Next Generation Very Large Array (ngVLA): System Reference Design

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Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	02/21/2017	Selina	All	First draft of outline.
0.2	07/28/2017	Selina	6, 7	Updated to match latest PBS.
0.3	08/25/2017	Selina	7	Reduced scope of some PBS elements. Added SBA.
04	09/20/2017	Selina	6	Incorporating feedback from M. Rupen.
05	05/23/2018	Selina	All	Updating to better reflect referenced document structure and latest WBS.
06	06/20/2018	Selina	1, 5	Updated Ops Concept section with introduction material by Ford et. al. Removed assumptions and constraints section. Other minor edits.
07	07/22/2018	Selina	Cover, 1.1, 1.2, 8	Updated author list. Updated document numbers in AD/RD tables. Other minor edits.
08	09/27/2018	Selina	All	Adding LBA. Updates to text and figures throughout in preparation for October internal RDR. Pulled Sci Case summary (redundant). Sync'd with Ref Design chapter of Sci Book.
09	10/01/2018	Selina	6.1, 6.2, 6.5	Text clarifications, corrections to imaging sensitivity.
10	01/03/2019	Selina	All	Addressing RIDs from internal review. Significant edits throughout document.

Contents

1 INTRODUCTION

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

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

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

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

1.1 Purpose of this Document

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

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

The overall system architecture is presented here, as well as supporting concepts for major system elements such as the antenna, receiving electronics, and central signal processing. The traceability from the requirements to the Reference Design is captured in a combination of the Requirements Traceability Verification Matrix (RVTM) and the allocation matrices incorporated in the System Architecture model.

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

1.2 Applicable Documents

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

Reference No.	Document Title	Rev / Doc. No.
AD 01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD 02	ngVLA Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD 03	ngVLA System Requirements	020.10.15.10.00-0003-SPE
AD 04	ngVLA Environmental Specification	020.10.15.10.00-0001-SPE
AD 05	ngVLA System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD 06	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD 07	ngVLA Requirements Traceability Verification Matrix	020.10.15.00.00-0002-REQ
AD 08	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD 09	ngVLA System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD 10	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK
AD 11	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK
AD 12	ngVLA Product Breakdown Structure	020.10.10.05.00-0001-LIS
AD 13	Array Configuration: Preliminary Requirements	020.23.00.00.00-0001-REQ
AD 14	Array Configuration: Reference Design Description	020.23.00.00.00-0002-DSN
AD 15	Preliminary Array Calibration Requirements	020.22.00.00.00-0001-REQ
AD 16	Preliminary Array Calibration Plan	020.22.00.00.00-0002-PLA

Reference No.	Document Title	Rev / Doc. No.
AD 17	ngVLA Antenna: Preliminary Technical Specifications	020.25.00.00.00-0001-SPE
AD 18	ngVLA Antenna: Optical Reference Design	020.25.01.00.00-0001-REP
AD 19	ngVLA Antenna: Reference Design	101-0000-001-CDD-001
AD 20	ngVLA Short Baseline Array Antenna: Preliminary Technical Specifications	020.47.05.00.00-0001-SPE
AD 21	ngVLA Short Baseline Array Antenna: Reference Design	020.47.05.00.00-0002-DSN
AD 22	Front End: Preliminary Requirements	020.30.03.01.00-0001-REQ
AD 23	Front End: Reference Design	020.30.03.01.00-0003-DSN
AD 24	Cryogenic System: Preliminary Requirements	020.30.10.00.00-0001-REQ
AD 25	Cryogenic System: Reference Design	020.30.10.00.00-0002-DSN
AD 26	Integrated Receiver Digitizer: Preliminary Requirements	020.30.15.00.00-0001-REQ
AD 27	Integrated Receiver Digitizer: Reference Design	020.30.15.00.00-0002-DSN
AD 28	Digital Back End & Data Transmission System: Preliminary Requirements	020.30.25.00.00-0001-REQ
AD 29	Digital Back End & Data Transmission System: Reference Design	020.30.25.00.00-0002-DSN
AD 30	DC Power Supply System: Preliminary Requirements	020.30.50.00.00-0001-REQ
AD 31	DC Power Supply System: Reference Design	020.30.50.00.00-0002-DSN
AD 32	Bins, Modules & Racks: Preliminary Requirements	020.30.55.00.00-0001-REQ
AD 33	Bins, Modules & Racks: Reference Design	020.30.55.00.00-0002-DSN
AD 34	Environmental Control: Preliminary Requirements	020.30.60.00.00-0001-REQ
AD 35	Environmental Control: Reference Design	020.30.60.00.00-0002-DSN
AD 36	LO Reference and Timing: Preliminary Requirements	020.35.00.00.00-0001-SPE
AD 37	LO Reference and Timing: Reference Design	020.35.00.00.00-0002-DSN
AD 38	Central Signal Processor: Preliminary Requirements	020.40.00.00.00-0001-SPE

Reference No.	Document Title	Rev / Doc. No.
AD 39	Central Signal Processor: Reference Design	020.40.00.00.00-0002-DSN
AD 40	Independent Phase Cal System: Preliminary Requirements	020.45.00.00.00-0001-REQ
AD 41	Independent Phase Cal System: Reference Design	020.45.00.00.00-0002-DSN
AD 42	Computing & Software Systems: Preliminary Requirements	020.50.00.00.01-0001-REQ
AD 43	Computing & Software Systems: Reference Design Architecture	020.50.00.00.01-0002-REP
AD 44	Monitor & Control System: Reference Design Concept	020.50.25.00.00-0002-DSN
AD 45	Monitor & Control System: Preliminary Requirements	020.50.25.00.00-0001-REQ
AD 46	Monitor & Control System: Hardware Technical Requirements	020.30.45.00.00-0002-REQ
AD 47	Buildings & Array Infrastructure Reference Design Study	020.60.00.00.01-0002-REP
AD 48	Integrated Construction Cost Estimate	020.05.15.05.00-0004-BUD
AD 49	Integrated Operations Cost Estimate	020.05.15.05.00-0007-BUD
AD 50	ngVLA Lexicon and Acronyms	020.10.10.10.00-0005-LIS
AD 51	Trident Correlator-Beamformer Preliminary Design Specification	TR-DS-000001
AD 52	ngVLA Up-Scope and Descope Options	020.05.05.00.00-0005-PLA
AD 53	ngVLA Assembly, Integration & Verification (AIV) Concept	020.10.05.00.00-0006-PLA
AD 54	ngVLA Commissioning & Science Validation (CSV) Concept	020.10.05.00.00-0006-PLA
AD 55	Long Haul Fiber Workgroup Preliminary Report	020.60.00.00.00-0002-REP

1.3 Reference Documents

The following documents provide additional material or supporting context.

Reference No.	Document Title	Rev / Doc. No.
RD 01	Summary of the Science Use Case Analysis	ngVLA Memo No. 18
RD 02	Key Science Goals for the ngVLA	ngVLA Memo No. 19

Reference No.	Document Title	Rev / Doc. No.
RD 03	ngVLA Science Book	Astronomical Society of the Pacific, 2018.
RD 04	Interferometry & Synthesis in Radio Astronomy.	Thomson, Moran, Swenson , Second Edition
RD 05	Science Ready Data Products System Concept	530-SRDP-014-MGMT
RD 06	Science Ready Data Products System Architecture	(In Prep. Doc # TBD)
RD 07	ngVLA Cost Model Memo	020.05.15.00.00-0004-REP
RD 08	ngVLA Cost Model Spreadsheet	020.05.15.00.00-0005-REP
RD 09	ngVLA Reference Design Development & Performance Estimates	ngVLA Memo No. 17.
RD 10	More on Synthesized Beams and Sensitivity	ngVLA Memo No. 16
RD 11	Possible Configurations for the ngVLA	ngVLA Memo No. 03
RD 12	SKA Design Studies Technical Memo 107	Lal, D., Lobanov, A., Jimenez-Monferrer, S., SKA Design Studies Technical Memo 107. (2011)
RD 13	Fast Switching Phase Calibration at 3mm at the VLA site	ngVLA Memo No. 1
RD 14	Calibration Strategies for the Next Generation VLA	ngVLA Memo No. 2
RD 15	An RFI Survey at the Site of the Long Wavelength Demonstration Array (LWDA)	Stewart, K. P. et al., BAAS 37, 1389 (2005).
RD 16	The ngVLA Short Baseline Array	ngVLA Memo No. 43
RD 17	Getting the Big Picture: Design Considerations for a ngVLA Short Spacing Array	Mason, B. et al., American Astronomical Society, (2018).
RD 18	SKA1 System Baseline Design	SKA Doc No. SKA-TEL-SKO-DD-001
RD 19	Imaging Capabilities: Protoplanetary Disks Comparison	ngVLA Memo No. 11
RD 20	The Strength of the Core	ngVLA Memo No. 12
RD 21	Short Spacing Considerations for the ngVLA	ngVLA Memo No. 14
RD 22	Resolution & Sensitivity of ngVLA-RevB	ngVLA Memo No. 47
RD 23	The Concept of a Reference Array for the ngVLA	ngVLA Memo No. 4
RD 24	Considerations for a Water Vapor Radiometer System	ngVLA Memo No. 10

Reference No.	Document Title	Rev / Doc. No.
RD 25	Polarization Calibration with Linearly Polarized Feeds	ngVLA Memo No. 45
RD 26	ngVLA Technical Study Offset Gregorian Antenna	ngVLA Memo No. 26
RD 27	Exploration of Suitable Mounts for a 15m Offset Antenna Next Generation Very Large Array NRC 15m Mount	ngVLA Memo No. 25
RD 28	Various Suitable Mounts for an 18m Antenna	ngVLA Memo No. 27
RD 29	Advanced Cryocoolers for the Next Generation VLA	ngVLA Memo No. 24
RD 30	Short Baseline Array: Reference Design Description	ngVLA Memo No. 43
RD 31	RFI Flagging Algorithms	(ngVLA Memo #TBD)
RD 32	Imaging Algorithms	(ngVLA Memo #TBD)
RD 33	Computing System Sizing	(ngVLA Memo #TBD)
RD 34	ngVLA Legacy Science Program	020.10.05.00.00-0004-PLA
RD 35	ngVLA Front End Thermal Study Analysis Report	Calisto REP/1406/4366
RD 36	An Integrated Receiver Concept for the ngVLA	ngVLA Memo No. 29
RD 37	TM's View of the Mid.CBF Frequency Slice Approach.	Rupen, M. 2017
RD 38	Precipitable Water at the VLA: 1990-1998	VLA Scientific Memo 176
RD 39	hase Fluctuations at the VLA Derived from One Year of Site Testing	VLA Test Memo 222
RD 40	An RFI Survey at the Site of the Long Wavelength Demonstration Array (LWDA)	Stewart, K. P. et al. BAAS 37, 1389 (2005)
RD 41	A Preliminary Survey of Radio-Frequency Interference Over the U.S. in Aqua AMSR-E Data	Li et al. IEEE TGRS, 42, 380, (2004)
RD 42	Subarray Processing for Projection-based RFI Mitigation in Radio Astronomical Interferometers	Burnett, M et al. AJ, 155, id.146, (2018)
RD 43	The Very Large Array	Thomson, A. R. et al. ApJSS, 44, 151 (1980)
RD 44	Snapshot UV Coverage of the ngVLA: An Alternate Configuration	ngVLA Memo No. 49
RD 45	A Dedicated Pulsar Timing Array Telescope	ngVLA Memo No. 34

Reference No.	Document Title	Rev / Doc. No.
RD 46	Next Generation Low Band Observatory: A Community Study Exploring Low Frequency Options for ngVLA	ngVLA Memo No. 20

2 SCIENCE REQUIREMENTS

The Science Requirements for the facility can be found in the following documents (AD[01]):

- *ngVLA Science Requirements*
  020.10.15.00.00-0001-REQ

Additional supporting material the led to the definition of these science requirements can be found in the following documents (RD[01-03]):

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

In order to develop the facility science case, the project solicited science use cases from the user community. A total of 80 science use cases were compiled by more than 200 authors and submitted to the Science Working Groups (SWGs). These use cases were ranked by the Science Advisory Council (SAC) based on scientific merit, degree of development, feasibility, and other relevant metrics. The outcome of this ranking process are the five Key Science Goals (KSGs) of the ngVLA. [RD02]

The KSGs were chosen to satisfy three criteria: (1) each addresses an important, unanswered question in astrophysics that has broad scientific and societal implications; (2) progress in each area is uniquely addressed by the capabilities of the ngVLA; (3) each exhibits key synergies and complementarity with science goals being pursued by existing or planned facilities in the 2025 and beyond time frame.

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

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

Continuum Sensitivity: A continuum sensitivity of better than 0.02 μJy/bm at 30 GHz and 0.2 μJy/bm 100 GHz is required for studying protoplanetary disks (KSG1). This requires a combination of large collecting area and wide system bandwidth. VLB continuum sensitivity of better than 0.23 μJy/bm at 10 GHz is required to detect gravitational wave (GW) events at a distance of 200 Mpc

Line Sensitivity: A line sensitivity of 30 μJy/bm/km/s for frequencies between 10 and 50 GHz is simultaneously required to support both astrochemistry studies and deep/blind spectral line surveys. A line sensitivity of 1 – 100 mK at 0.1" – 5" angular resolution and 1 – 5 km/s spectral resolution between 70 and 116 GHz is required to simultaneously support detailed studies of CO and variations in gas density across the local universe. The spectral line cases push the system design towards quantum-limited noise performance at the expense of bandwidth above 10 GHz.

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

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

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

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

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

Beamforming for Pulsar Search, Pulsar Timing and VLBI: The array shall support no less than 10 beams spread over 1 to 10 subarrays that are transmitted, over the full available bandwidth, to a pulsar search engine, or pulsar timing engine. The pulsar search and timing engine must be integral to the baseline design. VLBI recording of a single element, or phased array ouptu, for a minimum of three beams is required.

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

3 SYSTEM REQUIREMENTS

The System Requirements for the facility, the flow-down process, and supporting analysis can be found in the following documents (AD[03-06]). The relationship of these documents within the requirements hierarchy is shown in Figure 1:

- *ngVLA System Requirements* 020.10.15.10.00-0003-SPE
- *ngVLA Environmental Specification* 020.10.15.10.00-0001-SPE
- *ngVLA System EMC and RFI Mitigation Requirements* 020.10.15.10.00-0002-REQ
- *ngVLA Requirements Management Plan* 020.10.15.00.00-0001-PLA

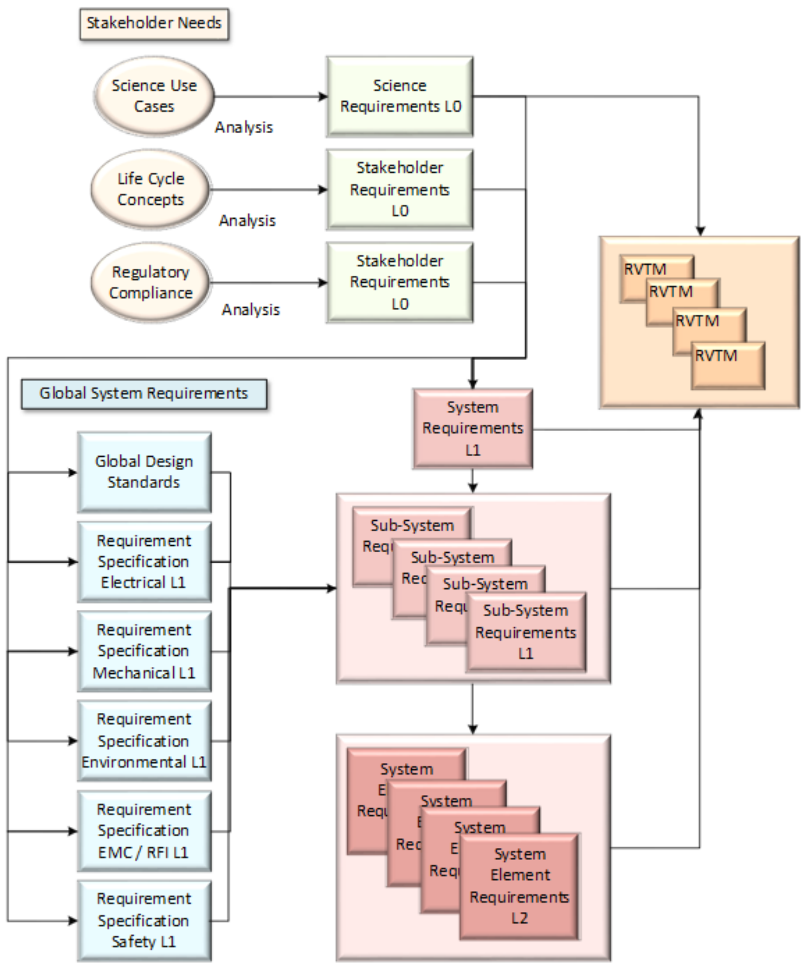

Figure 1 - Relationship between L0 Science Requirements, L1 System Requirements, and associated specifications. [AD06]

The system requirements support the science requirements [AD01] as well as other stakeholder requirements [AD02] elicited through the development of life cycle concepts and other identified programmatic or regulatory requirements. The traceability from science use cases, to science requirements, to system requirements is captured in the Requirements Traceability Verification Matrix [AD07].

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

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

A total of 179 system requirements are identified in the main document, not including the global design standards. In order to provide some indication of importance, the following Measures of Performance (MOPs) have been identified as the most important for overall system effectiveness.

Table 1 - System Level Measures of Performance (MOPs)

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

Parameter	Req. #	Value	Traceability
Shortest Baseline	SYS1302	The shortest baselines between antennas shall be shorter than 22 m, with a goal of 10 m.	[SCI0104]
Longest Baseline	SYS1301	The longest baseline between antennas in the main array shall be greater than 420 km with extended baselines (VLB) out to 8600 km.	[SCI0103, SCI0118]

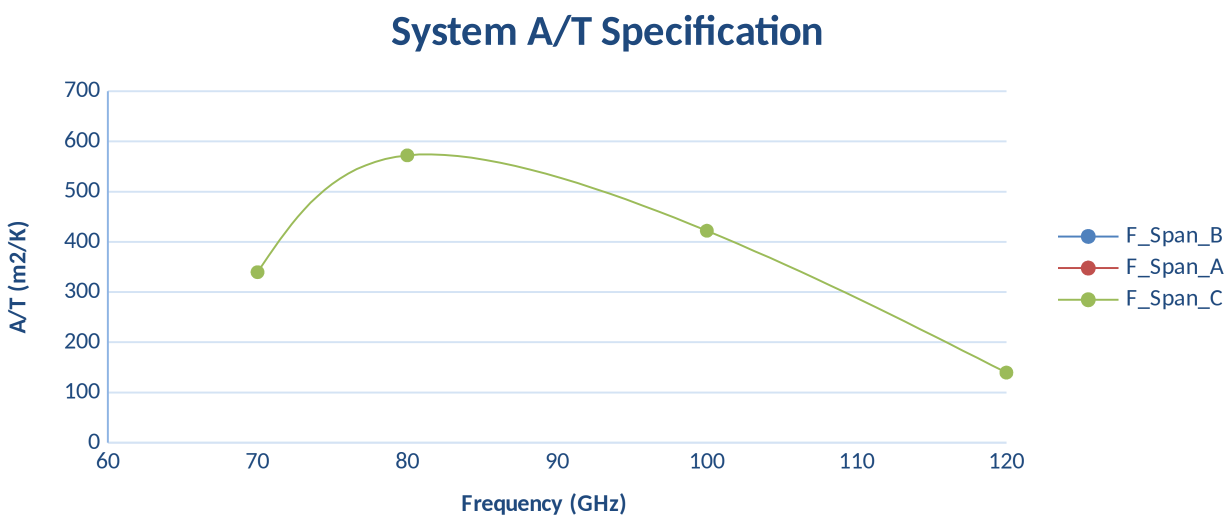

Figure 2 - System A/T specification in m²/K. (SYS1001)

4 LIFE-CYCLE CONCEPTS

4.1 Operations Concept

The operations and maintenance concept for the facility can be found in the following document (AD[08]):

- *ngVLA Operations Concept* 020.10.05.00.00-0002-PLA

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

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

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

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

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

4.2 Assembly, Integration and Verification Concept

The Assembly, Integration & Verification (AIV) concept for the facility can be found in the following document (AD[53]):

- *ngVLA Assembly, Integration & Verification Concept*
  020.10.05.00.00-0005-PLA

The AIV concept describes the production/construction concept for the deliverables of each work package, the degree of verification, and the point of delivery. It then elaborates on how these deliverables are assembled into integrated systems and are verified to the system requirements. The AIV concept describes these steps qualitatively, identifying likely resources and supporting infrastructure to achieve these goals.

The AIV concept imposes requirements on the packaging of systems, their deployment schedule, and the degree of ancillary equipment or processes required for component or sub-system verification. These requirements and their impacts are reflected in the stakeholder requirements, with subsequent flow down to the system requirements and this reference design.

The overall construction concept for the ngVLA has work-packages delivering qualified sub-systems or sub-assemblies to the AIV team, the AIV team assembling these into integrated and verified systems, and handing over these verified systems to the Commissioning & Science Validation (CSV) team for progressive commissioning of capabilities. Construction ends with the hand-over of a commissioned telescope to Operations. The final AIV milestone, where capabilities are handed over to CSV, is stable computer-controlled fringes on a calibrator source. These hand-offs are expected to be incremental, with a goal of completing the construction phase by 2035 (10 years for all construction activities, see Figure 3).

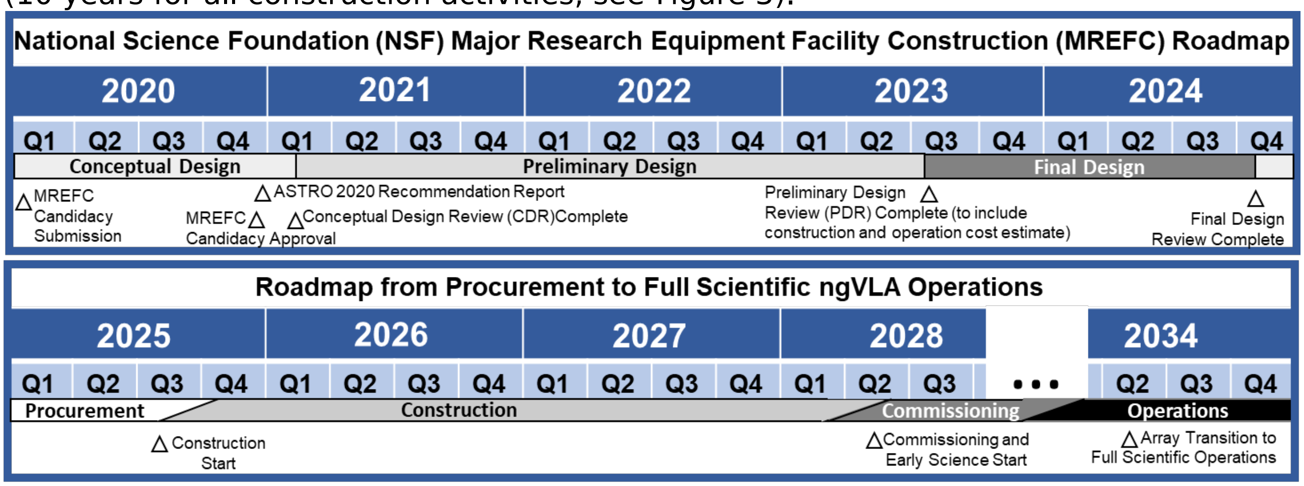

Figure 3 - Preliminary roadmap through Design (Conceptual, Preliminary, Final) to Construction and Operations.

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

4.3 Commissioning and Science Validation Concept

The Commissioning & Science Validation concept for the facility can be found in the following document (AD[54]):

- *ngVLA Commissioning & Science Validation Concept*
  020.10.05.00.00-0006-PLA

The split between AIV and CSV is based on team specialization. AIV aims to deliver sub-systems to specification and an integrated system with demonstrated core functionality. CSV is responsible for taking those verified components and performing any necessary integrated performance tests to release useful observing modes to users.

The CSV concept defines a set of early commissioning milestones that show a progressive integration of the system and provide useful observing capabilities. Example milestones include phase closure, long-baseline fringe tracking, short baseline manual imaging, long baseline manual imaging, full-beam and full-bandwidth modes, automated instrumental calibration, and automated imaging.

CSV ends when all capabilities that are required to meet the Science Requirements and Operations Concept are reached and the facility is handed over to Operations. The general exit criterion is that for any delivered mode the data can be acquired using a standard scheduling block (SB) created using the Proposal Submission Tool (PST) and post processed by the automated system.

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

5 SYSTEM ARCHITECTURE

The System Architecture for the facility is described in the following documents and drawings (AD[09-12]):

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

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

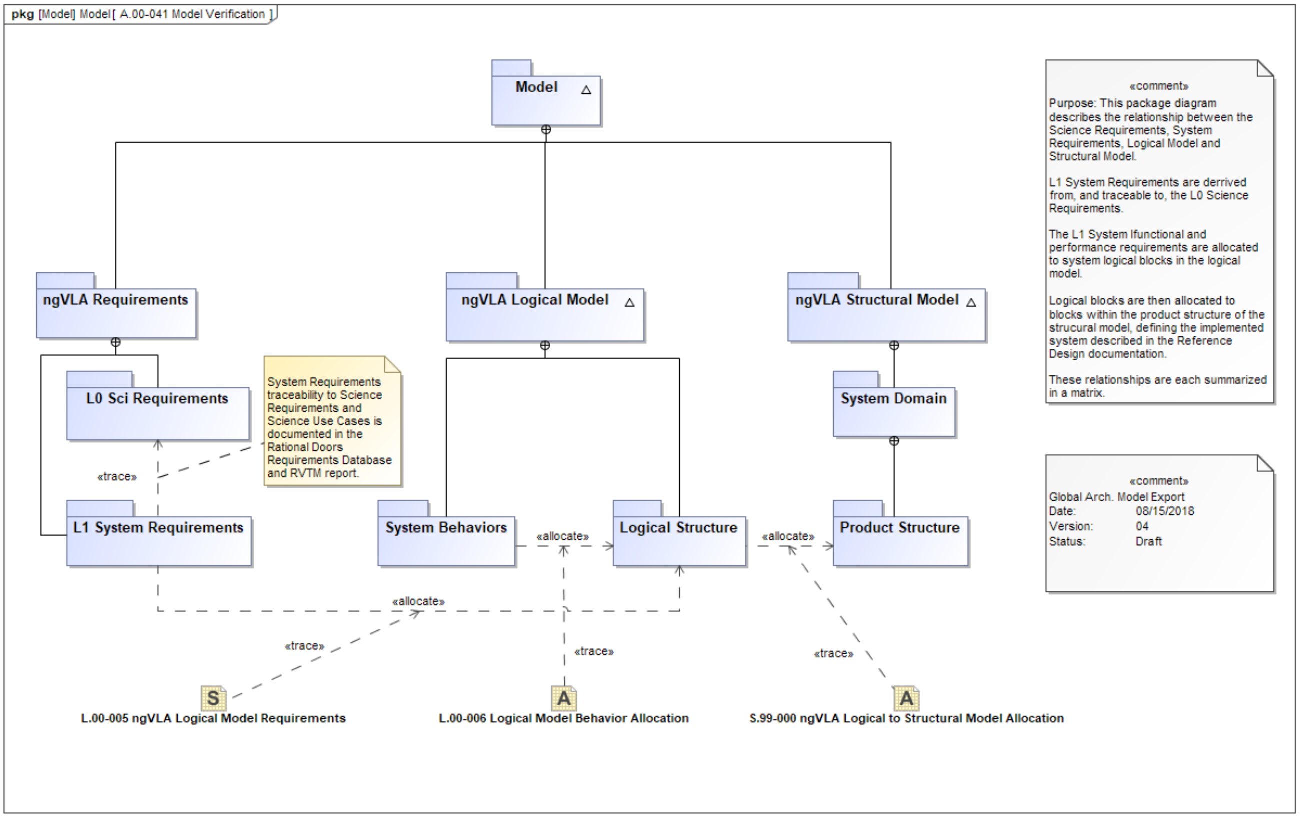

Figure 4 - System Architecture model hierarchy and verification strategy. Traceabilty from L0 Science Requirements to L1 System Requirements is captured in the RVTM [AD07]. Requirements and functional behaviors are allocated to blocks in the logical model, and summarized in a Satisfy and Allocate matrix.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

The system architecture aims to be:

- Loosely coupled, with high cohesion within sub-systems, to enable parallel development with clean interfaces.
- Flexible, scalable and extensible to adjust to evolving performance requirements and programmatic constraints.
- Maintainable over the lifetime of the instrument.

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

6 SYSTEM OVERVIEW

The following section provides an overview of the reference design at the system level. The concept for the facility, its projected performance, and the data products delivered to users are described. Concepts for major sub-systems follow in Section 7.

6.1 Overview

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

A main array of 214 reflector antennas each of 18 meters diameter, operating in a phased or interferometric mode. The main array is distributed to sample a wide range of scales from 10s of meters to 1000 km. A dense core and spiral arms provide high surface brightness sensitivity, with mid-baseline stations enhancing angular resolution.

A short baseline array (SBA) of 19 reflector antennas of 6m aperture will be sensitive to a portion of the larger angular scales undetected by the main array. The SBA may be combined with 4 18m (main-array) antennas used in a total power mode to completely fill in the central hole in the (*u,v*)-plane left by the 6m dishes.

A long baseline array (LBA) will add an additional 30 reflector antennas each of 18m diameter in 10 clusters providing continental scale baselines (B_{MAX} ~ 8860 km). The LBA is designed to sample a broad range of scales for stand-alone sub-array use, as well as for integrated operation with the main array.

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

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

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

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

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

6.2 Reference Array Performance

The predicted performance of the array is summarized in Table 1. This is an update to the performance estimates originally documented in [RD08].

Table 2 - ngVLA Key Performance Metrics

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

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

The continuum and line rms values in Table 2 are for point source sensitivity with a naturally weighted beam. Imaging sensitivity is estimated based on [RD06] and provided as a function of angular resolution in Table 3. The table is by necessity a simplification and the imaging sensitivity will vary from these reported values depending on the quality of the (sculpted) synthesized beam (defined as the ratio of the power in the main beam attenuation pattern to the power in the entire beam attenuation pattern as a function of the FWHM of the synthesized beam [AD01]) required to support the science use case.

The brightness sensitivity of an array is critically dependent on the array configuration. The ngVLA has the competing desires of both good point source sensitivity at full resolution, and good surface brightness sensitivity on scales similar to the primary beam size. Different array configurations that might provide a reasonable compromise through judicious weighting of the visibilities for a given application have been explored [RD10] (See RD11 for similar studies for the SKA). It is important to recognize the fact that for any given observation, from full resolution imaging of small fields, to imaging structure on scales approaching that of the primary beam, some compromise will have to be accepted to enable a practical and flexible general purpose facility.

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

Receiver Band	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**
Center Frequency, f	**2.4 GHz**	**8 GHz**	**16 GHz**	**27 GHz**	**41 GHz**	**93 GHz**
Resolution [mas]	**1000**					
Continuum rms, 1 hr, Robust [μJy/beam]	0.52	0.34	0.35	0.39	0.59	2.24
Line rms 1 hr, 10 km/s Robust [μJy/beam]	88.9	61.1	43.3	47.9	70.9	179.6
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	0.110	6.4E-3	1.7E-3	0.7E-3	0.4E-3	0.3E-3
T_B rms line, 1 hr, 10 km/s, Robust [K]	18.76	1.16	0.21	0.08	0.05	0.03
Resolution [mas]	**100**					
Continuum rms, 1 hr, Robust [μJy/beam]	0.50	0.30	0.27	0.28	0.40	1.14
Line rms 1 hr, 10 km/s Robust [μJy/beam]	85.0	53.6	33.6	34.8	48.4	91.3
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	10.58	0.56	0.13	0.05	0.03	0.02
T_B rms line, 1 hr, 10 km/s, Robust [K]	1794.1	101.9	15.9	5.8	3.5	1.3
Resolution [mas]	**10**					
Continuum rms, 1 hr, Robust [μJy/beam]	0.41	0.27	0.26	0.27	0.38	0.97
Line rms 1 hr, 10 km/s Robust [μJy/beam]	69.9	48.3	32.4	33.2	46.3	77.7

Receiver Band	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**
Center Frequency, f	**2.4 GHz**	**8 GHz**	**16 GHz**	**27 GHz**	**41 GHz**	**93 GHz**
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	870.6	50.51	12.42	4.53	2.77	1.36
T_B rms line, 1 hr, 10 km/s, Robust [K]	1.5E5	9173	1540	555	335	109
Resolution [mas]	**1**					
Continuum rms, 1 hr, Robust [μJy/beam]	-	20.87	0.31	0.21	0.29	0.90
Line rms 1 hr, 10 km/s Robust [μJy/beam]	-	3789.8	38.2	25.7	34.7	72.0
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	-	4.5E5	1466	350	207	126
T_B rms line, 1 hr, 10 km/s, Robust [K]	-	7.2E7	1.8E5	4.3E4	2.5E4	1.0E4
Resolution [mas]	**0.1**					
Continuum rms, 1 hr, Robust [μJy/beam]	-	-	-	-	-	20.96
Line rms 1 hr, 10 km/s Robust [μJy/beam]	-	-	-	-	-	1683.2
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	-	-	-	-	-	2.9E5
T_B rms line, 1 hr, 10 km/s, Robust [K]	-	-	-	-	-	2.0E7

Imaging sensitivity will be dependent on the required resolution and imaging fidelity. Figure 5 and Figure 6 show the effects of adjusting imaging weights to vary the resolution and PSF quality. These figures are based on a 4 hour simulation at 30 GHz using the 244 antenna array configuration (Main Array and Long Baseline Array combined), for a source at +24° Declination observed during transit. The reported beam size is the geometric mean of the major and minor axes full width at half maximum (FWHM) of the synthesized beam as parameterized by Gaussian fitting in the CASA 'tclean' task.

The centrally condensed antenna distribution leads to a naturally weighted beam that is not well characterized by a Gaussian function. Specific science applications may need to adjust the uv-weighting and image parameters to 'sculpt' a synthesized beam that is adequate for the particular science goal being considered. The results in Figure 5 and Figure 6 should be considered representative of the possibilities, and optimizing sensitivity vs. resolution will be a major area of investigation during telescope development.

In order to account for the change in sensitivity due to use of imaging weights (relative to the naturally weighted rms (σ_{NA}), an efficiency factor η_{weight} is adopted such that the expected image rms after weighting is $\eta_{weight} * \sigma_{NA}$. The sensitivity calculations in Table 3 include η_{weight}, estimated using the blue and red data series in Figure 5 scaled by frequency.

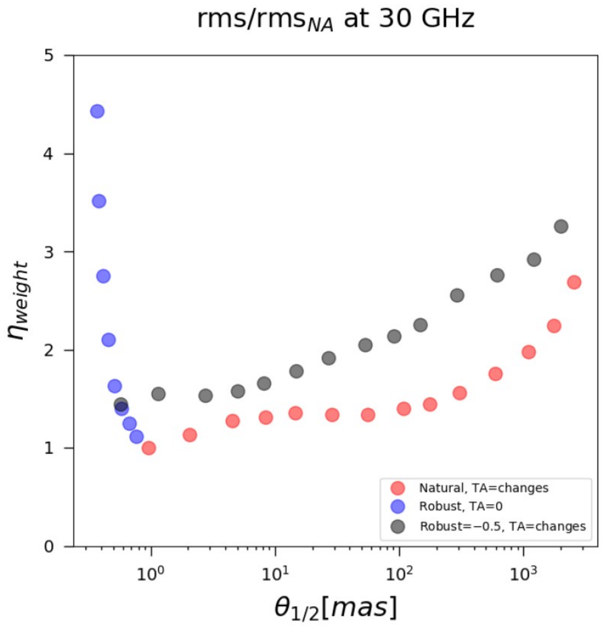

Figure 5 – Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz. The noise has been scaled relative to that of the naturally weighted image (σ_{NA}). The red symbols correspond to use of a UV taper and natural weights, and the blue symbols to Briggs robust weighting without a taper. The gray symbols are for Briggs robust = -0.5 and a varying UV taper, which has a large effect on beam quality (see Figure 6).

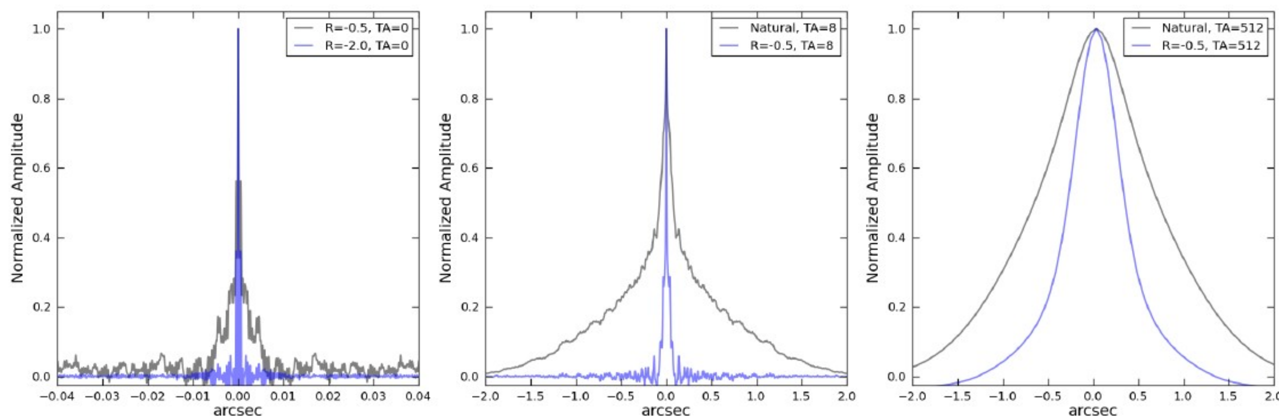

Figure 6 - Simulated 30 GHz PSFs over a range of resolutions, showing the effect of different imaging weights (TA: UV-taper in mas, R: Briggs robust parameter). The PSFs are a selection of the data presented in Figure 5: left panel (blue circles), central and right panels (gray and red circles). These examples illustrate how combinations of robustness and tapering allow for a beam of much higher quality at the expense of sensitivity.

6.3 New Parameter Space

Figure 7 shows a slice through the parameter space, resolution versus frequency, covered by the ngVLA along with other existing and planned facilities that are expected in the 2030s at all wavelengths. The maximum baselines of the ngVLA imply a resolution of better than 0.5mas at 1cm. Coupled with the high sensitivity of the array, this resolution provides a unique window into the formation of planets in disks on the scales of our own Solar system at the distance of the nearest active star forming regions.

Figure 8 shows a second slice through parameter space: effective collecting area versus frequency. A linear-linear plot highlights the parameter space opened by the ngVLA. Note that the SKA-1 will extend to below 100MHz while ALMA extends up to almost a THz.

It is noted that there are other aspects of telescope phase space that are relevant, including field of view, mapping speed, surface brightness sensitivity, bandwidth, system temperature, dynamic range, etc. Presented are the two principle and simplest design goals, namely, maximum spatial resolution and total effective collecting area (as a gross measure of system sensitivity).

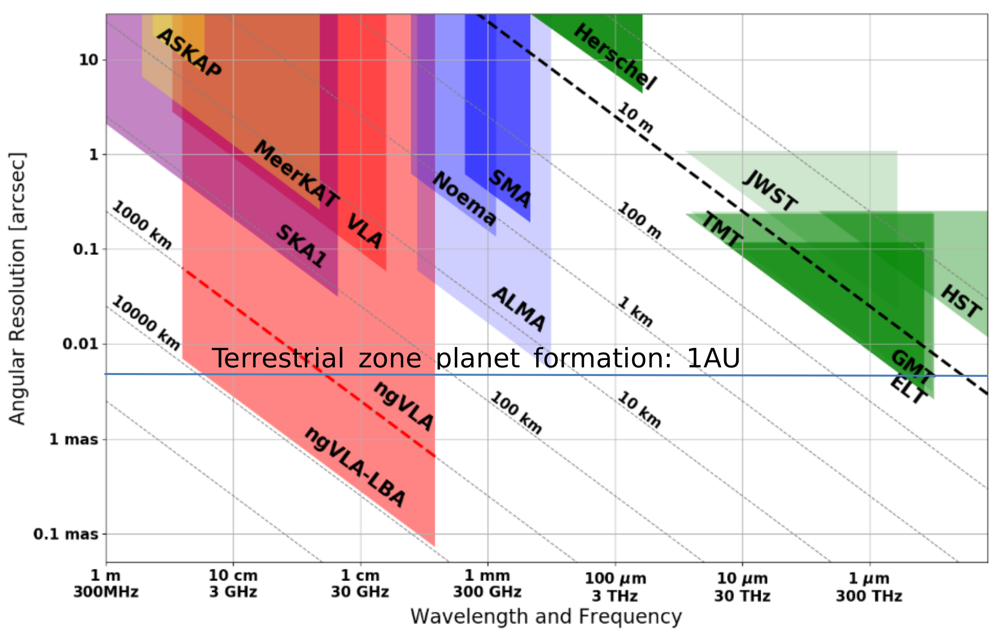

Figure 7. Spatial resolution versus frequency set by the maximum baselines of the ngVLA as compared to that of other existing and planned facilities.

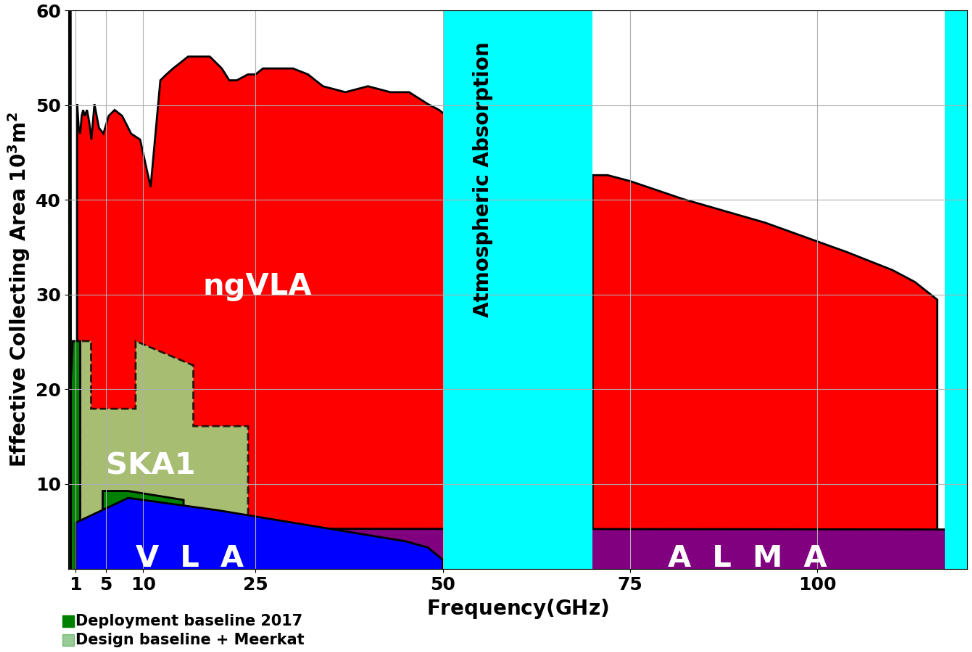

Figure 8. Effective collecting area versus frequency for the ngVLA as compared to that for other existing or planned facilities. Note that lower and higher frequencies are not shown (e.g. SKA-1 will extend to below 100 MHz and ALMA extends up to about a THz). Both the SKA1 'deployment baseline' (dark green) and 'design baseline' (light green) are shown, inclusive of the MeerKAT array. [RD14]

6.4 Data Products

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

The Observatory will provide sufficient computing resources for the data processing associated with normal operations using standard modes and capabilities (including delivery of Science Ready Data Products to PIs) as well as reasonable reprocessing by PIs and a broader community of users of archival (public) data.
Delivery of a fully-commissioned standard observing mode or capability will include an operational SRDP pipeline before it is offered for regular use through PI proposals.

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

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

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

6.5 Site Selection

The VLA site on the plains of San Agustin was originally chosen as the location for the array because of its desirable properties: relatively flat, undeveloped (to minimize RFI) yet not too remote (for accessibility), at low latitude (for sky coverage), and at high elevation (to minimize atmospheric effects) [RD 43]. These properties still hold true, and motivate examination of the VLA site as the center of the ngVLA. Furthermore, with extensive existing infrastructure, the VLA site leverages an already-existing system of power, fiber, and buildings, which will reduce cost. The three main environmental or atmospheric quantities that may affect data, and what is known about them at the VLA site, are discussed in the following sections.

6.5.1 RFI

The VLA site is remote enough that Radio Frequency Interference (RFI) is not a debilitating problem, so it will be possible to observe at the lower frequencies of the ngVLA [RD 40]. Furthermore, the ngVLA will benefit from advanced studies of RFI detection and excision that are currently ongoing [RD 42]. The degree of RFI characterization of the site reduces the risk in site selection, and leveraging existing infrastructure could create significant cost savings for both the construction and operation of the array. Given the large extent of ngVLA (B_{MAX} ~ 8860 km), it is clear that the antennas which are outside the plains will experience different RFI environments than that at the site. However, there are locations which are relatively free of locally generated RFI (downward RFI from orbiting satellites is ubiquitous and nearly site-independent), and the US southwest has many such locations [RD 41].

6.5.2 Atmospheric Phase Stability

Analysis of data from the VLA site atmospheric phase monitor shows that fast switching phase calibration at 3mm should be viable for most of the year with a 30s total calibration cycle time [RD 13]. This analysis was based on one year of atmospheric phase monitoring at the VLA site [RD 39]. A much longer time base of these values is now available. Figure 9 shows median values of the rms phase on the 300 m E-W baseline of the atmospheric phase monitor from 1995 through 2017, plotted as a function of UTC hour, and month. It is easy to see that these fluctuations are small for much of the time, and only become greater than 10° (rms @ 11.7 GHz, over 10 minutes) in the summer during daytime. Little information is available on phase fluctuations at locations outside the plains; this is a topic to be studied to determine the ability to use the remote sites at the highest frequencies of ngVLA. Note that there should also be a 25 mJy calibrator source within 2° in 98% of observed fields, ensuring short slews. Such a calibrator is adequate to ensure that the residual rms phase noise due to the signal-to-noise ratio on the phase calibrator is much less than that due to the troposphere, even for a 30s cycle time with only 3s on the calibrator each visit [RD 13]. The project is also investigating radiometric phase correction techniques as part of the ngVLA project to increase the total phase calibration cycle time.

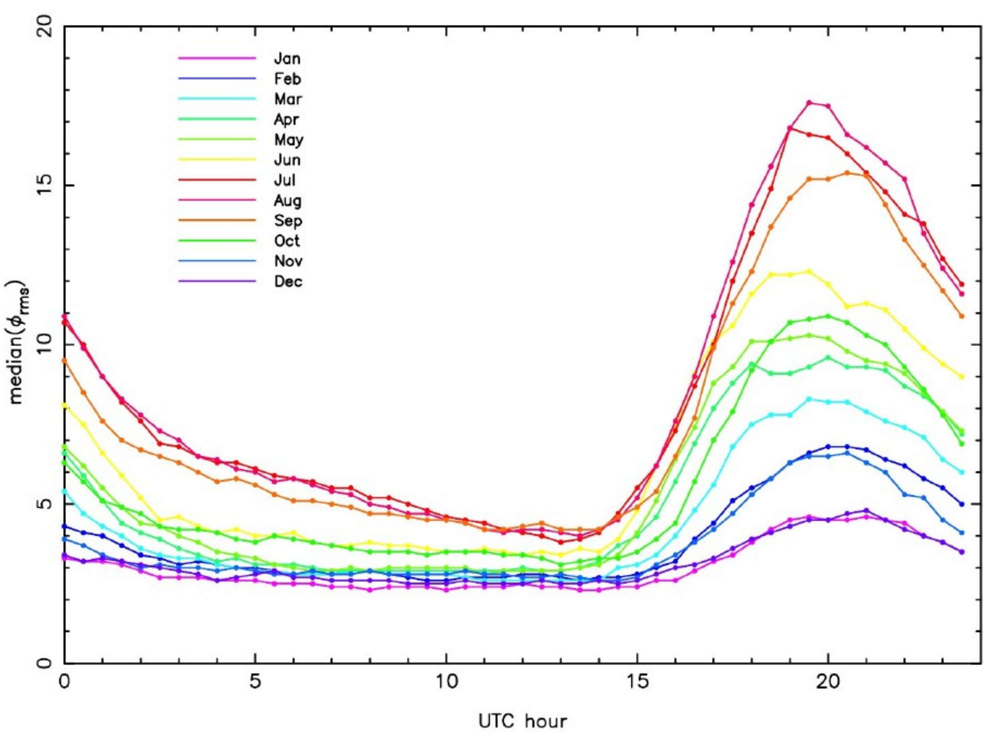

Figure 9 - The median rms phase measured with the atmospheric phase monitor at the VLA (300 m E-W baseline, 11.7 GHz beacon), from 1995 to 2017. Measurements are calculated over a 10 minute period after subtracting any linear trend. Different months are plotted as different colors, as shown in the legend.

6.5.3 Atmospheric Opacity

While at centimeter wavelengths atmospheric opacity is a relatively minor issue compared to phase stability, it becomes a much bigger issue at millimeter wavelengths. Similar to the atmospheric phase stability data, there is a long-time baseline of surface weather data at the VLA site. This can be used to estimate the atmospheric Precipitable Water Vapor (PWV), which is the main contributor to the fluctuating part of atmospheric opacity [RD 38]. Figure 10 shows this value for the years 2010 through 2017. In winter months, the median over all hours is around 3mm, and over the entire year the median over all hours is 5.4mm. Vertical opacity for 5.4mm PWV at 90 GHz is less than 7%, so opacity should not be a major problem for ngVLA. As with RFI and phase stability, there is little information on atmospheric opacity at other locations, though it is almost always clear that higher sites have less opacity. The project does have access to surface weather data, and to radiosonde launch data (twice per day) from NOAA for some tens of sites across the southwest US, which will be the subject of a future study to determine opacity properties across the extent of the ngVLA.

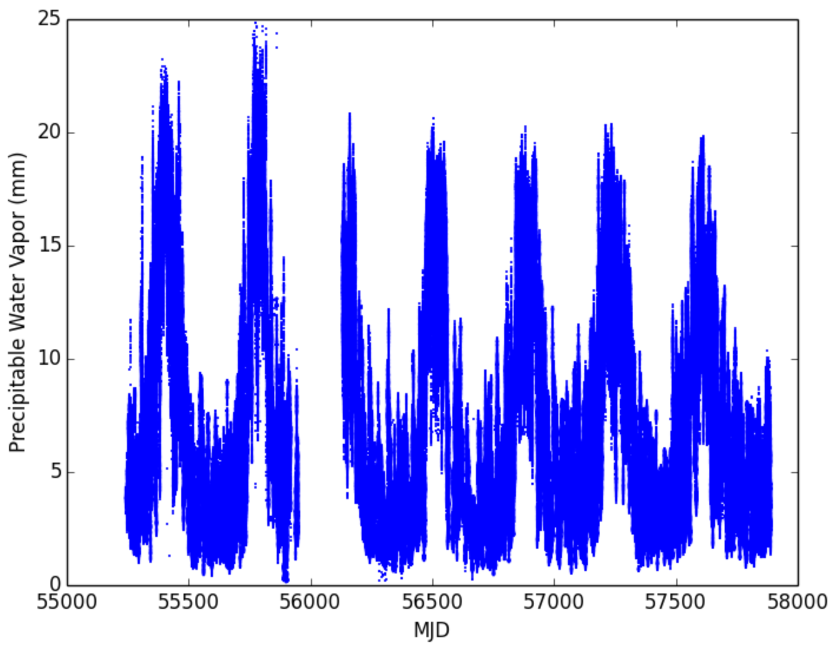

Figure 10 - PWV at the VLA site, estimated using surface weather measurements, from 2010 to 2017. Note that a PWV of 6mm produces an opacity of less than 7% at 90 GHz.

6.5.4 Final Site Selection

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

7 REFERENCE DESIGN

7.1 Array Configuration

The Reference Array Configuration for the facility can be found in the following documents (AD[13-14]):

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

Additional supporting material the led to the selected reference design can be found in the following documents (RD[11, 16-17, 19-23]):

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

The ngVLA array design includes three main subarrays: a main interferometric array (MA), a short baseline array (SBA), and a long-baseline array (LBA) providing a wide range of angular scales.

The main array configuration will consist of 214 18m antennas at the approximate locations shown in Figure 11. The array collecting area is distributed to provide high surface brightness sensitivity on a range of angular scales spanning from approximately 1000 to 10 mas (see Table 3). In practice, this means a core with a large fraction of the collecting area in a randomized distribution to provide high snapshot imaging fidelity, and arms extending asymmetrically out to ~1000 km baselines, filling out the *(u, v)*-plane with Earth rotation and frequency synthesis.

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

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

Radius	Collecting Area Fraction	Number of 18m Antennas
0 km < R < 1.3 km	44%	94
1.3 km < R < 36 km	35%	74
36 km < R < 1000 km	21%	46

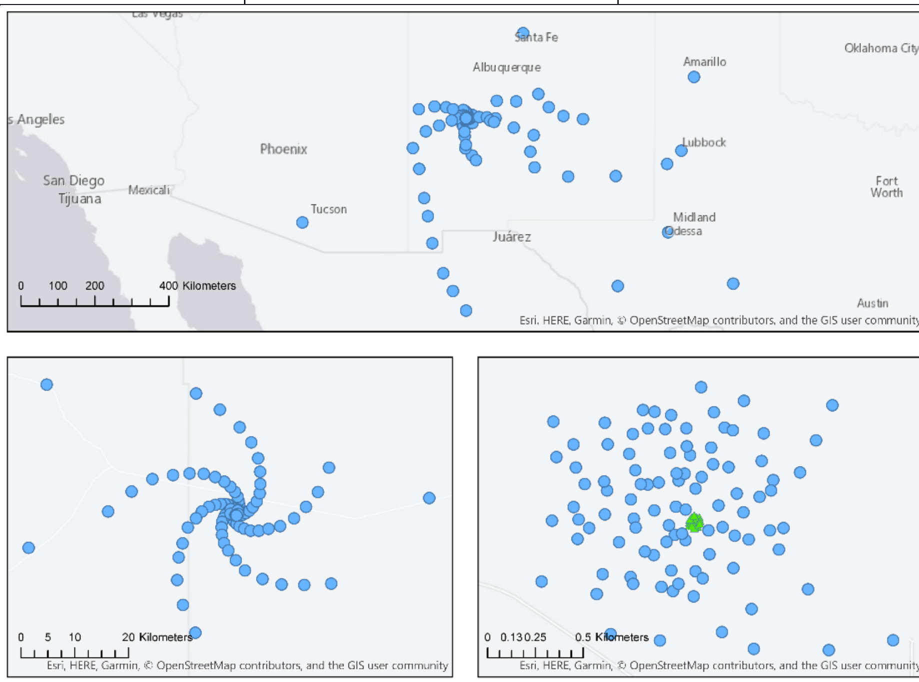

Figure 11 - Top: ngVLA Main Array Configuration Rev. B (Spiral-214). The antenna positions are still notional, but are representative for performance quantification and cost estimation. Bottom Left: Zoom view of the plains of San Agustin. Bottom Right: Zoom view of the compact core. SBA antennas are shown in green.

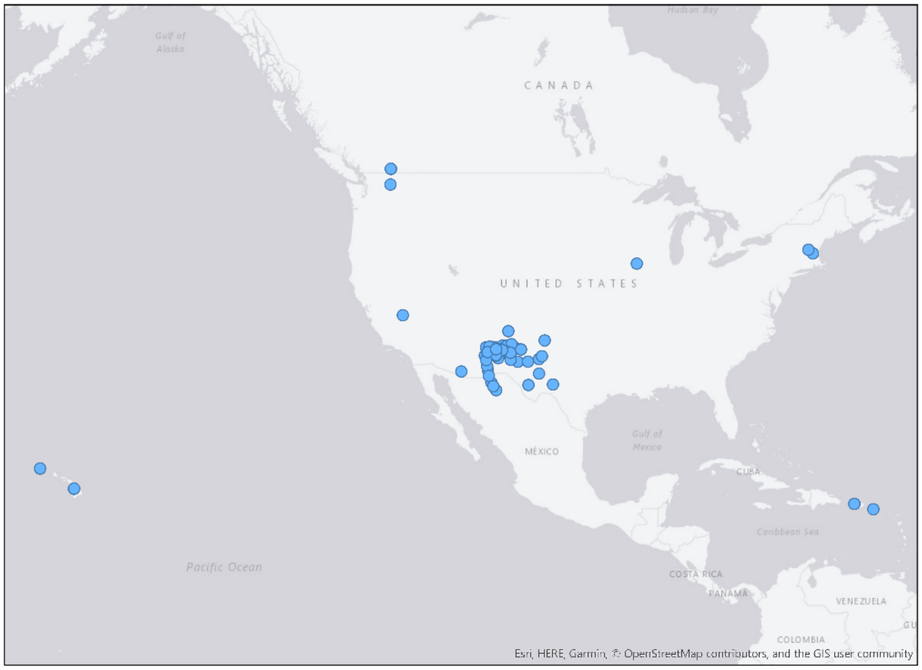

Figure 12 - View of the Main Array and Long Baseline Array stations. Multiple antennas are located at each LBA site.

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

The design has been extended from the main interferometric array to include a long baseline array, a short spacing array, and total power dishes [RD12]. This is necessary after a review of the key science goals, as these are dependent on the recovery of both small scale structure requiring continental-scale baselines, and large scale structure that approaches the size of the antenna primary beam.

An auxiliary short baseline array (SBA) of 19 reflector antennas of 6m aperture will be sensitive to a portion of the larger angular scales undetected by the main array. The SBA will provide spacings from 11m to 60m, providing comparable surface brightness sensitivity to the main array, in equal observing time, when the main array is *(u, v)*-tapered to the natural resolution of the SBA. This allows for commensal observing, and more importantly, full cross-correlation and cross-calibration of the SBA and main array. The array distribution is semi-randomized to improve the point spread function. [RD16]

The SBA will be combined with four 18m (main-array) antennas used in total power (TP) mode to completely fill the central hole in the *(u, v)* plane left by the 6m dishes. It is a design goal to share the mount design of the 18m interferometric array antennas and the TP antennas, but this will require further study.

The long baseline array consists of 30 antennas of 18m diameter at ten sites. The LBA provides continental scale (B_{MAX} = 8860km) baselines while also providing scales from 100m to 1000km within the subarray. This will enable the LBA to function effectively as a stand-alone array or as an integrated part of the main array. The notional sites of the LBA are summarized in Table 5. The ngVLA array configuration elements are summarized in Table 6.

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

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

Table 6. Elements within the ngVLA configuration.

Array Element	Aperture Diameter	Quantity	B_{MIN}	B_{MAX}	F_{MIN}	F_{MAX}
Long Baseline Array	18m	30	100 m	8000 km	1.2 GHz	116 GHz[1]
Main Interferometric Array	18m	214	30 m	1005 km	1.2 GHz	116 GHz[1]
Short Baseline Array	6m	19	11 m	56 m	1.2 GHz	116 GHz
Total Power / Single Dish[2]	18m	4	-	-	1.2 GHz	116 GHz

7.2 Array Calibration

The array calibration strategy for the reference design can be found in the following documents (AD[15-16]):

- *ngVLA Calibration Requirements* 020.22.00.00.00-0001-REQ
- *ngVLA Reference Array Calibration Strategy* 020.22.00.00.00-0002-PLA

Supporting analysis leading up to this strategy can be found in the following documents (RD[13, 14, 23-25]):

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

The calibration strategy for ngVLA is being developed early in the design so that it may guide the design of the hardware, software, and computing elements. The size and complexity of the calibration and imaging pipeline requires that the system design be responsive to its needs, and it should drive the design where possible.

A secondary concern is the efficiency of the calibration process. Algorithms used must be suitable for parallel processing, antennas must not require much individual

1 May not extend to 116 GHz at all sites. Sites below 1000m elevation to operate up to 50 GHz.

2 Included in 214-element main array total.

attention, and minimal human intervention should be required. The calibration overheads applied will vary with the science requirements of a given observation, and less rigorous (and computationally or time efficient) calibration approaches will be applied when possible.

The operations concept [AD08] calls for guaranteed time on source to each observer, with calibration overheads being the responsibility of the facility. This enables the reuse of calibration observations for adjacent observations when their requirements are sufficiently similar, further improving observation efficiency.

The general calibration strategies under consideration for the reference design are summarized below.

Fast Atmospheric Phase Calibration: Rapid atmospheric phase fluctuations will be mitigated by a combination of relative water vapor radiometry (WVR) and antenna switching cycles to astronomical phase calibrators. The switching cycle time will depend on empirical validation of the strategy, but is expected to be necessary on one to ten minute scales. The antenna is designed to both house the WVR and enable fast switching cycles. The later calls for moving 4° on sky and to settle within the pointing specification within 10 seconds of time for elevation angles <70º. [AD 17]

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

Amplitude Calibration: A list of known astronomical amplitude calibrators will be used to correct for system gain fluctuations within an observation and between observations taken over an extended period of time. The calibration pipeline will maintain a history of recent solutions to enable look-up of prior values.

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

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

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

Absolute Flux Calibration: Absolute flux scale calibration will employ similar methods to relative calibration, with two notable changes. First, atmospheric tipping scans will be used to empirically determine atmospheric opacity, with improved fidelity. Second, observations of astronomical flux calibrators will be used, along with the switched power system, to determine the absolute flux of the source.

The ngVLA will need to maintain multiple lists of calibrators by calibration intent. The flux calibrator list can be relatively small and based on the one built and maintained by the VLA. An extensive grid of sources will be required for phase and amplitude calibration. The large range of baselines present on the ngVLA means that it cannot be assumed that the source is unresolved at all scales, and the calibrators themselves must be imaged before use in the calibration process.

7.3 Antennas

The requirements and supporting reference design of the antennas is described in the following documents (AD[17-21]):

- *ngVLA Antenna: Preliminary Technical Specifications* 020.25.00.00.00-0001-SPE
- *ngVLA Antenna: Optical Reference Design* 020.25.01.00.00-0001-REP
- *ngVLA Antenna: Reference Design* 101-0000-001-CDD-001
- *ngVLA Short Baseline Array Antenna: Preliminary Technical Specifications* 020.47.05.00.00-0001-SPE
- *ngVLA Short Baseline Array Antenna: Reference Design* 020.47.05.00.00-0002-DSN

Supporting analysis leading up to this design can be found in the following documents (RD[16, 26-28]):

- *ngVLA Technical Study Offset Gregorian Antenna* ngVLA Memo No. 26
- *Exploration of Suitable Mounts for a 15m Offset Antenna* ngVLA Memo No. 25
- *Various Suitable Mounts for an 18m Antenna* ngVLA Memo No. 27
- *The ngVLA Short Baseline Array* ngVLA Memo No. 43

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

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

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

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

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

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

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

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

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

The short baseline array 6m aperture design shares the majority of its specifications with the main antenna, including the interfaces with the front end equipment such that feeds, receivers and other antenna electronics are interchangeable between the two arrays. The design employs a composite reflector and backup structure on a steel pedestal mount. The mount includes space to house the digital electronics, power supplies and servo system, Figure 13.

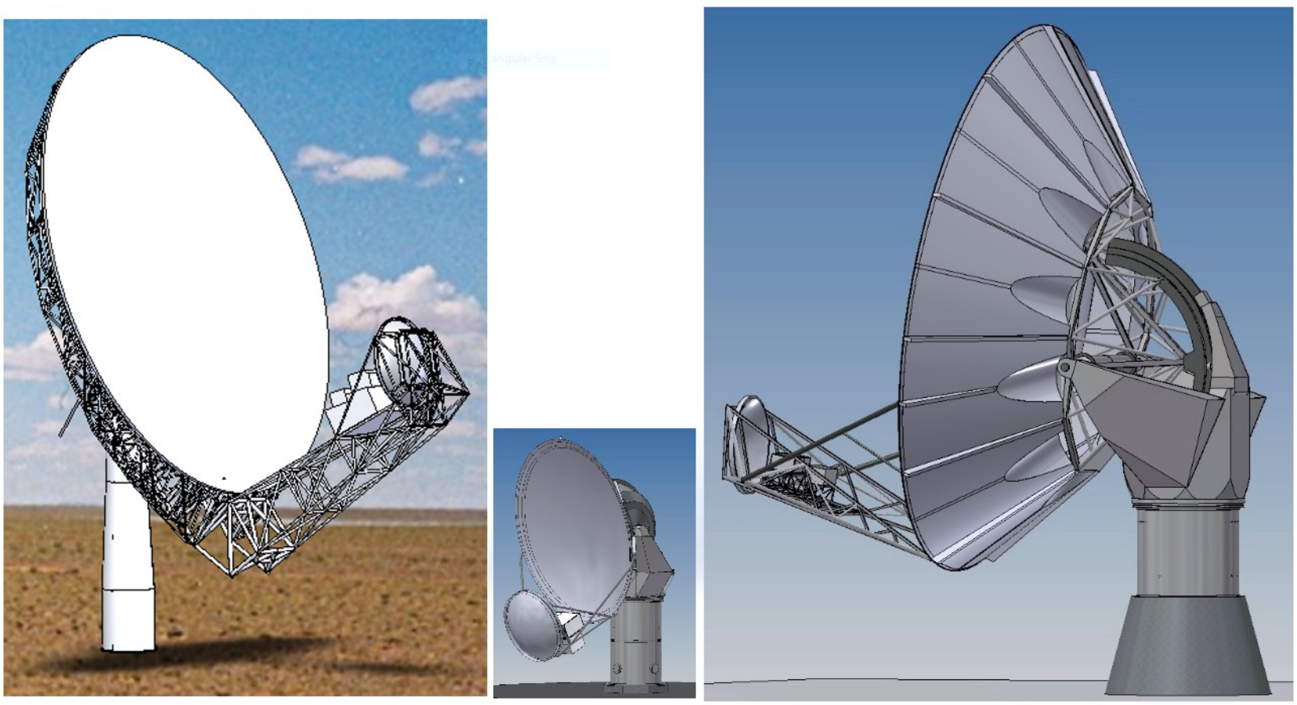

Figure 13 - Left: ngVLA 18m antenna reference design concept prepared by GDMS. Right: 18m antenna concept prepared by NRC. Center: 6m short spacing array antenna concept prepared by NRC.

7.4 Antenna Electronics

7.4.1 Front Ends

The requirements and supporting reference design of the front end system is described in the following documents (AD[22-23]):

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

The ngVLA will provide continuous frequency coverage from 1.2 – 50.5 GHz and 70 – 116 GHz in multiple bands. Receivers will be cryogenically-cooled, with the receiver cryostats designed to integrate multiple receiver bands to the extent possible. Limiting the number of cryostats will reduce both maintenance and electrical power costs. The total number of bands required strongly depends on their fractional bandwidths: maximizing bandwidths will reduce the number of cryostats, with a possible penalty in sensitivity. Feeds for all receiver bands are cooled, and fully contained within the cryostat(s).

The reference design receiver configuration consists of the low-frequency receiver (1.2 – 3.5 GHz) in one cryostat, and five receivers spanning from 3.5 to 116 GHz in a second cryostat.

Bands 1 and 2 employ wideband feed horns and LNAs, each covering L+S bands, and C+X bands. Quad-ridged feed horns (QRFHs) are used, having dual coaxial outputs. Due to improved optical performance (improving illumination efficiency and reducing T_{SPILL}), cooled feeds, and the simplified RF design sensing linear polarization, the T_{SYS} is lower than current VLA L, S bands and comparable for C and X bands. Overall aperture efficiency and T_{SYS} are slightly degraded from optimal due to the wider bandwidths spanned, but permits a compact package that can be affordably constructed and operated.

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

Table 7 - Key parameters of the baseline receiver configuration.

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

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

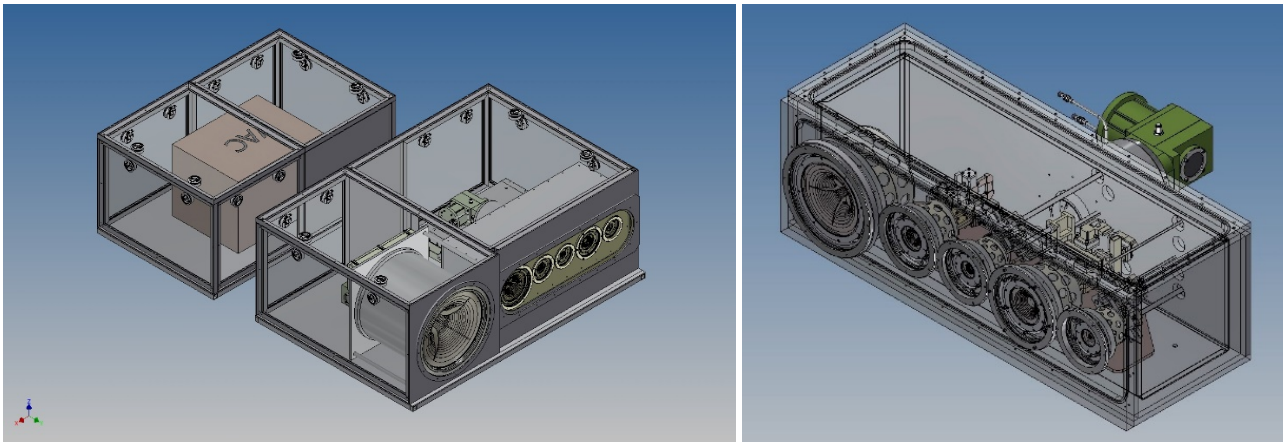

Figure 14. Left: Front end component packaging at the secondary focus of the antenna. Band selection and focus are achieved with a dual-axis translation stage. The integrated receiver packages are located in close proximity to the cryostats, minimizing the analog signal path length. (See Section 7.4.3) Right: Bands 2-6 are housed within in single cryostat.

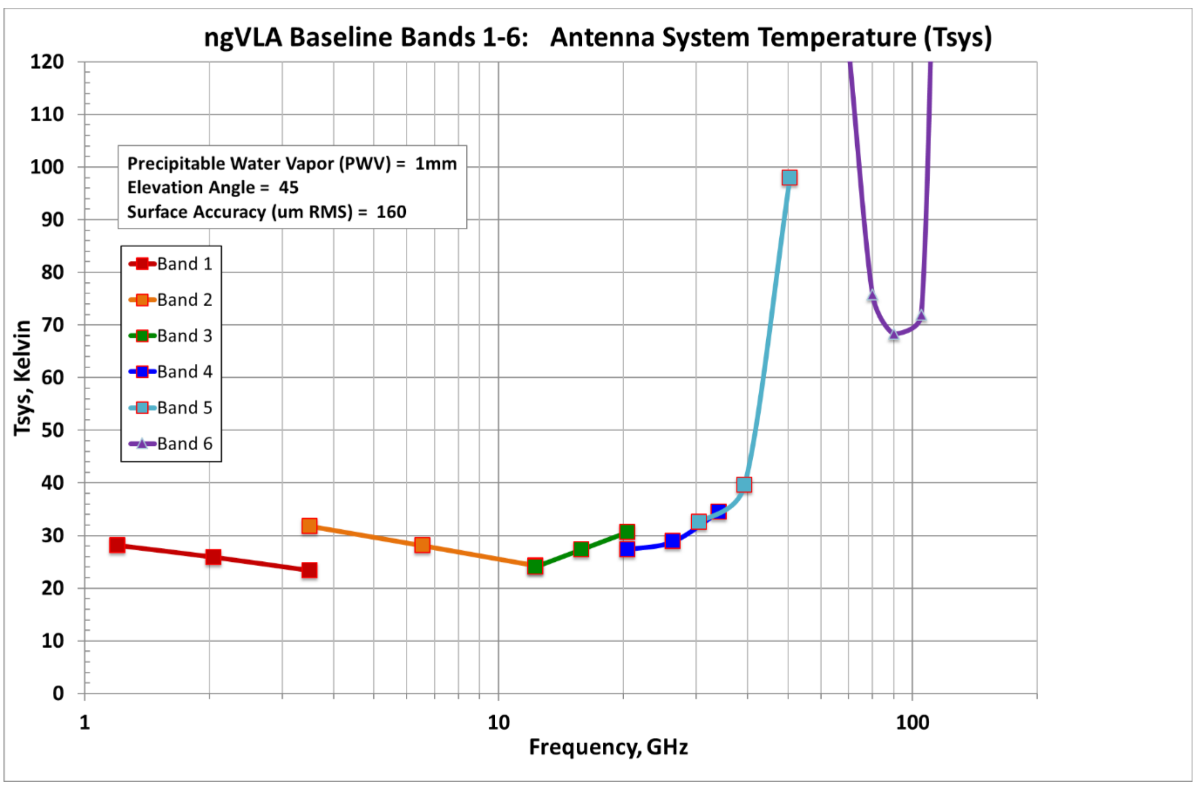

Figure 15: System Temperature for ngVLA 6-Band Receiver Configuration

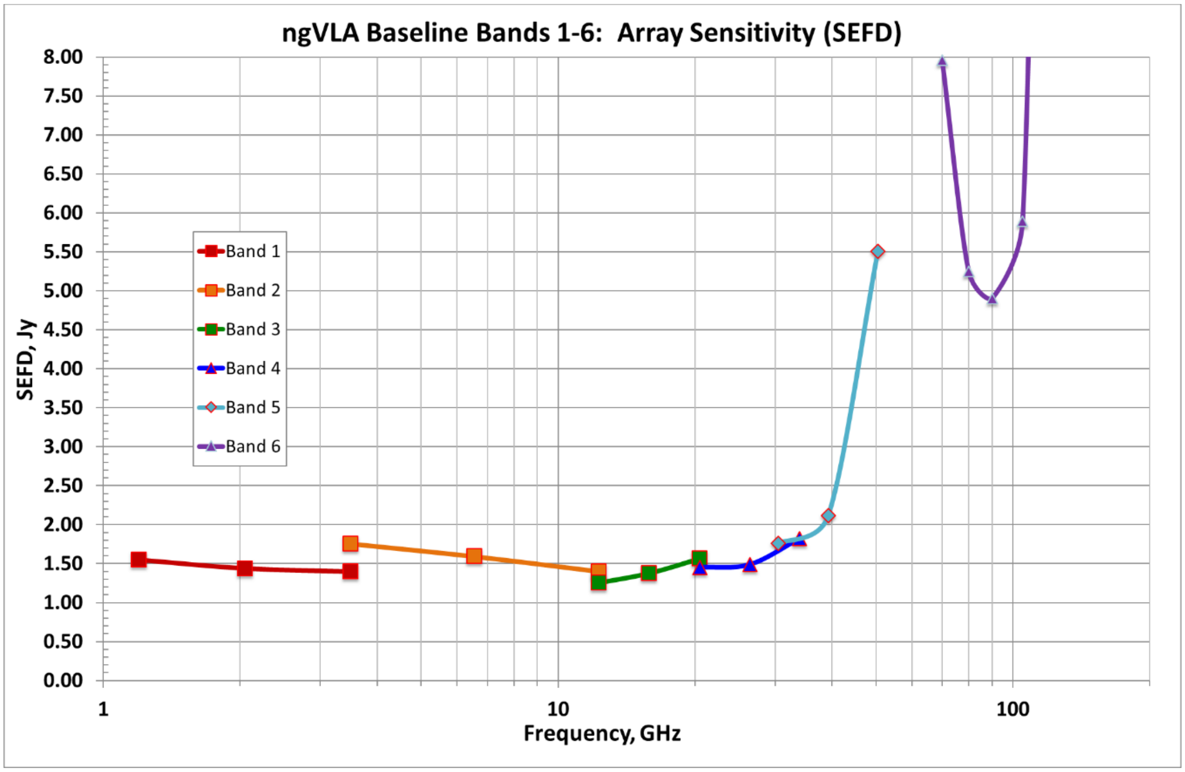

Figure 16: System SEFD for full 263 Element Array (244 @ 18m, 19 @ 6m).

7.4.2 Cryogenic System

The requirements and supporting reference design of the cryogenic system is described in the following documents (AD[24-25]):

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

Supporting analysis leading up to this design can be found in the following documents (RD[29]):

- *Advanced Cryocoolers For Next Generation VLA* ngVLA Memo No. 24

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

In order to meet the programmatic requirements, the number of croystats per antenna has been reduced to two (housing 6 receivers), reducing the preventative maintenance effort, corrective maintenance effort, and power consumption per antenna (See Figure 14). Various cryogenic cycles and refrigerator concepts were explored in RD22, and a two-stage Gifford-McMahon design was selected for the reference design. While other cooling cycles (such as the Sterling cycle) look attractive, the GM system was selected based on a preliminary thermal analysis of the loads for each dewar [RD35]. Projected thermal lift required on the 1st and 2nd stages for each dewar is comparable to that of the well characterized CTI350 GM Refrigerator, and too large for a Sterling cycle system that expels waste heat in the vicinity of the dewar.

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

The cryogenic system design also includes the vacuum roughing pumps required to cool the refrigerators from room temperature. Due to the feedback loops required to effectively control the VFD system, the design is integrated with both the Front End and the Monitor and Control system. The major elements of the Cryogenic system and their interfaces are summarized in Figure 17.

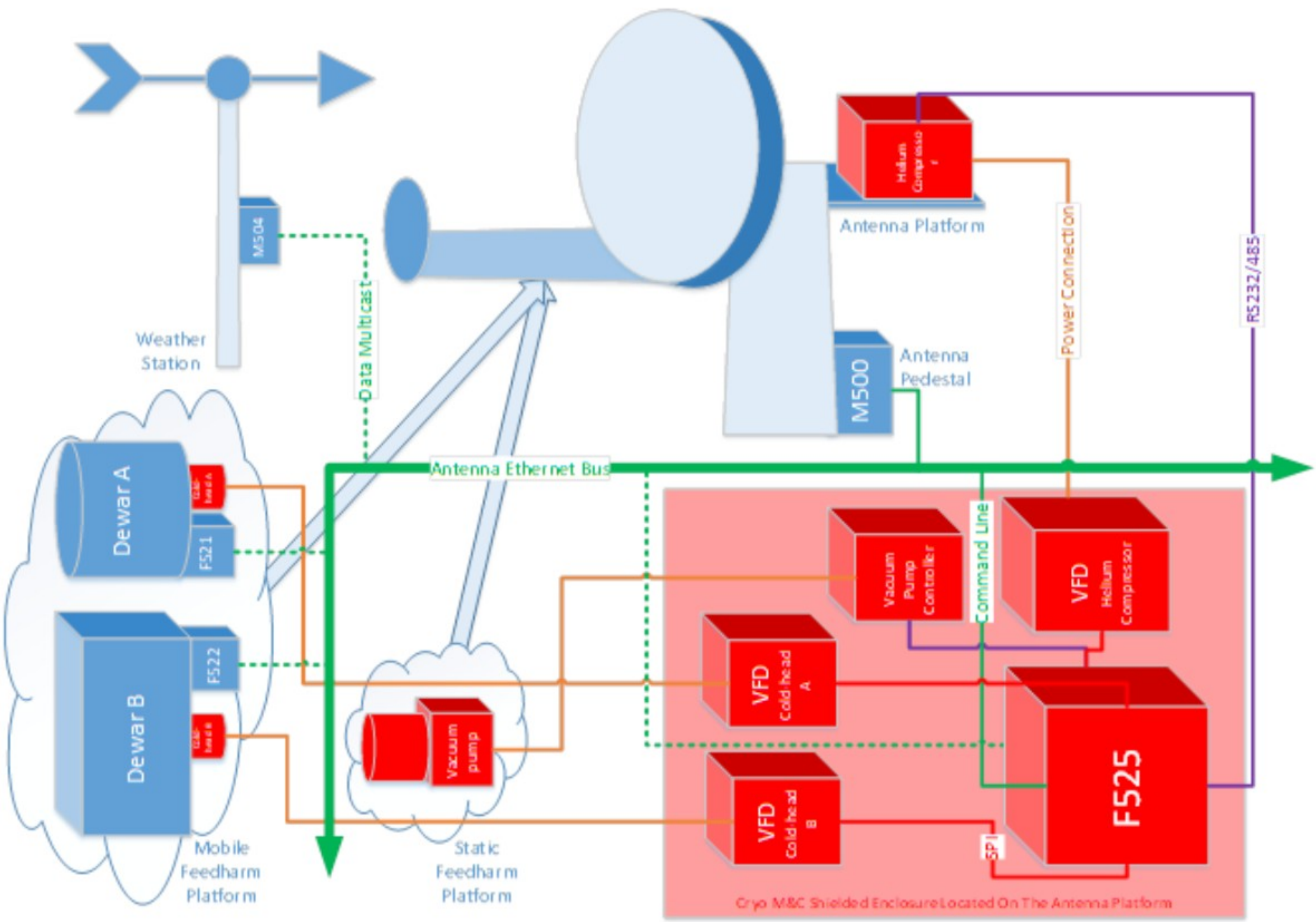

Figure 17 - Cryogenic system interfaces within the antenna. Cryogenic system components are shown in red, with interfacing components in blue. [AD25]

7.4.3 Integrated Down Converters, Digitizers & Serializers

The requirements and supporting reference design of the integrated downconverter digitizer system is described in the following documents (AD[26-27]):

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

Supporting analysis leading up to this design can be found in the following documents (RD[36]):

- *An Integrated Receiver Concept for the ngVLA* ngVLA Memo No. 29

The role of the Integrated Receiver and Digitizer (IRD) packages [AD26] is to further amplify the signals provided by the cryogenic front end, downconvert them where necessary, digitize them, and deliver the resultant data streams by optical fiber to a moderately remote collection point from the focal plane (but possibly still inside the antenna base) where they can be time-stamped and launched onto a more conventional network for transmission back to the array correlator and central processing facility. Hooks are needed to provide for synchronization of local oscillators (LO's) and sample clocks, power leveling, command and control, health and performance monitoring, and diagnostics for troubleshooting in the event of component failure.

This subsystem consists of direct-sampled and sideband-separating modules for all telescope bands, which include warm amplification, filtering, power leveling, analog-to-digital conversion, and fiber-optic transmission, as well as external splitters and combiners as needed to feed them from the cryogenic signal paths. Cryogenic systems and thermal transitions, as well as front-end cabling, waveguide runs, and fiber-optic signal paths outside the IRD modules themselves are outside the scope of this work package, though interfaces must be considered. The frequency plan for the reference design is shown in Figure 18. [AD27]. The IRD modules are located adjacent to the cryostats on the antenna feed arm, as shown in Figure 14.

The design of the IRD modules for ngVLA evolved from an internal research program (the Integrated Receiver Development program) which has been perfecting the techniques used in their construction for more than a decade. The aims of the original program were to leverage the advantages of modern electronic integration and digital signal processing, to digitize as closely to the antenna feed-point as possible without comprising the ultimate performance, and to re-optimize legacy receiver architectures in light of these new techniques and in anticipation of future telescope facilities such as the ngVLA. Integration and DSP are deemed complementary in this program, in that the latter provides for greater signal fidelity and precision in concert with detailed calibrations than purely analog techniques, while the former guarantees the long-term stability and uniformity of those calibrations. This resulted also in compact, low-power, field-replaceable receiver units which were a perfect fit for ngVLA's maintenance and operability requirements.

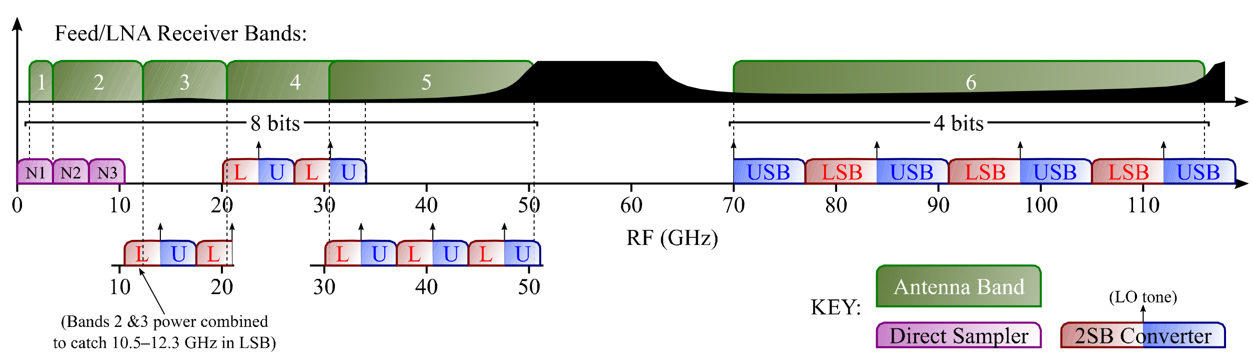

Figure 18. Present sampling concept employing integrated receiver technology for both direct and dual sideband converter/samplers. Nyquist zones 1 through 3 are direct sampled single-sideband at 8-bits. From 10 GHz to 50 GHz the system uses single-stage down conversion to baseband and IQ sampling at 8-bits. 4-bit quantization is used above 70 GHz due to the reduced risk of persistent RFI at these frequencies.

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

The requirements and supporting reference design of the digital back end and data transmission system is described in the following documents (AD[28-29]):

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

The ngVLA digital back-end (DBE) is responsible for two critical pieces of functionality. First, it must ingest the unformatted datastream from the integrated receiver digitizer and align it with a known timing reference.
Secondly, it must perform bandwidth selection and provide data at the correct bitrate and format for transmission to the correlator. The first task will be performed in a custom sampler interface block, and the second by down-converting the sampled data, re-quantizing the incoming data-stream, and re-framing it for further network transmission. Internal block diagrams of the DBE can be found in AD09 and AD28.

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

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

7.4.5 DC Power Supply System

The requirements and supporting reference design of the DC power supply system is described in the following documents (AD[32-33]):

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

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

The DC Power Supply System (specifically P500) receives 208V 3-phase AC @ 17A and converts it to -48V DC. Lithium batteries will be used as a backup source for the 48V in the event the AC is lost. A battery charger will be used to charge the batteries when AC is available. The batteries and battery charger will be located in the pedestal area of each antenna. The 48V is then fed into three power supply modules (P501, P502, and P503) that convert the 48V to +32.5V, ±17.5V, +15.5V, ±7.5V, ±5.5V, and +3.8V depending on the module. Each power supply module has monitor and control (M&C) and temperature sensors in them so they can be shut down for over current or over temperature. The P500 is also used to power the Fire Alarm, Ethernet switch, Digital Back End (DBE) and Data Transmission System (DTS).

The P501 power supply module is used to power the Front End (FE) Low Noise Amplifier (LNA) noise diodes, and bias voltages for Bands 1-6. The P501 also powers the Local Oscillator (LO) Reference Sample Clock Generator and LO A-K Generator modules and the Integrated Downconverter/Digitizers (IRD) for Bands 1-6. The P501 will be located next to the IRDs in the Front End Enclosure.
The P502 power supply module is used to power the LO Clock Receiver module, two Band 4 IRDs, the Water Vapor Radiometer (WVR) antenna amplifier, and cooling system. The P502 will be located in the WVR Enclosure.

The P503 is used to power the LO Reference Receiver Generator and Distribution module and the four Monitor Control Modules located in the pedestal area of each ngVLA antenna. A block diagram of these connections is shown in Figure 19.

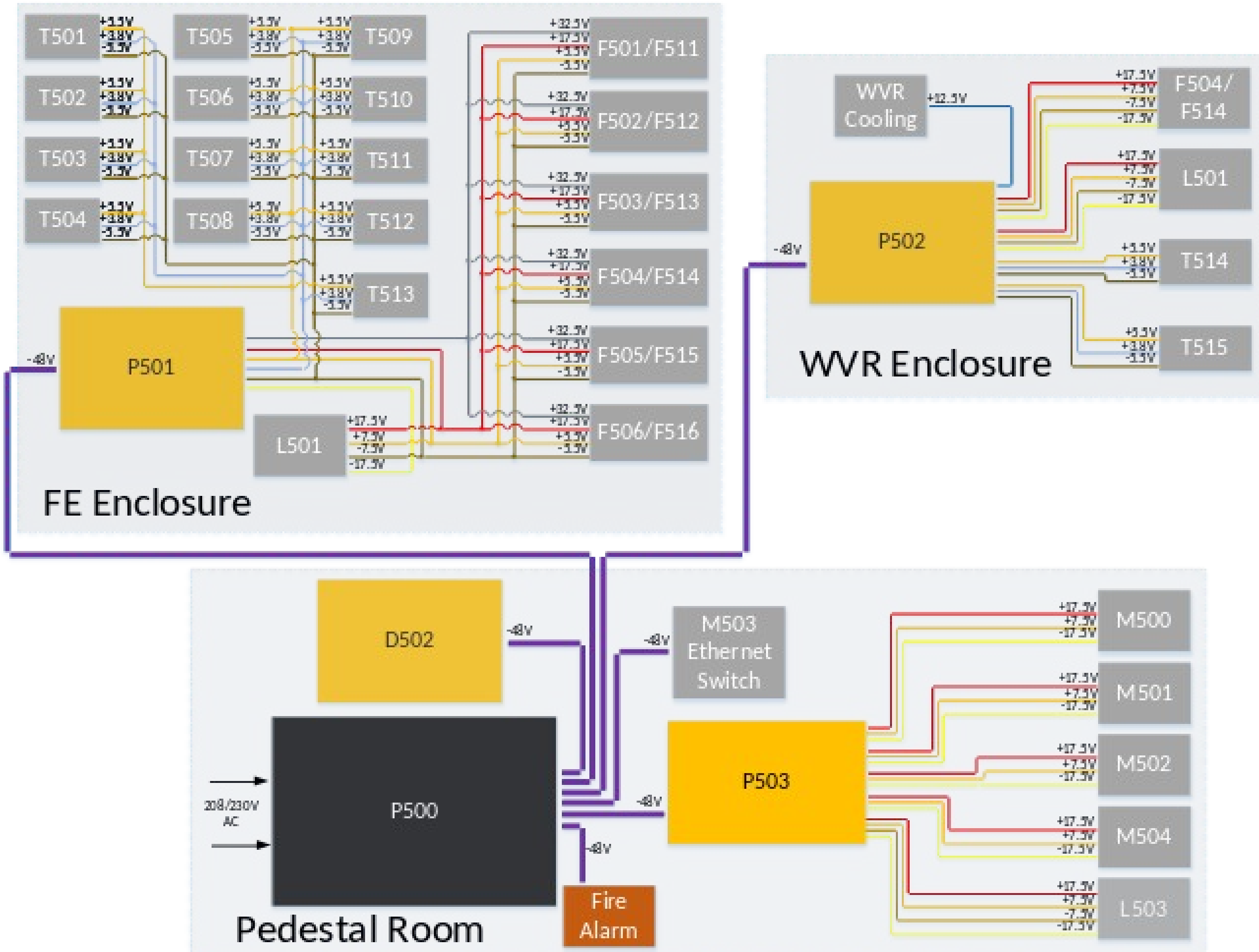

Figure 19 - Block diagram of the DC Power Supply System.

7.4.6 Bins, Modules & Racks

The requirements and supporting reference design for the antenna electronics packaging (Bins, Modules & Racks) is described in the following documents (AD[32-33]):

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

The Bins, Modules, and Racks sub-system consists of individual modules (LRU's) housed in a number of bins all inside of an EIA standard electronics rack located in the pedestal room of the antenna. The work package may also include a number of modules and bins in locations other than the electronics rack and other than the pedestal room. Its key function is to house the LRU's that make up the antenna electronics, and make assembly and maintenance of the antenna electronics as simple as possible while providing adequate RFI shielding for the antenna and any other sensitive equipment.

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

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

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

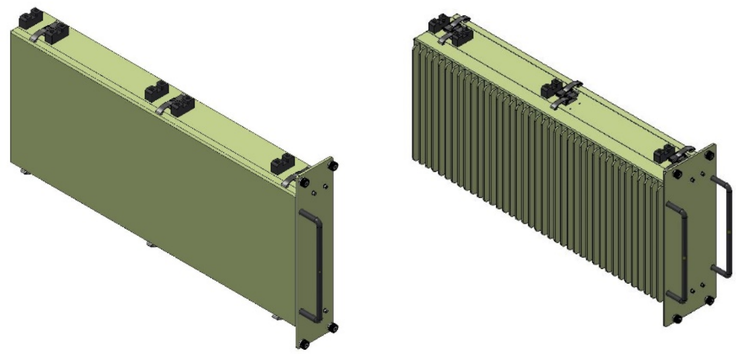

Figure 20 - Series 100 and 300 ARCS Module housings employed in the reference design. Standard 100 on left and 300 w/ heatsink on right.

7.4.7 Environmental Control

The requirements and supporting reference design for the environmental control system is described in the following documents (AD[34-35]):

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

The antenna electronics are located in various places around the antenna (Figure 21). Primary locations include but are not limited to the electronics rack in the pedestal room, the front end on the feed arm, the WVR enclosure near the base of the feed arm, and the compressor platform/enclosure at the top rear of the pedestal. Environmental control of the antenna electronics consists of temperature control of all the electronics in these locations as well as protection from water, dust, animals, or other environmental hazards.

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

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

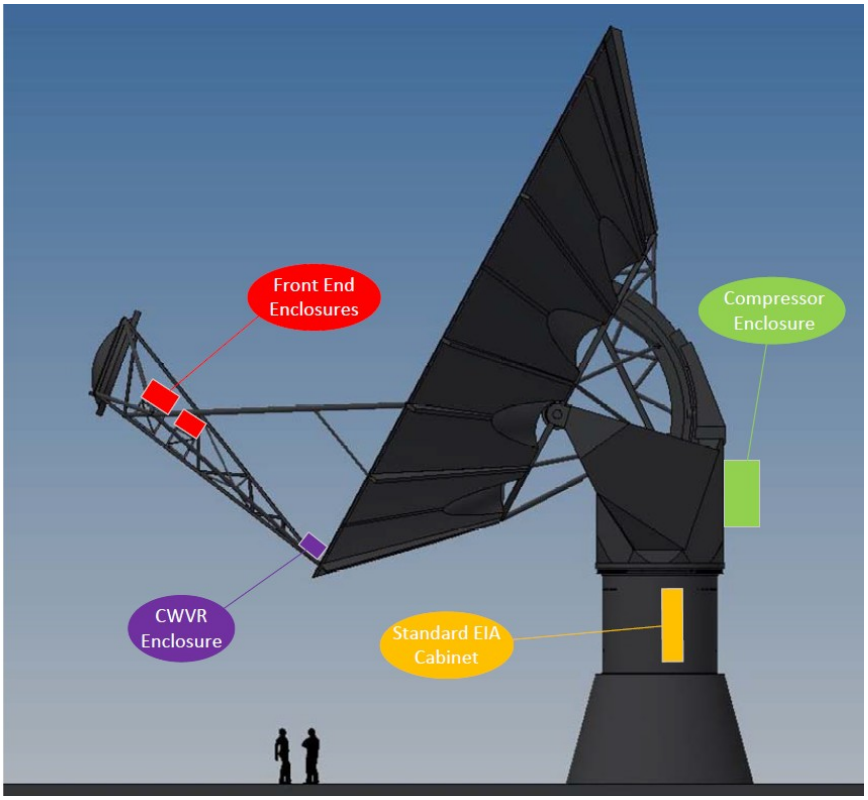

Figure 21 - Location of the thermally regulated enclosures and environmental control system hardware. NRC 18m antenna shown as reference.

7.5 Time and Frequency Reference Signal Generation and Distribution

The requirements and supporting reference design for the time and frequency reference generation and distribution system are described in the following documents (AD[36-37]):

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

In these documents, the antenna time and frequency system is treated as part of an integrated ngVLA-wide time and frequency distribution system, with AD[36-37] documenting the requirements and reference design from the generation of references to the delivery of synchronized time and frequency systems to both the correlator and antenna electronics modules.

The LO Reference and Timing work element is responsible for supplying accurate and reliable local oscillator, sampler clock, and timing references to the antenna stations and the central signal processor. The block diagram shown in Figure 22 illustrates the major functional blocks of the LO reference and timing for antennas within 300km of the array center. The references are generated and synchronized in the central building, and a frequency reference and timing signal are provided to the central signal processor. The references are then distributed with all necessary amplification, buffering, splitting, etc., and the required signals are transmitted to each antenna. For the reference design, the following assumptions are made:

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

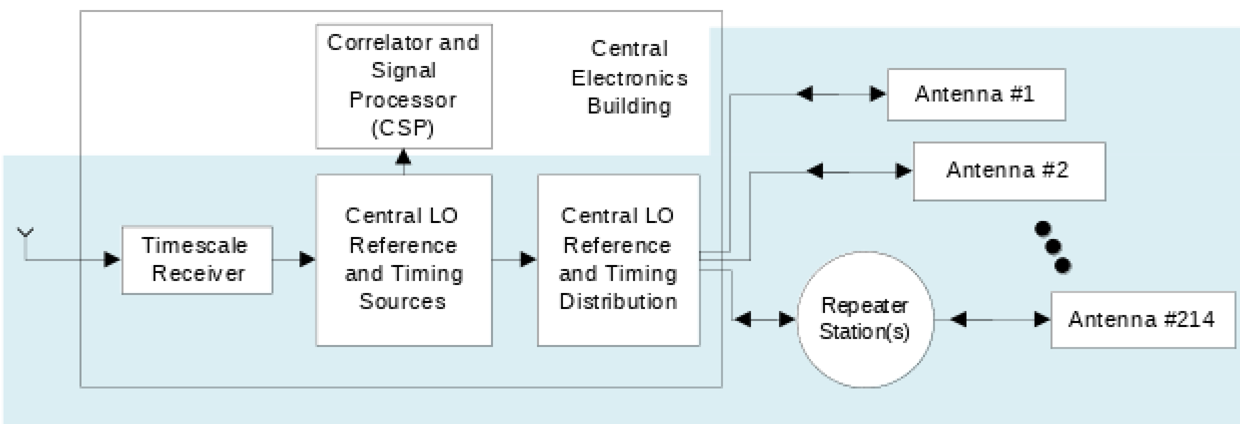

Figure 22 - Block Diagram of LO Reference and Timing for the Main Array. LO Reference and Timing System parts are shaded in blue.

Antennas further than 300km from the array center will follow a VLBI model with their own primary frequency and time references, using a local active hydrogen maser and GPS receiver. This approach is proven in the VLBA and reduces the risk of distributing a coherent reference over the extent of the array, and is also consistent with the DTS concept proposed in Section 7.6. Further development in the conceptual design phase would aim to provide coherent references to all antennas in the main array, if the fiber optic infrastructure can support the frequency reference distribution requirements.

The reference design calls for the distribution of a single high-frequency reference tone to each antenna, to which is added:

- 1 PPS encoded for digital backend timing.
- A small (antenna-dependent) frequency offset for minimization of digitizer self-interference and coherent out-of-band interference.

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

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

7.6 Data Transmission System

The requirements and supporting reference design data transmission system is described in the following documents (AD[28-29, 55]):

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

The Data Transmission System provides connectivity from the antennas to the correlator. Monitor and control connectivity is also provided, but the associated data rates are immaterial compared to the digitized bandwidth of the front end.

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

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

The correlator includes the requisite functionality to buffer the incoming data streams and correctly sequence the packetized and formatted data for all three topologies. The required network infrastructure per antenna is comparable to what ISPs provide to small metropolitan areas and can be procured off-the-shelf today (at significant cost). Technology cycles over the design phase of the project are expected to make the selected DTS concept affordable for both construction and operation. Should this assumption not be realized, the bandwidth at the 46 remote antennas could be throttled at the DBE to fit within cost constraints.

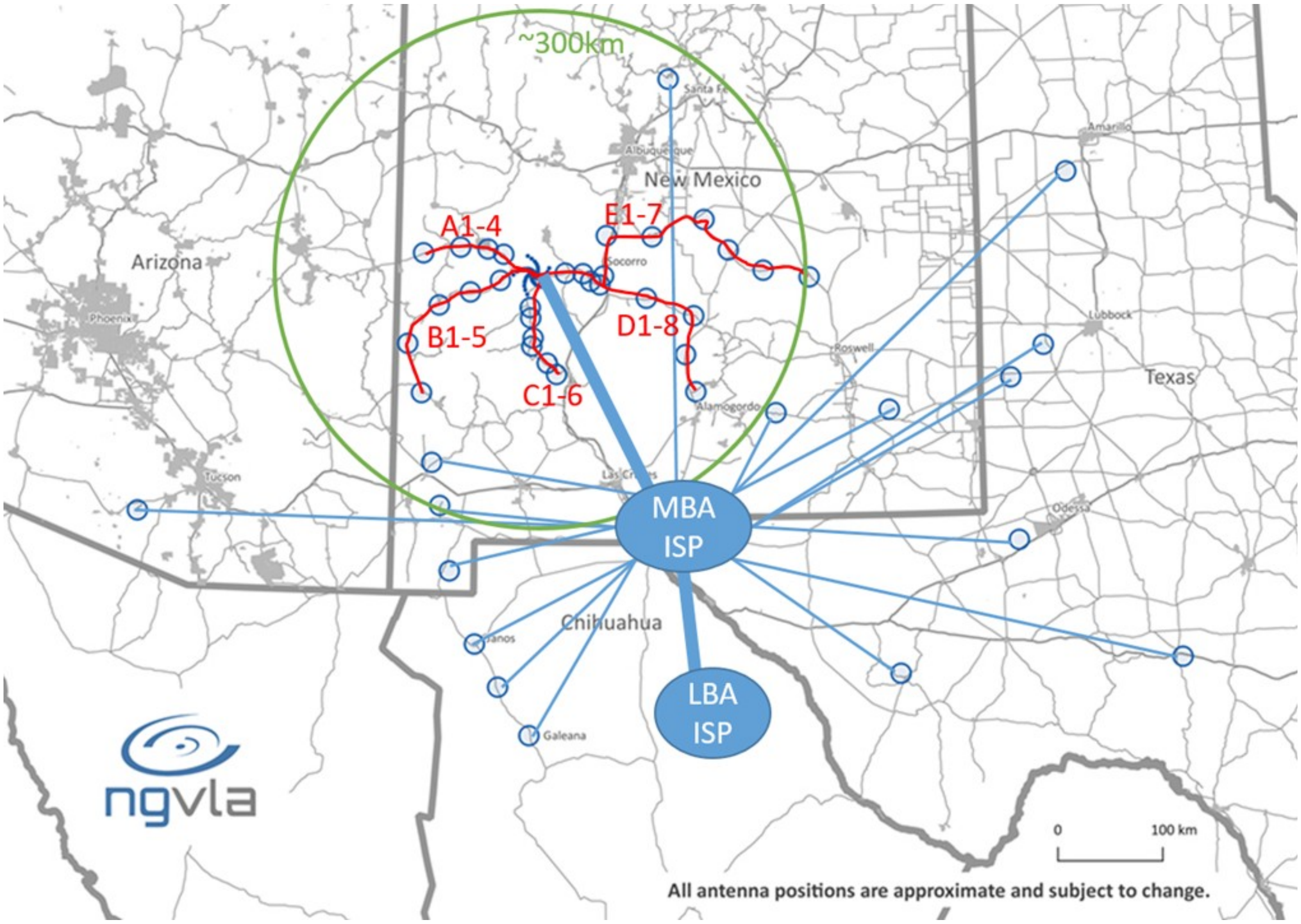

Figure 23 - Data transmission network topology. Antennas within the core and spiral arms are direct point-to-point connections over ngVLA operated fiber. Mid-baseline stations within ~300km are connected over dedicated fiber links with repeater infrastructure hosed at each antenna station. Mid-baseline stations outside the ~300 km radius, and all long-baseline stations, rely on leased bandwidth provided by network operators.

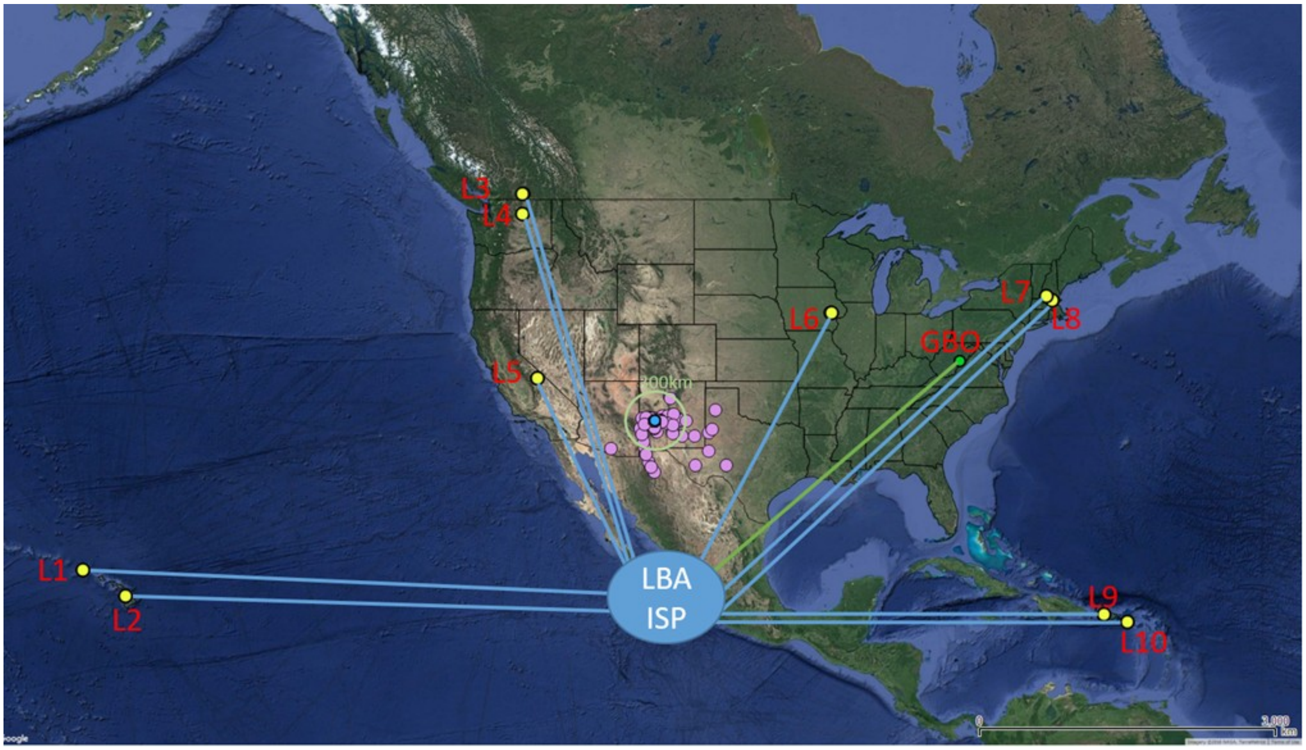

Figure 24 - ngVLA LBA ISP data links. LBA sites are shown in yellow, and the GBT site shown in green. The ngVLA core and main array are in blue and purple, respectively. A total of thirty antennas are included in the LBA configuration (See Section 7.1) and share links from the ten sites.

7.7 Central Signal Processor

The requirements and supporting reference design of the central signal processor is described in the following documents (AD[38-39,51]):

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

The Central Signal Processor (CSP) ingests the voltage streams recorded and packetized by the antennas and transmitted via the data transmission system, and produces a number of low-level data products to be ingested by the archive. Among its many functionalities, the CSP is responsible for compensating the large transmission delays from the remote stations, tracking the delay and phase differences between antennas, flagging the spectral channels corrupted with RFI at a pre-correlation stage, selecting the spectral window of interest within the digitized and transmitted bandwidth, offsetting the different frequency standards used by the remote stations, and achieving the desired spectral resolution.

In addition to synthesis imaging, the CSP will support other capabilities required of modern telescopes to enable VLBI and time-domain science. The functional capabilities of the CSP include full-polarization auto- and cross-correlation computation, as well as beamforming capabilities for pulsar timing, pulsar/transient search, and VLBI recording. The CSP data products will vary by operation mode. The most common will be raw/uncalibrated visibilities, recorded in a common data model. The CSP will include all necessary "back end" infrastructure to average visibilities and package them for the archive, where they will be recorded to disk in a standard format. Calibration of these data products will be carried out through asynchronous data post-processing pipelines.

The CSP will support multiple sub-arrays operating simultaneously and fully independent from each other. Two key requirements for the system are the degree of commensality supported within a sub-array and the desired capabilities for sub-arrays operating simultaneously. At a minimum, the CSP will be able to compute auto- and cross-correlation products within a sub-array, as well as simultaneous cross-correlation and either pulsar timing, pulsar search or VLBI capabilities for different sub-arrays. Enabling correlation and beamforming products simultaneously within a sub-array is also under evaluation. Such a mode would reduce calibration overheads of the beamformer, and provide for localization/imaging concurrent with time-domain observations. The degree of commensality is expected to be a cost/complexity driver in the system and will be optimized on a best value basis.

The CSP is split into two systems: a correlator-beamformer and a pulsar timing engine. (The pulsar search engine is collocated with the post-processing compute cluster) The ngVLA correlator-beamformer [AD51] will employ an FX architecture, and will process an instantaneous bandwidth of up to 20GHz per polarization. The correlator-beamformer (CBF) Frequency Slice Architecture developed by NRC Canada for the SKA Phase 1 mid-frequency telescope in South Africa is well suited to ngVLA demands and is adopted for the reference design. The project has entered an NDA with NRC to share relevant design documentation and to collaborate on the CBF design.

This frequency slide architecture will scale to the additional ngVLA apertures, bandwidth, and commensal mode requirements. Adopting this architecture could significantly reduce the non-recurring engineering costs during the design phase, while additional improvements in electrical efficiency can be expected from one additional FPGA manufacturing process improvement cycle due to ngVLA's later construction start date as compared to SKA Phase 1. Key performance requirements for the correlator are summarized in Table 8.

Table 8 - Correlator-beamformer key specifications.

Requirement Description	Specification
Number of Connected Antennas	263 total
Maximum Baseline Length	10,000 km
Maximum Instantaneous Bandwidth	20 GHz per polarization

Requirement Description	Specification
Maximum Number of Channels	≥ 750,000 channels
Highest Frequency Resolution	400 Hz, corresponding to 0.1 km/s resolution at 1.2 GHz.
Pulsar Search Beamforming	≥10 beams. ≥ 60 km diameter sub-array, 1” coverage
Pulsar Timing Beamforming	≥5 independent sub-arrays ≥ 1 beam per subarray

7.8 Independent Phase Calibration System

The requirements and supporting reference design of the independent phase calibration system is described in the following documents (AD[40-41]):

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

Supporting analysis leading up to this design can be found in the following documents (RD[13, 14, 23-25]):

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

Early studies into the phase calibration required to correct for atmospheric disturbances [RD 13] suggested relatively fast phase correction would be required, with correction cycle times of order 30 seconds. Correcting for the atmospheric phase with astronomical observations of phase calibrators (high SNR sources) would then require a fast slewing antenna, and a significant portion of observing time would be spent observing the calibrator or slewing between the calibrator and science target.

In order to improve observational efficiency (time on science target), an independent phase calibration system is incorporated into the system architecture. For the reference design, this system will employ water vapor radiometry (WVR).

The WVR system constantly observes an atmospheric water vapor emission line centered at 22GHz in order to calculate the column density of water vapor in the WVR beam (the primary contributor to atmospheric phase perturbations). Before the observation, a calibrator is observed (as in switching) to establish an absolute phase offset between antennas, while WVR column density is noted. By monitoring changes in the water vapor column density throughout an observation, estimates of change in phase can be applied to the science data. Periodically – but with a much larger interval than that of fast switching – the calibrator can be re-observed to re-establish absolute phase offset.

The WVR consists of a 1.2-meter antenna mounted to the main feed arm. The fixed WVR beam is aligned parallel to the main antenna beam. The WVR antenna architecture is offset prime focus. The feed, receivers, digitizers, and support electronics are located in a module mounted to the main feed arm at the offset focal point. A mounting plate connected to the antenna's liquid cooling system provides a heat reservoir. Front-end and receiver and digitizer electronics are thermally stabilized using Peltier heat pumps. A band from 18 – 32 GHz is digitized in the receiver module and digital data is streamed via fiber to the WVR processor in the pedestal room. Low-data-rate output is emitted into the Monitor and Control data stream.

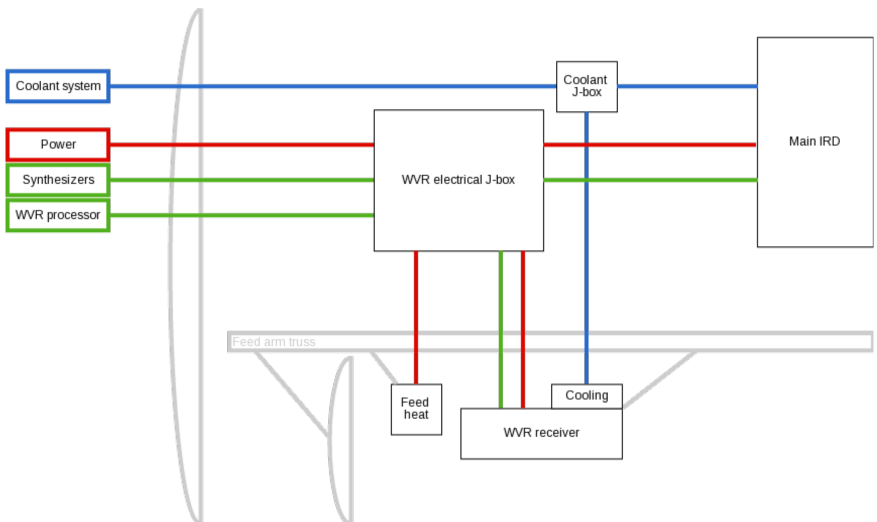

Figure 25: WVR system block diagram and interfaces.

7.9 Computing & Software System

The requirements and supporting reference design architecture of the on-line and off-line computing and software systems are described in the following documents (AD[42-43]):

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

Supporting analysis leading up to this design can be found in the following documents (RD[31-33]):

- *RFI Flagging Algorithms* (ngVLA Memo #TBD)
- *Imaging Algorithms* (ngVLA Memo #TBD)
- *Computing System Sizing* (ngVLA Memo #TBD)

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

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

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

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

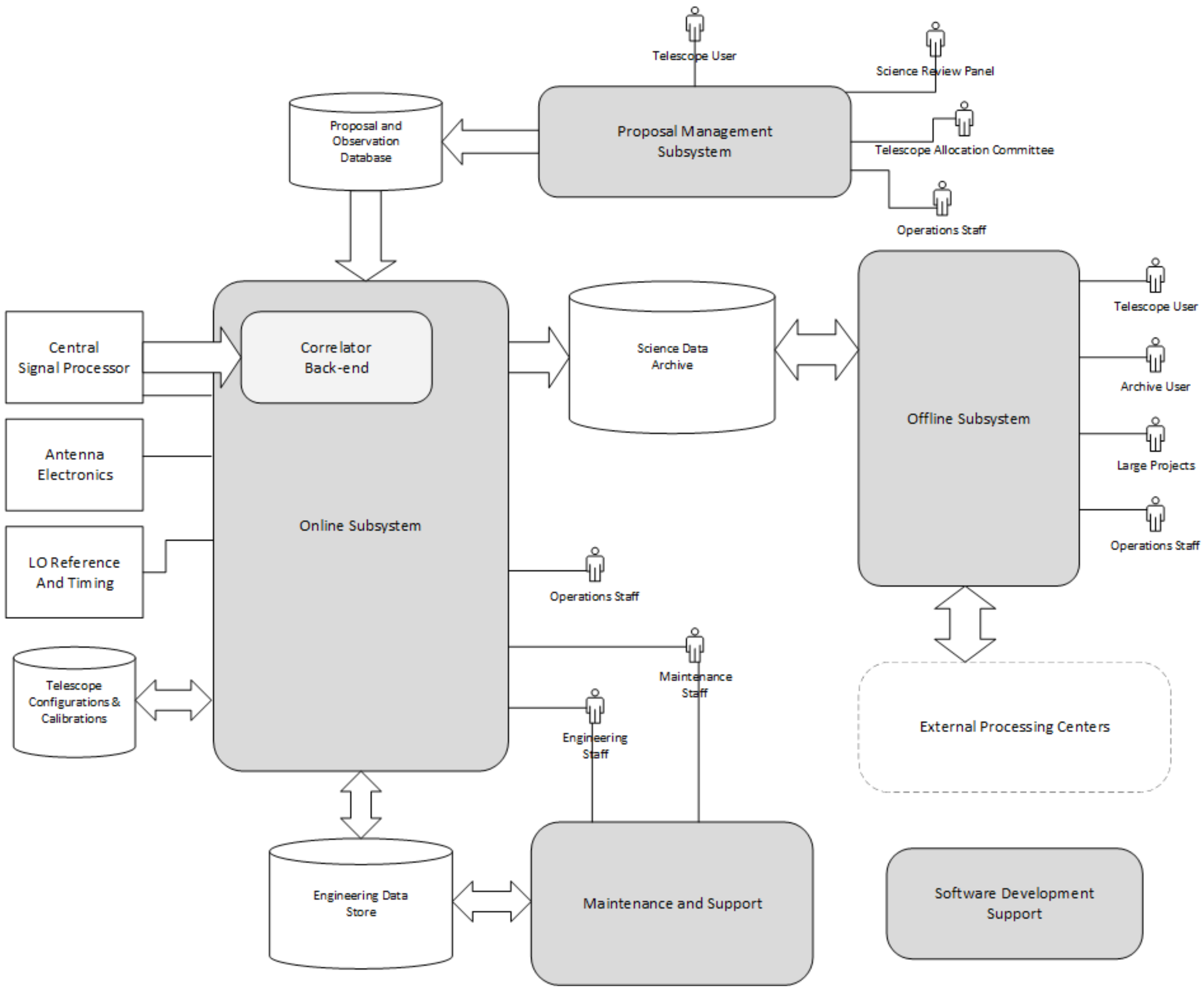

Figure 26: General CSW architecture. The major subsystems are shown as gray boxes. Also shown are the interfaces and dataflows between the subsystems, data stores, main actors and other external system elements.

7.9.1 Monitor & Control System

The overall concept, requirements, and supporting reference design for the monitor & control system are described in the following documents (AD[44-46]):

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

The monitor and control system leverages NRAO experience with both the VLA and ALMA M&C systems, and is designed to achieve a high degree reliability, maintainability and usability, in order to decrease operational and maintenance costs. In general, the ngVLA monitoring and control concept is guided by two principles:

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

Following these considerations, the ngVLA control system will be structured in 5 layers, as shown in Figure 27. The bottom Hardware Device layer represents the hardware devices that compose the telescope. The electronics devices will be packaged as Line Replacement Units, identified by a unique serial number.

The Hardware Controller Layer corresponds to controller boards (analogous to MIB boards in the VLA, or AMBSI boards for ALMA), which provide a standardized Ethernet interface to its connected hardware devices. They translate Ethernet messages to the low level interfaces used by hardware devices: SPI, I2C and GPIO. This layer also includes the CSP Local Control System and other central electronic systems (e.g. local oscillator and timing). In this case, the Hardware Controller won't necessarily be Controller boards, but they could consist in 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.

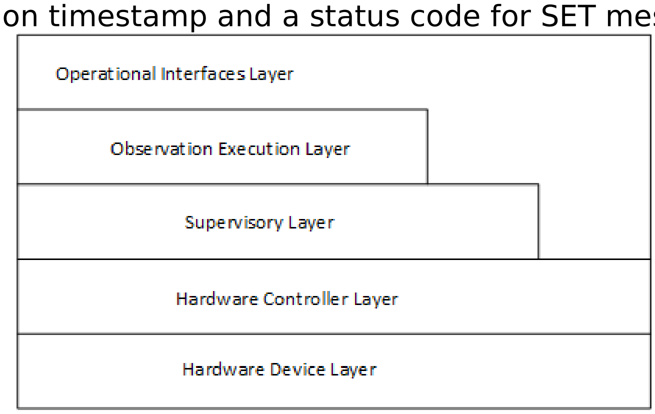

Figure 27. Control architecture layers.

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 has 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, which identifies its function in the system; and a role, which identifies where it is installed in the system. As an example, each antenna has two LRUs of the IF processor type, each one connected to receive different polarizations. As soon as the LRU reaches the operational state, it will send a multicast message containing identifying information such as its serial number(s), its type, role, and its 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, the system architecture is divided in hard real-time requirements and soft real-time requirements, the distinction residing on how critical is for a task to miss its defined deadlines. Any deadline that cannot be missed without placing humans and/or equipment in danger should be regarded as a hard deadline, and should be implemented in the Controller or Device layers. The Supervisory and above layers will deal only with soft deadlines, where the outcome of missing them will result in most cases in an interval of flagged science data. In general, LRUs (which are composed by 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 & control system.

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

7.10 Buildings & Array Infrastructure

The requirements and supporting reference design for the buildings and array infrastructure are described in the following documents [AD47]:

- *Buildings & Array Infrastructure: Reference Design Study*
  020.60.00.00.01-0002-REP

The array infrastructure includes the foundations, electrical infrastructure, fiber infrastructure and ancillary structures necessary to support each antenna within the array. The buildings work package includes all structures required for the construction, commissioning and operation of the array.

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

Average total power load is estimated at 3.5MW for the array, central infrastructure, and off-site buildings combined. This is approximately three times the current VLA load. Significant savings are achieved in the design of the antenna electronics, correlator system, and computing cluster when compared to existing facilities Estimates are based on a combination of parametric scaling from the VLA actual power loads, and bottom-up estimates for new designs and is apportioned as shown in Table 9. The main power source on the plains is expected to be grid power provided by the local utility company. Green power sources (photovoltaic and wind turbines) have been considered, and are increasingly attractive on operating price metrics, but are presently outside the scope of construction.

Table 9: Approximate average electrical power load.

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

The fiber infrastructure will share the utility trench with the power distribution system. It is a start topology, with all fibers terminating at the central control building (housing the correlator). Other infrastructure systems at the site include water and waste systems, landfill, fire suppression and service roads.

Stations outside the plains will leverage existing infrastructure where available, with electrical infrastructure providing “last mile” connections, and fiber strung along existing pole line right-of-ways. Sites beyond 300 km from the core will rely on commercial fiber links for data backhaul as shown in Figure 23. Off-Grid photovoltaic power and battery backup will be compared to “last mile” connections to existing utility systems and may be preferred for distances greater than a few kilometers.

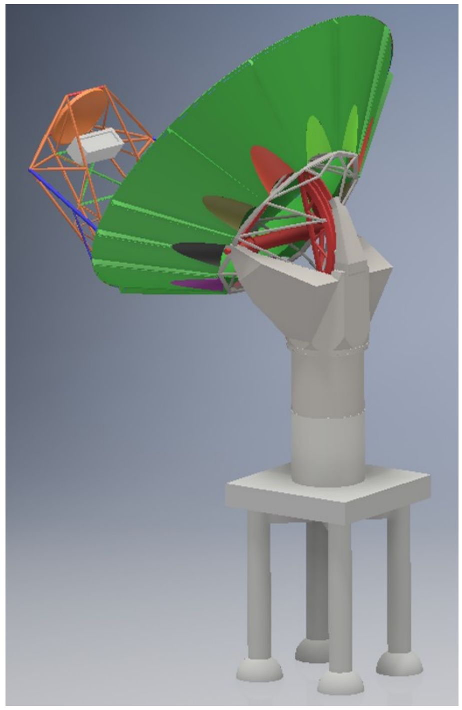

Figure 28 - Foundation design used for costing. The slab below the antenna is at ground level, with concrete caissons extending below grade.

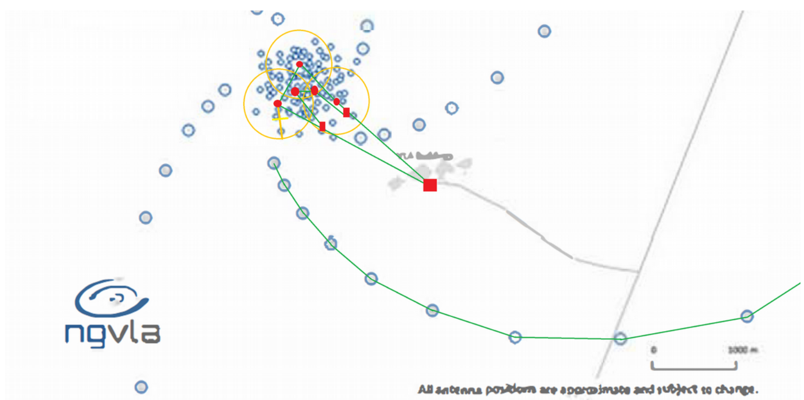

Figure 29 – Example locations of the backup power plant and switchgear locations (red) and utility trenching along arms (green).

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

Additional operation centers are included within the building package required for facility operation. These include an array operations and repair station in Socorro, as well as a Science Center and Data Center at a remote metropolitan area.

8 CONSTRUCTION COST ESTIMATE

The integrated construction cost estimate is provided in the following documents [AD48]:

- *Integrated Construction Cost Estimate*
  020.05.15.05.00-0004-BUD

This estimate was built from supporting information provided for each major sub-system:

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

- *Operations Buildings: Cost Estimate*
  020.65.00.00.00-0001-BUD

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

- *ngVLA Quantitative eXchange Model - Report*
  020.05.15.00.00-0004-REP
- *ngVLA Quantitative eXchange Model - Spreadsheet*
  020.05.15.00.00-0005-REP

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

9 OPERATION COST ESTIMATE

The integrated operations cost estimate provided in the following documents [AD49]:

- *Integrated Operations Cost Estimate*
  020.05.15.05.00-0007-BUD

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

- *ngVLA Quantitative eXchange Model - Report*
  020.05.15.00.00-0004-REP
- *ngVLA Quantitative eXchange Model - Spreadsheet*
  020.05.15.00.00-0005-REP

The operations cost estimate is consistent with the Operations Concept [AD10] discussed in section 4. This will be further developed into an Operations Plan in future stages of the design. Please consult AD49 for the current projected annual operations cost breakdown and details on the cost methodology.

10 PROJECT OPTIONS (UPSCOPES AND DESCOPES)

Possible up-scopes and descopes to the project are discussed at a high-level in the following document [AD53]:

- *ngVLA Up-Scope and Descope Options*
  020.05.05.00.00-0005-PLA

The ngVLA Architecture is highly flexible and can be scaled on many axes. The approximate cost and performance differences associated with various scope or specification changes are presented. The following up-scope options are elaborated:

- Improved snapshot imaging performance on 1000 km scales. [RD44]
- A dedicated Pulsar Timing Array Telescope. [RD45]
- A commensal low frequency system. [RD46]
- Additional collecting area in the Main Array.

In addition to the optional additions to the project scope and capabilities, the following descopes to the project are described:

- Long Baseline Array.
- Short Baseline Array.
- Reductions in Main Array sensitivity / collecting area.
- Reductions in Main Array angular resolution.
- 1.2-12.3 GHz Observing Capability.
- 70-116 GHz Observing Capability.

In aggregate, the discussed options can vary the cost of the project at the +/-50% level. Please consult AD53 for further information.

These changes are to requirements and scope, rather than simple scope deferments, where the latter are recoverable changes to the deployment plan to adjust the project cost at the 10-20% level, with the hope of re-instating these capabilities from supplementary funds sought during the operations phase. These deferment options remain available for cost/schedule/scope management of the project. Examples of such deferments include:

- Reduction in compute and storage capacity, and deferment of the most demanding operating modes. (High time resolution, w-projection, etc.)
- Deferment of SRDP pipelines for one to all operation modes and bands.
- Deferment of select receiver bands.

11 APPENDIX

11.1 Acronyms & Abbreviations

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

Acronym	Description
AD	Applicable Document
AEC	Architecture, Engineering and Construction
ALMA	Atacama Large Millimeter/submillimeter Array
ARCS	Advanced RFI Containment System
AST	Division of Astronomical Sciences (NSF)
BW	Band Width
CBF	Correlator Beam-Former
CDL	Central Development Laboratory
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSP	Central Signal Processor.
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
DBE	Digital Back End
DTS	Data Transmission System
EDFA	Erbium-Doped Fiber Amplifiers
EIA	Electronics Industries Association / Electronics Industries Alliance
EIRP	Effective Isotropic Radiated Power
EMC	Electro-Magnetic Compatibility
ENOB	Effective Number of Bits
FE	Front End
FOV	Field of View
FSA	Frequency Slice Architecture
FWHM	Full Width Half Max
GM	Gifford-McMahon
GW	Gravitational Wave
HPC	High Performance Computing
HVAC	Heating, Ventilation & Air Conditioning
IF	Intermediate Frequency
IRD	Integrated Receiver Digitizer
ISP	Internet Service Provider
KPP	Key Performance Parameters
KSG	Key Science Goals
LBA	Long Baseline Array
LNA	Low Noise Amplifier
LO	Local Oscillator
MA	Main Array
MoE	Measure of Effectiveness

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