



LO Reference and Timing Design Description

020.35.00.00.00-0002-DSN Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
B. Shillue	Central Development Lab, NRAO	2022-05-27

APPROVALS	ORGANIZATION	SIGNATURES
B. Shillue, LO Reference & Timing IPT Lead	ngVLA Project Office	William Shillue William Shillue (Jun 1, 2022 03:41 EDT)
R. Selina, Project Engineer	ngVLA Project Office	R. Selina R. Selina (Jun 1, 2022 06:11 MDT)
T. Küsel, System Engineer	ngVLA Project Office	Thomas Kusel (Jun 1, 2022 08:55 EDT)
W. Esterhuyse, Antenna Project Manager	ngVLA Project Office	NALAY

RELEASED BY	ORGANIZATION	SIGNATURES
W. Esterhuyse, Antenna Project Manager	ngVLA Project Office	NHAN



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

Change Record

Version	Author		Affected Section(s)	Reason	
I	2018-06-29	B. Shillue	All	Initial (incomplete) draft	
2	2018-07-23	B. Shillue	All	Completed draft	
3	2018-09-30	B. Shillue	All	Inclusion of Long Baseline Array	
4	2018-11-16	B. Shillue	All	 Post-Internal Review Updates: All sections – minor edits New Section 8.2 added "Antenna Time and Frequency Design Approach" Sections 8.4, 8.5, and 8.6 extensively modified so that the LO frequency plan matches the Front End and IRD frequency plan. 	
5	2019-05-30	R. Selina	2.1, 3.1, 4.3, 6.1	Minor edits for release.	
А	2019-07-26	A. Lear	All	Incorporated edits by R. Selina & M. McKinnon; prepared PDF for signatures and release.	
A.01	2022-04-14	B. Shillue	All	Redrafted for Conceptual Design review.	
A.02	2022-05-16	B. Shillue	All	Incorporated revisions from document review.	
A.03	2022-05-27	B. Shillue	All	Formatting, copy edits.	
В	2022-05-30	A. Lear	All	Prepared PDF for signatures & release.	



Title : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

Table of Contents

I	Introduction	. 5
1.1	Purpose and Scope	5
2	Related Documents and Drawings	. 5
2.1	Applicable Documents	5
2.2	Applicable Interface Control Documents	5
2.3	Reference Documents	7
3	Subsystem Overview	. 8
3.1	, High-Level Description	8
3.2	Design Driving Requirements	8
3.2.1	Maximum Fiber Length	8
3.2.2	Number of Antennas	8
3.2.3	Number of Subarrays	9
3.2.4	Simultaneous LOs	9
3.2.5	LO Phase Noise	9
3.2.6	LO Phase Drift	9
3.2.7	Return to Phase	10
3.2.8	Timing to CSP/Antenna	10
3.2.9	Spurious Narrowband Tones	10
3.2.10	Mean Time Between Failure/Mean Time Between Maintenance	10
3.3	Key Risks	10
3.4	Design Assumptions	11
3.4.I	Configuration	11
3.4.2	Fiber Infrastructure	11
3.4.3	Architecture	11
3.4.4	Frequency and Timing transfer	12
3.4.5	Antenna Time and Frequency	12
4	LO Reference and Timing Design	13
4.I	Product Structure	13
4.1.1	Product Context RTG	13
4.1.2	Product Context RTD	13
4.1.3	Product Context ATF	15
4.1.4	Product Breakdown Structure	16
4.1.5	Top Level Central Block Diagrams	18
4.1.6	Top-Level Station Block Diagram	19
4.1.7	RTG Subsystem Block Diagram	20
4.1.8	RTD Subsystem Block Diagrams	21
4.1.9	ATF Subsystem Block Diagrams	27
4.2	Product Design	28
4.2.I	Functional Architecture RTG	28
4.2.2	RTG Design Features	29
4.2.3	Functional Architecture RTD	30
4.2.4	RTD Design Features	30
4.2.5	Functional Architecture for ATF	32
4.2.6	ATF Design Features	33
4.2.7	Design Modification for Long Baseline Array and Distant MID stations	34
4.3	Design for Key Requirements	35

0	
ngvla	

<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

4.3.1	Phase Drift	
4.3.2	Phase Noise	
4.3.3	Timing	
4.4	Environmental Protection	
4.5	RFI, EMC, and Lightning Protection	
4.6	Power Supply and Distribution	
4.7	Reliability, Availability, and Maintainability	
4.8	Safety Analysis	
4.9	Technology Readiness Assessment	
5	Appendix A: Trade Studies	
5.I	Local Oscillator Trade Study	
5.2	Frequency Transfer Trade Study	
5.3	Time Transfer Trade Study	
5.4	Connected Antennas versus Standalone	
6	Appendix B: Abbreviations and Acronyms	42



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

I Introduction

I.I Purpose and Scope

The purpose of this document is to define the design of the ngVLA LO Reference and Timing for the Conceptual phase of its development. The LO Reference and Timing consists of Reference and Timing Generation (RTG), Reference and Timing Distribution (RTD), and Antenna Time and Frequency (ATF) subsystems. Thus, the scope of this design document includes all of the local oscillator, time, and frequency services for the array.

The design is driven by the requirements stated in [AD01, AD02] and the purpose of the design description is to define a design that can meet all the requirements stated in [AD01, AD02].

The design description is a holistic definition of the design, including performance, functional, mechanical, environmental, safety, reliability, availability and maintainability characteristics. The design should also show compliance to external interfaces in cases where the interfaces have a direct impact on the design.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev/Doc. No.
AD01	Antenna Time and Frequency Technical Requirements	020.30.35.00.00-0004-REQ
AD02	Local Oscillator Reference and Timing: Generation &	020.35.00.00.00-0003-REQ
	Distribution Technical Requirements	
AD03	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	020.10.40.05.00-0006-ICD
	Electronics DC Power Supply (PSU) and Antenna	
	Electronics Subsystem: Section on LO Reference and	
	Timing and Distribution (RTD) Subsystem (interface 0058)	
AD21	Interface Control Document Between: Antenna	020.10.40.05.00-0040-ICD
	Electronics Bins, Modules, and Racks (BMR) and Antenna	
	Electronics Subsystem: Section on LO Reference and	
	Timing and Distribution (RTD) Subsystem (interface 0064)	
AD22	Interface Control Document Between: LO Reference and	020.10.40.05.00-0069
	Timing and Distribution (RTD) Subsystem and Antenna	
	Electronics Environmental Control System (EEC)	
	Subsystem	



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

Ref. No.	Document Title	Rev./Doc. No.
AD23	Interface Control Document Between: Monitor and	020.10.40.05.00-0077
	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	
AD24	Interface Control Document Between Computing/CSP	020.10.40.05.00-0095
	Subsystems: Section on LO Reference and Timing	
	Generation (RTG) and Distribution (RTD) Subsystems	
	(interface 0099, 0100) and ngVLA Site Buildings (NSB)	
	subsystem	
AD25	Interface Control Document Between Monitor and	020.10.40.05.00-0106
	Control System and LO Reference and Timing Generation	
4534		
AD26	Interface Control Document Between Central Fiber	020.10.40.05.00-0120
	Distribution (RTD)	
AD27	Interface Control Decument Petrusen Dicital Pedrend	
AD27	Subsystem (DBE) and LO Reference and Timing	020.10.40.03.00-0122
	distribution (RTD)	
<u>۵</u> 028	Interface Control Document Between: Central Signal	020 10 40 05 00-0123
AD20	Processing (CSP) and $I \cap Reference and Timing$	020.10.40.03.00-0123
	Generation (BTG)	
AD29	Interface Control Document Between: LO Reference and	020.10.40.05.00-0124
	Timing – Distribution (RTD) and LO Reference and	
	Timing – Generation (RTG)	
AD30	Interface Control Document Between: LO Reference and	020.10.40.05.00-0125
	Timing – Distribution (RTD) and Antenna Time and	
	Frequency (ATF)	
AD31	Interface Control Document Between: Antenna	020.10.40.05.00-0005
	Electronics Integrated Receiver and Downconverters	
	(IRD) and Antenna Time and Frequency (ATF)	
AD32	Interface Control Document Between: Antenna	020.10.40.05.00-0059
	Electronics DC Power Supply (PSU) and Antenna Time	
	and Frequency (ATF)	
AD33	Interface Control Document Between: Front End (FED)	020.10.40.05.00-0016
	and Antenna Time and Frequency (ATF)	
AD34	Interface Control Document Between: Water Vapor	020.10.40.05.00-0028
	Radiometer (WVR) and Antenna Time and Frequency	
4.5.25		
AD35	Interface Control Document Between Antenna	020.10.40.05.00-0040
	Electronics: Bins, Modules, Kacks (BMK) and Antenna	
4034	Interfere Control Desument Detruction Automatic	
AD36	Electronics: Antonno Electronics: Antonno	020.10.40.05.00-0041
	Antonna Time and Erequency (ATE)	
	Antenna Time and Frequency (ATF)	

0	
ngvla	

<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

Ref. No.	Document Title	Rev./Doc. No.
AD37	Interface Control Document Between Antenna Time and	020.10.40.05.00-0070
	Frequency (ATF) and Antenna Electronics Environmental	
	Control System (EEC)	
AD38	Interface Control Document Between: Antenna	020.10.40.05.00-0078
	Electronics Monitor and Control Hardware Interface	
	Layer (HIL) and Antenna Time and Frequency (ATF)	

2.3 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev/Doc. No.
RD01	Configuration: Reference Design Rev D Description	Next Generation Very Large Array Memo No. 92
RD02	Timing Requirements & Considerations	Draft memo
RD03	ngVLA Antenna Local Oscillator Trade Study	020.30.35.00.00-0003-REP
RD04	VLA Pie Town Project Handbook	VLA Technical Reference No. 77,
		https://library.nrao.edu/public/mem os/vla/tech/VLATR_77.pdf
RD05	Phase Coherence of the EVLA Radio Telescope	EVLA Memo 105
RD06	"Effect of correction timing error in chromatic	Draft paper, submitted IEEE
	dispersion compensation scheme frequency transfer	Journal, April 2022
	System," H. Kiuchi, B. Shillue	
RD07	Kiuchi, Hitoshi	Private communication, April 2022
RD08	Schediwy, S. W., et al. "The mid-frequency square	Publications of the Astronomical
	kilometre array phase synchronisation system."	Society of Australia 36 (2019).
RD09	Kiuchi, Hitoshi, et al. "High extinction ratio Mach–	IEEE Transactions on Microwave
	Zehnder modulator applied to a highly stable optical	Theory and Techniques 55.9
	signal generator."	(2007): 1964-1972
RD10	Kiuchi, Hitoshi. "Highly stable millimeter-wave signal	IEEE transactions on microwave
	distribution with an optical round-trip phase stabilizer."	theory and techniques 56.6
		(2008): 1493-1500
RDII	Kiuchi, Hitoshi. "Postprocessing phase stabilizer for	IEEE Transactions on Terahertz
	wide frequency range photonic-microwave signal	Science and Technology 7.2
	distribution."	(2017): 177-183.
RD13	B. Carlson, "A novel clock and timing approach for	ALMA Memo 619
	achieving 200+ km ALMA baselines"	
RD14	White Rabbit Open Hardware Repository	https://ohwr.org/project/white- rabbit
RD15	Boven, Paul. "DWDM stabilized optics for white	2018 European Frequency and
	rabbit."	Time Forum (EFTF). IEEE, 2018



3 Subsystem Overview

3.1 High-Level Description

The LO Reference and Timing work element is responsible for supplying accurate and reliable local oscillator, sampler clock, and timing references to the relevant subsystems located at the antennas, and timing for the central signal processor (CSP) and the computing and software (CSW) subsystem.

3.2 Design Driving Requirements

A subset of the key requirements that drive the design is shown in Table I below.

Parameter	Requirement Number	Reference
Maximum Fiber Length	LRTII20	SYS1301, RD01
Number of Antennas	LRTI100	SYS1001, SYS1021
Number of Subarrays	LRTII40	SYS0601, SYS0603
Simultaneous LOs	LRT1205	SYS0903, SYS0905
LO Phase Noise	LRT1240	SYS5001, SYS1503,
		CAL0314, [AD30]
LO Phase Drift	LRT1250	SYS5001, SYS1504,
		SYS1505, [AD30]
Return to Phase	LRT1280	SYS0602
Timing to CSP	LRTI300	SYS2002, SYS2003,
		SYS0404, RD02
Spurious Narrowband Tones	LRTI500	[AD31], SYS2104
Mean Time Between Failure/Mean Time	LRT2310	SYS2610, SYS2605, [AD03]
Between Maintenance		

Table I: Key Antenna Time and Frequency Requirements. Note that the phase noise and phase drift requirements will be studied further.

3.2.1 Maximum Fiber Length

The requirement is for a direct connection of the fiber optic time and frequency service up to at least 300 km. Goal of 1000 km. The maximum distance will be based upon a costed trade study. The great distances present infrastructure, installation, and cost challenges. The scope of the LO Reference and Timing work is to support that fiber optic distance with installed hardware that not only supports the signal transport over the maximum distance, but corrects for phase and timing delays associated with the transport.

3.2.2 Number of Antennas

RTD subsystem distribution shall be provided to support up to 263 antennas. Note that the 30 LBA antennas, and possibly additional MID antennas will use a standalone time and frequency design, so the main distribution network from the central building will need to serve <=233 antennas.



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

3.2.3 Number of Subarrays

The RTD subsystem shall support a minimum of ten subarrays. This is one of the main design drivers for the use of a fixed frequency reference frequency transmission to the antenna. Thus, no switching or intelligence is needed at the central building (in the LO Reference and Timing system) to map antennas into subarrays.

3.2.4 Simultaneous LOs

The progression of the baseline design plan for Band 6 from four to eight downconverters, and thus the need for eight simultaneous LOs - was a prime driver for the decision to use fixed frequency LOs (not tunable frequency synthesizers) for the antennas LO [RD03].

3.2.5 LO Phase Noise

Note: the current phase noise requirement will be reviewed to determine if it is too stringent. Any future revision would be subject to formal change processes.

The requirement is for < 76 fs integrated from I Hz to maximum IF frequency offset. The antenna local oscillators are used to downconvert fairly large chunks of RF bandwidth. The maximum IF frequency is 2.9 GHz so any phase noise at offsets from zero to 2.9 GHz will contribute additively to the overall RMS phase noise. In general, oscillators have phase noise that decreases further away from the carrier, and in practice it may be that there are insignificant contributions beyond, say, 10 MHz offset. Nevertheless this needs to be demonstrated and verified. Meeting this requirement means taking into account the contributions from all reference frequencies used to construct the antenna LO, and making careful design of PLLs and offset frequency synthesis. Amongst the subsystems:

- RTG: maser and central references will be high performance fixed frequency oscillators which should not appreciably drive the final LO phase noise performance.
- RTD: Long fiber links can add phase noise to distributed oscillators. This affects primarily 0-30 kHz frequency offset ranges
- ATF: At the antenna, ATF subsystem will lock a fixed frequency low phase noise oscillator to the distributed reference with a narrow band PLL to remove as much of the link noise as possible. Additional offset locking and use of harmonics or multipliers must not add significant phase noise or spurious.

3.2.6 LO Phase Drift

Note: the current phase drift requirement will be reviewed to determine if it is too stringent. Any future revision would be subject to formal change processes.

The requirement is for < 42 fs at 300 s (linear term removed) and < 250 fs (absolute). The former is 0.03 rad (0.2 deg) at 116 GHz, while the latter is 0.18 rad (1.14 deg) at 116 GHz. These numbers are orders of magnitude less than the uncorrected phase delays, as described below. Thus, a robust method of correcting for the delays is required.

Uncorrected phase delays: The distance from the central building to the most distant antennas connected by fiber is at least 300km. Typically in synthesis arrays the variation in fiber delay can be dominated by above ground antenna fiber runs if the fiber is well-buried at 1m depth or greater. However, for hundreds of km, there will be a non-negligible delay contribution even in the unlikely case that it is all well buried. At a depth of 1m, the underground temperature can vary by about 0.1 deg C per day [RD04], in a mostly linear way since short term fluctuations are attenuated in the soil. For 300km, this is equivalent to 1.5 nsec per day, or 62 psec per hour. On top of this we can expect something similar to what has been measured on the EVLA which includes above ground fiber, and varies diurnally by about 160 psec



peak-to-peak [RD05]. Finally, in the event that there are significant Sections of above ground fiber, polemounted fiber for instance, then the delay excursions will be much higher (5 nsec delay per 10km-10deg exposure).

3.2.7 Return to Phase

Any derived LO or timing signal shall return to phase upon change in frequency from F_1 to F_2 to F_1 . This means that in the antenna-based frequency synthesis, there shall be no frequency dividers that could lead to phase ambiguous locking. Also, design with direct digital synthesizers shall be done in such a way as to account for the ability to return to phase after frequency switching. The accuracy of the return to phase must be such that the system phase meets baseline stability requirements when the off-state switch is removed from a measured frequency switching time series.

3.2.8 Timing to CSP/Antenna

The timing accuracy to CSP and Computing shall be within 10 nsec (goal of 1 nsec). This implies careful design of the cable and timing protocol to these subsystems in the Central building. For antennas, it is required that a subset of the antennas is stable to within 2nsec to the central timing signal. This implies an actively measured or corrected timing signal.

3.2.9 Spurious Narrowband Tones

As detailed in [AD01], the local oscillator requirement is to provide a local oscillator for each IRD module in the front end. The LO must be relatively high power (+13 dBm), low phase-noise, and having very low spurious levels, less than -103 dBc/Hz for all frequencies within 3.5 GHz of the carrier.

3.2.10 Mean Time Between Failure/Mean Time Between Maintenance

For both the RTG and RTD subsystems, MTBF and MTBM must be at least three years with a goal of five years [AD03].

3.3 Key Risks

Fiber Infrastructure and Long Baseline Phase Stability: On the VLA site, the fiber infrastructure is low risk, insofar as the ngVLA will pursue an installation very similar to what has already been in use for the EVLA. Beyond the VLA site, there is risk due to the fact that as yet there is not a clear understanding of the existing fiber: installed fiber base, existing fiber ownership, opportunities for fiber lease. Additionally, for fiber runs that need to be newly developed, there are issues of cost, rights-of-way, commercial partnerships, ...etc. Additionally, the long baseline phase stability may depend on whether the distant MID stations are fiber connected or using standalone timing. The main mitigation strategy is a planned trade study (see Section 5.4) examining all of the issue related to the installed infrastructure, analyzing the cost-performance tradeoff, and assessing any science impacts.

LO Spurious: The LO Spurious requirement is quite stringent, and will be challenging to meet for all bands over all RF and IF frequency ranges. The presence of low level spurious depends on the detailed design of the LO and how it interfaces with the IRD modules. The mitigation strategy is to conduct early prototyping tests to better assess the probability of the risk, and then conduct a cost/scope assessment if further risk mitigation is required.



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

3.4 Design Assumptions

The design of the LO Reference and Timing work element described herein makes the following assumptions:

3.4.1 Configuration

- The array consists of 263 antenna stations, 19 in the small baseline array (SBA), 114 in the core, 54 on spiral arms, 46 on MID-baselines, and 30 in the long baseline array (LBA).
- The Revision D Configuration of Antennas is assumed [RD01]
- The following table details the Rev D Composition of ngVLA by number and type of antenna, type of connection to fiber networks, and distance from array center. Asterisk signifies area that is subject of further technical-cost study:

Sub-Array	Number of Antennas	Antenna diameter	Trenched fiber	Commercial fiber - dark	Internet Service Provider	Distance from Array Center
MA - Core	114	18m	114	0	0	0–1 km
MA - Spiral	54	I8m	54	0	0	I–30 km
Arms						
Mid-Baseline	46	I8m	0*	30*	16*	30–1000 km
Main Array Total	214		168*	30*	16*	
Small Baseline	19	6 m	19	0	0	0.1 km
Array (SBA)						
Long Baseline	30	18m	0	0	30	1050-5300
array (LBA)						km
ngVLA Total	263		187	30	46	

3.4.2 Fiber Infrastructure

- Fiber connection will be made for all stations up to 300 km. Beyond 300km, additional fiber connection will be made if permitted by cost and technical feasibility.
- LBA and some of the furthest out MID stations will not have a direct connection to the central building for supply of LO and Timing. (Instead local clock and timing and data backhaul by networked fiber). From the table above, the number of antennas currently in this category for the MID array is 16, but a full tradeoff will be conducted prior to the LO Reference and Timing CDR.
- Up to 30km, inclusive of the SBA, Core and Spiral arms, fiber can reach each antenna station in a direct shot with no need for amplification or repeaters.
- From 30km-300km, bidirectional fiber amplifiers (BiDi-EDFAs) and optical-electronic-optical (OEO) repeaters will be required.
- The optical fiber transmission for both the frequency and timing links allows bidirectional transmission.

3.4.3 Architecture

- 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.
- The references are generated and synchronized in the central building, and a frequency reference and timing signal are provided to the CSP. The references are then distributed with all necessary amplification, buffering, splitting, etc., and the required signals are transmitted to each antenna station.



- The central building has space available for housing the central RTG and RTD subsystem equipment and is an RFI shielded structure. Building requirements pertaining to the RTG and RTD subsystem will be included in the ICD with ngVLA Infrastructure group.
- Long Baseline stations have their own central frequency and timing sources, one for each group of three stations at a single site.
- The RTG subsystem is nominally located in the Central Electronics building. Additional versions of the RTG will be located at LBA station location, and possibly for far out MID stations not directly connected to the ngVLA fiber network.
- The RTD subsystem is located at (a) the central building (b) midpoint repeater stations and (c) the antenna stations. For LBA stations and remote MID stations the "central" part of the RTD will be similar but with a much lower fan-out. (For example, at LBA sites, where there are three antenna stations, reference sources and RTD modules will fan-out to each of the three antennas).
- For long baseline array stations, and any other stations not connected to the central building by fiber, the design will be based on a single standalone frequency reference, but will mirror the main array design to the extent possible (i.e. distribution of the reference to local stations)

3.4.4 Frequency and Timing transfer

- A central GNSS time standard is co-located with the primary frequency reference.
- A system clock is derived from the primary frequency reference, and differences between the system clock and GNSS time will be monitored and logged.
- The system clock and frequency reference are distributed to the CSP in the central building.
- The system clock and frequency reference are distributed to each antenna station which is connected by fiber, as well as a continuous monitoring of those signals so that fluctuations in the one-way propagation (due especially to thermal effects) can be mitigated.
- The accurate transfer of time and frequency can be made by direct link or by daisy chain.
- Additional remote station clocks and frequency reference will be generated for stations that are too distant for connection by fiber.

3.4.5 Antenna Time and Frequency

- The ATF phase noise for local oscillators and digitizers refers to phase noise relative to a "perfect" reference. The assumption is that any opportunity for coherent common mode antenna-to-antenna phase noise is eliminated by (a) very long fiber links, (b) narrow band PLLs at the antenna, and (c) antenna-based frequency offsets.
- 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.
- Each antenna station will be equipped with a receiver "package" consisting of six frequency bands, with each band comprising a feed horn and a low-noise cryogenic amplifier assembly. The receivers are located on the feed arm at the secondary focus. Located physically just behind this cryogenic receiver will be an additional electronics enclosure housing nineteen highly engineered assemblies that combine the functions of downconversion and digitization (these are called IRD modules: integrated receiver-digitizer). The receiver and the additional electronics assemblies have strict size, weight and power limits and are located in a secondary focus enclosure (SFE) that is in an exposed mounting on the telescope near the secondary focus.
- There are 20 IRD modules, 19 of which require a unique LO frequency, and all of which require a digitizer reference frequency.



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

4 LO Reference and Timing Design

4.1 **Product Structure**

4.1.1 Product Context RTG

The Reference Timing and Generation subsystem is shown in Figure I. The RTG has five major products including a separate product number for LBA antenna sources. The RTG also has four major interfaces, with ngVLA Site buildings, Monitor and Control system, Central Signal Processor, and Reference and Timing Distribution.



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

4.1.2 Product Context RTD

The Reference Timing and Distribution subsystem is shown in Figure 2 (on the next page). The RTD has seven major products including separate product numbers for long haul equipment at a repeater station and long haul repeater equipment located at an antenna station. The RTD also has ten major interfaces, four with Antenna Electronics IPT (BMR, EEC, PSU), three with CSP and Timing IPT (RTG, ATF, DBE), and additional interfaces with ngVLA Site buildings, fiber infrastructure, and HIL/Monitor and Control system. Note that the design assumptions in Section 3.4.5 include

- I. digital backend located in antenna pedestal, and
- 2. receiver and downconverters at secondary focus area.

The RTD subsystem will interface directly to the DBE in the pedestal. At the secondary focus electronics enclosure, the RTD subsystem terminates at the completion of the round-trip phase correction, and supplies a reference frequency to the ATF subsystem which then generates LO and digitizer clocks.

0	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
gvla	NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

Г



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



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

4.1.3 Product Context ATF

The Antenna Time and Frequency (ATF) subsystem is shown in Figure 3. The ATF has twenty major products including nineteen LO modules, and nine major interface definitions.



Figure 3: Antenna Time and Frequency subsystem product breakdown and interfaces with other antenna subsystems.



Title : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

4.1.4 Product Breakdown Structure

The complete list of product breakdown structure for LO Reference and Timing is shown in Table 2.

Configuration	cion Component		Туре
25.00.00.00	Peference signals		
35.00.00.00	10 Reference & Timing - Constantion (PTG) Subsystem		
35.05.00.00	Masor and CDS Sources		Pack(s)
25 05 20 02	Hydrogon Masor		
35.05.20.02	Phase and Timing Superscription		
35.05.20.04		BLD.CEB	
35.05.20.06		BLD.CEB	
35.05.20.08	GNSS Antenna	BLD.CEB	
35.05.30.00	Frequency Transfer Fixed Sources	BLD.CEB	Rack
35.05.30.02	Narrow Linewidth Laser	BLD.CEB	LRU
35.05.30.04	Fixed Microwave Source	BLD.CEB	LRU
35.05.40.00	Frequency Transfer Offset Sources	BLD.CEB	Rack
35.05.40.02	Tunable Source	BLD.CEB	LRU
35.05.50.00	Time Transfer Sources	BLD.CEB	Rack
35.05.50.02	Timing Laser	BLD.CEB	LRU
35.05.50.04	Optical Modulator PSK	BLD.CEB	LRU
35.05.50.06	PN Code-1 Modulator	BLD.CEB	LRU
35.05.80.00	LBA antennas time and frequency reference system	LBA	Rack
	Components to be added		
35.10.00.00	Reference and Timing Generation (RTD) Subsystem		
35.10.20.00	Reference Distributor Rack	BLD.CEB	Rack
35.10.20.02	NLL Distributor	BLD.CEB	LRU
35.10.20.04	RF Distributor	BLD.CEB	LRU
35.10.20.06	1PPS Distributor	BLD.CEB	LRU
35.10.40.00	Frequency Transmitter Rack		Rack
35.10.40.02	Frequency Transmitter	BLD.CEB	LRU
35.10.40.04	LO Reference	BLD.CEB	LRU
35.10.60.00	Timing Transmitter Rack	BLD.CEB	Rack
35.10.60.02	Time Transmitter	BLD.CEB	LRU
	Time transmitter optical assembly	BLD.CEB	SRU
	Time transmitter electronic assembly	BLD.CEB	SRU
35.10.60.04	Timing Controller	BLD.CEB	LRU
35.10.70.00	RTD central infrastructure	BLD.CEB	INF
35.10.70.02	RTD fiber cabling - central processor building	BLD.CEB	CBL
35.10.80.00	RTD long-haul repeater station equipment	NET.REP	1
35.10.80.02	RTD long-haul repeater station amplifiers (BiDi-FDFA)	NET.REP	LRU
35.10.80.04	RTD long-haul repeater station splice trav	NET.REP	LRU
35.10.85.00	RTD long-haul antenna repeater equipment	NET.ANT	
35.10.85.02	RTD long-haul antenna repeater (OFO Repeater)		LRU
35.10.85.04	RTD long-haul antenna amplifier (BiDi EDFA)	NET.ANT	LRU

0
ngvla

<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

Configuration	Component		Location	Туре
35 10 90 00	PTD for LPA and Standalone Stations			
35.10.30.00		1503 Reference Receiver and Timing module		IRII
35 10 10 02		1503 Frequency Receiver Assembly		SRII
35 10 10 04		1503 Timing Receiver Assembly		SRU
35 10 10 06		1503 Timing Relay Transmitter		SRU
30,35,00,00	Α	ntenna Time and Frequency Subsystem (ATE) Subsystem		5110
30,35,20,00		1504 Band 2-110	ANT FED	SRU
30.35.21.00		1505 Band 2-210	ANT.FED	SRU
30.35.30.00		L506 Band 3-1 LO	ANT.FED	SRU
30.35.31.00		L507 Band 3-2 LO	ANT.FED	SRU
30.35.40.00		L508 Band 4-1 LO	ANT.FED	SRU
30.35.41.00		L509 Band 4-2 LO	ANT.FED	SRU
30.35.42.00		L510 Band 4-3 LO	ANT.FED	SRU
30.35.50.00		L511 Band 5-1 LO	ANT.FED	SRU
30.35.51.00		L512 Band 5-2 LO	ANT.FED	SRU
30.35.52.00		L513 Band 5-3 LO	ANT.FED	SRU
30.35.53.00		L514 Band 5-4 LO	ANT.FED	SRU
30.35.60.00		L515 Band 6-1 LO	ANT.FED	SRU
30.35.61.00		L516 Band 6-2 LO	ANT.FED	SRU
30.35.62.00		L517 Band 6-3 LO	ANT.FED	SRU
30.35.63.00		L518 Band 6-4 LO	ANT.FED	SRU
30.35.64.00		L519 Band 6-5 LO	ANT.FED	SRU
30.35.65.00		L520 Band 6-6 LO	ANT.FED	SRU
30.35.66.00		L521 Band 6-7 LO	ANT.FED	SRU
30.35.67.00		L522 Band 6-8 LO	ANT.FED	SRU
30.35.10.00		L501 main LO module	ANT.FED	SRU
30.35.10.01		L501 main LO module internal cabling	ANT.FED	SUB
30.35.10.02		L501 M&C board	ANT.FED	SUB
30.35.10.03		L501 Regulator board	ANT.FED	SUB
30.35.10.06		L501 Frequency Receiver and Reflector	ANT.FED	SUB

Table 2: List of configuration item numbers for the LO Reference and Timing subsystems (Location key: BLD.CEB=Central Elec Building, NET.REP=Network equipment at Repeater Station, NET.ANT=Network equipment at Antenna Station, ANT>PED=Antenna Pedestal, ANT.FED=Antenna Feed Indexer) (Type key: LRU=Line Replaceable Unit, SRU=Shop Replaceable Unit, SUB= subassembly, CBL=Cabling, INF=infrastructure).



itle : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
IRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

Top Level Central Block Diagrams 4.1.5

The top-level block diagram shown in Figure 4 depicts the RTG subsystem as a self-contained unit in the Central Building, with outputs going to CSP, CSW, and RTD. The former two connections represent timing in the Central building, whereas the RTD connection passes the central references to the reference distribution network which ultimately connects to all antennas. The dashed line to the LBA station indicates that this is not a direct fiber connection. Figure 5 (on the next page) elaborates on this structure.



Figure 4: Top-level functional block diagram showing central building RTG and RTD subsystem. RTD subsystem links central building to antenna stations and includes receivers at the stations.



Figure 5: Elaboration of Top-level RTG, RTD subsystem functional block diagram. Added detail includes number of fibers, number of antenna stations, and standalone stations.

Note that the MDA010 antenna station is shown separately, though it is part of the MID D arm, because it is somewhat geographically isolated [RD01]. Also note that Figure 5 shows all MID stations connected by fiber. However, as noted in Sections 3.4.1 and 3.4.2, the decision exactly how many MID stations have a direct LO fiber connection will be subject to further study.

4.1.6 Top-Level Station Block Diagram

The top-level block diagram shown in Figure 6 (next page) depicts the portions of the LO Reference and Timing that are located at the antenna station. Boxes labelled "AFD Fiber Management," "Fiber Connector and Splice Tray," and "BMR Auxiliary Enclosure," are pass through modules only included to indicate the fiber optic routing on the antenna. The antenna station serves as the terminus for the frequency and time transfer links. The time transfer link terminus is in the "L503 Reference Receiver and Timing" module. The frequency link terminus is in the "L501 LO Module." Within the L501 module is the interface between the RTD subsystem, which captures the frequency reference, and the ATF subsystem, which is responsible for distributing LO references and digitizer references to the receiving band IRD modules located in SA501 and SA502 IRD/LO modules.

0	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
ngvla	NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

Antenna Station LRT – Block Diagram



Figure 6: Antenna Time and Frequency (ATF) subsystem (PBS: 30.35.00.00) at Antenna Station. Dark shaded blocks are ATF line replaceable units, hatched blocks are Antenna Electronics modules with ATF subsystem shop replaceable units (LO modules) within. Light gray shaded blocks are Antenna Electronics elements with fiber optic pass-through. (Red=fiber optic connection)

4.1.7 RTG Subsystem Block Diagram

Figure 7 shows more detail of the RTG subsystem. Functionally, the RTG role is to generate reference and timing sources. There are four subassemblies shown: Maser and GNSS sources, Time transfer sources, Frequency transfer fixed sources, and Frequency transfer offset sources. The hydrogen maser is a highly accurate frequency source over short and medium timescales. To provide long term accuracy, a timing pulse referenced to the maser will be compared to a GNSS pulse, and any timing pulse delay difference will be tracked. On command, the station timing pulse can be reset to the closest maser zero crossing to the GNSS timing pulse. This re-sync is only needed infrequently to stay within timing margins needed for real-time timing operations. This station timing pulse is assumed to be I PPS, and is sent as a reference to the CSP subsystem, and input to the time transfer block where it becomes the modulation source for the timing links. The maser is also the central frequency reference and its output will lock the primary frequency transfer reference (in the frequency transfer fixed sources block) which will also be used to

	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
'la	NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

modulate a laser in a two-way round-trip phase transfer. The "frequency transfer tunable sources" block is a place holder for the possibility of using centrally generated frequency offsets to satisfy the LO and digitizer offset requirement, though the most recent design iteration generates the offset at the antenna station.



Figure 7: LO Reference & Timing - Generation (RTG) subsystem.

4.1.8 RTD Subsystem Block Diagrams

4.1.8.1 Central RTD

The central portion of the RTD subsystem is shown in Figure 8. Three signals are passed (on the left) from the RTG subsystem: a I PPS optical signal for the timing, an RF signal, and a reference laser input for the frequency transfer. The latter two are split 256 ways (allowing some spare capacity), and combined to form a frequency transfer transmitter, one per antenna station. The I PPS, meanwhile is split to support N outputs, where N is the maximum number of supported high-accuracy timing links. The current design target is that we are intending N will be equal to the number of LO fiber connected antennas, so that the flexible subarray requirement can be met in all instances. Note that (as noted in Section 3.4.2) there will be LBA and distant MID stations beyond the reach of direct connection to the central building by fiber. The RTD implications for these antennas are discussed in Section 4.1.8.4 and Section 4.2.7.





Figure 8: LO Reference and Timing: Central Distribution (RTD) Transmitters only.

4.1.8.2 Frequency Transfer Link

The far end of the frequency transfer link is shown in Figure 9, *located at the secondary focus so that the fiber run up the antenna can be fully compensated.* Note that the frequency receiver is fully contained in the L501 modules (see Figure 6). The transmitted frequency is frequency shifted and reflected to support the two-way phase measurement in the central building. Also, it is amplified (if necessary) and detected.



Secondary Focus Located

Figure 9: Frequency Transfer Link LO Reference Receiver and Reflector. FFS=fiber frequency shifter, FRM=Faraday rotator mirror, EDFA=erbium-doped fiber amplifier, UTC-PD=uni-traveling carrier photodiode.

	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
/la	NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

In addition, it may be necessary to synchronize lower frequency references in the antenna station pedestal to the main LO reference. Thus, there will be an additional tap on the LO reference located in the pedestal as shown in Figure 10.



Figure 10: LO reference for pedestal located electronics.

4.1.8.3 Timing Transfer Link and Station Timing

The timing transfer between central building and antenna stations will take place by means of a timing transmitter and receiver pair. The timing receiver shown in Figure 11 will be located in the pedestal within the L503 LRU. At least one fiber link will be required per subarray, however, and at the conceptual design stage we are planning (space) for a full complement of timing links (one per fiber-connected station).



Figure 11: Timing Link Transmitter-Receiver Pair.

The L503 Module has additional assemblies:

- Frequency Receiver Assembly: Needed for accurate high frequency reference used to synchronize station timing pulse. (Another frequency receiver is in the secondary focus enclosure, used to generate LO and digitizer clocks, see Section 4.1.9.1).
- As needed: A Timing Relay Transmitter only in case of daisy chaining of the timing links for selected MID antennas.

	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
Б.	NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

The timing receiver capture the main timing pulse for the antenna station, which is then used for timing and synchronization of IRDs, DBE, Antenna, Front End noise diodes, and the WVR. The most accurate timing is needed for digital timestamping, currently a DBE function. To account for absolute delay variations the round trip timing is also measured, a function incorporated in the Timing Receiver Assembly. This round trip delay measurement will be used to periodically compensate the I PPS to maintain long term timing accuracy. However, the I PPS will always be synchronous with the frequency reference clock edge of the station frequency reference.

4.1.8.4 Long Haul Considerations

For the MID antenna stations there are two extenuating factors: the fiber distances are very large (30 to 800 km) and the installed fiber infrastructure is underdeveloped. The distance issue means that links to the MID antennas must be designed with adequate signal-to-noise to overcome distance related signal losses. This in turn means that some stations will require repeaters, either as an amplification or as an O-E-O (optical-to-electronic-to-optical) repeat. (Generally, bidirectional amplifiers at 80km and O-E-O repeaters at 300 km are assumed for now, but this will be optimized by a link signal-to-noise analysis).

With regard to the installed fiber infrastructure, at distances beyond 30 km, (i.e. the 46 MID stations), ngVLA will have to optimally choose one of three options: use existing fiber for the station connection (with perhaps some last "few" miles new fiber), run new fiber connections (by pole or trench), or plan for the station to utilize standalone timing and networked ISP data backhaul. For this conceptual design, we assume that all MID stations are connected by fiber, and in the following Section we block out how the time and frequency transfer links design is implemented.

The most recent configuration study has 46 MID stations on five extended arms with a maximum distance of 800 km [RD01]. Each of the five arms has a different set of antenna spacings and distances and could have a slightly different layout of the link. To represent a typical spiral arm, the average distance to the nth station is compiled in Table 3.

	Distance	Distance
	between	from center
	stations km	km
Array center	0	0
MID station I	31	31
MID station 2	33	65
MID station 3	57	122
MID station 4	81	203
MID station 5	73	276
MID station 6	81	357
MID station 7	105	462
MID station 8	145	607
MID station 9	173	780

 Table 3: Typical distances for nine-station MID spiral arm.

5	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
vla	NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

Note that the array becomes more sparse (inter-station distances become greater) as the distance from the center increases. Using Table 3 as a guide, the typical spiral arm can be implemented as shown in Figure 12. It consists of nine antenna stations and four repeater stations. The repeater stations have bidirectional amplifiers to extend the link range. In addition to the time and frequency link receivers for a given station, the MID stations also necessarily have link amplification and repeaters (OEO) for the upstream stations. Overall, each MID spiral arm may be expected to contain 36 bidirectional amplifiers and 7 OEO repeaters for the frequency reference links. The timing links have not been shown on this figure. The timing links, when needed for distant antennas, are expected to be implemented in a daisy chain arrangement rather than a "home run" connection from the array center. Therefore the maximum footprint in a MID station would consist of a timing receiver and transmitter pair.



Figure 12: Implementation of "typical" MID spiral arm.

A typical repeater station is shown in Figure 13. The station and rack infrastructure are part of a different ngVLA product group, therefore the LO Reference and Timing deliverable includes just the electronic and optical instrumentation and cabling.

0	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
ngvla	NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B



Figure 13: Reference Timing and Distribution - Frequency Link Repeater.

A more detailed and expanded block diagram of the antenna station layout is shown in Figure 14 including the reference distribution repeater equipment necessary to support MID long haul stations:







<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

4.1.9 ATF Subsystem Block Diagrams

4.1.9.1 L501 Module

The L501 module is used to capture the transmitted reference frequency. Local oscillators and digitizer clock are then developed and locked to this reference. The RTD Frequency Receiver assembly captures the central reference (as already depicted in Figure 9), then the ATF subsystem locks a VCO to the transmitted reference (to remove fiber phase noise) and the resulting reference is used to develop all of the LO and digitizer references as shown in Figure 15.



Figure 15: L501 LO Module Block Diagram.

4.1.9.2 SA501 Module

The SA501 module includes 12 integrated-receiver-digitizer modules, each with an LO reference input and LO offset. For example, one of the LO modules is shown in Figure 16.



Figure 16: LO Module in SA501.

	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
/la	NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

4.1.9.3 SA502 Module

The SA502 module includes 7 integrated-receiver-digitizer modules, each with an LO reference input and LO offset. For example, one of the LO modules is shown in Figure 17.



Figure 17: LO Module in SA502.

4.2 **Product Design**

The following Sections detail the architecture and design features of the RTG, RTD, and ATF subsystems.

4.2.1 Functional Architecture RTG

A functional overview of the RTG subsystem is shown in Figure 18.

Central time and frequency sources are generated from a stable short and medium term clock (H-maser), and stable longer term clock (GNSS timescale). There are signal path references distributed to CSP and RTD subsystems, and hardware and timescale monitor data outputs.



(*) – also secondary instances for LBA and distant MID stations

Figure 18: Functional overview: LO Reference Generation Subsystem.



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

4.2.2 RTG Design Features

RTG products are listed in Table 4. These consist of LRUs housed in standard equipment racks. The equipment racks in turn are located in a dedicated central electronics building that is RFI shielded. The LRUs and racks electronic, mechanical, and thermal design will include:

- RFI suppression at the building level, with additional RFI protection at the rack or module level as needed
- Design for stable temperature by forced air flow supplied by the central building
- Will meet LO Reference and Timing requirements for signal path performance, monitor and control, reliability and lifetime, EMC, and electronic design standards [AD 02].
- RTG equipment including the monitor and control, power supplies, modules, bins, and racks are the responsibility of the Timing IPT. However, where well developed solutions are available from the Antenna Electronics IPT, then those designs will be re-used or adapted when possible.
- As indicated in Figure 18, and by configuration item number 35.05.80.00 in Table 4 below, although the main instance of the RTG subsystem is in the central building, there are additional smaller instances of the RTG subsystem at LBA sites and distant MID stations.

Configuration Item Number	Component		Location	Туре
35.00.00.00	Ref	erence signals		
35.05.00.00	LO Sub	Reference & Timing - Generation (RTG) system		
35.05.20.00		Maser and GPS Sources	BLD.CEB	Rack(s)
35.05.20.02		Hydrogen Maser	BLD.CEB	LRU
35.05.20.04		Phase and Timing Synchronization	BLD.CEB	LRU
35.05.20.06		Timescale Receiver	BLD.CEB	LRU
35.05.20.08		GNSS Antenna	BLD.CEB	LRU
35.05.30.00		Frequency Transfer Fixed Sources	BLD.CEB	Rack
35.05.30.02		Narrow Linewidth Laser	BLD.CEB	LRU
35.05.30.04		Fixed Microwave Source	BLD.CEB	LRU
35.05.40.00		Frequency Transfer Offset Sources	BLD.CEB	Rack
35.05.40.02		Tunable Source	BLD.CEB	LRU
35.05.50.00		Time Transfer Sources	BLD.CEB	Rack
35.05.50.02		Timing Laser	BLD.CEB	LRU
35.05.50.04		Optical Modulator PSK	BLD.CEB	LRU
35.05.50.06		PN Code-1 Modulator	BLD.CEB	LRU
35.05.80.00		LBA antennas time and frequency reference system	LBA	Rack

Table 4: RTG product tree.



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

4.2.3 Functional Architecture RTD

A functional overview of the RTD subsystem is shown in Figure 19.

The frequency reference and timing reference are the primary inputs. These are distributed to each antenna and a return signal is measured to form a round trip measurement. An antenna specific frequency offset is added to LO and digitizer clocks at the antenna. Round trip and hardware monitoring is implemented at the central building, repeater stations, and antenna station.



Figure 19: Functional overview: LO Reference and Timing Distribution (RTD) Subsystem.

4.2.4 RTD Design Features

RTD products are listed in Table. These consist of rack-mounted LRUs in the central building, rackmounted LRUs in repeater stations, and a combination of rack mounted LRU and shop replaceable units in the antenna stations. Additionally, product item 35.10.90.00 denotes RTD equipment at LBA and remote MID-stations.



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

Configuration Item Number	Ca	omponent	Location	Туре
35.10.00.00	Re	ference and Timing Generation (RTD) Subsystem		
35.10.20.00		Reference Distributor Rack	BLD.CEB	Rack
35.10.20.02		NLL Distributor	BLD.CEB	LRU
35.10.20.04		RF Distributor	BLD.CEB	LRU
35.10.20.06		1PPS Distributor	BLD.CEB	LRU
35.10.40.00		Frequency Transmitter Rack	BLD.CEB	Rack
35.10.40.02		Frequency Transmitter	BLD.CEB	LRU
35.10.40.04		LO Reference	BLD.CEB	LRU
35.10.60.00		Timing Transmitter Rack	BLD.CEB	Rack
35.10.60.02		Time Transmitter	BLD.CEB	LRU
		Time transmitter optical assembly	BLD.CEB	SRU
		Time transmitter electronic assembly	BLD.CEB	SRU
35.10.60.04		Timing Controller	BLD.CEB	LRU
35.10.70.00		RTD central infrastructure	BLD.CEB	INF
35.10.70.02		RTD fiber cabling - central processor building	BLD.CEB	CBL
35.10.80.00		RTD long-haul repeater station equipment	NET.REP	
35.10.80.02		RTD long-haul repeater station amplifiers (BiDi-EDFA)	NET.REP	LRU
35.10.80.04		RTD long-haul repeater station splice tray	NET.REP	LRU
35.10.85.00		RTD long-haul antenna repeater equipment	NET.ANT	
35.10.85.02		RTD long-haul antenna repeater (OEO Repeater)	NET.ANT	LRU
35.10.85.04		RTD long-haul antenna amplifier (BiDi EDFA)	NET.ANT	LRU
35.10.90.00		RTD for LBA and Standalone Stations		
35.10.10.00		L503 Reference Receiver and Timing module	ANT.PED	LRU
35.10.10.02		L503 Frequency Receiver Assembly	ANT.PED	SRU
35.10.10.04		L503 Timing Receiver Assembly	ANT.PED	SRU
35.10.10.06		L503 Timing Relay Transmitter	ANT.PED	SRU

Table 5: RTD Product Tree.

0
ngvla

Title : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

For central building equipment, the LRUs will be housed in standard equipment racks. The LRUs and racks electronic, mechanical, and thermal design will include:

- RFI suppression at the module, rack, and/or building level
- Design for stable temperature by forced air flow supplied by the central building
- Will meet LO Reference and Timing requirements for signal path performance, monitor and control, reliability and lifetime, EMC, and electronic design standards [AD 02].
- RTD central building equipment including the monitor and control, power supplies, modules, bins, and racks are the responsibility of the Timing IPT. However, where well developed solutions are available from the Antenna Electronics IPT, then those designs will be re-used or adapted when possible.

For repeater station equipment, the LRUs will be housed in an equipment rack or sub rack depending on space needed. The LRUs and racks electronic, mechanical, and thermal design will include:

- RFI suppression at the module, rack, and/or container level
- Temperature control suitable for performance requirements to be met
- Will meet LO Reference and Timing requirements for signal path performance, monitor and control, reliability and lifetime, EMC, and electronic design standards [AD 02].

For antenna station equipment, the RTD equipment includes:

- L503 module located in pedestal
- Repeater equipment located in pedestal
- Frequency receiver assembly located in the L501 module

The L503 and repeater equipment will be LRUs and will include RFI suppression housing and design for rack-mount with vertical air flow. The frequency receiver will be a subassembly of the L501 which is a shop-replaceable unit built into the Front End enclosure.

4.2.5 Functional Architecture for ATF

A functional overview of the ATF subsystem is shown in Figure 20. The frequency reference is passed to ATF from RTD. The frequency reference is used to form LO and digitizer signals for each receiving band.



Figure 20: Functional overview: Antenna Time and Frequency Subsystem.



<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

4.2.6 ATF Design Features

ATF products are listed in Table 6. These consist of assemblies or shop replaceable units.

Configuration	Component	Location	Туре
item Number			
30.35.00.00	Antenna Time and Frequency		
	Subsystem (ATF) Subsystem		
30.35.20.00	L504 Band 2-1 LO	ANT.FED	SRU
30.35.21.00	L505 Band 2-2 LO	ANT.FED	SRU
30.35.30.00	L506 Band 3-1 LO	ANT.FED	SRU
30.35.31.00	L507 Band 3-2 LO	ANT.FED	SRU
30.35.40.00	L508 Band 4-1 LO	ANT.FED	SRU
30.35.41.00	L509 Band 4-2 LO	ANT.FED	SRU
30.35.42.00	L510 Band 4-3 LO	ANT.FED	SRU
30.35.50.00	L511 Band 5-1 LO	ANT.FED	SRU
30.35.51.00	L512 Band 5-2 LO	ANT.FED	SRU
30.35.52.00	L513 Band 5-3 LO	ANT.FED	SRU
30.35.53.00	L514 Band 5-4 LO	ANT.FED	SRU
30.35.60.00	L515 Band 6-1 LO	ANT.FED	SRU
30.35.61.00	L516 Band 6-2 LO	ANT.FED	SRU
30.35.62.00	L517 Band 6-3 LO	ANT.FED	SRU
30.35.63.00	L518 Band 6-4 LO	ANT.FED	SRU
30.35.64.00	L519 Band 6-5 LO	ANT.FED	SRU
30.35.65.00	L520 Band 6-6 LO	ANT.FED	SRU
30.35.66.00	L521 Band 6-7 LO	ANT.FED	SRU
30.35.67.00	L522 Band 6-8 LO	ANT.FED	SRU
30.35.10.00	L501 main LO module	ANT.FED	SRU
30.35.10.01	L501 main LO module internal cabling	ANT.FED	SUB
30.35.10.02	L501 M&C board	ANT.FED	SUB
30.35.10.03	L501 Regulator board	ANT.FED	SUB
30.35.10.06	L501 Frequency Receiver and Reflector	ANT.FED	SUB

Table 6: ATF Product Tree

0	Title Desc
ngvla	NRA

The L503 assembly in the pedestal is housed in an LRU that is an RTD subsystem deliverable. The LRU will be a rack mount, RFI sealed unit designed for vertical air flow.

The L501 will be a shop replaceable unit built into the Front End enclosure. It will be packaged for RFI suppression and for thermal management by conduction.

The LO modules will be shop replaceable units built into the SA501 modules, also going in the Front End enclosure. These will also be packaged for RFI suppression and for thermal management by conduction.

All assemblies will meet ATF requirements for signal path performance, monitor and control, reliability and lifetime, EMC, and electronic design standards [AD01].

4.2.7 Design Modification for Long Baseline Array and Distant MID stations

For the Long Baseline Array (LBA) antenna stations, and for MID stations beyond the reach of the fiber optic time and frequency distribution, certain small modifications are made to the RTG and RTD subsystems. This mainly allows for support of a smaller number of antennas (LBA stations are in groups of three). The diagram in Figure 21 shows the design for a set of three LBA stations (or for one or more MID stations) with central time and frequency sources developed in a similar way as for the main array. The RTD distribution is then designed along similar lines as well, with the primary difference being that the common time and frequency references only need to be split a few ways instead of ~256-way. For the product structure, identical LRUs will keep their original PBS number, whereas any items that are unique to the LBA deployment will fall under a new product numbering of 35.05.80.xx for RTG items and 35.10.90.00 for RTD items. No modification is envisioned for the equipment at the antenna station, and in particular the ATF subsystem design is identical for LBA.



Figure 21:- Central reference generation and distribution for Long Baseline Array and Standalone MID stations.



4.3 Design for Key Requirements

4.3.1 Phase Drift

The phase drift requirement is < 42 fs at 300 s (linear term removed), and < 250 fs (absolute). Note that since the requirement is written as a delay, then the applicable phase drift requirement is frequency dependent, i.e. 42 fsec=0.03 radians at 113.1 GHz at the high end of the frequency range, and 42 fsec=1.5e-3 radians at 5.8 GHz (the lowest LO frequency). Preliminary results of a proof-of-concept approach to the frequency transfer has demonstrated phase Allan Variance of 5e-16 at 300 sec for a 100 GHz frequency transferred over 250 km [RD06]. This preliminary demonstration gives us confidence that the requirement can be met even for long haul links. Additional description of this approach is provided in Section 5.2.

4.3.2 Phase Noise

The phase noise requirement is < 76 fs integrated from I Hz to maximum IF frequency offset. For a fixed frequency oscillator phase locked to a reference frequency and an offset frequency, there are several contributors to the phase noise. Commercial phase locked DROs with integrated jitter less than 10 fsec are available up to 30 GHz, and in principle the jitter delay is unaffected by frequency multiplication to higher frequencies; see Table 6. The design concept calls for generating the LO reference, digitizer reference, and offset frequency from a single microwave station reference frequency. The station reference is equal to or harmonically related to the RTD frequency transferred over the link. However, in capturing the transfer frequency, a low phase noise microwave oscillator will be locked to it with a slow PLL such that the output rejects as much as possible any of the link phase noise. Therefore, a key aspect of the design for low phase noise is generation of the digitizer clock and the offset frequency from the station microwave reference, and careful design of the station LO phase lock loops.

22.80 GHz COTS PLDRO	
Offset frequency	Single sideband phase noise dBc/Hz
100 Hz	-80 dBc/Hz
l kHz	-110 dBc/Hz
10 kHz	-120 dBc/Hz
100 kHz	-120 dBc/Hz
l MHz	-135 dBc/Hz
RMS Integrated	8.5 fsec
phase delay	

 Table 7: Phase locked DRO typical phase noise.

4.3.3 Timing

The system level requirement for temporal accuracy (SYS2002) of 10 nsec has been flowed down to require an accuracy of 2 nsec time error between antenna timing and the central system clock (LRT1360) and 2 nsec from the antenna timing to the DBE (LRT1300) [AD01, AD02, RD02]. Though this is required for at least one antenna per subarray, the design concept has implemented an accurate time transfer measurement to support every antenna station. This will meet the timing requirements as well as the flexible subarraying systems requirement (SYS0603).

For absolute time tracking the design will rely on a combination of GNSS for long time scales and an accurate frequency reference (like a hydrogen maser) for shorter time scales. The system clock derived

0	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
ıg∨la	NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

from the frequency reference will be distributed locally to the CSP and by time transfer across fiber to the antenna stations.

This clock will be continuously monitored and measured versus GNSS, which can be used offline for purposes of adjusting data product timestamps. Over long periods, any accumulate difference between the system clock and the GNSS clock may be removed by a one-time adjustment of the system timing clock. (Note that the frequency reference is only monitored versus absolute time, not steered or in any way adjusted).

The current System CDR baseline design uses a time transfer technique with direct optical measurement of round trip time. This approach has been successfully demonstrated at NAOJ with < I nsec accuracy at 250 km [RD07].

The most accurate timing is needed for CSP timestamping but there are several other ngVLA functions requiring accurate timing, detailed in subsystem interface definitions. The timing design will be carried forward to the LO and Timing Conceptual Design Review so that all of these timing requirements will be demonstrably supported. Additionally, for the most demanding requirements a detailed timing budget will be developed with allocations for GNSS accuracy, antenna station time transfer, cable delay contributions, and frequency reference accuracy – while including possible thermal effects.

4.4 Environmental Protection

Г

The diagram in Figure 22 shows the product deliverables of the LO Reference and Timing (LRT) subsystems grouped by location and environment. In the central building the equipment and racks are the responsibility of LRT, whereas in the repeater station and antenna stations the equipment goes into a rack provided by another IPT. This arrangement delineates a deliverable and responsibility, but in every case there will be an interface definition which specifies an appropriate temperature range and stability, and a thermal design that meets the interface requirement. In addition to the deployed, operating environmental specifications, there are requirements for survival temperature range, shock and vibration, seismic effects, and altitude range [AD02], [AD03].



Figure 22: LO Reference and Timing products grouped by environment. INF= Infrastructure IPT, FIB: Fiber Infrastructure, ANT= antenna IPT.



Fitle : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

4.5 RFI, EMC, and Lightning Protection

All of the electronic design for LO Reference and Timing will be subject to maximum RFI and emission requirements. Electronics will be contained within RFI suppressing housings, with further measures taken as necessary to keep emission levels below the ngVLA threshold values. Lightning protection will be detailed in the rack and LRU interface definitions and implemented as necessary depending on the equipment location. This includes surge protection at AC and DC power entries, and all racks shall be properly grounded to a ground bus.

4.6 **Power Supply and Distribution**

Antenna Station assemblies shall receive DC power from the Antenna Electronics DC power supply subsystem, defined in [AD04]. This includes voltage levels, current capacity, and voltage rms noise levels. In the central building and the repeater stations, mains AC will be distributed in the racks by COTS Power Distribution Unit (PDU) to support commercial equipment, and a custom DC power supply design will be implemented for the custom RTG and RTD equipment. This design will leverage the antenna electronics power supply design to the extent possible.

4.7 Reliability, Availability, and Maintainability

The LRT requirements [AD02, AD03] include specification for Mean-Time-Between-Maintenance and Mean-Time –Between-Failure. For commercial parts, high reliability components will be selected and for custom designs reliability will be assessed and documented. Additionally, to support maximum operational availability, the equipment will be designed with maintenance indicator and failure prediction, and with all maintenance performed at the line-replaceable-unit (LRU) level.

4.8 Safety Analysis

All equipment shall comply with ngVLA safety guidelines including hazard analysis and safety labeling. Optical safety shall comply with ANSI Z136 and IEC 60825-1 standards as noted in [AD02], [AD03].

4.9 Technology Readiness Assessment

The technologies associated with the LO Reference and Timing are generally at a TRL level of three. In most cases there are paper designs using technologies that are well proven and which have been deployed on telescopes with TRL levels of nine. The ngVLA LO requirement, for example, could be met for some frequencies by ALMA or EVLA LO modules. Designing for ngVLA requires a new but in many ways similar design. Similarly for the RTD subsystem, prior synthesis arrays have used similar equipment at a TRL level of 9. In the case of ngVLA, a new design is required to optimize the performance versus cost, but presents new risk mainly in meeting phase drift over very long (1000 km) fiber links.



5 Appendix A: Trade Studies

5.1 Local Oscillator Trade Study

See [RD03], ngVLA Antenna Local Oscillator Trade Study. This study analyzed four types of LO configurations: fixed frequency electronic, tunable frequency electronic, tunable remote (pedestal) photonic, and tunable remote (central building) photonic. The Fixed frequency electronic approach was chosen, while keeping the remote photonics pedestal configuration as a backup to mitigate size, weight, and power risks at the secondary focus enclosure.

5.2 Frequency Transfer Trade Study

The study of best technique for frequency transfer is being conducted and will be completed prior to a downselect during the LO Reference and Timing Conceptual Design Review. A short discussion of some aspects of that study is included here.

A design assumption is that there will be a provision for the distribution of a reference and timing signal to each antenna station, as well as a continuous monitoring of those signals so that fluctuations in the one-way propagation (due especially to thermal effects) can be mitigated.

The LO frequency plan is currently arranged so that each LO frequency is a multiple of 2.9 GHz, and thus strong consideration will be given to implementing a frequency transfer design that supports this frequency plan with simplicity. For instance, frequency transfer of 2.9 GHz or a frequency that is harmonically related to 2.9 GHz is being studied.

A design that utilizes (only) two wavelengths separated by the transfer frequency is attractive because with only two wavelengths there is no chromatic dispersion induced amplitude fading. Design based on this principle is used for instance by the Square Kilometre Array frequency distribution system for the MID-Array [RD08]. The approach detailed in prior work by H. Kiuchi of NAOJ [RD09] and discussed in Section 4.3.1 also uses the two-wavelength approach and has architectural flexibility in choice of frequency and type of receiver, and in regard to real time vs offline correction [RD10, RD11]. Figure 23 and Figure 24 show a recent proof of concept architecture and measurement result using the NAOJ approach for a 100 GHz-250km frequency transfer.

	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
а	NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B



Figure 23: Proof of concept test for RTD subsystem including reference sources and laser, frequency transmitter and receiver, and elements of long haul repeater station. Test apparatus is shaded yellow.

	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
/la	NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B



Figure 24: Allan deviation versus integration time for a 250km, 100 GHz frequency transfer link with correction applied offline. The parameter "offset time" indicates the cadence at which the measured round-trip phase is applied to the data as a correction. "0 sec" is the result for a real-time correction with bandwidth ~ 100 Hz. The case without compensation shows the drift increasing at T>10 sec.

Finally, there is another technique being developed at NRC-Canada called Incoherent Clocking [RD12], that allows for the antenna station LO to be *not* phase locked to a common distributed reference. This is a fundamentally different assumption and approach, and will not be included in the trade study but will be discussed at the time of the downselect. In this approach, the LO oscillator is nominally free running but its phase is digitally "tagged" and transmitted to the central site. The thermal fluctuations of the fiber transmission are measured and corrections are applied at the central correlator to correct both the time-of-flight fluctuations and the LO wandering.

5.3 Time Transfer Trade Study

The study of best technique for time transfer is being conducted and will be completed prior to a downselect during the LO Reference and Timing Conceptual Design Review. A short discussion of some aspects of that study is included here.

As mentioned in Section 4.3.3, the baseline approach at the time of Systems CDR is an all optical approach [RD07]. This is sketched in the form of a block diagram in Figure 25. The input I PPS timing signal is used to modulate an RF carrier, transmitted to the antenna stations, and the demodulated I PPS is recovered at the antenna. The recovered signal then remodulates a return signal so that the round trip timing "round

	<i>Title</i> : LO Reference and Timing Design Description	Owner: Shillue	Date : 2022-05-30
/la	NRAO Doc. #: 020.35.00.00.00-0002-DSN		Version: B

trip delay" can be measured. This technique is amenable to a closed timing loop or an open loop in which the timing delay is continuously measured and recorded.



Figure 25: Optical two-way time link.

The optical time transfer method has been bench tested in a proof of concept experiment, with a result of < 1 nsec residual timing delay after the measured round trip delay is subtracted from the "station" time. This was demonstrated over 250 km, and the technique is extendable by either the addition of repeater gain or by implementing a daisy chain.

In addition to the all optical approach, the White Rabbit approach will be included in the trade study and downselect. This will be based on the open source White Rabbit development (an open-source Ethernet based synchronous Ethernet solution) [RD14] and on the SKA white Rabbit effort which focused on long baseline and enhanced accuracy [RD15]. The SKA demonstrated transfer accuracy of <10 nsec at 173 km, and < 2 nsec for the case using higher accuracy DWDM components.

The techniques will be evaluated for performance versus the requirement, timing accuracy versus link distance, overall cost of development, manufacture, and operation, and technical and operational risk.

5.4 Connected Antennas versus Standalone

A future trade study will examine the cost, technical trade study to determine the best point (fiber length) to transition from directly connected antennas to stand-alone antennas. (Cost of fiber infrastructure vs cost of stand-alone RTGs)



6 Appendix B: Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
AFD	Antenna Fiber Distribution subsystem
AIV	Acceptance, Integration, and Verification
ALMA	Atacama Large Millimeter Array
ANSI	American National Standards Institute
ATF	Antenna Time and Frequency
BMR	Bins, Modules, and Racks subsystem
CDR	Critical Design Review
CEB	Central Electronics Building
CI	Configuration Item
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
DRO	Dielectric Resonator Oscillator
DWDM	Dense Wave Division Multiplexing
EEC	Antenna Electronics Environmental Control subsystem
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge
EVLA	Extended Very Large Array
FDR	Final Design Review
FED	Front End subsystem
FIB	Central Fiber Infrastructure
GHz	Gigahertz
GNSS	Global Navigation Satellite System
HIL	Hardware Interface Layer
HVAC	Heating, Ventilation, and Air Conditioning
I/F	Interface
ICD	Interface Control Document
IEC	International Electrotechnical Commission
IPT	Integrated Product Team
IRD	Integrated Receiver Digitizer
KPP	Key Performance Parameter
LBA	Long Baseline Array
LED	Light Emitting Diode
LO	Local Oscillator
LOC	Limit Operation Conditions
LRT	LO Reference and Timing
LRU	Line Replaceable Unit
M/C	Monitor and Control
MCL	Monitor and Control subsystem
MOE	Measure of Effectiveness



Title : LO Reference and Timing Design Description	Owner: Shillue	Date: 2022-05-30
NRAO Doc. # : 020.35.00.00.00-0002-DSN		Version: B

Acronym	Description
MOP	Measure of Performance
MTBF	Mean Time Between Failure
MTTM	Mean Time to Maintenance
MTTR	Mean Time to Repair
NAOJ	National Astronomical Observatory of Japan
ngVLA	Next Generation Very Large Array
NLL	Narrow Linewidth Laser
NOC	Normal Operation Conditions
NRAO	National Radio Astronomy Observatory
NRC	National Research Council (Canada)
NSB	ngVLA Site buildings
OEO	Optical-Electronic-Optical
OLED	Organic Light Emitting Diode
PBS	Product Breakdown Structure
PCB	Printed Circuit Board
PDF	Portable Document Format
PDU	Power Distribution Unit
PE	Project Engineer
PLDRO	Phase Locked Dielectric Resonator Oscillator
POC	Precision Operating Conditions
PPS	Pulse Per Second
PSU	DC Power Supply subsystem
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
RTD	LO Reference and Timing - Distribution
RTG	Reference Timing Generation
SBA	Small Baseline Array
SFE	Secondary focus Enclosure
SKA	Square Kilometer Array
ТВС	To Be Confirmed
TBD	To Be Determined
TPM	Technical Performance Measure
TRL	Technology readiness level
VCO	Voltage Controlled Oscillator
WVR	Water Vapor Radiometer

020.35.00.00.00-0002-DSN-B-LO_Reference_Ti ming_Design_Description

Final Audit Report

2022-06-01

Created:	2022-05-31
Ву:	Anne Lear (alear@nrao.edu)
Status:	Signed
Transaction ID:	CBJCHBCAABAAaEKWQKgWv-iZxnQJUu8_IDMykfHrcpQ4

"020.35.00.00.00-0002-DSN-B-LO_Reference_Timing_Design_ Description" History

- Document created by Anne Lear (alear@nrao.edu) 2022-05-31 - 3:20:28 PM GMT- IP address: 75.161.220.198
- Document emailed to William Shillue (bshillue@nrao.edu) for signature 2022-05-31 - 3:21:37 PM GMT
- Email viewed by William Shillue (bshillue@nrao.edu) 2022-06-01 - 7:40:40 AM GMT- IP address: 89.7.222.10
- Document e-signed by William Shillue (bshillue@nrao.edu) Signature Date: 2022-06-01 - 7:41:06 AM GMT - Time Source: server- IP address: 89.7.222.10
- Document emailed to R. Selina (rselina@nrao.edu) for signature 2022-06-01 - 7:41:09 AM GMT
- Email viewed by R. Selina (rselina@nrao.edu) 2022-06-01 - 12:07:43 PM GMT- IP address: 97.123.171.205
- Document e-signed by R. Selina (rselina@nrao.edu)
 Signature Date: 2022-06-01 12:11:20 PM GMT Time Source: server- IP address: 97.123.171.205
- Document emailed to Thomas Kusel (tkusel@nrao.edu) for signature 2022-06-01 - 12:11:23 PM GMT
- Email viewed by Thomas Kusel (tkusel@nrao.edu) 2022-06-01 - 12:54:38 PM GMT- IP address: 192.131.232.128
- Document e-signed by Thomas Kusel (tkusel@nrao.edu) Signature Date: 2022-06-01 - 12:55:13 PM GMT - Time Source: server- IP address: 192.131.232.128



- Document emailed to Willem Esterhuyse (westerhu@nrao.edu) for signature 2022-06-01 12:55:15 PM GMT
- Email viewed by Willem Esterhuyse (westerhu@nrao.edu) 2022-06-01 - 1:33:41 PM GMT- IP address: 105.186.158.158
- Document e-signed by Willem Esterhuyse (westerhu@nrao.edu) Signature Date: 2022-06-01 - 1:34:22 PM GMT - Time Source: server- IP address: 105.186.158.158
- Agreement completed.
 2022-06-01 1:34:22 PM GMT

