Wideband Low-Phase-Noise High-Power W-Band Signal Sources

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***Abstract* --- This paper describes the development of electronically-tunable wideband low-phase-noise millimeter-wave signal sources. These sources are designed to drive cooled Schottky multipliers to supply the LO for the ALMA telescope array. Each phase-locked driver consists of a YTO, active multiplier chain (AMC), and a power amplifier. Measurements of a prototype driver electronically tunable from 72-85 GHz with greater than 50 mW output power are presented. Additive phase noise of individual amplifiers and multipliers is described. Long-term phase drift measurements are reported. Preliminary W-band amplitude noise measurements using a SIS mixer with a YTO-based driver chain and Gunn oscillator LO are also presented. All measurements indicate that the stringent ALMA LO specifications can be met with this architecture.**

I. Introduction

The Atacama Large Millimeter Array (ALMA) is a millimeter wavelength telescope array presently under development in the United States, Europe, and Japan. The array consists of 64 12-meter antennas located at an elevation of 16,400 ft. on the Atacama plateau in northern Chile. Each antenna will contain ten receivers covering ten bands from 31 to 950 GHz.

The receiver front ends will be either InP HFET LNAs for the low frequencies (<115 GHz) or SIS mixers for the higher bands. The IF is at 4-12 GHz. Since the receivers are all sideband separating or double sideband, the LO needs to cover 24 GHz less bandwidth than the receiver front ends, though it still requires >20% bandwidth for some bands. The LO power required ranges from 10-100 μW for the SIS receivers. One other important requirement is the desire to eliminate mechanical tuning of any sort.

The baseline plan for achieving these ambitious specifications is to use a suite of phase-locked electronically tunable "drivers" up to 122 GHz based on a YIG-tuned oscillator (YTO) operating from 16.5-26.0 GHz, as shown in Fig. 1. The YTO will drive an active multiplier chain (AMC) up to the 68-122 GHz range where the phase-locked loop (PLL) will be closed. The last power amplifier will be outside the PLL. The high-power output of the driver is routed inside a dewar to a cold multiplier assembly at the 77 K station. The output power of this amplifier should be at least 100 mW to adequately drive the cold multipliers. If placing this final amplifier outside the PLL causes the phase drift to be higher than the specification, than the PLL can be closed after the amplifier. Table I summarizes the frequency requirements for the ALMA LO .

The low-phase-noise reference is delivered over fiberoptic cable as the beat note between two optical frequencies [1], generated at a central building.

One of the most important tasks of the development phase is to measure the phase noise, phase drift, and amplitude noise properties of a prototype LO driver and determine if they meet acceptable specifications. This paper summarizes these measurements.

II. Measurements

A. Phase Noise

The ALMA phase noise budget assigns 31 fs integrated phase noise to the electronics as a goal [2]. This gives 90% interferometric coherence at 950 GHz in the best atmospheric conditions at the site.

The HP E5500 Phase Noise Measurement System is used for all the measurements described here. The PLL can be closed anywhere in the chain following the YTO by placing a directional coupler at that point. The frequency of the coupled signal is set to N * 600 MHz + 103.65 MHz. We chose 103.65 MHz as the offset because a low phase noise voltage-controlled crystal oscillator (VCXO) was available. The 600-MHz reference is a

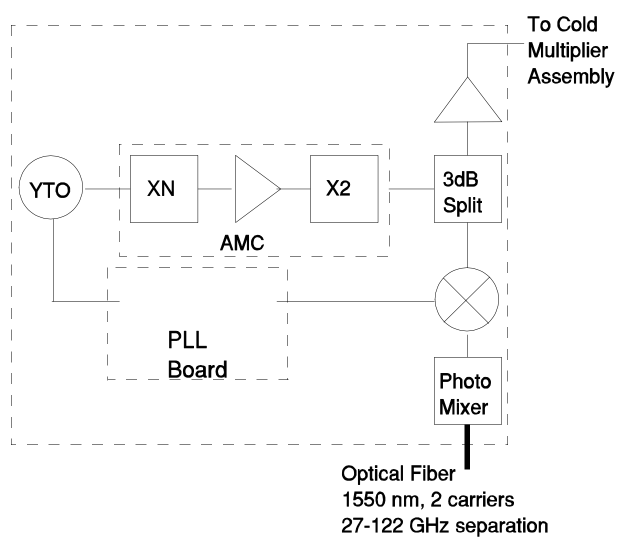

Fig. 1. Block diagram of ALMA phase-locked LO driver.

very low phase noise signal provided by the test set. This passes through a comb generator into a balanced mixer to downconvert the coupled signal to 103.65 MHz. The 103.65 MHz IF is filtered and amplified to drive the phase detector. The phase detector output is passed through an active second-order loop filter, where it is then used as the correction voltage for the YTO. The loop bandwidth is controlled by the component values of the loop filter.

The RF output is sent to the test set where it is also downconverted with a harmonic of the 600-MHz signal. The phase reference for the resulting signal is provided by a tunable HP 8663 synthesizer. The output of the internal phase detector is analyzed by the test set to measure phase noise and to close the loop by tuning the 103.65 MHz VCXO.

For these measurements, the reference includes the multiplied 600-MHz signal used for downconversion as well as the VCXO. For the final ALMA version, the reference will be a variable millimeter-wave reference generated by the difference frequency between two optical carriers in a photomixer [1].

To measure phase noise contributions from individual components, the loop was locked after the YTO at 19.90365 GHz before any additional components. This enables accurate measurements of additive phase noise of components by not including variations in loop parameters by locking at different frequencies.

Phase noise measurements were then performed at the YTO output and at the output of each successive stage of multiplication and amplification. Fig. 2 shows the integrated phase noise from 1-100 kHz in femtoseconds at each point in the chain. Above 100 kHz, the measurements were already below the noise floor of the W-band harmonic mixer. However, since any additive phase noise would decrease with offset frequency, measurements below 100 kHz are the most crucial.

Band	Rcvr. Band (GHz)	YTO Band (GHz)	Driver Band (GHz)	LO Band (GHz)
1	31.3-45	27.3-33	27.3-33	27.3-33
2	67-90	22.2-26	89-104	89-104
3	89-116	25.2-26	101-104	101-104
4	125-163	17.1-18.9	68.5-75.5	137-151
5	163-211	21.8-24.9	87.5-99.5	175-199
6	211-275	18.5-21.9	74.3-87.6	223-263
7	275-370	17.9-22.4	71.7-89.5	287-358
8	385-500	16.5-20.4	99.2-122	397-488
9	602-720	17.0-19.7	102.3-118	614-708
10	787-950	16.6-19.6	99.8-117.3	799-938

Table 1. Frequency specifications, by band, of the ALMA receivers (column 2), required LO (column 5), base YTO (column 3), and phase-locked room temperature LO driver (column 4).

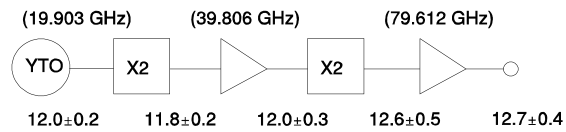

Fig. 2. Measured phase noise in femtoseconds integrated from 1-100 kHz at each point in the YTO driver chain. The uncertainty range is three standards of deviation.

The chain consists of the YTO, a FET doubler using the HP HMMC5040 MMIC, a Q-band power amplifier made with the same device, a balanced diode doubler [3], and a 72-85 GHz power amplifier on loan from JPL [4]. It should be noted that both amplifiers were heavily saturated. Ten independently calibrated measurements were made at each point in the chain. The uncertainty range shown is three standards of deviation.

The most precise measurements in this chain were made before and after the W-band power amplifier. Based on these measurements, we determine that the additive phase noise of that amplifier is 1.3 +/- 0.7 fs. In terms of phase noise, therefore, placing the final power amplifier outside the loop does not cause any problems.

This measurement also gives us an estimate of the additive phase noise that can be expected from the cold multipliers, since the balanced 40 to 80-GHz doubler used here is of similar design as some of the out-of-loop cold multipliers. Even keeping in mind that the phase errors add in quadrature, the contribution of each multiplier is minimal.

Fig. 3 shows the phase noise measurement of the full YTO driver LO chain at 79.615 GHz. The PLL is closed at the YTO frequency, 19.903 GHz. This is the same setup used for the additive phase noise measurements described earlier. We have also made measurements with the PLL locked at 79.615 GHz. The results, in terms of phase noise, are basically identical since the doublers and amplifiers add little if any phase noise as demonstrated earlier. The primary advantage in locking at the higher frequency is in terms of phase *drift*.

Labeled on the plot is the integrated phase noise from 1-100 kHz, 12.65 fs, and the calculated phase noise from 100 kHz to infinity, 17.84 fs, assuming a 20 dB/decade drop in phase noise outside the phase lock loop as represented by the dashed line superimposed on the plot. The

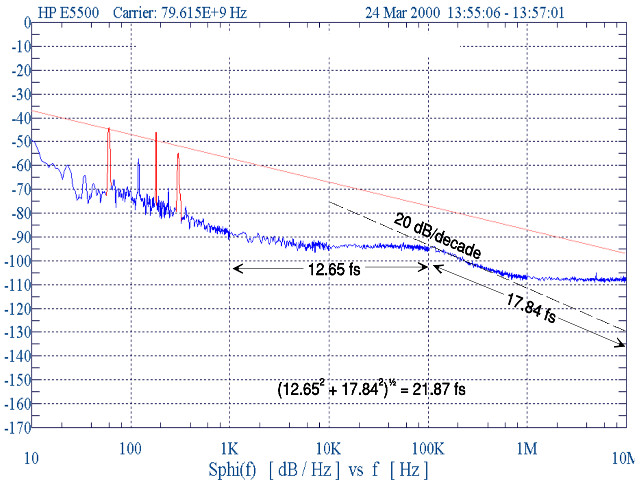

Fig. 3. HP E5500 phase noise measurement of 79.615 GHz LO driver.

flattening of the phase noise spectrum near 500 kHz is not due to the noise floor of the YTO, but rather due to measurement equipment.

B. Phase Drift

The ALMA goal for the phase drift associated with the electronics on time scales greater than one second is 2.1 um, or 2.4 degrees of phase at 950 GHz. A convenient timescale to characterize drift is 10 minutes, which is long enough to be of practical use for astronomy yet short enough to permit useful engineering measurements. The goal of 2.4 degrees at 950 GHz represents the standard deviation between the true phase of the electronics and an estimate made by linearly interpolating between two calibrations taken 10 minutes apart.

Phase drift is measured by tracking the output of the HPE5500's internal phase detector using a similar setup as that used for the phase noise measurements described earlier. The PLL was closed before the final amplifier at 76 GHz.

The measurement shown in Fig. 4 was taken over a weekend starting about 4:45pm on a Friday afternoon. Less than two hours later, the air conditioning was shut off for the weekend and we see over the course of the weekend a 12 degree rise in temperature and a corresponding decrease in phase with a similar time constant. Points were taken every ten seconds.

Fig. 5 shows the calculated standard deviation from a linear fit over a ten-minute time span. Except for places where there was a sudden temperature change, i.e. when the a/c shut off, this averages about 0.15 degrees of phase at 76 GHz and slowly decreases as the temperature stabilizes over the weekend. This is a measurement of the entire system, but does indicate that even for large temperat-

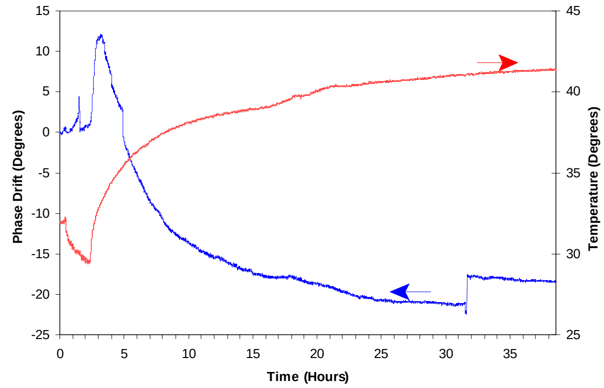

Fig. 4. Measured temperature and phase drift of 76-GHz LO driver.

ure swings, the extra phase drift incurred by placing the final power amplifier outside the PLL will not be a problem. In the future, we will perform similar measurements with the last amplifier isolated in a controlled temperature oven.

C. Amplitude Noise

The proposed goal and specification for the amplitude noise contributed by the LO is 3 and 10 K/μW respectively [2]. Noise at the IF (4-12 GHz away from the carrier of the LO) will be downconverted into the IF passband and add to the total system noise temperature at a level

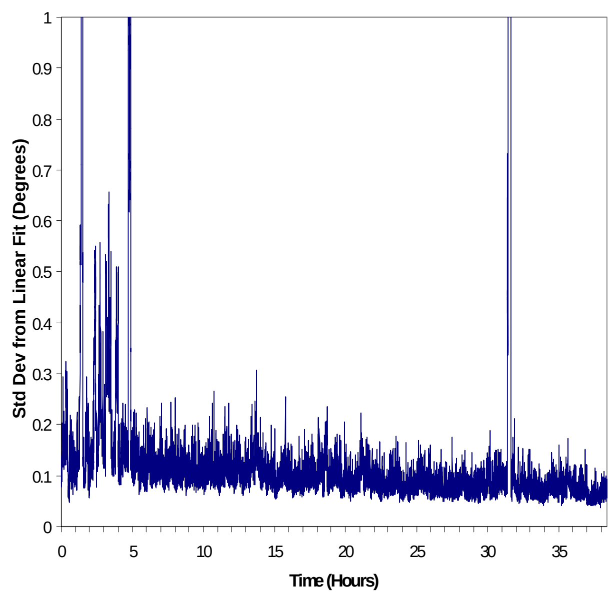

Fig. 5. Calculated standard deviation from linear fit over 10-minute time span for long-term phase drift measurement. Each point represents the standard deviation from a linear fit between the phase at that time and the phase ten minutes later.

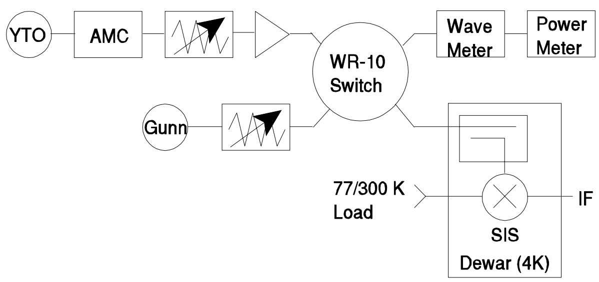

Fig. 6. Measurement setup for amplitude noise comparison of Gunn oscillator LO versus YTO-based LO.

equal to the noise temperature of the LO power. For a balanced mixer, this added noise would be less by a factor equal to the LO isolation provided by the mixer (typically 10-20 dB).

To measure the noise-to-signal ratio (N/S) of a YTO chain LO, a W-band SIS mixer with 1.4 GHz IF was used. This is shown in Fig. 6. The LO supplied was switched between a Gunn oscillator and a YTO driver LO identical to the chain used for the phase noise measurements described in the previous section. The frequency of the Gunn and YTO driver LO were both unlocked and tuned to 78.0 GHz.

The total receiver noise with the Gunn oscillator LO was 185.2 +/- 1.0 K with the SIS mixer being operated below its optimum tuning range of 90-116 GHz. The additional receiver noise measured using the YTO driver chain LO was 5.1 +/- 1.2 K. Based on the knowledge that the N/S of the Gunn is approximately 1 K/μW and the loss of the LO coupling into the dewar, the N/S of the YTO chain was calculated to be 3.7 +/- 0.9 K/μW. This figure is expected to be less for higher IF frequencies. A 240-GHz wideband varactor tripler is currently being developed at the CDL for use on the ALMA test interferometer. Future work includes making the same amplitude noise measurements at 240 GHz at the ALMA IF (4-12 GHz) over the full frequency range of the band.

A similar measurement was performed by Mehdi et al on the Caltech Submillimeter-wave Observatory (CSO) [5]. A slight *decrease* in receiver noise temperature was measured when inserting a MMIC power amplifier into their LO chain after a Gunn oscillator.

III. Conclusions

We have presented measured data of phase noise from the prototype ALMA LO drivers. These measurements show that with a loop bandwidth of only a few hundred kHz, we can meet the specifications for phase noise. The additive phase noise of amplifiers and multipliers was measured and found to be negligible. Phase drift measurements show that even for large temperature swings, the phase drift is sufficiently linear to maintain specifications with calibrations every ten minutes and the final millimeter-wave power amplifier outside the PLL. Preliminary amplitude noise measurements were presented with encouraging results, meeting specifications and very close to the goal. Future work includes extending the bandwidth of the driver chain and verifying that the noise specifications can be met over the full bandwidth.

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References

[1] J. Payne, B. Shillue, and A. Vaccari, "Photonic techniques for use on the Atacama Large Millimeter Array," ALMA Memo No. 267, June 1999, http://www.alma.nrao.edu/memos

[2] E. Bryerton, D. Thacker, K. Saini, and R. Bradley, "Noise measurements of YIG-tuned oscillator sources for the ALMA LO," ALMA Memo No. 311. Aug 2000, http://www.alma.nrao.edu/memos

[3] D. W. Porterfield, T. W. Crowe, R. F. Bradley, and N. R. Erickson, "A high-power fixed-tuned millimeter-wave balanced frequency doubler," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 419-425, Apr. 1999.

[4] L. Samoska, T. Gaier, A. Peralta, S. Weinreb, J. Bruston, I. Mehdi, Y. C. Chen, H. H. Liao, M. Nishimoto, R. Lai, H. Wang, and Y. C. Leong, "MMIC power amplifiers as local oscillator drivers for FIRST," in *UV, Optical, and IR Telescopes and Instruments* (Munich, Germany), Proceedings of SPIE Vol. 4013, pp. 275-284.

[5] I. Mehdi, T. Gaier, J. Kooi, B. Fujiwara, and R. Lai, "A W-band HEMT based power amplifier module for millimeter-wave LO multipliers," *9^{th} Int. Symp. On Space Terahertz Tech.*, (Pasadena, CA), pp. 573-578, Mar 1998.