ngVLA Local Oscillator Reference and Timing: Generation and Distribution Requirements

020.35.00.00.00-0001 REQ

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-05-30	B. Shillue	All	First Draft
02	2018-09-30	B. Shillue	All	Incorporation of Long Baseline Array Requirements Incorporate reviewer edits
03	2018-11-16	B. Shillue	All	Minor edits after Internal Review
04	2019-04-23	B. Shillue	3.4,6,5	Small changes to sections 3.4.6 and 5, other minor edits
05	2019-06-04	B. Shillue	3.4.2, 3.4.3, 4.2.2, 4.2.3, 4.3.1	Changed detail of reqts -0260, -0300 and added -0251
A	2019-07-26	A. Lear	All	Incorporated minor edits from R. Selina & M. McKinnon; prepared PDF for signatures & release
A.01	2022-04-14	B. Shillue	All	Initial Draft for internal review.
A.02	2022-05-27	A. Lear	All	Formatting, copy edits.
B	2022-05-30	A. Lear	All	Prepare PDF for signatures and release.
B.1	2024-01-24	B. Shillue	3.4	Content added and sections expanded as 3.41—3.4.3
C	2024-02-28	M. Archuleta	All	Removed requirements LRT5350-5390 in Sections 7.2, 11.2 per B. Shillue (these have been moved to/accounted for in ATF requirements document – 020.30.35.00.00-0004-REQ). Minor edits and formatting; prepared for release.
D	2024-06-01	B. Shillue	All	Consistent use of fsec. Update LRT0330, LRT0400. Elaborate LRT4200, LRT4210, LRT4220.

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1 Introduction

1.1 Purpose

This document presents the complete set of Level 2 subsystem requirements that should guide the design and development of the LO Reference and Timing Generation (RTG) and Distribution (RTD) Subsystem. Requirements described in this document are derived from applicable ngVLA System Requirements and System-Level Specification documents as listed in the Applicable Documents table. The overall requirements hierarchy and management strategy are outlined in [AD01] and [AD02].

The content of these requirements is at the subsystem level, conforming to the system architecture [AD06], but aims to be implementation agnostic within the subsystem boundaries. Some assumptions about the subsystem may be given, but only to the degree necessary to unambiguously define the subsystem requirements.

1.2 Scope

The scope of this document is the LO Reference and Timing Generation (RTG) and Distribution (RTD) Subsystem, as delivered for ngVLA integration. This includes the following:

- Assumptions upon which the requirements are based
- Definition of environmental requirements to be used as applicable conditions in the definition of the requirements
- A complete set of requirements for the subsystem needed for the development, operation and maintenance of the subsystem, including interface requirements that are derived from the applicable list of ICDs.
- Nonfunctional requirements unique to this subsystem (e.g., safety, quality, reliability, maintainability).
- List of Interface Requirements (I/F) and link to Interface Control Documents necessary to integrate with other Systems and Subsystems.
- Numbering of all requirement and establishment of traceability to higher level requirements.
- Technical Performance Measures (TPMs) at the subsystem level, which support the Measures of Performance (MOPs) at the system level.
- Requirements specified for the complete lifecycle of the subsystem, including any requirements that are applicable for operations, maintenance, decommissioning, and disposal.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents apply to this Requirements Specification to the extent specified. In the event of a conflict between the documents referenced herein and the content of this Requirements Specification, the content of the *highest*-level specification (in the requirements flow-down) shall be considered the superseding requirement for design elaboration and verification.

Ref. No.	Document Title	Rev./Doc. No.
AD01	ngVLA Systems Engineering Management Plan	020.10.00.00.00-0001 PLA
AD02	ngVLA Requirements Management Plan	020.10.15.00.00-0001 PLA
AD03	ngVLA System Requirements	020.10.15.10.00-0003 REQ
AD04	L1 System Environmental Specifications	020.10.15.10.00-0001 SPE
AD05	L1 System EMI/RFI Requirements	020.10.15.10.00-0002 REQ
AD06	System-Level Architecture Model	020.10.20.00.00-0002 DWG
AD07	L1 Safety Specification	020.80.00.00.00-0001 REQ
AD08	L1 Security Specification	020.80.00.00.00-0003 REQ
AD09	ngVLA System Electronics Specifications	020.10.15.10.00-0008 REQ
AD10	Calibration Requirements	020.22.00.00.00-0001 REQ
AD11	System Technical Budgets	020.10.25.00.00-0002 DSN

2.2 Applicable Interface Control Documents

Ref. No.	Document Title	Rev./Doc. No.
AD20	Interface Control Document Between: Antenna Electronics DC Power Supply (PSU) *and* Antenna Electronics Subsystem: section on LO Reference and Timing and Distribution (RTD) Subsystem (interface 0058)	020.10.40.05.00-0006
AD21	Interface Control Document Between: Antenna Electronics Bins, Modules, and Racks (BMR) *and* Antenna Electronics Subsystem: section on LO Reference and Timing and Distribution (RTD) Subsystem (interface 0064)	020.10.40.05.00-0040
AD22	Interface Control Document Between: LO Reference and Timing and Distribution (RTD) Subsystem *and* Antenna Electronics Environmental Control System (EEC) Subsystem	020.10.40.05.00-0069
AD23	Interface Control Document Between: Monitor and Control Hardware Interface Layer (HIL)(interface 0077)/Monitor and Control Subsystem (MCL) (interface 0107) *and* LO Reference and Timing and Distribution (RTD) Subsystem	020.10.40.05.00-0077
AD24	Interface Control Document Between Computing/CSP subsystems : section on LO Reference and Timing Generation (RTG) and Distribution (RTD) Subsystems (interface 0099, 0100) and ngVLA Site Buildings (NSB) subsystem	020.10.40.05.00-0095

Ref. No.	Document Title	Rev./Doc. No.
AD25	Interface Control Document Between Monitor and Control System (MCL) and LO Reference and Timing Generation (RTG)	020.10.40.05.00-0106
AD26	Interface Control Document Between: Central Fiber Infrastructure (FIB) and LO Reference and Timing Distribution (RTD)	020.10.40.05.00-0120
AD27	Interface Control Document Between: Digital Backend (DBE) and Antenna Time and Frequency (ATF)	020.10.40.05.00-0152
AD28	Interface Control Document Between: Central Signal Processing (CSP) and LO Reference and Timing Generation (RTG)	020.10.40.05.00-0123
AD29	Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* LO Reference and Timing – Generation (RTG)	020.10.40.05.00-0124
AD30	Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* Antenna Time and Frequency (ATF)	020.10.40.05.00-0125
AD31	Interface Control Document Between: LO Reference and Timing – Generation (RTG) *and* Hardware Interface Layer (HIL)	020.10.40.05.00-0129
AD32	Interface Control Document Between: LO Reference and Timing – Generation (RTD) *and* Antenna Fiber Optic System (AFD)	020.10.40.05.00-0153
AD33	Interface Control Document Between: LO Reference and Timing – Generation (RTD) *and* Water Vapor Radiometer (WVR)	020.10.40.05.00-0128

2.3 Reference Documents

The following documents are referenced within this text or provide supporting context:

Ref. No.	Document Title	Rev./Doc. No.
RD01	Science Requirements	020.10.15.05.00-0001 REQ
RD02	ANSI Z136 Standards for Implementing a Safe Laser Program	ANSI Z136.1 through .9
RD03	Safety of Laser Products – Part 1: Equipment Classification and Requirements	IEC 60825-1:2014
RD04	R. Selina, B. Shillue, O. Ojeda, M. Schiller, "Timing Requirements & Considerations"	ngVLA Electronic Memo #15, July 2023
RD05	Configuration: Reference Design Rev D Description	ngVLA Memo No. 92

3 Overview of Subsystem Requirements

3.1 Document Outline

This document presents the technical requirements for the LO Reference and Timing Generation (RTG) and Distribution (RTD) Subsystem. These parameters determine the overall performance of the subsystem and the functional requirements necessary to enable its operation and maintenance.

The Level 2 Subsystem Requirements, along with detailed explanatory notes, are found in Section 7. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirement and should guide the verification procedures.

In many cases, the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers have a degree of ambiguity or are insufficiently substantiated, this is also documented in the notes. In this way, the trade-space available is apparent to scientists and engineers who will guide the evolution of the ngVLA concept.

In certain cases, parameters may be simply noted with a TBD or TBC value. The goal in such cases is to identify parameters that will require definition in future releases of these requirements as the associated technical issues are understood.

Section 10 identifies performance metrics that will be monitored throughout the conceptual design phase. These are metrics to assist in the trade-off analysis of various concepts, should tensions be identified between requirements.

3.2 Subsystem General Description

The LO Reference and Timing Generation (RTG) and Distribution (RTD) Subsystem compromises a set of modules that perform a function of hardware timekeeping: generation and routing of an electronic signal, pulse, or digital rising or falling edge from a common reference input to another module or subsystem. The RTG subsystem is fully located in the ngVLA central electronics building (CEB) (or, for very distant antenna stations – at a secondary central facility). The RTD subsystem takes signal generated and developed by the RTG subsystem and delivers them to the antenna stations by optical fiber. The hardware will include electronic and optical (laser) clocks and sources, amplifiers and splitting distribution systems, optical fiber and modems, amplifiers, frequency multipliers and dividers, and phase lock loops.

3.3 Subsystem Boundary and External Interfaces

Figure 1and Figure 2 show the RTG and RTD subsystem boundaries, in the context of other systems on the antenna. External systems are shown in boxes with their Configuration Item (CI) number, in accordance with the Product Breakdown Structure (PBS) generated from the system architecture model. The ICD document number corresponding to each interface is displayed above the interconnect, where it exists.

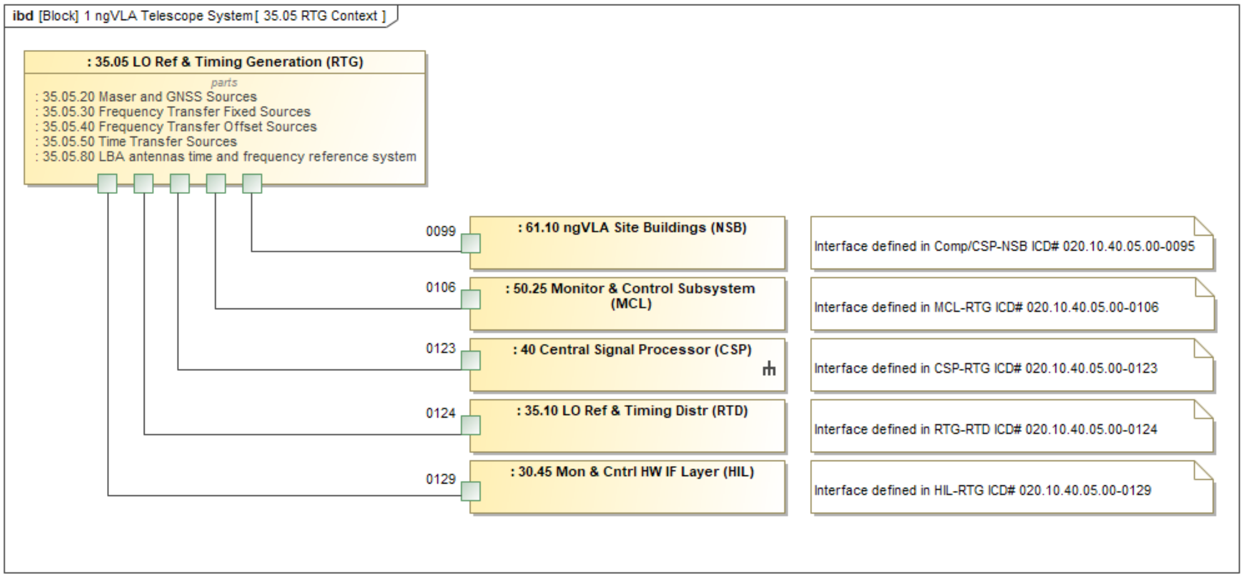

Figure 1: Reference and Timing Generation subsystem product breakdown, interfaces with other antenna subsystems.

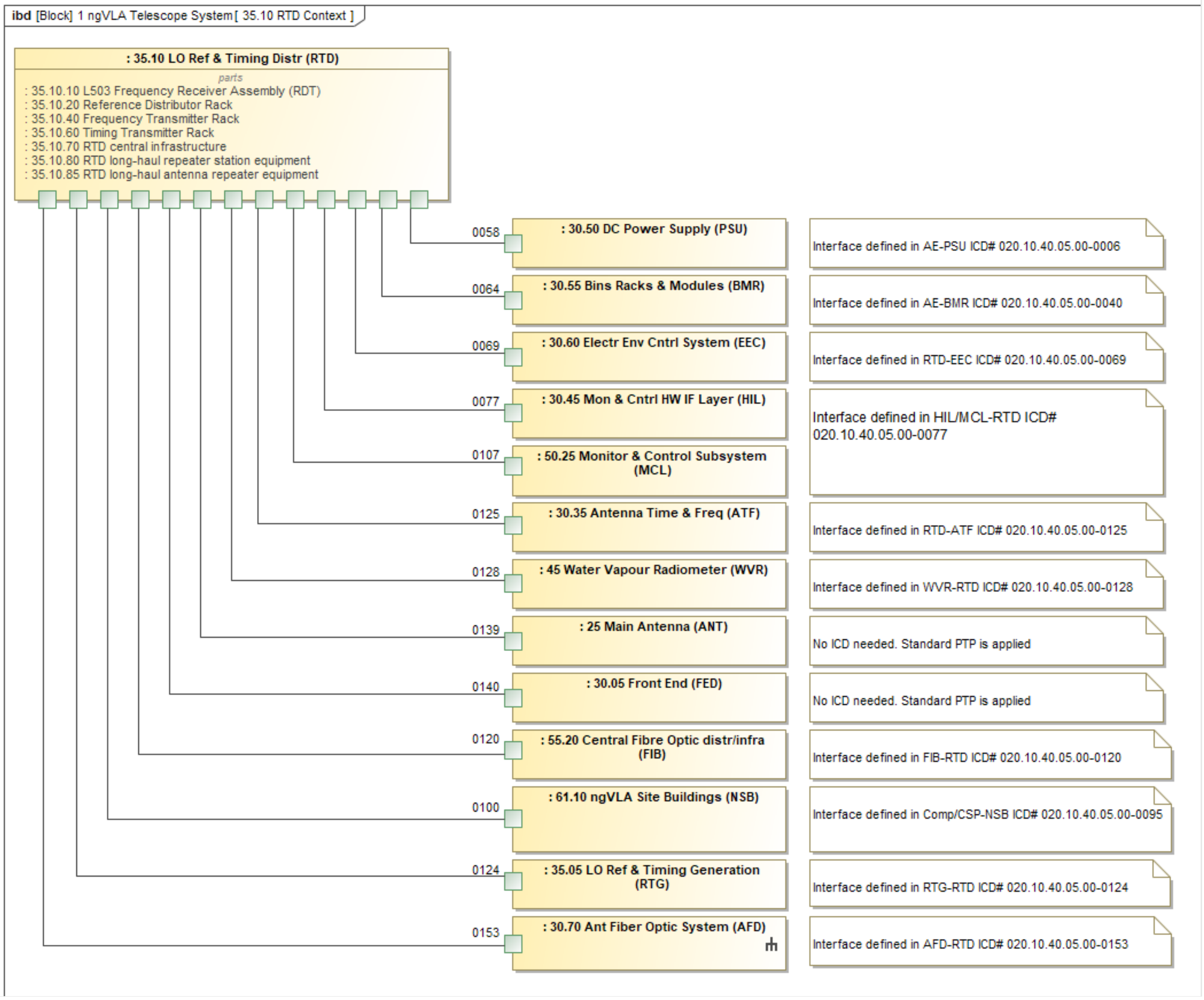

Figure 2: Reference and Timing Distribution subsystem product breakdown, interfaces with other antenna subsystems.

3.4 Key Requirements Summary

This LO Reference and Timing requirements document encompasses all of the requirements for the RTG and RTD subsystems. Here we extract a subset of these requirements that are considered driving requirements for the RTG subsystem design. Further details of these requirements including traceability are included in Section 7.

3.4.1 RTG Subsystem Key Requirements

Table 1: Key requirements of the RTG Subsystem

Parameter	Value	Requirement #
LO Phase Noise	< 76 fsec integrated from 1 Hz to maximum IF frequency offset Goal < 50 fsec	LRT1240

This is the phase noise requirement directly flowed down from Systems Requirements. The phase noise is most important at the antenna local oscillator and digitizer clock. References generated by RTG in the central electronics building must be consistent with meeting the antenna LO phase noise requirement. In most cases the design of a distributed LO or clocking system will utilize phase lock loops or jitter cleaners in the distribution that make parts of the original central source phase noise spectrum irrelevant. So, the interpretation of this requirement is that the RTG source phase noise spectrum must be consistent with meeting the overall system phase noise requirement at the antenna. See also 7.3		
LO Phase Drift	< 42 fsec at 300 s (linear term removed) < 250 fsec absolute	LRT1250
This requirement is for applicable to the entire distributed LO system for ngVLA. Most significant sources of LO phase drift may be expected to be incurred in the RTD and ATF subsystems. What is important for the RTG subsystem is that the frequency references be reasonable compact and well-regulated thermally, with careful attention to cables and/or components that could cause spurious thermal phase drifts. Additionally, the central reference source frequency stability should meet this requirement, in anticipation of the need for far-out ngVLA antennas stations to run on independent frequency sources (i.e. H-maser). See also 7.3		
RTD Input Frequency Accuracy from RTG	The frequency reference supplied from RTG to the RTD subsystem must have long term accuracy from T=1 to 1000 seconds T=1 sec AV<=2e-13 T=100 sec AV<=1e-14 T=1e3 sec AV<=2e-15	LRT5220
This requirement pertains specifically to the need to maintain adequate coherence when there are far-out antennas that are not sharing a single frequency source. Thus, the RTG source must have very high coherence. The stability set forth here is meant to require "hydrogen maser or better" stability. (It is estimated that an H-maser will give from 1-3% coherence loss at 116 GHz)		
RTD Input Frequency Phase Noise from RTG	Phase Noise at offset frequency from 1 Hz to 100 MHz < 50 fsec, goal < 30 fsec rms integrated phase noise	LRT5230
Note that the transfer of RTG oscillator stability to RTD and thence to ATF subsystem depends on the phase lock loop bandwidths at each stage. This requirement specifies 100 MHz offset frequency in case the antenna PLL locks to the fiber frequency transfer with such a wide bandwidth. If in the final design the PLL bandwidth is less than this then the upper frequency bound of the offset frequency in this requirement may be derated.		
RTD Timing Stability from RTG	Timing accuracy to RTD shall be within 0.3 nsec. (also see Sec 7.4.3 and Table 12)	LRT1350
For an overall timestamp accuracy of 10 nsec, each part of the timing transfer chain must be well controlled. This requirement stipulates that between the creation of the reference point for the central timing pulse and the input of the RTD, the accuracy should be less than 1 nsec. As an example, this is equivalent to a 30cm cable length. Common mode paths and calibration can be used to meet this requirement.		
Timing to CSP	Timing accuracy to CSP shall be within 2 nsec (goal of 1 nsec) (Relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging)	LRT1300

	Note: If data timestamps are tagged at the antenna, this requirement can be relaxed	
At this point in the project it is firmly planned that timestamps will be applied at the telescope. Therefore, the timing accuracy of 2 nsec shall be applicable to the DBE input rather than the central CSP. In fact, the central CSP does not currently envisage the need of any timing input from RTG, but rather can rely on network time. If a future need arises it will be simple to make a 1 PPS available to CSP by a short fiber connection via same method as will be in use for the station timing transfer.		
Availability	The MTBF and MTTR for the RTG and central RTD parts are TBD. They should support a system budget to achieve 95% system availability	LRT2305
The RTG shall be designed with some combination of hot-spare, hot-swap, redundant and backup power, as needed to meet this requirement.		
Mean Time Between Failure/Mean Time Between Maintenance	The RTG subsystem shall have a minimum MTBM of 3000 hours Here failures are considered in the same category as maintenance, any equipment status that would require a human intervention to address	LRT2310
Network Time to MCL/HIL	PTP Timing support	LRT1330

Note that the RTG subsystem establishes central time and frequency functions but does not provide tuning, offset frequencies, or switching. Thus, the critical requirements listed above mainly concern with: noise, stability, and accuracy; rather than -- tuning ranges, return-to-phase, and switching times. These latter types of requirements will be more prominent in the RTD and ATF subsystems.

3.4.2 Frequency Transfer Key Perfomance Requirements

This LO Reference and Timing requirements document encompasses all of the requirements for the RTG and RTD subsystems. Here we extract a subset of these requirements that are considered driving requirements for the RTD frequency transfer subsystem design.

Table 2: Key requirements of the RTD Frequency Transfer

Parameter	Value	Summary of Requirement
LO Phase Noise	< 76 fsec integrated from 1 Hz to maximum IF frequency offset Goal < 50 fsec	LRT1240
This is the phase noise requirement directly flowed down from Systems Requirements. The phase noise is most important at the antenna local oscillator and digitizer clock. References provided by RTG in the central electronics building must be consistent with ultimately meeting the antenna LO phase noise requirement. In most cases the design of a distributed LO or clocking system will utilize phase lock loops or jitter cleaners in the distribution that make parts of the original central source phase noise spectrum irrelevant. So, the interpretation of this requirement is: a) The RTG source phase noise spectrum provided as input to RTD frequency transfer subsystem must be consistent with ultimately meeting the overall system phase noise requirement at the antenna.		

b) The RTD frequency transfer subsystem must transfer the phase noise from the central electronics building to the antenna, over an appropriate portion of the frequency spectrum. For instance, if the output of the RTD frequency transfer subsystem at the antenna is used to lock an antenna local oscillator with a PLL bandwidth of 1 kHz, then the RTD phase noise spectrum used in verification of this requirement is DC-1 kHz. Phase noise above 1 kHz that is effectively filtered out may be ignored.		
LO Phase Drift	< 42 fsec at 300 s (linear term removed) < 1250 fsec absolute	LRT1250
This requirement is applicable to the entire distributed LO system for ngVLA. Most significant sources of LO phase drift may be expected to be incurred in the RTD and ATF subsystems. In particular, in the RTD subsystem it is necessary to compensate for phase drift associated with the fiber link. The requirements noted above are applicable after the compensation is applied. These requirements come from SYS1504, 1505, 5001 in "ngVLA System Requirements," NRAO Doc# 020.10.15.10.00-0003-REQ: SYS1504 The (relative) system phase drift residual shall not exceed 95 fsec rms per antenna over 300 seconds. Goal to meet this specification over a period of 1000 seconds. SYS1505 The absolute phase drift per antenna over 300 seconds shall not exceed 4 psec. Goal to meet this specification over 1000 seconds. SYS1501 takes the relative (95 fsec) and absolute (4000 fsec) drifts and allocates them to different subsystems. The frequency transfer subsystem is allocated 1/5th of the total rms noise (i.e. 95/sqrt(5)=42 fsec) for residual noise and about ten percent of the absolute drift budget (4000 psec/sqrt(10) ~ 1.25 psec.) For absolute drift over 1000 seconds, $\tau = 1250$ fsec is equivalent to .0078 rad of phase scaled to a frequency of 1 GHz. For the frequency transfer system, the allowable absolute phase in 1000s will scale with the transmitted frequency: $\emptyset_{rad} \leq .0078 * f_{GHz}$		

3.4.3 Key Requirements of Time Transfer

This LO Reference and Timing requirements document encompasses all of the requirements for the RTG and RTD subsystems. Here we extract a subset of these requirements that are considered driving requirements for the RTD time transfer subsystem design.

Table 3: Key Requirements for Time Transfer

Parameter	Value	Requirement#
Timing to CSP/DBE	Timing accuracy to CSP shall be within 3 nsec (goal of 2 nsec): Relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging **Note:** DBE subsystem is located at antenna pedestal. This requirement includes correction for fiber link delay, and accurate transmission of the corrected timing signal to the DBE subsystem at the antenna	LRT1300
The data timestamping is planned for the antenna rather than central electronics building. The central CSP clock domain will be a virtual clock determined by the timestamps and the antenna delay models, with one antenna (per subarray) selected as the reference antenna.		
Antenna Timing	The antenna clock domain shall be stable relative to the antenna LO reference to within 1 ns. This requirement supports synchronization of LO, digitizer and antenna timing signal.	LRT1357

Parameter	Value	Requirement#
The design calls for the antenna station 1 PPS to be derived directly from the frequency reference. This requirement defines the required accuracy of that division.		
Subarray Timing	Timing correction of at least one antenna per subarray shall be supplied by measurement or active correction to within 3 nsec for support of accurate data timestamping. The requirement is relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging. *This is the most challenging timing requirement.*	LRT1360
Since there is a flexible subarraying requirement, and each subarray requires at least one antenna with 3 nsec accuracy, the design presented herein provides for the accurate transfer of 1 PPS timing to ***all*** antennas.		

4 Requirements Management

4.1 Requirements Definitions

Consistent with the Requirements Management Plan [AD02], the following definitions of requirement "levels" are used in the ngVLA program. The requirements in this document are at the L2 subsystem level.

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

4.2 Requirements Flow Down

Individual subsystem specifications (Level 2) flow from the Level 1 requirements, and may not always be directly attributable to a single system requirement. For example, phase drift specifications at the system level may be apportioned to multiple subsystems, or a subsystem spec may be in support of multiple higher-level requirements. Completeness of the Level 2 requirements is assessed at the requirements review of each subsystem.

While this is a top-down design process, the process is still iterative rather than a "waterfall" or linear process. The feasibility and cost of requirements implementation lead to trade-offs that feedback to higher-level requirements. The end goal is to build the most generally capable system that will support the Key Science Goals within the programmatic constraints of cost and schedule.

Maintaining enumerated and traceable science requirements, system requirements, and subsystem specifications ensures this trade-off process is complete and well understood by the project team. The effect of a change in a subsystem specification can be analyzed at the system level, and thereafter the impact on a specific scientific program can be ascertained.

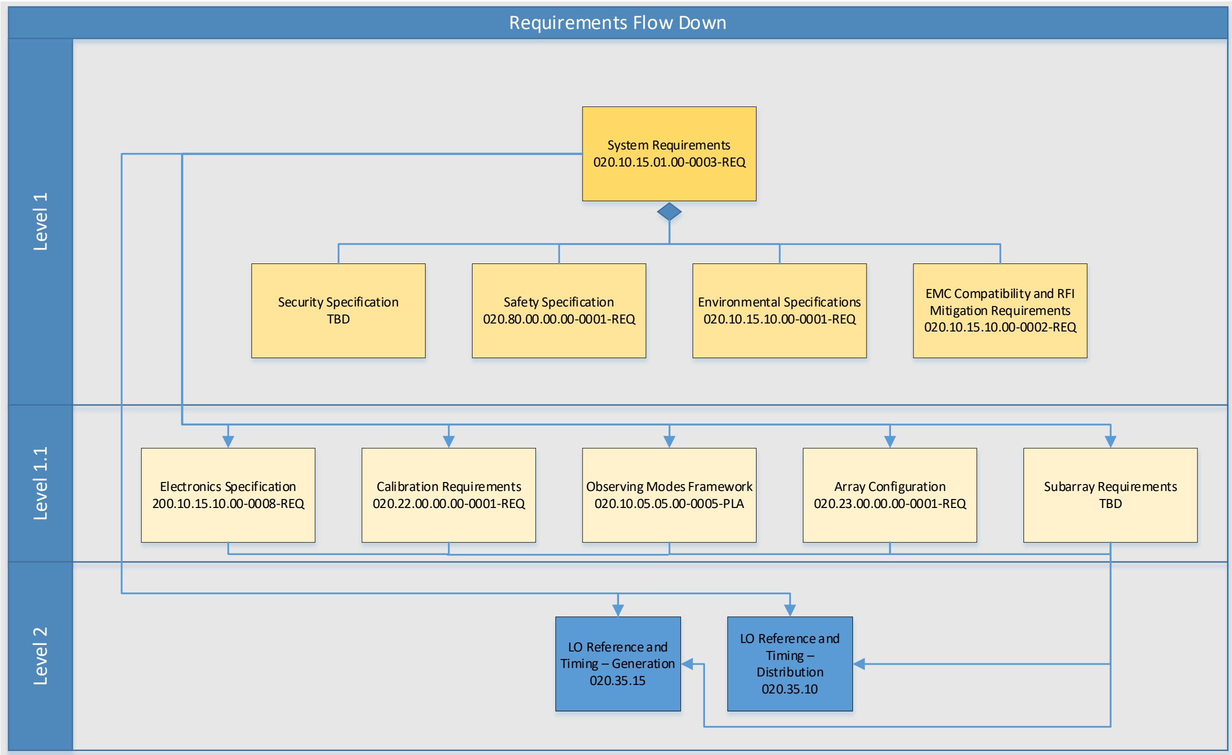

Figure 3: Requirements flow-down to the Antenna Time and Frequency Subsystem Requirements.

4.3 Verb Convention

This document uses "shall" to denote a requirement. The verbs "should" and "must" denote desired but not strictly required parameters. "Will" denotes a future happening. Desired but not required features are noted as "desirable" or "goals."

5 Assumptions

The following assumptions are made in the definition of these subsystem requirements:

- Subsystem requirements apply to performance before any operational calibration corrections are applied unless explicitly stated otherwise.
- Hardware requirements apply to a properly functioning system under the precision operating environmental conditions unless explicitly stated otherwise.
- Hardware requirements assume that all system parts that would normally be in place during observations are working within their respective specifications (e.g., HVAC, RTP system) unless explicitly stated otherwise.
- Notwithstanding the desire that these requirements be implementation agnostic, a set of subsystems is assumed that interfaces with the RTG and RTD subsystems. These are defined and an overview of the interface requirements included in Section 9.
- A receiver and water vapor radiometer are located on the elevated moving structure of the antenna
- A digital backend is located in the antenna pedestal

- The RTG subsystem is nominally located in the Central Electronics building. Annex versions of the RTG will be located at LBS station locations, and possibly for far out MID stations not directly connected to the ngVLA fiber network.
- The RTD subsystem instances are located at (a) the central electronics building (b) midpoint repeater stations and (c) the antenna stations. For LBS stations and remote MID stations the "central" part of the RTD will be similar but with a much lower fan-out. (For example, at LBS sites, where there are three antenna stations, reference sources and RTD modules will fan-out to each of the three antennas).
- A central hydrogen maser is the master frequency source for the array. For remote antennas where referencing to this source is not possible, additional hydrogen masers (or other highly stable reference) will be used.
- The master frequency source will serve as the basis for the system timing clock. A counter will accumulate time and be compared to a GPS absolute time standard over long intervals (~ 1 day). This accumulated measurement will be recorded and then time counter reset.
- There will be no steering of the master frequency source to track absolute time.
- The most recent array configuration is [RD05]. Further revisions are expected but the overall number of antennas and geographical expanse of the array is not expected to change drastically.

6 Environmental Conditions

The ngVLA Environmental Requirements [AD04] details both environmental conditions and requirements, in general, for the ngVLA as whole. In the Level 2 subsystem requirements documents, like this one, it is necessary to extrapolate and interpret which of these conditions and requirements is applicable. In the case of the RTG and RTD subsystems, this extrapolation relies in most cases primarily on the ***location*** of the installed equipment.

6.1 Equipment Location

The LO Reference and Timing Generation (RTG) subsystem components will be located entirely within the ngVLA Central building. The LO Reference and Timing Distribution (RTD) Subsystem components will be located in the ngVLA Central building, in repeater stations between antenna stations, and within or on the Antenna Stations. The RTD equipment associated with the antenna station can be located either: inside the antenna pedestal, or on the elevated (and moving) structure of the antenna. The relation between the RTG and RTD equipment and the structures that they are housed ***within*** is shown in Figure 4. In the Central Electronic Building, the ***equipment and racks*** are the responsibility of the RTG and RTD subsystem work packages. In the repeater stations, the RTD equipment will be housed in racks supplied by the FIB work package. At the antenna stations the RTD equipment will be housed in racks supplied by the Antenna Electronics IPT, Bins, Modules, and Racks work package, with temperature control delivered by the EEC work package.

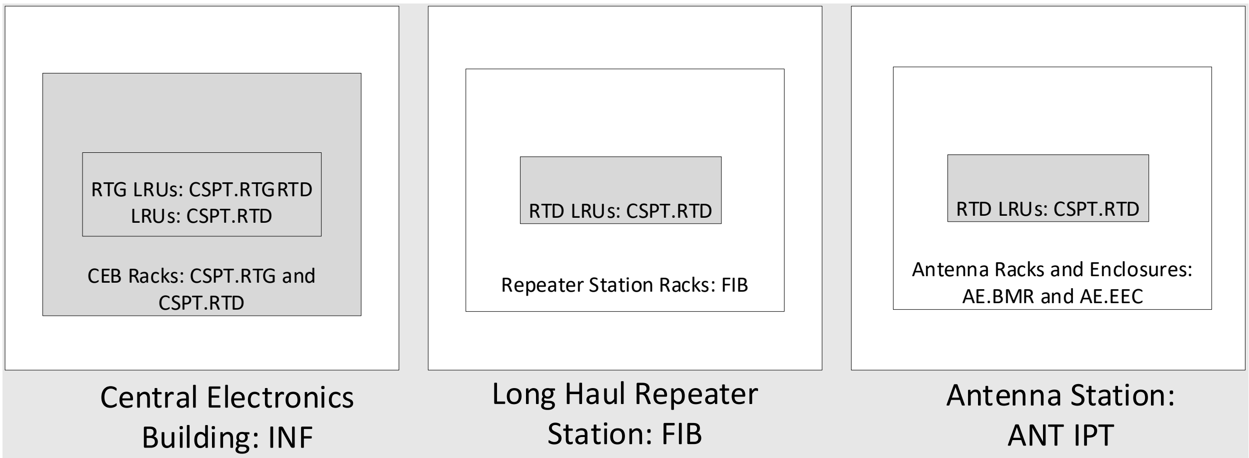

Figure 4: RTG and RTD equipment as-installed location and housing. Shaded items are deliverables of the RTG and/or RTD work packages.

The RTG and RTD equipment must be designed to meet requirements in the environmental conditions of these locations. These conditions will be defined in the relevant ICDs, as shown in Table 4 below.

Table 4: ICD References for detailed environmental requirements based on equipment location.

	ICD Number		**Ref**	**Subsystem 1**	**Subsystem 2**
	primary	**secondary**			
Central Electronics Building	0095	0099	AD24	Computing/CSPT(RTG)	ngVLA Site Buildings (NSB)
	0095	0100	AD24	Computing/CSPT(RTG)	ngVLA Site Buildings (NSB)
Long Haul Repeater Station and Remote Stations	120	n/a	AD26	Central Fiber Infrastructure (FIB)	LO Reference and Timing – Distribution (RTD)
Antenna Station	0040	0064	AD21	Bins, Modules, and Racks	Antenna Electronics (RTD)
	0069	n/a	AD22	LO Reference and Timing – Distribution (RTD)	Antenna Electronics Environmental Control System (EEC)

6.2 *Survival Conditions*

The RTD subsystem when installed on an antenna or in a repeater station shall survive without sustaining residual damage the following conditions:

Parameter	**Req. #**	**Value**	**Traceability**
Temperature	LRT0110	–30 C ≤ T ≤ +50 C	ENV0342

All RTD equipment is expected to be housed in a temperature-controlled environment. The operational temperature ranges associated with the deployment will be detailed in [AD22], [AD24], and [AD26]. However, in case of power outage, the survival temperature ranges noted above are applicable.

6.3 Transportation conditions

All transportation requirements area applicable for LRUs in a configuration of being packaged for regular maintenance transportation.

Parameter	Req. #	Value	Traceability
Packaging for Transportation	LRT0160	All LRT LRUs shall be transported using ESD, thermal and vibration protective packaging in accordance with the System Environmental and Electronics Specifications	ETR0503 ENV0381 ENV0382 ENV0531
Solar Thermal Load	LRT0170	Exposed to full sun, 1200W/m^2 (within transport cases)	ENV0381
Transportation Temperature	LRT0180	–30 C ≤ T ≤ +60 C (within transport cases)	ENV0382
General Vibration	LRT0190	Vibration on all three axes, for 60 minutes.	ENV0531
Mechanical Shock	LRT0200	LRUs packaged for shipping shall survive a mechanical shock level defined in [AD04]. In case of shop replaceable units (SRU), these shall be designed to withstand the drop requirement when they are packaged for shipment within the LRU.	ENV0582

6.4 Storage Conditions

Parameter	Req. #	Value	Traceability
Packaging for Storage	LRT0210	All LRT LRUs shall be stored using ESD and thermal protective packaging in accordance with the System Environmental and Electronics Specifications.	ETR0503
Storage temperature	LRT0212	-20 deg C < T < +50 deg C	ENV0372
Storage humidity	LRT0214	10% < RH < 90%	ENV0373

6.5 Site Elevation

Parameter	Req. #	Value	Traceability
Altitude Range	LRT0220	All LRT elements shall be designed for operation and survival at altitudes ranging from sea level to 2500 m.	ENV0351, [AD22], [AD24], [AD26]

Equipment using air flow as a means of temperature regulation shall account for reduced air pressure at 2500m.

6.6 Environmental Protection Requirements

6.6.1 Seismic

Parameter	Req. #	Value	Traceability
Seismic Protection	LRT0230	The RTG and RTD subsystem shall be designed to withstand a low-probability earthquake with up to 0.2g peak acceleration in either the vertical or the horizontal axis. Units shall not sustain residual damage under these conditions while in the installed and operational state.	ENV0521

6.6.2 Lightning, Dust, Fauna, Rain/Water Infiltration and Corrosion Protection

Parameter	Req. #	Value	Traceability
Equipment Protection	LRT0240	Protection against lightning, dust, fauna, solar radiation, rain/water infiltration and corrosion shall be provided by the environmentally controlled facilities or racks in which the RTG and RTD elements are installed, as defined by the applicable ICD [AD21], [AD24], [AD26]. No RTG or RTD element shall be installed outside these facilities or racks.	ENV0541, ENV0542, ENV0571, ENV0591

6.7 Precision Operating Conditions (POC)

The RTG and RTD subsystems shall have precision performance as defined in [AD04] under the following conditions:

6.7.1 Central Electronics Building

Parameter	Req. #	Value	Traceability
Temperature POC	LRT0270	$+15$ C $\leq T \leq +25$ C	ENV0323
Temperature Rate of Change POC	LRT0280	< 0.2 °C per 300s	ENV0324
Air Flow	LRT0290	Sufficient air flow shall be provided by the central electronics building air handlers to maintain temperature range and stability	ENV0324

[AD24] will specify in further detail the temperature and humidity ranges which will surround the RTG and RTD subsystem LRUs in the central electronics building during precision operating conditions.

Note 1: For any LBS sites with a central facility housing RTG and RTD subsystem components, these environmental requirements are applicable.

Note 2: For any annex sites that support standalone timing for MID stations, and thus housing RTG and RTD subsystem components, these environmental requirements are applicable.

6.7.2 Repeater Stations

Parameter	Req. #	Value	Traceability
Temperature POC	LRT0300	+10 C ≤ T ≤ +30 C	ENV0313, [AD26]
Temperature Rate of Change POC	LRT0310	< 0.5 °C per 300s	ENV0314, [AD26]

[AD26] specifies in further detail the temperature and humidity ranges applicable to RTD subsystem LRUs and subassemblies in the repeater station during precision operating conditions.

6.7.3 Antenna Stations

Parameter	Req. #	Value	Traceability
Temperature POC	LRT0320	FEC: Tmin < T < Tmin+5.0 deg C; Tmin=5-10 deg C Pedestal: Tmin < T < Tmin+15.0 deg C; Tmin=5-10 deg C	ENV0313, [AD22]
Temperature Rate of Change POC	LRT0330	< 0.1 °C per 3hr	ENV0314, [AD22]

[AD22] specifies in further detail the temperature and humidity ranges which will surround the RTD subsystem LRUs and subassemblies in the antenna station during precision operating conditions. The temperature stability specification LRT0330 is a derived specification that the LRT system has to meet.

6.8 Normal Operating Conditions (NOC)

The RTG and RTD subsystem shall have normal performance as defined in [AD04] under the following outside ambient conditions:

6.8.1 Central Electronics Building

Parameter	Req. #	Value	Traceability
Temperature NOC	LRT0340	+15 C ≤ T ≤ +25 C	ENV0323, [AD24]
Temperature Rate of Change NOC	LRT0350	< 0.5 °C per 300s	ENV0324, [AD24]
Air Flow	LRT0360	Sufficient air flow shall be provided by the central electronics building air handlers to maintain temperature range and stability	ENV0324, [AD24]

[AD24] will specify in further detail the temperature and humidity ranges which will surround the RTG and RTD subsystem LRUs in the central electronics building during normal operating conditions.

Note 1: For any LBS sites with a central facility housing RTG and RTD subsystem components, these environmental requirements are applicable.

Note 2: For any annex sites that support standalone timing for MID stations, and thus housing RTG and RTD subsystem components, these environmental requirements are applicable.

6.8.2 Repeater Stations

Parameter	Req. #	Value	Traceability
Temperature NOC	LRT0370	+10 C ≤ T ≤ +30 C	ENV0323, [AD26]
Temperature Rate of Change NOC	LRT0380	< 0.5 °C per 300s	ENV0324, [AD26]

[AD26] specifies in further detail the temperature and humidity ranges applicable to RTD subsystem LRUs and subassemblies in the repeater station during normal operating conditions.

6.8.3 Antenna Stations

Parameter	Req. #	Value	Traceability
Temperature NOC	LRT0390	FEC: Tmin < T < Tmin+5.0 deg C; Tmin=5-10 deg C Pedestal: Tmin < T < Tmin+15.0 deg C; Tmin=5-10 deg C	ENV0323, [AD22]
Temperature Rate of Change NOC	LRT0400	< 0.25 °C per hr	ENV0324, [AD22]

[AD22] specifies in further detail the temperature and humidity ranges which will surround the RTD subsystem LRUs and subassemblies in the antenna station during normal operating conditions. The temperature stability specification LRT0400 is a derived specification that the LRT system has to meet.

6.9 Limits to Operating Conditions (LOC)

The RTG and RTD subsystem shall be able to operate for extended periods without sustaining residual damage and without meeting performance under the following outside ambient conditions, applicable to equipment in any location.

Parameter	Req. #	Value	Traceability
Temperature LOC	LRT0410	+5 C ≤ T ≤ +30 C	ENV0332, [AD22], [AD24], [AD26]

[AD22], [AD24] and [AD26] specify in further detail the temperature and humidity ranges applicable to RTG and RTD equipment under limit conditions.

6.10 Standby Conditions

The RTG and RTD subsystem shall be put into standby mode when ambient standby environmental conditions noted below are present. While in standby, the system shall remain capable of resuming operation within five minutes of conditions returning to within the Limits of the Operating Conditions. Should the environment then reach the Normal Operating Conditions, the system shall perform to the performance specifications associated with that environment.

Parameter	Req. #	Value	Traceability
Temperature LOC	LRT0420	+25 C ≤ T ≤ +45 C	ENV0362, [AD22], [AD24], [AD26]

[AD22], [AD24] and [AD26] specify in further detail the temperature and humidity ranges applicable to RTG and RTD equipment under standby conditions.

7 Subsystem Requirements

Requirements for the RTG and RTD subsystem are listed below, with requirements encoded as follows:

- Parameter: Short (unique) name for the requirement.
- Req. #: Unique requirement number per [AD02]. The format is LRTNNNN where LRT is an abbreviation for "LO Reference and Timing" and NNNN is a four-digit number typically starting with 0001. Note that requirements can be applicable to either LO Reference and Timing Generation (RTG) or LO Reference and Timing Distribution (RTD) or to both.
- Value: Textual description of the requirement.
- Traceability: Identifies which higher-level requirement(s) this specific requirement is derived or copied from.

7.1 General

Parameter	Req. #	Value	Traceability
Number of Antennas	LRT1100	RTD subsystem distribution shall be provided to support at least 263 antennas	SYS1001, SYS1021
Antenna Stations Configuration	LRT1110	The RTD subsystem shall support the final antenna station configuration. All configuration studies have in common: a denser array of close in (0-2 km spacing), extended arms with lower density out to ~30 km, and further arms with greater spacing out to ~800km. Finally, long baseline subarray (LBS) on continental scale.	RD05
Maximum Fiber Length	LRT1120	350 km. Goal 1000 km	SYS1301, RD05
Connected vs Independent Stations	LRT1130	LBS stations will have standalone time and frequency sources. Select MID stations beyond 350km ***may*** have standalone time and frequency sources.	SYS1301, SYS1306, SYS1309
Number of Subarrays	LRT1140	The RTD subsystem shall support a minimum of ten subarrays	SYS0601, SYS0603
Subarray Creation and Modification	LRT1150	Subarrays shall be able to be created, assigned, and re-assigned flexibly, without disturbing active observing.	SYS0607, SYS0608

Maximum Fiber Length: The longest baseline requirement is > 700km. The Rev D layout to support this includes stations out to 800 km from the center of the array. Adding 25% for deviations from line-ofsight, the fiber distance to support this will be 1000 km. Many factors like borders, difficult terrain, and expense may prevent the extension of the fiber to these stations. Thus, we require fiber connectivity at least up to 350 km. Beyond that, a cost-performance study will determine if the stations are connected or standalone.

Subarrays: Three possible design architectures are shown below in Figure 5. In (A) the LO frequency and any frequency offset are generated in the central electronics building and split to many antennas. To support the ten-subarray requirement for this configuration, then, there would need to be at least ten of the frequency generation functions. And to support completely flexible subarraying they would each need to have the maximum number (N) of outputs (i.e. ~ 263) with a switching network to map sources to subarrays. (ALMA used this configuration with 6 subarrays, 66 antennas). For architecture B or C, there are more frequency generation functional units (one per antenna), the only difference being if they are located centrally or at the antenna. In either case they are mapped one-to-one with the antennas, and there is no need for a hardware subarray switch function. In these later two cases, the flexible subarraying requirement is met with no restriction on number of subarrays. Note that reassignment of an antenna shall not require length tuning or settling of the LOs or offset frequencies.

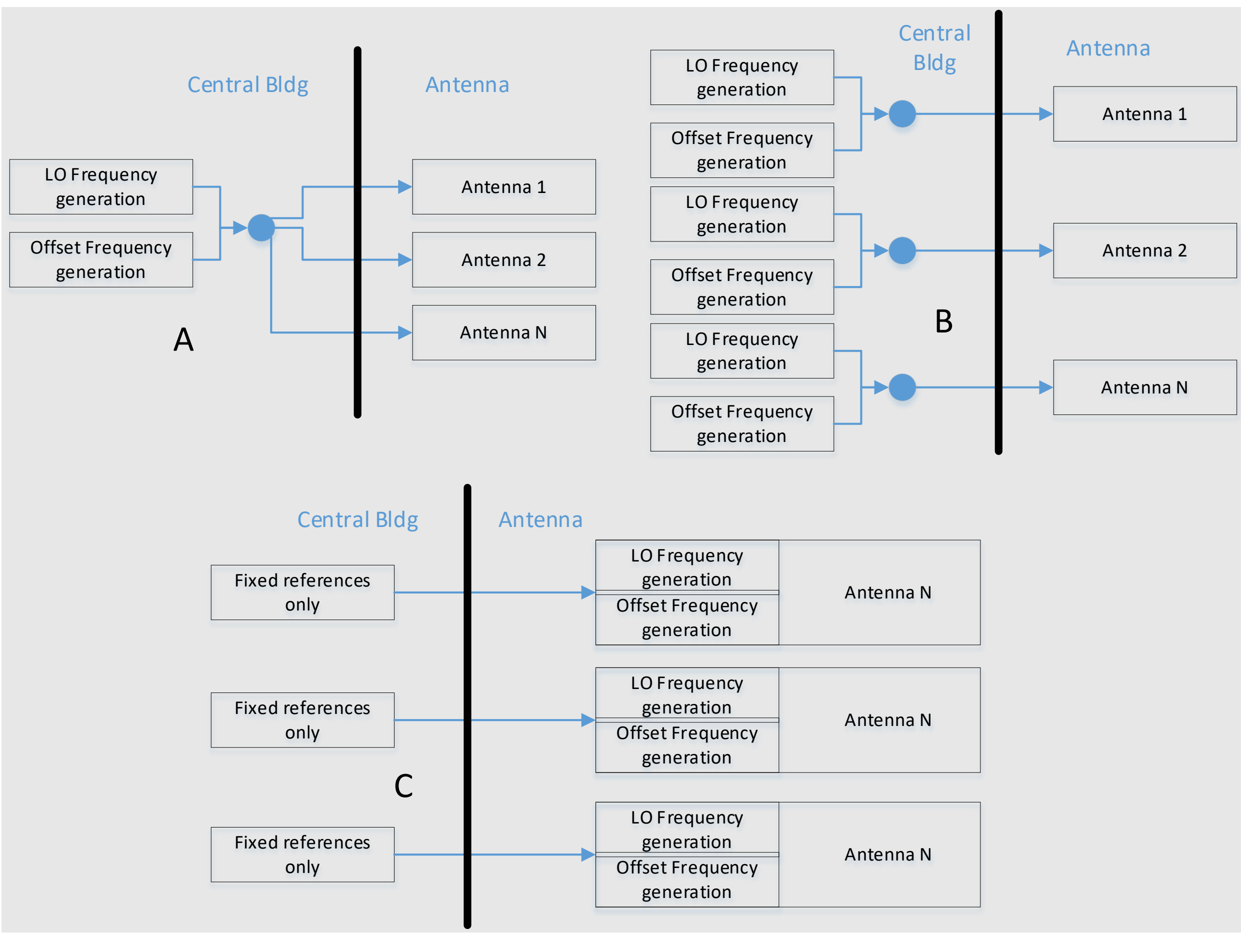

Figure 5: How design choice of RTD architecture impacts configuring of subarrays: (A) Frequencies setup centrally and split to all antennas (B) Frequencies setup centrally but mapped one-to-one with antennas (C) Central reference only. Frequencies setup at antenna, also mapped one-to-one with antennas.

7.2 Frequency

Parameter	Req. #	Value	Traceability
LO Frequency Ranges	LRT1200	LO frequencies shall be provided to support downconversion (except instances of direct conversion). These shall fall in or near to the range of sky frequencies required for ngVLA: 1.2—8 GHz, 8-50 GHz, and 70-116 GHz. Fixed or tunable LOs must allow for continuous frequency coverage across these spans. Additionally, the design plan must allow for simultaneously multiple LOs in a given receiver band so that the full available instantaneous downstream processing bandwidth can be achieved, and so that discontinuous portions of a band may be selected.	SYS0801, SYS0803, SYS0804, SYS0805, SYS0806, SYS0903, SYS0905, [AD30]
Simultaneous LOs	LRT1205	All LOs in a particular receiving band must be simultaneously available	SYS0903, SYS0905
LO Frequency Offsets	LRT1210	Nominal LO frequencies must be capable of frequency offsetting on a per antenna basis	SYS2105, SYS0603, SYS2217, [AD30]
Tuning Resolution	LRT1220	The LO shall be tunable if necessary to cover the required full frequency spans. If tuning is required, the resolution shall be 250 MHz or less.	SYS0906, SYS0907, [AD30]
Switching Speed	LRT1225	Frequency switching between or within a band shall be accomplished in < 1.5 s. The switching time is defined as time to reach full performance	SYS0908, [AD30]
Interface Signal Requirements			
Parameter	**Req. #**	**Value**	**Traceability**
RTD Input Frequencies from RTG	LRT5210	RTG shall supply 1 PPS and a stable reference frequency to the RTD subsystem	[AD29]
RTD Input Frequency Accuracy from RTG	LRT5220	The frequency reference supplied from RTG to the RTD subsystem must have long term accuracy from T=1 to 1000 seconds T=1 sec AV<=2e-13 T=100 sec AV<=1e-14 T=1e3 sec AV<=2e-15	[AD29]
RTD Frequency Input Stability from RTG	LRT5230	Phase Noise at offset frequency from 1 Hz to 100 MHz < 50 fsec, goal < 30 fsec rms integrated phase noise	[AD29]
RTD Frequency Input Signal Type from RTG	LRT5240	Signal interface between RTG and RTD per [AD29]	[AD29]

Parameter	Req. #	Value	Traceability
ATF Frequency Input Tuning Resolution	LRT5250	If the ATF frequency input from RTD has a tunable component, then the frequency resolution shall follow the specifications in [AD30]	[AD30]
ATF Input Frequencies	LRT5260	The ATF input frequency (-ies) shall follow the specifications in [AD30]	SYS0801, SYS0803, SYS0804, SYS0805, SYS0806, SYS0903, SYS0905
ATF Input Frequency Accuracy	LRT5270	Locked to central H-maser derived clock Phase measured by round-trip method for post-correction to < 42 fsec at 300 s (linear term removed) < 1250 fsec (absolute)	SYS1501 SYS1502 SYS5001 SYS1504 SYS1505
ATF Frequency Input Signal Type	LRT5290	The ATF frequency input signal type shall follow the specifications in [AD30]	[AD30]
ATF Frequency Input Signal Level	LRT5300	The ATF frequency input signal level shall follow the specifications in [AD30]	[AD30]
CSP Input Frequency	LRT5310	The CSP frequency input from RTD shall have phase noise following the specifications in [AD28]	[AD28]
CSP Input Frequency Accuracy	LRT5320	The CSP frequency input accuracy shall follow the specifications in [AD28] and be no worse than T=1 sec AV<=2e-13 T=100 sec AV<=1e-14 T=1e3 sec AV<=2e-15	[AD28]
CSP Frequency Signal Type	LRT5330	The CSP frequency input signal type shall follow the specifications in [AD28]	[AD28]
CSP Frequency Signal Level	LRT5340	The CSP frequency input signal level shall follow the specifications in [AD28]	[AD28]

LO Frequency Ranges, Tuning Resolution, Switching Speed: RTG and RTD subsystems are nominally responsible for supplying reference frequencies to the ATF subsystem, which in turn is responsible for supporting the LO tuning range, tuning resolution, and switching speed. These requirements are included in case an architecture is developed which includes some aspect of the LO tuning in the reference transmission.

LO Frequency Offsets: The role of the per antenna small frequency offset is to provide a mechanism for image suppression and self-generated spurious that would otherwise be coherent antenna-to-antenna. Most recent design includes provision of in increments of 15.68 kHz, with an individual antenna offset = m*15.68 kHz, m = {-131, -130,…,-1,0,1,…130,131}. Support for this requirement can be implemented by either RTD or ATF subsystem [RD04]

7.3 Phase

Parameter	Req. #	Value	Traceability
LO Phase Noise	LRT1240	< 76 fsec integrated from 1 Hz to maximum IF frequency offset Goal is < 50 fsec	SYS5001, SYS1501, SYS1502, SYS1503, CAL0314, [AD30]
LO Phase Drift	LRT1250	< 59 fsec at 300 s (linear term removed) < 1500 fsec (absolute) Connected array up to 250km only (see note 1)	SYS1501, SYS1502, SYS5001, SYS1504, SYS1505, [AD30]
Digitizer Clock Phase Noise	LRT1260	< 76 fsec integrated from 1 Hz to maximum IF frequency offset Goal < 50 fsec	SYS5001, SYS1503, CAL0314, [AD30]
Digitizer Clock Phase Drift	LRT1270	< 59 fsec at 300 s (linear term removed) < 15000 fsec (absolute)	SYS5001, SYS1504, SYS1505, [AD30]
Return to Phase	LRT1280	Any derived LO or timing signal shall return to phase upon change in frequency from F_1 to F_2 to F_1	SYS0602, [AD30]
ATF Frequency Input Phase Noise	LRT5280	Less than 44 fsec integrated from 1 HZ to 1 KHz See Table 6	SYS5001, SYS1501, SYS1502, SYS1503, CAL0314

These system level phase critical requirements must be fulfilled by elements of the Antenna Time and Frequency subsystem (ATF). However, the ATF is in turn dependent upon receiving accurately phased reference signals from the RTD subsystem. The drift and noise stability that is required at the RTD-ATF interface will be carefully detailed in the ICD [AD30]. Generally, the stability of the reference needs to be better than the output clock/LO, at least in offset frequency regimes where there is perfect tracking (i.e. within phase lock loop bandwidths). Thus, the RTD frequency reference may be allowed significant additional phase noise at high offset frequencies, that is, at offset frequencies higher than the antenna-based oscillator phase lock loop.

Note 1: LRT1250 specifies phase drift performance of the main array out to maximum baseline length of 350 km. The requirement is stricter than the equivalent phase drift between two physically separated hydrogen masers. Consistent with SYS5001 and discussion in [AD03] the requirement beyond 350km is relaxed to account for the need to have H-masers as independent frequency references at each site.

Note 2: LRT1240 specifies the rms phase noise integrated up to the maximum IF frequency. In practice, it is seldom the case for an oscillator to have significant phase noise contribution above ~ 10 or 20 MHz. Whereas in the most recent design the IF frequency goes to 2.9 GHz. Therefore, it is sufficient to measure only up to the maximum offset frequency at which non-negligible contribution to phase noise occurs, for the particular oscillator type used in the design.

Note 3: LRT1280 shall be verified by implementing a frequency switching test set, with repeated switch cycles frequency from F_1 to F_2 to F_1 over a long period (one hour or more). The phase measurement at F_2 is then thrown out, and the phase samples measured at F_1 are kept. The linear drift may be removed from these samples and then the resulting concatenated phase time series shall meet the LRT1250 requirement of 42 fsec RMS averaged at 300 seconds. If the RTD design consists of only a single fixed frequency transfer to the antenna, then the requirement is met by design.

7.3.1 Phase Noise and Phase Drift Budget

For each of these requirements (LRT 1240, LRT1250, LRT1260, LRT1270, LRT1280) the design of the antenna time and frequency (ATF) subsystem contains the output LO or clock that defines the performance requirement. The LRT subsystem design must support the ATF requirements and design by supplying adequately clean and accurate references.

The overall system phase noise and drift requirements from [AD03] are shown below.

Table 5: System Phase Noise and Drift Requirements from ngVLA System Requirements

Parameter	**System Req. #**		
Allocation of Phase Noise & Drift	SYS5001		
Component	**Noise**	**Drift Residual**	**Absolute Drift**
	(fsec, rms)	**300 sec fsec, rms**	**300 sec psec**
System	**132**	**95**	**4.3**
Sub-System Allocations:			
ANT	76	42	2
ATF (LO)	76	42	0.25
ATF (DTS Clock)	76	42	0.25
ATF (RTP)	0	42	0.25
RTD	0	42	1.25
Estimated System Total	**131.64**	**93.91**	**4**

- The 76 fsec from LRT1240 appears in the second row under sub-system allocations
- The 59 fsec drift residual from LRT1250 is the root sum of the 2nd and 5th row
- The 1500 fsec from LRT1240 absolute drift is the sum of the 2nd and 5th row

We also allocate a phase drift at the output of the RTD (i.e. the RTD/ATF interface). At this interface the antenna subsystem will perform cleanup phase lock loop and frequency multiplication. Nevertheless, the low frequency phase noise from the RTD output will be "copied" to the antenna system. Therefore, the relevant integration limits for verification of the RTD/ATF interface is in the low frequency regime, which we choose to be 1 Hz to 1 KHz (this can be revisited as the design matures).

Table 6: Phase noise allocation breakdown for 1st LO

Phase Noise source	Frequency offset limits	Phase noise allocation rms	RSS contribution
RTD output integrated from 1 Hz to 1 kHz	1 Hz to 1 kHz	44 fsec	33 %
Contribution of Cleanup loop 2.9 GHz oscillator	1 Hz to 2.9 GHz	31 fsec	16.6 %
Output of Cleanup Loop Oscillator	1 Hz to 2.9 GHz	54 fsec	50 %
Higher frequency multiplication and synthesis	1 Hz to 2.9 GHz	53.7 fsec	50 %
LO Output	1 Hz to 2.9 GHz	76 fsec	100 %

7.4 Timing

The requirement for accurate array timing impacts the Central clocks, the distribution of the clocks to the CSP, and the distribution of the clocks to the antennas. These are discussed below. The following documents provide more information and context for this requirement:

- ngVLA Systems Requirements [AD03]
- System Technical Budgets [AD11]
- "Timing Requirements and Considerations" [RD04]

The two driving systems requirements are:

- ***Temporal Accuracy (SYS2002):*** Data Product timestamps must be referred to an absolute time standard (e.g., GPS or TAI) with an error of less than 10 ns (goal of 1 ns).
- ***Timestamp Corrections (SYS2003):*** Timestamps may be applied or corrected retroactively (i.e., it is not necessary for it to be known in real time.) Any timestamp corrections shall be made through a metadata table that is incorporated into the data model.

We further posit the existence of three main clock domains:

- A central system clock domain: referenced to an absolute time standard and implemented in the RTG subsystem
- A CSP clock domain
- An antenna clock domain: unique to each antenna

Requirements are given below for the central electronics building and the antenna stations. For remote stations not connected by optical fiber for LO and Timing (such as LBS stations, or the more remote MID-stations), there will be a secondary instantiation of the central electronics building with and RTG subsystem and central system clock domain. One or more stations connected to these will have a round trip corrected frequency reference serving as the basis for remote antenna clock domains. All of the requirements in Section 7.4.1 and 7.4.2 are therefore also applicable to these secondary RTG/clock systems.

Note that the SYS2002 requirement will require the development of a system budget allocating contributions to the 10 nsec. A preliminary budget is detailed in [RD04] including the 2 nsec requirements given below in LRT1300 or LRT1360, applicable to timestamp accuracy.

7.4.1 Central Building

Parameter	Req. #	Value	Traceability
Timing to output of RTD	LRT1300	Timing accuracy to output of RTD shall be within 2 nsec Relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging Note: DBE subsystem is located at antenna pedestal. This requirement includes correction for fiber link delay, and accurate transmission of the corrected timing signal to the DBE subsystem at the antenna	SYS2002, SYS2003, SYS0404
System Domain Clock Accuracy	LRT1305	Measurement error between System Domain Clock (RTG) and GPS Time: 1.67 nsec Note: 100 nsec/s noise integrated over one hour	SYS2002
Timing signal type to CSP	LRT1310	CSP Timing signal type shall follow specifications in [AD28]	[AD28]
Timing Signal level to CSP	LRT1320	CSP Timing signal level shall follow specifications in [AD28]	[AD28]
Timing to CSW	LRT1330	Network time shall meet the requirements detailed in [AD25]. PTP Timing interface	[AD25]
RTD Timing Stability from RTG	LRT1350	Timing accuracy to RTD shall be within 0.30 nsec. Note: this is an interface tracking requirement.	[AD29]

7.4.2 Antenna Stations

Parameter	Req. #	Value	Traceability
Time Accuracy – Antenna Station Functions	LRT1355	The relative difference between local antenna time and the system clock shall not exceed ±5 μs. This requirement is for relative accuracy of antenna tracking, switched power, and fringe search functions. (all antenna functions except DBE-timestamping)	SYS2002, SYS2003, SYS0404, [RD04]
Antenna Timing	LRT1357	The antenna clock domain shall be stable relative to the antenna LO reference to within 1 ns. This requirement supports synchronization of LO, digitizer and antenna timing signal.	SYS2002, SYS2003, SYS0404, [RD04]
Subarray timing	LRT1360	Timing correction of at least one antenna per subarray shall be supplied by measurement or active correction to within 2 nsec for support of accurate data timestamping. The requirement is relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging.	SYS2002, SYS2003, SYS0404, SYS0603, [RD04]

Parameter	Req. #	Value	Traceability
Timing to DBE	LRT1380	From the output of the RTD, 1 PPS timing accuracy to digitizer and DBE using JESD protocols shall result in not more than 1 nsec residual timing error	SYS2002, SYS2003

LRT1355:

The antenna timing is constrained by at least three functional needs:

- Antenna tracking: Timing accuracy <= 660 us
- Switched Power: Timing accuracy <=50 us
- Fringe search: Timing accuracy <=50 us

These three needs, inclusive of some design margin, lead to a requirement for the timing of the antenna system to not deviate from the system clock by more than about 5 μs. i.e., the relative difference between local antenna time and the system clock shall not exceed ±5 μs. This requirement must be met by the hardware alone, before the application of time corrections (online or offline) derived from astronomical calibration. We note that this is within the capabilities of the IEEE 1588 Precision Time Protocol.

LRT1357:

The design implementation will use the antenna station frequency reference to derive the antenna station timing signal. Therefore, to within the accuracy of cable drifts and/or edge jitter the antenna station references are all synchronized.

LRT1360:

Additionally, there is a need for accurate timing by either model, measurement, or active correction to at least one reference antenna in any given subarray. To fully satisfy SYS0603 (Arbitrary subarraying) the design will be implemented with an accurate timing correction to every fiber connected antenna.

7.4.3 Timing Performance Budget

A timing performance budget has been developed and set forth in [RD04].

Table 7: Timing Performance Budget

Sub-System Timing Precision Allocation	Sub-system	Error (nsec)	Notes	Associated LRT Requirement	Timing reference planes for measurement
Measurement Error: System Domain Clock Drift vs GPS Time	RTG	1.67	GPS timing error long term average	LRT1305	Maser 1 PPS output versus GPS 1 PPS
Uncorrected Time Drift from System Domain Clock (RTG) to CSP	RTG	0.00	CSP time domain is derived from DBE timestamping	N/A	N/A
Uncorrected Time Drift between System Domain Clock (RTG) and Time Distribution System (RTD)	RTD	0.30	Assumes short cable lengths in temp controlled environment	LRT1350	Maser 1 PPS output versus RTD 1 PPS input to time transmitter
Uncorrected Time Drift from System Domain Clock (RTG) to Reference Antenna Domain Clock (RTD)	RTD	2.00	Residual after round-trip correction of timing signal	LRT1300	Maser 1 PPS output to corrected 1 PPS output of Timing Receiver
Antenna Structural & Electronic Delay Drift (preceding digitizer)	ANT, SBA	0.05	4 psec over 300 sec (48 psec/hr.), combined across all systems in an antenna, between astronomical calibrations.		N/A for LRT subsystem
DBE Time Error w.r.t. Antenna Domain Clock	ATF/DBE	1.00	Assumes JESD 204D timestamping of digitized data	LRT1380	1 PPS timing input to ADC JESD clocking circuit versus 1 PPS delivered through 25m optical fiber to the DBE
Other Delay Model Errors	ONL	1.00			N/A for LRT subsystem
Sub-System Error Sub-total		**2.98**	**RSS Combination of Independent Errors**		
		6.02	**Linear Sum of Correlated Errors (worst case)**		
Margin - only true if terms are independent.		9.55	(Aiming towards 1 nsec goal in allocations)		
System-level Total Error Budget		**10.0**	**RSS Combination of Errors**		

The budget shows how potential sources of timing inaccuracy are accounted for within the overall systems timing budget of 10 nsec (SYS2002). Note: shaded lines in the table refer to subsystems within LO Reference and Timing design described in this document.
For purposes of test and verification it is necessary to have a well-defined test point for the timing signals described in Table 7. A description of the reference planes appears as column six in the table.

7.5 Modes

Parameter	Req. #	Value	Traceability
Standby Mode	LRT1400	A low power standby mode shall be available for all RTG and RTD modules. Monitor and Control shall remain operational in this mode	SYS0010, SYS0011, SYS9990, ETR0809, ETR0810
Automatic Initialization	LRT1410	RTG and RTD modules shall automatically boot into standby mode on power-up, absent any command from M&C.	SYS0011, SYS2304, SYS3114, ETR0811

Parameter	Req. #	Value	Traceability
Operating Modes	LRT1420	Any functional operating mode can be reached by command from Standby Mode.	SYS0010

7.6 *Spurious/RFI*

7.6.1 Signal Path Spurious

Parameter	Req. #	Value	Traceability
Spurious Narrowband Tones	LRT1500	Within 3.5 GHz of carrier < -103 dBc. Spurious narrowband tones introduced in the RTD frequency references can potentially appear in the antenna station LO system. Careful design should be made to limit this effect. Antenna LO has very stringent spurious requirement. For any reference signals developed by the RTD subsystem, the maximum acceptable spurious level shall be specified in the RTD-ATF ICD [AD30].	[AD30], SYS2104

Spurious Narrowband Tones: Spurious narrowband tones introduced in the RTD frequency references can potentially appear in the antenna station LO system. Careful design should be made to limit this effect. Antenna LO has very stringent spurious requirement. For any reference signals developed by the RTD subsystem, ***the maximum acceptable spurious level shall be specified in the RTD-ATF ICD [***AD30***]***. The level indicated above is derived from a level that would be harmful if passed directly to the LO downconverter. Thus, if the RTD subsystem design, or the ATF design at the RTD interface includes a mitigating filtering effect (such as a phase locked loop), the acceptable level could be higher than -103 dBc.

7.6.2 Spurious RFI Emission – Discussion

EMC0310 specifies spurious emission level versus frequency for spectral line and continuum emission. For the RTG and RTD subsystems these are both applicable but spectral line emission is likely to be the greater concern due to the transmission and distribution of continuous-wave frequency sources and offset frequency synthesis.

For reference, the spectral line emission requirement from [AD05] is shown below (reformatted). The columns reflecting 10m distance match [AD05] and would be pertinent for equipment located in the antenna pedestal. For equipment at the secondary focus (nearly co-located with the receiver, the numbers have been reworked to reflect lower acceptable limits (by 20 dB). For equipment located in the central electronics building, the acceptable limits are higher by 14 dB, just using path loss assumptions (50m is the closest antenna to the central electronics building and thus the worst case).

Table 8: Spectral Line emission limits from [AD05].

		Central building 50m		Pedestal 10m		Secondary Focus 1m	
Freq	BW (kHz)	EIRP	dBm/Hz	EIRP	dBm/Hz	EIRP	dBm/Hz
1	0.3	-115	-104	-129	-124	-149	-144
3	1	-101	-95	-115	-115	-135	-135
6	2	-92	-89	-106	-109	-126	-129
10	3	-86	-85	-100	-105	-120	-125
30	10	-70	-74	-84	-94	-104	-114
45	15	-64	-70	-78	-90	-98	-110
90	30	-53	-62	-67	-82	-87	-102

Table 8 is used in the formulation of the requirements in Sections 7.6.3, 7.6.4, and 7.6.5. Shielding levels may be required to meet the limits detailed there. In the central electronics building the shielding can be provided at the building, room, rack, or module level. If at the building or room level, it would be included in the appropriate ICD [AD24]. In the antenna station, custom shielded modules are anticipated, and this would be included in the ICD with the Antenna Electronics Bins, Modules, and Racks work package [AD21].

Figure 6 graphs the permitted emission level versus frequency for a wide range of frequencies expected for ngVLA. Not all of these frequencies may be in use by the RTG or RTD subsystem. Note that below 2 GHz a maximum level of -136 dBm/kHz (secondary focus), -116 dBm/kHz (pedestal), -102 dBm/kHz (central electronics building) is permitted.

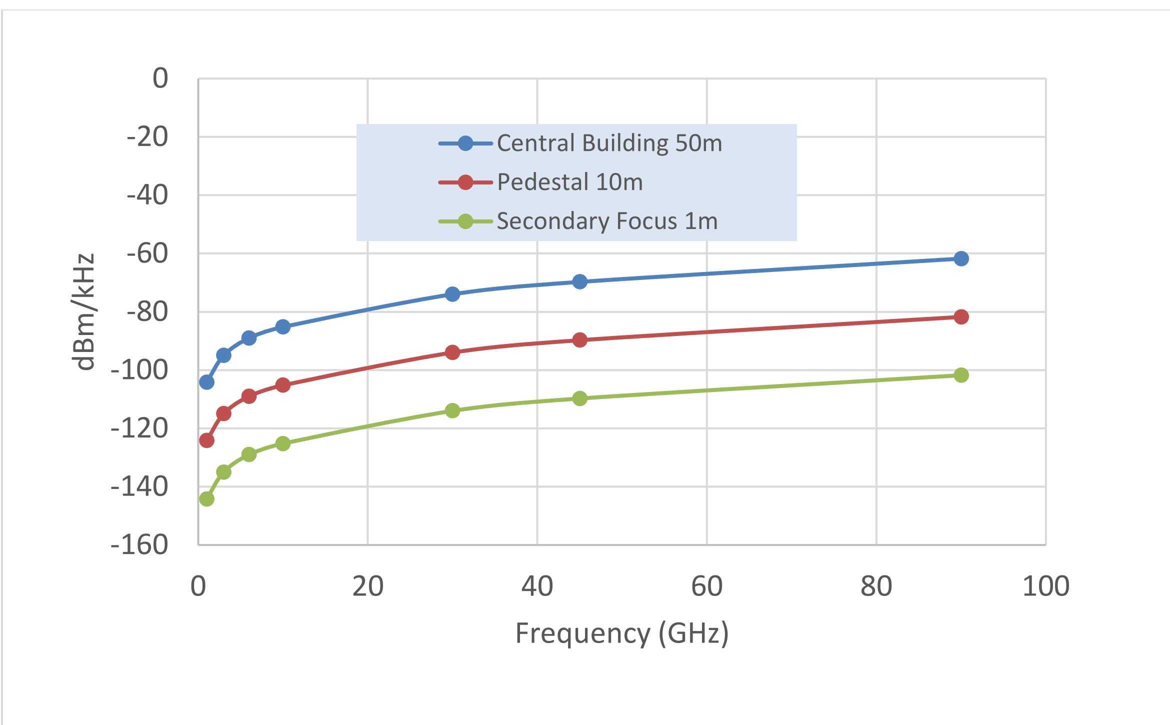

Figure 6: Emitted power level from antenna station located RTD equipment for two locations in or on the antennas.

Spurious Emission Impacting IRD and ATF:

Note that in the secondary focus enclosure, direct coupling to the LO or IRD modules without benefit of shielded enclosure may be possible. Special design consideration shall be given to this possibility, minimizing opportunity of spurious emissions particularly at harmonics of clock and oscillator frequencies of the RTD.

Parameter	Req. #	Value	Traceability
Emission Verification Frequencies	LRT1610	Spurious signal emission levels shall be verified by test over a minimum range of 1 GHz up to 12 GHz. Modules or devices that may contain frequency content above 12 GHz shall be tested at least up to 50 GHz.	SYS2104, EMC0311
Low Frequency Emission	LRT1620	Spurious signal emission levels shall be quantified by test over an extended frequency range of 5 MHz to 1 GHz. While there is no emission threshold within this range, this information shall be collected to inform future system expansion.	SYS2104, SYS5602, EMC0312
RFI suppressing housings	LRT1630	RFI Suppression housings shall be used to contain and suppress spurious emissions, in order to meet the requirements	SYS2104, SYS2106, SYS2107

7.6.3 Central Building

Parameter	Req. #	Value	Traceability
Spurious Signal Level Emission – Central Building	LRT1602	Spurious signals generated by the system shall not exceed the equivalent isotropic radiated power limits specified in Table 8 and Figure 6	SYS2104, EMC0310 [AD24]

7.6.4 Spurious RFI Emission – Repeater Stations

Parameter	Req. #	Value	Traceability
Spurious Signal Level Emission	LRT1604	Spurious signals generated by the system shall not exceed the equivalent isotropic radiated power limits specified in Table 8 and Figure 6. The allowable emission level shall be derived by accounting for the distance from the repeater station to the nearest antenna station.	SYS2104, EMC0310 [AD26]

7.6.5 Spurious RFI Emission – Antenna Stations

Parameter	Req. #	Value	Traceability
Spurious Signal Level Emission – Antenna Station	LRT1600	Spurious signals generated by the system shall not exceed the equivalent isotropic radiated power limits specified in [AD05], as elaborated in Table 8 and Figure 6. Note that different allowable emission level is applicable to modules in the pedestal vs at the secondary focus.	SYS2104, EMC0310 [AD21], [AD29]

Spurious Emission impacting IRD	LRT1605	Spurious signals generated by the system shall not exceed the equivalent isotropic radiated power limits specified in [AD05]. See note Section 7.6.2 "Spurious Emission Impacting IRD, ATF."	SYS2104, EMC0310, [AD21], [AD29]
Spurious Emission impacting ATF	LRT1608	Spurious signals generated by the system shall not exceed the equivalent isotropic radiated power limits specified in [AD05]. See note Section 7.6.2 "Spurious Emission Impacting IRD, ATF."	SYS2104, EMC0310, [AD21], [AD29]

7.7 Monitor and Control

Parameter	Req. #	Value	Traceability
Self-Monitoring	LRT1635	The RTG and RTD subsystem shall measure, report and monitor a set of parameters that allow for determination of its status and may help predict or respond to failures. This shall include but not be limited to on/off status, power levels, frequency lock status, and bias voltages.	SYS2405, SYS2406, SYS2601, SYS3101
LRU Alerts	LRT1640	A subsystem alert shall be generated when an RTG or RTD LRU has an abnormal condition or failure.	SYS3102
High-Cadence Monitoring	LRT1650	The M&C interface shall be fast enough to support streaming of diagnostic data. This shall be applicable in operational mode without affecting other performance requirements.	SYS3105, SYS2408
LRU Hot Swapping	LRT1660	RTG or RTD LRUs intended for field replacement shall be hot-swappable by design, and recover with minimal intervention by maintenance and operations staff.	SYS3111
Remote Updates	LRT1670	Firmware in embedded processors and configuration data in FPGAs shall be updateable remotely, in-situ.	SYS3223, ETR0907
Automatic Configuration on Restart	LRT1680	The RTG or RTD subsystem shall be capable of reaching an operationally-ready Standby state after a full power cycle without human intervention.	SYS3114
Front End Engineering Console	LRT1690	The RTG or RTD subsystem shall include an engineering console to display status and aid in real-time problem diagnosis.	SYS2407
M&C Commanded Reset for DC Powered Devices	LRT1700	All DC powered LRUs and complex programmable devices shall be provided with a physical reset line connected to a local M&C device to allow remote reset commands to be sent. This could be implemented as a ganged reset to all devices in an LRU or as individual lines to each device (or group of devices) as determined by the designer.	ETR0909
M&C Commanded Reset for AC	LRT1710	All AC powered LRUs shall be connected to a remotely controllable Power Distribution Unit (PDU) or similar device which can be remotely commanded	ETR0912

Parameter	Req. #	Value	Traceability
Powered Devices		via the M&C system to power cycle each individual device.	

With regard to the self-monitoring, alerts, and high cadence monitoring: these requirements may be satisfied by:

- an RTG or RTD LRU alone, in a module which has the onboard intelligence to report status and/or alarms
- by a combination of the RTG or RTD modules and the hardware interface layer as specified in [AD23]

7.8 *Lifecycle*

Parameter	Req. #	Value	Traceability
Design Life	LRT1800	The integrated modules shall be designed to be operated and supported for a period of 30 years.	SYS2801, ETR0903
Lifecycle Optimization	LRT1810	The RTG and RTD design shall minimize its lifecycle cost for 30 years of operation.	SYS2802
Parts Selection and Procurement Criteria	LRT1820	Parts selection and procurement criteria shall include: a. Sustainability and environmental impact b. Adequate Supply of critical spares for array lifecycle c. Risk mitigation against parts obsolesce and long-term availability	SYS2803, SYS2805, SYS2812, ETR0901, ETR0902
Packaging Supply	LRT1830	When applicable, shipping cases and packaging shall be supplied for transportation and storage of RTG and RTD elements in compliance with LRT0160 packaging for transport requirement	SYS3904 SYS3905 SYS3912
Quality Control of Deliverables	LRT1840	Stand-alone acceptance testing of software and hardware deliverables shall occur before delivery and installation on the array.	SYS3702
Test Fixtures	LRT1850	Test fixtures and procedures shall be provided for RTG and RTD subsystem verification tests	SYS2811
Testing of Software and Firmware	LRT1860	All software and firmware shall be delivered with automated unit, integration, and regression testing suites.	SYS2814
AIV Software Tools	LRT1870	Development tools, compilers, source code, and the build system shall be delivered to enable maintenance over the life of the facility.	SYS2815
Incremental Delivery to Operations	LRT1880	Operational capabilities and modes shall be made available in stages during the transition from construction to full operations. For the RTG and RTD subsystems, this might imply a limited build-out of the distribution network in the first years(s) to keep pace ahead of antenna deliveries. Full support for LBS stations can be staged according to the overall remote station deployment schedule.	SYS2830

Accounting for product development, integration, and array commissioning, it is reasonable to target a 30-year minimum overall lifetime.

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

7.9 Configuration

The following table lists the configuration management requirements applicable to the RTG and RTD subsystem equipment.

Parameter	Req. #	Value	Traceability
Serial Numbers	LRT1900	Each LRU shall have both a visible and electronic serial number.	SYS3600
Version Control for Software and Firmware	LRT1910	All custom software and firmware delivered as part of the RTG or RTD subsystem shall be version controlled via a configuration management process.	SYS3602
Configuration Retrieval	LRT1920	Any configurable equipment shall retrieve its hardware configuration immediately after installation and power up.	SYS3603
Physical Tracking	LRT1930	Any hardware deliverable or equipment not connected to the M/C subsystem shall be equipped with a physical tracking label or device (bar code or RFID tag), to allow quick and unique identification.	ETR0404
Remote Identification	LRT1940	The RTG and RTD modules shall report the following information to the M&C system, to the extent applicable, upon request: 1. Module/Model Number 2. Serial Number 3. CID Number 4. Hardware Revision Level 5. Software Revision Level 6. Firmware Revision Level Note that the software and firmware revision codes together represent a configuration that is tracked under version control	SYS3600, ETR0403
Documentation	LRT1950	Clear and complete documentation shall be delivered with the RTG or RTD LRUs and equipment, meeting project format and standards	SYS6001-SYS6005

7.10 EMC/Immunity

ngVLA standards for Electromagnetic Compatibility and Immunity are developed and described in [AD03], [AD05], and [AD09].

Parameter	Req. #	Value	Traceability
Analog shielding	LRT2200	Analog electronics, especially those containing oscillators and amplifiers, shall be shielded so that emission limits can be met. Careful EMC design shall limit conducted emission between and among	SYS2106, SYS2107, EMC0322

		subsystems – including by power supply wiring or ground loops.	
Digital shielding	LRT2210	All digital equipment shall be shielded and have its AC or DC power line and communication line(s) filtered at the chassis.	SYS2106, SYS2107, EMC0327
Commercial equipment	LRT2220	Any Commercial off-the-shelf (COTS) equipment shall conform to IEC product family standards for immunity standards, or to the generic standard IEC 61000 – Part 6: Generic Standards if no product family standard is given. Additionally, the equipment shall have a CE mark or FCC compliance ID	SYS2016, EMC0401, EMC0402
Conducted Immunity, Testing	LRT2230	LRUs shall be designed and tested for immunity to conducted voltage and noise	SYS2106, EMC0411-0412, EMC0421-0424, EMC0431-0432, EMC0451-0452, EMC0461-0462
Electrostatic Discharge, Testing	LRT2240	LRUs shall be designed for and tested to meet ESD discharge requirements	SYS2106, EMC0471-0473, ETR0501, ETR0505, ETR0506
Hi-Speed Design	LRT2250	RTG and RTD modules incorporating high speed digital logic shall be designed for low emission, incorporate best EMC practices, and be subject to rigorous review	SYS2016, ETR0714
ESD, Storage and Shipment	LRT2260	ESD sensitive components and modules shall use best practices for storage, shipment, and handling	SYS3904, ETR0503

7.11 Reliability, Availability, and Maintainability

Parameter	Req. #	Value	Traceability
Spurious Signal Level Emission – Central Building	LRT1602	Spurious signals generated by the system shall not exceed the equivalent isotropic radiated power limits specified in Table 8 and Figure 6	SYS2104, EMC0310 [AD24]
Reliability Analysis	LRT2300	A Reliability, Availability, Maintainability analysis shall be performed and documented as a memo by each designer at the LRU level to locate weak design points and determine whether the design meets the Maintenance and Reliability requirements.	ETR0904, SYS2402, SYS2801, SYS2802, SYS2805

Availability	LRT2305	The MTBF and MTTR for the RTG and central RTD parts shall be 3000 hours and 12 hours, respectively. They should support a system budget to achieve 95% system availability	SYS2601, SYS2602
Mean Time Between Failure/Mean Time Between Maintenance	LRT2310	The RTD subsystem shall have a MTBM of 3000 hours (Note: see below) Here failures are considered in the same category as maintenance, any equipment status that would require a human intervention to address	SYS2610, SYS2605, AD11
Array Element MTTR	LRT2330	The RTD subsystem shall have a maximum MTTR of 12 hours.	SYS2611, SYS2605
Modularization	LRT2340	The system shall be modularized into Line Replaceable Units (LRUs) to facilitate site maintenance.	SYS2403
Spares Planning	LRT2350	Failure analysis shall be used in the planning of spares inventory. Factors considered shall include the projected availability for spares, the time required to repair the failure, and the viability of critical vendors.	SYS3204
Operations and Maintenance: Transfer of Deliverables	LRT2360	All procedures, test equipment, and test software shall be delivered to the Operations and Maintenance staff prior to full operations.	SYS3211
Preventive Maintenance	LRT2370	The parts of the RTG and RTD subsystems that have a direct impact on system availability should, as far as practically possible, allow for preventive maintenance without interrupting observations	SYS2603
LRU Interchange ability	LRT2380	LRUs should be interchangeable with no on-site calibration, tuning or alignment.	SYS3232
Identify Failures Physically	LRT2390	All LRUs shall identify a failed state via physical display (e.g., LED).	SYS3234
Report Predicted Failures	LRT2400	All LRUs, where possible, shall report fault prediction sensor data via the M&C system.	SYS3236
Failure Information Source	LRT2410	All LRUs shall report failure information in line with failure isolation as identified in a FMECA analysis.	SYS3237
Robustness Analysis	LRT2420	All ngVLA electronics designs shall be subject to a robustness analysis. Results of this analysis are a required part of the design review process. Robustness shall be demonstrated against environmental, power supply disturbance, vibration, monitor and control, inputs out-of-range.	ETR0905

LRT2300, LRT2305, LRT2310, and LRT2330: [AD11] has preliminary allocations for MTBF and MTBM for central and antenna-located LRUs such that the system level availability requirement is met. These preliminary allocations allow for a mean time between maintenance period that covers both preventive maintenance and corrective maintenance such that:

- There is a minimum MTBF/MTBM of 3000 hours ***total*** for elements of the RTG subsystem in the Central Electronics Building
- There is a minimum MTBF/MTBM of 3000 hours ***total*** for elements of the RTD subsystem in the Central Electronics Building
- There is a minimum MTBF/MTBM of 18520 hours ***total*** for elements of the RTD subsystem located at the antenna

In each of the three cases above, the sum of MTBFs of all modules and assemblies in the subsystem shall meet these limiting values.

7.12 Design Requirements

7.12.1 Printed Circuit Boards and Electrical Connections

Parameter	**Req. #**	**Value**	**Traceability**
Printed Circuit Boards-Standards	LRT3200	For printed circuit boards incorporated into RTG or RTD subsystem design: (a) Design and manufacture shall meet the IPC Standard IPC-A-600K Design and manufacture Shall meet RoHS 2 and 3 standards	ETR0701, ETR0712, SYS2402, SYS2803, SYS2805
Printed Circuit Board-Design	LRT3210	Requirements for PCB materials, markings, and test and maintainability shall be met by design	ETR0704-07011, ETR0713, ETR0715-0717
Soldered Electrical Connections	LRT3220	Soldered electrical connections shall use Class 2 of the IPC J-STD-001G Requirements for Soldered Electrical and Electronic Assemblies, per [AD09]	ETR1301

Note: For commercial-off-the-shelf PCBs, these requirements are recommendations, with best effort to attempt to procure boards that meet as many of these requirements as possible.

7.12.2 Power and Ground

Parameter	**Req. #**	**Value**	**Traceability**
Power Supply noise and stability	LRT3300	RTG or RTD shall achieve full performance with power supply voltage stability and rms noise levels specified in ICD	AD21
DC Voltages available	LRT3310	All RTD equipment in the ngVLA antenna station powered from DC voltages shall utilize voltages produced by the PSU modules, currently + 5 VDC, +/– 7.5 VDC and +/– 17.5 VDC.	ETR0821, ETR0803
PSU Voltage Tolerance	LRT3320	Devices powered from the PSU modules shall tolerate +/– 10% of the rated voltages.	ETR0823
LRU Physical Ground	LRT3330	LRU chassis or housing shall be electrically connected to the antenna or building structure using a proper grounding wire. This wire can be a separate ground connection or included in the connectorized harness carrying power to the device.	ETR0804

Parameter	Req. #	Value	Traceability
Power Supply Returns Separate from Ground	LRT3340	Structural/Chassis components and signal grounds shall never be used as a power supply return path.	ETR0814
Overcurrent Protection	LRT3350	All ngVLA Electronics systems shall implement overcurrent protection on LRUs.	ETR0805
Overcurrent Protection Device Monitoring	LRT3360	The ngVLA M&C system shall be able to monitor the state of overcurrent protection devices in an LRU. An exception is if the circuit protection device activated disables the LRUs M&C interface.	ETR0806
Thermal Protection	LRT3370	ngVLA LRUs shall be thermally protected.	ETR0807
Thermal Protection Monitoring	LRT3380	The LRU shall be able to monitor the state of thermal protection features. An exception is if the thermal protection activated disables the LRUs M&C interface.	ETR0808
Thermal Analysis	LRT3390	The designer shall analyze their designs and take steps to optimize thermal performance with a focus on proper cooling, thermal stability and the elimination of hot spots. The thermal design shall be published as a report and included in design reviews.	ETR0816
Power On Indicators	LRT3400	LRUs and power supplies shall contain externally visible LED power indicators with "steady blue" indicating "nominal operation" and "blinking blue" indicating "power is on but not meeting nominal conditions." In RFI shielded enclosures, these may be implemented with small LEDs or light pipes.	ETR0812
Battery Use	LRT3410	Batteries shall not be used in the ngVLA system except in the case of the antenna –48 VDC power system and a commercial UPS device for critical AC line powered equipment.	ETR0817
Transient Protection of LRU I/O & Power Connections	LRT3420	Transient Voltage Suppression devices shall be used on sensitive analog and digital I/O signals and power supplies entering or exiting an LRU. RF and other signals that will be adversely affected by the inclusion of these devices are exempt from this requirement.	ETR0818

7.12.3 Electrical Wiring, Cables, Connectors

Parameter	Req. #	Value	Traceability
Wiring Documentation and Labeling	LRT3500	Wiring documentation and labeling shall meet project standards [AD09]	ETR1101, ETR1102
DC voltage Wire Colors	LRT3510	DC voltages shall use a wiring color scheme as specified in [AD09]	ETR1103-ETR1123, ETR1154, ETR1155
AC power wiring colors	LRT3520	All AC wiring colors shall conform to US NEC requirements.	ETR1125

Parameter	Req. #	Value	Traceability
Wire and Cable installation	LRT3530	Wire and cable protection, materials, ruggedness, installation, and insulation shall be implemented according to [AD09]	ETR1125-ETR1132, ETR1156, ETR1157, ETR1189
Connector Documentation and Labeling	LRT3540	Connector documentation and labeling shall meet project standards [AD09]	ETR1133, ETR1134
Connector Selection	LRT3560	Connectors shall be selected for appropriate current rating, environmental rating, and expected number of mating cycles	ETR1135-ETR1137
Connectors for Hot Swap	LRT3570	If hot swapping is used, the design must be supported by the selection of an appropriate connector to eliminate arcing, abnormal current flow, and sequencing issues	ETR1139
Connector Design for Ease of Operation	LRT3580	Connectors shall be chosen for ease of operational and maintenance use. This includes: a. Use of keying to prevent incorrect mating b. Use of clear labeling and/or color coding Use of standardized pinouts for cables/connectors used in multiple places	ETR1141, ETR1185, ETR1142
Crimped Connectors	LRT3590	Crimped wire connections shall be preferred over solder cup, and shall utilize best assembly practice per [AD09]	ETR1186, ETR1187
Connector Type, Retention, and Locking	LRT3600	Connectors must meet project standards for reliable performance by complying with retention and locking standards. This is applicable to external electronic, RF, and fiber optic connectors, single and multi-pin. Internal to LRUs, PCB board connections and other critical interconnects must be designed for positive retention. ETR1212 requires a documented analysis for satisfying this requirement.	ETR1197-ETR1212

7.12.4 Materials, Lighting, and Mechanical

Parameter	Req. #	Value	Traceability
Metalwork	LRT3700	Metalwork used for modules, bins, and racks shall use project standard recommendations for use of materials, plating and coating, surface preparation and painting.	ETR1143-ETR1147, ETR1188
Lighting	LRT3710	Status lighting shall be by means of long-life LED or OLED sources. BLUE shall be used solely to indicate presence of power supply. RED shall be used solely to indicate faults or alarms conditions. WHITE shall be used only for illumination. Other colors may be used at the designer's discretion for other conditions or status indication. Brightness shall be set to the minimum necessary for the desired function.	ETR1148-ETR1153

Fasteners	LRT3720	All screws or any type of assembly hardware shall use metric standard, and materials, labeling, and design shall be according to [AD09].	ETR1161-ETR1169, ETR1171, ETR1190, ETR1184
LRUs, mechanical	LRT3730	LRU shall be designed for ease of installation and removal, be free of rough edges, and follow project recommendations for assembly, installation, and handling per [AD09]	ETR1170, ETR1172, ETR1176-ETR1178, ETR1183
LRU documentation and dimensions	LRT3740	LRUs shall be documented with engineering dimensions, units and tolerances per [AD09].	ETR1173-ETR1175

8 Safety

8.1 Safety Requirements

This section defines all design requirements necessary to support the Level-1 Safety, Security and Cybersecurity requirements.

Parameter	Req. #	Value	Traceability
Safety Specification	LRT4200	The RTG and RTD equipment shall comply with ngVLA Safety Specifications [AD07] including physical security and monitoring	SYS2700, SYS2704
Security Specification	LRT4210	The RTG and RTD equipment shall comply with Security Plan and Requirements [AD08] • Includes training, policy, planning in addition to hardware and physical elements • Documented hazard analysis with standards approved by Safety and Systems IPT • Established physical security control for each ngVLA location May include access control, entry locks, fire alarms or detectors, key control (equipment and doors), identification of sensitive property	SYS2703
Cybersecurity Specification	LRT4220	• Compliance with NRAO Master Information Security Policy • Compliance with NRAO Cyber Security Incident Response Policy • Compliance with Cyber Security Access Control Policy	SYS2702

Parameter	Req. #	Value	Traceability

		• Follows guidelines of NSF19-68 Section 6.3 "Guidelines for Cyber Security of NSF's Major Facilities"
		• Password control, least privilege policy, identity management, strong access authentication
		• Most recommendations, policy, and protocols applicable at level outside or above the hardware IPT, except perhaps:
		    • Apply security updates in timely manner
		    • Embedded device firmware with version control and update features
		    • Use of segregation and firewalls
		    • Reduce software to barest minimum	

Hazard Analysis	LRT4230	The RTG and RTD subsystem shall have hazard analysis performed.	SYS2700
LRU Weight Labels	LRT4240	LRUs in the RTG and RTD subsystems shall include at least one clearly visible label indicating the weight of the LRU in pounds. The label shall be compliant with applicable standards at the time of installation.	SYS2700, SYS3202, ETR0406
Hot Connect & Disconnect Warning Labels	LRT4250	In situations where, disconnecting cables or pulling of equipment with power on can cause damage, clearly visible labels shall be applied to warn on this condition.	SYS2700, SYS3202, ETR0410
Electrical and Optical Label Safety Standards	LRT4260	All electrical and optical safety labels shall be compliant with applicable standards at the time of installation.	ETR1016, SYS2700
Design for Optical Safety	LRT4270	All LRUs using Lasers or high intensity LEDs at levels defined as dangerous in the ANSI Z136 series of standards (RD02) shall be designed to minimize or prevent human exposure.	ETR1018, SYS2700
Optical Safety Labels	LRT4280	In all LRUs containing lasers, clearly visible labels in accordance with the IEC 60825-1:2014 Standard (RD03) shall be applied.	ETR1019, SYS2700
Connectors for Hot Swap	LRT4290	If hot swapping is used, the design must be supported by the selection of an appropriate connector for personnel and equipment safety	ETR1138
No Exposed Live Terminals	LRT4300	Live signal or power pins in connectors shall not be exposed while connectors are unmated.	ETR1140

9 Interface Requirements

Antenna Time and Frequency has interfaces with the several major subsystems as detailed in the subsections below.

9.1 *Interface to PSU*

[AD20] 020.10.40.05.00-0006: Interface Control Document Between: Antenna Electronics DC Power Supply (PSU) *and* Antenna Electronics Subsystem: section on LO Reference and Timing and Distribution (RTD) Subsystem (interface 0058)

This interface details the requirements for DC power needed to supply RTD equipment. Mechanical, thermal, and electronic interfaces are included.

A specific subset of these interface requirements (representing critical requirements) which will be fully defined in the ICD have been included in this document for tracking purposes and for completeness, as follows:

Table 9: RTD subsystem requirements tracked in ICD to PSU.

Parameter	Req. #	Value	Traceability
Power Supply noise and stability	LRT3300	Power supply for RTD equipment at the antenna shall have DC voltage power supply with low noise rms voltage level TBD	LRT1240
DC Voltages available	LRT3310	Antenna-located RTD equipment shall utilize voltages produced by the PSU modules, currently + 5.0 VDC, +/– 7.5 VDC and +/– 17.5 VDC.	ETR0821
PSU Voltage Tolerance	LRT3320	Devices powered from the PSU modules shall tolerate +/– 10% of the rated voltages.	ETR0823
LRU Physical Ground	LRT3330	LRU chassis or housing shall be electrically connected to the antenna structure using a proper grounding wire. This wire can be a separate ground connection or included in the connectorized harness carrying power to the device.	ETR0804
Power Supply Returns Separate from Ground	LRT3340	Structural/Chassis components and signal grounds shall never be used as a power supply return path.	ETR0814

Additional interface requirements will be detailed in the ICD for connector and wire types and mechanical and thermal interfaces.

9.2 *Interface to BMR*

[AD21] 020.10.40.05.00-0040 Interface Control Document Between: Antenna Electronics Bins, Modules, and Racks (BMR) *and* Antenna Electronics Subsystem: section on LO Reference and Timing and Distribution (RTD) Subsystem (interface 0064)

This interface details the requirements for any bins, modules, or racks needed for RTD equipment. Mechanical, thermal, and electronic interfaces are included. Specific requirements which will be fully defined in the ICD have been included in this document for tracking purposes and for completeness, as shown in Table 10.

Table 10: RTD subsystem requirements tracked in ICD to BMR.

Parameter	Req. #	Value	Traceability
RFI suppressing housings	LRT1630	RFI Suppression housings shall be used to contain and suppress spurious emissions, in order to meet the requirements	SYS1201, SYS2104 SYS2106 SYS2107 ETR0601
RTD subsystem size in pedestal	LRT5410	RTD equipment shall be housed in NRAO designed RFI-shielded rack mount ARCs modules. Size allocation TBD [AD21]	ETR0601 ETR1170
RTD subsystem weight in pedestal	LRT5420	RTD equipment shall be housed in NRAO designed RFI-shielded rack mount ARCs modules. Weight allocation TBD [AD21]	ETR0601 ETR1170
RTD subsystem size in front end enclosure	LRT5430	RTD equipment shall be housed in NRAO designed RFI-shielded ARCs modules within the 1800mm wide X 1150mm deep X 600mm enclosure Allowable space within the enclosure will be detailed in [AD21]	SYS1001, SYS1101, SYS2403, CAL0201, CAL0205, CAL0206
RTD subsystem weight in front end enclosure	LRT5440	RTD equipment shall be housed in NRAO designed RFI-shielded ARCs modules within enclosure, which itself shall have a maximum mass of 522kg Allocation of weight for RTD equipment within the enclosure will be detailed in [AD21]	SYS1001, SYS1101, SYS2403, CAL0201, CAL0205, CAL0206

9.3 *Interface to EEC*

[AD22] 020.10.40.05.00-0069: Interface Control Document Between: LO Reference and Timing and Distribution (RTD) Subsystem *and* Antenna Electronics Environmental Control System (EEC) Subsystem

This interface details the requirements for environmental control of the RTD equipment. Mechanical, thermal (air or liquid heat transfer), and electronic interfaces are included. The interface requirement will include specific detailed requirement for the EEC subsystem for thermal control such that the environmental requirements detailed in Sections 6.7, 6.8, and 6.9 are met.

Table 11: RTD subsystem requirements tracked in ICD to EEC.

Parameter	Req. #	Value	Traceability
Precision condition temperature range	LRT320	Antenna-located RTD equipment shall operate over a precision temperature range FEC: Tmin < T < Tmin+5.0 deg C; Tmin=5-10 deg C Pedestal: Tmin < T < Tmin+15.0 deg C; Tmin=5-10 deg C	ENV0313, LRT0320
Precision condition	LRT330	Antenna-located RTD equipment shall operate with precision temperature stability	ENV0314 SYS4902

Parameter	Req. #	Value	Traceability
temperature stability		< 0.5 °C per 300s	SYS4904 LRT1250 LRT0330
Normal condition temperature range	LRT390	Antenna-located RTD equipment shall operate over a normal temperature range FEC: Tmin < T < Tmin+5.0 deg C; Tmin=5-10 deg C Pedestal: Tmin < T < Tmin+15.0 deg C; Tmin=5-10 deg C	ENV0313, LRT0390
Normal condition temperature stability	LRT400	Antenna-located RTD equipment shall operate with normal temperature stability < 0.5 °C per 300s	ENV0324 SYS4902 SYS4906 LRT1250 LRT0400

9.4 Interface to MCL/HIL

[AD23] 020.10.40.05.00-0077 Interface Control Document Between: Monitor and Control Hardware Interface Layer (HIL)/Monitor and Control Subsystem (MCL) (interface 0064) (incl MCL: interface 107) *and* LO Reference and Timing and Distribution (RTD) Subsystem

This interface details the requirements for interface between the RTD equipment hardware layer and the M&C hardware and software supervisory layers.

[AD31] Interface Control Document Between: LO Reference and Timing – Generation (RTG) and Hardware Interface Layer (HIL)

This interface details the requirements for interface between the RTG equipment hardware layer and the M&C hardware and software supervisory layers.

9.5 Interface to NSB

[AD24] 020.10.40.05.00-0095 Interface Control Document Between Computing/CSP subsystems: section on LO Reference and Timing Generation (RTG) and Distribution (RTD) Subsystems (interface 0099, 0100) and ngVLA Site Buildings (NSB) subsystem.

Table 12: RTD/RTG subsystem requirements tracked in ICD to NSB.

Parameter	Req. #	Value	Traceability
Precision condition temperature range	LRT270	+15 C ≤ T ≤ +25 C NSB shall maintain temperature in this range	ENV0313, LRT0270
Precision condition temperature stability	LRT280	CEB-located RTD and RTG equipment shall operate with precision temperature stability < 0.2 °C per 300s NSB room temperature controller and air flow shall be defined to achieve this condition	ENV0314 LRT0280
Precision condition air flow	LRT290	CEB-located RTD and RTG equipment shall have sufficient air flow be provided by the central electronics building air handlers to maintain temperature range and stability	ENV0314 LRT0290

Parameter	Req. #	Value	Traceability
		TBD cubic meters per hour supplied by NSB	
Normal condition temperature range	LRT340	+15 C ≤ T ≤ +25 C NSB shall maintain temperature in this range	ENV0323 LRT0340
Normal condition temperature stability	LRT350	CEB-located RTD and RTG equipment shall operate with precision temperature stability < 0.5 °C per 300s. NSB room temperature controller and air flow shall be defined to achieve this condition	ENV0324 LRT0350
Normal condition air flow	LRT360	CEB-located RTD and RTG equipment shall have sufficient air flow be provided by the central electronics building air handlers to maintain temperature range and stability TBD cubic meters per hour supplied by NSB [AD24]	ENV0324 LRT0360
LRT Space Allocation by NSB	LRT5500	Space shall be allocated in CEB for LRT central equipment, with space allocation TBD	SYS3800
Grounding Point	LRT5510	A grounding design for LRT equipment racks shall be provided by NSB, with design and installation of all conforming to US National Electrical Code NFPA 70	ETR0601, ETR0801
Equipment Rack Mounting Interface	LRT5520	A pre-defined mechanical interface for physical mounting of LRT equipment racks shall be provided by NSB	SYS3800
Cable Trays	LRT5530	Overhead cable trays for supporting fiber optic and other signal cables shall be installed in CEB, provided by NSB. Provision for routing of cables to CSP, Computing, or building egress shall be made.	SYS3800
LRT AC Power provided by NSB	LRT5540	Design and installation of all AC Power and Grounding wiring shall conform to US National Electrical Code NFPA 70 (RD23).	ETR0801
LRT UPS Power provided by NSB	LRT5550	UPS power shall be provided by NSB with capacity and duration TBD	ETR0817
LRT Maximum power consumption in CEB	LRT5560	A maximum power consumption of LRT equipment shall be defined, supplied by NSB	SYS3800

9.6 *Interface to MCL (RTG)*

[AD25] 020.10.40.05.00-0106 (Interface 0081): Interface Control Document Between Monitor and Control System and LO Reference and Timing Generation (RTG)

This interface details the requirements for interface between the RTG equipment hardware layer and the M&C software supervisory layers.

Table 13: RTG subsystem requirements tracked in ICD between MCL/HIL and RTG.

Network Time to MCL/HIL. Delivery of 1 PPS for support of network PTP via 10 GbE SFP+ transceiver	LRT1330

9.7 *Interface to FIB*

[AD26] 020.10.40.05.00-0120: Interface Control Document Between Central Fiber Infrastructure (FIB) and LO Reference and Timing Distribution (RTD).

Table 14: RTD subsystem requirements tracked in ICD to FIB.

Parameter	Req. #	Value	Traceability
Temperature range	LRT300	RTD Repeater equipment shall operate over a temperature range $+10\ C \leq T \leq +30\ C$	ENV0323, LRT0370
Temperature stability	LRT310	RTD Repeater equipment shall operate with temperature stability $< 0.5\ °C$ per 300s	ENV0324 LRT0380

9.8 *Interface to CSP*

[AD28] 020.10.40.05.00-0123: Interface Control Document Between: Central Signal Processing (CSP) and LO Reference and Timing Generation (RTG)

The most recent planning calls for CSP to get timing from the network and run on its own clock. Thus, this is a nonexistent interface.

Should CSP at the central facility require external time and frequency references from RTG then this ICD would define the mechanical and electrical definition of the interface.

In case of future need placeholder requirements are numbered as:

Table 15: RTD subsystem requirements tracked in ICD to CSP, if needed

CSP Input Frequency	LRT5310
CSP Input Frequency Accuracy	LRT5320
CSP Frequency Signal Type	LRT5330
CSP Frequency Signal Level	LRT5340
CSP Timing	LRT5350

Additional interface requirements would be detailed in the ICD for connector, cable and wire types and mechanical and thermal interfaces.

9.9 *Interface to ATF*

[AD30] 020.10.40.05.00-0125: Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* Antenna Time and Frequency (ATF)

This interface details the requirements for the Antenna Time and Frequency subsystem to receive time and frequency signal from the RTD subsystem, with specified accuracy, stability, level and signal types. Physical interfaces and full mechanical, thermal, and electronic interfaces are included.

A specific subset of these interface requirements (representing critical requirements) which will be fully defined in the ICD have been included in this document for tracking purposes and for completeness, as follows:

Table 16: RTD subsystem requirements tracked in ICD to ATF.

Parameter	Req. #	Value	Traceability
Precision Temperature range	LRT0320	FEC: Tmin < T < Tmin+5.0 deg C; Tmin=5-10 deg C	ENV0323,
ATF Frequency Input Tuning Resolution	LRT5250	If the ATF frequency input from RTD has a tunable component, then the frequency resolution shall follow the specifications in [AD30]	[AD30]
ATF Input Frequencies	LRT5260	2.9 GHz – determined by LO frequency plan	ATF1205, SYS0801, SYS0803, SYS0804, SYS0805, SYS0806, SYS0903, SYS0905
ATF Input Frequency Accuracy	LRT5270	Locked to central H-maser derived clock Phase measured by round-trip method for post-correction to < 42 fsec at 300 s (linear term removed) < 1250 fsec (absolute)	SYS1501 SYS1502 SYS5001 SYS1504 SYS1505
ATF Frequency Input Phase Noise	LRT5280	Less than 44 fsec integrated from 1 Hz to 1 KHz See Table 6	SYS5001, SYS1501, SYS1502, SYS1503, CAL0314, [AD30]
ATF Frequency Input Signal Type	LRT5290	The ATF frequency input signal type shall follow the specifications in [AD30]	[AD30]
ATF Frequency Input Signal Level	LRT5300	The ATF frequency input signal level shall follow the specifications in [AD30]	[AD30]

Additional interface requirements will be detailed in the ICD for connector types and mechanical and thermal interfaces.

9.10 Interface between RTG-RTD

[AD29] 020.10.40.05.00-0124: Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* LO Reference and Timing – Generation (RTG)

This interface details the requirements for the Antenna Time and Frequency subsystem to receive time and frequency signal from the RTD subsystem, with specified accuracy, stability, level and signal types. Physical interfaces and full mechanical, thermal, and electronic interfaces are included. A specific subset of these interface requirements (representing critical requirements) which will be fully defined in the ICD have been included in this document for tracking purposes and for completeness, as follows (see 7.2):

Table 17: RTD subsystem requirements tracked in ICD between RTG and RTD.

RTD Input Frequencies from RTG	LRT5210
RTD Input Frequency Accuracy from RTD	LRT5220
RTD Frequency Input Stability from RTD	LRT5230
RTD Frequency Input Signal Type from RTG	LRT5240
Timing from RTG to RTD	LRT1350

Additional interface requirements will be detailed in the ICD for connector types and mechanical and thermal interfaces.

9.11 Interface between RTD-AFD

[AD29] 020.10.40.05.00-0124: Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* Antenna Fiber Optic System

This ICD will describe the fiber optic interface requirements to RTD. This mainly consists of single fiber instances and will be designed in concert with the antenna electronics group.

9.12 Interface between RTD-WVR

[AD33] 020.10.40.05.00-0128: Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* Water Vapor Radiometer
This will detail requirements – if any – for LO reference or timing signals to the WVR

10 Technical Metrics

Technical Metrics are used throughout the project and should be monitored throughout project design and development. These parameters strongly influence the eventual effectiveness of the facility and are useful high-level metrics for trade-off decisions. Technical Performance Measures are a category of technical metrics defined at the subsystem level.

10.1 Technical Performance Measures

The Technical Performance Measures are requirements that closely impact the overall performance of the ngVLA system and are therefore considered of higher importance. The following Technical Performance Measures are identified for optimization and monitoring throughout the design phase.

Table 18: ngVLA Key Performance Parameters

Technical Performance Measures	Req. #	Traceability L1 Req. #
LO Phase Noise	LRT1240	SYS5001, SYS1503, CAL0314
LO Phase Drift	LRT1250	SYS5001, SYS1504, SYS1505

11 Verification

The design will be verified to meet the requirements by analysis (A), inspection (I), a demonstration (D), or a test (T), each defined below.

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

Verification by Inspection: The compliance of the developed system is determined by a simple inspection (of the design documentation or deliverables) or measurement.

Verification by Demonstration: The compliance of the developed feature is determined by a demonstration.

Verification by Test: The compliance of the developed subsystem with the specified performance shall be demonstrated by an acceptance test.

Multiple verification methods are allowed over the course of the design phase, although the primary (final) verification method is identified below.

11.1 Environmental Testing

The following environmental test conditions are defined:

Precision Operating Conditions: temperature range and max rate of change (POC):
corresponding to requirements ATF0320, ATF0330

- Critical requirements shall be tested at the minimum, median, and maximum temperature
- Stability testing shall be conducted under temperature rate of change defined for POC

Normal Operating Conditions: temperature range and max rate of change (NOC):
corresponding to requirements ATF0390, ATF0400

- Critical requirements shall be tested at the minimum, median, and maximum temperature
- Stability testing shall be conducted under temperature rate of change defined for NOC

Limit Operating Conditions (LOC):
Components exposed to Limit conditions during operations shall be tested for safe operation and for not incurring residual damage. Test profiles shall include:

- Start-up sequence from off to operational at minimum temperature (ATF0410) (at least 20 cycles).
- Extended operation (60 minutes) at maximum operating temperature (ATF0410)
- Maximum rate of change of temperature (up and down) between minimum and maximum values (at least 20 cycles) (ATF0420)

Transport conditions (Shock &Vibe)(SV):

- All LRUs that are transported shall be tested for not incurring residual damage at maximum transportation temperature over an extended period (at least 4 hours) (ATF0180)
- Prior to and after conducting SV testing, critical operational performance measures shall be tested (ATF0190, ATF0200)

11.2 Subsystem Verification Table

Req. #	Parameter/Requirement	A	I	D	T
LRT0110	Temperature	*			
LRT0160	Packaging for Transportation		*		
LRT0170	Solar Thermal Load	*			
LRT0180	Transportation Temperature	*			
LRT0190	General Vibration				*
LRT0200	Mechanical Shock				*
LRT0210	Packaging for Storage		*		
LRT0212	Storage temperature		*		
LRT0214	Storage humidity		*		
LRT0220	Altitude Range	*			
LRT0230	Seismic Protection	*			
LRT0240	Equipment Protection		*		
LRT0270	Temperature POC	**Test conditions for verification of performance requirements**			
LRT0280	Temperature Rate of Change POC				
LRT0290	Air Flow				
LRT0300	Temperature POC – Repeater station				
LRT0310	Temperature Rate of Change POC – Repeater station				
LRT0320	Temperature POC – Antenna				
LRT0330	Temperature Rate of Change POC - Antenna				
LRT0340	Temperature NOC – CEB				
LRT0350	Temperature Rate of Change NOC – CEB				
LRT0360	Air Flow - CEB				
LRT0370	Temperature NOC – Repeater				
LRT0380	Temperature Rate of Change NOC – Repeater				
LRT0390	Temperature NOC – Antenna				
LRT0400	Temperature Rate of Change NOC - Antenna				
LRT0410	Temperature LOC	*			
LRT0420	Standby			*	
LRT1100	Number of Antennas	*			
LRT1110	Antenna Stations Configuration	*			
LRT1120	Maximum Fiber Length	*			
LRT1130	Connected vs Independent Stations	*			
LRT1140	Number of Subarrays	*			
LRT1150	Subarray Creation and Modification	*			
LRT1200	LO Frequency				*** POC, LOC, SV**
LRT1205	Simultaneous LOs				***POC**
LRT1210	LO Frequency Offsets				*** NOC**
LRT1220	Tuning resolution				*** NOC**
LRT1225	LO Switching Speed				*** NOC**

Req. #	Parameter/Requirement	A	I	D	T
LRT1230	LO Amplitude				* **POC, LOC, SV**
LRT1235	LO Amplitude Stability				* **POC**
LRT1240	LO Phase Noise				* **POC**
LRT1250	LO Phase Drift				* **POC**
LRT1260	Digitizer Clock Phase Noise				* **POC**
LRT1270	Digitizer Clock Phase Drift				* **POC**
LRT1280	Return to Phase				* **NOC**
LRT1300	Timing to Output of RTD				* **POC**
LRT1305	System Domain Clock			***POC**	
LRT1310	Timing signal type to CSP			*	
LRT1320	Timing Signal level to CSP			*	
LRT1330	Timing to CSW				*
LRT1350	RTD Timing Stability from RTG				*
LRT1355	Time Accuracy - Station	*			
LRT1357	Antenna Timing				* **POC**
LRT1360	Subarray Timing				* **POC**
LRT1380	Timing to DBE				*
LRT1400	Standby Mode			*	
LRT1410	Automatic Initialization			*	
LRT1420	Operating Modes			*	
LRT1500	Spurious Narrowband Tones				* **NOC**
LRT1600	Spurious Signal Level Emission - Antenna Station				* **NOC**
LRT1602	Spurious Signal Level Emission - Central Building				* **NOC**
LRT1604	Spurious Signal Level Emission - Repeater Stations				* **NOC**
LRT1605	Spurious Emission impacting IRD				* **NOC**
LRT1608	Spurious Emission impacting LRT				* **NOC**
LRT1610	Emission Verification Frequencies		*		
LRT1620	Low Frequency Emission			*	
LRT1630	RFI Suppression Housings			*	
LRT1635	Self-Monitoring				* **NOC,LOC, SV**
LRT1640	LRU Alerts				* **NOC,LOC, SV**
LRT1650	High-Cadence Monitoring			*	
LRT1660	LRU Hot Swapping	*		*	
LRT1670	Remote Updates			*	
LRT1680	Automatic Configuration on Restart			*	
LRT1690	Front End Engineering Console		*		
LRT1700	M&C Commanded Reset for DC Powered Devices				* **NOC**
LRT1710	M&C Commanded Reset for AC Powered Devices				* **NOC**
LRT1800	Design Life	*			
LRT1810	Lifecycle Optimization	*			

Req. #	Parameter/Requirement	A	I	D	T
LRT1820	Parts Selection and Procurement Criteria		*		
LRT1830	Packaging Supply		*		
LRT1840	Quality Control of Deliverables		*		
LRT1850	Test Fixtures		*		
LRT1860	Testing of Software and Firmware		*		
LRT1870	AIV Software Tools		*		
LRT1880	Incremental Delivery to Operations		*		
LRT1900	Serial Numbers		*		
LRT1910	Version Control for Software and Firmware		*		
LRT1920	Configuration Retrieval			*	
LRT1930	Physical Tracking		*		
LRT1940	Remote Identification			*	
LRT1950	Documentation		*		
LRT2200	Analog shielding	*	*		
LRT2210	Digital shielding	*	*		
LRT2220	Commercial equipment		*		
LRT2230	Conducted Immunity, Testing				* **NOC**
LRT2240	Electrostatic Discharge, Testing				* **NOC**
LRT2250	Hi-Speed Design	*			
LRT2260	ESD, Storage and Shipment		*		
LRT2300	Reliability Analysis	*			
LRT2305	Availability	*			
LRT2310	Mean Time Between Failures	*			
LRT2320	Mean Time between Maintenance	*			
LRT2330	Array Element MTTR	*			
LRT2340	Modularization		*		
LRT2350	Spares Planning	*			
LRT2360	Transfer of Deliverables		*		
LRT2370	Automated Failure Reporting			*	
LRT2380	LRU Interchangeability		*		
LRT2390	Identify Failures Physically			*	
LRT2400	Report Predicted Failures			*	
LRT2410	Failure Information Source		*		
LRT2420	Robustness Analysis	*			
LRT3200	Printed Circuit Boards- Standards		*		
LRT3210	Printed Circuit Board-Design		*		
LRT3220	Soldered Electrical Connections		*		
LRT3300	Power Supply noise and stability		*		
LRT3310	DC Voltages available		*		
LRT3320	PSU Voltage Tolerance		*		
LRT3330	LRU Physical Ground		*		
LRT3340	Power Supply Returns Separate from Ground				* **NOC**
LRT3350	Overcurrent Protection		*		

Req. #	Parameter/Requirement	A	I	D	T
LRT3360	Overcurrent Protection Device Monitoring			*	
LRT3370	Thermal Protection		*		
LRT3380	Thermal Protection Monitoring			*	
LRT3390	Thermal Analysis	*			
LRT3400	Power On Indicators			*	
LRT3410	Battery Use		*		
LRT3420	Transient Protection		*		
LRT3500	Wiring Documentation and Labeling		*		
LRT3510	DC voltage Wire Colors		*		
LRT3520	AC power wiring colors		*		
LRT3530	Wire and Cable installation		*		
LRT3540	Connector Documentation and Labeling		*		
LRT3560	Connector Selection		*		
LRT3570	Connectors for Hot Swap		*		
LRT3580	Connector Design for Ease of Operation		*		
LRT3590	Crimped Connectors		*		
LRT3600	Connector Type, Retention, and Locking		*		
LRT3700	Metalwork		*		
LRT3710	Lighting		*		
LRT3720	Fasteners		*		
LRT3730	LRUs, mechanical		*		
LRT3740	LRU documentation and dimensions		*		
LRT4200	Safety Specification	*			
LRT4210	Security Specification	*			
LRT4220	Cybersecurity Specification	*			
LRT4230	Hazard Analysis	*			
LRT4240	LRU Weight Labels		*		
LRT4250	Hot Connect & Disconnect Warning Labels		*		
LRT4260	Electrical and Optical Label Safety Standards		*		
LRT4270	Design for Optical Safety	*			
LRT4280	Optical Safety Labels		*		
LRT4290	Connectors for Hot Swap		*		
LRT4300	No Exposed Live Terminals		*		
LRT5210	RTD Input Frequencies from RTG			*	
LRT5220	RTD Input Frequency Accuracy from RTG				*
LRT5230	RTD Frequency Input Stability from RTG				*
LRT5240	RTD Frequency Input Signal Type from RTG			*	

Req. #	Parameter/Requirement	A	I	D	T
LRT5250	ATF Frequency Input Tuning Resolution				*
LRT5260	ATF Input Frequencies			*	
LRT5270	ATF Input Frequency Accuracy				*
LRT5280	ATF Input Frequency Noise				*
LRT5290	ATF Frequency Input Signal Type			*	
LRT5300	ATF Frequency Input Signal Level			*	
LRT5310	CSP Input Frequency			*	
LRT5320	CSP Input Frequency Accuracy				*
LRT5330	CSP Frequency Signal Type			*	
LRT5340	CSP Frequency Signal Level				*
LRT5500	LRT Space Allocation by NSB		*		
LRT5510	Grounding Point		*		
LRT5520	Equipment Rack Mounting Interface				*
LRT5530	Cable Trays		*		
LRT5540	LRT AC Power provided by NSB		*		
LRT5550	LRT UPS Power provided by NSB		*		
LRT5560	LRT Maximum power consumption in CEB			*	

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
AE	Antenna Electronics
AFD	Antenna Fiber Distribution subsystem
AIV	Acceptance, Integration, and Verification
ATF	Antenna Time and Frequency
AV	Allan Variance
BMR	Bins, Modules, and Racks subsystem
CDR	Conceptual Design Review
CEB	Central Electronics Building
CI	Configuration Item
CID	Configuration Item Data
CoDR	Conceptual Design Review
COTS	Commercial-off-the-Shelf
CSP	Central Signal Processing
CSPT	CSP and Timing IPT
CSW	Computing and Software
DBE	Digital Backend
DC	Direct Current
EEC	Antenna Electronics Environmental Control subsystem
EIRP	Emitted Isotropic Radiated Power
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge
FDR	Final Design Review
FED	Front End subsystem
FIB	Central Fiber Infrastructure
GHz	Gigahertz
HIL	Hardware Interface Layer
HVAC	Heating, Ventilation, and Air Conditioning
I/F	Interface
I/O	Input-Output
ICD	Interface Control Document
IPC	Institute for Printed Circuits
IPT	Integrated Product Team
IRD	Integrated Receiver Digitizer
KPP	Key Performance Parameter
LBS	Long Baseline Subarray
LED	Light Emitting Diode
LO	Local Oscillator
LOC	Limit Operation Conditions
LRT	LO Reference and Timing
LRU	Line Replaceable Unit

Acronym	Description
M/C	Monitor and Control
MCL	Monitor and Control subsystem
MID	the MID array of ngVLA+F47
MOE	Measure of Effectiveness
MOP	Measure of Performance
MTBF	Mean Time Between Failure
MTTM	Mean Time to Maintenance
MTTR	Mean Time to Repair
ngVLA	Next Generation Very Large Array
NOC	Normal Operation Conditions
NRAO	National Radio Astronomy Observatory
NSB	ngVLA Site buildings
OLED	Organic Light Emitting Diode
PBS	Product Breakdown Structure
PCB	Printed Circuit Board
PDF	Portable Document Format
PDU	Power Distribution Unit
PE	Project Engineer
POC	Precision Operating Conditions
PPS	Pulse per second
PSU	DC Power Supply subsystem
PTP	Precision Time Protocol
RD	Reference Document
RFI	Radio Frequency Interference
RH	Relative Humidity
RTD	Reference Timing and Distribution
RTG	Reference Timing Generation
RTP	Round Trip Phase
TBC	To Be Confirmed
TBD	To Be Determined
TPM	Technical Performance Measure
UPS	Uninterruptible Power Supply
WVR	Water Vapor Radiometer

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