Local Oscillator Reference and Timing Design Description

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Status: **RELEASED**

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Change Record

Version	Date	Author	Affected Section(s)	Reason
1	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.
A	2019-07-26	A. Lear	All	Incorporated edits by R. Selina & M. McKinnon; prepared PDF for signatures and release.

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1 Introduction

1.1 Purpose

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

1.2 Scope

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

It does not include specific technical requirements or budgetary information.

The document is arranged as follows:

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

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

2 Related Documents and Drawings

2.1 *Applicable Documents*

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

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

2.2 *Reference Documents*

The following documents are referenced within this text:

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

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

3 Subsystem Overview

3.1 Array Expanse

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

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

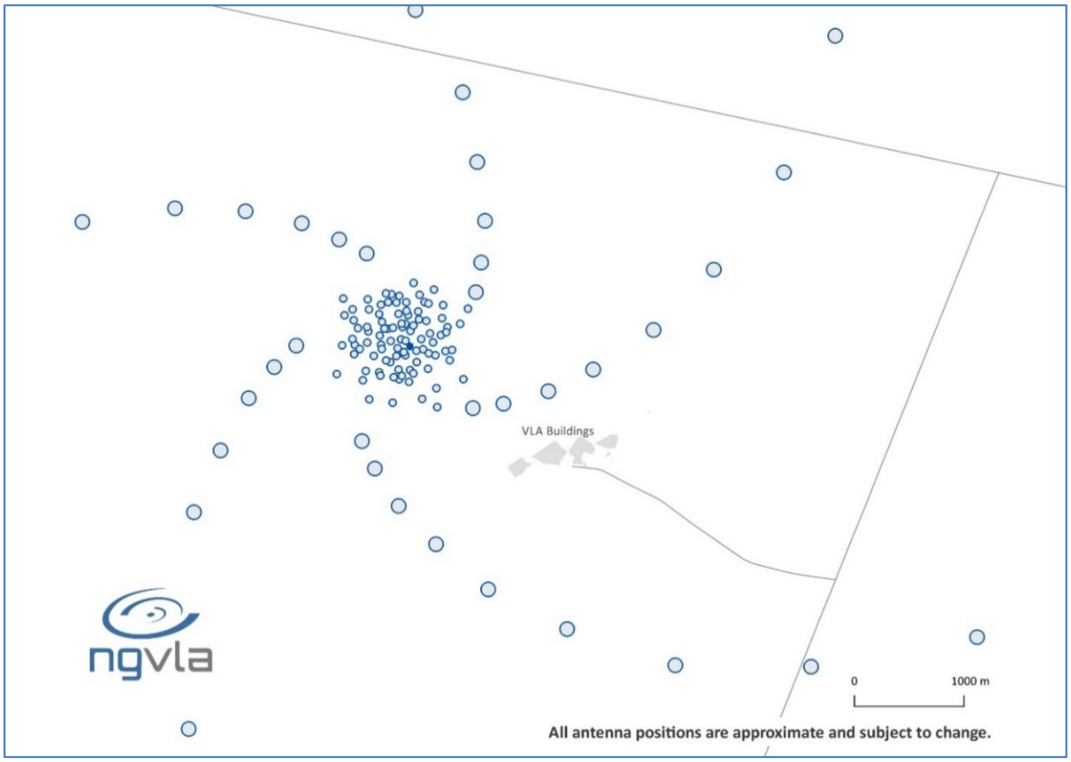


Figure 1 - A preliminary (rev B, Apr 2018) configuration map for only the antennas included in the core. Note that the symbol sizes in the core have been scaled down for visibility. All antennas in the main array including the core are 18 m diameter. However, there are additionally 19 6 m antennas of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

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

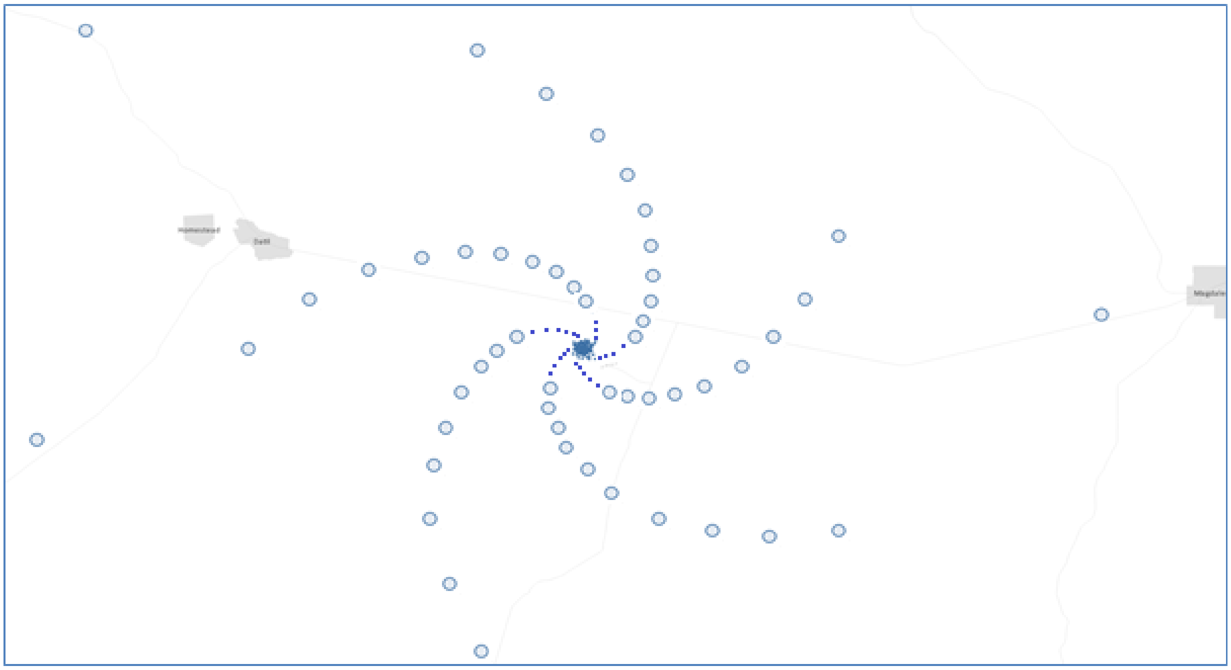
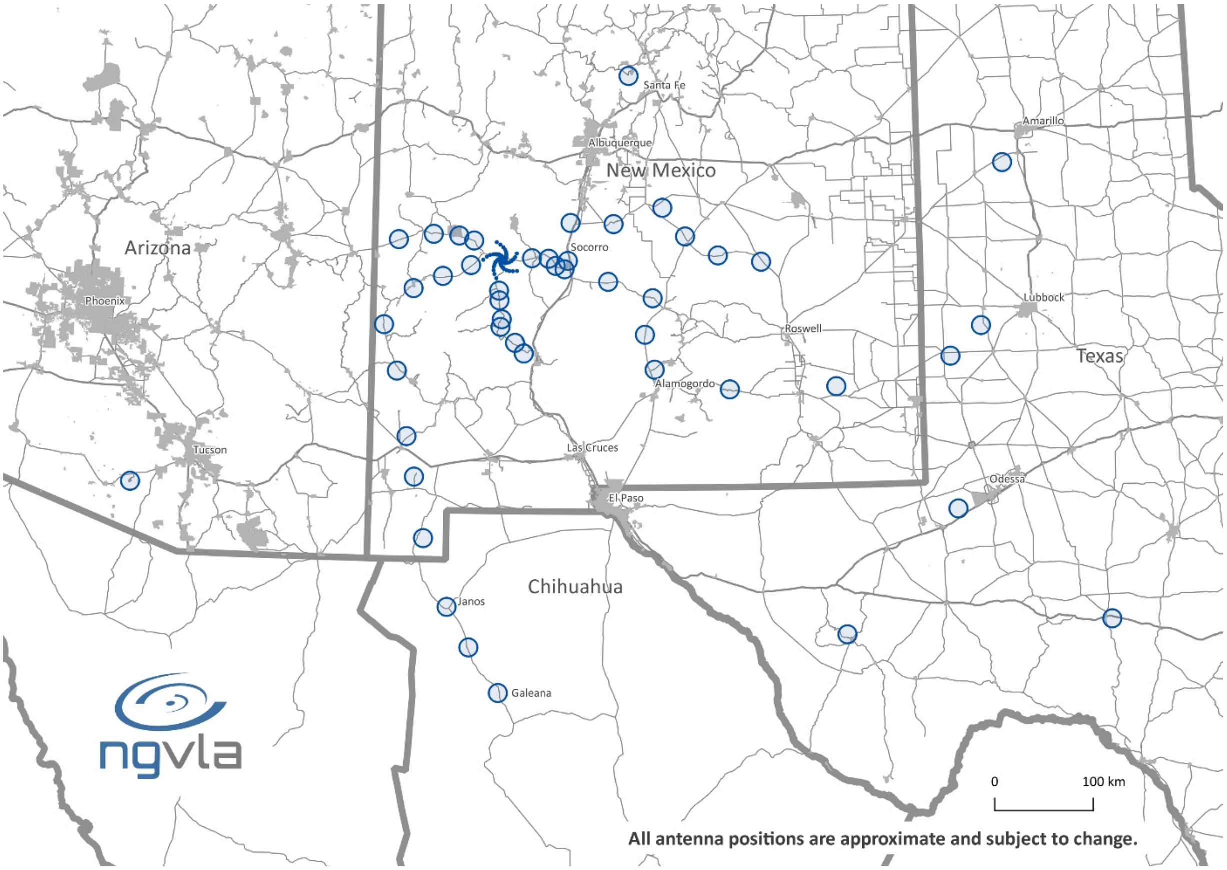


Figure 2 - Central cluster plus five spiral arms. The spiral arms contain 74 18 m antennas. The figure shows approximately 60 km east-west and 40 km north-south. The distance along the spiral arms is approximately 25 to 30 km.

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



All antenna positions are approximate and subject to change.

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

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

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

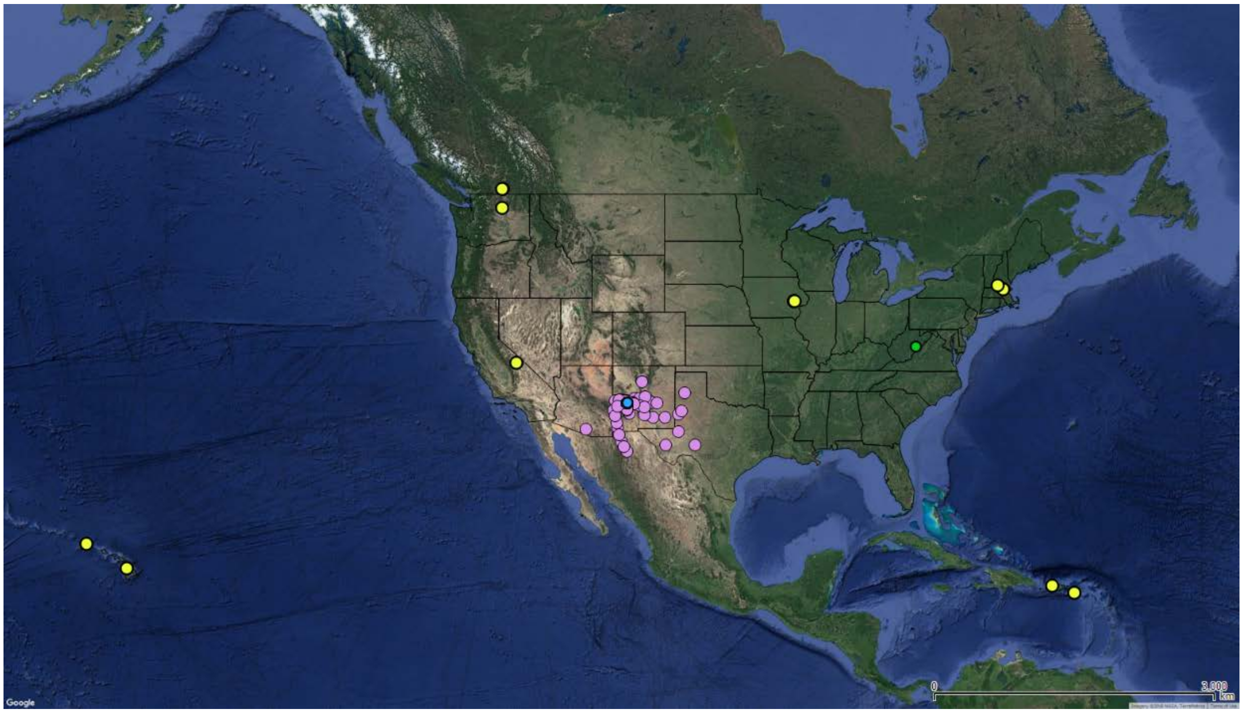


Figure 4 - ngVLA LBA sites shown in yellow. GBT site shown in green. ngVLA core and main array in blue and purple, respectively. 30 antennas are included in the LBA configuration, distributed per Table 1 below.

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

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

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

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

3.2 *Top Level Description: LO Timing and Reference*

The LO Reference and Timing work element is responsible for supplying accurate and reliable local oscillator, sampler clock, and timing references to the antenna stations and the central signal processor (CSP). The block diagram shown in Figure 5 illustrates the major functional blocks of the LO Reference and Timing. The references are generated and synchronized in the central building, and a frequency reference and timing signal are provided to the central signal processor. The references are then distributed with all necessary amplification, buffering, splitting, etc., and the required signals are transmitted to each antenna. Since this is a much generalized functional diagram, the following assumptions and caveats are made:

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

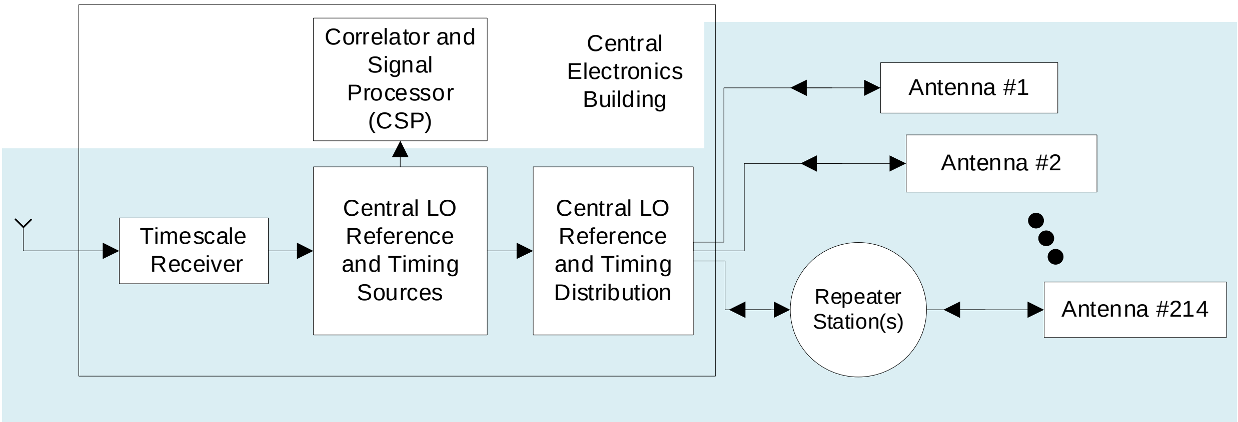


Figure 5 - Block Diagram of LO Reference and Timing: LO Reference and Timing parts are shaded.

3.3 Design Assumptions and Drivers

The following assumptions are reflected in this reference design:

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

4 LO Reference and Timing Requirements

4.1 *Key Requirements*

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

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

Table 3 - Critical LO reference and timing requirements.

4.2 *Number of Antennas*

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

4.3 *Phase Drift*

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

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

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

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

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

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

4.4 Phase Noise

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

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

4.5 Spurious Level and LO Noise Level

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

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

4.6 Flexible Subarrays

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

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

4.7 Number of Simultaneous LOs

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

5 Central Time and Frequency Reference

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

5.1 Central LO Reference and Timing Overview and Block Diagram

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

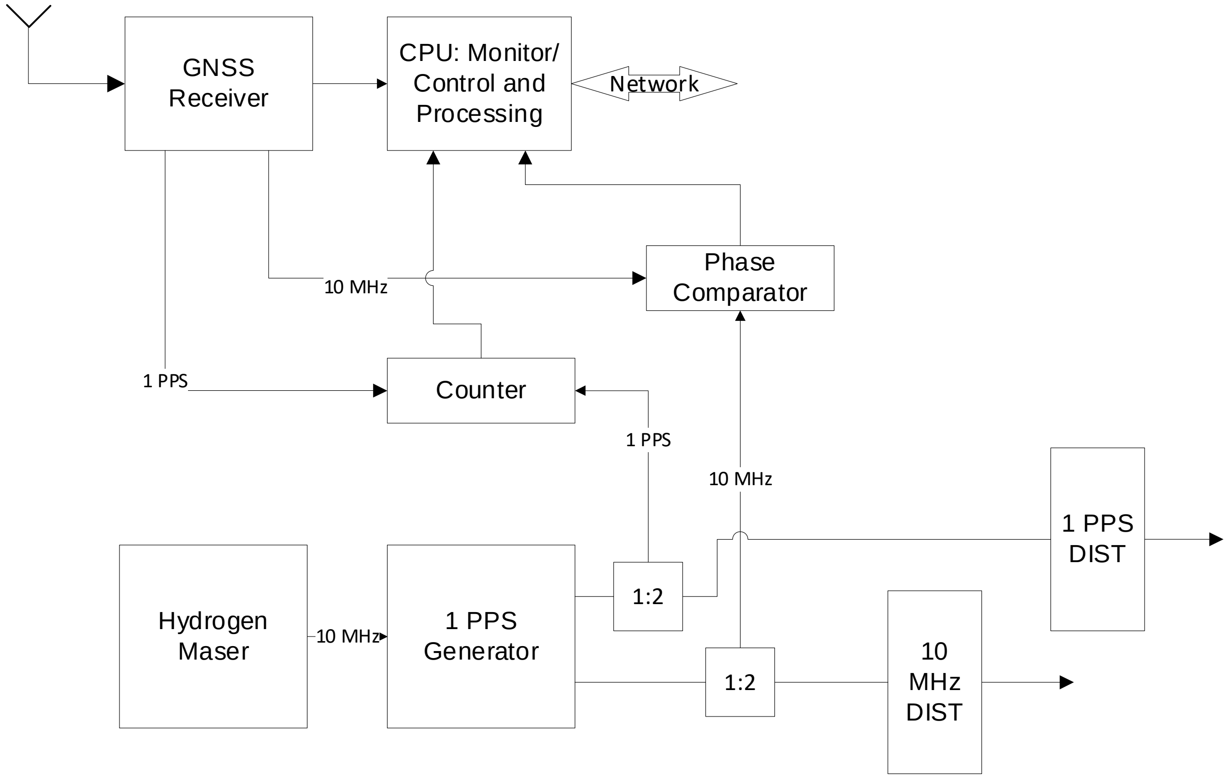


Figure 6 - Block diagram of central timing.

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

5.2 Central LO Reference and Timing Components

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

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

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

Table 4 - Typical Allan deviation of hydrogen maser.

5.3 Central LO Reference and Timing Interfaces with other Subsystems

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

6 Time and Frequency Reference Distribution

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

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

6.1 Frequency Synchronization - Background

6.1.1 ALMA System

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

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

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

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

6.1.2 EVLA System

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

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

6.1.3 SKA System

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

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

6.1.4 SKA-low

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

6.1.5 SKA-mid

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

6.1.6 Comparison of SKA-mid and SKA-low

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

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

6.1.7 Other Examples of Remote Frequency Dissemination

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

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

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

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

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

6.1.8 Phase Correction Dynamic Range

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

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

6.2 Time and Frequency Reference Distribution Overview

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

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

6.3 Time and Frequency Reference Distribution Block Diagrams

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

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

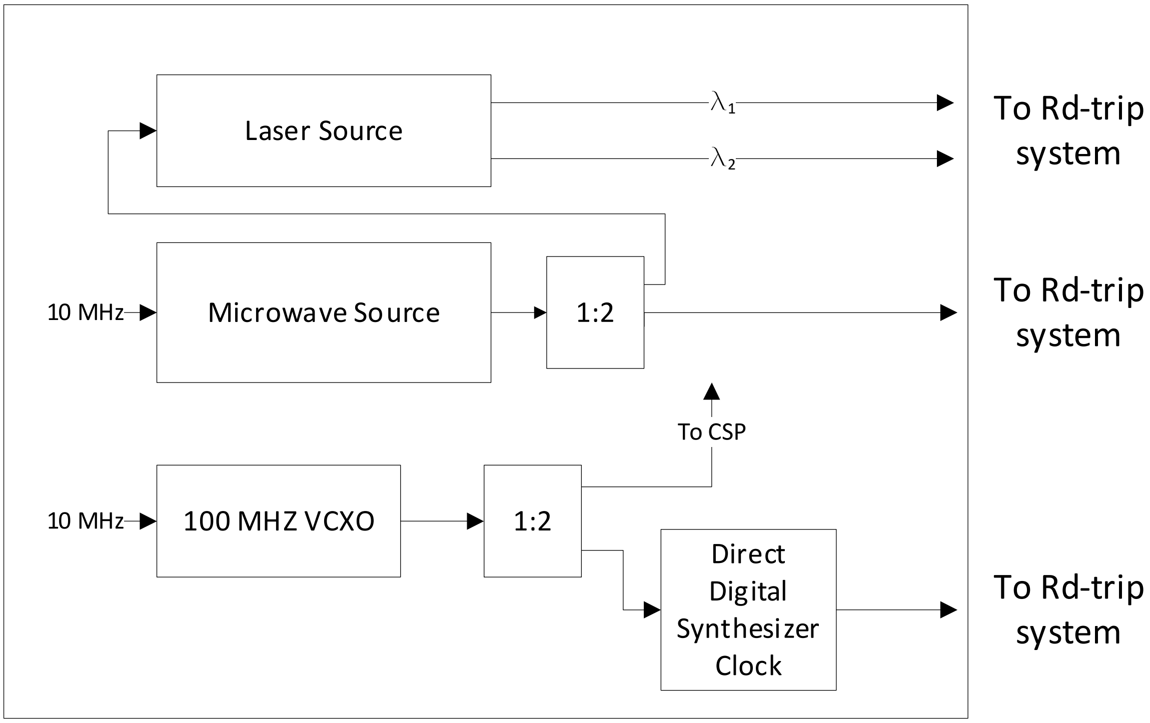


Figure 7 - Block diagram of central reference and timing sources.

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

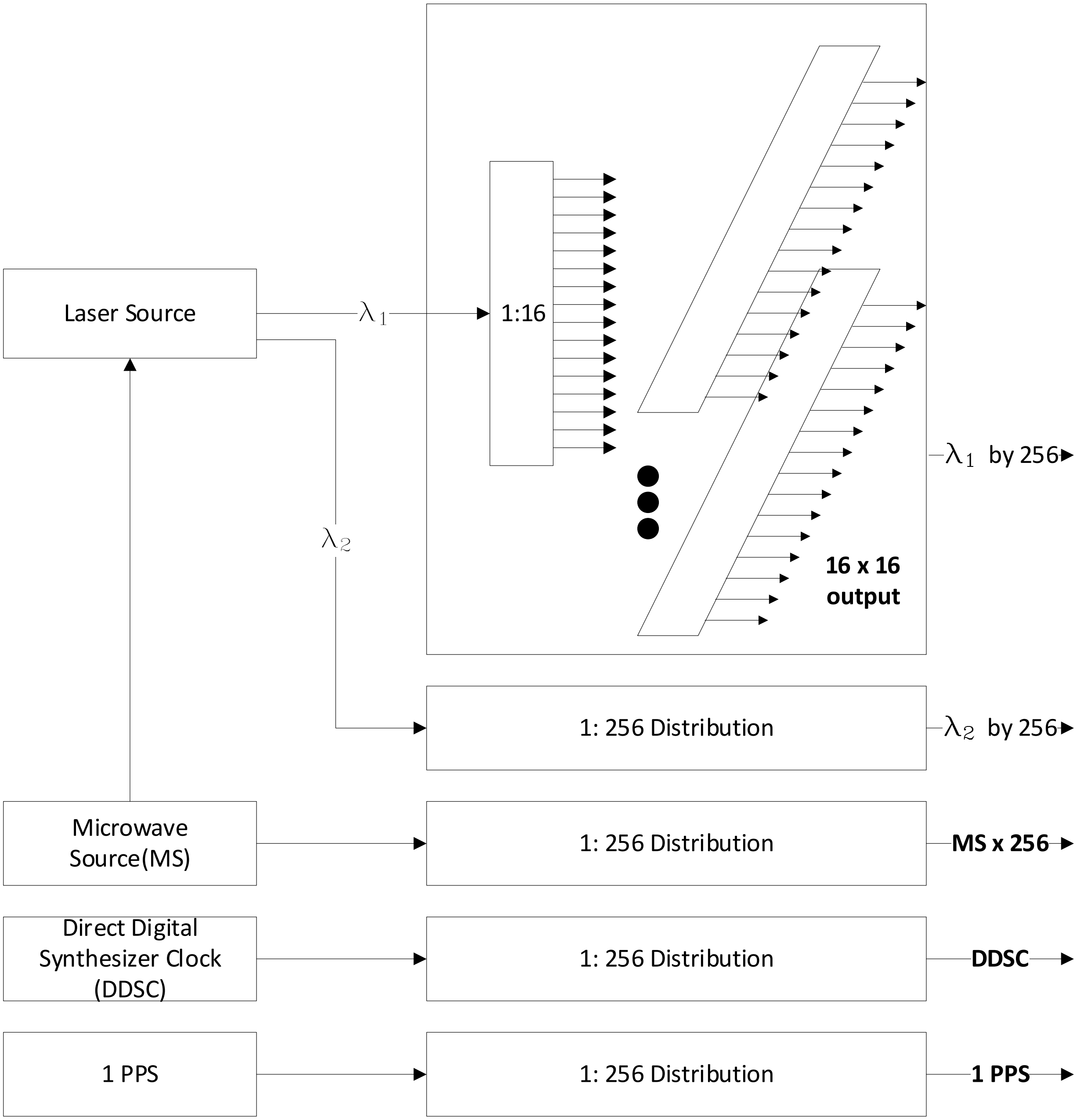


Figure 8 - Detail of reference clock and timing distribution (256-way).

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

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

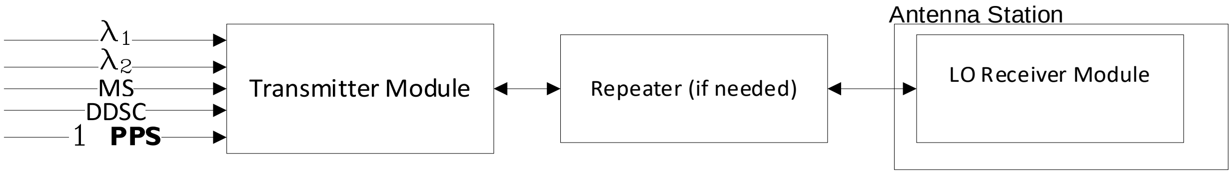


Figure 9 - Simplest view of round-trip circuit.

6.3.1 Round-Trip Phase Transmitter

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

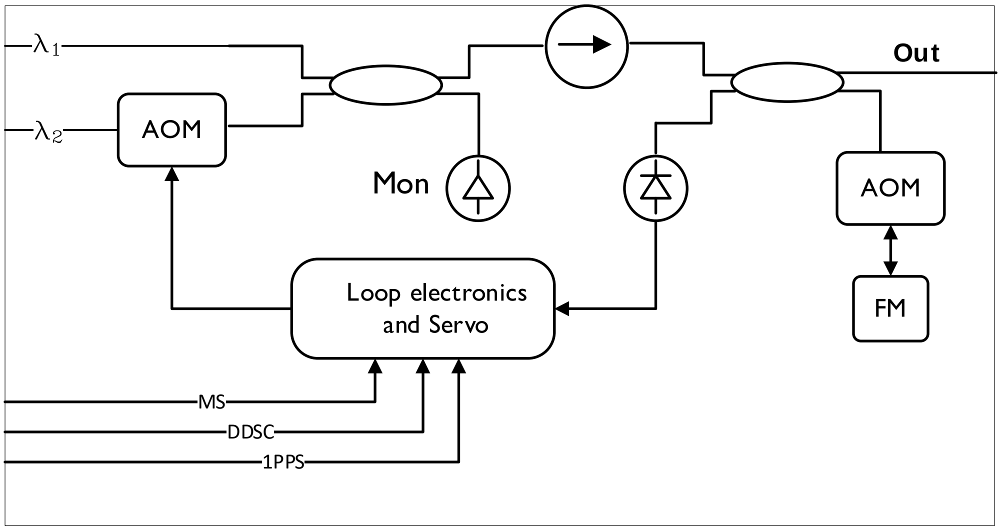


Figure 10 - Detail of round-trip transmitter module.

6.3.2 Bidirectional Repeaters

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

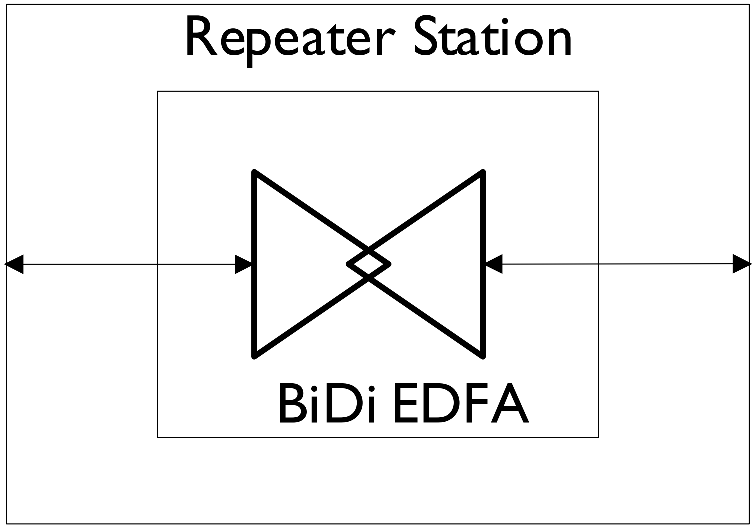


Figure 11 - Detail of bidirectional amplifier hut and repeater hut.

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

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

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

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

6.3.3 LO Receiver Module

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

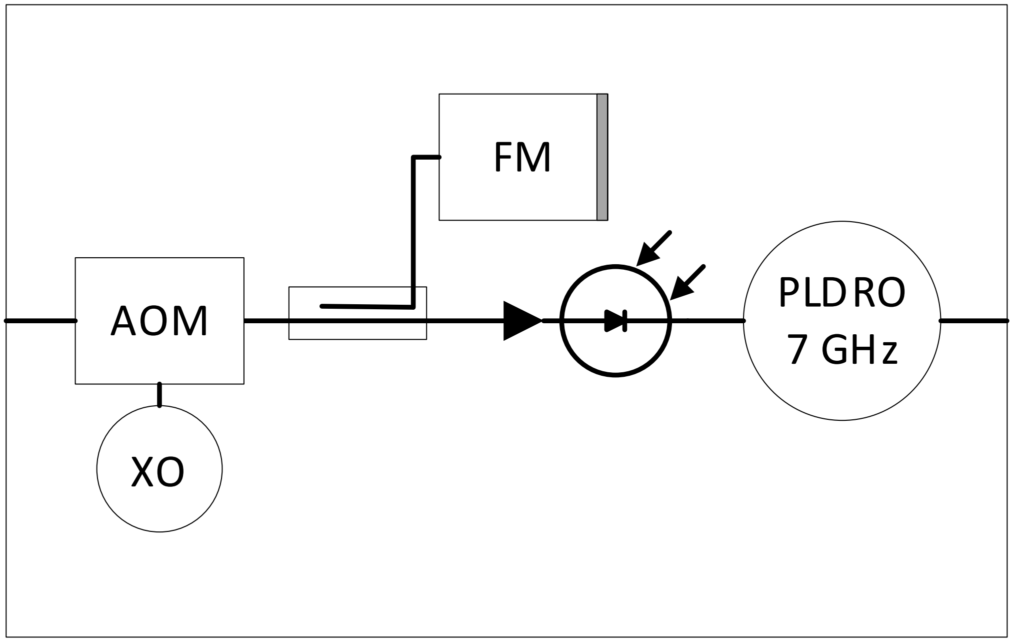


Figure 12 - LO receiver module (antenna).

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

6.4 LO Reference and Timing Distribution Components

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

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

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

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

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

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

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

6.5 LO Reference and Timing Distribution Interfaces with Other Subsystems

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

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

7 Antenna Time and Frequency System

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

7.1 Antenna Time and Frequency Reference Interfaces and Block Diagram

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

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

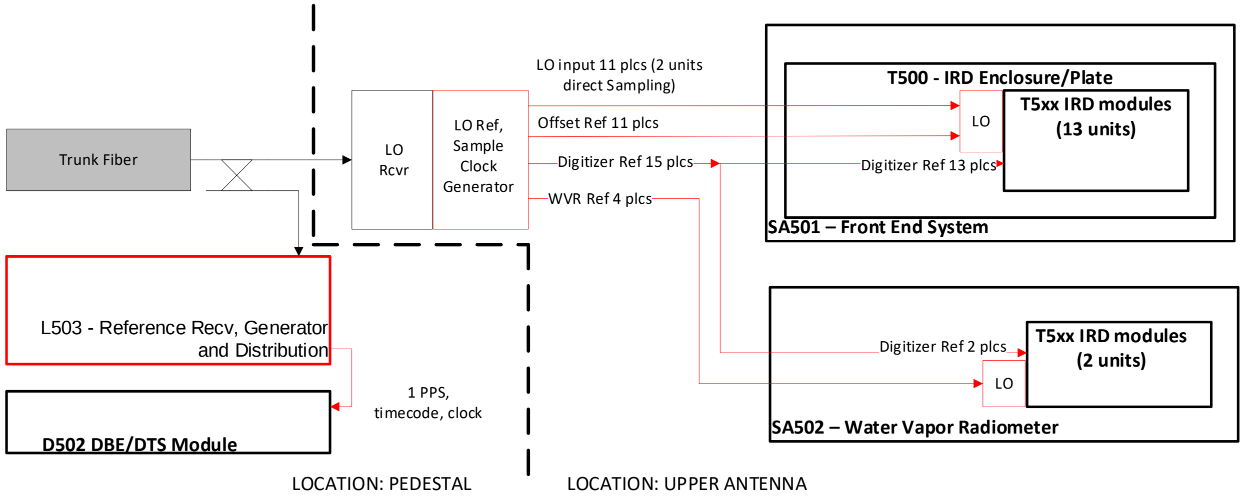


Figure 13 - Antenna time and frequency components (marked in red) and showing interfaces with Front End and DBE/DTS.

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

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

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

7.2 Antenna Time and Frequency Reference Design Approach

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

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

7.3 Reference Receiver, Generator, Distribution Module

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

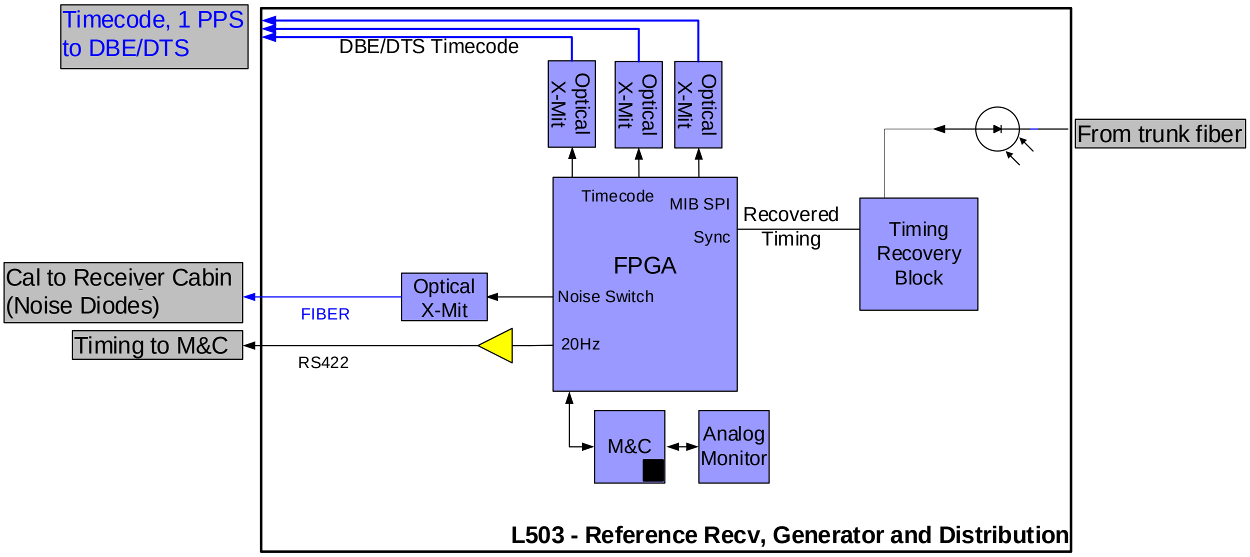


Figure 14 - Reference receiver, generator, and distribution.

7.4 LO Reference and Sample Clock Generator module

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

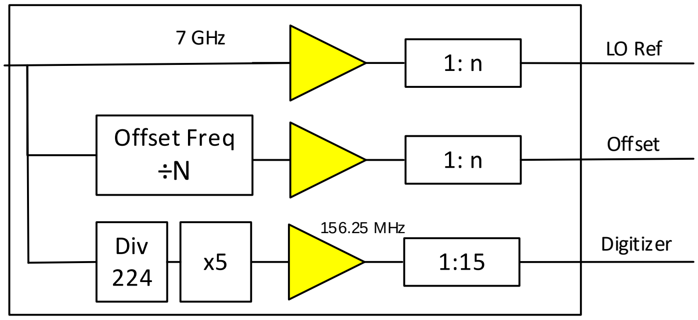


Figure 15 - LO reference and sample clock generator.

7.5 LO Frequency Plan

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

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

Table 5 - Proposed LO and RF plan for ngVLA.

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

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

Band	RF low	RF hi	Nominal LO Frequency	VCO Frequency (GHz)	Reference Divider, R	RF Divider, N	Phase Detector Frequency (MHz)	M$_1$	M$_2$	Actual LO Frequency (GHz)
3	10.5	17.5	14 GHz	14	1	2	7000	1	1	14
	17.5	21	21 GHz	21	1	3	7000	1	1	21
4	20.1	27.1	23.6 GHz	23.6	35	118	200	1	1	23.6
	27.1	34.1	30.6 GHz	15.297	27	59	259.26	2	1	30.59
5	30.1	37.1	33.6 GHz	16.8	5	24	700	2	1	33.6
	37.1	44.1	40.6 GHz	20.3	5	29	700	2	1	40.6
	44.1	51.1	47.6 GHz	23.8	5	17	1400	2	1	47.6
6	70	77	70 GHz	17.5	2	5	3500	2	2	70
	77	91	84 GHz	21	2	6	3500	2	2	84
	91	105	98 GHz	24.5	2	7	3500	2	2	98
	105	119	112 GHz	28	2	8	3500	2	2	112
WVR1	24	27.5	24 GHz	24	7	24	1000	1	1	24
	27	30.5	27 GHz	27	7	27	1000	1	1	27
WVR2	18	21.5	18 GHz	18	7	18	1000	1	1	18
	21	24.5	21 GHz	21	7	21	1000	1	1	21

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

Note that:

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

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

7.6 Local Oscillator Modules

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

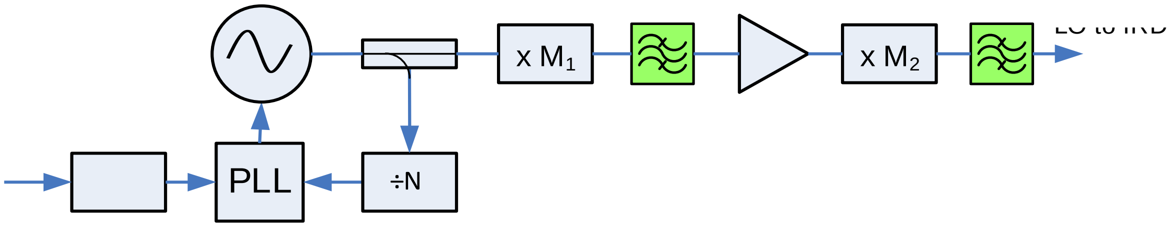


Figure 16 - LO source module generalized schematic.

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

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

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

Table 7 - Shifted frequency plan.

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

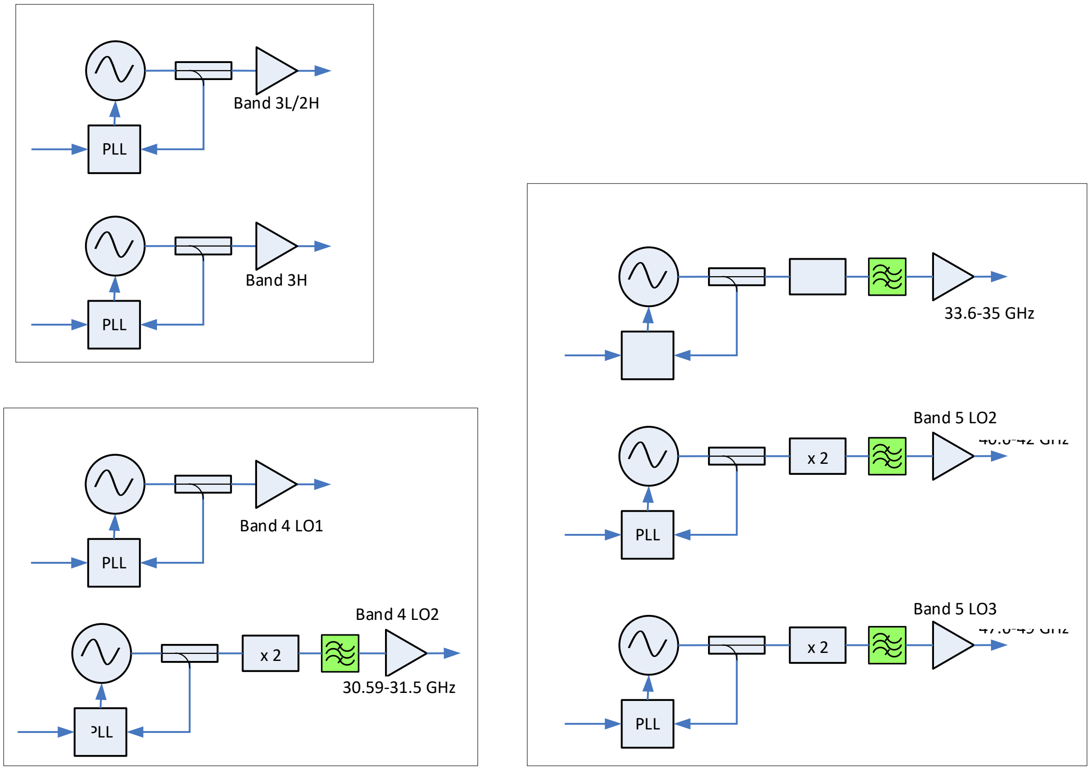


Figure 17 - Implementation of LO for IRD modules for ngVLA Bands 3, 4, and 5.

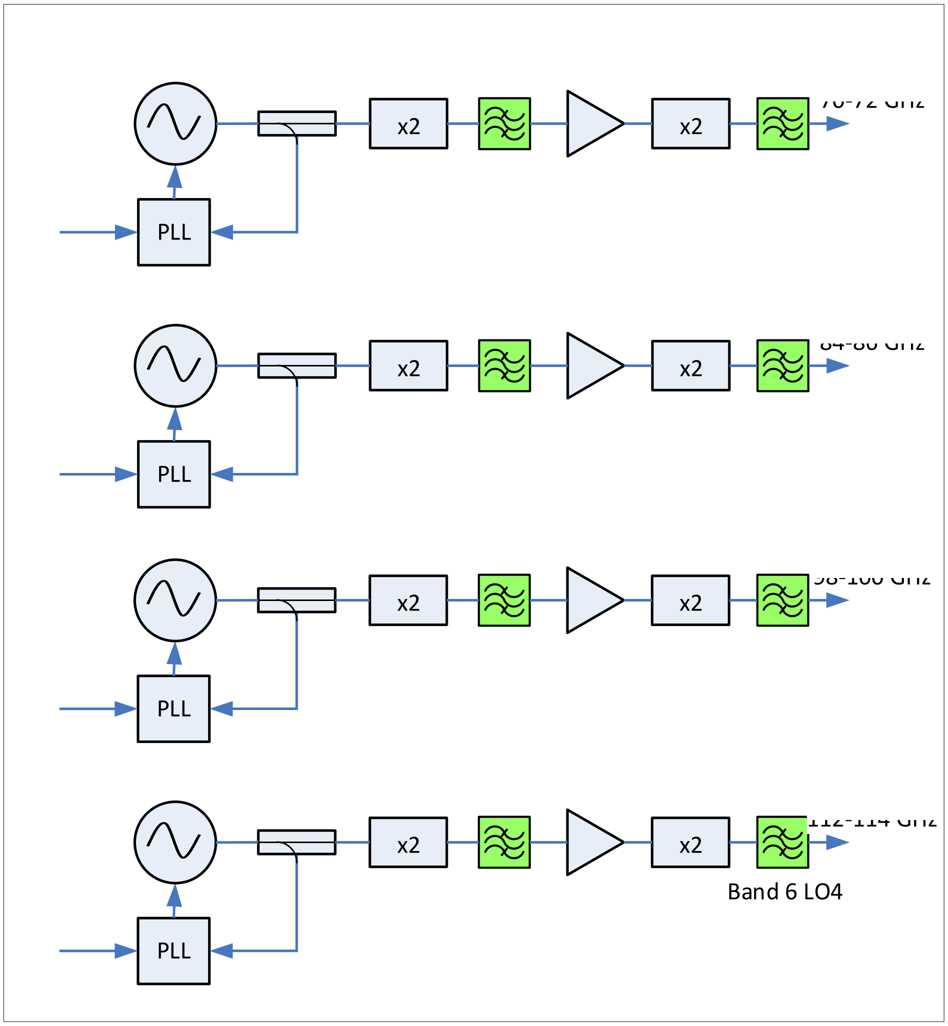


Figure 18 - LO modules for ngVLA Band 6.

7.7 Standalone Antenna Station

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

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

7.8 Antenna Time and Frequency Reference Components

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

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

7.9 Antenna Time and Frequency Reference Interfaces with Other Subsystems

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

8 Appendix

8.1 Abbreviations and Acronyms

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