



ngVLA LO Reference and Timing: Preliminary Technical Specifications	Date: TBD
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## ***ngVLA LO Reference and Timing: Preliminary Technical Specifications***

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## I INTRODUCTION

### 1.1 Purpose

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

### 1.2 Scope

This document includes descriptions of requirements that will be enforced at an interface with some other part of the ngVLA, and this description will later be superseded by a formal interface control document. This document does not detail the design, planning, test and measurement, or performance verification of the LO reference and timing.

This document may be superseded in the future after breaking the present extent of the LO Reference and Timing into two or more subsystems, and remapping the requirements accordingly.

## 2 RELATED DOCUMENTS & DRAWINGS

### 2.1 Applicable Documents

The following documents are applicable to this requirements document.

Reference No.	Document Title	Rev / Doc. No.
AD01	ngVLA Preliminary System Requirements	V3, 5/10/2018
AD02	ngVLA Environmental Specification	020.10.15.10.00-0001-SPE, v3, 05-09-2018
AD03	ngVLA System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ, v3, 05-09-2018
AD04	Inclusion of the “Long Baseline Major Option” into the ngVLA Baseline Design	020.05.60.01.01-0002-ECO, v 0.05, Aug-02-2018

### 2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev / Doc. No.
RD01	A Next Generation Very Large Array	<a href="http://adsabs.harvard.edu/abs/2017arXiv171109921M">http://adsabs.harvard.edu/abs/2017arXiv171109921M</a>
RD02	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK, 04-27-2018
RD03	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK, 04-27-2018



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RD04	ngVLA memo 43 (B. Mason, R. Selina, A. Erickson, E. Murphy)	V3, April 18, 2018
RD05	ngVLA Configuration rev B 4/24/2018	<a href="http://ngvla.nrao.edu/page/tools">http://ngvla.nrao.edu/page/tools</a>
RD06	ngVLA CSP Preliminary Technical Specifications	020.40.00.00.00-0001-SPE, 03-23-2018, Version: 05
RD07	ngVLA Integrated Receivers and Downconverters: Preliminary Technical Specifications/Requirements	020.30.15.00.00-0001-REQ-05, v0.5, 05-03-2018

### 3 OVERVIEW

#### 3.1 Document Outline

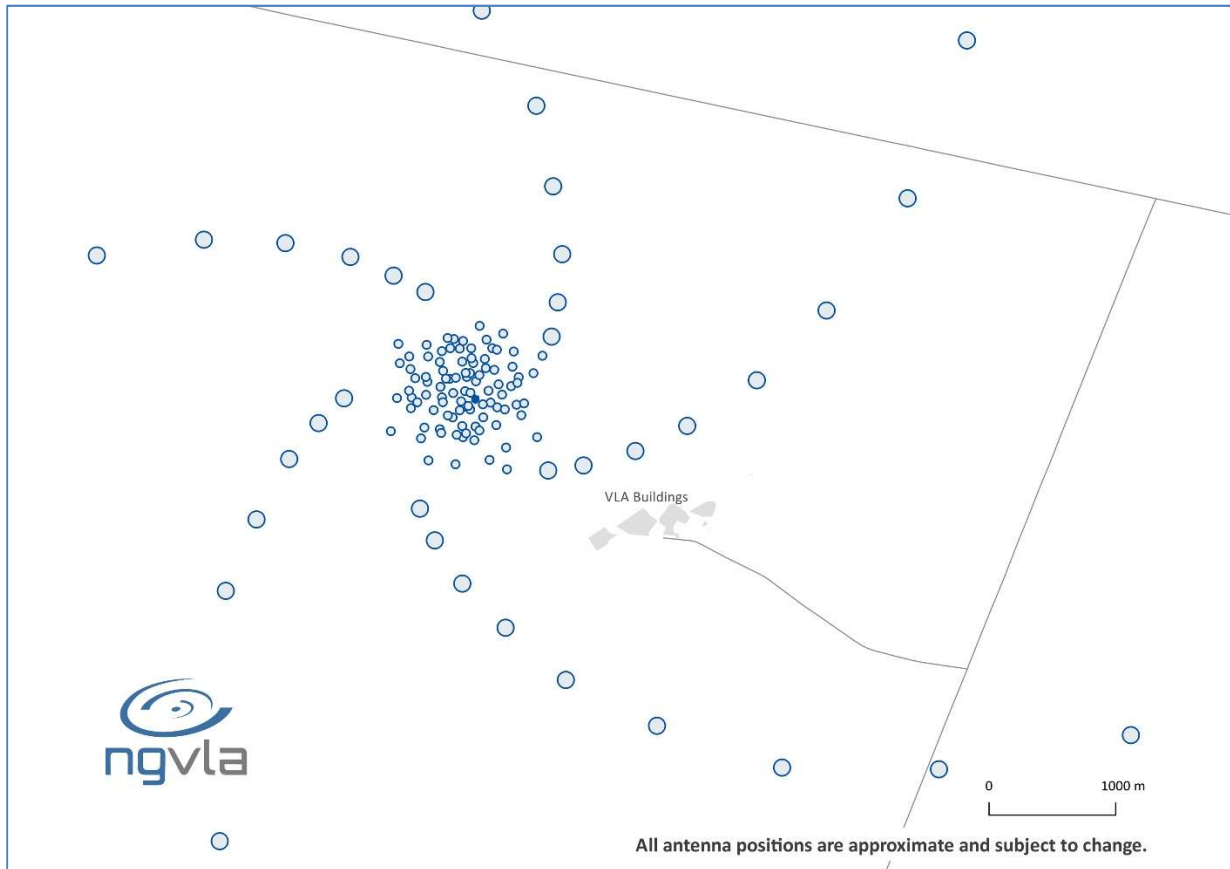
This document presents the technical specifications of the ngVLA LO Reference and Timing Work Element.

#### 3.2 Project Background

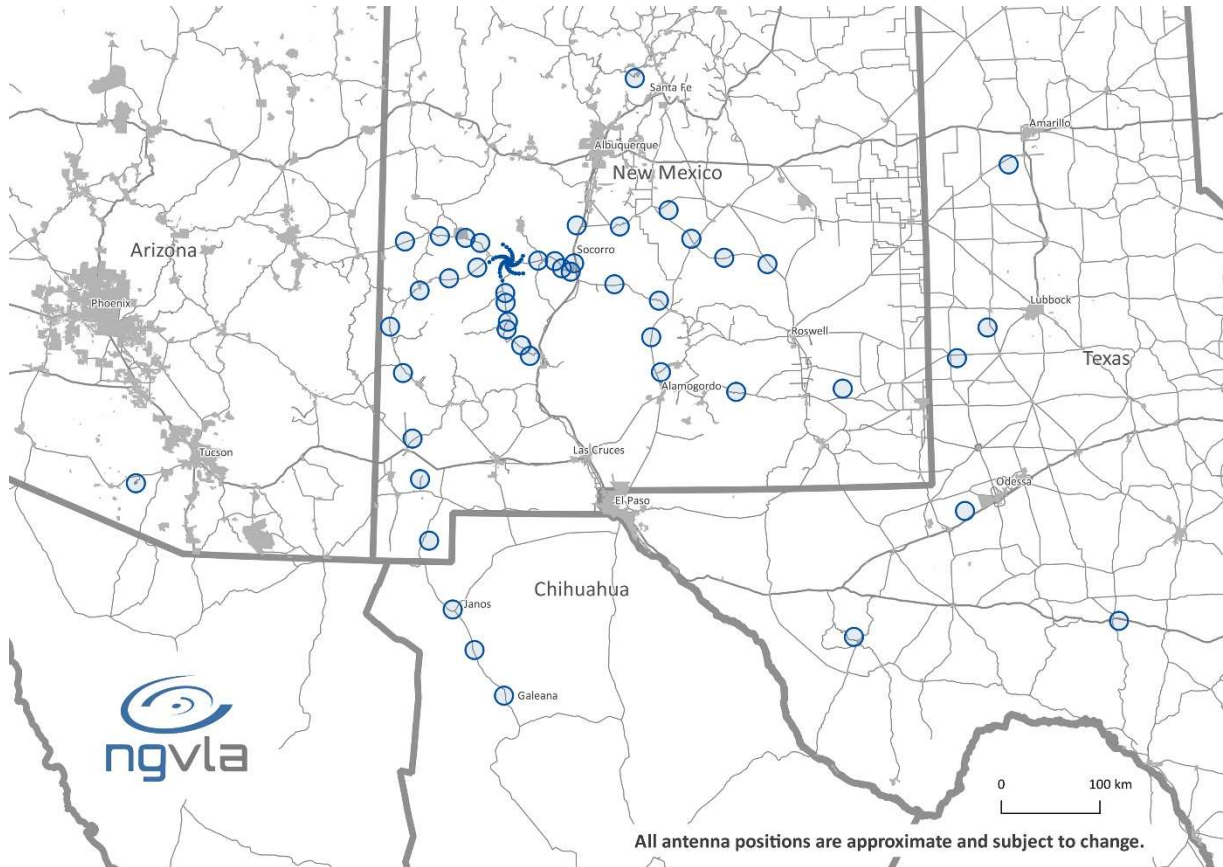
The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will include: a main array of approximately 214 reflector antennas each of 18 meters diameter [RD01], a Short Baseline array (SBA) with 19 6-m antennas [RD 04], and a Long Baseline Array (LBA) with 30 additional 18m antennas on very long baselines [AD04].

#### 3.3 General LO Reference and Timing Description

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



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



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



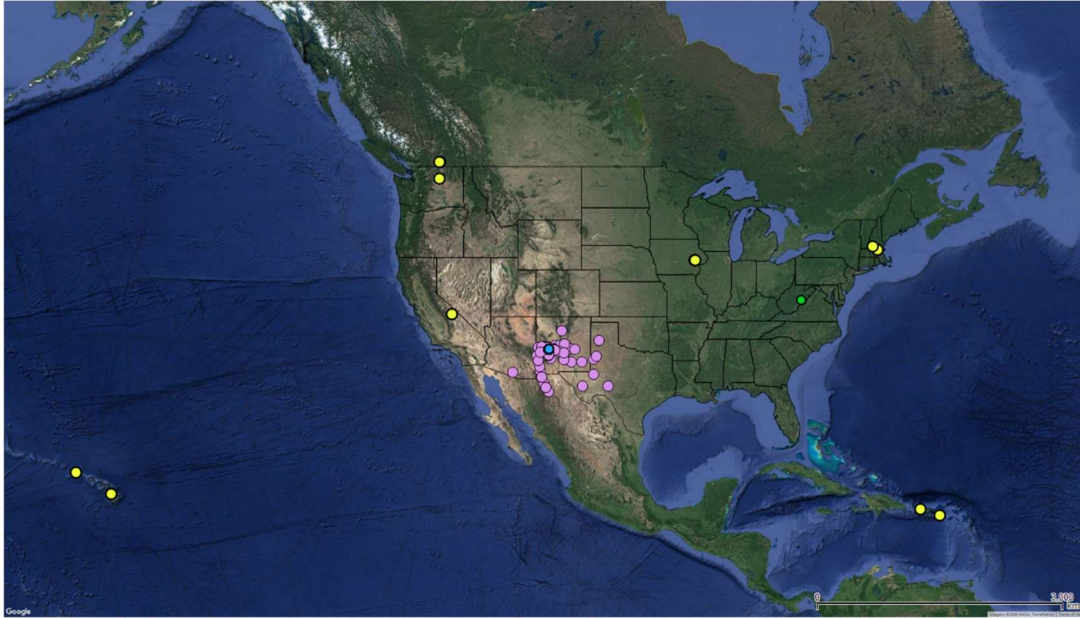


Figure 3 - ngVLA LBA Sites shown in yellow. GBT site shown in green. ngVLA core and main array in blue and purple respectively. 30 antennas are included in the LBA configuration, distributed per the table below.

Antenna Qty	Location	Possible Site Notes	Distance from Array Center (km)
3	Puerto Rico	Arecibo Observatory.	4370
3	St. Croix	Existing VLBA site.	4580
3	Kauai, Hawaii	Kokee Park Geophysical Observatory.	5260
3	Hawaii, Hawaii	<u>NOT</u> on MK. New site.	<u>5000</u>
2	Hancock, NH	Existing VLBA site.	3200
3	Westford, MA	Haystack Observatory.	3240
2	Brewster, WA	Existing VLBA site.	1870
3	Penticton, BC	Dominion Radio Astrophysical Observatory	1990
4	North Liberty, IA	Existing VLBA site.	1610
4	Owens Valley, CA	Existing VLBA site.	1056

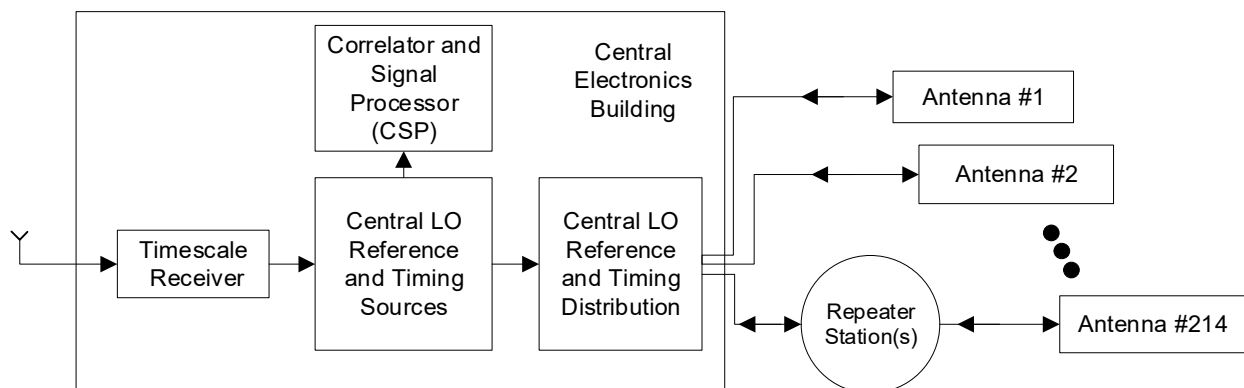
Table I –List of LBA sites



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The LO Reference and Timing work element is responsible for supplying accurate and reliable local oscillator, sampler clock, and timing references to the antenna stations and the central signal processor. The block diagram shown in Figure 4 illustrates the major functional blocks of the LO reference and timing. The references are generated and synchronized in the central building, and a frequency reference and timing signal are provided to the central signal processor. The references are then distributed with all necessary amplification, buffering, splitting, etc. and the required signals are transmitted to each antenna. This is a very generalized functional diagram, and the following assumptions and caveats are made:

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



**Figure 4 - Block Diagram of LO Reference and Timing**



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### 3.4 Summary of LO Reference and Timing Requirements

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

#### 3.4.1 General Requirements

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

Table 2 – General System Requirements

#### 3.4.2 LO and Digitizer Frequency Requirement

LO and Digitizer Frequency Requirement			
Parameter	Summary of Requirement		Reference
Required Nominal LO Frequencies	156.25 MHz Sampler Reference	156.25 MHz	LRT-0080
	156.25 MHz Sampler Reference	156.25 MHz	LRT-0090
	Band 2H/3L 2SB LO	14.0 GHz	LRT-0100
	Band 3H 2SB LO	21.0 GHz	LRT-0110



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	Band 4 2SB LO1	23.6 GHz	LRT-0120
	Band 4 2SB LO2	30.6 GHz	LRT-0130
	Band 5 A1/B1 2SB LO1	33.6 GHz	LRT-0140
	Band 5 A2/B2 2SB LO2	40.6 GHz	LRT-0150
	Band 5 A3/B3 2SB LO3	47.6 GHz	LRT-0160
	Band 6 A1/B1 2SB LO1	70 GHz	LRT-0170
	Band 6 A2/B2 2SB LO2	84 GHz	LRT-0180
	Band 6 A3/B3 2SB LO3	98 GHz	LRT-0190
	Band 6 A4/B4 2SB LO4	112 GHz	LRT-0200
	WVR LO1	18 GHz	LRT-0210
	WVR LO2	21 GHz	LRT-0220
	WVR LO3	24 GHz	LRT-0230
	WVR LO4	27 GHz	LRT-0240
Frequency Offset	All Local Oscillator bands	+ or - 2 GHz	LRT-0250
Simultaneous LOs	Two		LRT-0260
Self-Generated Spurious Signal Power Level	Self-generated signals shall not exceed -43dB relative to the system noise level on cold sky over a 1 MHz bandwidth.		LRT-0270
Sampler Offset	The provision of frequency offsets and/or sampler clock offsets at the antenna level is highly desired to provide additional attenuation of spurious signals		LRT-0280

**Table 3 – LO and Digitizer Frequency Requirements**

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

### 3.4.3 LO and Timing Phase Stability and Accuracy

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

**Table 4 – LO and Timing Phase Stability and Accuracy**

### 3.4.4 Design and Engineering Requirements



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

**Table 5 – Design and Engineering Requirements**

### 3.4.5 Reliability and Lifetime Requirements

Antenna Maintenance Interval	Central LO, LO Reference and time distribution shall be designed with a preventative maintenance interval of no less than 4 years.	LRT-0390
LRU MTBF	Portions of the LO reference timing and distribution that are located at an antenna shall contribute to an overall antenna MTBF according to a budgeted allocation, such that the number of antenna failures is less than 50% of the array elements per year.	LRT-0400
Antenna System Availability	Portions of the LO reference timing and distribution that are located at an antenna shall contribute by MTBF allocation to an overall minimum 90% availability for all antenna systems combined.	LRT-0410
Centralized LO Availability	Portions of the LO reference timing and distribution that are centrally located shall contribute by MTBF allocation to an overall minimum 95% availability	LRT-0420
Design Life	The LO Reference and Timing system shall be designed for an expected operational life of 20 years.	LRT-0430

**Table 6 – Reliability and Lifetime Requirements**

### 3.4.6 Interface Requirements

There follows a preliminary list of interface requirements. These interface requirements have been



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developed with reference to **preliminary** designs for the front end electronics, pedestal electronics, and Central Signal Processor.

### 3.4.6.1 Interface to Monitor and Control

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

### 3.4.6.2 Interface to Central Electronics Building

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

Table 7 – Interface to Central Electronics Building

### 3.4.6.3 Interface to Central Signal Processor

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

Table – Interface to Central Signal Processor

### 3.4.6.4 Interface to Site

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



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**Table 8 – Interface to Site**

### 3.4.6.5 Interface to Antenna Pedestal

With reference to [RD 02], three LRUs are detailed as follows:

- L503 Reference Receiver, Generator, and Distribution
- L502 Local RTP Monitor
- L500 LO/Sample Clock Generator.

The functionalities of **these LRUs taken together** have interfaces with: (a) the Site/Network connector (b) DBE/DTS subsystem (c) Front End connector (d) Antenna Pedestal. In the table below, the functionalities of these three modules taken together is referred to as the **Reference and Time Receiver (RTR)**. Internal interfaces to the three modules are not considered here.

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

**Table 9 – Interface to Antenna Pedestal**

Note that the designations of L500, L502, L503, and the Reference and Time Receiver can be considered placeholder designations. However, the interfaces detailed here will be associated with some equipment of the antenna-located LO Reference and Timing System.

### 3.4.6.6 Interface to Front End Enclosure

The following abbreviations are used:

- FES = SA501 Front End System
- WVR = SA502 Water Vapor Radiometer
- RTL = Round-trip Loopback

Interface	Interface Summary	ICD Reference
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Interface to Front End Enclosure	LO Reference and Timing Interface to Front End System: Local Oscillators	ICD-FES-LRT-0010
	LO Reference and Timing Interface to Front End System: Digitizer Clock(s)	ICD-FES-LRT-0020
	LO Reference and Timing Interface to Water Vapor Radiometer: Local Oscillators	ICD-WVR-LRT-0010
	LO Reference and Timing Interface to Water Vapor Radiometer: Digitizer Clock(s)	ICD-WVR-LRT-0020
	LO Reference and Timing Interface to Fiber Round Trip Phase loopback	ICD-RTL-LRT-0010

**Table 10 – Interface to Front End Enclosure**

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

## 4 FUNCTIONAL AND PERFORMANCE REQUIREMENTS

### 4.1 General Requirements

Table 11 summarizes the array configuration in terms of number of antennas and distance from array center.

**Table 11- Summary of Array Configuration: Number of Antennas and Distance from Array Center**

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





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#### 4.1.1 Number of Antennas

Parameter	Req. #	Value	Traceability
Maximum number of antennas	LRT-0100	The LRT shall support as many antennas as required for the NGVLA design. As shown in Table 11 that is 263 at this time, consisting of 214 antennas in the main array [RD 01], 19 additional 6m small baseline array antennas [RD 04], and 30 antennas in the long baseline option [AD 04].	N/A

There is not a higher-level requirement for the number of antennas in [AD01] although a baseline of 214 18-m and 19 6-m have been referenced [RD01] and [RD04]. Additionally, in August of 2018 a change request was approved to include 30 additional 18m antennas on long baselines [AD 04].

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

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

#### 4.1.2 Maximum fiber length

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

This flows down from the systems requirement for maximum baseline length of greater than 650 km with 1000 km desirable. However, baseline length refers to distance between two antennas, and in an array with a centrally located reference and timing generation the straight line distance to the furthest antenna is always less than the maximum baseline. For practical reasons fiber to antennas must be run along roadways and in general this means the fiber lengths are configuration dependent. The most recent configuration set forth [RD 05] will have a maximum fiber length of approximately 1000 km. For LBA, it is assumed that the LO is not centrally generated although this would be allowed if it were technically practical.

#### 4.1.3 Number of Subarrays

Parameter	Req. #	Value	Traceability
Number of subarrays	LRT-0030	$\geq 10$	SYS0601



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

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

#### 4.1.4 Phase Preservation

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

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

#### 4.1.5 Band Switching

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

The system level requirement is for band switching between receiver bands, which must take place within 20 seconds. The requirement of 2 seconds is set forth here arbitrarily so that the LO and digitizer frequency switching is much faster than the receiving band. It should be a design goal to make this switching time as fast as practical.

#### 4.1.6 Phase Calibration Efficiency

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

This does not impact the LO and timing directly. The main effect of this requirement may be to



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increase the length of time on source between phase calibrations. This needs to be factored in when setting the requirement and design for the LO and timing stabilities on longer timescales. Additionally, any overhead due to the electronics (i.e. – band switching, settling time, etc.) that could be part of a calibration cycle should be minimized.

#### 4.1.7 Compact Core

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

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

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

## 4.2 LO and Digitizer Frequency Requirements

### 4.2.1 Required Nominal LO Frequencies

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

The set of required LO and digitizer frequencies can be traced at a high level to the systems requirements referenced here, but the specific set of frequency and bands devolves from [RD03] and [RD 07]. Insofar as this represents a preliminary or reference design, the frequency plan may be subject to change to accommodate changes of these designs. The LO reference and Timing design should be able to provide a set of fixed frequency LOs but not be constrained by the particular values, i.e. – a *flexible* design is desired.



#### 4.2.2 Frequency Offset

Parameter	Req. #	Value	Traceability
Frequency Offset	LRT-0250	+ or - 2GHz	SYS0806

To remove gaps in frequency coverage, a fixed frequency offset to the nominal LO frequency of + or - 2 GHz is required. See also [RD 07].

#### 4.2.3 Number of Simultaneous LOs

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

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

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

#### 4.2.4 Incoherent Spurious

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

#### 4.2.5 Sampler Offset

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

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

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



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### 4.3 LO and Digitizer Phase Stability and Accuracy

#### 4.3.1 Phase Drift

Parameter	Req. #	Value	Traceability
Phase Drift	LRT-0300	LO < 84 fsec rms Digitizer < 42 fsec	SYS1501

Table 3 of [AD01] lists phase drift contributions of 42 fsec each from five sources: antenna structure, 1<sup>st</sup> LO, Digitizer, Antenna round trip phase system, and LO distribution system. The output of the LO in the front end enclosure represents contributions from all of these except for the antenna structure. Therefore the RSS rms phase drift allowable for the LO is  $\sqrt{4 * 42^2} = 84$  fsec. If either the LO distribution or the antenna distribution is done open-loop, then the requirement must be met after corrections are applied. The digitizer requirement is 42 fsec which refers “effective” delay added at the maximum LO frequency of 112 GHz, or 0.03 radians applied at the digitizer frequency.

#### 4.3.2 Phase Noise or Jitter

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

The LO phase noise shall be ensured from a 1 Hz offset frequency to the highest significant frequency where jitter is contributing, ~ 1-10 MHz

The jitter is again applicable at the highest LO frequency, 112 GHz, so 0.05 radians at the digitizer frequency. For instance, at a digitizer clock frequency of 7 GHz this is 1.2 psec jitter.

#### 4.3.3 Timing Accuracy

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

From [AD01]:

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



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#### 4.3.4 VLBI Phase

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

#### 4.4 Design and Engineering Requirements

The following requirements on the design of the LO Reference and Timing are presented as direct flowdown from the systems requirements [AD 01].

Parameter		Req. #	Traceability
Fixed Analog Tunings	LRT-0340	Minimize analog tunings	SYS0906
Modularization	LRT-0350	The LO reference timing and distribution electronics and assemblies shall be modularized into Line Replaceable Units (LRUs) to facilitate maintenance.	SYS2403
Sub-system self-monitoring	LRT-0360	The LO Reference and Timing LRUs shall measure, report and monitor a set of parameters that allow for determination of its status and may help predict or respond to failures.	SYS2701
Network Hardening	LRT-0370	LO Reference and Timing systems should be built to withstand expected hack attempts. Should only respond to commands from authorized sources.	SYS2702
Cost Optimization	LRT-0380	LO Reference and Timing system shall be designed to minimize total life-cycle costs over the projected design life.	SYS2704

#### 4.5 Reliability and Lifetime

The following requirements on the design of the LO Reference and Timing are presented as direct flow down from the systems requirements [AD 01].

Development of a design that meets the functional requirements must prioritize highly reliable components and assemblies and be designed for extended lifetime.

Parameter		Req. #	Traceability
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Antenna Maintenance Interval	LRT-0390	Central LO, LO Reference and time distribution shall be designed with a preventative maintenance interval of no less than 4 years.	SYS2401
LRU MTBF	LRT-0400	Portions of the LO reference timing and distribution that are located at an antenna shall contribute to an overall antenna MTBF according to a budgeted allocation, such that the number of antenna failures is less than 50% of the array elements per year.	SYS2402
Antenna System Availability	LRT-0410	Portions of the LO reference timing and distribution that are located at an antenna shall contribute by MTBF allocation to an overall minimum 90% availability for all antenna systems combined.	SYS2901
Centralized LO Availability	LRT-0420	Portions of the LO reference timing and distribution that are centrally located shall contribute by MTBF allocation to an overall minimum 95% availability	SYS2602
Design Life	LRT-0430	The LO Reference and Timing system shall be designed for an expected operational life of 20 years.	SYS2703

## 5 INTERFACE REQUIREMENTS

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

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

- Monitor and Control
- Central Electronics Building
- Central Signal Processor
- Site



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- Antenna Pedestal
- Front End Enclosure

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

### 5.1 Interface to Monitor and Control

### 5.2 Interface to Central Electronics Building

### 5.3 Interface to Central Signal Processor

### 5.4 Interface to Antenna Pedestal

### 5.5 Interface to Front End Enclosure

The following abbreviations are used:

- FES = SA501 Front End System
- WVR = SA502 Water Vapor Radiometer
- RTL = Round-trip Loopback

Interface	Interface Summary	ICD Reference
Interface to Front End Enclosure	LO Reference and Timing Interface to Front End System: Local Oscillators	ICD-FES-LRT-0010

Parameter		Req. #	Traceability
Local Oscillator Spurious Signal Level	LRT-0390	LO spurious < -140 dBc, See discussion below	LRT0270, SYS2104

The following communication from Matt Morgan details logical background for this (preliminary) requirement for the spurious level at the interface between the LO and the RF mixer input in the integrated downconverter module.

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

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

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





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

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

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

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

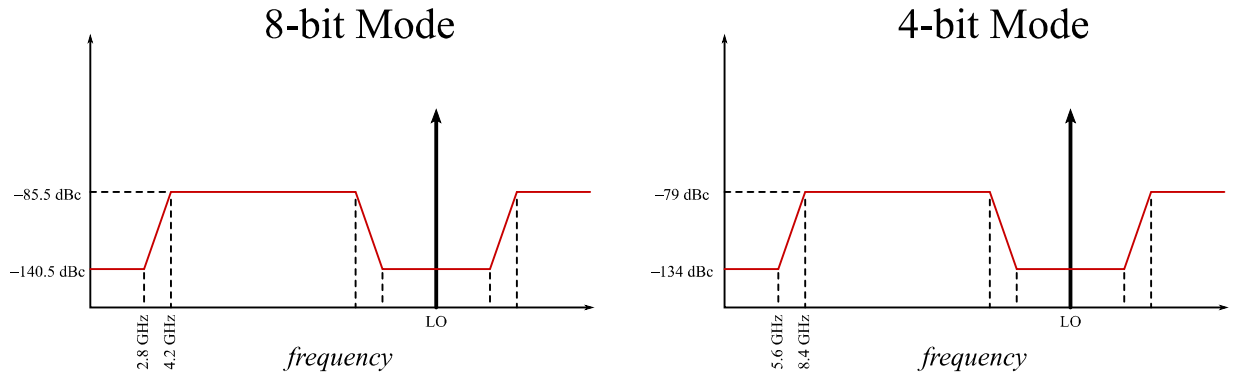
The signal path in the IRD modules is still under development, and will vary from band to band, but a typical number for the IF gain would be 45 dB, and 10 dB for the mixer conversion loss. This would make the expected power spectral density at the input to the mixer to be

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

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

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

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



These are scary numbers! There some caveats that may help a little bit:

1. I have not accounted for added noise in the gain stages after the mixer (just the gain). Unfortunately, this is unlikely to be more than a percent or so, otherwise the IF stages would substantially impact the sensitivity of the receiver.
  2. I have not accounted for LO noise (or in this case, sideband spur) suppression due to the mixer being balanced. Assuming the mixer is single balanced (very likely), suppression could be 15-20 dB. That will only help in the IF range around the LO, though, outside of that the hybrid will not provide the correct phase shifts.
  3. For the spectrum further out than the IF limit, other IF components will be rolling off than just the anti-aliasing filters. This could give you another 10-20 dB suppression.
- So overall, the numbers could be about 20 dB better than the masks above, but I don't see how it could be any better than that.



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## 6 ENVIRONMENTAL REQUIREMENTS

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

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

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

## 7 RFI and EMC REQUIREMENTS

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

## 8 Appendix

### 8.1 System Requirements

A subset of the system technical requirements filtered for requirements that directly or indirectly impact the LO reference and timing requirements are listed below. These are taken from [AD01].

Parameter	Req. #	Value	Comment
<b>General System Requirements</b>			
Sub-Array Capabilities	SYS0601	System shall be divisible into a minimum of 10 sub-arrays for operation, calibration and maintenance purposes. It is a goal that all functional capabilities listed above should be available in a sub-array.	Features of the Centrally-located LO Reference and timing that depend on LO and digitizer frequency must be appropriately switched or



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			multiplexed (no impact if central LO and timing is "sky frequency agnostic")
Phase Preservation	SYS0602	It shall be possible to preserve electronic phase when adding and/or subtracting an element from a sub-array.	
Band Switching Time	SYS0908	Switching between any receiver bands shall be achievable within 20 seconds. Goal of 10 seconds.	Impact only if there is a slow tuning element in the LO and timing
Phase Calibration Efficiency	SYS1068	Phase calibration overheads shall not exceed 100% of on-source time for observations at 116 GHz when operating in the precision operating conditions.	Secondary impact only. Choice of calibration cycle time may impact LO round trip timing specification or design choice
Longest Baseline	SYS1301	The longest baseline between antennas shall be greater than 650km. It is a goal to have baselines longer than 1000km.	LO reference and timing accuracy and power levels must meet specifications over maximum distances with appropriate power and noise budgeting
Compact Core	SYS1305	The system shall include a compact core. Approximately 40% of the array collecting area shall be located within 1.25km of the array vertex.	Possible design impact if cost-performance optimization dictates two-tiered design: one for close-in antennas and one for far-out antennas
<b>System Requirements Impacting LO and Digitizer Frequency</b>			
System Frequency Range	SYS0801	System frequency range shall cover the 1.2 to 50 GHz and 70-116 GHz windows.	LO frequencies must cover this band as needed after design choices are made for RF band breakdowns
Freq. Span A:	SYS0803	1.2-8 GHz	
Freq. Span B:	SYS0804	8-50 GHz	
Freq. Span C:	SYS0805	70-116 GHz	



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Continuity of Frequency Coverage	SYS0806	There shall be no gaps in frequency coverage within each frequency span (A, B, C) listed above. It is a goal that any band edges shall include 1% overlap.	LO and sampler design and frequency plan must meet this requirement. For instance, frequency offsetting capability of the LO could fill in baseband frequency gaps
Front End Bandwidth Ratio	SYS0901	A minimum bandwidth ratio of 1.5:1 is required, with a 4:1 goal over Frequency Span A	Possible impact to LO tunability (though early design emphasizes fixed LO with wideband digitizers)
Instantaneous Digitized Bandwidth	SYS0902	It is desirable for the system to digitize the full bandwidth of each receiver band.	Possible impact if multiple simultaneous LOs needed for a band
Total Instantaneous Processed Bandwidth	SYS0903	The system shall transmit and process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	
Frequency Tunability	SYS0905	It shall be possible to select discontinuous sub-bands for transmission and processing. I.e., transmitting both the top and bottom of the 70-116 GHz band.	
Self-Generated Spurious Signal Power Level	SYS2104	Self-generated signals shall not exceed -43dB relative to the system noise level on cold sky over a 1 MHz bandwidth.	May require LO or sampler offsetting
Frequency or Clock Offsets	SYS2105	The provision of frequency offsets and/or sampler clock offsets at the antenna level is highly desired to provide additional attenuation of spurious signals.	
<b>System Requirements Impacting LO and Timing Phase Stability and Accuracy</b>			
Delay/Phase Variations Magnitude	SYS1501	The delay variations caused by the instrument should be smaller than those caused by the natural environment for at least 90% of the time. These natural limits are those imposed by the residual delay fluctuations of the troposphere after all available corrections (e.g., fast switching, WVVR, etc.) have been applied.	See also [AD 01] Table I for allocations of phase drift
SNR Loss to Delay/Phase	SYS1502	The instrumental delay/phase noise not degrade overall system SNR by more than	See also [AD 01] Table I for



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Variations		1%.	allocations of phase noise/jitter
Phase Noise Specification	SYS1503	< 132 fsec	Flows down from SYS1502
Phase Drift Specification	SYS1504	< 95 fsec over 300 sec, goal over 1000 sec	Flows down from SYS1501
Temporal Accuracy	SYS2002	Data time-stamps shall be accurate to better than 20 usec.	Note: may be changed to 10 nsec, goal of 1 nsec
VLBI Capabilities	SYS0502	It is desirable, but not required, to interface with network-connected VLBI stations as real-time correlated elements of the ngVLA.	VLBA Integration / ngVLB Option
System Requirements Impacting LO and Timing Amplitude Stability			
Gain Stability for Total Power Measurements	SYS1601	System dG/G post-calibration shall not exceed 10-3 over a 20-minute period. Goal to not exceed 10-4. (TBC)	LO amplitude stability must be stable over time, temperature, and antenna orientation
Gain Stability for Interferometric Observations	SYS1602	System dG/G post-calibration shall not exceed 10-4 over a 20-minute period. (TBC)	
Gain Variations with Antenna Pointing Angle	SYS1603	TREC shall vary by no more than 0.1% over 1 hr in the precision operating conditions defined in AD 09.	
System Temperature Stability over Time	SYS1604	TREC shall vary by no more than 0.1% over 1 hr in the precision operating conditions defined in AD 09.	
System Temperature Variations with Antenna Pointing Angle	SYS1605	TSPILL and TREC shall vary by no more than 1.5K combined, over the full range of antenna elevation in the precision operating conditions defined in AD 09.	
System Requirements on Design and Engineering			
Shielding & Emission Limits	SYS2106	Shall comply with [AD 03]	Governs RFI emission limits from LRUs, shielding practice for amplifiers, oscillators, displays, and digital equipment
Fixed Analog Tunings	SYS0906	While supporting the Frequency Tunability requirement, the analog system setup options shall be minimized to facilitate calibration from catalog values.	Design requirement
Antenna Maintenance Interval	SYS2401	The antenna, antenna electronics, and array infrastructure shall be designed with a	Flows down to reliability and



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		preventative maintenance interval of no less than 4 years.	maintenance requirements
Antenna MTBF	SYS2402	The antenna, antenna electronics and array infrastructure shall be designed with an expected number of failures to be less than 25% of the array elements per year.	Reliability requirement
Modularization	SYS2403	The system shall be modularized into Line Replaceable Units (LRUs) to facilitate maintenance.	Design requirement
Antenna System Availability	SYS2901	Minimum 90% availability for all antenna systems combined. Availability is defined as time available for science operations, excluding scheduled and unscheduled maintenance downtime.	Flows down to reliability and maintenance requirements
Centralized Systems Availability	SYS2602	For all centralized systems (LO distribution, correlator, etc.) that are required for data collection, system availability shall be no less than 95%. See definition of availability above.	Flows down to reliability and maintenance requirements
Sub-system self-monitoring	SYS2701	All sub-systems to monitor system health and prohibit actions likely to cause damage.	Flows down to monitor and control requirement
Network Hardening	SYS2702	System should be built to withstand expected hack attempts. Should only respond to commands from authorized sources.	Interface requirement
Design Life	SYS2703	The system shall be designed for an expected operational life of 20 years.	Design Lifetime requirement
Cost Optimization	SYS2704	The system shall be designed to minimize total life-cycle costs over the projected design life.	Design requirement