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Operational Performance of the EVLA LO Round-trip Phase System

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ABSTRACT

The goal of the Expanded Very Large Array (EVLA), project is to upgrade a world-class astronomical instrument in the meter-to-millimeter wavelength bands. The project combines modern technologies with the sound design of the existing Very Large Array (VLA) to increase by an order of magnitude the sensitivity, resolution, and frequency coverage of the existing instrument. This paper discusses the techniques used to maintain phase coherence of the EVLA system. The enhancements to the VLA system include improved feeds and receivers, new Local Oscillator (LO) and Intermediate Frequency (IF) systems, a fiber optic LO distribution system, high speed digitizers, 10Gbps digital links, a dense wavelength division multiplexed fiber transmission system, and a new high speed correlator. The phase requirement for the LO system requires that a phase stability of 2.8 picoseconds per hour at 40 GHz be maintained across the entire array. To accomplish this, a near real time continuous measurement will be made of the phase delay in the fiber optic cable distributing the LO reference signals to each antenna. This information will be used by the correlator to set the delay on each of the baselines in the array.

Keywords : Fiber optics, Round-trip phase, Cable wrap, NRAO, 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 radio antennas configured in the shape of a 35km diameter "Y". The data from these antennas are combined electronically to give the resolution of an antenna 36km (22 miles) across, with the sensitivity of a dish 130 meters (422 feet) in diameter. As designed and built in the late 1970s, 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]. One of the tasks required to accomplish this goal is to replace the current waveguide system with a fiber optic system. The fiber optic system will transmit phased Local Oscillator (LO) signals to each of the antennas and digitized raw astronomy data from the antennas to the new high performance correlator. The EVLA project will require new synthesizers, reference generators, Intermediate Frequency (IF) converters, and samplers. The top-level system requirements for the LO System are shown in Table 1.

Table 1, LO System Requirements

Phase Stability	2.8 picoseconds per hour at 40 GHz
Optical Channel Wavelengths:	1310 nm and 1550 nm
Fiber System Signal to Noise Ratio:	Initial ~ 8:1, End of life ~ 6:1
Maximum Fiber length:	22 km
Minimum Fiber Length:	0.625 km
Operating Temperature:	-12°C to +35°C

2. SYSTEM SPECIFICATIONS

Phase stability is the key for proper operation of any radio frequency 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 per second.
(5% coherence loss at 100 GHz)

Long Term Slope: Less than 200 femtoseconds / minute per 30 minutes
(Approximately 90° of phase shift at 40 GHz)

Peak-to-Peak Phase Deviation: Less than 1.4 ps per 30 minutes
(20 degrees at 40 GHz after removal of linear slope components)

Phase shift with Pointing Change:
Less than 0.7 ps over the whole sky
(10 degrees at 40 GHz)
Less than 0.07 ps per degree of slew for short slew at elevations less than 60 degrees
(1 degree of phase at 40 GHz)

The phase instability of each individual sub-system in the EVLA affects the total phase stability of the antenna. The total stability must adhere to the specifications outlined above. A direct, uncompensated fiber optic LO distribution system would contribute substantial phase instability to the system, close to 80% of the available margin. 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.

In the current EVLA design, the round trip phase will be measured ten times per second in the fiber optic distribution system. These measurements are reported back to the correlator via the array monitor and control system. Phase corrections are applied in the correlation process in the form of delays. The correlation process runs ¼ second behind real time allowing the correction to be inserted as the data arrives at the correlator.

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

The fiber optic system is the one major source of phase instability that cannot be controlled by thermal compensation or design. The primary instabilities are introduced either by temperature variations acting on non-buried fiber or by mechanical stretching of the fiber during antenna movement. Additionally, seasonal temperature changes result in phase changes in the buried fiber

3. FIBER PERFORMANCE

Lucent Technologies Standard Single Mode Fiber (SMF) will be used in the EVLA. The predicted attenuation of the Lucent SMF fiber is approximately 0.40 dB/km, or 8.8 dB over 22 km of fiber at 1310 nm The predicted pulse spread at 512 MHz is about 38ps [2]. The predicted performance of the fiber is summarized in Table 2. The table assumes a continuous wave signal at 512 MHz and a distance of 22 km to the farthest antenna.

Table 2. Predicted Fiber Performance for the EVLA IF System

Parameter	SMF
Attenuation Penalty (22 km)	**8.8 dB**
Pulse spread @ 512MHz	**38 ps**
Maximum Launch Power	**2.5 dBm**
Maximum Laser Spectral Width	**0.1 nm**

3.1 Loss Budget

The optical attenuation loss budget is shown in Table 3. Both paths are listed: the path to the antenna and the round trip path back to the central electronics building. An optical splitter is used to tap off 5% of the signal for use at the antenna and return the remaining 95% to the central electronics building. The insertion loss for the splitter is about 1 dB. The predicted attenuation to the antenna is about 28 dB and the laser launch power is specified to be 6 dBm. The difference of these numbers is the signal strength available at the antenna receiver, -19 dBm. The specified receiver can produce an output with a signal to noise ratio of 6:1 with an optical signal strength of -30 dBm. This design provides an optical signal of about -19 dBm at the antenna providing 7.8 dB of margin. The predicted attenuation of the round trip path is about 32 dB. The optical signal strength at the central electronics building receiver is about -25 dBm providing about 5 dB of optical margin.

Table 3. Optical Attenuation Loss Budget Using SMF

	Number of Units	Loss per Unit (dB)	Round Trip Loss (dBm)	To Antenna Loss (dBm)
Laser Launch Power 1310nm	1		6	
Connectors FC/APC	11	-0.3	-3.3	
Connectors FC	2	-0.5	-1	
Splices	3	-0.1	-0.3	
Bends	18	-0.1	-1.8	
Fiber loss (22 km)	22	-0.4	-8.8	
95 % - 05 % splitter			-1	-13
Signal at Antenna			-10.2	-21.2
Antenna Receiver Sensitivity				-30
Antenna Receiver Margin				7.8
Connectors FC/APC	11	-0.3	-3.3	
Connectors FC	2	-0.5	-1	
Splices	3	-0.1	-0.3	
Bends	18	-0.1	-1.8	
Fiber loss (22 km)	22	-0.4	-8.8	
Signal at Central Electronics Building			-25.4	
Central Electronics Bldg Receiver Sensitivity			-30	
Central Electronics Bldg Receiver Margin			4.6	

4. CHANGE OF PATH LENGTH DUE TO TEMPERATURE

Changes in temperature affect the fiber length. To characterize the effect on the LO system, the change in length of each segment per unit time was calculated. Duhamel's theorem [3] was used to predict the change of path length due to temperature in the optical fiber reference distribution system. The system was modeled by breaking the path down into segments that are exposed to different environments. Table 4 shows the different segments with their corresponding maximum expected path length.

Table 4: Fiber Segments

Segment	Max expected path length
1. Central electronics building (Antenna LO rack to underground segment)	30 meters
2. Underground (Central Electronics Building to antenna pad)	22000 meters
3. Antenna pad (From underground manhole to antenna entry point)	8 meters
4. Antenna (Antenna entry point to demodulation rack in the vertex room)	20 meters

Exposed segments will be insulated and shielded from the sun. Analysis will be performed using characteristics of standard single mode fiber, which has a temperature coefficient of expansion of about 2ppm/ °C. The length change is shown as an average change per second.

Segment 1: Central Electronics Building

The central electronics building temperature variations are expected to be about ±1°C per hour from a nominal temperature of 25°C. This variation is the result of the air handling system cycling.

$$\Delta L = 2\text{ppm}/{}^\circ\text{C} \times 30\text{m} \times 2^\circ\text{C/hr} \times 1\text{hr}/3600\text{s} = 0.032\ \mu\text{m/second}$$

Segment 2: Underground Fibers

For segment 2 underground fibers, two calculations were performed, one at 1 meter and one at 1.5 meters. This was done to determine the impact on the system if the fiber was buried at 1.5 meters instead of 1 meter. It is assumed for these calculations that outside temperature varies sinusoidally on a seasonal basis. From Duhamel's theorem we know that the ground temperature varies by:

$$T(x,t) = x/(2*\sqrt{\pi*\alpha})*\int_0^t T_s(\lambda)*e^{-\left[x^2/(4*k(t-\lambda))\right]} \Big/ (t-\lambda)^{\frac{3}{2}}\, d\lambda \qquad \text{(EQ 1)}$$

This is a boundary value problem where $T_s(\lambda)$ is the surface temperature:

$$T_s(\lambda) = A_1 \cos(\omega_1 t) + A_2 \cos(\omega_2 t) + M \qquad \text{(EQ 2)}$$

M is an offset term that can be ignored since we are only interested in the temperature change. The first term is the daily variation and the second term is the seasonal variation. The effect on the soil temperature 1 - 1.5 meters deep by daily ambient temperature variations is assumed to be negligible and is also ignored. Only the second term, the seasonal variation, will be determined.

A_2 is the amplitude of the average seasonal variation. Actual temperature data for the 1999 to 2000 year show that the average low was about -1°C and the average high was about 27°C. The average temperature swing is 28°C. A study performed by Calhoun [4] buried thermocouples at various depths at NASA's Goldstone Tracking Station. The results for actual temperature measurements from this study agree with the VLA temperature swing data. A_2 equals the deviation from normal or 14°C.

Ignoring the first term and the third term and substituting equation 2 into equation 1, the problem has been solved by Carslaw and Jaeger [3]. The solution is A_2 times T(x,t) where T(x,t) is

$$T(x,t) = e^{-x*\sqrt{\omega/2\kappa}} * \cos\left(\omega t - x*\sqrt{\omega/2\kappa}\right) \qquad \text{(EQ 3)}$$

ω is the frequency of the seasonal temperature cycle - for a 1 year period 2* π /365 = 0.017 cycles/day

κ is the Diffusivity constant and is a measured quantity depending upon the type of soil. It is assumed that κ for the EVLA area is 0.0045 cm²/s. Substituting into equation 3:

$$T(x,t) = e^{-x*\sqrt{.017/(2*(0.0045*3600*24/(100*100)))}} * \cos\left(.017t - x*\sqrt{.017/(2*(0.0045*3600*24/(100*100)))}\right) \qquad \text{(EQ 4)}$$

or

$$T(x,t) = e^{-.47*x} * \cos(.017t - .47x) \qquad \text{(EQ 5)}$$

Looking only at the amplitude, the temperature variation from nominal per year = $|T(x,t)| * A_2$.

For a 1 meter depth the temperature variation from nominal per year will be 8.7° C

For a 1.5 meter depth the temperature variation from nominal per year will be 6.9° C

This means that for a 1 meter depth, the temperature will vary on average 17.4° C per year, peak to peak. For a 1.5 meter depth, the temperature will vary on average 13.8° C per year, peak to peak. Note the peaks are 180 days apart.

Calculating the average per second length change of the buried fiber:

At 1 meter $?L_{1\ meter}$ = 2ppm/°C x 17.4°C/yr/24hr/3600s/180 x 22,000m=0.05μm/second

At 1.5 meters $?L_{1.5\ meter}$ = 2ppm/°C x 13.8°C/yr/24hr/3600s/180 x 22,000m=0.04μm/second

With such a high rate of temperature change it is recommend that the burial depth be 1.5 meters. This is also the recommend burial depth suggested by JPL [4&5].

Segment 3: Antenna Pad

The temperature variations of the exposed length of fiber from the antenna pedestal to the bottom of the antenna is dependant on a number of variables such as the absolute temperature changes, wind effects, and solar effects. The fiber will be insulated and shielded from the sun. A worse case analysis assumes a 10°C change in temperature will occur in one hour.

$?L_{segment\ 3}$ = 2ppm/°C x 8m x 10°C /hr x 1hr/3600s = 0.044 μm/second

Segment 4: Antenna Internal

The temperature variations of the fiber in the antenna is assumed to be ±1°C per hour from a nominal temperature of 25°C, however, the cable is outside the antenna in the elevation cable wrap. The baseline plan states that this portion of the cable will be wrapped with heat tape and kept at a constant 35°C. The temperature change per hour is assumed to be 5°C.

$?L_{segment\ 4}$ = 2ppm/°C x 20m x 5°C /hr x 1hr/3600s = 0.055 μm/second

Segment Results

Adding together all of the variations from each of the four segments and assuming a burial depth of 1.5 meters:

?L. = 0.032μm/s + 0.04μm/s + 0.044μm/s+ 0.055μm/s= 0.171μm/second

Converting this number to degrees of phase shift:

?L = 18 degrees at 40 GHz per 30 minutes

Comparing this to the system specification of only 20 Degrees of phase shift at 40 GHz it is easy to see that the EVLA will require a phase measurement and correlator correction system.

5. CABLE WRAP

There are two locations where the cable is bent as the antenna moves: the elevation cable wrap and the azimuth cable wrap. The location of the antenna LO equipment, including the optical splitter, is in the vertex room near the top of the antenna. This means the 512 MHz LO signal must travel through each cable wrap twice so that the round trip phase measurement can be made.

The elevation cable wrap is located on the outside of the antenna directly on axis with the elevation bearing. The total motion of this wrap is 133 degrees at a maximum rate of 20 degrees per minute. This portion of the cable is insulated, wrapped with heat tape and shielded from the sun. The elevation cable wrap bends the cable in one axis only and is similar to the motion of the proposed azimuth cable wrap.

The present azimuth cable wrap is a "May-pole" configuration and can rotate 540 degrees at a rate of 40 degrees per minute. The power and signal cables on the present "May-pole" are both twisted and bent. This type of motion would provide excessive phase jitter to the 512 MHz LO signal in the fiber. A "Watch-spring" configuration similar to the azimuth wrap used in the Green Bank Telescope [6] is preferred since the cable is only bent in one axis. A "Watch-spring" cable wrap test fixture was built and tested at NRAO in Socorro, New Mexico, Figure 1. The prototype has an inner diameter of 0.4 meters and an outer diameter of 1.2 meters and can rotate 360 degrees using a small electric motor at a rate of 6 degrees per second. A 15-meter section of the same type fiber optic cable used in the Green Bank Telescope was installed in the test fixture. The cable contains 24 single mode fibers and 72 multi-mode fibers in a loose tube configuration.

Figure 1, Watch-spring Cable Wrap Test Fixture.

For the azimuth cable wrap test, a JDS Uniphase (CQF938/50) DFB 1550 nm laser and a JDS Uniphase Mach-Zender type modulator (21001361) were used as an optical source. A Hewlett Packard E4422B signal generator was used to feed a 1.2 GHz sine wave reference signal to the RF input of the modulator. The modulated optical signal was fed through the cable wrap and returned on two single mode fibers. The returned optical signal was then converted back to an electrical signal using a JDS Uniphase SIRU 2300 optical receiver. The receiver output was compared to the original reference signal using a phase comparator and filtered to a bandwidth of 1 kHz and the resulting DC signal was measured using a Fluke 189 voltmeter. The resolution of the test fixture was determined to be approximately 0.05 degrees with accuracy of 0.5 degrees at 1.2 GHz. The results of twenty complete cycles through the full 200 degrees of movement in both directions showed that the effect of cable wrap was less than or equal to the accuracy of the test fixture, less than 0.5 degrees of phase shift per second at 1.2 GHz through 360 degrees of wrap. Since the elevation wrap has a similar bend motion, it is anticipated that these results can also be applied to the performance of the LO fiber in the elevation wrap.

6. EVLA ROUND TRIP PHASE SYSTEM DESCRIPTION

A block diagram of the EVLA Round Trip Phase System is shown in Figure 2. The Round Trip Phase System (RTPS) is based on a 512 MHz signal generated in the Master Local Oscillator System (MLOS) using a Hydrogen Maser. This signal is amplified and distributed to the central electronics building portion of each antenna's LO electronics. The MLOS also generates a 512 MHz + Δ signal by steering a voltage controlled crystal oscillator (VCXO) off frequency by 128 Hz. The 128 Hz signal is also derived from the maser and distributed to the antenna LO electronics. All high frequency signals generated and distributed within MLOS are distributed on cables that are matched in length to keep the phase change with temperature the same for each antenna.

The 512 MHz signal is modulated onto a 1310 nm laser and sent out to each antenna. Separate laser systems are used for each antenna. Lucent Technologies Standard Single Mode Fiber (SMF) is used throughout the system and the length varies from 0.5km to 22km depending upon antenna location. The 512 MHz signal is received at the antenna and immediately divided using an optical splitter and 95% is returned to the central electronics building on a different fiber. This configuration is similar the to system installed by Berkeley at Hat Creek [7]. The two-fiber approach provides the required isolation between the signals since even –60db of crosstalk will translate into a phase measurement error.

The 512 MHz signal returned from the antenna is demodulated from the fiber using a low distortion InGaAs PIN diode optical receiver with a bandpass of 200-1200 MHz. To reduce amplitude variations, which can introduce phase measurement errors in the phase detector, the signal is then sent through a Phase Lock Loop (PLL). The 512 MHz signal is then mixed with the 512 MHz + Δ creating a difference signal of 128 Hz which contains the phase information. The 128 Hz signal is then compared to the original 128 Hz generated by the MLOS using a phase detector. The difference is counted and the result is proportional to the round trip phase relationship of the original 512 MHz signal. The absolute round trip phase is calibrated out and the residual phase is monitored and used to determine the change in phase every 1/10 second. The proposed correlator can support this measurement rate.

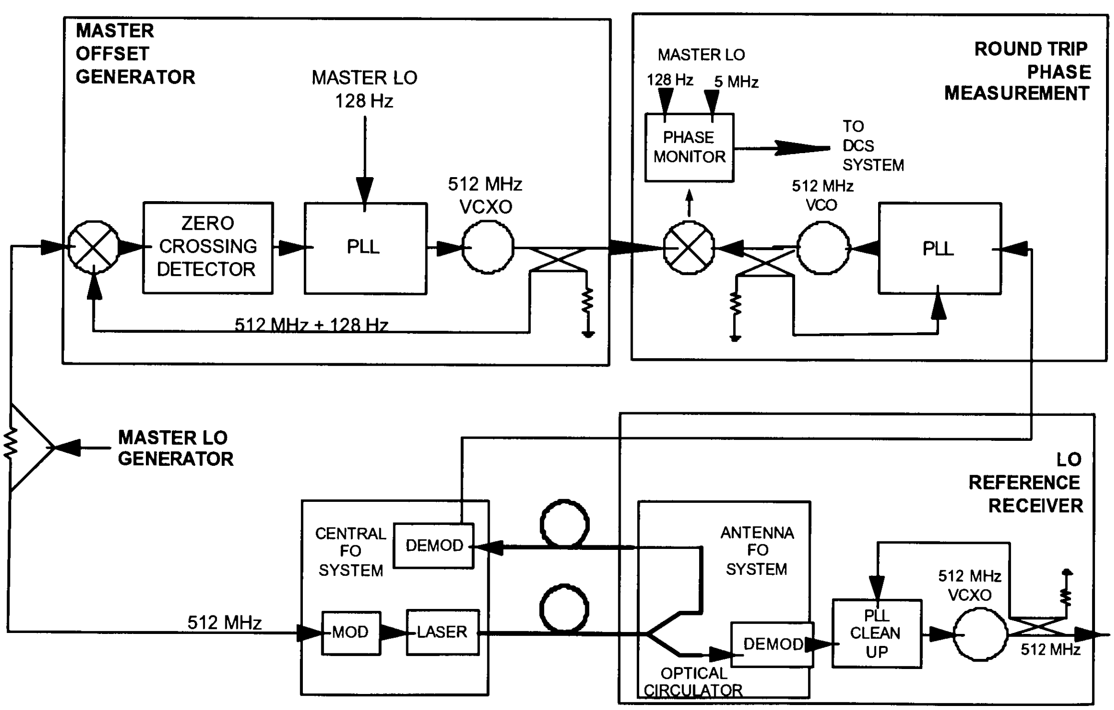

Figure 2. LO System Block Diagram

7. SUMMARY

The EVLA digitizes the astronomical signals at the antennas and transmits these data over fiber links to the central electronics building. Each antenna requires five LO reference frequencies to maintain a coherent phase and frequency relationship at the correlator input. These LO references are modulated on to the fiber optic system for distribution to each antenna. The fiber optic distribution of the signals requires that the optical path be stabilized in order to preserve phase coherence of the array. The primary instability of the LO signal is caused by optical path length variations in the fiber optic cable. These path length variations are mainly due to temperature variations in the fiber. The predicted affect of these variations indicates that the 58 meters of above ground fibers affect the system performance as much as the 22km of buried fiber and, in total, uses most of the available margin for the entire EVLA LO/IF system. An active Round Trip Phase Correction System is clearly required for the EVLA. To accomplish this, a real time continuous measurement (10 times per second) will be made of the phase delay in the fiber optic cable distributing the LO reference signals to each antenna. This information will be used by the correlator to set the delay on each of the baselines in the array.

The present system topology uses a single 1310 nm laser per antenna for the round trip phase measurement. The use of this single laser eliminates the instabilities caused by two lasers of slightly different frequencies and operates the system at a wavelength near the zero dispersion point of the single mode fiber. Minimizing dispersion within the fiber reduces pulse spreading which can introduce a phase measurement error. Although the fiber attenuation at 1310 nm is about 25% higher than the attenuation at 1550 nm, the longest roundtrip distance is only 44 km and with presently available lasers a comfortable margin can be achieved.

The EVLA LO system is designed to use three fibers, #1 transmits the 512 MHz LO signal to the antenna, #2 returns the 512 MHz LO signal to the central electronics building, #3 transmits the other four LO signals to the antenna. This configuration has the advantage that there is no cross talk modulated onto the 512 MHz LO signal. This is required because the 512 MHz signal is multiplied up to 50 GHz and any instability is also multiplied.

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