EVLA Memo 105

Phase coherence of the EVLA radio telescope

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ABSTRACT

The design of the National Radio Astronomy Observatory's Expanded Very Large Array (EVLA) project is approaching completion. Four of the twenty-seven antennas have been upgraded into the final configuration. The 2200 miles of fiber optic cables have been installed underground and are functional. The master oscillator and the round trip phase hardware have been operating uninterrupted since November 2003. Hundreds of hours of test observations have been performed as we start the task of characterizing the upgraded system. This paper discusses the results of this testing and describes the techniques used to maintain phase coherence of the EVLA LO chain and of the new wideband receivers. The enhancements to the VLA system include a new local oscillator (LO) system, a fiber optic LO distribution system, and a digital round trip phase measurement system. The phase requirement for the LO system requires that the long term phase drift slope be less than 6.0 picoseconds per 30 minutes at 40 GHz and be maintained across the entire array. To accomplish this, a near real time continuous measurement is made of the phase delay in the fiber optic cable distributing the LO reference signals to each antenna. This information is used by the correlator to set the phase on each of the baselines in the array.

Keywords: phase coherence, fiber optics, round-trip phase, EVLA

1. INTRODUCTION

The Very Large Array (VLA), located on the Plains of San Agustin fifty miles west of Socorro, New Mexico, consists of twenty-seven 25 meter parabolic antennas configured in the shape of a 35 km diameter "Y". The data from these antennas are combined electronically to give the resolution of an antenna 35 km (22 miles) across, with the sensitivity of a dish 130 meters (422 feet) in diameter. As designed and built in the 1970's, the VLA was a state-of-the-art radio telescope. Since that time, however, the need for a more sensitive instrument has arisen. Increasing scientific requirements coupled with aging electronic equipment and major advancements in technology has led to the Expanded Very Large Array (EVLA) project. The goal of the EVLA project is to increase the overall system bandwidth by a factor of 80 and to increase the sensitivity and spatial resolution of the present VLA [1]. The design and prototype phase of the EVLA project is now nearing completion. Prototype hardware has been installed on four antennas and is in regular use. Many hundreds of hours of test observations have been run on the complete system using actual astronomical signals to evaluate EVLA performance. In addition, the EVLA antennas are now beginning to be used in routine scientific observations with the existing VLA system. The local oscillator and reference system has been in continuous operation since November 2003, allowing substantial time for performance testing of the central and antenna electronics and the fiber optic LO transmission system. One of the keys to the performance of the EVLA system is the long term phase stability specification 6.0 picoseconds per 30 minutes at 40 GHz across the entire array. This specification is challenging to meet and requires continuous monitoring and correction to ensure optimum performance. The top-level system requirements for the LO system are shown in Table 1.

Table 1. Local oscillator (LO) system requirements

Phase Stability	6.0 ps per 30 minutes at 40 GHz
LO Optical Channel Wavelength:	1310 nm

Distributed LO Frequency:	512 MHz
Maximum Fiber length:	22 km
Minimum Fiber Length:	0.625 km
Operating Temperature:	-12^{o}C to +35^{o}C

2. SYSTEM SPECIFICATIONS

Phase stability is the key for proper operation of any interferometer. The following parameters delineate the phase stability specifications for the entire EVLA electronics system. These specifications do not include phase instabilities that are the result of the antenna's structural components, the drive system, or the atmosphere.

Short Term: Less than 0.5 picoseconds RMS over 1 second.
(2% coherence loss at 40 GHz), (7.2 degrees RMS at 40 GHz)

Peak-to-Peak Phase Deviation: Less than +/- 0.7 picoseconds about a linear slope calibration.
(20 degrees at 40 GHz after removal of calibration linear slope components)

Long Term Phase Drift Slope: Less than 6.0 picoseconds over any 30 minute period.
(Approximately 90^o of phase shift at 40 GHz)

To meet these stability requirements, every module, component, and cable must be designed and built for phase stability. Most of this stability can be achieved by controlling the temperature environment of the electronic sub-systems and by using sound engineering design practices.

The phase instability of each individual sub-system in the EVLA affects the total phase stability of the antenna. A direct, uncompensated fiber optic LO distribution system would contribute substantial phase instability to the system. The use of a round trip phase measurement system coupled with a correlator based correction will reduce the effect the fiber optic system has on the phase stability and relaxes the stability requirements on the other electronic sub-systems.

The LO system starts with a hydrogen maser. The output of the maser is the master frequency reference for the central LO racks and is distributed to the antennas through a fiber optic link. The antennas phase lock to the distributed maser signal and multiply up the frequency to over 50 GHz. The IF signals are mixed with these upconverted LO's to produce the baseband signals. The following sections describe the phase noise contribution of the major blocks starting with the maser.

3. HYDROGEN MASER

The hydrogen maser used in the EVLA is model number VLBA-112, serial number SN#2, made by Sigma Tau Standards Corporation (now called Sigma Tau Group owned by Symmetricom). It was delivered to NRAO in September 1987. The stability of typical hydrogen masers is about 1fs/day for frequency drift and 0.2ps for phase jitter(2). The performance requirements of the EVLA are shown in Table 2.

Table 2. Performance requirements of the hydrogen maser

Item	**Requirement**	
Maximum Frequency Error	1 part in 10^{12} averaged over 10 sec	
Wide-band phase noise at 5 MHz	1.4 ps RMS	
Phase noise Allan Variance	1<t<1000secs 1000<t<10,000secs	$2E\text{-}13t^{-3/5}$ 3E-15

The only standard to which NRAO can compare a maser is to another maser. SN#13 is the present reference maser. Figure 1 shows a plot of the Allan standard deviation obtained in 2005, comparing maser SN#2 to maser SN#13. The performance requirements from Table 2 are plotted as the specification line on Figure 1. This plot shows that the EVLA maser performance can be divided into two regions: 1) the short term noise region - dominated by either white-phase noise or white-frequency noise, and 2) the flicker-frequency noise region – referred to as the flicker floor [(2)]. Time periods greater than 10^4 seconds are considered long term noise and are typically dominated by random frequency drift. Two other parameters can be specified, a frequency drift rate and a frequency accuracy. The frequency drift rate is the linear change in frequency per unit time, typically less than $1x10^{-15}$ Allan deviation for time periods greater than 10^4 seconds. The average frequency offset during the Allan standard deviation test of maser SN#2 was 6 $x10^{-15}$. The accuracy refers to how well the maser can be set to the nomial frequency of 5 MHz, typically less than +/-10^{-12} Hz over ten seconds Allan deviation. Again, maser SN#2 is within this specification.

Maser SN#2 is used as the primary reference for the EVLA telescope. Although small changes in frequency and phase that are common to all 27 antennas can be rejected, the short and long term performance of maser #2 has an impact on the performance of the entire telescope.

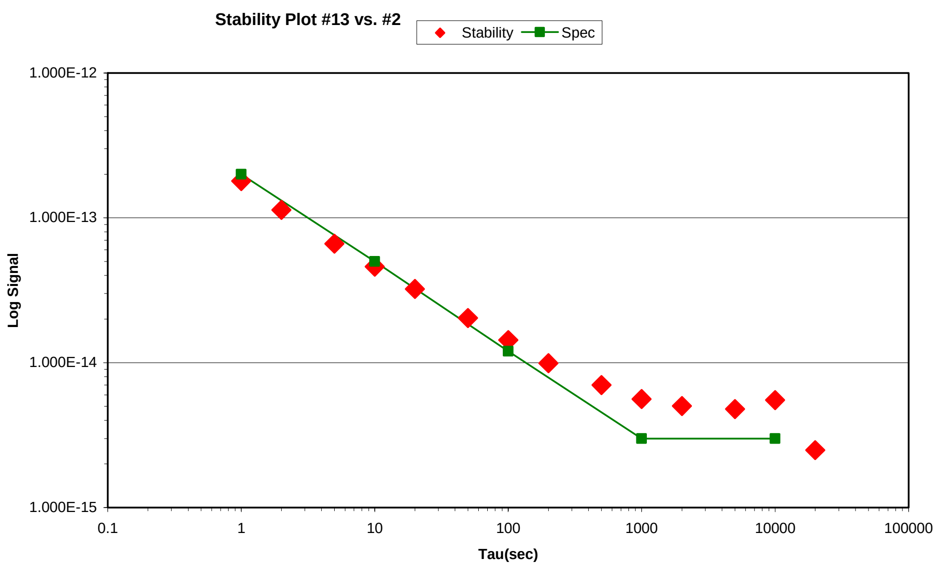

Figure 1. Allan standard deviation of masers SN#2 versus SN#13

4. LOCAL OSCILLATOR SYSTEM

The EVLA local oscillator system consists of two subsystems, the central LO and the antenna LO. The central LO produces a reference signal that is common to all antennas and is phase locked to hydrogen maser SN#2. This common LO signal is then distributed to all 27 antennas via a system of lasers, fiber optic cables, and photodiodes. A second oscillator located in the antenna is phase locked to this reference and used to clean up the noise introduced by the LO distribution system. A detailed description of each of these systems follows.

4.1 Central LO system

Maser SN#2 is the primary reference for the central EVLA LO system. The central reference generator (the L350) uses the 5 MHz from the maser to generate all of the local oscillator signals needed by the control building EVLA racks, the correlator, and the antenna LO signal, Figure 2. The reference 5 MHz supplied by the maser is used to phase lock a 128 MHz oscillator. The output of the oscillator is then directly multiplied to 512 MHz, which is used as the primary reference. The 128 MHz is digitally divided down to 5.12 MHz, 19.2 Hz, 128 Hz, and 0.1 Hz. The 5.12 MHz is the digital clock used by the round trip phase system. The 128 Hz is the beat frequency used by the round trip phase system. The 19.2 Hz is the heartbeat timing signal used for maintaining communications and for noise calibration timing. The 0.1 Hz signal is used to time the reset signal sent to align the phase of the antenna reference signals.

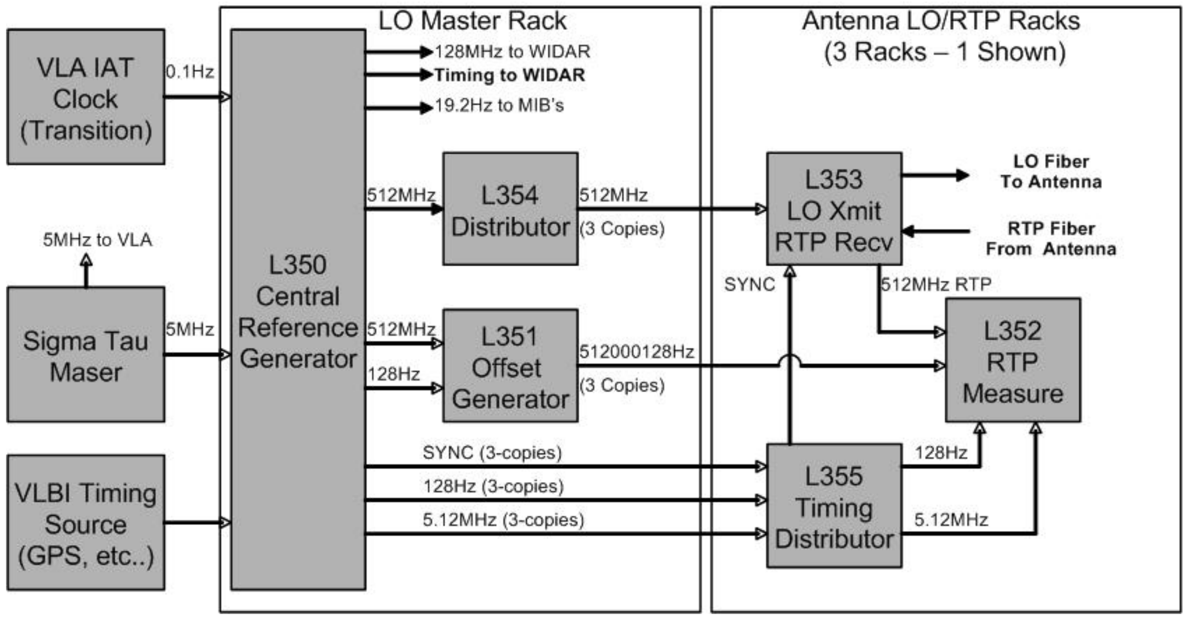

Figure 2. Block diagram of the central EVLA LO system

The central EVLA LO system is based on a high quality 128 MHz voltage controlled phase locked crystal oscillator (PLXO) located in the L350 central reference generator. The 128 MHz is upconverted to 512 MHz and then down converted in the antenna. The 128 MHz PLXO in the L350 central reference generator is manufactured by Wenzel Associates, Inc. part number 5000-09196. The long term temperature stability of the PLXO is +/- 5 x 10^{-7} over 0-50°C. The phase characteristics of this PLXO are shown in Table 3. These characteristics are more than adequate since the performance of the L350 module is controlled by many factors. The first is that the PLXO is directly locked to the maser which dominates the long term stability. The second is that the output of the L350 is common to the entire EVLA which tends to correlate out common to all antenna characteristics. The third is that the output of the L350 is used to drive the fiber optic LO distribution system. The fiber system is sensitive to ambient temperature changes which are many orders of magnitude worse than the phase stability of the L350 PLXO.

Table 3. Wenzel Associates phase locked crystal oscillator factory specifications when locked to a reference – in this case the Hydrogen Maser

Output Phase Noise (locked)		
	1 Hz	-82dBc/Hz
	10 Hz	-82dBc/Hz
	100 Hz	-112dBc/Hz
	1 KHz	-142dBc/Hz
	10 KHz	-162dBc/Hz
Temperature Stability		
	+/- 5 x 10^{-6} 0º-50ºC	

One method to estimate the short term phase jitter contribution of the L350 PLXO is to integrate the noise energy from 1 to 100 Hz, convert from power to voltage and multiply by the upconversion factor (40 GHz/128 MHz=240). Using this method the contribution from this L350 PLXO is about 17.4º at 40 GHz, worst case. On the surface this seems to be a large portion of the project specification, 20 degrees at 40 GHz. There is only one L350 module in the EVLA project so any jitter will be common to all antennas and can be ignored. In addition, the L350 is phase locked to the maser so long term drift will not be an issue.

4.2 Antenna LO system

The antenna LO system is based on a Wenzel Associates 128 MHz voltage controlled phase locked crystal oscillator located in the L305 antenna reference generator module. The frequency of 128 MHz was selected to provide adequate synthesizer resolution. The L305 module phase locks the 128 MHz reference to the 512 MHz provided by the LO reference receiver module (L304) via the fiber system, Figure 3. The 128 MHz is multiplied to 1024 MHz, 2048 MHz, and 4096 MHz. These signals are used by the LO synthesizers, the IF converter modules and the data transmission system. Due to this frequency conversion of the reference, there can be a timing ambiguity in the antennas. This ambiguity is resolved by using the reset signal to align antenna phase and by astronomical calibration. The 128 MHz is also divided by an FPGA to 19.2 Hz and 9.6 Hz to provide timing for the module interface boards and the cal switching, respectively.

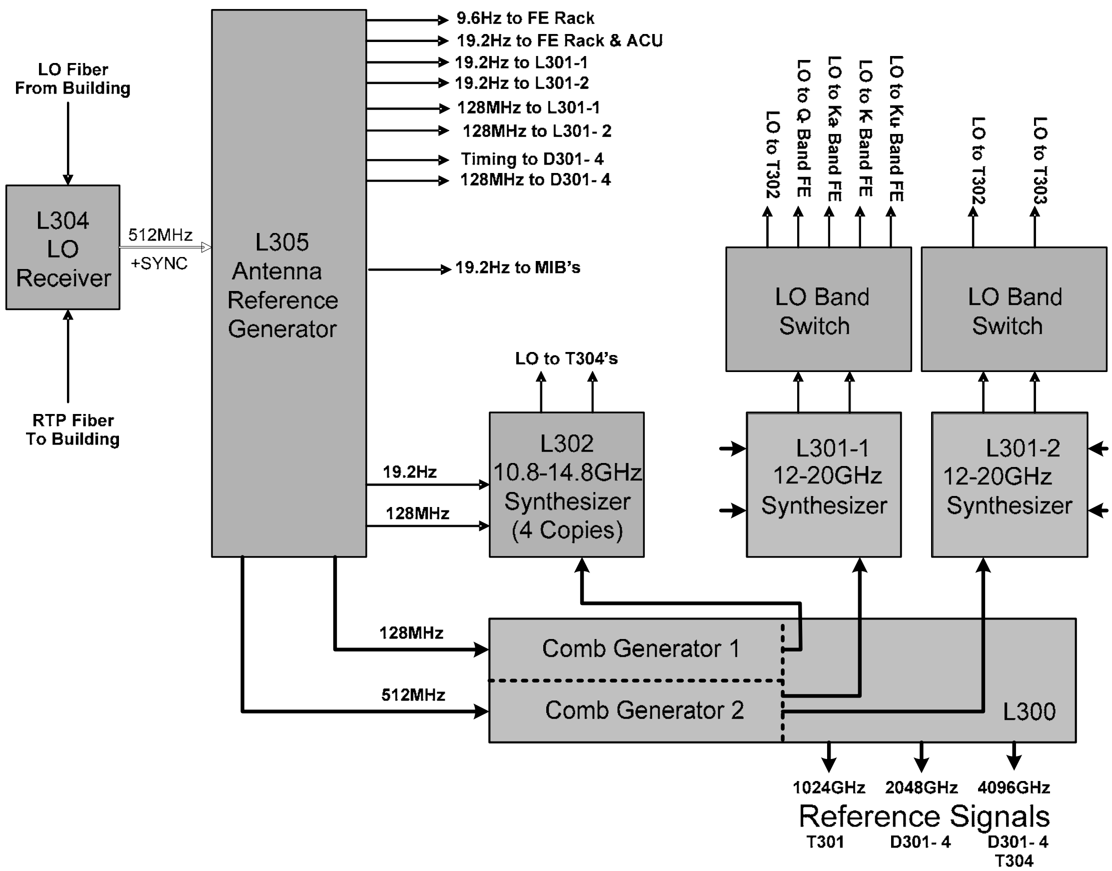

Figure 3 Block diagram of the antenna LO system

The antenna LO system receives the reference 512 MHz over the fiber. This reference contains the reset signal that is recovered and used to reset the antenna timing. A portion of the optical 512 MHz is returned to the central system through an optical coupler. The returned 512 MHz is mixed with a 512.000128 MHz signal to produce a 128 Hz signal that is representative of the change in round trip phase. This change in phase is used by the round trip phase measurement system to determine changes in fiber phase delay due to temperature and fiber stress. The frequency of 512 MHz was selected to provide a robust round trip phase measurement system with a resolution of +/-1.0ps.

4.3 Short term phase noise of the LO system

The short term phase noise or jitter of the system is determined by the properties of the phase locked crystal oscillators (PLXO) in both the L350 central reference generator and L305 antenna reference generator modules. The transition between these two oscillators occurs at 50 Hz. This is the cutoff frequency of the low pass filter portion of the phase locked loop in the L305 module located in the antenna. For offsets greater than 50 Hz from the 512 MHz carrier, the phase noise of the oscillator in the L305 module is the primary contributor. The L305 is based on the Wenzel Associates model #500-11197 SC Sprinter Oscillator. The typical phase noise specifications for this device are shown in Table 4. This device was chosen due to its excellent phase noise performance at higher offsets. For offsets smaller than 50 Hz from the 512 MHz carrier, the phase noise of the system is primarily determined by the performance of the PLXO in the L350 module located in the central LO system and locked to the maser. The Wenzel Associates, Inc. part number 5000-09196 PLXO used in the L350 module was chosen for its superior performance at small offsets from the carrier. The typical specifications for this oscillator are shown in Table 3. The phase noise specification at offsets greater than 50 Hz are less critical for this device since they are effectively removed by the PLXO in the antenna.

In the antenna, the 512 MHz output of the L305 module is multiplied in the L301 (12-20 GHz) synthesizer and finally by a dedicated frequency tripler located at the LO input of the mixer in the Q-Band receiver. One method used to estimate the phase jitter contribution of this phase locked crystal oscillator is to integrate the noise energy from 1-100 Hz, convert from power to voltage, and multiply by the up-conversion factor from the 512 MHz reference to the sky frequency. For a sky frequency of 40 GHz, this multiplier is approximately 80. Using this method the combined contribution from the L305 and L350 PLXO's is about 4.6º at a 40 GHz sky frequency. This assumes that the fiber optic transmission system does not affect the phase performance of the oscillator.

Table 4. Performance of the Wenzel Sprinter Oscillator in the L305 when locked to the 512 MHz from the L350. The * values are determined by the L350 oscillator.

Output Phase Noise (locked)		
	1 Hz	-82dBc/Hz*
	10 Hz	-82dBc/Hz*
	100 Hz	-104dBc/Hz
	1 KHz	-132dBc/Hz
	10 KHz	-147dBc/Hz
	20 KHz	-152dBc/Hz
Temperature Stability		
	+/- 3 E-7, 0º-50ºC	

5. FIBER ROUND TRIP PHASE SYSTEM

The fiber optic LO distribution system is the one major source of phase instabilities that is not thermally stabilized or in an electrical servo loop. These instabilities are introduced either by temperature variations acting on the fiber or by mechanical stress on the fiber during antenna movement [(3)]. The EVLA fiber optic round trip phase (RTP) system attempts to measure these instabilities. The present RTP system uses two fibers. The first fiber is used to transmit the LO (512 MHz) out to the antenna. A portion of the optical 512 MHz is returned to the central system through an optical splitter and a second fiber. This returned 512 MHz signal is compared to the reference 512.000128 MHz to determine the RTP measurement. It is assumed that the two fibers are in the same bundle and have identical temperature coefficients. If this assumption is true, then any RTP change can be divided by 2 to estimate the phase change at the antenna.

In the current EVLA design, the round trip phase is measured once per second. These measurements are reported back to the correlator via the array monitor and control system. The phase corrections are applied in the correlation process in the form of delays. Most of the temperature induced phase deviation can be measured by the round trip phase system and compensated by correlator delays. Figure 4 shows 48 hours of typical round trip phase data from EVLA Antenna 16. The total phase varied about +/- 80 ps and follows the ambient pad temperature shown in Figure 5. The first order diurnal temperature effects can be measured but the difference of the two fibers adds error.

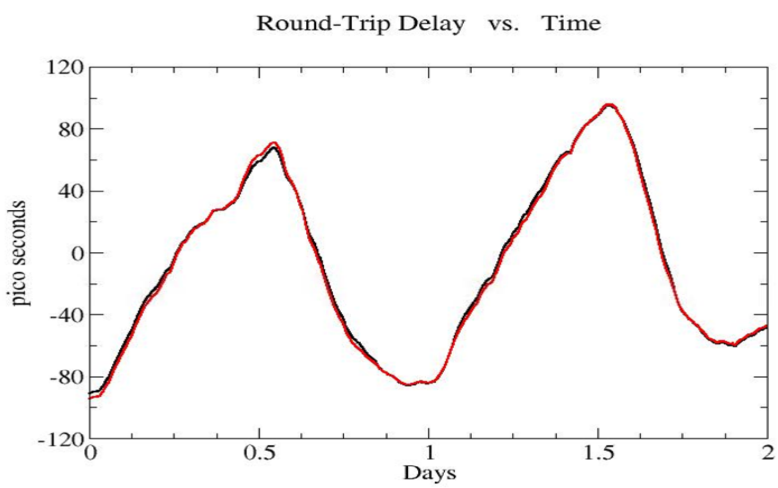

Figure 4. Diurnal temperature effects of LO delay to Antenna 16

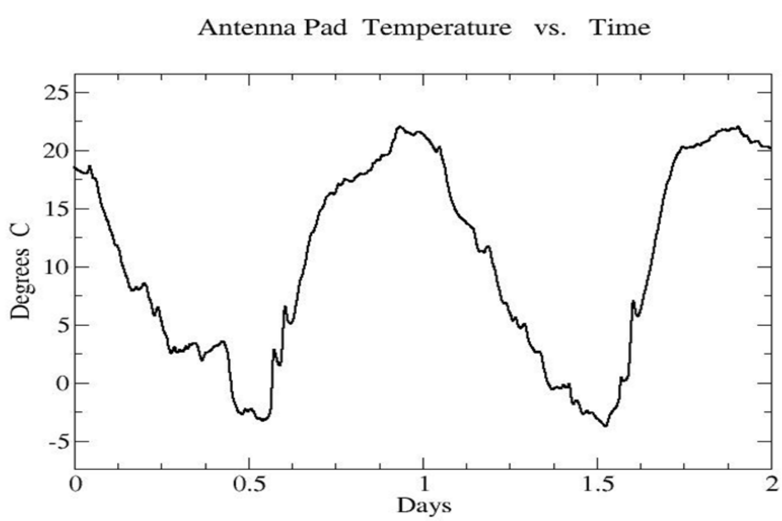

Figure 5. Temperature of the Antenna 16 pad

The difference of the phase of two fibers on Antenna 16 is shown in Figure 6. These data show how the difference of the two fibers effects the LO by +/- 4 ps over the two day period. The current specification states that the uncompensated long term phase deviation shall be less than 6.0 ps over any 30 minute period. The top curve in Figure 7 indicates that the change in delay in any 30 minute period is significantly less than the 6 ps long term slope specification and is estimated to be less than 3 ps.

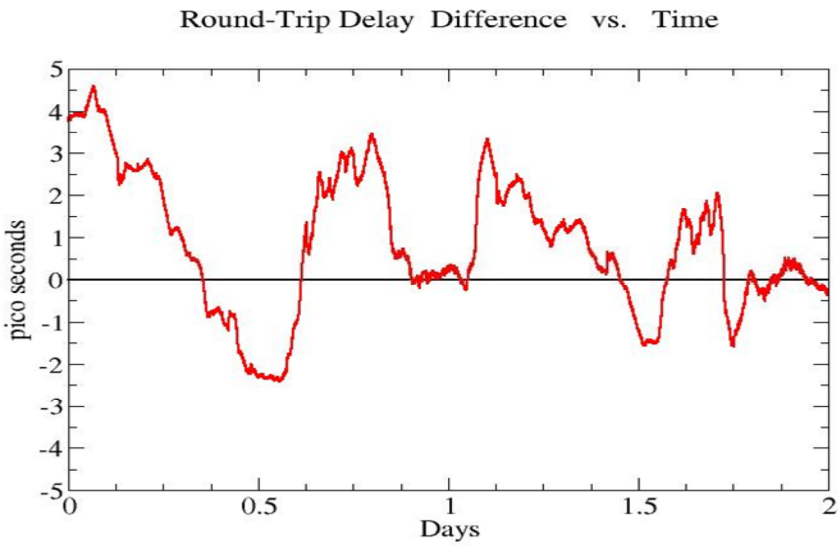

Figure 6. Diurnal temperature induced LO phase change at 512 MHz to Antenna 16

The upper curve in Figure 7 is the same data as in Figure 6 with the addition of a calibration curve. The calibration curve is generated by taking a single point measurement every 30 minutes and connecting them with a straight line. This determines a slope. This technique is similar to performing an astronomical calibration every 30 minutes and adjusting the delays linearly in post processing. The specification states that the uncompensated error shall be less than +/- 0.7 picoseconds about the linear slope. The lower curve in Figure 7 is the difference of the linear slope and the actual data, and is the residual errors caused by the difference of the two fibers. The lower curve shows typical data. A seven day data set indicates that the uncompensated error is about +/- 1.2 ps about the linear slope data.

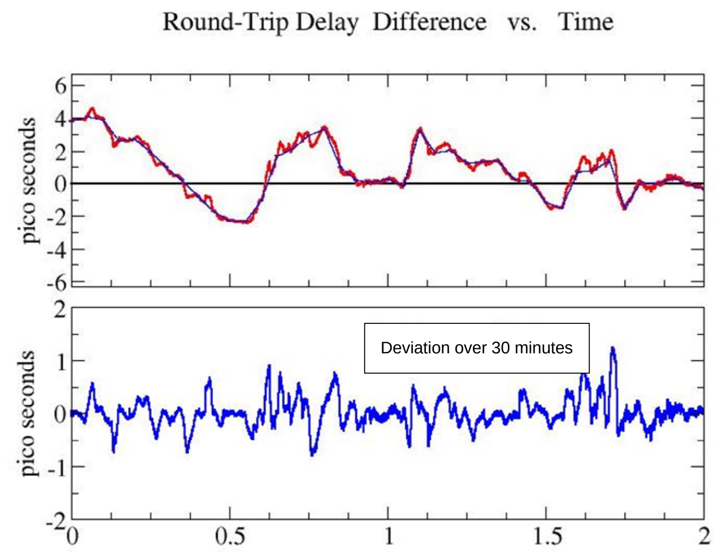

Figure 7. Delay about a linear slope astronomical calibration over 30 minutes.

6. ANTENNA SYNTHESIZERS

The synthesizers in the antennas use the reference derived from the 512 MHz LO, transmitted over the fiber, to generate the required LO's. The L300 module uses the 128 MHz and 512 MHz LO signals from the L305 module and produces the 512 MHz and the 128 MHz comb references that are used by the L301 and L302 synthesizers. The 128 MHz comb is amplified and provided to the four L302 (10.8-14.8 GHz) synthesizers. The 512 MHz comb is amplified and provided to the two L301 (12-20 GHz) synthesizers. These synthesizer outputs are fed to the mixers in the various frequency converter modules and the front-ends. The measured laboratory response of the L301 is shown in Figure 8. Using the method described above, the phase jitter contribution of the L301 upconverted from 12.7 to 40 GHz is about 6.5º at 40 GHz. This is a close to the phase noise budget in the project specification of 7.2º at 40 GHz.

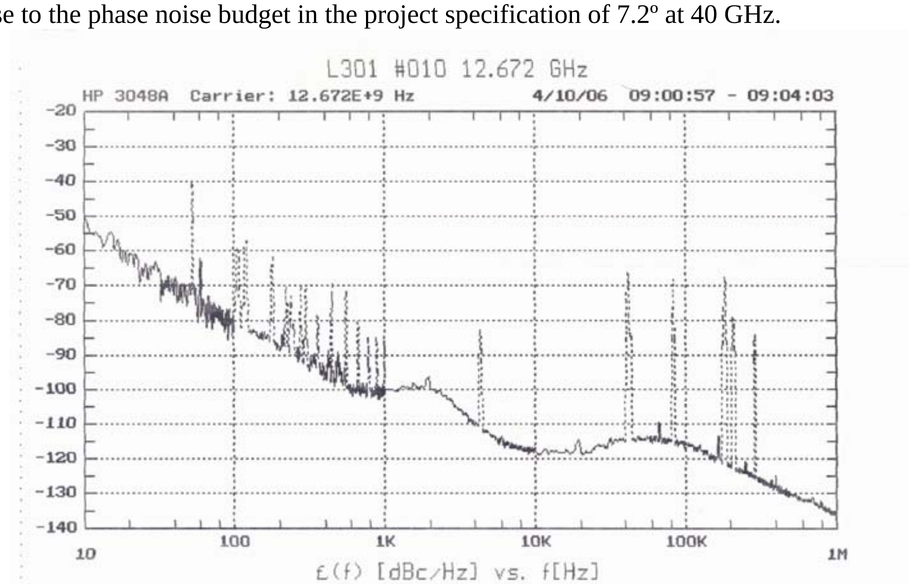

Figure 8. The laboratory response of the L301 synthesizer module.

The measured laboratory response of the L302 is shown in Figure 9. Using the method described above, the phase jitter contribution of the L302 is about 1.6º at 12.89 GHz. This synthesizer output is used directly by the baseband downconverter and is not upconverted.

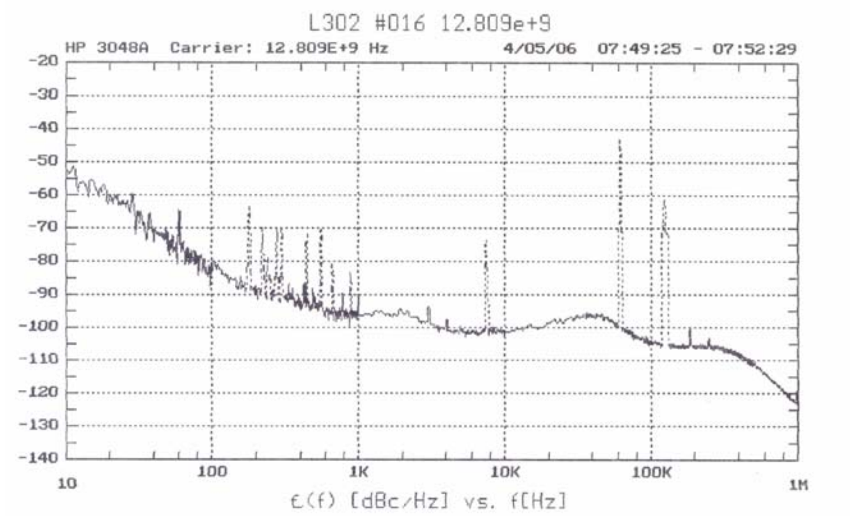

Figure 9. The laboratory response of the L302 synthesizer module

7. BASEBAND DOWN CONVERTERS

The baseband downconverters (T304's) primarily consist of amplifiers, splitters and mixers. These components would contribute minimally to the phase jitter of the system if they are kept at exactly the same temperature. The vertex room in the antenna is air conditioned; however the entire vertex room can tilt 110 degrees during pointing so the downconverters are not kept exactly at a constant temperature. The specification requires that at the baseband output frequency of 1-2 GHz phase change shall be less than 15º if the temperature changes by 20ºC. Chamber tests show that the converters change about 11º at 1-2 GHz with a 20ºC temperature change. The temperature in the vertex room is controlled to 19ºC and is specified not to change more than 0.25º in any 30 minute period. This will contain the jitter contribution of the downconverters to less than 0.14º at 1-2 GHz over 30 minutes per IF channel, (0.26 ps at 1.5 GHz over 30 minutes).

8. CONCLUSION

The phase coherence of an EVLA antenna was estimated by calculating the phase jitter contribution of each of the major sub-systems. The specification is divided into three time periods: short term deviation, peak-to-peak phase deviation, and long term phase drift slope. The short term deviation period result is the RMS value of the three sub-systems listed in Table 5. This specification states that the short term deviation shall be less than 7.2° RMS at 40 GHz. The calculated result is 8.1° RMS.

The peak to peak phase deviation performance is dominated by the fiber optic LO distribution and the round trip phase measurement system and is specified to be less than +/- 0.7 ps about a linear slope calibration. The calculated result of less than +/- 1.22 ps is about twice the specification. The impact of missing this specification will cause a few percent of closure errors.

The long term phase drift slope specification requires that the absolute change of the uncompensated error shall not change faster than 6.0 ps over any 30 minute period. This behavior is controlled by two parameters, the maser characteristics and the fiber stability. The calculated result is less than 3 ps over 30 minutes, easily meeting the specification.

Table 5. Phase coherence summary table

Short Term Deviation: Less than 7.2° RMS at 40 GHz 1-100 Hz	**Peak-to-Peak Phase Deviation:** +/- 0.7 ps about a linear slope astronomical calibration 20 degrees at 40 GHz after removal of calibration linear slope components	**Long Term Phase Drift Slope:** Less than 90° per 30 minute at 40 GHz 6.0 ps over any 30 minute period
L 305/L350 = 4.6°	LO Optical Fiber = +/- 1.2 ps	LO Optical Fiber = 3 ps
L301 = 6.5°	T304 Down Converter = 0.26 ps	Maser stabilized
L302 = 1.6°		
Results	**Results**	**Results**
RMS Value = 8.1°	Less than +/- 1.22 picoseconds	Less than 3 ps over 30 minutes

The EVLA LO system is well designed and meets the required coherence and phase stability specifications. This indicates that, as-built, the EVLA telescope will meet the proposed performance goals of increased sensitivity, spectral resolution and frequency coverage.

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