The ALMA photonic local oscillator system

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ABSTRACT

The Atacama Large Millimeter Array (ALMA) Photonic Local Oscillator (PLO) is an advanced photonics system that generates and distributes all of the Local Oscillator (LO) and timing references for the ALMA radio telescope array. These LO and timing references are used by the receivers and electronics at the antennas, and by the Correlator in the central building. Due to the unprecedented combination of high sky frequencies (up to 950 GHz) and long baseline lengths of up to 15 kilometers, the ALMA 1st LO requirement is particularly stringent, with extremely precise timing and synchronization needed down to the ~10 femtosecond level.

Keywords: ALMA, photonic, laser, heterodyne, femtosecond, radio telescope, local oscillator

1. INTRODUCTION

The unique requirements, the design, and the implementation of the ALMA local oscillator system is reviewed and presented. Further, detailed design and performance data are given on the 1st LO reference, also called the "ALMA Photonic LO System." For this system, the challenging phase coherence and phase drift requirements affected the design of all of the modules and subassemblies. The final system thus includes many novel and state-of-the-art optoelectronics and photonics modules. The system has been installed and is now in routine use supporting the ALMA Early Science program.

The local oscillator (LO) subsystem establishes the array time and phase synchronization on scales ranging from 20.833 Hz (48 msec) to 942 GHz. It is also responsible for generating the LOs necessary for converting the sky bands (RF) to IF and then to baseband, and for tuning these as required to establish the desired sky frequency and interferometer phase. This includes fringe tracking, phase switching and other interferometer-specific features. The subsystem also supplies various coherent references to other devices which are essential to establish synchronization and to provide accurate timing. These include digitizers, computers and the correlator. It does this by distributing periodic reference signals derived from a common master oscillator.

2. LOCAL OSCILLATOR SYSTEM DESIGN

The Central LO is shown in the left portion of Figure 1 and is housed in the ALMA Array Operations Site (AOS) Building. At the upper left of Figure 1 there is a Master Frequency Standard with a stable long term timebase which is used as an input to the Central Reference Module, which has a set of low-noise RF phase-locked oscillators and associated electronics necessary to provide multiple reference outputs on coaxial cable and optical fiber. One of these references is used locally as the main frequency reference for the ALMA Correlator. Another output locks a microwave synthesizer, which in turn is used as the reference for the Laser Synthesizer; a harmonic of the microwave synthesizer frequency determines the Laser Synthesizer two-laser difference frequency. This difference frequency is transmitted to the antennas by optical fiber and becomes the main LO reference for the ALMA 1st LO. A fiber optic output of the Central Reference module encodes timing signals at 48 msec, 25 MHz, and 2 GHz onto a 1532-nm wavelength lightwave. These low frequency references at 1532-nm, and the two-laser output at 1556-nm are then combined onto a single fiber by a wavelength division multiplexer (WDM). This combined signal is amplified and split to provide

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outputs for all antennas, before going through a line length correction (LLC) module (one per antenna), and onto the antenna. The LLC provides round-trip phase correction as compensation for differential fiber delays between different ALMA antennas, by means of a high dynamic range (5 mm) piezoelectric fiber stretcher.

The right hand portion of Figure 1 shows the LO reference schematic at the antennas. The 1556-nm two-laser source and the 1532-nm references are separated by a WDM, and then go to the 1st LO Receiver and 2nd LO receiver, respectively. From here the references are used by specialized LO assemblies. The 1st LO uses the 1st LO references as a high frequency millimeter-wave reference, and also uses a fast digitally tunable offset reference (20—40 MHz) for fine tuning, fringe rotation, and phase and frequency switching.

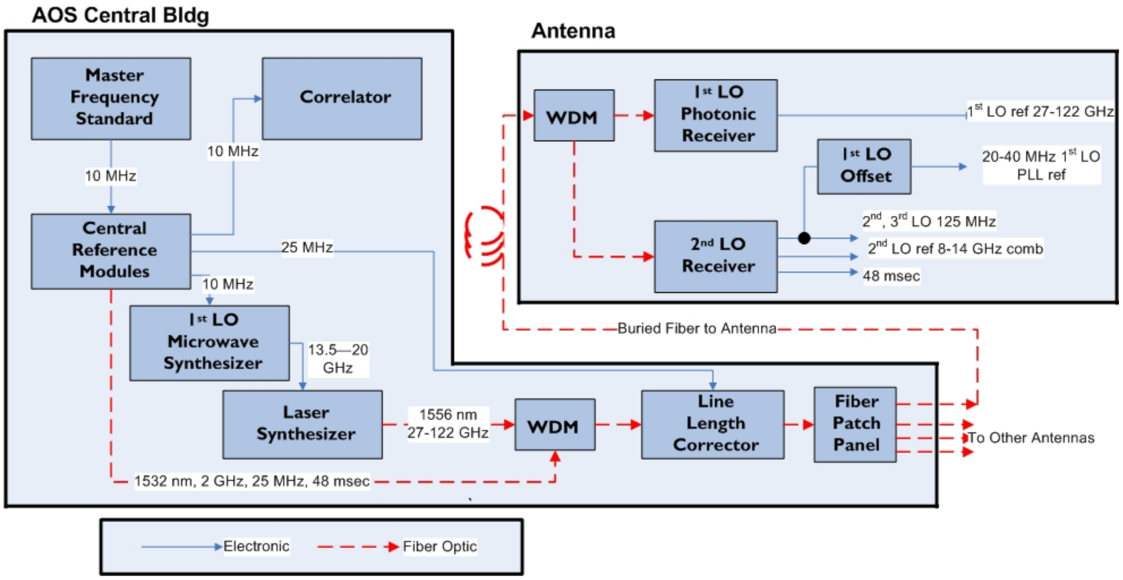

Figure 1. ALMA Local Oscillator Distribution

3. PHOTONIC LOCAL OSCILLATOR SUB-SYSTEM

The devices necessary to create the two-laser 1st LO reference and the round-trip phase correction is shown in Figure 2. The master laser (ML) is a stable and highly-coherent laser and its output goes to the Laser Synthesizer (LS). The LS contains four semiconductor slave lasers which allows continuous tuning and band switching over difference frequency ranges of 27-122 GHz. Multiple parallel LS units support subarraying: the ability of ALMA for doing simultaneous science at different frequencies. To meet the requirement that any of the four Laser Synthesizers can provide an LO reference source to any antenna, with arbitrary and instantaneous configurability, each LS output goes to a distribution module which has an erbium-doped fiber amplifier (EDFA) and 96-way splitter. This is followed by Subarray Switch and Line Length Corrector (LLC) modules, one per antenna, where the subarray selection and round-trip phase correction functions are implemented. The subarray switch modules are located in a single, thermally stable rack with 576 input fibers and 132 output fibers.

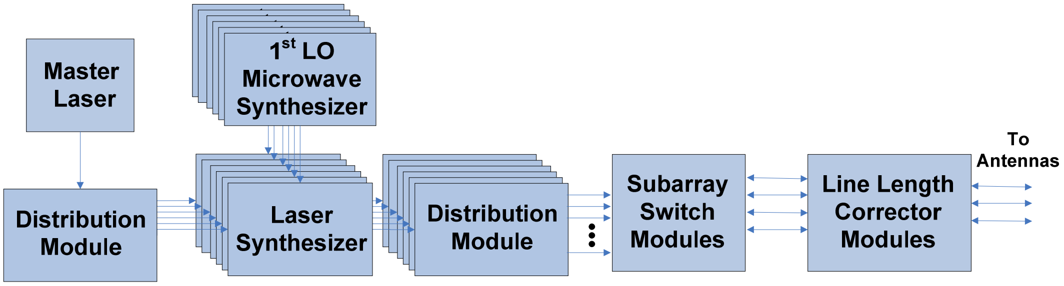

Figure 2. ALMA Photonic LO at the Central Building

The 1st LO reference is sent to the antenna on a single-mode fiber where the 1st LO photonic receiver is located. Figure 3 shows the design detail of the 1st LO Photonic Receiver. This module is tightly integrated with the ALMA Front End so that the terminus of the round-trip phase correction is as close as possible to the 1st LO output going to the receiver. The lightwave is split into a one-way path and a two-way path. The one-way path has an EDFA and a 1:10 switch, followed by the ten ALMA receiving band LO assemblies, each integrated with a waveguide-mounted high-speed photodetector[1] which is used to convert the two lightwaves to a millimeter-wave difference frequency. The two-way path provides for the round-trip phase correction by applying a 50 MHz single-sideband frequency shift to the lightwaves (25 MHz in each direction), and then by reflection at a Faraday rotation mirror. To provide the best phase correction, the total fiber path length from the input splitter to the photomixers is matched in each case to the length of fiber from the splitter to the Faraday mirror. Additional care is taken in the design to ensure good thermal and mechanical stability of the fibers.

Figure 3 also shows a typical 1st LO assembly (Band 10) in inset. The First Local Oscillators span the frequency range 27-938 GHz in ten discrete bands, with tuning bandwidths ranging from 16% to 25%. The Band 10 sky frequency is 787-950 GHz, with the LO being generated by an electronically tunable YIG oscillator, followed by a fixed-tuned x6-multipler, and a cooled and fixed-tuned x9-multiplier.[2] Each of the other nine cartridges is of similar design, with variation mainly in the YIG oscillator frequency range and the multiplier ratios. The first LO is phase locked to the photonic reference at the output of the x6 multiplier.

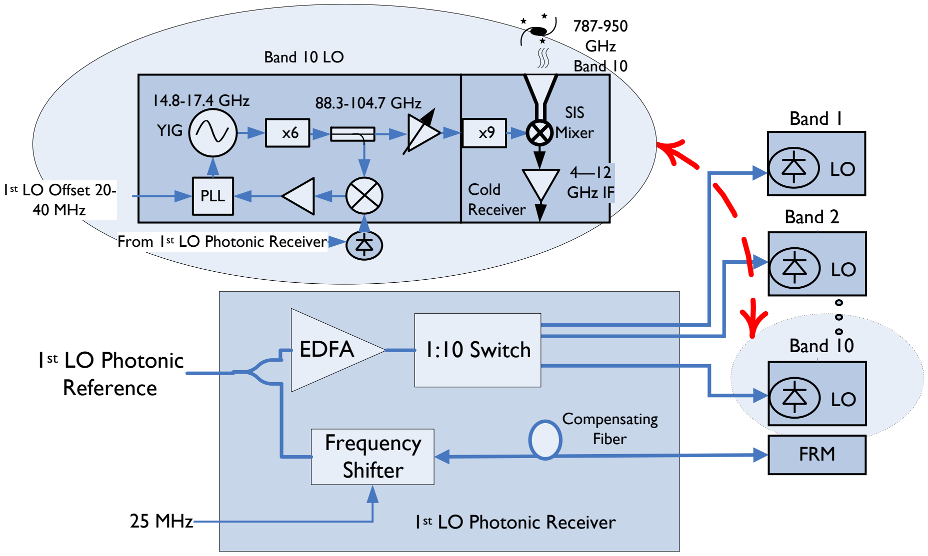

Figure 3. ALMA Photonic LO at the Antennas

4. MASTER LASER AND LASER SYNTHESIZER

The photonic reference is provided by the combination of a master and slave laser. The master laser serves a dual purpose. It provides a stable reference for the slave laser so that the tuning and phase locking is stable and repeatable, and it provides a stable and highly coherent lightwave that is used as the basis for the round-trip phase correction. The absolute frequency reference used by the Master Laser is a 2-photon transition of an ^{85}Rb atomic gas.[3] A DFB fiber laser source is frequency doubled and locked to this transition at 778 nm. This laser has frequency stability of 4e-13 at 1 sec, and less than 1e-12 at 1000 seconds. Additionally, the coherence is greater than 50% for an interferometer fiber length of 30 km, which is a necessary condition for forming the optical interferometer used in the phase correction.

The Laser Synthesizer must be phase-locked with low residual phase noise, must be continuously tunable from 27-122 GHz, and must be capable of fast frequency switching. To achieve the fast switching (< 500 msec), four slave lasers are used in parallel and an unused laser can be steered in advance to the correct frequency by firmware. To cover the wide frequency range, the lasers are temperature tuned and precisely calibrated. The phase locking is done by first converting the two lightwaves to a low frequency (125 MHz) electronic signal by means of a photomixer followed by a harmonic mixer that is pumped by a microwave synthesizer. Four of these photomixer receivers are implemented in parallel to cover the entire tuning range.[4,5] The phase noise of the 1st LO when phase locked to the Laser Synthesizer is < 53 fsec when integrated between 1 kHz and 40 MHz from the carrier.

5. ROUND TRIP PHASE CORRECTION

The round-trip phase correction is shown schematically in Figure 4. A 6:1 switch selects the appropriate Laser Synthesizer. The output is polarization-aligned and passed through a polarizing beamsplitter (PBS) which also serves as the start of the round-trip phase path. The faraday-reflected return-path lightwaves are redirected by the PBS to a coupler, where they are combined with a local copy of the master laser recovered by fiber bragg grating filtering. These recombined lightwaves produce a 50 MHz beatnote formed by the local and round-trip master laser, and contain the round-trip phase information. This beatnote is compared to local references and the integrated output is used to drive a voltage-actuated piezoelectric fiber stretcher assembly to stabilize the phase.[6] The two-way phase is stabilized to the same level as the wavelength accuracy of the master laser. Reciprocity is necessary for a round-trip correction technique to work well for one-way path stabilization. This is satisfied by the use of low-PMD fiber and low-DGD (differential group delay) fiber components, so that the outgoing and return fiber path delays are well-matched and stable. Additionally, polarization-to-phase conversion has been minimized by the inclusion of a polarization rotator prior to the fiber stretcher. This is adjusted periodically so that the optimum input polarization for the stretcher is selected to minimize unwanted polarization change when the stretcher is actuated.[7] This is discussed further in the next section.

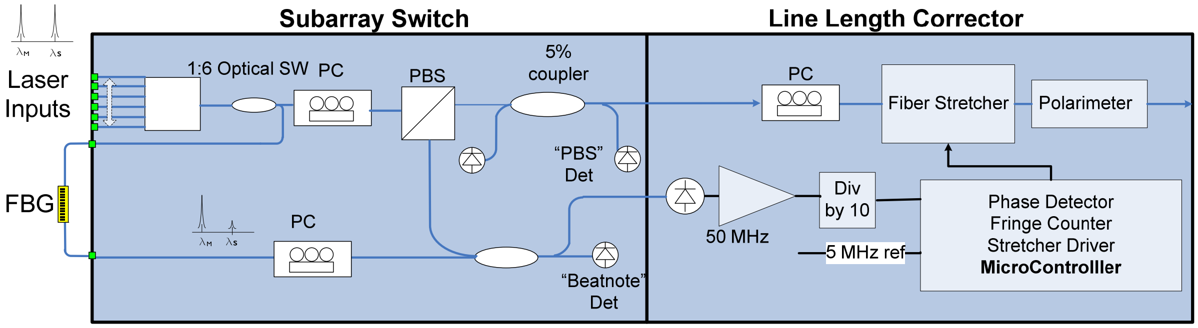

Figure 4. Round Trip Phase Correction (PC = polarization control, PBS = polarization beamsplitter, FBG= fiber Bragg grating)

6. POLARIZATION STABILITY

During the on-site installation and testing phase, great care was taken to measure all possible output channels, subarrays, and LO frequencies. In this way, a complete verification was made of the signal levels and stability. Additionally, for guaranteeing the phase stability, the subsystem polarization alignment and stability needed to be verified. Previously work had shown that the LLC fiber stretchers perturb the outgoing lightwave polarization as a function of the stretcher throw. The resulting interaction of the polarization variation with the polarization mode dispersion of the fiber and the photonic receiver causes an unwanted phase change at the antenna.[7] In order to minimize this effect, the polarization of the lightwave entering the fiber stretcher is aligned with one of the Principle States polarizations of the fiber stretcher. This is done by a microprocessor controlled algorithm which simultaneously varies the input polarization, moves the fiber stretcher, and measures the output polarization. The algorithm optimizes the input polarization so that the total variation of the fiber stretcher output polarization is less than 0.05 radians, and the system is required to maintain stability over long periods to less than 0.2 radians. This polarization optimization and stability was verified on-site. Figure 5, shown below, is a time series of evolution of the polarization variation of each of the 66 fiber stretchers for the full range of stretcher motion. Each unit was optimized to fall below the initial 0.05 radian threshold, and then was re-measured every minute for a 2 hour 45 minute period. The behavior of the polarization is highly uniform so the data for all 66 are almost overlaid. With the exception of three units, all stayed below 0.1 radian variation for the time period, and all of the units were below 0.2 radians. After the initial optimization, the units can be re-optimized within a short timeframe (about 30 seconds) if any stray above the 0.2 radian threshold. In this way, the polarization alignment is preserved and the ALMA phase stability is not impacted by polarization to phase conversion.

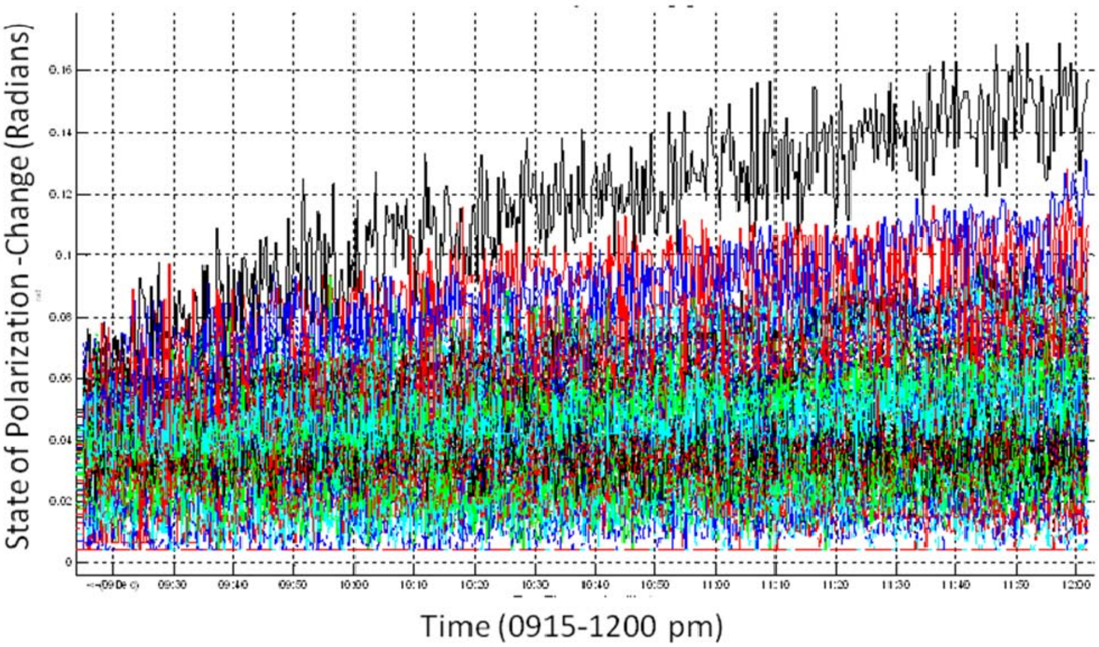

Figure 5. Polarization drift versus time in the Fiber Stretcher Assemblies

7. PHASE STABILITY

At the time of the first installation, on-site testing confirmed the long term phase stability was meeting the ALMA specification of 13 fsec in Allan deviation of phase at 300 seconds. This measurement was done by use of a test receiver that directly measured the millimeter-wave phase at the output of two LO reference links. For convenience this was located in the central building, but one of the links included a buried fiber path to an ALMA antenna and a 14-km fiber spool. In Figure 6 below, the result of the phase stability measurement is shown. In the top part of the figure the LLC fiber stretcher displacement (for each of two LLCs) is shown along with the phase difference between the outputs of the two separate LO reference arms at 84 GHz. The stretcher voltage scale is approximately 1 micron per volt. The corrected phase maximum excursion is 1.2 deg at 84 GHz with 14 km of fiber. The bottom plot is the two-point phase structure function corresponding to this period, given by $\sigma^2(2,T,\tau) = 0.5 * <[\varphi\tau(t+T) - \varphi\tau\ (t)]^2>$, where σ is plotted in units of time. Both the measured phase and the phase that would have been measured with no correction (calculated using the stretcher voltages) have been plotted. This was remeasured after the second upgrade installation for many channels and fiber lengths with similar results.

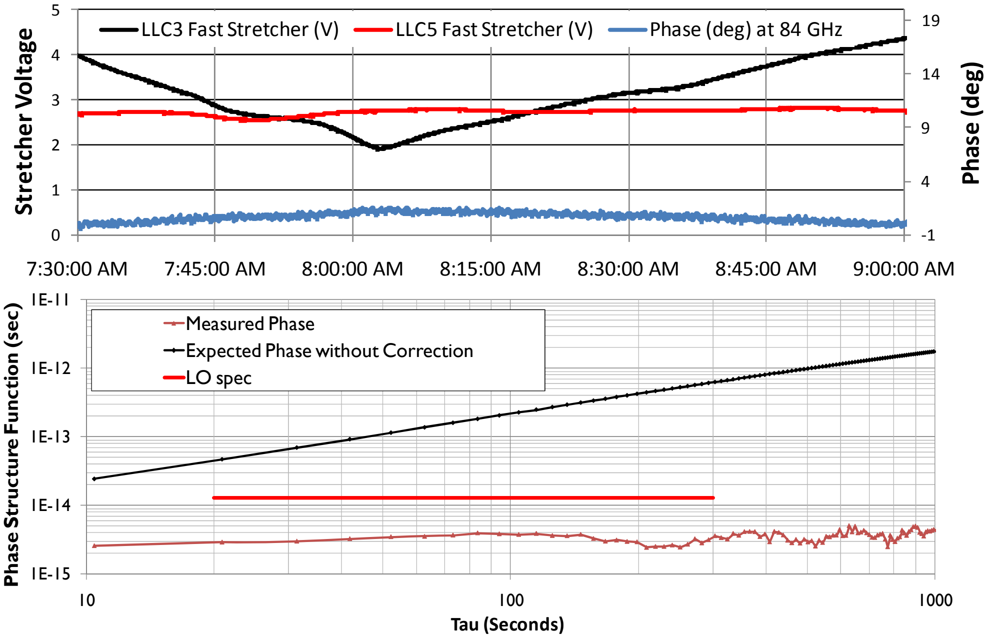

Figure 6. Measured Phase Stability at the ALMA Site. The corrected path includes 0.5 km fiber to one antenna plus a 14-km fiber spool located in the central building.

8. CONCLUSION

The ALMA Photonic LO system is a unique implementation of a radio astronomy phase referencing system for the ALMA telescope array. The design and implementation incorporate many novel design elements and new techniques. The system has been installed at the ALMA site and the on-site measurements indicate that the installed system meets the stringent ALMA requirements. The system is now in use in support of the ALMA Early Science program.

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