Maximizing SNR in LO Chains for ALMA Single-Ended Mixers

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I. Abstract

This paper describes the design methodology used to develop local oscillators for the ultra-sensitive single-ended sub-millimeter wave mixers used in ALMA. Recent results of the ALMA LO system are presented, showing little or no noise added to the receiver. Measurements of excess amplitude noise from ALMA LO prototypes in the development phase are also shown. A design methodology is presented for suppressing amplitude noise in LO chains, using examples from different ALMA bands. We conclude with recommendations for future sub-millimeter LO systems.

II. Introduction

THE Atacama Large Millimeter Array (ALMA) telescope currently under construction on the Atacama plateau in northern Chile will have at least 66 antennas and will cover 30 to 950 GHz in ten bands using dual-polarized heterodyne receivers. Currently, all bands under construction use single-ended SIS mixers. In a single-ended mixer, noise on the sidebands of the LO is downconverted into the IF and is indistinguishable from the desired IF signal. It therefore is equivalent to an increased mixer noise temperature. The amount of noise downconverted to the IF is equal to the LO power used to pump the mixer divided by the signal-to-noise-ratio (SNR) of the LO.

In this paper, we briefly outline the early development of the ALMA local oscillator drivers, primarily in regards to addressing amplitude noise. Measurements of early prototypes showed considerable amplitude noise originating from the LO. Further measurements at several receiver bands along with some simple calculations and models indicated a few key steps to take to suppress this noise contribution. The current LO design, taking into account these findings, is presented with measurement examples showing minimal receiver noise contributions. We then concentrate on two remaining potential problem areas, which can be very difficult to fully eliminate in broadband LO systems.

III. Design and Development

A block diagram of the band 6 (211-275 GHz) ALMA LO system is shown in Fig. 1 as being representative of the ALMA LO system. Noise is introduced into the system predominately from each of the amplifiers in the chain. The YIG tuned oscillator module also contains an amplifier.

The first LO prototypes employed discrete connectorized modules for each of the amplifiers, multipliers, and filters following the YTO with SMA adapters and coaxial cable in between the components. The first WR-10 power amplifiers used in these prototypes used the MMICs and packages developed by the HIFI project [1]. The output power of these initial chains had very large ripples as might be expected from all the mismatches and cable lengths. A more critical problem with such an arrangement was the resulting sideband noise. Fig. 2 shows the measured receiver noise when using this LO. The receiver noise with this LO wildly varies with both LO frequency and across the 4-12 GHz IF band. This is a result of the long mismatched lengths between all the components in the LO chain. Focusing on only two LO frequencies only one GHz apart (250 and 251 GHz) in Fig. 3, it is seen how much the noise contribution can vary over a small frequency range.

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The Atacama Large Millimeter Array is an international astronomy facility. ALMA is an equal partnership between Europe and North America, in cooperation with the Republic of Chile, and is funded in North America by the U.S. National Science Foundation in cooperation with the National Research Council of Canada, and in Europe by the European Southern Observatory and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory, which is managed by Associated Universities, Inc., and on behalf of Europe by ESO.

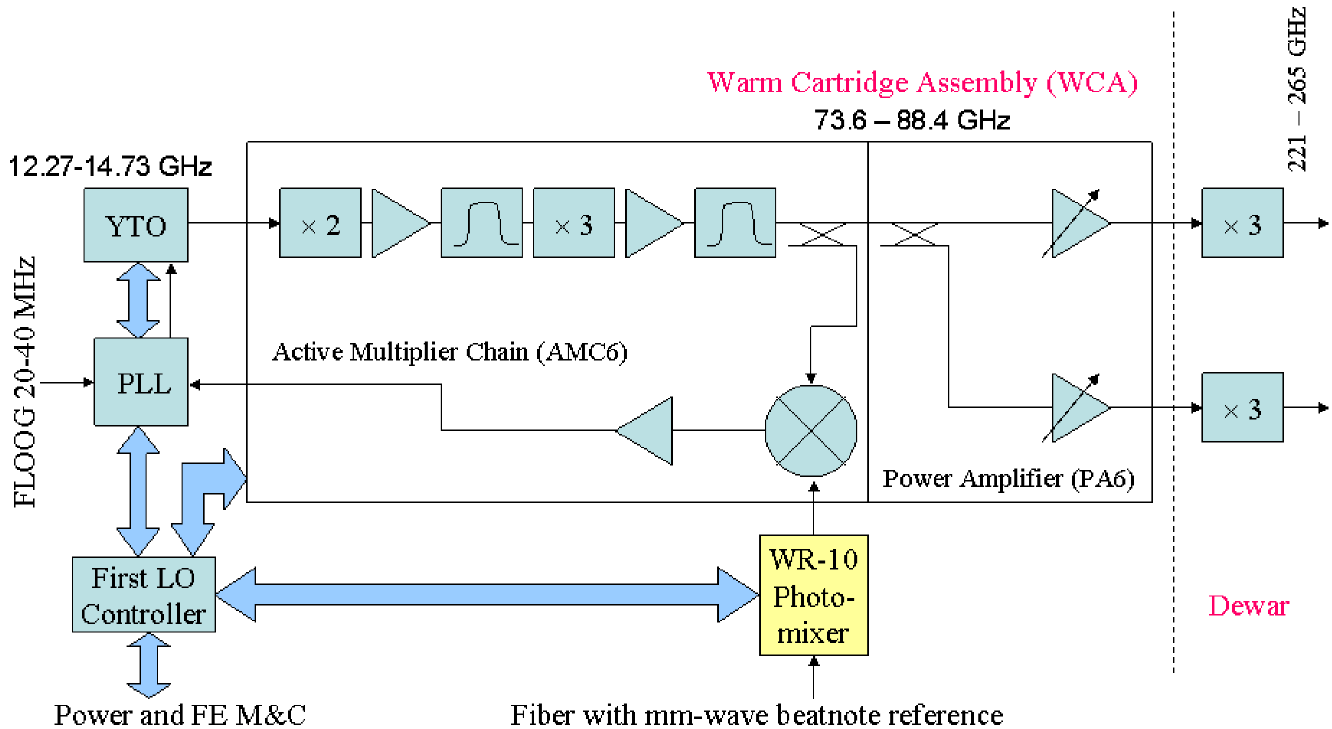

Fig. 1 Block diagram of local oscillator (LO) for ALMA Band 6 (211-275 GHz).

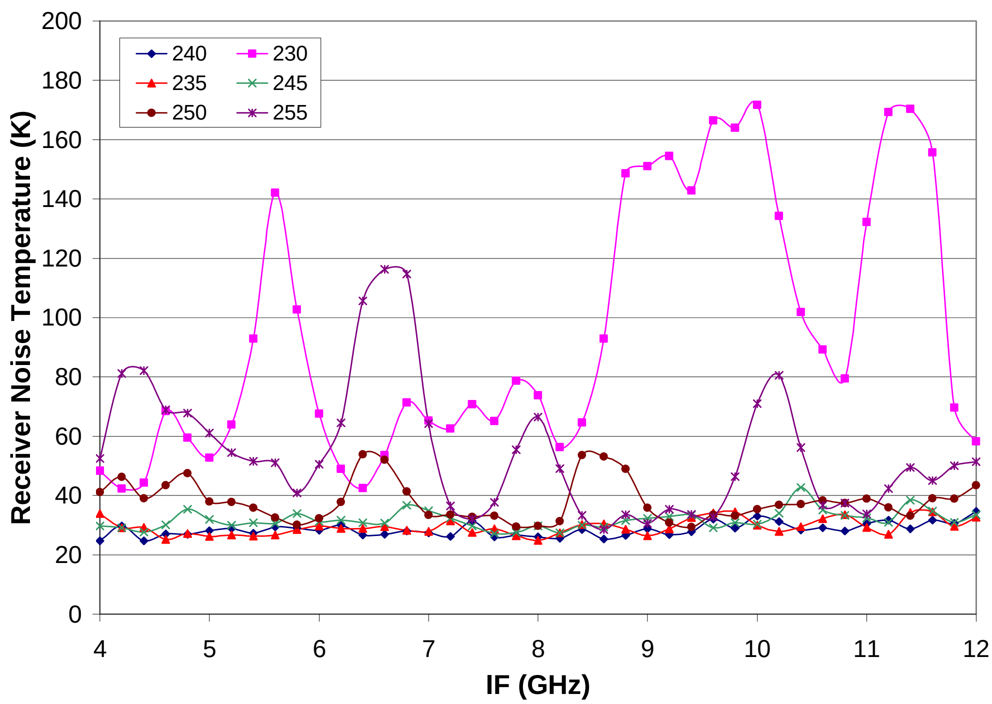

Fig. 2 Measured receiver noise temperature of a prototype ALMA Band 6 (211-275 GHz) mixer with a prototype LO driver at LO frequencies of 230, 235, 240, 245, 250, and 255 GHz.

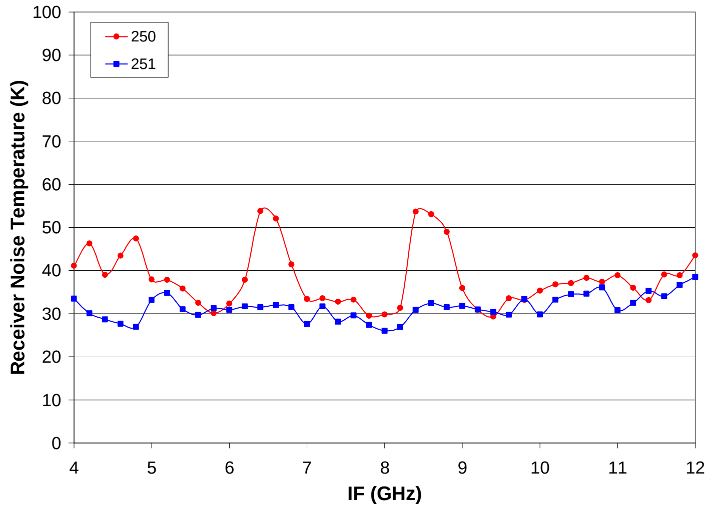

Fig. 3 Measured receiver noise temperature of a prototype ALMA Band 6 (211-275 GHz) mixer with a prototype LO driver at LO frequencies of 250 and 251 GHz.

Based on these and other early measurements, a set of guidelines for maximizing SNR in LO chains was developed. These are: (1) modest saturation of amplifiers (3-5 dB gain compression); (2) bandpass filters after each multiplication where possible; (3) integration as much as possible to minimize mismatch and standing waves; (4) properly pumped frequency multipliers.

Using these guidelines, highly integrated LO modules were designed and built. An example of one of these is shown in Fig. 4. This is an Active Multiplier Chain (AMC) module used for ALMA band 6. To minimize the effects of mismatch, the amplifier, multiplier, and filter functions are all integrated on MMICs and interconnected with 0.002” bond ribbons. Up to about 45 GHz, commercial-off-the-shelf (COTS) MMICs were available. Above that frequency, wideband MMIC multipliers and amplifiers are still not available commercially and had to be developed. We therefore developed a set of custom MMICs using a few different processes. First of all, multiplier and mixer MMICs from 60-145 GHz were designed and tested with the UMS Schottky process [2]. 5-section coupled-line bandpass filters were designed and fabricated on 0.003” Alumina. Alumina microstrip-to-waveguide transitions are used based on the design in [3]. Power amplifier MMICs were developed in both 0.1 µm GaAs pHEMT [4] and 0.1 µm InP HEMT [5] processes.

Receiver noise measurements from the highest ALMA band currently being built (band 9, 602-720 GHz) are shown in Fig. 5. These are measurements carefully comparing this LO to a Gunn oscillator based LO, showing no noticeable difference. These noise measurements are performed using the band 9 mixer test set, not the actual band 9 receiver. The noise of the actual band 9 receiver is much lower [6].

IV. Modeling of AM and PM Noise Sidebands

In a LO chain consisting of a cascade of amplifiers and multipliers, the white noise introduced by each amplifier is half AM and half PM, since the noise in any given sideband is uncorrelated with the noise in the other sideband. A single-sideband (SSB) pure noise signal can be decomposed into four components, an AM and PM component of equal magnitude at each sideband. The AM components are in phase with the LO signal and the PM components are in quadrature with the carrier. Therefore in one sideband, the AM and PM components cancel, and in the other sideband, they add coherently [7,8].

A single-ended mixer is sensitive only to the AM noise components. This is easy to see in the frequency domain, since the two sidebands downconverted to the same IF add in phase, so that the AM components add coherently at the IF, while the PM components cancel each other. Note this is also true for a sideband-separating mixer (SSM), since in a SSM the sidebands of the LO are not separated.

It is therefore necessary to concentrate on propagation of the AM noise components. The AM noise is limited and suppressed in a saturated amplifier. This was experimentally shown in [9] and can be understood intuitively and modeled by looking at the input-output response of the amplifier:

$$\frac{SNR_{out}}{SNR_{in}} = \frac{\left(P_{out} / P_{in} \right)}{\left(dP_{out} / dP_{in} \right)} \qquad (1)$$

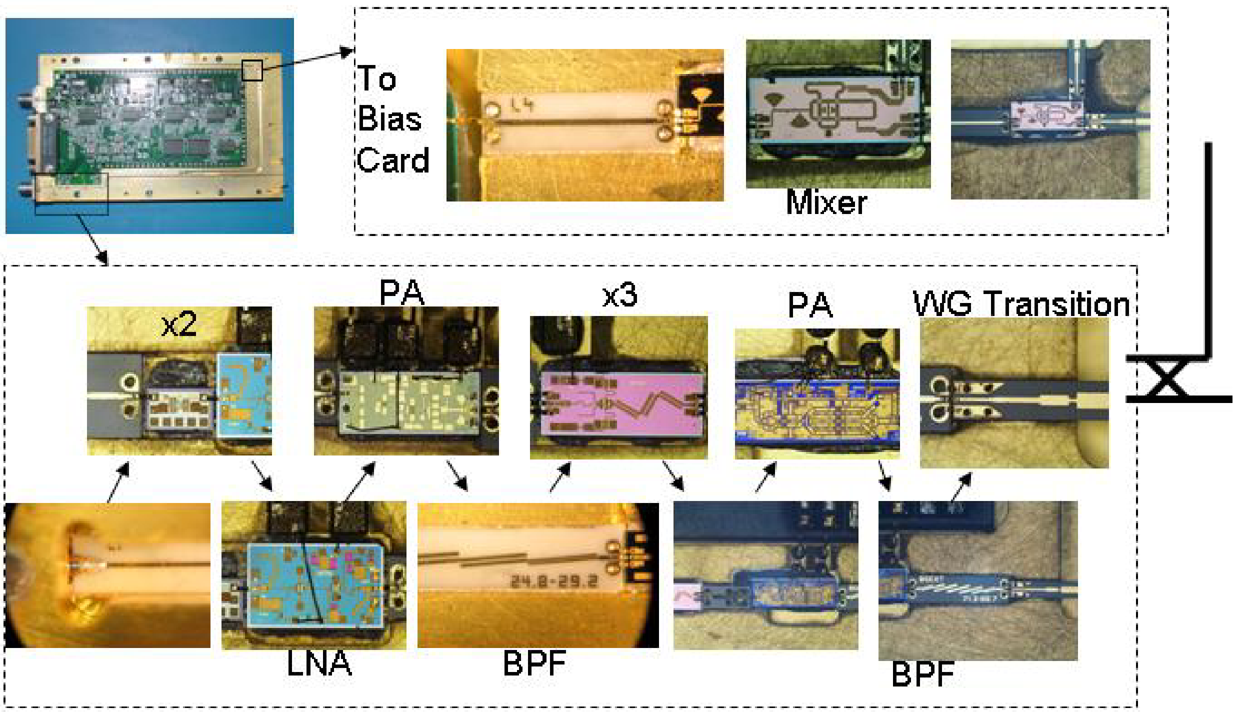

Fig. 4 Photograph of Active Multiplier Chain (AMC) module for LO driver of ALMA 211-275 GHz receiver. Substrate and MMIC areas are expanded and shown in detail.

To determine dP_{out}/dP_{in}, either the output power can be measured at very finely spaced input power levels or a polynomial function can be fitted to the measured P_{out} versus P_{in} curve and the derivative can then be calculated from that polynomial. A typical SNR improvement of 6-10 dB is obtained at a moderate level of gain compression (3-5 dB). PM noise is not, however, suppressed in a saturated amplifier since, to the first order, the phase response does not depend on input power.

In a multiplier, assuming it is properly pumped, the AM contribution to SNR remains constant since the output power is linearly dependent on input power. PM noise contribution to SNR is increased by the square of the multiplication factor. The consequence therefore of a cascade of amplifiers and multipliers is to decrease the AM noise and increase the PM noise, such that by the end of the cascade, the noise is dominated by PM. Since the single-ended mixer is only sensitive to AM noise and not to PM noise, the downconverted IF contains little noise contributions from the LO chain and does not contribute to overall receiver noise.

V. Potential Problems

A. Underpumped multipliers

AM noise in a properly pumped multiplier does not increase, as explained in the previous section. However, if the multiplier is operated with a low input power, the amplitude of the output signal is no longer linearly, but exponentially, dependent on the input signal. For example, the ALMA band 7 LO was designed to provide 25-100 uW LO power. However, less than 10 uW is required at most frequencies, meaning that, absent a cold attenuator after the final tripler, the tripler must be operated in its underpumped mode. Using Eq. (1) and the measured output versus input power response of the tripler, the AM noise enhancement is calculated to be 6-10 dB. The result is seen in Fig. 6. By adding a cold attenuator after the final LO tripler before the mixer, the multiplier was required to be pumped harder to give the same pump power to the mixer, reducing the amplitude noise contributed by the LO to a minimal amount. This effect was also seen in the ALMA Band 9 (602-720 GHz) LO, causing an increase in receiver noise over a small frequency range. By using a thinner beamsplitter, thereby increasing the required drive power to the multiplier, the excess noise disappeared.

The solution seems simple—avoid underpumping multipliers. However, in broadband systems, this can be quite difficult to achieve in practice. First of all, sub-millimeter wave power sources are typically designed for maximum power and system designers are hesitant to specify a lower power level than what is achievable, since receiver systems at these wavelengths have traditionally been LO starved. Secondly, for wideband systems, it is difficult to maintain relatively flat power versus frequency. If the LO power is not sufficiently flat across the band, then in order to have sufficient LO power at the weakest part of the band, the strongest part of the band will need to be underpumped.

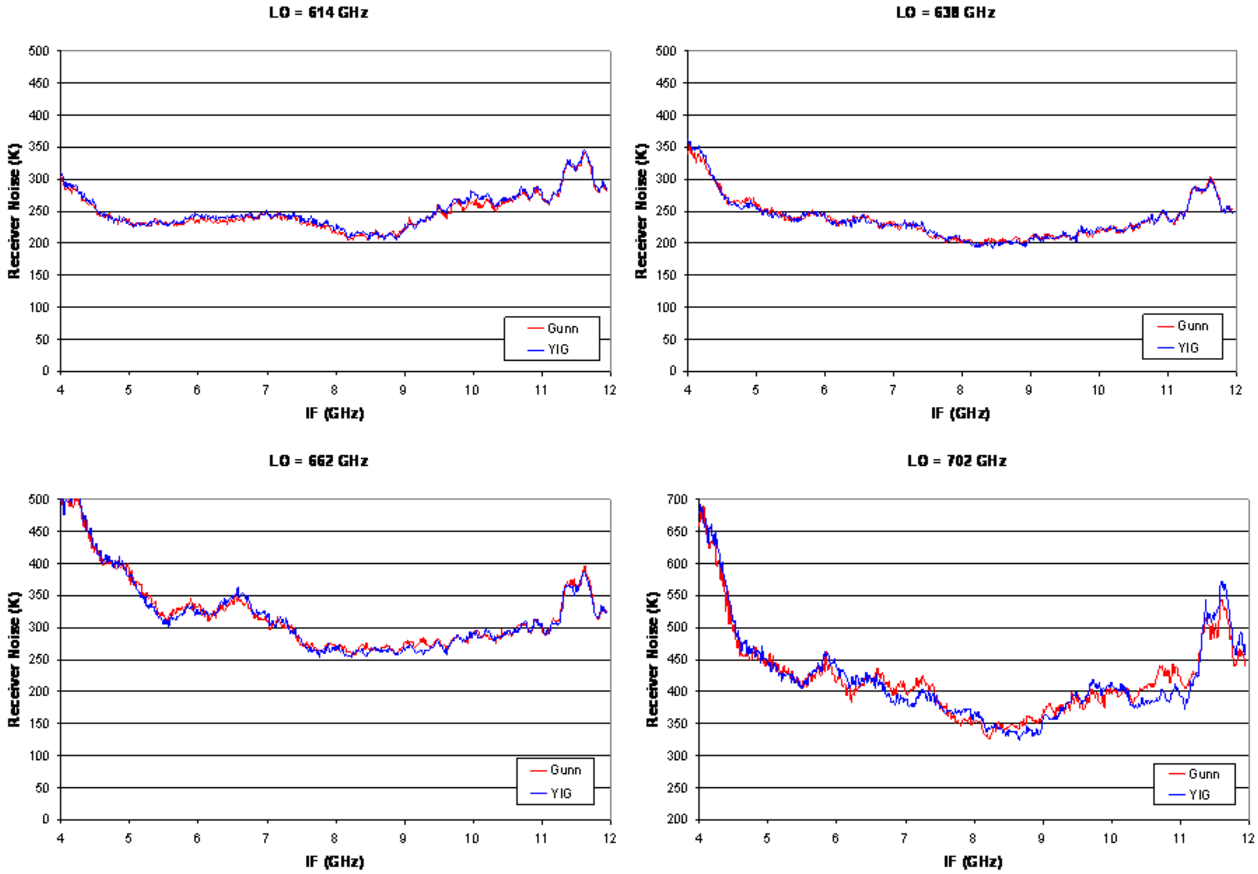

Fig. 5 Measured receiver noise of a Band 9 (600-720 GHz) ALMA mixer with the ALMA LO versus Gunn oscillator LO for LO frequencies of 614, 638, 662, and 702 GHz.

B. PM-AM conversion

Since the PM component of the noise dominates as the noise progresses through the chain of amplifiers and multipliers, even a small amount of PM to AM conversion at the end of the chain can cause a large increase in the AM noise, which will then negatively impact receiver noise.

It is instructive to look at PM-AM conversion in the frequency domain. AM modulation appears as double sideband (DSB) modulation where the two sidebands are in phase with one another with respect to the carrier. PM modulation shows up as DSB modulation where the two sidebands are opposite in phase with respect to the carrier. SSB modulation is therefore equal parts AM and PM where the AM and PM components are correlated with each other in such a way as to cancel each other out in one of the sidebands. [7,8]

The introduction of any element which has an amplitude or phase response which differs at one sideband from the other will therefore cause conversion from AM to PM and vice versa. For example, consider a signal with only PM modulation, and therefore double sideband. Passing this signal through a filter with rejects completely one sideband while passing the carrier and other sideband, essentially generating a single sideband modulation, converts half the PM modulation to AM modulation, since a single sideband modulation is half AM and half PM. This can be generalized for any level of amplitude or phase imbalance.

VI. Conclusions and Recommendations

Recommended guidelines for maximizing the SNR in sub-millimeter LO chains are: (1) modest saturation of amplifiers; (2) integration as much as possible to minimize mismatch and standing waves; (3) properly pumped frequency multipliers; and (4) bandpass filtering where, to avoid PM-AM conversion, the best approach is to filter both sidebands as high in frequency as possible, after as many amplifier stages as possible. This final point requires the bandwidth of the final amplifier stage to be less than the lowest IF. Besides moving to a higher IF band, this leads the design toward lower-frequency, higher-power final amplifiers, saturated and filtered, followed by a higher order multiplier chain.

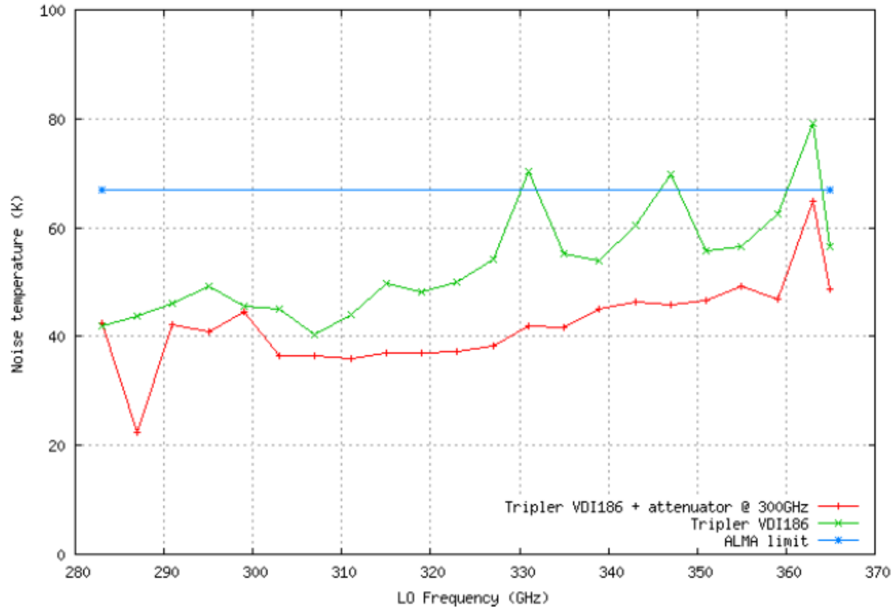

Fig. 6 Measured receiver noise of an ALMA Band 7 (275-370 GHz) mixer with an ALMA LO driver with and without an attenuator between the final LO tripler and mixer [10].

ACKNOWLEDGMENTS

We would like to acknowledge all the ALMA cartridge groups, whose receiver noise measurements were all used to understand and solve the problems of LO sideband noise. This includes: (Band 3) Herzberg Institute of Astrophysics (HIA), (Band 6) National Radio Astronomy Observatory (NRAO), (Band 7) Institut de Radioastronomie Miliimetrique (IRAM), (Band 9) Space Research Organization of the Netherlands (SRON), (Bands 4, 8) National Astronomy Observatory of Japan (NAOJ). We would also like to acknowledge the Jet Propulsion Lab (JPL), particularly Todd Gaier and Lorene Samoska, for their support in development of the power amplifier MMICs used in the LO drivers.

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