices. This option can be realized with either upgrading the existing JVLA site structures or by the construction of new facilities away from the site.

7.4 Option 4: Remote Support Station Option

The far-lying antennas will be far away enough that maintenance from the central site would require constant travel and lodging for the service technicians. In some cases, this could be problematic in that long travel distances could be required, and overnight lodging could be difficult to locate.

One option to avoid this is to place remote support stations near clusters of far-lying antennas. The idea is similar to the VLBA sites, providing a work location with all required equipment on site. Depending on the final configuration plan for the mid-baseline antennas, four to six regional stations with four to six site technicians each would be stationed in towns nearest to a cluster of remote antenna. The number of these support stations will in part be determined by the distance between the station and each antenna within the region. Travel to and from an antenna, in addition to the work performed, would ideally be completed in one day.

The site technicians would be responsible for coordinating with the warehouse for replacement LRUs, and maintaining and servicing the remote antennas in their assigned region. The stations would consist of office space, a repair area, nominal storage space, and restroom facilities. Establishing these remote stations rather than relying on long travel routes for antenna maintenance technicians is highly recommended. It will remain an option to include these facilities regardless of the decision whether to include the stations in the baseline construction plan.

8 Assessment of Current Facilities

8.1 VLA Buildings and Utility Infrastructure

The existing buildings and infrastructure at the central VLA site have been serving the observatory for over 40 years, and though well maintained, they are naturally showing their age. To better determine if these structures are candidates for renovation and upgrading, NRAO contracted the engineering firm Bohannan Huston to perform a high-level site building and infrastructure assessment. The purpose of this study is to evaluate the suitability of the current facilities and infrastructure for ngVLA use. A brief summary is provided in the sections below. The full report is provided as [AD03], Bohannan Huston JVLA Site Assessment.

8.1.1 Buildings

The site buildings evaluated for this study include the two-story brick Control Building and the pre-fabricated metal Warehouse, Technical Services, Track, Generator, Carpentry, Auto/Electrical Shop, and Antenna Barn buildings.

The Control Building, erected in 1975, was determined to be in overall good condition. However, if major renovation to the building were to occur, the standards to which the building were originally constructed would no longer be applicable. Several improvements would be required to bring the building into compliance with current American with Disabilities Act (ADA) standards. Structurally, the Control Building is sound, though extensive structural efforts would be required to modify the elevator core and the access areas. The mechanical and electrical systems in the building are in good condition and have undergone consistent and routine maintenance, but all are original and would be likely targets for replacement, with the exception of the newly installed main electrical panel. Plumbing fixtures are older and in fair condition. Finally, it was noted that most of the Cat 5 technology wiring in the building is unshielded and provides a source for EMI emissions.

Based on the Bohannan Huston observations of the existing control building, it is our opinion that the current building will not adequately serve the needs of the proposed expansion due to substantial reconfiguration of the current floor plans needed to meet current Building Code and Accessibility requirements as well as upgrades and replacements of the mechanical and electrical systems. Performing the required renovations and upgrades on the existing structure will be met with limitations that may hinder the facility from reaching its complete, planned potential in support of ngVLA.

The site's pre-fabricated metal buildings appear structurally sound. At present, an initiative is underway to replace the exterior windows and doors. Should the buildings be called into future service, new exterior skins should be considered. The electrical systems are a combination of original and upgraded sections. Most of the HVAC systems have been upgraded over the past decade.

Potable water is available at all facilities at the VLA via an onsite closed-loop system. The facilities are supplied by a groundwater well that pumps into a 30,000-gallon above-ground steel storage tank. The distribution system piping varies in size and material type depending on its location. Piping has been reliable with minimal leaks and repairs. The fire pump is rated for 1,000 gal/min and has been recently upgraded with a new controller unit. Although adequate for their current use, upgrades to the domestic water system will be needed to meet the 50-year expectancy of the proposed facility.

The onsite sanitary sewer system consists of a gravity collections system that serves the control building, visitor center, and most of the other site buildings. This collection system drains to a lift station that then transports waste water to a two-cell facultative lagoon system for processing and disposal. The lagoons are in good condition and are adequate to provide service for the future facility, though they may have to be modified to a more appropriate size depending on the expected site occupancy. The sewage lift station is in good condition, but it has been identified as needing to be replaced to meet code requirements and provide better efficiency. The existing collection system is in good condition. Without additional lift stations, the extent of service that can be provided to the site buildings is limited by the site topography. The ability to connect new buildings that may be a part of the proposed expansion to the current gravity system will be location-dependent.

8.2 JVLA Antenna Pads

Once the ngVLA is in an operational state, the old JVLA will require decommissioning, while the old site buildings will either be upgraded and repurposed, or demolished. The current thought process is that all JVLA antenna pads will be removed to just below ground level. The current ngVLA antenna design does not follow the same configuration of the existing array, nor does it fit the JVLA antenna footprint. Furthermore, repurposing the piers will complicate foundation design. Additionally, the current design does not have any antennas located at the current antenna pad locations. Finally, by not utilizing the current VLA pads, this allows for the VLA to continue to operate during ngVLA construction.

8.3 Domenici Science Operations Center

The Domenici Science Operations Center (DSOC), located on the campus of New Mexico Tech (NMT) in Socorro, NM, is home to the offices and labs that support JVLA and VLBA operations. Scientific, Computing, Engineering, Fiscal, and Human Resources staff are located in this building. Most NRAO New Mexico staff are stationed here. NRAO has a 99-year lease on the building at virtually no cost. However, NRAO pays NMT $280K/year for maintenance services.

The DSOC as it is currently configured will not support the electronics division staff needed for ngVLA. The basement is not suited for any of the large-scale production lines that will be needed for building and testing ngVLA assemblies. The building does not have a proper loading dock to receive and ship components and assemblies, or to allow for reasonable transportation of the larger LRUs. For this reason, we believe a larger, more production-oriented electronics integration and repair center is needed. The DSOC, however, remains well suited to house Operations, Administration, Correlator Support, Computing Support, Safety, and some engineering support other than what is proposed to be located in the new electronics repair facility.

If the electronics division were to move out of the DSOC, as is our recommendation, the entire area could be remodeled into office space for additional staffing numbers required by ngVLA. The current VLBA operations and correlator area can also be remodeled to accommodate more office area. In addition to the electronics support groups, the correlator engineering support group that currently resides at the DSOC would also move to the new electronics repair facility.

9 Reference Design

The ngVLA Reference Design is described and estimates are provided in this section. The reference design is based on the needs of the project, the operations concept, environmental concerns, and economics. It is our opinion that options 2, 3, and 4, as defined in Sections 7.2, 7.3, and 7.4, will best serve the ngVLA.

9.1 Site Electrical Infrastructure

9.1.1 Assumptions

The ngVLA will use the existing utility feed from Socorro Electric Cooperative. Total power consumption of all ngVLA antennas will be similar to the total power consumption of existing JVLA antennas. Correlator power consumption will be similar. Office and industrial loads will be mostly located outside the array site. System reliability is prioritized as high. Remote antennas will be no more than one mile from existing electrical grid components.

9.1.2 Goals

Primary goals include minimizing system downtime for preventive maintenance, eliminating all single-point failures during regular operations, and minimizing single-point failures during preventative maintenance.

9.1.3 System Description

9.1.3.1 Plains Array

9.1.3.1.1 Design

The electrical grid proposed by this document follows a circular distribution model (see Figure 1). To this end, the backbone consists of multiple switchgear enclosures, each with at least two power sources. This level of redundancy allows for individual components of the grid to be removed for maintenance with minimal impact to site performance. The specific level of impact varies depending on the placement and function of each switchgear cabinet, and will be discussed further on.

As a point of comparison, the existing JVLA uses a centralized distribution model. At the present site, all loads can be traced back to a single distribution switchgear. This necessitates that any maintenance to this central piece of switchgear requires the array to go dark.

The ngVLA grid will be supported by three generators. Two will be rated as prime sources, and one rated for emergency backup. While all three generators are expected to be utilized in a backup capacity, generators rated as prime sources meet more stringent environmental regulations and are capable of prolonged operation. The two prime sources will each support one of the main branches, the CW (clockwise) and CCW (counter clockwise) busses.

The third generator will be connected to both of the main branches via interlocked disconnects. As configured, it may be connected in the place of either prime source while one is down for maintenance or testing. For purposes of conservative budgeting, all three generators have been costed out to be capable of powering the entire ngVLA Plains Array. As design details become more fleshed out, the prime source rated generators will most likely approach a rating of two-thirds the total site load.

This reference design includes five switchgear cabinets to supply major site loads. Four of these switchgear cabinets will supply antennas in chains of approximately five. The fifth cabinet will provide power to both the new processor and various support buildings.

Figure 1 (next page) illustrates the main electrical grid components for the ngVLA central site.

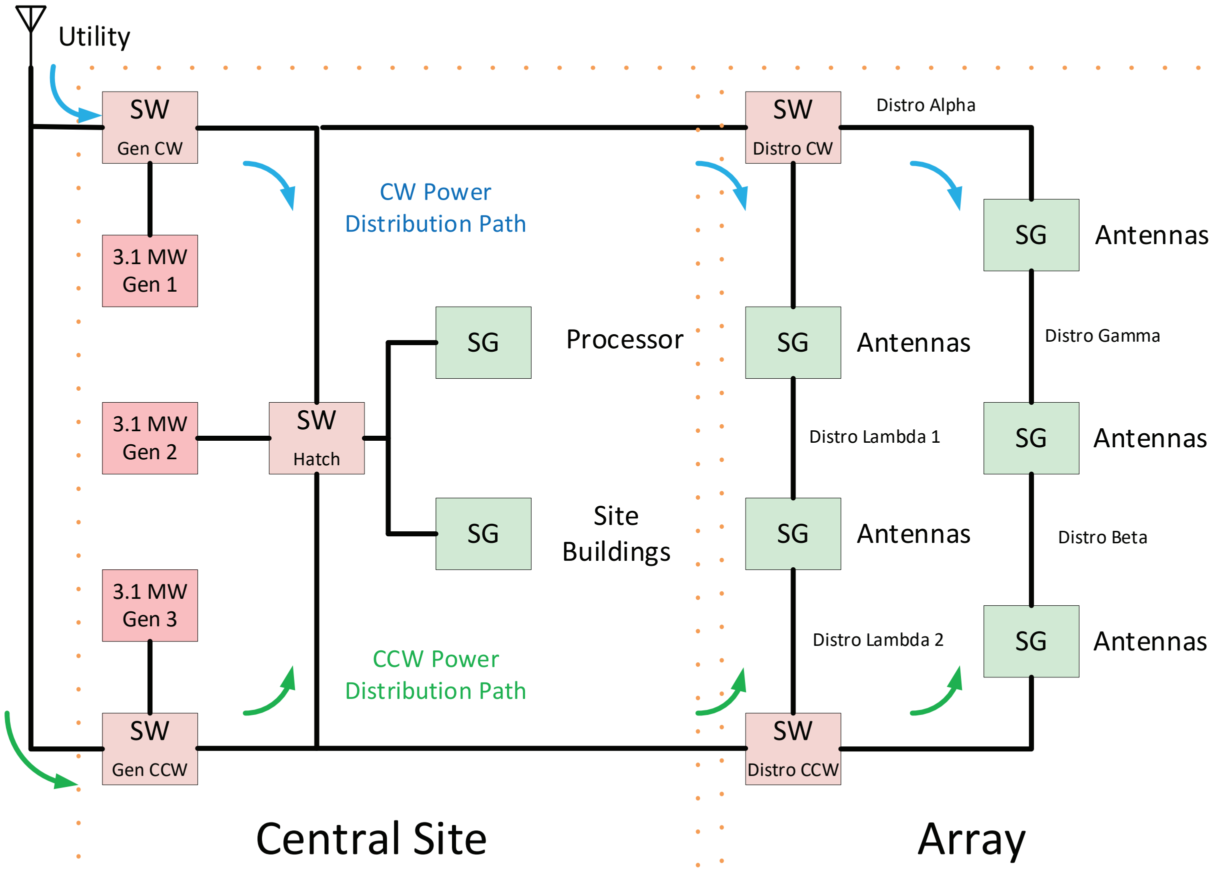

Figure 1 - ngVLA central site electrical grid components.

9.1.3.1.2 Construction

Current expectations are for the ngVLA to be centered slightly northwest of the existing JVLA. This placement seeks to minimize interference with JVLA operations prior to ngVLA coming online. To shorten construction schedules and support other ngVLA construction and testing efforts, NRAO proposes that the following electrical infrastructure components be prioritized for installation:

- High priority
  - Hatch_Gear
  - Generator_Gear_CW or Generator_Gear_CCW
  - Processor_Xform
  - TS_Xform
  - Utility_Xformer

- Moderate priority
  - Trenching
  - Concrete foundations

- Low priority
  - Distribution switchgear
  - Low voltage infrastructure

Completing the high-priority items, along with the power cabling to interconnect them, will provide medium voltage power to all array support facilities. This provides two benefits throughout ngVLA construction. As electronic systems are installed, power will be available for testing. Initially this will be limited to the processor and networking systems, but as the remaining electrical switchgear is set in place, field testing of antennas is possible without relying on large numbers of portable generators. The second benefit is that having workshops and storage spaces on site provides a staging facility throughout the construction process.

Trenching and concrete foundations follow in the proposed list of priorities. This is largely due to the interference between trenching operations and access roads. Given the scattered and disjointed arrangement of antenna groupings, trenches will frequently cross convenient roadways to limit conflicts between trenching efforts and logistics around the construction site.

The concrete foundations are included in this subset as they must be at both ends of a trench to allow power cables to be pulled and their terminations protected. Trenching operations will also be coordinated with installation of fiber optics and any other data connections throughout the array. Doing so will minimize duplication of effort when trenching. The electrical power grid infrastructure for the core and plains portions of the ngVLA are provided in [RD05], ngVLA Core and Plains Power Infrastructure.

9.1.3.2 Remote Array

9.1.3.2.1 Design

Remote ngVLA antenna sites fall into two classifications, new and existing. Existing remote antenna sites are anticipated to use existing VLBA infrastructure or its equivalent, whereas new remote antenna sites will be constructed from the ground up. In either case, these sites will be supplied with a single switchgear enclosure, a transformer per antenna, and a temporary generator connection point.

The current remote locations of the VLBA are supported by backup power generators. These will not be used to support ngVLA remote antennas at existing remote sites. Neither will backup generators be implemented for new remote antenna locations. Rather, remote antenna locations will rely solely on local power infrastructure to operate.

For VLBA sites, it is unlikely that existing backup power can support additional large loads, although this may be revisited once power requirements become more tightly defined. At the new remote sites, to do otherwise would require frequent trips to each remote site to perform preventive maintenance and inspections on both the generators and their associated fuel storage facilities.

Limited backup power will be supplied to each individual antenna via a UPS system. This power source will be sufficient to stow the antenna and gracefully shutdown electrical systems. The UPS system is considered an internal component to the antenna, and is not discussed in this document.

Utility power will be supplied to new remote antenna sites via a single low-voltage switchgear cabinet. These enclosures will contain three breakers and a multi-function relay. In addition to these basic components, remote ngVLA switchgear units will tie into the Supervisory Control and Data Acquisition (SCADA) system for the entire array. In the case of existing antenna locations, this switchgear cabinet will include additional breakers for every additional ngVLA antenna collocated with the first.

Qualified personnel will have access to view data pertaining to current power quality and status. Qualified personnel will also have the ability to operate the breaker in order to remove and apply utility power to the antenna. This is expected to be a desirable feature in order to allow hard resetting of antenna systems in order to clear potential faults, rather than dispatching repair crews.

Each site will be provided with a connection point for installation of a temporary generator. This will allow teams dispatched to the antenna site to power up the antenna in the event that reliable utility power is unavailable at the time of work being performed.

9.1.3.2.2 Construction

Construction of the remote sites may be accomplished independently of one another and of the plains array. Installation of electrical infrastructure at these sites is a relatively simple endeavor, compared to the number of teams and systems to be involved in the plains array.

Unlike the plains array, electrical work at the remote sites can be accomplished independently from other construction tasks. The point to point nature of a remote site's connection to utility power allows cabling to run parallel to access roads, avoiding disruption in regards to which is created first. Furthermore, the small number of components involved drives a work schedule with very low scheduling risk.

9.1.4 System Behaviors

9.1.4.1 Normal Operation

Referring to Figure 1, during normal operations the site will be fed by utility power through both the clockwise (CW) and counter clockwise (CCW) generator buses. Loads will be shared in approximately equal division between the CW and CCW buses. Generators 1 and 3 will be on standby ready to transition power.

9.1.4.2 System Fault Response

In the event of a system fault, trained array staff will be able to reroute power through the grid to remove the impacted components. Where possible, these transitions will be automated to minimize impact to array observations. When automatic transitions are not possible or the automated response leaves the array in an impacted state, trained NRAO electrical staff will be relied upon to manually transition the array to an optimal configuration.

All array antennas will rely upon local UPS systems to maintain power during electrical grid configuration changes. With the exception of switchgear feeding 480 volt loads, there is no impact. The impact to the array's performance due to faults in other busses varies throughout the system.

Table 2 (next pages) identifies the effects of faults throughout the ngVLA electrical distribution system. Events in the first protective action and second protective action columns are automatic system responses. The array impact column identifies the worst-case loss of function following the automated response. Short-term and long-term corrective actions identify actions taken by site personnel to mitigate and eventually correct the system impact.

Fault Location	1st Protective Action	2nd Protective Action	Array Impact	Short Term Corrective Action	Long Term Corrective Action	After Hours Call-Out Required?
Processor Switchgear Load	Upstream Breaker Trips		Drop Processor Load	Remove faulted load	Replace faulted load	Consider
Processor Switchgear	Upstream Breaker Trips		Drop Processor	If breaker, replace	Develop corrective maintenance plan	Yes
Tech Services Switchgear Load	Upstream Breaker Trips		Drop non-essential load	Remove faulted load	Replace faulted load	No
Tech Services Switchgear	Upstream Breaker Trips		Drop all non-essential load	If breaker, replace	Develop corrective maintenance plan	Consider
Hatch	Upstream Breaker Trips		Drop processor and all non-essential load	If breaker, replace	Develop corrective maintenance plan	Yes
Distro CW	Upstream Breaker Trips	Re-route power through Distro CCW and Distro Gamma	None	If breaker, replace	Develop corrective maintenance plan	No
Distro CCW	Upstream Breaker Trips	Re-route power through Distro CW and Distro Gamma	None	If breaker, replace	Develop corrective maintenance plan	No
Distro Alpha	Upstream Breaker Trips	Re-route power through Distro Beta as necessary	Drop 30 Core Antennas	If breaker, replace	Develop corrective maintenance plan	Consider
Distro Beta	Upstream Breaker Trips	Re-route power through Distro Alpha as necessary	Drop 30 Core Antennas	If breaker, replace	Develop corrective maintenance plan	Consider

Fault Location	1st Protective Action	2nd Protective Action	Array Impact	Short Term Corrective Action	Long Term Corrective Action	After Hours Call-Out Required?
Distro Gamma	Upstream Breaker Trips		Drop 30 Core Antennas	If breaker, replace	Develop corrective maintenance plan	Consider
Distro Lambda 1	Upstream Breaker Trips		Drop 36 Arm Antennas	If breaker, replace	Develop corrective maintenance plan	Consider
Distro Lambda 2	Upstream Breaker Trips		Drop 24 Arm Antennas	If breaker, replace	Develop corrective maintenance plan	Consider
Generator Gear CW	Upstream Breaker Trips	Re-route power through Generator Gear CCW	None	If breaker, replace	Develop corrective maintenance plan	No
Generator Gear CCW	Upstream Breaker Trips	Re-route power through Generator Gear CW	None	If breaker, replace	Develop corrective maintenance plan	No
208 VAC Antenna Load	Upstream Breaker Trips		Drop single antenna	Remove faulted load	Replace faulted load	No
480 VAC Antenna Chain Component	Upstream Breaker Trips		Drop six antennas	Open disconnect	Repair fault	Consider
Generator1	Generator Breaker trips	Generator 2 starts and routes power through Hatch	None	None	Develop corrective maintenance plan	No
Generator3	Generator Breaker trips	Generator 2 starts and routes power through Hatch	None	None	Develop corrective maintenance plan	No

Table 2 - Impact of single-system faults.

9.1.5 System Components and Costs

9.1.5.1 Plains Array

Component	# Needed	Cost
MV Breakers	62	
Switchgear Buses	11	$4.7M[1]
MV Transformers:		$3.5M[2]
1MVA	2	
650kVA	5	
100kVA	90	
50kVA	66	
LV Breakers and Enclosures	197	$2M
Cable Trenching		$31M[3]
Generators		$6M[4]
Total Cost		**$47.2M**

Table notes:
1. Based on EIU quotes, scaled by number of medium voltage breakers.
2. Based on vendor ROM pricing.
3. Based on recent contracted cable installation.
4. Based on EIU quotes and doubled to encompass construction of fuel storage and supporting infrastructure.

9.1.5.2 Remote Antennas

Component	# Needed	Cost
New Antenna Sites:		
MV Breakers	46	
Switchgear Buses	46	$4.6M
MV Transformers	46	$460,000
LV Breakers	138	
Existing Antenna Sites:		
Switchgear Buses	30	$3M
MV Transformers	30	$300,000
LV Breakers	50	
Cable Trenching	76 sites	$7.6M
Total Cost		**$15.96M**

9.1.5.3 Total Costs

Plains Array	$47.2M
Remote Antennas	$16M
Electrical Grid	$63.2M

9.1.6 Lifecycle Support

Electrical maintenance performed at the JVLA is largely corrective in nature. This is due in part to the age of the facility. This is exemplified by the faulty performance of the Hatch switchgear and generator sets that prompted the Electrical Infrastructure Upgrade (EIU) project. The nature of the JVLA as a collection of antennas periodically relocated also adds to this. Ultimately, the largest contribution to this approach is the impact to array performance caused by any maintenance operations.

For any given JVLAconfiguration, antenna feeders are either disused or vital to array operations. In the former case, this prevents data collection to predict future maintenance needs. In the latter case, this magnifies the impact of de-energizing the circuit by exercising mechanical components or in order to conduct repairs. Work that drops an arm of the array prohibits observing. De-energizing a single antenna deactivates almost 4% of the array. Dropping the distribution switchgear deactivates the entire array.

By comparison, the vast majority of maintenance, both preventative and corrective, performed on the proposed ngVLA will have minimal impact. The number of antennas reduces the impact of dropping a single antenna to less than 1%. Table 3 offers a comparison of impacts related to performing maintenance on various regions of the array.

Component Level	% of JVLA Array Impacted	% of ngVLA Array Impacted
Antenna	3.7%	0.4%
Antenna Chain	33%	2%–4.5%
Switchgear	100%	0%–13.6%
Correlator/Processor Switchgear	100%	100%
Generator	Loss of backup power	No impact

Table 3 - Comparison of maintenance impact on array regions.

Due to the impact of removing an antenna from the JVLA array for maintenance, great effort is taken to conduct all maintenance simultaneously and in as short a time as possible. This leads to tighter scheduling needs and a tendency to schedule work based on availability rather than functional priorities. The much smaller impact of removing an antenna from the ngVLA allows for maintenance to be scheduled independently of other tasks, exclusively by level of importance.

One of the more common corrective maintenance issues at the JVLA involves replacement of the plugs and jacks used to disconnect and reconnect antennas to their pedestals. These connection points tend to wear and rust during periods of disuse, both while connected or disconnected. The fixed nature of the ngVLA antennas will completely eliminate this issue.

Another facet improved by the lack of physical alterations to array configuration is that it will be possible to monitor all system components throughout the year. At the JVLA, the majority of transformers and disconnect switches are unloaded, limiting the usefulness of thermal scans in documenting component degradation. This increase in available data is expected to improve the ability of staff to better coordinate repairs.

Preventive maintenance, in the form of testing and inspections, will be conducted on a rolling basis throughout the array. It is intended that every component of the electrical grid, within the plains array, will be inspected either every three or six months. Components requiring regular exercising will be operated on a similar schedule. All remote antennas will be inspected and maintained on an annual basis.

9.2 *Antenna Pads*

9.2.1 Pad Design

The 18-meter antennas will require a substantial foundation to meet the stability requirements of the ngVLA. The initial loading requirements are listed in Table 4 and detailed in the foundation interface drawings shown in Figure 2, Figure 3, and Figure 4.

	Axial lb	Radial lb	Torsion lb*ft	Tipping lb*ft
Wind Load	16,636	29,293	133,572	1,696,393
Static Load	225,035	0	0	501
	X(ft)	Y(ft)	Z(ft)	
Load Placement ft	−1.64	0.00	41.01	
Foundation Natural Frequency (Hz)	8			

Table 4 - Initial loading requirements for 18-meter ngVLA antenna foundations.

The reference design for the antenna foundation consists of a 25' x 25' base pad 4' deep. The base pad will have four 4' diameter piles extending down 30' into the earth. A 3' x 3' grade beam will tie the antenna foundation to the piers and strengthen the foundation overall. Final antenna specifications and interface will be needed for the final antenna foundation conceptual design.

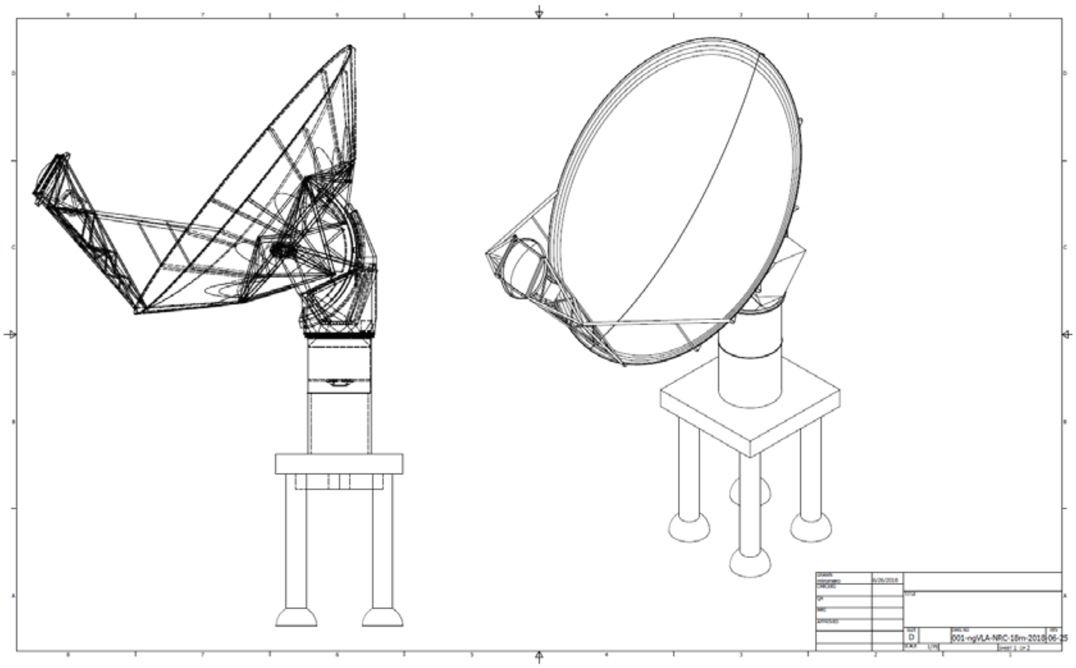

Figure 2 - Antenna foundation supports. Note that site grade is level with the pad, and the piles extend below grade.

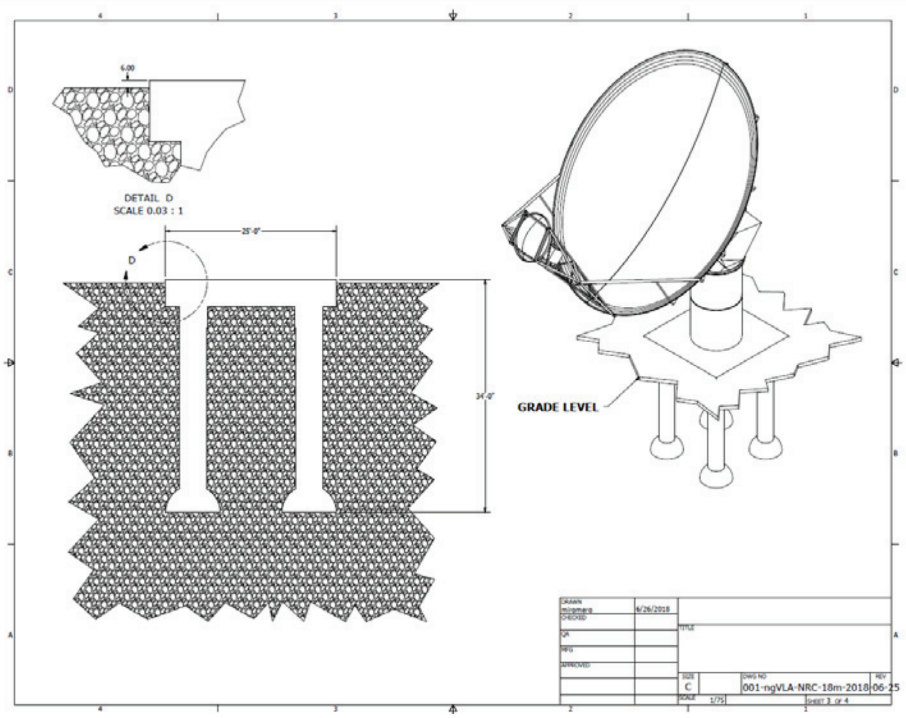

Figure 3 - Antenna foundation placement in concrete.

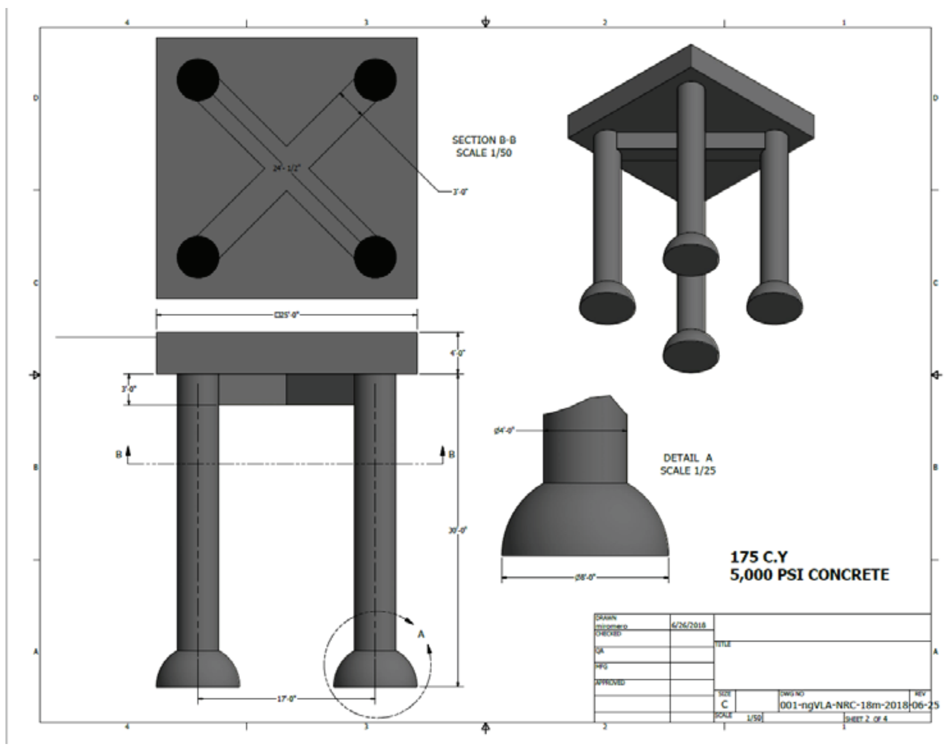

Figure 4 - Antenna foundation specifications.

Table 5 and Table 6 provide antenna foundation costing based on 2018 RSMeans data.

ngVLA Antenna Foundation Cost Estimate										
PILES										
	RSMeans REF	Diameter	L.F	QTY:			Volume C.Y		Costing	Sub Total
Drill Concrete Piles, each	31 63 26.13 0500	4	30				13.96		$134.00	$4,020.00
Bell Piles	31 63 26.13 1080	8		1			4.96		$3,575.00	$3,575.00
75 LB/C.Y Reinforcement	31 63 26.13 4300						18.93		$34.75	$657.72
Load and Haul Excavation, bore	31 63 26.13 4500						18.93		$6.45	$572.08
Load and Haul Excavation	31 23 23.20 1084						18.93		$19.20	$813.40
Pile Sub Total										**$7,595.00**
4 Piles										$30,380.00
Mobilization Each Location	31 63 26.13 4650			1						$3,925.00
Pile Total				4						**$34,305.00**
PILE CAP/BASE SLAB With GRADE BEAM										
	REF	Width F.	Length F.	Height F.	Ea	L.F.	Tons	Volume C.Y	Costing	Sub Total
Slab Concrete, 5000 psi	03 31 13.35 0400	25	25	4				92.59	$148.00	$13,703.70
Grade Beam Concrete, 5000 psi	03 31 13.35 0400	3	24	3				16.00	$148.00	$2,368.00
Forming (SFCA)	03 11 13.40 0020					400			$25.50	$10,200.00
Mobilization Each Location	01 54 36.50 1500				1				$960.00	$960.00
Remote Mobilization Cost	01 54 36.50 2500				5				$96.00	$480.00
Excavation	31 23 16.42 0250							135.74	$2.14	$290.49
Load and Haul Excavation	31 23 23.20 1084							135.74	$19.20	$2,606.22
Placing Concrete	03 31 13.70 1600							108.59	$28.50	$3,094.89
Placing ReBar (75lb/CY)	03 21 11.60 0600						4.07		$2,200.00	$8,958.89
Slab total										**$42,662.19**
TOTAL										**$76,967.19**

Table 5 - Antenna foundation costs, detailed.

Antenna Location	Antennas	Subtotals
Local Antenna	168	$12,930,487.73
Remote Antenna	46	$3,540,490.69
VLBI Sites	30	$2,309,015.67
SBA Antenna*	19	$731,188.29
Total Cost	**263**	**$19,511,182.38**

Table 6 - Antenna foundation costs, summarized.

In summary, each antenna foundation is estimated at $76,967.19. Antenna foundations for all 263 antennas will cost $19,511,182.38. (* 6m SBA antenna foundations were estimated at half the price of the 18m antennas.)

9.2.2 Antenna Security Fences

Many ngVLA antennas will be located in areas also used for grazing. These antennas require protection, such as a perimeter fence, from any damage that could be caused by cattle and other wild beasts. Like the JVLA, it is assumed the closest-in antennas for the ngVLA will be situated on federally controlled property. This section will require a barbed wire fence to delineate it from the local ranches, and to keep cattle away. Four-tier barbed wire fencing installed to surround a one square mile perimeter comes with a cost estimate of $38K.

Of the remaining antennas away from the core (the mid-baseline stations and those installed beyond the federal boundary) protection from animals and security in general must be provided. An estimated cost of $2,000 for chain-link fencing for each of these approximate 100 antennas is recommended, for a total construction cost increment of $200K.

It is assumed the long-baseline stations will be constructed on established sites, which will already provide a suitable level of protection.

The cost estimate for protective fencing around the antennas totals $238K.

9.2.3 Site Geotechnical Surveys

The antenna foundations will be designed based on the geotechnical attributes of the area. For the local antennas, this information is readily available from the days of VLA construction. For the 46 remote antennas, borings and a report are estimated to cost $2,500 per station for a total of $115K.

9.3 Roads

The central core and five spiral arms will require adequate roads during the construction phase and during operations for antenna maintenance. Roads will connect all the antennas in the central core to the support buildings and allow for easy access from one antenna to another for maintenance. The road configuration will require approximately 11.5 miles of access road for the central core alone. Figure 5 details the road concept for the central core from the existing VLA site.

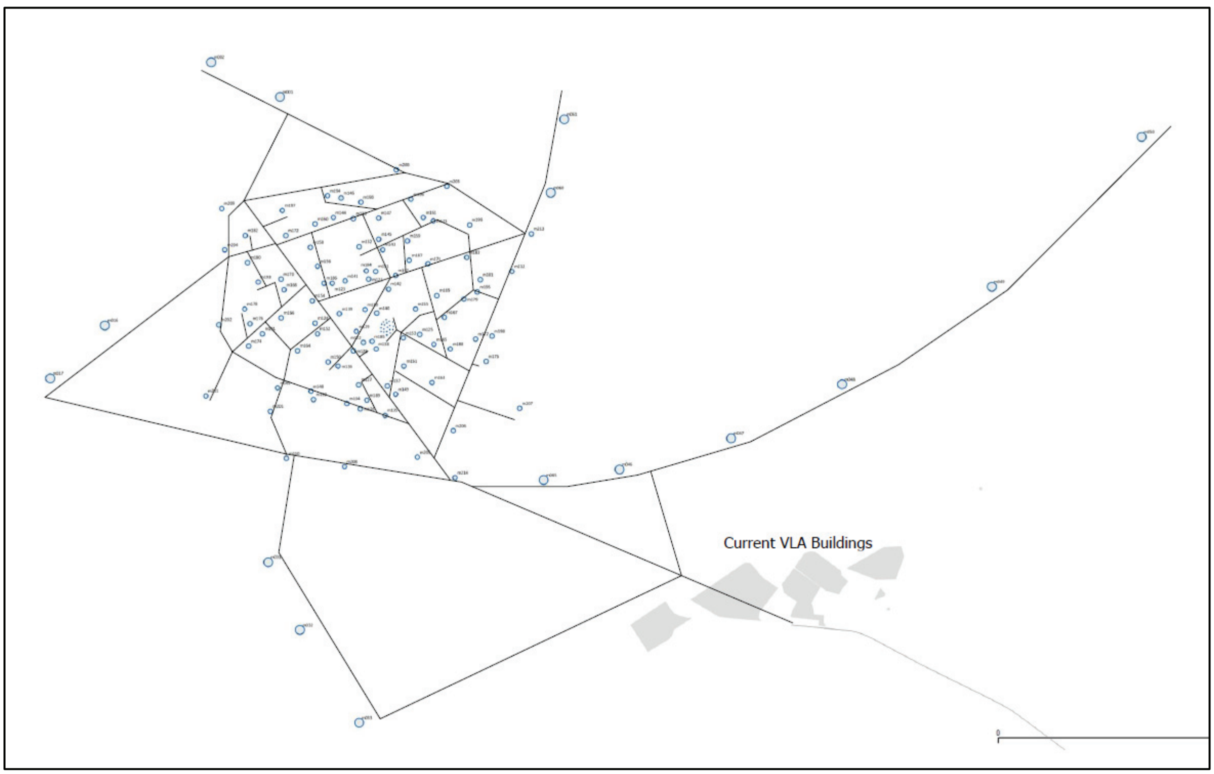

Figure 5 - Road configuration for ngVLA central core and spiral arm antennas.

An access road will follow the five spiral arms and connect all antennas to the central site. Approximately 15 miles of access road will be needed for each of the five arms. In addition to the roads following the spiral arms, a pentagon shortcut located around the 7.5-mile mark on each arm will be added to aid travel from one arm to the next without the need to travel back to the central core. Additionally, an estimated one-mile road extension for remote antennas to be linked to current roads is being used in the estimate. Figure 6 details the spiral arm access roads and pentagon shortcut roads.

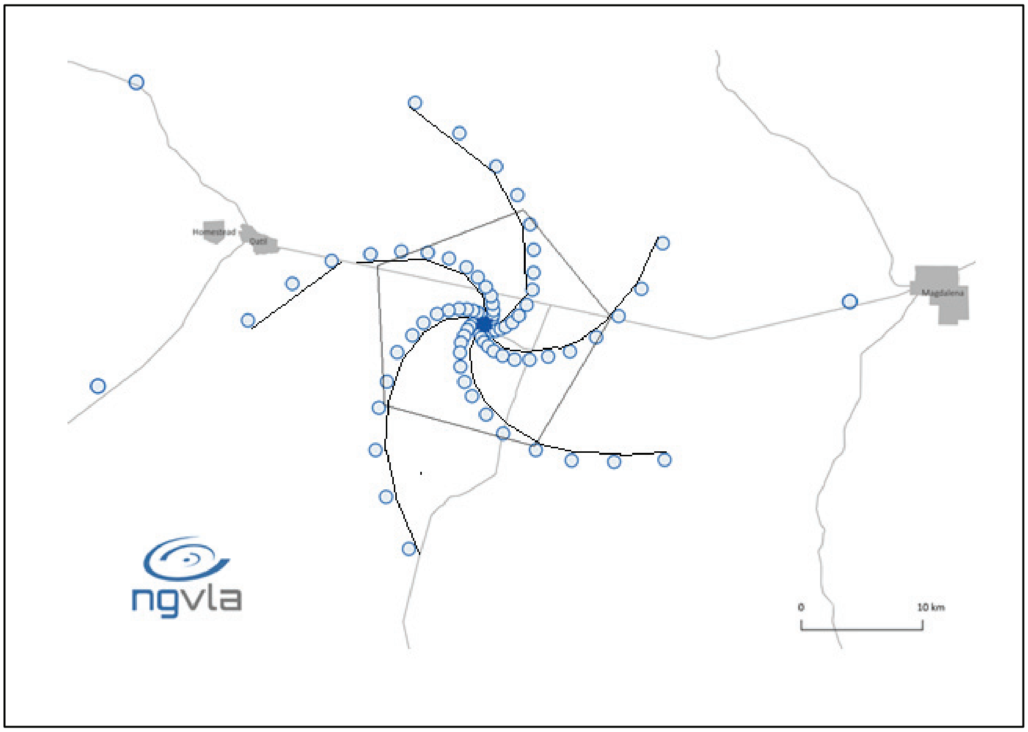

Figure 6 - Road configuration including spiral arm and pentagon short-cut roads.

To assure long life and the ability to facilitate the antenna assembly and maintenance, 6" deep, ¾" crushed stone base will be used on all roads. Furthermore, these improved roads will be more resistant to inclement weather conditions, resulting in considerably less washout, sand migration, and other negative impacts to the surrounding ecosystem.

Table 7 details road costing for the access roads.

ngVLA Road Estimate					
	RSMeans Ref	**Central Core**	**Spiral Arm, Each**	**Pentagon**	**Remote Antennas**
Total Road Required (mi)		11.5	15	32	1
Road Width (ft)		12	12	12	12
Road Area S.Y.		80,960	105,600	225,280	7,040
Crushed 3/4 Stone Base 6", $/S.Y	32 11 23.23 0100	$7.40	$7.40	$7.40	$7.40
Prepare Subbase, $/S.Y	32 11 23.23 8050	$1.20	$1.20	$1.20	$1.20
Subtotal		$696,256.00	$908,160.00	$1,937,408.00	$60,544.00
QTY		1	5	1	48
Total		$696,256.00	$4,540,800.00	$1,937,408.00	$2,906,112.00
Site Total		**$10,080,576.00**			

Table 7 - Cost estimate for ngVLA access roads.

9.4 Buildings

9.4.1 Science and Computing/Array Support Center in Major Metropolitan Area

The following rental rate examples are based on a need for approximately 50,000-70,000 sqft to house the science and array staff. For estimation purposes, a 60,000 sqft building using the $21.17 $/sqft average rate for Dallas is used ($1.27M/yr).

Rental Rate Examples			
Dallas			
Example Location	S.Q.F.T	$/S.Q.F.T Per Year	Yearly Lease
14651 N Dallas Pky	51,283	$15.50	$794,886.50
2401 Cedar Springs	53,012	$36.00	$1,908,432.00
1508 W Mockingbird	65,000	$12.00	$780,000.00
Average		**$21.17**	
Phoenix			
Example Location	S.Q.F.T	$/S.Q.F.T Per Year	Yearly Lease
NW Cooper Rd	60,000	$18.50	$1,110,000.00
3201 E Elwood	76,600	$12.50	$957,500.00
1515 W 14th St	65,000	$19.50	$1,267,500.00
Average		**$16.83**	
Denver			
Example Location	S.Q.F.T	$/S.Q.F.T Per Year	Yearly Lease
3601 Walnut St.	50,801	$34.00	$1,727,234.00
2375 15th St.	69,300	$37.00	$2,564,100.00
2000 S Colorado Blvd	54,700	$30.00	$1,641,000.00
Average		**$33.67**	

The rate table above is for building construction as is and would still require office furniture and support equipment.

9.4.2 New Electronics Repair Facility in Socorro

ngVLA Electronics Repair Center				
	S.Q.F.T	$/S.Q.F.T	RSMeans Ref	Total
Electronics Repair Center	15,000	$271.00	50 17 00 26 0500	$4,065,000.00

The construction cost provided for the Electronics Repair Center does not include laboratory equipment or extra features such as a building Uninterruptible Power Supply (UPS).

9.4.3 Domenici Science Operations Center

Despite the recommendation to relocate science and array support to a city and the electronics support staff to their own facility, the DSOC remains an integral site for observatory support. The DSOC is not optimal to house an electronics repair shop capable of supporting the high volume of ngVLA assemblies and components. With the relocation of a separate electronics repair facility in Socorro, additional DSOC space will become available for overhead departments such as Fiscal, CIS, Purchasing, and HR. $500K is the anticipated cost of any renovation to the DSOC to convert lab space into office space, and to update the infrastructure (power, communications, etc.) of the building.

9.4.4 New Shops, Warehouse, and Offices Near Magdalena

Magdalena Campus Buildings Estimated Costs									
				UNIT COST $/SQFT			COST IN 2018 $		
Building	SQFT	RSMeans Ref	Building Type Comparison	0.25	MEDIAN	0.75	0.25	MEDIAN	0.75
Auto Shop	5,000.00	50 17 00 01 0500	Auto Sales & Repair	165	$173.00	$177.00	$825,000.00	$865,000.00	$885,000.00
Grounds & Facilities	5,000.00	50 17 00 01 0500	Auto Sales & Repair	165	$173.00	$177.00	$825,000.00	$865,000.00	$885,000.00
Machine Shop	8,000.00	50 17 00 26 0500	Eng & Lab Buildings	265	$271.00	$295.00	$2,120,000.00	$2,168,000.00	$2,360,000.00
Warehouse	15,000.00	50 17 00 28 0500		65	$116.00	$226.00	$975,000.00	$1,740,000.00	$3,390,000.00
HVAC & Site Electrical	7,000.00	50 17 00 26 0500	Eng & Lab Buildings	265	$271.00	$295.00	$1,855,000.00	$1,897,000.00	$2,065,000.00
Antenna Technician Work Area	15,000.00	50 17 00 26 0500	Eng & Lab Buildings	265	$271.00	$295.00	$3,975,000.00	$4,065,000.00	$4,425,000.00
Antenna Technician, General R&R									
Cryogenics Technicians									
Servo and Electronics Technicians									
RFI Chamber Building, 900 sqft RFI chamber	2,000.00	See RFI Chamber					237335	237335	$237,335.00
Covered Parking	5,000.00	50 17 00 15 0050		36	$43.50	$47.00	$180,000.00	$217,500.00	$235,000.00
ES&S	2,500.00	50 17 00 01 0500	Auto Sales & Repair	165	$173.00	$177.00	$412,500.00	$432,500.00	$442,500.00
						TOTAL	$11,404,835.00	$12,487,335.00	$14,482,335.00

The warehouse and larger buildings such as the antenna technician work building can be designed from the beginning to serve as integrations centers during construction, and then be modified into operations support centers once construction is complete.

9.4.5 Processor Building at ngVLA Site

This building, which will house the ngVLA Central Processor, will be located in the vicinity of the array core. It will necessarily require a room which is shielded against RFI along with an HVAC system capable of maintaining a safe temperature for the processor. A building-wide or processor-dedicated UPS will also be required.

Locating the building partially underground would increase the RFI protection significantly. An underground processor building has a cost estimate of $3.2M, based on 2018 RSMeans data.

ngVLA Processor Building									
				UNIT COST $/SQFT			COST IN 2018 $		
	SQFT	RSMeans Ref	Building Type Comparison	0.25	MEDIAN	0.75	0.25	MEDIAN	0.75
Processor Building at ngVLA central site	10,000.00	50 17 00 26 0500	Eng & Lab Buildings	265	$271.00	$295.00	$2,650,000.00	$2,710,000.00	$2,950,000.00
with underground construction							$250,000.00	$250,000.00	$250,000.00
						TOTAL	$2,900,000.00	$2,960,000.00	$3,200,000.00

9.4.6 Heavy Equipment Depot at ngVLA Site

A 5,000 square foot covered parking area will be used to house heavy equipment such as cranes and man lifts while not in use. This area will decrease weathering and prolong equipment life.

ngVLA Equipment and Parking depot				
	S.Q.F.T	$/S.Q.F.T	RSMeans Ref	Total
Equipment Depot	5,000	$47.00	50 17 00 15 0500	$235,000.00

The current VLA warehouse and Track/HVAC areas could be repurposed as heavy equipment depots, but given their size they may be better suited for cold storage.

9.4.7 Auto and Heavy Equipment Repair Facility at ngVLA Site

A 5000 square foot auto/heavy equipment repair facility will be needed to perform maintenance and repair to the vehicles needed to maintain the array. The table below details the building costing for such a facility based on RSMeans data.

ngVLA Auto Repair Facility, On Site				
	S.Q.F.T	$/S.Q.F.T	RSMeans Ref	Total
Repair Facility	5,000	$97.00	50 17 00 09 0500	$485,000.00

9.4.8 Remote Support Stations

Remote support stations located strategically to support the most outlying antenna will be capable of housing a staff of 5 technicians and support equipment. The remote support stations are estimated to be approximately 2,700 sqft. Each station will have 1,500 sqft of office and lab area including required facilities. A 1200 sqft high bay shop area will house service vehicles and other required equipment. The table below details costing based on RSMeans data.

ngVLA Remote Support Station				
	S.Q.F.T	**$/S.Q.F.T**	**RSMeans Ref**	**Total**
Remote Support Station	2,700	$97.00	50 17 00 09 0500	$261,900.00

9.4.9 RFI Chamber

The testing and characterization of assemblies and equipment for potential RFI is a constant requirement for a radio astronomy observatory.

RFI Chamber Cost Estimate		**RSMeans Ref**
Building size S.F.	2000	
RFI Chamber size S.F.	900	
W (FT)	30	
L (FT)	30	
H (FT)	10	
Building Unit Cost	$97.00	50 17 00 09 0500
Building Cost	$194,000.00	
Wall and Ceiling S.F.	2100	
Floor S.F	900	
Wall and Ceiling Shielding, 12 OZ panel, Unit price	$12.60	13 49 33.50 0100
Floor Shielding, 12 OZ copper panel, Unit Price	$18.75	13 49 33.50 0150
Total Shielding	$43,335.00	
Total	**$237,335.00**	

9.5 Site Support

9.5.1 Site Water and Sewer, Trash Removal

The aging VLA water and sewer systems were designed to accommodate over 100 employees stationed at the site. While the ngVLA will not have this many people working on the site at one time, a well to provide water for firefighting remains a requirement. The current sewage lagoon is in good shape, but it may require a redesign for smaller capacity. Alternatively, an underground septic system may be the wiser choice.

The cost to re-work or drill a new site well, install pipe to the Processor building, and install a small septic system is estimated to be approximately $250K.

The current method of trash disposal at the JVLA is not sustainable. The on-site landfill which has served as the repository for decades of trash generated at the JVLA is quickly running out of space, with no clear way of expanding the pit. Furthermore, environmental regulations are much stricter than at the time of original construction. Obtaining a permit from the New Mexico Environmental Department (NMED) is not a given. The ngVLA site will produce much less volume of trash than the JVLA. It is the recommendation that in lieu of building a new landfill, a kind of mobile transfer station be employed. At a cost of approximately $250K, a garbage truck with compactor that could be periodically driven to the Socorro landfill would serve this purpose.

9.5.2 Fiber Communications

On the ngVLA site, fiber between the processor building and the array will be direct buried along with the power cables. For remote locations, a similar technique will be used. For estimation purposes, the lengths of the antenna access roads and other roads at the site are used as a basis to estimate fiber length. For remote locations, an average distance of one mile per location is used. No provision is made to estimate the cost of the fiber between the ngVLA site and Socorro, nor is any attempt made here to estimate the cost of rented fiber for the long-baseline stations. The cost estimate for a sufficient length of 24-strand Single Mode Fiber (SMF) to outfit the ngVLA is $900K.

9.5.3 Site Communications

$200K is estimated for site phones and internet installation.

9.5.4 Trash Transfer Station and Recycling

$250K for a compacting garbage truck is estimated.

9.5.5 Weather Station Infrastructure

Weather stations are required at each of the 46 remote mid-baseline and ten long-baseline locations, with another seven situated around the core and spiral arms site. The infrastructure for 63 weather stations, which includes the pad, tower, and hardware has a cost estimate of $656K. This does not include any electronics associated with the weather stations.

ngVLA Weather Station Tower							
	L.F	**C.Y**	**$/L.F.**	**$/C.Y**	**Qty.**	**RSMeans Ref**	**Total**
Center Foundation Pile 2'-6" Diameter, 4' Deep	4		$68.50		1	31 63 26.13 0300	$274.00
Pile Mobilization					1	31 63 26.13 4600	$2,975.00
Guy Wire Anchor Blocks (footings)		1.33		$430.00	3	03 30 53.40 3825	$1,715.70
Guyed Tower, 50' 90 MPH Wind						33 81 13.10 0100	$5,450.00
	Total Per Tower						$10,414.70
	Estimated Towers						63
	Total						**$656,126.10**

The weather stations will also require power and fiber for each location. Trenching planned for antenna power and fiber should be used for the weather station infrastructure, if possible. The approximate cost to purchase armored direct burial fiber ($0.59/ft) and power conductor ($0.80/ft) to each weather station is estimated to be $356K. Infrastructure required to support the ngVLA weather stations has a total cost estimate of $1.012M.

10 Alternative Design and Cost Reduction Options

10.1 Leverage Existing VLA Buildings and Infrastructure

Section 8.1 presents an overview of the findings of the VLA buildings and infrastructure assessment. At the time of this report, a cost estimate to update the site to acceptable standards is not available.

In addition to cost, there are additional concerns with re-purposing the existing structures and utilities to serve the ngVLA mission. Installation of fiber and power to the new array from existing buildings would necessarily cross paths with existing buried lines. Any transition between JVLA and ngVLA that involves having both operational at the same time would have additional and severe complications. Furthermore, the work required to excavate for new lines could easily damage existing ones, rendering the JVLA inoperable until repairs could be made.

10.2 Power Redundancy for Processor Building and Central Site

As specified in this reference study, the Processor Building has but a single power feed. If the switchgear that supplies this feed is down due to failure or maintenance, the array will not be operational. To mitigate this situation, a secondary feeder from an alternate point in the grid could be installed, but whether the cost is justified to implement this is not clear.

Maintenance on the switchgear that feeds the Processor Building is anticipated to take a single day per year. With proper spares on hand, failures such as a defective breaker would require a relatively straight forward maintenance visit from the electricians to replace the defective assembly. Nonetheless, in the event of a massive failure in the switchgear, a redundant unit would be welcome.

Redundancy could be designed in to the electrical infrastructure design to mitigate this type of power failure at an approximate cost of $250K. This would include the additional routing of power cable from the grid to a separate enclosure containing two breakers capable of sustaining power to the Processor Building.

10.3 Potential Cost Reductions

In the event that it becomes necessary to reduce the expense of this project there are several tradeoffs that may be made with only moderate impact to the design and functionality of the proposed system.

10.3.1 Plains Array Switchgear

The proposed arrangement of distribution switchgear divides antennas into 23 groupings. Reducing the number of groupings by 25% yields a corresponding reduction in equipment costs. Based on the quotes received during the EIU at the JVLA, this reduction is estimated as being approximately $300,000.

The tradeoff provided by this cost reduction is primarily a reduction in array performance during maintenance operations. Shrinking the number of antenna groupings necessitates an increase in the number of antennas within those groups, and, consequently, the number of antennas brought offline during maintenance of any line-side components between those antennas and the distribution switchgear.

10.3.2 Generators

Several avenues exist for reducing equipment costs related to generators. In what is likely the simplest method of reducing these costs, it may be possible to reuse the backup generator installed new at the VLA in 2018. This 3MW unit is expected to have few hours of use by the time ngVLA begins construction. As such, it will likely be a prime candidate for generator #2, reducing the $6M estimate down by roughly one-third. There is some risk in reusing the generator instead of purchasing a new one, but, barring the unforeseen, this should be negligible.

Another method to significantly reduce system cost would be to downgrade the proposed generators from prime source ratings to emergency backup rated units. This would cut construction costs for the generators by approximately 10%. Downgrading the units in this fashion would impact EPA permitted runtimes, and warrants further investigation.

10.3.3 Above Ground Processor Building

$250K in savings could be realized should the project decide upon an above-ground processor building.

10.3.4 Eliminate Remote Support Stations

At a future date, should the operations plan no longer require remote support stations, construction costs would be reduced by $1.31M.

11 Options vs. Cost

11.1 Assumed Costs

Assumed Costs			
Electrical Grid, HV Equipment	$60.2M	Water/Sewer (central site only)	$250K
Antenna (Pads and Fences)	$20M	Communications (central site only)	$200K
Fiber (24 SMF cable only)	$900K	Waste Transfer Station (central site)	$250K
Roads	$10.08M	Weather Station Pads, Towers, Fiber, Power (65)	$656K
DSOC lease with renovation	$500K + $280K/year	Visitor Center	$705K
UPS for Machine Shop	$150K	Geotechnical surveys for remote sites	$115K
Total Assumed Costs			**$94M + $280K/yr**

11.2 Building Costs – Options

Building Costs - Options			
1. Renovate existing VLA Buildings and Infrastructure	$20M	6. Central Processing Building – below ground	~$3.2M
2. Science/Computing Support Center lease (metro location)	$1.27M/yr.	7. Heavy Equipment Depot	$235K
3. Magdalena Campus	$14.48M	8. Heavy Equipment Repair Facility	$485K
4. Electronics Repair Facility in Socorro	$4.07M	9. Remote Support Stations (5)	$1.31M
5. Central Processing Building – above ground	$2.95M	10. RFI Chamber for Processor	$237K

11.3 Building Plan Options

The table below provides a snapshot of the key building plan options. Overall, the implemented building scheme does not have a great impact on overall construction cost.

Scheme	Description	Cost	Notes
Assumed Costs & 1	Existing VLA structures, utilities, and other infrastructure will be upgraded to current standards and leveraged to accommodate the ngVLA. Duty stations remain mostly unchanged.	\$114M + \$280K/yr	Concerns: RFI exposure, Insufficient space for maintenance staff, no extra space for integration during VLA to ngVLA transition and other major transition problems.
Assumed Costs & 3–5, 7, 8–10	Discontinue operations at the current site. Current site buildings could be reutilized for storage. Renovate DSOC for Science, Computing, & Electronics repair. Create Magdalena Campus, remote stations, and above ground site Processor & Heavy Equipment facilities.	\$117.8M+ \$280K/yr	Concerns: Sufficient space for staff in DSOC, DSOC not well suited for product integration, difficulty in recruiting/retaining scientific and computing staff to Socorro. Reduced, but present RFI concern at site.
Assumed Costs & 2–5, 7, 8-10	Same as above, with relocation of Scientific and Computing staff to a major metropolitan area. Above ground Processor building.	\$117.8M + \$1.6M/yr	Same as above, with better RFI protection for Processor and more favorable location for Science and Computing recruitment and retention.
Assumed Costs & 3, 4, 6–10	Renovate DSOC for science, computing, and observatory support groups, establish technical repair facility in Socorro, remote stations, and a Magdalena campus. Processor building is under ground. Current site buildings could be reutilized for storage.	\$118M + \$280K/yr	Concerns: Scientific and Computing staff recruiting and retention, RFI protection for processor could be better.
Assumed Costs & 2–4, 6–10	Same as above, with relocation of Scientific and Computing staff to a major metropolitan area. Underground Processor building.	\$118M + \$1.6M/yr	Reference Design Recommendation. Above concerns mitigated.

12 Recommendation

The existing JVLA buildings and infrastructure are outdated and in need of an expensive renovation (and likely expansion) to support the project mission of the ngVLA. For some of the infrastructure, complete replacement must take place. Also, any major work done on the existing facilities would have a severe impact on a successful transition between JVLA and ngVLA operations. For these reasons, we believe entirely new structures must be built to support the regular operations and maintenance of the array.

Furthermore, in agreement with the operations concept and due to RFI concerns, it is recommended that only the minimum number of staff be stationed near the core and plains arrays. One way to accomplish this is to create a "Magdalena Campus" for Tier 1 technical staff and other support staff who require close proximity to the antennas. Additional technical staff who require more sophisticated laboratories will be located in Socorro, NM, in a new state-of-the-art facility on or near the campus of New Mexico Tech. The existing DSOC building will continue to be used for other NRAO personnel, such as Fiscal, Purchasing, HR, and CIS.

To improve recruitment and retention of scientific and computing staff, the establishment of a center in or near a major metropolitan area is recommended.

Finally, it is the recommendation of this study to establish five regions for the mid-baseline antennas. The antennas in each region would be serviced by staff working out of a remote support station within the region. These facilities could be located in towns that are centrally located within the region.

13 Appendix

13.1 Abbreviations and Acronyms

ADA	Americans with Disabilities Act
AIV	Antenna Integration and Verification
CNC	Computer Numerical Control
DBE	Digital Back-End
DSOC	Domenici Science Operations Building
DTS	Data Transmission System
EIU	Electrical Infrastructure Upgrade
EMS	Emergency Medical Services
ES&S	Environment, Safety, and Security
HVAC	Heating, Ventilation, and Air Conditioning
kVA	kilo-Volt-Ampere
LV	Low Voltage
LRU	Line Replaceable Unit
M&C	Monitor and Control
MV	Medium Voltage
MVA	Medium-Volt-Ampere
NMT	New Mexico Tech (New Mexico Institute of Mining & Technology)
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
SCADA	Supervisory Control and Data Acquisition
SOC	Science Operations Center
UPS	Uninterruptible Power Supply
VLA	Very Large Array
VLBA	Very Large Baseline Array

13.2 VLA Demolition Costs

The table below details the estimated cost to demolish the existing site buildings. These costs are provided for reference only, and are not considered for ngVLA construction.

Building Demolition														
							RSMeans Ref		RSMeans Ref	RSMeans Ref	RSMeans Ref			
							02 41 16.30 0020-0080		02 41 16.17 0420	02 41 16.17 1080	02 41 16.17 4250			
	Occupied	Common	Total S.F	Height	Volume C.F	Volume C.Y	Demolition Cost C.F.	Footing Length L.F	Slab Demo S.F	Footing Demo L.F		Disposal	Demolition Cost	Total Demo Cost
Warehouse	266	4595	4861	15	72915	2700.555556	$0.36	300	$1.09	$14.00	$17.90	$48,339.94	$36,277.74	$84,617.68
Tech Services	1029	7347	8376	15	125640	4653.333333	$0.36	420	$1.09	$14.00	$17.90	$83,294.67	$61,153.22	$144,447.89
Maintenance Building	359	6294	6653	15	99795	3696.111111	$0.36	370	$1.09	$14.00	$17.90	$66,160.39	$49,083.15	$115,243.54
Track+HVAC	N/A	5000	5000	30	150000	5555.555556	$0.36	300	$1.09	$14.00	$17.90	$99,444.44	$64,195.00	$163,639.44
Generator Building	0	2003	2003	20	40060	1483.703704	$0.36	186	$1.09	$14.00	$17.90	$26,558.30	$19,427.20	$45,985.49
Carpenter Shop	119	1271	1390	15	20850	772.2222222	$0.36	154	$1.09	$14.00	$17.90	$13,822.78	$11,328.61	$25,151.39
A.A.B. Building w/ Transporter	1005	21570	22575	115	2596125	96152.77778	$0.36	408	$3.00	$14.00	$17.90	$1,721,134.72	$1,014,814.50	$2,735,949.22
Paint Booth	0	2600	2600	15	39000	1444.444444	$0.36	216	$1.09	$14.00	$17.90	$25,855.56	$20,181.40	$46,036.96
Control Building			22321	30	669630	24801.11111	$0.38	455	$1.09	$14.00	$17.90	$443,939.89	$287,592.28	$731,532.17
Visitors Center			2851	12	34212	1267.111111	$0.38	184	$1.09	$14.00	$17.90	$22,681.29	$18,994.91	$41,676.20
Cafeteria			5175	15	77625	2875	$0.38	312	$1.09	$14.00	$17.90	$51,462.50	$40,070.33	$91,532.83
										TOTAL		**$2,602,694.47**	**$1,623,118.33**	**$4,225,812.80**

The table below details the estimated cost for VLA antenna pad demolition. The cost is to cut the concrete antenna piers flush with ground level and dispose. These costs are provided for reference only, and are not considered for ngVLA construction.

Antenna Pier Demolition	
	CY.
Pier Volume	5.25
Total Volume	1380.75
# of Piers	263
Tons	2796.01875
Loading Charge	$33,138.00
Haul Charge, 50 mi	$8,543.39
Dump Charge	$226,477.52
Pier Cut Cost/Pier	$250.00
Pier Cut cost	$65,750.00
Mobilization 8 weeks	$2,680.00
Crew Subsistence & Lodging	$14,000.00
Total	**$350,588.91**

13.3 VLA Demolition Gains

The VLA rail system contains over 144 miles of 90lb rail. This rail has a high scrap value and there are companies that will come remove the rail and pay for the steel. This means that not only is the rail a zero cost demolition, but we can actually recoup money for the rail. The table below details the scrap value of the rail based on a 50% scrap price. This estimate is provided for reference only, and is not included in this reference design.

Rail Demolition	
Track Length (mi)	36.00
Rail Length (mi)	144.00
Rail Length (Y)	253,440.00
Rail Weight (lb/Y)	90.00
Rail Weight lb	22,809,600.00
Rail weight (TON)	11,404.80
Splice Bar Spacing (Y)	10.00
Splice Bar Weight (lb)	66.00
Splice Bar Weight lb	1,672,704.00
Splice Bar Weight (TON)	836.35
Total Steel Weight (TON)	12,241.15
Scrap Steel Price $/TON	$100.00
Total Scrap Price	**$1,224,115.20**

13.4 Electrical Staffing

The following FTE estimates are for sufficient electrical staffing to maintain the ngVLA. This information is outside the scope of this document and is provided here for reference only. All values are subject to change.

The JVLA currently has an electrical power division consisting of five members. These staff members include one engineer, three electricians, and one technician. This number is expected to grow to approximately eight. Maintenance of the JVLA is estimated as follows:

- Corrective Maintenance
  - Array------------------------- 0.50 man-years
  - Facilities --------------------- 1.25 man-years
- Preventative Maintenance
  - Array------------------------- 0.75 man-years
  - Facilities --------------------- 1.00 man-years
- Engineering--------------------------- 0.75 man-years
- Management -------------------------- 0.25 man-years
- Training-------------------------------- 0.50 man-years

What these numbers fail to show is the efficiency of the time spent. For example, many corrective maintenance tasks around the array require support from Emergency Medical Services (EMS) trained personnel and removal of power from portions of the array. Both of these concerns affect staffing from other departments (where EMS is pulled from) and impacts the ability of other groups to perform their own work. As such, electricians are often stuck waiting on other groups to complete a job prior to beginning their own tasks.

While the ngVLA will increase the number of antennas tenfold, there isn't a corresponding increase in the level of effort required to maintain the array. For all antennas located in the plains array, engineering estimates maintenance workloads to double. As discussed in the previous section, the maintenance schedule for the ngVLA is expected to be much more relaxed. As such, many of the conflicts between groups working on antennas will be avoided by spacing out maintenance tasks.

As discussed in the preceding section, the fixed locations of the ngVLA antennas is expected to remove one of the largest corrective maintenance tasks within the array. Repairing antenna plugs and jacks will no longer be an issue.

The majority of time currently spent on preventative maintenance tasks throughout the array is travel. Neither inspections nor exercising breakers takes much time for an individual antenna, it is more the physical distance between each location that limits the number of inspections that can be performed within a day. The distances involved with the plains array are comparable between the JVLA and the ngVLA, leading Engineering to estimate this as a 50% increase.

Present expectations are for the supporting facilities (offices, labs, and workshops) will require only a slight increase in support, between 0.5 and 1.0 man-years. The rough equivalency is based on the assumption that the number of support facilities will not likely change. Rather it is simply the size of the electrical services involved that will increase.

The largest increase in workload is expected to come from the existence of the remote sites. Simply visiting a remote site is expected to be at least a two-day endeavor: one day travel in each direction, in addition to the work assigned for that trip. Added to that is that at least two electricians will be dispatched for any given assignment. This adds up to an expected 2240 man-hours (56 locations x 2 staff x 20 hours round trip), or slightly more than one man-year, in preventative maintenance travel time alone.

Overall ngVLA electrical staffing is planned as follows:

- Corrective Maintenance
  - Plains Array: 1.00 man-years
  - Remote Sites: 1.00 man-years
  - Facilities: 1.50 man-years
- Preventative Maintenance
  - Plains Array: 1.00 man-years
  - Remote Sites: 1.50 man-years
  - Facilities: 1.50 man-years
- Engineering: 0.75 man-years
- Management: 0.25 man-years
- Training: 0.50 man-years

Land Acquisition and Regulatory Compliance Scope and Requirements

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PREPARED BY	ORGANIZATION	DATE
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APPROVALS (Name and Signature)	ORGANIZATION	DATE
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Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
1.3 Project Background 5
2 Related Documents and Drawings 5
2.1 Applicable Documents 5
3 Regulatory Compliance 6
3.1 Design Phase 6
3.1.1 NSF-Led NEPA Antecedents 6
3.1.2 Site Quantity/Location 6
3.1.3 Potential Site Size 6
3.1.4 Land Ownership 6
3.1.5 Utilities 6
3.1.6 Lifecycle 7
3.1.7 Operations Model 7
3.2 National Environmental Policy Act (NEPA) 7
3.2.1 NEPA Scope 7
3.2.2 Potential Areas of Impact Evaluated 8
3.2.3 NSF Cooperating Agency Options 9
3.3 Other Environmental Aspects 9
3.3.1 National Historic Preservation Act (NHPA) 10
3.4 Owner Required Environmental Studies 10
4 Land Acquisition 11
4.1 Design and Development Phase 11
4.1.1 Scope 11
4.1.2 Land Use Agreement Forms 11
4.1.3 Land Use Agreement Content 11
4.1.4 GIS Support of LA/RC Efforts 12
4.1.5 Land Acquisition Actions 13
4.1.6 Construction Permits 13
4.1.7 Permit and Land Use Renewals 13
4.1.8 Possible Delays to LA/RC Processes 14
4.1.9 Alternative Site Selection Criteria 14
4.1.10 Potential Site Location Sources 15
4.1.11 Communicating and Identification of Site Risks 16
4.1.12 Operations Activities 16
5 LA/RC Requirements 17
6 Appendix 18
6.1 Abbreviations and Acronyms 18

1 Introduction

1.1 Purpose

This document identifies and captures the requirements for the Land Acquisition and Regulatory Compliance IPT and associated Work Packages through the entire lifecycle of the ngVLA effort. The requirements are intended to address the ngVLA efforts through design including reviews and prototyping, construction, commissioning, operation, and ultimate decommissioning.

This LA/RC requirements document will assist to ensure compliance with federal, state, and local environmental permitting requirements. This plan will contribute to the successful design, construction, characterization, operation, and ultimate decommissioning of the ngVLA site.

1.2 Scope

The ngVLA project funding source is targeted for the NSF Major Research Equipment and Facility Construction (MREFC) account or the Research and Related Activities (R&RA) account and requires National Science Board (NSB) approval. R&RA funds are typically used for smaller-scale construction up to tens of millions of dollars. In either case, the project requires compliance with the NSF policies for planning and management of large facilities. This project will be a "major federal action" subject to full National Environmental Policy Act (NEPA) compliance.

This document, designed for the LA/RC project effort, follows the NSF defined lifecycle stages:

- Development and Design,
- Construction,
- Operation, and
- Termination.

This document discusses the efforts leading through construction, although operational considerations for lease renewal are not to be overlooked. The project may progress to the Design Phase once the NSF Astronomy (AST) Division prepares a proposal to the NSF Director and an internal NSF review supports the effort. After this proposal approval, the project may progress to the Design Phase. The Design Phase commences with the Conceptual Design effort. Overall project schedule is beyond the scope of this document.

The Conceptual Design Phase (after Development) signals the initiation of budget estimates, prioritization of science goals, and other forecasts including risks. The potential environmental and safety impacts must be considered in the site selection, resulting in a clearly articulated project element for the Conceptual Design Review (CoDR). The preliminary parametric budgetary estimates for land acquisition, including schedule estimates, must also be prepared at this time. Importantly, the Project Execution Plan (PEP) must be drafted and updated by the CoDR. The CoDR progresses to the Preliminary Design Phase.

The scope of this document extends to all Integrated Product Teams, all project reviews, work practices in labs and worksites, and all subcontractors that provide documentation, procedures, or work at any ngVLA site.

Implementation of successful Land Acquisition and Regulatory Compliance efforts is complex and critical to the success of the project. Many of the actions needed to acquire access to a property can be directly addressed. However, the identification, investigation, and ultimate acquisition of each parcel of land must remain a priority effort throughout the project or the project itself may be at risk.

After the project is approved and funded, ngVLA must execute land use permits or agreements with the site host or owners. The completion of these agreements will allow site access to complete the remaining actions. As access is authorized, additional studies may be required to identify environmental constraints. After site location and characterization is complete and the final site locations are selected, construction permits must be addressed. Finally, once the site is under construction, operational permits may be necessary.

LA/RC actions including any termination requirements for the VLA site are not contemplated in this document. Any extension of the ngVLA effort and site selection to foreign, non-United States locations or sites may introduce additional regulatory compliance, permitting, and environmental studies beyond the scope of this document.

1.3 Project Background

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

Construction and integration will be distributed across several existing NRAO and partner sites and in new facilities for this purpose. Operations will be conducted from both the VLA site and an Array Operations Center.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this document to the extent specified. In the event of conflict between the documents referenced herein and the content of this Safety Specification, the content of this document shall be considered as a superseding requirement.

Reference No.	Document Title	Rev / Doc. No.
AD01	ngVLA Preliminary System Requirements	V1.0, 2017-03-30
AD02	Environment, Safety, and Security Policy and Program Manual	Version D, October 2016

3 Regulatory Compliance

The Regulatory Compliance work package includes critical permitting and environmental project impact completion. The initial impacts are evaluated and land acquisition efforts begin in earnest in the Preliminary Design Phase. The project-wide Environmental Assessment, including the NSF NEPA action described herein, must be fully completed with the exception of additional landowner-required assessments. Any owner-required assessments are completed during the construction phase of the project.

3.1 Design Phase

3.1.1 NSF-Led NEPA Antecedents

To commence with efficient use of resources and meet project scheduling, the LA/RC effort relies on a stable project concept. The following identifies some early issues the ngVLA project must address in preparation for the LA/RC effort.

3.1.2 Site Quantity/Location

This step establishes the optimal observation configuration through modeling to begin identifying potential site locations. The configuration must identify how many sites are anticipated on existing land in use by NRAO, i.e. VLA, and how many sites are required to complete the project. It also provides an acceptable error range for fine location adjustments, or micro-siting, of sites. The project must identify the process to adjust configuration should a location be unavailable for siting. If candidate sites are already identified, these must be communicated to LA/RC to begin tracking the locations and establishing early contacts.

3.1.3 Potential Site Size

It is essential to identify the required land area for siting the telescopes. Some candidate sites may be available at a <1 acre size requirement, but the land acquisition effort will be more difficult and locations limited if the required plot exceeds 5–10 acres. Additionally, the intent to construct identical facilities needs to be known. Should the telescope sites differ materially, the locations must be identified where the differences occur. This is required for later environmental evaluation efforts.

3.1.4 Land Ownership

Sites located outside the US will require additional effort and coordination with foreign authorities. These locations will require significant effort and time and must be coordinated with both the local authorities as well as the NSF. For US-based sites, the land acquisition strategy may include a mix of approaches. There are several impacts to the project effort resulting from the final approach selected. For example, leasing land from private landowners is generally quicker to execute, but potentially brings increased potential cost implications for annual lease fees. Federal land availability varies depending on the agency. Some agencies have the local authority to enter into land use agreement, whereas for other agencies, such as National Park Service, navigating the land use requirements process is complex. Once the strategy is developed, LA/RC should be able to develop a schedule for the project based on the anticipated availability of the selected sites. Additional strategies are discussed later in this document.

3.1.5 Utilities

The project must identify the largest anticipated demand for utilities. Such issues as water and sewer needs will drive later environmental and construction permitting efforts. Maximum anticipated electrical power demands and any requirements for alternative power generation will affect permitting. Identification for fiber needs must be addressed as well. Even if land acquisition is successful, power delivery may require identification of power easements and thus affect the construction schedule as well as project cost.

3.1.6 Lifecycle

The required lifecycle affects the land use agreement. Owners must understand the implications of a 20–50 year agreement. In addition, the agreement must address restoration requirements upon completion of the operational life of the site. As the NSF may not own the land, this component must not be overlooked. The site restoration plan may be a factor for some landowners, and there are potential cost implications to the funding agency.

3.1.7 Operations Model

The operations model does not need to be complete early in the project; however, a conceptual operational model must be available. This will assist in determining onsite/offsite storage capacity, parts inventorying, site staffing plans, and similar issues. This is important as the site storage and staffing affects site size and potentially affects the NEPA environmental evaluation.

3.2 National Environmental Policy Act (NEPA)

The significance and complexity of the ngVLA effort will require NRAO to work with the NSF Program Officer for full compliance with National Environmental Policy Act of 1969 (NEPA) requirements for the project. This may require consultation and coordination with the NSF Environmental Compliance Team in the NSF Office of General Counsel to ensure compliance with this aspect of the program.

3.2.1 NEPA Scope

The initial NEPA effort (outlined in Figure 1, next page) can take over a year to complete and may include compliance with the National Historic Preservation Act and the Endangered Species Act, as described below. Sites considered for construction on Native American land, or with the potential to affect Native Americans, require consultations with the appropriate Native American authorities. Any issues related to compliance can introduce significant schedule and cost risks to the effort. NSF is responsible for these consultations. The consultation for these efforts must be initiated early in the Conceptual Design Phase.

The NSF is required under NEPA to evaluate the potential environmental effects of actions they propose to fund. The NSF commissioned assessment will be conducted in accordance with NEPA requirements, the Council on Environmental Quality (CEQ) regulations of 1978, and 45 Code of Federal Regulations (CFR) Part 640. This evaluation requires an analysis of the proposed actions and various alternatives depending on the significance of a proposed project's effects on the environment. The most detailed and expensive is the completion of an Environmental Impact Statements (EIS) to the less comprehensive Environmental Assessments (EA) and Categorical Exclusions (CATEX or CE).

If, prior to or during development of an EA, the NSF determines the project may cause significant environmental impacts, an EIS would be considered at significant cost and delay. However, if the NSF determines there are no significant impacts from the proposed project, then a Finding of No Significant Impact (FONSI) is issued. If the proposed project fits within a category of activities that the NSF has already determined normally has no potential for significant environmental impacts (CATEX), there is no need to complete an EA or EIS. For example, the Bureau of Land Management (BLM) within the Department of the Interior has CATEX in place for certain activities, such as snow fences for safety.

The NSF does not currently have an extensive listing of CATEX for proposed actions. However, the magnitude of the proposed ngVLA effort will require an EA as a minimum and a CATEX is unlikely. This initial environmental effort is submitted at the completion of the NSF's Institution/Organization Environmental Impacts Checklist. This checklist identifies at an early stage the potential impacts of the project. NRAO is able to complete this checklist internally. However, the authority and responsibility for environmental determination for the ngVLA effort, as with all projects, lies with the NSF.

The required Environmental Assessment in compliance with NEPA is intended to address the proposed action with the ultimate objective to identify whether the NSF should establish and support the ngVLA proposal. This assessment is designed to identify the effects of establishing the project as detailed in the conceptual design, at the locations described. Under NEPA, this is the Preferred Alternative.

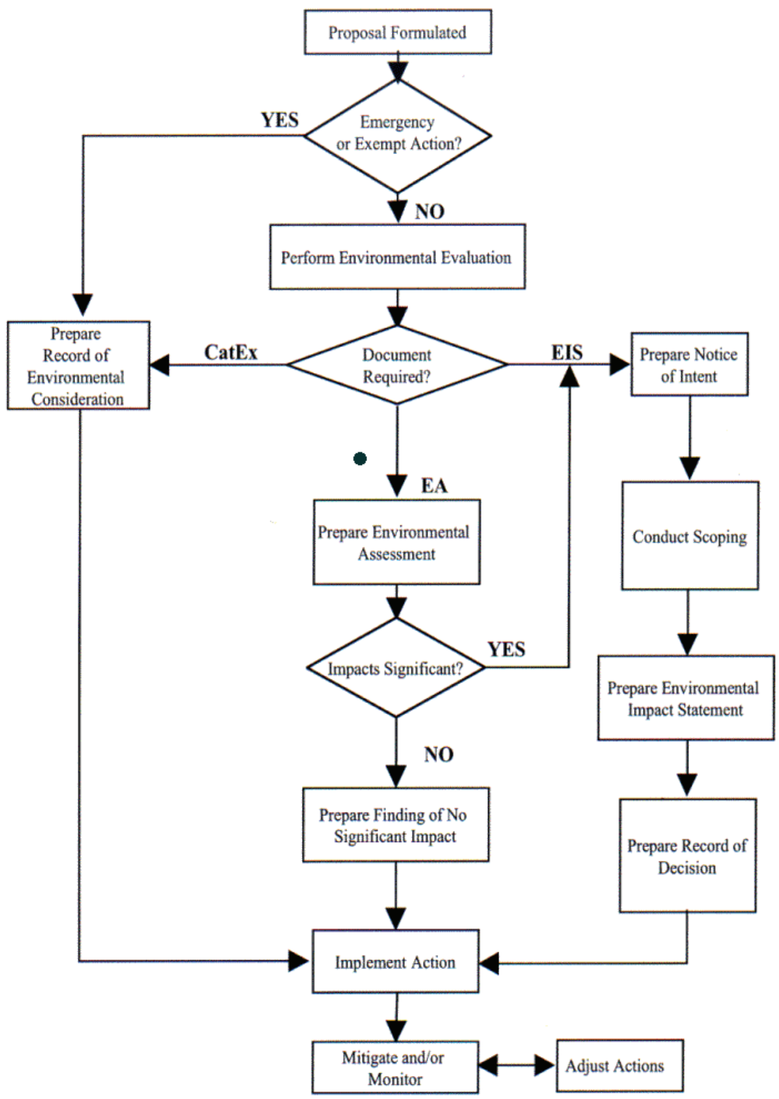

Figure 1 - The NEPA process (source: NASA).

3.2.2 Potential Areas of Impact Evaluated

As the NEPA EA continues, it includes agency and public participation including public meetings to review and discuss the impacts from the individual locations selected. Select areas of analysis include the following:

- Land Use: Impacts to existing or planned land use
- Topography: Alterations to the gross topography
- Hydrogeology and Groundwater: Use of and impact to groundwater
- Demographics: Change in community demographics during construction and operations
- Community Resources: Level of service provided by the community

- Hydrology: Potential for hydrologic impacts from water runoff
- Socioeconomic Impacts on Local Economy: benefits to local economy spending
- Air Quality: Potential emissions and generation of fugitive dusts from the proposed project
- Noise: Impacts to human and wildlife receptors
- Water Quality: Impacts to water quality from sedimentation or erosion
- Common Vegetation and Plant Communities: Whether vegetation would be altered or removed
- Common Fauna: Whether common fauna would be displaced or killed as a result of project activities
- Sensitive Ecological Communities: Looks for habitat types that are rare in the general area and that may be at risk by the development
- Sensitive Species: Examines the presence of protected species and the impact to their ecosystems
- Cultural resources: Addresses archaeological sites and sites of cultural importance
- Utilities: Considers existing utility system and whether the impact to other resources could occur
- Environmental Justice: Evaluates fair treatment and meaningful involvement of all people
- Aesthetics and Visual Resources: Relates to the existing views and landscape character

As the NEPA statute requires federal agencies to evaluate the potential environmental effects of proposed projects on the human environment, the NSF has historically funded and conducted this effort separate from the project funding. LA/RC would be expected to provide significant support for the environmental contractor selected to perform this effort. This effort may progress in parallel with conceptual design and development activities as long as the development effort is funded and there is no significant alteration in impacts to the above areas because of project changes.

3.2.3 NSF Cooperating Agency Options

It is possible to identify large federal landowners such as BLM or US Forest Service (USFS) for multiple proposed ngVLA sites. In such cases, it may benefit the project to encourage the NSF Program Officer to pursue an agreement with the federal landowner to become a cooperating agency for the EA. The cooperating agency role derives from NEPA, which called on federal, state, and local governments to cooperate with the goal of achieving "productive harmony" between humans and their environment. The CEQ's regulations implementing NEPA allow federal agencies (as lead agencies) to invite other federal agencies to serve as cooperating agencies in preparing environmental impact statements.

3.3 Other Environmental Aspects

In addition to the programmatic Environmental Assessment described below, sites may require additional environmental studies to assure that the identified environmental constraints are avoided, or where not possible to avoid an identified environmental constraint, mitigation measures are taken to reduce the impact of the ngVLA project to the environment.

Other studies that may be reasonably anticipated include the following:

- Additional focused EA effort
- Wetlands delineations
- Archaeological or cultural resources studies (NHPA/SHPO)
- Viewshed analysis
- Sensitive species studies
- Biological assessment studies

Not all possible actions are listed in this document but must be included in the Project Execution Plan. The LA/RC Department is responsible to identify all required site-specific studies. Costs for the studies must be included in the project costing.

3.3.1 National Historic Preservation Act (NHPA)

While NEPA efforts include consideration of historical facilities, the project will need to address site-specific impacts considered in the construction activities, including routing for any infrastructure. Under NHPA, Section 106, any federal project requires the NSF to take into account the effects of the project on historic properties. NSF is also required to consult on the Section 106 process with State Historic Preservation Offices (SHPO), Tribal Historic Preservation Offices (THPO), and Native American Tribes.

Historic properties are any prehistoric or historic districts, sites, buildings, structures, or objects that are eligible for or already listed in the National Register of Historic Places. Also included are any artifacts, records, and remains (surface or subsurface) in any properties of traditional religious and cultural importance to Tribes. This requirement applies regardless of the location of the historic property.

Even if an historic property is not listed in the National Register or has not previously been determined eligible, it will need evaluated to determine if it meets NHPA eligibility. This effort may be contracted to consultants and included in the project costs separately from the NEPA effort for site-specific clearances.

3.4 Owner Required Environmental Studies

The Project Execution Plan (PEP) requires inclusion of the detailed Site Selection Criteria as well as a description of the selected sites. The PEP must identify the need for any environmental studies, permitting requirements, and specific site assessments.

A FONSI determination from the NEPA analysis does not exempt the project from additional studies required by the site host or local regulations. Initially, by use of the completed NEPA/EA, the project should identify sites/locations where additional studies are known to be required. The project must consult with local authorities to identify locations requiring additional studies on environmental impacts or other permit restrictions that may be in place to protect the most threatened habitats. Construction activities including power delivery and communication efforts may require separate environmental studies along the planned power route where no existing infrastructure exists.

The project must work with ngVLA contracts and procurement to select a qualified consultant(s) to complete the studies as needed. It is likely that a consultant(s) with regional or national capabilities will be needed. The most effective means to complete additional studies is to develop a Basic Ordering Agreement with the selected consultant(s). This agreement will allow work to be completed as additional environmental study requirements are identified.

Monitoring the effort is essential to track progress and allow construction scheduling to occur efficiently. Each site will require tracking and progress monitoring on a weekly basis. Sites that are encountering difficulties in permitting and environmental mitigation efforts must be flagged and mitigation managed.

Costing and schedule implications are to be tracked with the project's controls. Environmental studies are a construction-related cost and must be tracked accordingly. Progress metrics must be developed and reported by the LA/RC team.

4 Land Acquisition

4.1 Design and Development Phase

4.1.1 Scope

The Land Acquisition work package requires development of initial budgetary estimates for developing land acquisition agreements. The scope encompasses requirements for any partnership agreements, risks facing the project, and termination liabilities. Upon successful completion of the NEPA process and the NSF filing of the Record of Decision for the project, the NSF will consider the project construction funding levels. Typically, this requires finalized project designs and successful design reviews. While preliminary agreements may be initiated, only after receipt of construction funding may the project enter into the final Land Use Agreements. It is preferable from the project schedule perspective to initiate preliminary land use agreements prior to construction funding, but agreements must contain termination clauses in case project funding is not achieved.

4.1.2 Land Use Agreement Forms

During NEPA efforts, LA/RC together with the ngVLA Program Management team should develop a standard NSF approved MOU/MOA to utilize for land use agreements. Standardized agreements allow for prompt approval with minimal NSF review and reduces the number of iterations needed between the signatories. Where use of federal land is anticipated, the NSF should be encouraged to enter into agreements with identified federal agencies to facilitate land use acquisition. For example, where an ngVLA construction site is proposed on BLM land, an existing cooperative agreement between the NSF and the BLM will identify and facilitate completion of any Special Use Permits required for project execution.

The agreements between NRAO and the site host can include Memoranda of Agreement, Special Use Permits, revocable agreements, and nonrecorded easements. This also includes MOUs and Lease Agreements. Generally, the ngVLA will use primarily the standard NSF-approved MOU/MOA described above to define the relationship between ngVLA and the host site, owner, or organization. However, in some cases a Special Use Permit or client-preferred agreement may be utilized to authorize use on some federal lands. The exact vehicle used will depend on the site ownership and management.

4.1.3 Land Use Agreement Content

The ngVLA project team and the LA/RC Department will seek a standard agreement for NSF approval that details the terms of the relationship with the site. This agreement will address shared costs, any buffer zone requirements, access, in-kind contributions, etc. As some of the agreements are prepared prior to the commitment of construction funds, the details will describe contingencies if there is a funding failure. Site-specific land use agreements will be prepared for locations where the required agreement form differs from the pre-approved agreement. Such individual site agreements require NSF Program Office review. Upon NSF approval, the landowner or representative will iterate with LA/RC for final contractual execution. Each agreement must detail the following at a minimum:

- Contact information
- Legal details of the agreement
- Effective period and any limitations on the planned use
- Any specific requirements for protected species, historical features, or additional studies required
- Preliminary design contents, if available
- The planned location(s) of the ngVLA project infrastructure
- Renewal period information and remuneration details
- Where required, prepare site-specific land use agreements (e.g., Special Use Permits)

If the agreements are prepared prior to the commitment of construction funds, the details will describe contingency if there is funding failure.

4.1.4 GIS Support of LA/RC Efforts

GIS tools and models will be used to geo-locate the parameters of the environmental studies, site locations, and utility routing in support of LA/RC efforts and applications. Under such a system, permits and new applications will be incorporated into a geodatabase to provide accurate and site-specific data needed to make permitting decisions. Permits must determine proposed easements for access routes, surveyed land boundaries, construction limits, and any identified protected features located on a site-specific basis.

Permit applications with potential environmental impacts will require engineering drawings or plans with precise location information and identified environmental constraints. Applications that have no potential for impact will consist of county maps, topographic maps, or other digital elevation model (DEM) maps with point shape(s) entered on a data layer to identify the site and project boundaries. Application maps will be created for each permit application, as needed, with geographic information. The application maps will define the limits of acceptable site boundaries and include images of approximately 5 km around the estimated site on a high-resolution, geo-rectified, color aerial image.

With locations adequately identified, environmental studies, construction plans, and site characterization sampling will identify appropriate restriction areas. In locations where constraints are identified, such as threatened and endangered species, influence areas will be mapped based on existing data or, where needed, additional environmental studies. If a critical area is impacted by construction activities, ngVLA will investigate an alternate location. After construction, all the site facilities and infrastructure should be surveyed and mapped to allow for future permitting and decommissioning activities. Figure 2 shows an early example of the need for and use of GIS mapping.

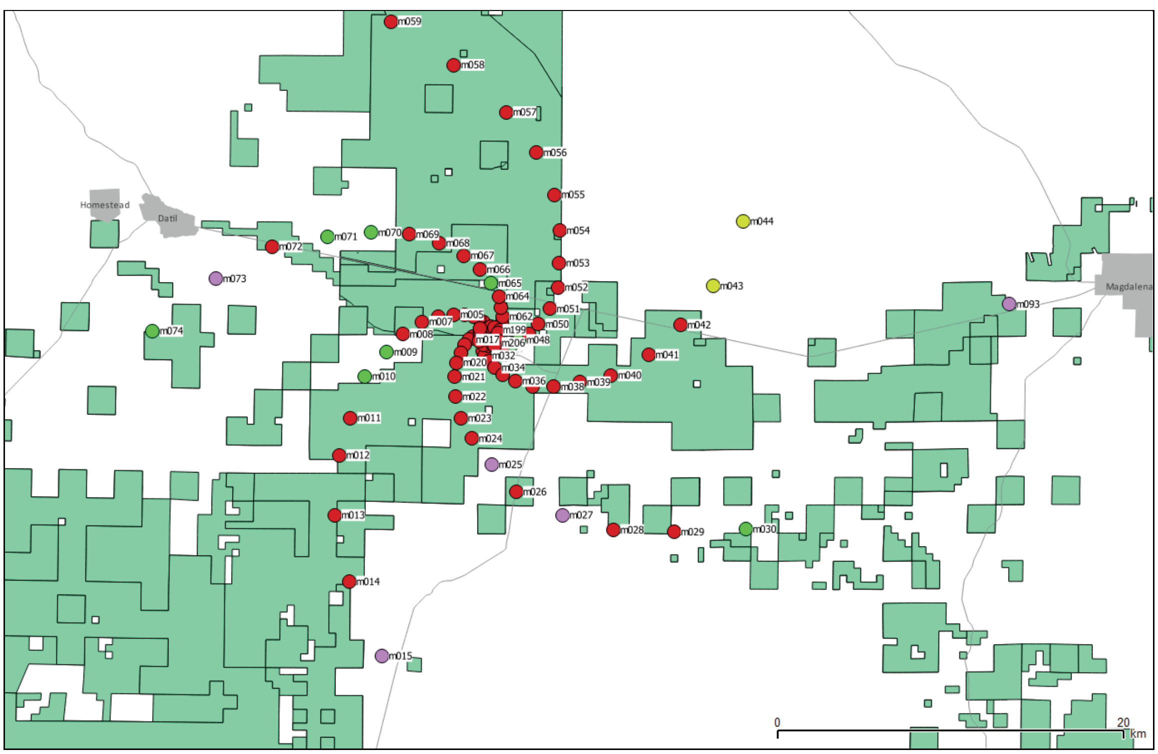

Figure 2 - Preliminary state land ownership mapped for construction phase.

4.1.5 Land Acquisition Actions

Upon award of construction funds, the LA/RC Department is responsible to initiate formal negotiations with property owners and legal representatives. Land Use Agreements allow for all future access, site characterization, construction, operations, and maintenance. The ngVLA LA/RC IPT is responsible for land acquisition, easements for access and utilities, land rights, licenses, leases, permits, and other documents necessary for the construction, operation, and maintenance of facilities. Specific responsibilities include the following:

- Conduct diverse and complex negotiations with landowners
- Work on the settlement of damage claims with land owners relative to property damage caused or created during the construction
- Advise and assist in establishing market values used in the acquisition of land and land rights
- Prepare documents for rights of entry, contracts, easements, licenses, leases, permits, options to purchase, and other documents as necessary to acquire adequate rights for the project
- Explain the purpose of the project and development to individual landowners, to consortium groups, and/or at public meetings
- Make independent decisions within established parameters on approach of landowners and conduct lease negotiation
- Explain project to landowners including expectations, procedures, timing, and financial arrangements
- Provide reports to Project Management and NSF on the status of negotiations and details of executed lease agreements
- Prepare lease agreements and other necessary documents related to the transaction

4.1.6 Construction Permits

This document does not attempt to describe design details of the facilities, the infrastructure, or other aspects of the project design. In general, any facility and telescope design will be prepared by a consultant and will meet all relevant building codes. A construction or building permit may be required in some jurisdictions for the construction of the ngVLA project. Generally, this requires inspections during and after construction activities are completed to assure compliance with national, regional, and local building and life safety codes.

For example, an electrical permit may be required in some jurisdictions. This permit may require rough-in inspections, service inspections, and final inspections prior to connecting electrical systems to the main service. Generally, the construction contract will require the contractor to obtain these permits. In ngVLA locations where construction permits are not required, the ngVLA project will be built according to plans and specifications that comply with national building codes.

Where construction permits are required, LA/RC must work with the construction team to identify which permits will be obtained by the contractor. The permit records for all construction activities must be maintained on a site-by-site basis and provided to Permitting for final recordkeeping. This may include water discharge permits (NPDES), air quality permits, and fuel tank permits. While not responsible to obtain the permits, LA/RC will support general contractor efforts in obtaining county/local permits.

4.1.7 Permit and Land Use Renewals

Each permit and land use agreement generated will be logged into a LA/RC database to ensure that any renewals are addressed on a timely basis for continuity of site operations. The information tracked will include the following:

- Permit name
- Permit number

- Permit type
- Issuing agency, with contact information
- Cost of the permit
- Supporting documentation
- Length of permit acquisition
- Renewal information, including details of any required reports
- Expiration date and estimate of time needed for renewal
- Copy/original of the permit

4.1.8 Possible Delays to LA/RC Processes

In addition to the above-described items, it should be noted that land use agreements and associated permits are processed by a variety of agencies across a variety of jurisdictions. This results in a complex permitting approach, and delays will occur due to legal review, the level of backlogged applications that exist at a given permit approver, local resistance to the construction, environmental mitigation issues, or any number of unanticipated issues. Permitting efforts may be required to address multiple property owners in the identification of easements, property boundaries, setbacks, etc. Clearly the more complex any given agreement or assessment, the more time the permit will require.

To address these concerns, procedures will be established to maintain communication between LA/RC and Project Management in ngVLA. It is highly recommended that permitting status and progress be reported at every management meeting with particular emphasis on schedule and cost. When acquisition of any particular site is recognized as a potential risk, a mitigation effort should be implemented and criteria established for potential alternative site selection.

4.1.9 Alternative Site Selection Criteria

The following considerations and guidelines are useful for determining if a candidate site is feasible for use and construction. Note that this list includes guidance on factors other than permitting and acquisition capability. When any of the following factors exceed project triggers, the project team must evaluate and decide if the project must mitigate the concerns or eliminate the site from consideration. This will assist in the review of a site's status and guide a determination of when an alternate site should be considered. Note this schedule is not comprehensive and must be established during project planning.

Review Area	**Considerations**
Scientific Requirements	Unable to meet established science requirements. Factors may include RFI mitigation or other established science goals and criteria.
Geotechnical Requirements	Slope too severe, or foundation unstable. Includes construction feasibility limits established by the project.
Geotechnical Requirements	Foundation construction would cause significant impact to the environment. Consideration with the NEPA and any other environmental studies required.
Power Requirements	Unable to obtain grid power within project limits, for example, approximately 3 miles from candidate site, or power delivery cost exceeds $1,000,000. Cannot obtain authorization for overhead power.
Land Use Agreement	Unable to develop acceptable terms with landowner. Unable to obtain NSF approval on land terms. Unable to obtain landowner approval. Agreements cannot cover the entire project life.

Review Area	Considerations
Environmental Findings	Sensitive species identified that requires site relocation. Archaeological or cultural sites discovered that require a new site. Wetland mitigation is required.
Environmental Assessments	Environmental Impact Studies are required. Studies do not result in a FONSI. Public comments are received during public comment period that cannot be resolved.
Permitting	Site cannot be permitted. Site permitting duration exceeds one year. Loss of permit. Public or special interest resistance to permit issuance.

4.1.10 Potential Site Location Sources

The land management agencies and owners of potential site locations for ngVLA antennas will determine the preferred Land Acquisition approach. The degree of process formality varies depending on the management agency. The acquisition process has a direct impact on the project schedule and introduces risk to the project planning. Naturally, the preferred approach is to minimize the overall cost of acquisitions and reduce the uncertainty introduced to the project construction schedule.

The following introduces several options and the potential benefits and concerns of each type of land agent.

Land Holder	Potential Benefits	Potential Issues
Private	• Reduced mandatory environmental studies • Possible timely closing, possession, and acquisition • Reduction in need for legal environmental consultation	• If purchased, inflated costs for land • If leased, negotiations for access of landowner and ongoing lease renewal • Impact of shared use with owner • Site specific conditions from negotiations
Federal Agency, Bureau of Land Management	• Generally amenable to projects • Lease agreements are not typically onerous • Moderate in terms of time needed to execute agreements • Typically limited or no fee for land use • Significant land holdings are present in the southwest areas of proposed antenna sites • Readily extended lease agreements	• Not likely to be able to purchase land • Requirements for additional archaeological studies • If archaeological sites are detected, antenna location may require relocation • Distance from power and fiber likely • May not be able to direct final antenna location; BLM may direct available sites • Land may already be leased for cattle grazing; introduces requirement for additional stakeholder

Land Holder	Potential Benefits	Potential Issues
Federal Agency, United States Forest Service	• Generally amenable to projects • Lease agreements are not typically onerous • Typically limited or no fee for land use; may require Special Use Permit • Significant land holdings are present in the southwest areas of proposed antenna sites	• Not likely to be able to purchase land • Requirements for additional biological, site-specific environmental studies, and archaeological studies • If sensitive sites are detected, antenna location may require relocation • Distance from power and fiber likely • May not be able to direct final antenna location; USFS may direct available sites • Agreements typically take additional time to execute through USFS review process
State Agency	Currently, land acquisition and use process is not sufficiently understood to determine benefits and issues	Currently, land acquisition and use process is not sufficiently understood to determine benefits and issues
Education Organizations or Universities	• Typically willing to share land use • Enthusiastic support of scientific efforts	• Legal and administration review are time consuming • Site specific requirements for the agency benefits included in agreement • Potential costs of land lease is an ongoing issue

4.1.11 Communicating and Identification of Site Risks

Any group or individual is expected to identify and communicate potential risks to a site selection. When a site is identified to have potential development issues or concerns, it must be reported to Project Management and LA/RC for mitigation plan development and tracking. LA/RC is responsible to track the concern and provide regular updates in the project status meeting. Part of the mitigation may include initiation of accelerated permitting efforts to mitigate potential delays.

Once a site has been declared "at-risk," the ngVLA science team(s) are responsible to identify potential alternative sites upon direction from ngVLA project management. The ngVLA science team(s) are responsible to report progress on alternative site selection to allow characterization activities, design work, and permitting to commence in a timely manner.

4.1.12 Operations Activities

LA/RC operational activities are anticipated to include permit renewals, lease monitoring and renewal, processing of lease fees, and GIS mapping activities. Staff ramp-down is anticipated. Other activities are not addressed in this document and shall follow the NRAO administrative polices.

5 LA/RC Requirements

The following requirements shall be fulfilled *as a minimum* to achieve the needed demands of the LA/RC scope of work across the ngVLA Project.

Requirement ID	Requirement Name	Requirements
LRC0018	Identify LA/RC Constraints	The ngVLA Project Office shall establish land acquisition constraints, including costs limits, technical constraints that may jeopardize site acquisition, and schedule constraints.
LRC0019	Address Environmental Issues in Change Requests	All project Change Requests shall be considered relative to impact on site selection and potential environmental impacts.
LRC0020	Report and Record Site Metadata	All site selection data (with metadata) regarding site boundaries, easement locations, etc., shall be reported to LA/RC and recorded in the GIS database.
LRC0021	Ensure Site Permits Are In Place	Site construction and development contractors shall obtain necessary permits for their contracted work, including required site inspections by authorities having jurisdiction.
LRC0022	Use Approved Land Use Agreements	Land Use Agreements shall conform to NSF pre-approved formats and content.
LRC0023	Review Exceptions to Land Use Agreements	Any exceptions to pre-approved Land Use Agreements shall be reviewed and approved by the LA/RC and Project Office.
LRC0024	Ensure All Agreements Are Executed by LA/RC	Only authorized LA/RC representatives may execute Land Use Agreements and commitments.
LRC0025	Review Proposed Site Shifts	After baseline locations are fixed, i.e. post-CoDR, any potential site or facility may be relocated or shifted only upon review of the Project Office and LA/RC.
LRC0026	Report LA/RC Discussions	Any land use or environmental discussion with land representatives must be reported and recorded with LA/RC.
LRC0027	Control Changes to Project for Environmental Integrity	The ngVLA project shall ensure stable project design to ensure integrity of Finding of No Significant Impact (FONSI).
LRC0028	Implement Mitigation as Directed	The ngVLA project shall implement mitigating actions required in completed NEPA.

6 Appendix

6.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
BLM	Bureau of Land Management
CATEX	Categorical Exclusions
CDR	Critical Design Review
CEQ	Council on Environmental Quality, regulations of 1978
CFR	Code of Federal Regulations
CoDR	Conceptual Design Review
DEM	Digital Elevation Model
EA	Environmental Assessment
EIS	Environmental Impact Statement
FONSI	Finding of No Significant Impact
GIS	Geographical Information System
ICD	Interface Control Document
IPT	Integrated Product Team
LA/RC	Land Acquisition and Regulatory Compliance
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MREFC	(NSF) Major Research Equipment and Facility Construction
NEPA	National Environmental Policy Act of 1969
NHPA	National Historical Preservation Act
ngVLA	Next-Generation VLA
NRAO	National Radio Astronomy Observatory
NSB	National Science Board
NSF	National Science Foundation
PEP	Project Execution Plan
R&RA	Research and Related Activities
RD	Reference Document
RFI	Radio Frequency Interference
SHPO	State Historic Preservation Offices
TBD	To Be Determined
THPO	Tribal Historic Preservation Offices
USFS	US Forest Service
VLA	Jansky Very Large Array

ngVLA Product Tree

020.10.10.05.00-0001-LIS-A-PRODUCT_TREE

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
R. Selina	Electronics Div., NRAO	2019-07-18
R. Treacy	Program Mgmt. Dept., NRAO	2019-07-18

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer — 2019.08.08 10:37:19 -06'00'	Electronics Division, NRAO	2019-08-01
R. Farnsworth, Project Manager — Richard L Farnsworth — Digitally signed by Richard L Farnsworth Date: 2019.08.08 12:41:16 -04'00'	Asst. Director, Program Management, NRAO	2019-08-01
M. McKinnon, Project Director — Mark McKinnon — Digitally signed by Mark McKinnon Date: 2019.08.08 17:05:50 -06'00'	Asst. Director, NM-Operations, NRAO	2019-08-01

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director — Mark McKinnon — Digitally signed by Mark McKinnon Date: 2019.08.08 17:06:04 -06'00'	Asst. Director, NM-Operations, NRAO	2019-08-01

Change Record

Version	Date	Authors	Affected Section(s)	Reason/Initiation/Remarks
1	2017-05-05	Selina, Treacy	All	Initial Draft based on VLA Product Tree.
2	2017-06-09	Selina, Treacy		Minor edits, distributed to NM Electronics Division for review.
3	2017-06-16	Selina, Treacy		Expanded PSN field one to 3 digits, added another level, deleted '99' designator, cleaned up some comments.
4	2017-07-17	Treacy		Replaced document header, aligned with Ver 1 WBS, removed lots of placeholders.
5	2017-07-17	Selina	Cover, 1, 2, 3, 4	Fixed release block, fixed header. Minor text corrections to make the document more ngVLA centric (than original VLA basis). Corrections for consistency with WBS.
6	2017-07-19	Treacy	all	Introduce gaps in the numbering for expansion, based on Ver 3 of the WBS.
7	2017-08-09	Treacy	several	Removed duplication of narrative and definitions, moved to source documents, added Short Baseline Array to a designation of 020.47, PM Sec 05, SE, Sec 10, Sec 30.05 FE, and Sec 30.10 Cryo.
8	2017-08-28	Treacy	05.50, 05.55, 47.05	Updated to reflect Ver 6 of the WBS.
9	2017-09-08	Treacy	020.22 020.05.60 020.05.60.05	Updated to reflect Ver 7 of the WBS, added Array Calib, Change Mgmt , Change Requests.
10	2017-09-28	Treacy	Multiple sections	Updated to reflect Ver 8 of the WBS.
11	2018-03-28	Treacy	020.25.01 020.30.03	Added 020.25.01 for Antenna optics and 020.30.03 for Integrated Electronics and sub branches, changed previous use of Front End to Receiver (for cartridge level docs).
12	2018-03-29	Treacy	020.60.00	Assigned 020.60.00.00.01 as Array Infrastructure – Existing Facilities.
13	2018-05-14	Treacy	020.05.60	Added branches to accommodate unique folders for each CR.
14	2018-05-17	Treacy	020.21.00 020.05.55	Added branches for Science Communication, StRR.
15	2018-05-29	Treacy	020.10.15.01	Added branch for Stakeholder requirements.
16	2018-06-15	Treacy	020.10.05.05	Added branch for Lifecycle plans.
17	2018-06-26	Treacy	020.40	Reassigned Central Signal Processor to previous branch designation as Correlator; Correlator is now a subsidiary branch to CSP.
18	2018-07-09	Treacy	020.35 020.40	Expanded ngVLA LO sections. Repurposed CSP subsections.

19	2018-10-01	Treacy	020.05.55 020.30.05 020.30.10	Added Decadal Reviews. Int. 020.05.55.05.02. Ext. 020.05.55.05.03. Moved Dewars to Receiver branch. Added Refrigerators to Cryo branch.
20	2018-10-16	Treacy	Multiple	Attempt to align with BU to WBS mapping 020.05.15.05.00-0002-BUD_WBS; significant mismatches remain, edits following IPDSR, removed WVR 020.45.05, changed to simpler example in Appendix, note IPDSR-159 remains unresolved at this time.
21	2019-03-01	Leff	020.30	Corrected Antenna Electronics summary items that were decomposed too far.
22	2019-07-18	Selina	Multiple	Updated for release with Reference Design (Appendix). Addressed comments from review by M. Stewart. Added clarifying context to sections 1 through 3. Removed extraneous entries that were inconsistent with adopted heuristics.
A	2019-08-01	Lear	All	Prepared PDF for approvals and release.

Table of Contents

1 Description 5
1.1 Purpose 5
1.2 Scope 5
2 Related Documents and Drawings 5
2.1 Applicable Documents 5
3 Product Tree Heuristics 6
4 Product Tree 7
4.1 020.00 ngVLA Project – General 7
4.2 020.05 Project Management and Administration 7
4.3 020.10 Systems Engineering 8
4.4 020.15 Assembly, Integration, Verification (AIV) 9
4.5 020.20 Commissioning and Scientific Validation (CSV) 9
4.6 020.21 Science Communication 10
4.7 020.22 Array Calibration 10
4.8 020.23 Array Configuration 10
4.9 020.25 Antenna 10
4.10 020.30 Antenna Electronics 10
4.11 020.35 Reference Signals 12
4.12 020.40 Central Signal Processor 12
4.13 020.45 Independent Phase Cal System 13
4.14 020.47 Short Baseline Array 13
4.15 020.50 Computing and Software 13
4.16 020.52 HPC Systems 15
4.17 020.55 IT Infrastructure 15
4.18 020.60 Array Infrastructure 16
4.19 020.65 Ops Buildings 16
4.20 020.70 Land Acquisition & Regulatory Compliance 17
4.21 020.75 Education & Public Outreach 17
4.22 020.80 Safety 17
5 Appendix 18
5.1 Abbreviations and Acronyms 18
5.2 Document Assignment Example 18

1 Description

1.1 Purpose

This document lists all products to the sub-assembly level incorporated within the ngVLA project.

This hierarchical list of products is the definitive map for assigning ngVLA project product documentation by the Product Structure Number (PSN). The Product Tree is also useful as a guide to organize other ngVLA supporting systems, such as issue tracking or configuration management systems.

This document should be helpful in determining where to place new documents or design artifacts within the product tree structure as well as where to find existing documentation. This is a living document that will be elaborated and updated as the ngVLA progresses through the project lifecycle.

Since the fundamental reason for this document's existence is the control of documents and design artifacts, some additional functional branches are included (e.g., PM, SE, Admin, Safety). Only artifacts which are configuration controlled should be assigned under these branches, and these artifacts are therefore deliverables for development milestones and reviews during the design and construction phase of the project. This differs from the traditional remit of a product breakdown structure, but it permits a single, stable reference for organizing project documentation and design artifacts that is decoupled from the organizational structure or work breakdown structure.

1.2 Scope

The scope of this document extends to all ngVLA deliverables. It fully encompasses the ngVLA so that it may be adopted project-wide and grow as the design evolves.

The scope of this document is limited to listing the assigned Product Structure Numbers. The details of documentation management are addressed in AD01, and the overall approach to configuration control is described in AD02.

The ngVLA product tree shall be maintained by Systems Engineering.

2 Related Documents and Drawings

2.1 Applicable Documents

Doc. #	Document Title	Document Number
AD01	ngVLA Product Documentation Management Plan	020.10.10.10.00-0001-PLA
AD02	ngVLA Configuration Control Plan	020.10.10.15.00-0001-PLA
AD03	ngVLA Work Breakdown Structure	020.05.05.00.00-0001-LIS

3 Product Tree Heuristics

The following rules or heuristics have informed the development of this product tree.

In order to provide capacity to add branches with logical placement, levels 2 and 3 initially skip by increments of five. It is acceptable to insert numbers within these incremental skips to preserve a logical assignment.

The breakdown at the second levels of the product tree shall be aligned with the ngVLA WBS where practical. The third through fifth levels are managed by the relevant group lead or lead engineer as applicable, with guidance from Systems Engineering. The decomposition at the third through fifth level of the tree should always be product/deliverable based.

The ngVLA document number or part number assignments require "fully qualified" part numbers. The definition of fully qualified requires that documents are only assigned at the fifth level of the tree. In cases where a document or artifacts is describing a higher level assembly, the 00 branch designator is reserved to refer to the parent element. E.g., a document or artifact with a PSN of 020.00.00.00.00 refers to the ngVLA project as a whole. These 00 branches have the descriptor "General" in the tree below. Please consult AD01 for further information.

There are TBDs in the Product Tree as placeholders, to demonstrate the pattern of the structure.

4 Product Tree

4.1 020.00 ngVLA Project – General

020.00.00 **ngVLA Project – General**
020.00.00.00 ngVLA Project – General
020.00.00.00.00 ngVLA Project – General

4.2 020.05 Project Management and Administration

020.05.00 **Project Management and Administration – General**
020.05.00.00 Project Management and Administration – General
020.05.00.00.00 Project Management and Administration – General

020.05.05 **Scope – General**
020.05.05.00 Scope – General
020.05.05.00.00 Scope – General

020.05.10 **Schedule – General**
020.05.10.00 Schedule – General
020.05.10.00.00 Schedule – General

020.05.15 **Budget – General**
020.05.15.00 Budget – General
020.05.15.00.00 Budget – General

020.05.20 **Quality Management – General**
020.05.20.00 Quality Management – General
020.05.20.00.00 Quality Management – General

020.05.25 **Human Resources – General**
020.05.25.00 Human Resources – General
020.05.25.00.00 Human Resources – General

020.05.30 **Communications – General**
020.05.30.00 Communications – General
020.05.30.00.00 Communications – General

020.05.35 **Risk – General**
020.05.35.00 Risk – General
020.05.35.00.00 Risk – General

020.05.40 **Procurement – General**
020.05.40.00 Procurement – General
020.05.40.00.00 Procurement – General

020.05.45 **Stakeholders – General**
020.05.45.00 Stakeholders – General
020.05.45.00.00 Stakeholders – General

020.05.50 **Community Engagement – General**
020.05.50.00 Community Engagement – General
020.05.50.00.00 Community Engagement – General

020.05.55 **Administrative – General**
020.05.55.00 Administrative – General
020.05.55.00.00 Administrative – General
020.05.55.05 Reviews– General
020.05.55.05.00 Reviews – General
020.05.55.05.01 StRR
020.05.55.05.02 Internal Pre-Decadal Submission Review
020.05.55.05.03 External Pre-Decadal Submission Review
020.05.55.10 Proposals – General
020.05.55.10.00 Proposals – General
020.05.55.15 Reports – General
020.05.55.15.00 Reports – General

020.05.60 **Change Management – General**
020.05.60.00 Change Management – General
020.05.60.00.00 Change Management – General
020.05.60.01.00 Change Management – 2018 General
020.05.60.01.01 2018 Sequential Entry 1
020.05.60.02.00 Change Management – 2019 General

4.3 020.10 Systems Engineering

020.10.00 **Systems Engineering – General**
020.10.00.00 Systems Engineering – General
020.10.00.00.00 Systems Engineering – General

020.10.05 **Life Cycle Management and Concepts – General**
020.10.05.00 Life Cycle Management and Concepts – General
020.10.05.00.00 Life Cycle Management and Concepts – General
020.10.05.05 Life Cycle Management Plans
020.10.05.05.00 Life Cycle Management Plans

020.10.10 **Documentation and Configuration Management – General**
020.10.10.00 Documentation and Configuration Management – General
020.10.10.00.00 Documentation and Configuration Management – General
020.10.10.05 Product Tree – General
020.10.10.05.00 Product Tree – General
020.10.10.10 Documentation Management – General
020.10.10.10.00 Documentation Management – General
020.10.10.10.01 Document Management Platform
020.10.10.15 Configuration Management – General
020.10.10.15.00 Configuration Management – General
020.10.10.15.01 Configuration Management Platform

020.10.15 **Requirements Definition and Management – General**
020.10.15.00 Requirements Definition and Management – General
020.10.15.00.00 Requirements Definition and Management – General
020.10.15.01 Stakeholder Requirements – General
020.10.15.01.00 Stakeholder Requirements – General
020.10.15.05 Science Requirements – General
020.10.15.05.00 Science Requirements – General
020.10.15.05.05 Science Requirements – Use Cases
020.10.15.05.10 Science Requirements – Use Case Analysis
020.10.15.10 System Requirements – General
020.10.15.10.00 System Requirements – General

020.10.20 **Architectural Definition and Analysis – General**
020.10.20.00 Architectural Definition and Analysis – General
020.10.20.00.00 Architectural Definition and Analysis – General

020.10.25 **System Level Studies – General**
020.10.25.00 System Level Studies – General
020.10.25.01 RFI Flagging & Excision

020.10.30 **System Level Standards**

020.10.35 **Quality Assurance**

4.4 020.15 Assembly, Integration, Verification (AIV)

020.15.00 **Assembly, Integration, Verification**
020.15.00.00 Assembly, Integration, Verification – General
020.15.00.00.00 Assembly, Integration, Verification – General

020.15.05 **TBD – General**
020.15.05.00 TBD – General
020.15.05.00.00 TBD – General

4.5 020.20 Commissioning and Scientific Validation (CSV)

020.20.00 **Commissioning and Scientific Validation – General**
020.20.00.00 Commissioning and Scientific Validation – General
020.20.00.00.00 Commissioning and Scientific Validation – General
020.20.00.00.01 Commissioning and Scientific Validation – TBD

020.20.05 **TBD – General**
020.20.05.00 TBD – General
020.20.05.00.00 TBD – General
020.20.05.00.01 TBD

4.6 020.21 Science Communication

020.21.00 **Science Communication – General**
020.21.00.00 Science Communication – General
020.21.00.00.00 Science Communication – General
020.21.00.00.01 Science Communication – TBD

4.7 020.22 Array Calibration

020.22.00 **Array Calibration – General**
020.22.00.00 Array Calibration – General
020.22.00.00.00 Array Calibration – General

4.8 020.23 Array Configuration

020.23.00 **Array Configuration – General**
020.23.00.00 Array Configuration – General
020.23.00.00.00 Array Configuration – General

4.9 020.25 Antenna

020.25.00 **Antenna – General**
020.25.00.00 Antenna – General
020.25.00.00.00 Antenna – General

020.25.01 Antenna – Optics
020.25.01.00 Antenna Optics General
020.25.01.00.00 Antenna Optics General

020.25.05 **Antenna - Mount**
020.25.05.00 Antenna Mount General
020.25.05.00.00 Antenna Mount General

4.10 020.30 Antenna Electronics

020.30.00 **Antenna Electronics General**
020.30.00.00 Antenna Electronics General
020.30.00.00.00 Antenna Electronics General
020.30.00.00.01 Antenna Electronics TBD

020.30.03 **Integrated Electronics**
020.30.03.00 Integrated Electronics – General
020.30.03.01 Integrated Front End Package – General (CI level)

020.30.05 **Front End**
020.30.05.00 Front End – General
020.30.05.01 Band 1 (CI)

020.30.05.01.01 – Band 1 Feed
020.30.05.02 Band 2 (CI)
020.30.05.02.01 – Band 2 Feed
020.30.05.03 Band 3 (CI)
020.30.05.03.01 – Band 3 Feed
020.30.05.04 Band 4 (CI)
020.30.05.04.01 – Band 1 Feed
020.30.05.05 Band 5 (CI)
020.30.05.05.01 – Band 5 Feed
020.30.05.06 Band 6 (CI)
020.30.05.06.01 – Band 6 Feed
020.30.05.08 Dewar A General
020.30.05.08.01 Dewar A
020.30.05.09 Dewar B General
020.30.05.09.01 Dewar B

020.30.10 **Cryogenic System**
020.30.10.00 Cryogenic Systems – General
020.30.10.00.01 Cryogenic Systems – TBD
020.30.10.01 Refrigerator A – General
020.30.10.01.01 Refrigerator A
020.30.10.02 Refrigerator B – General
020.30.10.02.01 Refrigerator B
020.30.10.03 Compressor & Distribution – General
020.30.10.03.01 Compressor & Distribution – TBD

020.30.15 **Integrated Down Converters & Digitizers**
020.30.15.00 Integrated Down Converters – General
020.30.15.00.01 Integrated Down Converters TBD
020.30.15.01 Digitizers & Serializers – General
020.30.15.01.00 Digitizers & Serializers – TBD

020.30.25 **Digital Back End (DBE)**
020.30.25.00 Digital Back End (DBE) – General
020.30.25.00.01 Digital Back End (DBE) – TBD

020.30.30 **Data Transmission System (DTS)**
020.30.30.00 Data Transmission System (DTS) – General
020.30.30.00.01 Data Transmission System (DTS) – TBD

020.30.35 **Antenna Time and Frequency References**
020.30.35.00 Antenna Time and Frequency References – General
020.30.35.00.01 Antenna Time and Frequency References – TBD

020.30.45 **M&C Hardware Interface Layer**
020.30.45.00 M&C Hardware Interface Layer – General
020.30.45.00.01 M&C Hardware Interface Layer – TBD

020.30.50 **DC Power Supply System**
020.30.50.00 DC Power Supply System – General
020.30.50.00.01 DC Power Supply System – TBD

020.30.55 **Bins, Modules, and Racks**
020.30.55.00 Bins, Modules, and Racks – General
020.30.55.00.01 Bins, Modules, and Racks – TBD

020.30.60 **Environmental Control**
020.30.60.00 Environmental Control – General
020.30.60.00.01 Environmental Control – TBD

4.11 020.35 Reference Signals

020.35.00 **Reference Signals – General**
020.35.00.00 Reference Signals – General
020.35.00.00.00 Reference Signals – General
020.35.00.00.01 Reference Signals – TBD
020.35.05 **Reference Signal Generation**
020.35.05.00 Reference Signal Generation – General
020.35.05.00.00 Reference Signal Generation – General
020.35.05.00.01 Reference Signal Generation – TBD
020.35.10 **Reference Signal Distribution**
020.35.10.00 Reference Signal Distribution – General
020.35.10.00.00 Reference Signal Distribution – General
020.35.10.00.01 Reference Signal Distribution – TBD

4.12 020.40 Central Signal Processor

020.40.00 **Central Signal Processor – General**
020.40.00.00 Central Signal Processor – General
020.40.00.00.00 Central Signal Processor – General
020.40.00.00.01 Central Signal Processor – Studies

020.40.05 **Correlator and Beamformer**
020.40.05.00 Correlator and Beamformer – General
020.40.05.00.00 Correlator and Beamformer – General
020.40.05.00.01 Correlator and Beamformer – TBD

020.40.10 **Pulsar Engine**
020.40.10.00 Pulsar Engine – General
020.40.10.00.00 Pulsar Engine – General
020.40.10.00.00 Pulsar Engine – TBD

020.40.20 **Test Correlators**
020.40.20.00 Test Correlators – General
020.40.20.00.00 Test Correlators – General
020.40.20.00.01 Test Correlators – TBD

4.13 020.45 Independent Phase Cal System

020.45.00 **Independent Phase Cal System – General**
020.45.00.00 Independent Phase Cal System – General
020.45.00.00.00 Independent Phase Cal System – General
020.45.00.00.01 Independent Phase Cal System – TBD

020.45.10 **Phase Cal System Front-End**
020.45.10.00 Phase Cal System Front-End – General
020.45.10.00.00 Phase Cal System Front-End – General
020.45.10.00.01 Phase Cal System Front-End – TBD

020.45.15 **Phase Cal System Back-End**
020.45.15.00 Phase Cal System Back-End – General
020.45.15.00.00 Phase Cal System Back-End – General
020.45.15.00.01 Phase Cal System Back-End – TBD

4.14 020.47 Short Baseline Array

020.47.00 **Short Baseline Array – General**
020.47.00.00 Short Baseline Array – General
020.47.00.00.00 Short Baseline Array – General
020.47.00.00.01 Short Baseline Array – TBD

020.47.05 **Short Baseline Array Antenna**
020.47.05.00 SBA Antenna – General
020.47.05.00.00 SBA Antenna – General
020.47.05.01 SBA Antenna Optics
020.47.05.01.00 SBA Antenna Optics – General

4.15 020.50 Computing and Software

020.50.00 **Computing and Software – General**
020.50.00.00 Computing and Software – General
020.50.00.00.00 Computing and Software – General
020.50.00.00.01 Computing and Software – TBD

020.50.01 **Computing and Software – General**
020.50.01.00 Computing and Software – General

020.50.05 **Software Engineering**
020.50.05.00 Software Engineering – General
020.50.05.00.00 Software Engineering – General
020.50.05.00.01 Software Engineering – TBD

020.50.10 **Software Architecture**
020.50.10.00 Software Architecture – General
020.50.10.00.00 Software Architecture – General

020.50.10.00.01 Software Architecture – TBD

020.50.15 **Common Infrastructure**
020.50.15.00 Common Infrastructure – General
020.50.15.00.00 Common Infrastructure – General
020.50.15.00.01 Common Infrastructure – TBD

020.50.20 **Integration & Test System**
020.50.20.00 Integration & Test System – General
020.50.20.00.00 Integration & Test System – General
020.50.20.00.01 Integration & Test System – TBD

020.50.25 **Monitor & Control**
020.50.25.00 Monitor & Control – General
020.50.25.00.00 Monitor & Control – General
020.50.25.00.01 Monitor & Control – TBD

020.50.30 **Correlator & CBE**
020.50.30.00 Correlator & CBE – General
020.50.30.00.00 Correlator & CBE – General
020.50.30.00.01 Correlator & CBE – TBD

020.50.35 **Telescope Calibration**
020.50.35.00 Telescope Calibration – General
020.50.35.00.00 Telescope Calibration – General
020.50.35.00.01 Telescope Calibration – TBD

020.50.40 **Observation Scheduling**
020.50.40.00 Observation Scheduling – General
020.50.40.00.00 Observation Scheduling – General
020.50.40.00.01 Observation Scheduling – TBD

020.50.45 **Observation Operation**
020.50.45.00 Observation Operation – General
020.50.45.00.00 Observation Operation – General
020.50.45.00.01 Observation Operation – TBD

020.50.50 **Observation Preparation**
020.50.50.00 Observation Preparation – General
020.50.50.00.00 Observation Preparation – General
020.50.50.00.01 Observation Preparation – TBD

020.50.55 **Data Processing**
020.50.55.00 Data Processing – General
020.50.55.00.00 Data Processing – General
020.50.55.00.01 Data Processing – TBD
020.50.55.01.00 Imaging Algorithms – General
020.50.55.01.01 Imaging Algorithms – TBD

020.50.60 **Data Pipelines**
020.50.60.00 Data Pipelines – General
020.50.60.00.00 Data Pipelines – General
020.50.60.00.01 Data Pipelines – TBD

020.50.65 **Data Archive**
020.50.65.00 Data Archive – General
020.50.65.00.00 Data Archive – General
020.50.65.00.01 Data Archive – TBD

4.16 020.52 HPC Systems

020.52.00 **HPC Systems – General**
020.52.00.00 HPC Systems – General
020.52.00.00.00 HPC Systems – General
020.52.00.00.01 HPC Systems – TBD

4.17 020.55 IT Infrastructure

020.55.00 **IT Infrastructure – General**
020.55.00.00 IT Infrastructure – General
020.55.00.00.00 IT Infrastructure – General
020.55.00.00.01 IT Infrastructure – TBD

020.55.05 **Antenna IT System**
020.55.05.00 Antenna IT System – General
020.55.05.00.00 Antenna IT System – General
020.55.05.00.01 Antenna IT System – TBD

020.55.10 **Computing IT System**
020.55.10.00 Computing IT System – General
020.55.10.00.00 Computing IT System – General
020.55.10.00.01 Computing IT System – TBD

020.55.15 **Ops IT System**
020.55.15.00 Operations IT System – General
020.55.15.00.00 Operations IT System – General
020.55.15.00.01 Operations IT System – TBD

4.18 020.60 Array Infrastructure

020.60.00 **Array Infrastructure – General**
020.60.00.00 Array Infrastructure – General
020.60.00.00.00 Array Infrastructure – General
020.60.00.00.01 Array Infrastructure – Existing Facilities

020.60.05 **Antenna Pads**
020.60.05.00 Antenna Pads – General
020.60.05.00.00 Antenna Pads – General
020.60.05.00.01 Antenna Pads – TBD

020.60.10 **Operations Roads**
020.60.10.00 Operations Roads – General
020.60.10.00.00 Operations Roads – General
020.60.10.00.01 Operations Roads – TBD

020.60.15 **Utility Trench**
020.60.15.00 Utility Trench – General
020.60.15.00.00 Utility Trench – General
020.60.15.00.01 Utility Trench – TBD

020.60.20 **Fiber Utility**
020.60.20.00 Fiber Utility – General
020.60.20.00.00 Fiber Utility – General
020.60.20.00.01 Fiber Utility – TBD

020.60.25 **Electrical Utility**
020.60.25.00 Electrical Utility – General
020.60.25.00.00 Electrical Utility – General
020.60.25.00.01 Electrical Utility – TBD

4.19 020.65 Ops Buildings

020.65.00 **Ops Buildings – General**
020.65.00.00 Ops Buildings – General
020.65.00.00.00 Ops Buildings – General
020.65.00.00.01 Ops Buildings – TBD

020.65.05 **Science Operations Buildings**
020.65.05.00 Science Operations Buildings – General
020.65.05.00.00 Science Operations Buildings – General
020.65.05.00.01 Science Operations Buildings – TBD

020.65.10 **Central Operations Buildings**
020.65.10.00 Central Operations Buildings – General
020.65.10.00.00 Central Operations Buildings – General
020.65.10.00.01 Central Operations Buildings – TBD

020.65.15 **Small Operations Buildings**
020.65.15.00 Small Operations Buildings – General
020.65.15.00.00 Small Operations Buildings – General
020.65.15.00.01 Small Operations Buildings – TBD

020.65.20 **Technical Services Buildings**
020.65.20.00 Technical Services Buildings – General
020.65.20.00.00 Technical Services Buildings – General
020.65.20.00.01 Technical Services Buildings – TBD

4.20 020.70 Land Acquisition & Regulatory Compliance

020.70.00 **Land Acquisition & Regulatory Compliance – General**
020.70.00.00 Land Acquisition & Regulatory Compliance – General
020.70.00.00.00 Land Acquisition & Regulatory Compliance – General
020.70.00.00.01 Land Acquisition & Regulatory Compliance – TBD

020.70.05 **Environmental Impact Statement**
020.70.05.00 Environmental Impact Statement – General
020.70.05.00.00 Environmental Impact Statement – General
020.70.05.00.01 Environmental Impact Statement – TBD

020.70.10 **Land Acquisition & Leases**
020.70.10.00 Land Acquisition & Leases – General
020.70.10.00.00 Land Acquisition & Leases – General
020.70.10.00.01 Land Acquisition & Leases – TBD

4.21 020.75 Education & Public Outreach

020.75.00 **Education & Public Outreach – General**
020.75.00.00 Education & Public Outreach – General
020.75.00.00.00 Education & Public Outreach – General
020.75.00.00.01 Education & Public Outreach – TBD

020.75.05 **Visitor Center**
020.75.05.00 Visitor Center – General
020.75.05.00.00 Visitor Center – General
020.75.05.00.01 Visitor Center – TBD

020.75.10 **Visitor Programs**
020.75.10.00 Visitor Programs – General
020.75.10.00.00 Visitor Programs – General
020.75.10.00.01 Visitor Programs – TBD

4.22 020.80 Safety

020.80.00 **Safety – General**
020.80.00.00 Safety – General
020.80.00.00.00 Safety – General
020.80.00.00.01 Safety – TBD

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Definition
ACU	Antenna Control Unit
BOM	Bill of Materials
CASA	Common Astronomy Software Applications
CI	Configuration Item
CID	Configuration Item Definition
CIL	Configuration Item List
CPU	Central Processing Unit
DTS	Data Transmission System
FRM	Focus Rotation Mechanism
ID	Identification
IF	Intermediate Frequency
LO	Local Oscillator
MIB	Module Interface Board
ngVLA	Next Generation Very Large Array
PSN	Product Structure Number
PCB	Printed Circuit Board
PSU	Power Supply Unit
VLA	Very Large Array

5.2 Document Assignment Example

An example of documents assigned under the Product Tree Hierarchy, in the **Reference Signals** branch might be:

020.35.00 **Reference Signals – General**

020.35.00.00 Reference Signals – General

020.35.00.00.00 Reference Signals – General

020.35.00.00.00-0001-REQ LO Reference and Timing: Technical Requirements
020.35.00.00.00-0002-DSN LO Reference and Timing: Reference Design
020.35.00.00.00-0003-BUD LO Reference and Timing: Cost Estimate

Project Lexicon and Acronyms

020.10.10.10.00-0005-LIS-A-PROJECT_LEXICON_ACRONYMS

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
B. Treacy, S. Leff	Program Mgmt., NRAO	2019-08-01

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A	2019-08-01	A. Lear	Prepared PDF for signatures and release.

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents 4
2.1 Applicable Documents 4
3 Abbreviations and Acronyms 5
4 Project Lexicon 11

1 Introduction

1.1 Purpose

This document provides a single compendium of acronyms and definitions used in the ngVLA project. Providing a master reference for definitions aims to standardize the use of these terms across the project team.

This is a living document that will be updated throughout the project lifecycle.

1.2 Scope

This document is applicable to all ngVLA deliverables. All project personnel should adhere to these definitions across project documentation.

The ngVLA Project Lexicon will be maintained by Systems Engineering.

2 Related Documents

2.1 Applicable Documents

The following documents are applicable to the extent specified:

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Systems Engineering Management Plan	020.10.00.00.00-0001-PLA

3 Abbreviations and Acronyms

Acronym	Meaning
AAB	Antenna Assembly Barn (VLA)
AAS	American Astronomical Society
AAT	Archive Access Tool
ACFH	Axially Corrugated Feed Horn
ACU	Antenna Control Unit
AD	Assistant Director / Applicable Document
ADC	Analog to Digital Converter
AE	Antenna Element
AEC	Architecture, Engineering and Construction
AIPS	Astronomical Image Processing Software
AIV	Assembly, Integration, and Verification
ALMA	Atacama Large Millimeter–Submillimeter Array
AMBSI	ALMA Monitor and Control Bus Standard Interface
AOC	Array Operation Center
API	Application Programming Interface
APM	Atmospheric Phase Monitor
ARCS	Advanced RFI Containment System
AST	Division of Astronomical Sciences (NSF)
AU	Astronomical Unit
AUI	Associated Universities Inc.
AWS	Amazon Web Services
BDF	Binary Data Format
BDP	Basic Data Product
BE	Back End
BH	Black Hole
BW	Band Width
CA	Cooperative Agreement
CAP	Contracts and Procurement
CATE	Cost and Technical Evaluation (Astro2010)
CASA	Common Astronomy Software Applications
CBE	Correlator Back End
CBF	Correlator Beam-Former
CCB	Change Control Board
CDL	Central Development Laboratory
CDP	Central Data Processor
CDR	Critical Design Review
CIS	Computing Information Services
CMMS	Computerized Maintenance Management System
CoDR	Conceptual Design Review
ConOps	Concept of Operations
COTS	Commercial Off-the Shelf
CRE	Change Request
CS	Computing/Software

Acronym	Meaning
CSA	Continuing Support Agreement
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSP	Central Signal Processor
CSV	Commissioning and Science Validation
CSW	Computing and Software
CV	Charlottesville (NRAO)
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
DAC	Digital to Analog Converter
DB	Database
DBE	Digital Back End
DC	Direct Costs
DMS	Database Management and Software
DO	Director's Office
DOORS	Dynamic Object Oriented Requirements System
DR	Dynamic Range
DSP	Digital Signal Processing
DTS	Digital Transmission System
ECO	Engineering Change Order
EDFA	Erbium-Doped Fiber Amplifiers
EDMS	Electronic Document Management System
EDP	Enhanced Data Products
EIA	Electronics Industries Association/Electronics Industries Alliance
EIRP	Effective Isotropic Radiated Power
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
ENOB	Effective Number of Bits
EOC	Extension and Optimization of Capabilities
EPO	Education and Public Outreach
ES	Early Science
ESS	Environmental Safety and Security
ETK	Electronic Time Keeping
EVM	Earned Value Management
FE	Front End (Subsystem)
FIT	Failures in Time
FITS	Flexible Image Transport System
FLS	First Look Science
FMECA	Failure Modes Effects and Criticality Analysis
FOV	Field of View
FSA	Frequency Slice Architecture
FTE	Full Time Equivalent
FWHM	Full Width Half Max
GBO	Green Bank Observatory
GBT	Green Bank Telescope
GM	Gifford-McMahon
GMC	Giant Molecular Clouds

Acronym	Meaning
GPIO	General Purpose Input–Output
GW	Gravitational Wave
HPC	High Performance Computing
HR	Human Resources
HVAC	Heating, Ventilation & Air Conditioning
I2C	Inter-Integrated Circuit (Interface)
ICC	Internal Common Costs
ICD	Interface Control Document
IDC	Indirect Costs
IF	Intermediate Frequency / Interface
IMS	Integrated Master Schedule
IPC	Institute for Packaging Electronic Components
IPT	Integrated Product Team
IQ	In-Phase and Quadrature
IRAM	Institut de Radioastronomie Millimétrique
IRD	Integrated Receiver Digitizer
ISO	International Organization for Standardization
ISP	Internet Service Provider
ITAR	International Traffic in Arms Regulations
JAO	Joint ALMA Observatory
JWST	James Webb Space Telescope
KPP	Key Performance Parameter
KSG	Key Science Goal
L0	Concept, Use Case, and Stakeholder-Level Requirement
L1	System-Level Requirement
L2	Subsystem-Level Requirement
LAST	Local Apparent Sidereal Time
LBA	Long Baseline Array
LBO	Long Baseline Observatory (VLBA)
LFM	Large Facilities Manual
LFO	Large Facilities Office
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LNA	Low Noise Amplifier
LO	Local Oscillator
LOE	Level of Effort
LOI	Letter of Intent
LRU	Line Replaceable Unit
LSP	Legacy Science Program
LSST	Large Synoptic Survey Telescope
LST	Local Sidereal Time
M&C	Monitor and Control
M&S	Materials and Services
MA	Main Array
mas	milli-arcsecond

Acronym	Meaning
MFS	Multi Frequency Synthesis
MMIC	Monolithic Microwave Integrated Circuit
MoE	Measure of Effectiveness
MoP	Measure of Performance
MoS	Measure of Suitability
MPI	Message Passing Interface
MREFC	Major Research Equipment and Facility Construction
MRR	Manufacturing Readiness Review
MS	Measurement Set
MTBF	Mean Time Between Failure
MTDC	Modified Total Direct Costs
MTMFS	Multi-Term Multi-Frequency Synthesis
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MVP	Minimum Viable Product
NASA	National Aeronautics and Space Administration
NDA	Non-Disclosure Agreement
NES	Near Earth Sensing
NGAS	Next Generation Archive System
ngVLA	Next Generation Very Large Array
NIO	New Initiatives Office
NIR	Near-Infrared
NRAO	National Radio Astronomy Observatory
NRC	National Research Council of Canada
NS	Neutron Star
NSF	National Science Foundation
NTC	NRAO Technology Center
NTP	Network Time Protocol
OMT	Orthomode Transducer
OODT	Object Oriented Data Technology
OpsCon	Operations Concept
OPT	Observation Preparation Tool
ORR	Operations Readiness Review
OST	Observer Support Tool
OT	Observing Tool
OTFM	On The Fly Mosaic
OWG	Operations Working Group
PA	Product Assurance
PAF	Phased Array Feed
PB	Primary Beam
PBT	Proposal Builder Tool
pc	Parsec
PDR	Preliminary Design Review
PE	Pulsar Engine
PEP	Project Execution Plan

Acronym	Meaning
PHT	Proposal Handling Tool
PI	Principal Investigator
PL	Project Leader
PLL	Phase Locked Loop
PM	Project Management
PMD	Program Management Department
PMP	Project Management Plan
POC	Point of Contact
POP	Program Operating Plan
PPI	Post Processing Interface
PPS	Pulse Per Second
PSD	Power Spectral Density
PSF	Point Spread Function
PST	Proposal Submission Tool
PWV	Precipitable Water Vapor
QA	Quality Assurance
QC	Quality Control
QRFH	Quad Ridge Feed Horn
R&D	Research and Development
RACI	Responsible Accountable Consulted Informed (matrix/chart)
RAOC	Remote Array Operation Center
RD	Reference Document
RefDR	Reference Design Review
REST	Representational State Transfer
RF	Radio Frequency
RFI	Radio Frequency Interference / Request for Information
RFID	Radio Frequency Identification
RFP	Request for Proposal
RFQ	Request for Quotation
RID	Review Item Discrepancy
rms	Root Mean Square
ROM	Rough Order of Magnitude
ROP	Reference Observing Program
RSD	Reference Signal Distribution
RSS	Root of Sum of Squares
RSS	Remote Support Station
RTP	Round Trip Phase
RVTM	Requirements and Verification Traceability Matrix
S/N	Serial Number
SAC	Science Advisory Council
SADC	Serial Analog to Digital Converter
SB	Scheduling Block
SBA	Short Baseline Array
SCT	Source Catalog Tool
SDM	Science Data Model

Acronym	Meaning
SE	Systems Engineering
SEFD	System Equivalent Flux Density
SEMP	Systems Engineering Management Plan
SIS	Semiconductor–Insulator–Semiconductor / Scientific Information Services
SKA	Square Kilometer Array
SMA	Sub-Millimeter Array
SNR	Signal to Noise Ratio
SO	Socorro (NRAO)
SOP	Standard Operating Procedure
SOW	Statement of Work
SPI	Serial Peripheral Interface
SRDP	Science Ready Data Products
SRR	System Requirements Review
SSA	Science Support and Archiving
SSR	Science Support and Research
StRR	Stakeholder Requirements Review
SV	Science Validation
SWG	Science Working Group
SysML	Systems Modeling Language
TAC	Technical Advisory Council / Time Allocation Committee/ Telescope Allocation Committee
TBC	To Be Confirmed
TBD	To Be Determined
TKIP	Travelling-Wave Inductance Parametric
TPM	Technical Performance Measure
TRACE	Technical Risk and Cost Evaluation (Astro2020)
TTO	Technology Transfer Office
UI	User Interface
URSI	Union Radio-Scientifique Internationale
UT	Universal Time
UVa	University of Virginia
UVML	UVa Materials Laboratory
V&V	Verification and Validation
VCC	Very Coarse Channelizer
VFD	Variable Frequency Drive
VLA	(Jansky) Very Large Array
VLASS	Very Large Array Sky Survey
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VO	Virtual Observatory
WBS	Work Breakdown Structure
WFIRST	Wide Field Infrared Survey Telescope
WVR	Water Vapor Radiometer
XSEDE	Extreme Science and Engineering Discovery Environment

4 Project Lexicon

AAT/PPI Release
Archive Access Tool Post Processing Interface Code base that is validated by an Operations Readiness Review (ORR) and made available for general use.

Agile
Methodology for adaptive development, typically used for software.

Array Maintenance
Monitoring of performance, preventive maintenance, and corrective maintenance of the array by engineers and technicians.

Array Operations
Operations of the array on a day-to-day basis, describing the degree of general automation, the scheduling approach, and operational overheads.

Astro2020
Astronomy and Astrophysics (Astro2020) Decadal Survey that is conducted by the US National Academy of Sciences.

Capability
A set of collective features which provide functionality to a product, defined either in totality or as a subset.

CASA Release
Common Astronomy Software Application Code base that is validated by an ORR and made available for general use.

Delivery
Code that is ready for validation; multiple deliveries constitute a release.

Deployment (Software)
Deployment is the task of releasing code for general use. This typically follows validation to be certain the capabilities function as intended and align with user requirements. Involves updating the release history.

Discovery Driven
A primary mechanism for developing requirements and defining work, typically in an adaptive environment, using rolling wave planning.

Earned Value Management
EVM is a system of programmatic metrics for project performance. Terminology and EVM Processes are defined in the NDIA EVMS Application Guide, which reflects the EIA-748-C-2013 Standard for an EVM System.

Feature
A set of collective stories that work together to realize a functional feature.

Iteration
A designated unit of time, typically sufficient to develop one or more features; requirements are fixed during an iteration.

Key Performance Parameter
KPPs are critical to product performance; each has performance thresholds and objective value.

Measure of Effectiveness
MOEs are developed for each of the L0 Requirements, typically ~6/system.

Measure of Performance
MOPs are derived from MOEs, system performance/capability against system requirements; typically ~5/MOEs are assigned to each L1 requirement.

Measure of Suitability
MOS indicates usefulness, capability, and operability within the given solution.

Metrics
Measures of programmatic processes, requirements compliance and performance. For project performance use terminology and EVM Processes defined in the NDIA EVMS Application Guide, which reflects the EIA-748-C_2013_Standard for EVMS.

Minimum Viable Product
The capability threshold necessary to enter into an ORR.

Plan Driven
A primary mechanism for developing requirements and defining work, typically in a predictive environment, using waterfall planning. Well suited to project management.

Preliminary Baseline
Project primary constraints (scope, schedule, and budget) and secondary constraints (resources, risk, quality), as reflected in the Project Charter, continue under progressive elaboration until changes stabilize and the baseline is relatively mature. Prior to baseline approval, change control does not apply to the preliminary baseline.

Progressive Decomposition
Requirements are progressively decomposed from L0 to L1/L2. They are aligned with the work packages and capability subset to be delivered during a particular planning wave.

Progressive Elaboration
Planning packages are decomposed to work packages in alignment with the level of requirement decomposition provided during a particular planning wave.

Quality
The degree to which a set of inherent characteristics fulfills the identified requirements.

Reference Design
The first technical baseline for the project. The basis of the Astro2020 Decadal Survey cost, risk and technical readiness assessment.

Requirements Backlog (progressive software development)
A requirements backlog is used in an adaptive development methodology where requirement management is flexible, unlike a strict waterfall approach. Requirements are queued in a backlog and prioritized for implementation in the ensuing development/deployment cycle. Frequently, not all requirements can be implemented in the development cycle and lower priority requirements may be carried forward to the next cycle in order to satisfy a fixed release date.

Requirements Fan-Out
As requirements are typically structured in a hierarchy, it can be helpful to establish a consistent fan-out across a system. This can help to ensure that requirements are being defined with the correct level of decomposition, the breakdown is consistent across different subsystems, and similar levels of complexity

are encountered as the integration, verification, and validation processes are executed. A typical ratio is as follows for a system of moderate complexity:

- L0 / MOE 2–12 (~6 per system) these fan out to multiple L1/MOP
- L1 / MOP 2–10 (~5 per L0/MOE) these fan out to multiple L2/TPM
- L2 / TPM 2–6 (~4 per L1/MOP)

Requirements Management and the Tracking Process

- L0 Requirements will be gathered and analyzed for the following:
    - Degree of overlap between science and use cases
    - Science and use cases that have unique and low priority needs
    - Science and use cases that present conflicting needs
- L0 requirements from science and use cases are rank prioritized and weighted.
- MOEs are developed for each of the L0 requirements, typically ~6/system.
- KPPs are identified from the MOEs.
- L0 requirements are assigned to an owner who can validate against the MOE and declare the requirement as met.
- L0 requirements are entered into the RVTM.
- Requirements are analyzed and decomposed from L0 to L1.
- MOPs are derived for each of the MOEs and aligned to the L1 Requirements.
- L1 requirements are assigned to an owner who can verify/validate against the MOP and declare the requirement as met.
- L1 requirements are entered into the RVTM
- For adaptive software development, L1 Requirements are entered into a rank prioritized backlog
- Requirements are analyzed and decomposed from L1 to L2; and associated with architectural elements, sub systems and/or work packages as a function of system complexity.
- L2 requirements are entered into the RVTM

Rolling Wave Strategy
Strategy used to manage the uncertainty of long-term requirements and work package definitions, where these can only be detailed in the short term. Progressive decomposition and elaboration are used to establish planning waves.

Science Ready Data Products (SRDP)
An NRAO project to deliver high-level data products to users, typically calibrated images and image cubes. The capability is provided through a set of releases that span the data processing and delivery system from proposal submission through archive access.

SRDP Release
Code base that is validated by an ORR and made available for general use.

Scientific Operations
The user-facing services provided by the telescope including observation preparation, scheduling, archive access, scientific performance of the array, and the delivered data products.

Specification
In the quality control domain, a stated measurable value with upper and lower control limits.

Specification Document
A set of requirements; can be at any requirement level.

Stakeholder Requirements Specification
A set of stakeholder requirements (L0) gathered into a Specification Document.

Story
The smallest unit of functional code, synonymous with a task.

Subsystem Requirements Specification
A set of subsystem requirements (L2) gathered into a Specification Document.

System Requirements Specification
A set of system requirements (L1) gathered into a Specification Document.

Technical Metrics for Requirements
See MOE, MOP, KPP, TPM.

Technical Specifications
Technical Specifications are derived from the System Requirements, within the functional limits established by the selection of a particular solution.

Updated Baseline
Project primary constraints (scope, schedule, and budget) and secondary constraints (resources, risk, quality), as reflected in the Project Charter, continue under progressive elaboration until changes stabilize and the baseline is relatively mature. Prior to baseline approval, change control does not apply to the preliminary baseline.

Work Backlog
The prioritized rank ordered list of capabilities, features, and stories that are scheduled for completion within a given planning wave, delivery, or iteration.

WBS
The Work Breakdown Structure. Each WBS work package shall have FTE estimates, which are rolled up to a high-level budget estimate. The WBS is traditional and plan driven to capture all project work and break it down to work packages. This is elaborated in the WBS Dictionary, costed, sequenced, and scheduled. This forms the project management baseline, the basis for Earned Value Management (EVM).

WBS Planning Package
The WBS is first established at a high level for planning, before the full extent of detailed work is known. In order to compile a preliminary budget, costs are associated with each package that is defined at this high level. (See WBS Work Package.)

WBS Work Package
The lowest level of the WBS to which resources are assigned, costs monitored, and schedule tracked.