Regarding Atmospheric and Mechanical Stability Requirements of (LO-Pumped) Mixers

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Abstract

In this paper we discuss atmospheric and mechanical stability requirements of heterodyne mixers. Though the analyses is general to any heterodyne system, we are particularly interested in "short" wavelength's ($\leq 200\ \mu$m) mixers where instabilities due to atmospheric and mechanical path length fluctuations become significant. We hope to draw attention to the stringent mechanical and atmospheric tolerance requirements of (HEB) mixers operating at terahertz frequencies.

Keywords

Hot electron bolometer (HEB) mixer, atmosphere and mechanical stability, standing waves, terahertz frequencies, Allan variance method, continuum vs. spectroscopic measurements, and LO power fluctuations.

I. Introduction

At submillimeter and terahertz frequencies the required LO power is typically coupled to the mixer by optical means. This is regardless of mixer type, e.g. waveguide or quasi-optical. LO injection is often performed by a thin beamsplitter that acts as a directional coupler, though it is also possible to use a Martin-Puplett, Fabry-Perot interferometer, or a narrow band Etalon beam combiner. Typically, the submillimeter or teraherz heterodyne mixer and LO source (be it a FIR laser or solid state LO) are separated spatially with air as the medium between the two. Due to physical constraints, the mixer and LO source have a finite input return loss. Inevitably, the LO and RF reflected signals generate a standing wave in the telescope and LO path cavity. It is the standing wave in the LO-mixer path that we concern ourselves with in this paper. As the LO-mixer path length changes, be it due to air or mechanical fluctuations, the standing wave between the two will change in amplitude and modulate the LO signal. In turn this causes short and long term gain instability (1/f noise and drift) at the IF output of the mixer. Hence the concern.

II. LO path length loss

If the LO Electric field propagating in the z direction is described as

$$E_{lo} = E_{lo}(0) \cdot e^{-\gamma z} \cdot e^{j\omega t} \tag{1}$$

TABLE I

Opacity and path length variation for a 1 meter column of air.

P$_{atm}$=990 mBar, T=29 °C, and relative humidity 30 %.

Parameter	**1.519 THz**	**1.544 THz**	**1.630 THz**
Opacity (np)	0.0642	0.1351	0.3529
Change in optical path length, ΔL (μm)	41.5	47	83

where γ is the complex propagation constant $\alpha + j\beta$. Then the time averaged power density can be found as

$$P_{lo} = P_{lo}(0) \cdot e^{-2\alpha z} \tag{2}$$

α is the opacity/meter, and Plo(0) the peak LO power at z=0 meters.

The opacity and change in optical path length in a 1 meter column of air was calculated by Juan Pardo [1]. Here we define ΔL as the path length increase due to water vapor in a 1 meter column of air. In the case of turbulent air, it is not the absolute path length we concern ourselves with, but the variation in ΔL. The conditions Pardo used were as follows: Atmospheric pressure 990 mBar, temperature 29 °C, and relative humidity 30 %.
The change in optical path length due to the refractive index (n) of air is

$$\Delta L = (n - 1) \cdot z \tag{3}$$

so that n=(z+$\Delta L)/z$, which for z=1 meter equals 1+ΔL. Uncertainty in opacity is estimated to be no more than 5%. The LO signal attenuation per meter of air is therefore

TABLE II

Lo Signal attenuation / meter of air

Parameter	**1.519 THz**	**1.544 THz**	**1.630 THz**
Attenuation (dB)	0.557	1.174	3.066

III. Standing waves in the LO-mixer path

Aside from the above mentioned atmospheric attenuation of the LO power, there will also be a LO induced standing wave present between the mixer and (FIR-laser or solid state) LO source. This is due to non-zero reflections at the mixer and LO ports. It is of interest to access the sensitivity of LO power fluctuation to small changes in path length by, for example, atmospheric turbulence and/or mechanical instability in the setup. Following Schieder & Goldsmith analyses [2] [3], we define the incident LO power on the mixer as:

$$P_{lo} = |r_{bs}|^2 \cdot P_{lo}(0) \cdot A_i(\nu_{lo}) \tag{4}$$

where $|r_{bs}|^2$ is the beam splitter power reflection coefficient, $P_{lo}(0)$ the incident LO power, and $A_i(\nu_{lo})$ the Airy function that describes the fractional transmitted power ($|T|^2 = I_t/I_0$). From literature, $A_i(\nu_{lo})$ equals:

$$A_i(\nu_{lo}) = \frac{1}{1 + Fsin^2(\frac{\delta}{2})}, \quad \delta = \frac{4\pi nz}{\lambda} \tag{5}$$

where n is the refractive index of air, and F the finesse coefficient of the mixer - LO cavity.

$$F = \frac{4|r|^2}{(1 - |r|^2)^2} \tag{6}$$

$|r|^2$ represents internal reflections, in this case the mixer - LO cavity. Rewriting Eqn 6 to include loss, we substitute $r \rightarrow re^{-\alpha z}$ so that

$$F = \frac{4|r|^2 e^{-2\alpha z}}{(1 - |r|^2 e^{-2\alpha z})^2} \tag{7}$$

Now substituting Eqn 7 into Eqn 5, and expressing the Airy function in terms of the the propagation constant β gives:

$$A_i(\nu_{lo}) = \frac{(1 - |r|^2 e^{-2\alpha z})^2}{(1 - |r|^2 e^{-2\alpha z})^2 + 4|r|^2 e^{-2\alpha z} sin^2(\beta nz)} \tag{8}$$

And finally, expressing $|r|^2$ in terms of the mixer reflection coefficient $|r_m|^2$, the LO reflection coefficient $|r_{lo}|^2$, and the beam splitter reflection coefficient $|r_{bs}|^2$

$$A_i(\nu_{lo}) = \frac{(1 - |r_{bs}|^2 \sqrt{|r_m^2 \cdot r_{lo}^2|} e^{-2\alpha z})^2}{(1 - |r_{bs}|^2 \sqrt{|r_m^2 \cdot r_{lo}^2|} e^{-2\alpha z})^2 + 4|r_{bs}|^2 \sqrt{|r_m^2 \cdot r_{lo}^2|} e^{-2\alpha z} sin^2(\beta nz)} \tag{9}$$

Looking at Eqn. 9, we see that the Airy function (standing wave interference pattern between LO and mixer) has a ripple period of $\beta nz = \pi$. In sections V and VI we examine the importance of tuning to the peak of the LO-Mixer cavity standing wave ($\beta nz = 0,\ \pi,\ 2\pi, \cdots$), rather than on steep slope ($\beta nz = \pi/4,\ 3\pi/4, \cdots$).

IV. ESTIMATE OF ALLOWED LO POWER FLUCTUATIONS

To get an estimate of the level of LO power fluctuation that may be tolerated, one has to consider the sensitivity of the mixer IF output power with respect to the input LO power (dP_{if}/dP_{lo}). Assuming that the mixer acts as a standard square law detector, $Acos(\omega_s t) \cdot Bcos(\omega_{lo} t)$, the IF output will be proportional to changes in the input signal ($V_{if} = ABcos(|\omega_s \pm \omega_{lo}|)t)$. If tiny LO fluctuations (am noise) modulate the IF output, they will be manifest themselves at the output of the mixer as instability. This is certainly true in standard total power (continuum) measurements, when for example performing a Y-factor measurement (Phot/Pcold). Under these conditions the sensitivity, and stability, of essentially all HEB and SIS mixer to date are measured. If however LO power instability is correlated across the entire IF band (for example due to microphonics in the LO beam-splitter) then a spectroscopic measurement (Eqn. 10) maybe more meaningful. In this case total power measured in two (or more) statistically uncorrelated sub-bands in the IF are differenced, and LO induced fluctuations common to both channels subtract away.

$$z_i = \frac{1}{\sqrt{2}}\left[\left(\frac{x_i}{< x >} - \frac{y_i}{< y >}\right)+1\right]\cdot\frac{< x > + < y >}{2} \tag{10}$$

z_i is the difference signal, x_i and y_i signals from independent bins, and <x> and <y> their mean expectation value.

In section's V & VI, we show the effect of atmospheric and mechanical fluctuations on LO power, and indirectly on the mixer IF output signal. Tolerances are seen to be very tight, and for mixers operating in the terahertz regime it may well be advisable to perform Y-factor and stability measurements in a spectroscopic, rather than in continuum mode as is typically the case in the submillimeter.

Of course, the level of improvement depends on the intrinsic HEB stability. Recent measurements suggest (Baselmans *et.al*) that LO-pumped HEB mixers have significant gain fluctuation (Fig. 10). The atmospheric, mechanical, and thermal effects described in this paper manifest themselves as 1/f and drift noise, and care should be taken to keep these on longer timescales than the intrinsic HEB stability. Note that 1/f noise does integrate down, though not at the same efficiency as white (radiometric) noise. If science goals call for the receiver to be used in continuum mode, than spectroscopic stability measurements may mask actual performance. What method is relevant thus depends on the science goals of the instrument.

V. Sensitivity to atmospheric turbulence

Consider that recent (SRON, Chalmers, Umass, AST/RO) stability measurements of HEB mixers indicate an Allan variance minima of 0.2-0.3 seconds in a 80 MHz noise fluctuation

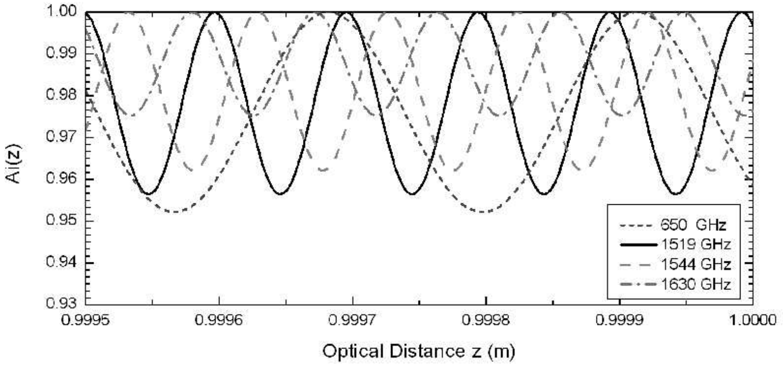

Fig. 1. Standing wave (Ai) for a cavity path length of z=1 meter. Note the effect of atmospheric loss (damping) on the standing wave. Shown here are the last 500 μm. In the example $|r_m|^2$ was taken to be 0.10 (-10 dB), $|r_{lo}|^2$ 0.16 (-8 dB), and $|r_{bs}|^2$ 0.10(-10 dB) for all four frequencies shown. If there were no atmospheric loss (space, or a high dry mountain site), the peak-to-peak standing wave amplitude in the example would be 4.934%. Solid curve is for ν_{lo}=1.519 THz, dashed 1.544 THz, dash-dot 1.630 THz, and dotted 650 GHz. We include 650 GHz as a reference where the loss is taken to be 4x less than at 1544 THz. At this frequency SIS receivers in the laboratory are known to be stable to 100 seconds in a 1 MHz resolution bandwidth[5].

bandwidth. In this case, we find from the radiometer equation

$$\sigma = \frac{< x(t) >}{\sqrt{B \cdot T_{int}}} \tag{11}$$

that LO signal fluctuations in excess of 0.025% of P_{lo} become visible at the mixer IF output. Given a typical spectrometer noise fluctuation bandwidth of 1.5 MHz, $\sigma/ < x >$=0.025% corresponds to a Allan variance stability time [4] of $\approx$ 10 seconds. For comparison sake, a typical laboratory operated submillimeter SIS receiver has, in the same bandwidth, an Allan variance stability time on the order 80-100 seconds [5].

The absolute path length change in air for three different frequencies is tabulated in Table I. From this data we obtain an estimate of the LO power fluctuation in the presence of air turbulence. It should be stressed that we do not concern ourselves with the absolute optical path length change, but with optical path length fluctuations due to changes in the refractive index of air. Thus is it useful to plot the change in LO power (Eqn. 9) against the percentage change in optical path length. If the air were to be absolutely stable, or humidity very low as would be the case on a high mountain, we'd expect $dP_{lo} \rightarrow$ zero. Note also that the loss term in Eqn. 9 has a damping effect on the LO standing wave. Thus, if a mixer is operated close to a water line, the path length turbulence will be more significant. This is however somewhat compensated by the decaying (loss) standing wave amplitude (Fig. 1). The increase in sensitivity to air turbulence with frequency is therefore not only related to wavelength, but also to the increase in atmospheric loss. This is demonstrated in Fig. 2.

Consider as an example a typical mixer with an input reflection coefficient of -10 dB ($|r_m|^2$=0.10), a LO source reflection coefficient of -8 dB ($|r_{lo}|^2$=0.16), and a beam splitter

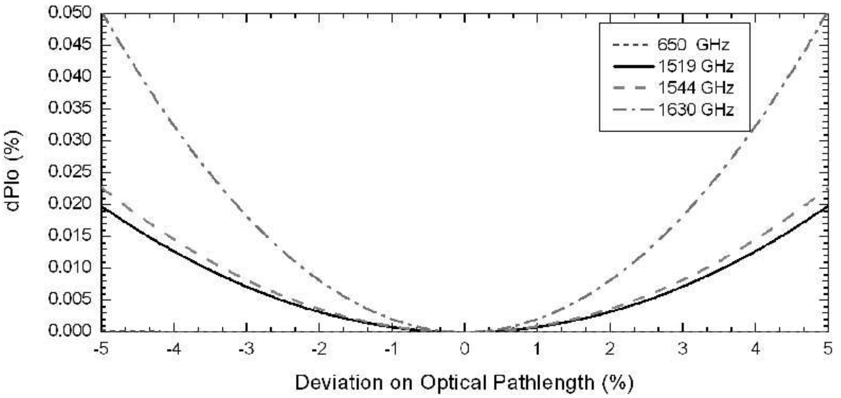

Fig. 2. LO power change (%) as a function of optical path length deviation for a z=1 meter cavity. The LO-mixer standing wave is tuned to a peak ($dP_{lo}/dz = 0$). $|r_m|^2$ was taken to be -10 dB, $|r_{lo}|^2$ -8dB, and $|r_{bs}|^2$ -10 dB. Solid curve is for ν_{lo}=1.519 THz, dashed 1.544 THz, dash-dot 1.630 THz, and dotted 650 GHz (barely visible at the bottom of the graph). For a 0.025 % LO power fluctuation, the allowed atmospheric path length turbulence at 1.519 THz & 1.544 THz (30% humidity, 990mBar atmospheric pressure) can be up to ± 6%. At the 1.63 THz CH_2F_2 FIR laser line (close to a water absorption line), the effect of air turbulence is quite a bit more significant (± 3.5% for dP_{lo} = 0.025%.) At 650 GHz the atmosphere has essentially NO influence on the LO, as may be expected. Reducing the path length and atmospheric humidity level (high mountain) will considerably improve the situation.

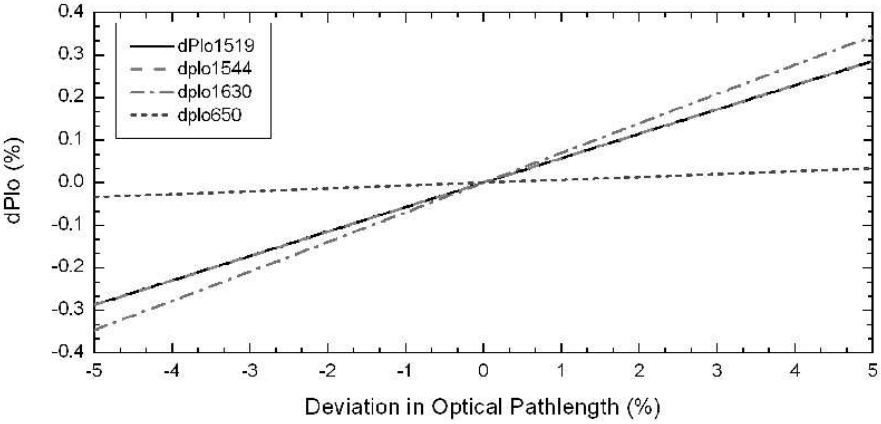

Fig. 3. Percent LO power change as a function of percent optical path length fluctuation, but now tuned to a maxima on dP_{lo}/dz. All else the same as in Fig. 2. With the LO tuned in this manner, it is essentially impossibly to get the LO power stable to better than 0.025%, with the exception of the 650 GHz frequency receiver. One should be careful therefore to always tune to a maxima (or minima) of the inevitable standing wave in the LO path. This usually means moving the dewar to or from the LO source, or by shifting the LO frequency to be on the peak of the standing wave. Note that LO power fluctuations maybe highly correlated across the IF band. If so, spectroscopic rather than continuum stability measurements are needed to separate atmospheric instability from mixer instability.

reflection 10% (-10 dB). In Fig. 1 we plot the Airy function(Eqn 9) for the last 500 μm of a 1 meter LO-mixer cavity path length. If there would be no atmospheric loss (space), the

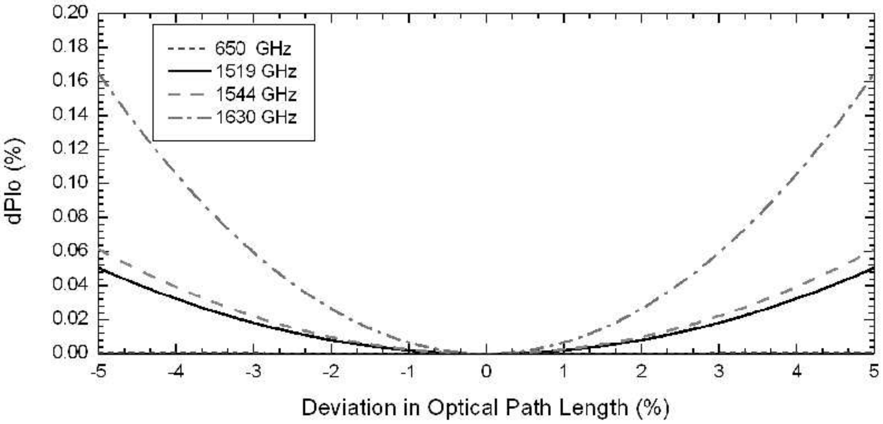

Fig. 4. Change in LO Power (%) as a function of optical path length deviation for a 0.5 meter total path length Martin Puplett LO injection scheme. $|r_m|^2$ was taken to be 0.10 (-10 dB), $|r_{lo}|^2$ 0.16 (-8 dB), and $|r_{bs}|^2$ 0.10(-10 dB). Solid curve is for ν_{lo}=1.519 THz, dashed 1.544 THz, dash-dot 1.630 THz, and dotted 650 GHz. To achieve a system imposed 0.025% LO power stability, the optical path length change due air turbulence at 1.519 THz & 1.544 THz (30% humidity, 990mBar atmospheric pressure) should be less than ± 3.5%. For the 1.63 THz CH_2F_2 FIR laser line (close to a water absorption line), the path length change due turbulent air must be kept less than (± 2.2% for dP_{lo} = 0.025%.) At 650 GHz the atmosphere has essentially no influence on the LO power stability, as expected. Reducing the path length and atmospheric humidity level (high mountain) will considerably improve the situation.

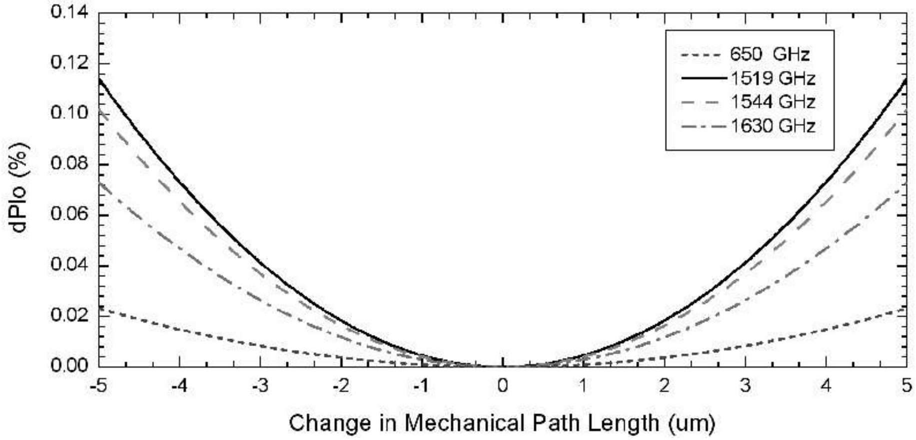

Fig. 5. LO power sensitivity as a function of path length change for a z=1 meter LO-mixer cavity length. $|r_m|^2$=0.10, $|r_{lo}|^2$=0.16, and $|r_{bs}|^2$=0.10. Solid curve is for ν_{lo}=1.519 THz, dashed 1.544 THz, dash-dot 1.630 THz, and dotted 650 GHz. To achieve a hypothetical 0.025% stability in LO power at 650 GHz, the allowed mechanical path length fluctuation will be on the order of ± 7 μm, which is easily achieved. A typical 650 GHz SIS receiver has a stability of ≈ 80-100 seconds in a 1 MHz spectral bandwidth. In this case micron level mechanical stability is to be required, which in general is accomplished by minimizing temperature drifts. At ν_{lo}=1519 GHz the situation has significantly degraded, and we find that for a system imposed 0.025% LO power fluctuation, that the mechanical stability needs to be better than ± 2.5 μm. Interestingly, at the 1630 GHz CH_2F_2 FIR laser line at sea level, the situation has actually slightly improved even though this is much closer to a water absorption line. This is due to atmospheric loss (Table 2) which dampens the LO-mixer cavity standing wave. Of course at a dry site, this advantage goes away and the sensitivity to mechanical fluctuations increases to ± 1.5μm in this particular example.

peak-to-peak amplitude variation for the given parameters would be 4.934%. In actuality, for a z=1 meter path length, the standing wave amplitude has damped to ≈ 4.8% for a 650 GHz LO signal, and 2.4% for the 1.63 THz CH_2F_2 FIR laser line, located near a water absorption line. Interestingly, a 5% standing wave value agrees well with measurements at 230 GHz, 352 GHz, 690 GHz, and 807 GHz obtained at the Caltech Submillimeter Observatory (CSO) in December 2003. A nice confirmation that the assumed mixer, LO source, and beam splitter reflections are reasonable. From Eqn. 9 it is clear that as $r_{bs} \rightarrow 0$ that the LO-mixer standing wave vanishes to zero. Thus it is advantages to use very low reflective (thin) beam splitters. Of course at terahertz frequencies, except for when an FIR laser is employed, this is not practical. In Fig. 2 the Airy function is evaluated for a mixer - LO path cavity of z=1 meter, a 10% reflecting beam splitter, and with the LO-Mixer standing wave tuned to a peak. This is the most stable LO configuration. In Fig. 3 we tune the LO to the most sensitive part of the standing wave, where dP_{lo}/dz is the largest. And finally, in Fig. 4 we plot LO power sensitivity at the mixer for a 0.5 meter optical path length Martin-Puplett LO injection scheme. Here the MP is assumed to have a 1 dB loss and is tuned to maximum transmission so that $sin^2(\beta nz) = 0$. Though not shown here, it is absolutely critical as far as receiver stability goes, that the mixer-LO cavity is tuned to a peak of the (inevitable) LO power standing wave. This is also the case for a dry-air mountain site.

VI. SENSITIVITY TO MECHANICAL FLUCTUATIONS

As an example of the effect of mechanical path length fluctuations, consider the same mixer with an input reflection coefficient of -10 dB ($|r_m|^2$=0.10), LO source with an reflection coefficient of -8 dB ($|r_{lo}|^2$=0.16), and a LO path beam splitter reflection of 10% as before. Evaluating Eqn. 9 at 1.544 THz, we again find a peak-to-valley standing wave amplitude of 4.934%. By evaluating Eqn. 9 for small perturbations in z, we get an estimate for the allowed optical path length change of the Lo-Mixer cavity. Figures 5 and 6 show the mechanical stability requirement of a mixer system that uses a beamsplitter for LO injection. Fig. 7 shows the stability requirement in the case of Martin-Puplett (MP) LO injection scheme. The Martin-Puplett is assumed to be tuned to maximum transmission which would be the most stable configuration. Loss in the interferometer is taken to be 1 dB. In the case of a MP interferometer LO injection scheme, mechanical stability requirements on the order of 0.5μm (or less) are needed in the tereahertz regime. This specification places very stringent thermal requirements on the hardware. For example: Given a thermal expansion of Aluminum at room temperature of $2.25{\cdot}10^{-5}\ K^{-1}$, a LO power drift of 0.025%, and a 1.5 MHz spectrometer noise bandwidth. Then we find (Eqn. 11) a maximum allowed temperature drift of 0.25°C/minute. At a physical temperature of 100°K the situation improves by approximately a factor of 2, due to a decrease in thermal expansion of Aluminum. In practice this means that thermal fluctuations of the LO - mixer assembly are to be kept to a minimum. Of course tuning to the most sensitive part of the LO standing wave when using a Martin-Puplett is horrendous, and should be avoided. This means in practice that if the mixer-LO cavity length is fixed (LO and Mixer cannot be moved) that one should only observe at discrete frequencies such that βnz is a multiple of π radians. This is the free spectral range, which for z=1 meters equals 150 MHz.

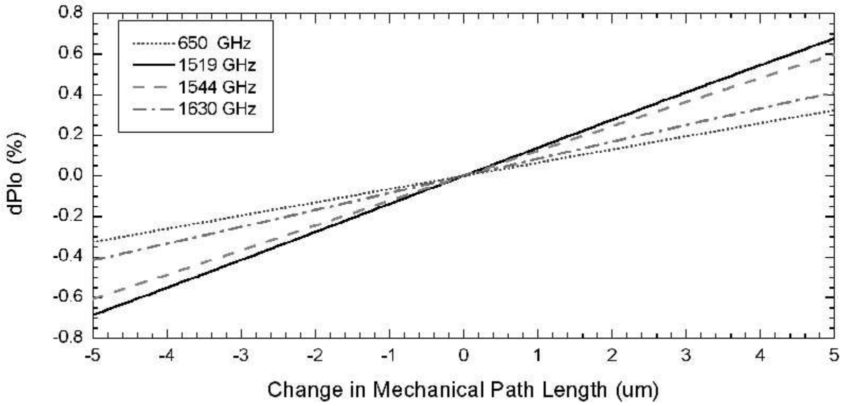

Fig. 6. LO power sensitivity as a function of percent path length change, but now with the LO position tuned to a maxima on the dP_{lo}/dz slope. All else being the same as in Fig. 5. With the LO tuned in this manner, it is essentially impossibly to get the LO power stable to better than 0.025%, even for the 650 GHz frequency receiver. One should be extremely careful therefore to always tune to a maxima (or minima) on the standing wave in the LO - mixer path. Typically this can be done by moving the dewar or LO source, though it is also possible to move the LO frequency such that βnz is a multiple of π radians (Eqn 9).

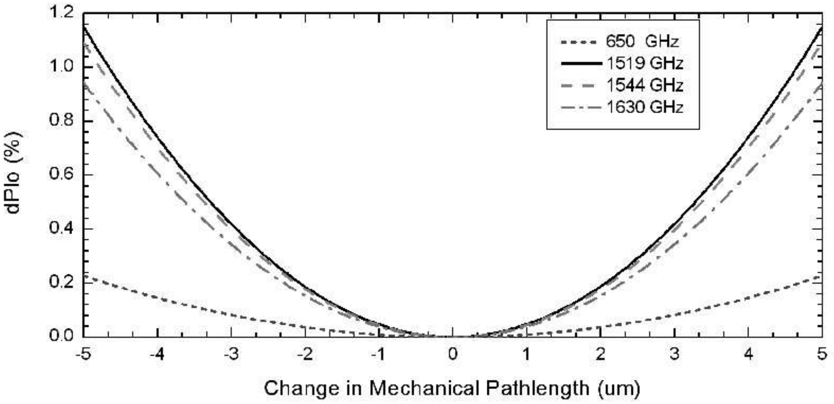

Fig. 7. LO Power sensitivity to path length change of a 0.5 meter Martin Puplett. Loss is taken to be 1 dB. $|r_m|^2$=0.10, $|r_{lo}|^2$=0.16, and $|r_{bs}|^2$=0.80. Solid curve is for ν_{lo}=1.519 THz, dashed 1.544 THz, dash-dot 1.630 THz, and dotted 650 GHz. To achieve a 0.025% stability in LO power, the path length change should be no more than a fraction of a micron during the time of a observation scan. This can only be achieved by keeping the MP temperature well stabilized. As before, depending on how dP_{lo} correlates across the IF, spectroscopic rather than continuum stability measurements may be needed to separate mechanical from mixer instabilities. For the 1630 GHz CH_2F_2 FIR laser line, at sea level, the situation has actually slightly improved due to atmospheric loss, even though this is much closer to a water absorption line. On a dry site, this advantage reverses itself and the sensitivity to mechanical fluctuations increases to roughly ± 0.3μm at 1.63 THz.

At this point, it should be clear that mixers operating at terahertz frequencies will, by their very nature, always be extremely sensitive to mechanical vibrations and atmospheric turbulence. It is probably not a good idea therefore to try to use these mixers as continuum detectors.

VII. Measured Results

A. Setup

To illustrate the issues discussed in the previous sections, we measured the Allan variance stability time of phonon cooled NbN hot electron bolometer mixers pumped at two different LO frequencies; 673 GHz and 1.52 THz. The expectation being that the effect of atmospheric and mechanical instability at 673 GHz is negligible, and that intrinsic HEB noise characteristics maybe measured directly. The drawing of the measurement setup is given in Fig. 8. We use a quasi-optical injection scheme for the LO, in which we glue the HEB die to the back of an elliptical Si lens. As LO source a solid-state multiplier chain, coupled to a phase locked Gunn Oscillator was used. The LO is attenuated using a wire grid, focused using a Teflon lens, and coupled reflectively to the Si lens of the mixer block through a 7 % reflective (14 μm) beam splitter. For the experiment at 1.52 THz we used a x16 multiplier chain from JPL[6], coupled to the same XL microwave Phase Locked Loop system. In this case the total output power of the HIFI test LO, 7 μW, is just barely enough to reach the optimal pumping level of the mixer. Hence the LO was coupled directly to the mixer lens without using a beam splitter or wire grid. At the output, the IF signal from the HEB passes through a Bias T, a 1-2 GHz isolator and a 1-2 GHz Berkshire low noise amplifier

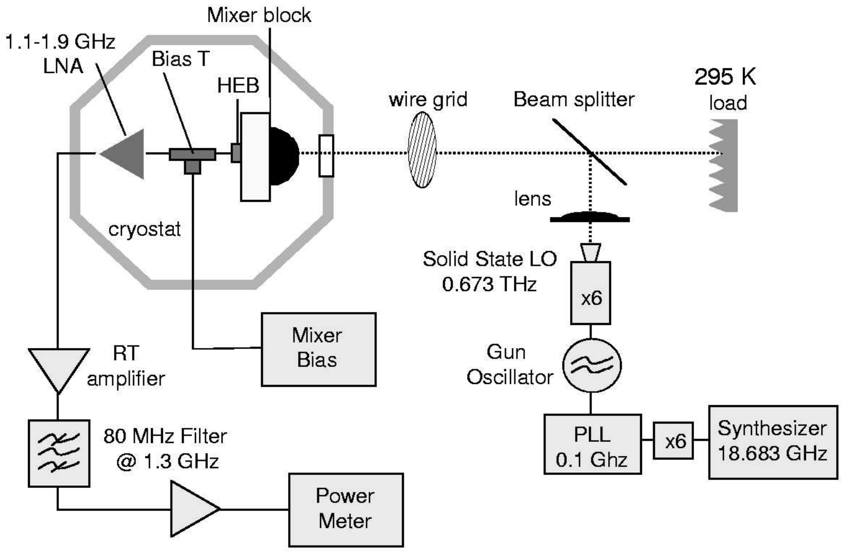

Fig. 8. Measurement setup used to measure the Allan variance. Shown here is the setup using a 673 GHz LO with a 7% reflective beamsplitter. For the high frequency experiment we used the same PLL with a x16 JPL multiplier chain to reach a LO frequency of 1.52 THz. In this case the LO is coupled directly into the cryostat, without the use of a beam splitter or wire grid, due to the limited output power of the LO chain at this high frequency.

(GaAs HEMT's), all thermally anchored to the 4.2 K plate of a liquid Helium dewar. The signal is further amplified at room temperature with a commercial Miteq amplifier and is measured in a 80 MHz bandwidth around 1.3 GHz using an Agilent E4418 B power meter at 200 samples/second. A computer program is used to calculate $\sigma_A/<x(t)>$ from this data.

B. HEB Stability

In Fig. 9 we show the measured HEB stability for different LO pump levels. A small volume 0.15 x 1 μm HEB mixer, with clean contact pads [7] and a twin slot antenna optimized for 1.6 THz was used in the experiment. At the measurement frequency of 673 GHz the antenna response is reduced by a factor two with respect to the antenna center frequency [8]. We measured a receiver noise temperature ($T_{N,DSB}$) of 1100 K at 673 GHz and used the exact same setup to measure the HEB mixer stability. This indicates that the mixer still has a reasonable sensitivity at a frequency in which the Allan variance is taken. A detailed description of the noise performance, LO power requirement and direct response of this device can be found in Ref. [8]. In Fig. 9 we plot in the left panel the normalized Allan variance ($\sigma_A/<x(t)>$) for several bias points along the optimally pumped IV curve (673 GHz). In the right panel we show the unpumped and optimally pumped IV curves, the 1.63 THz DSB receiver noise temperature (dots) along the optimally pumped IV, and the points at which the Allan variance has been taken (stars). At the optimal bias point, corresponding to a DC bias voltage of 0.8 mV, we obtain an Allan time of roughly 0.5 sec in a 80 MHz noise spectral bandwidth. Observe that the Allan time increases slowly with

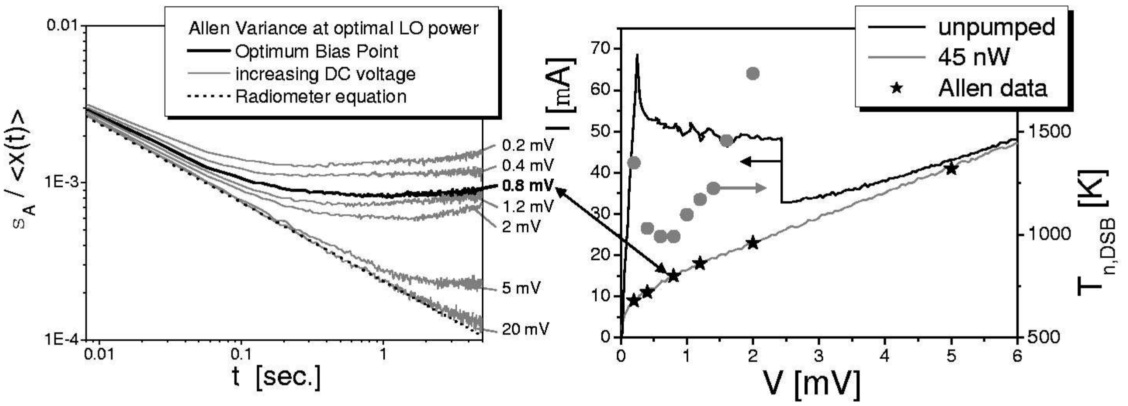

Fig. 9. 673 GHz HEB Allan variance stability measurements as a function bias voltage at optimal pump level with a 0.15 x 1 μm area twin slot NbN HEB mixer. Left panel: Normalized Allan variance ($\sigma_A/ < x(t) >$) as a function of integration time t for different values of the DC bias voltage along the optimally pumped IV curve. Right panel: Unpumped (black) and optimally pumped (grey) IV curve of the HEB, together with the measured double sideband receiver noise temperature (dots) at 1.63 THz, the center frequency of the antenna. The optimally pumped IV curve corresponds to a LO power of 30 nW according to the isothermal technique, however, the power needed to pump the device is significantly higher (see [8]). The black stars indicate the bias points at which the Allan variance was measured along the optimally pumped IV.

increasing DC bias, and decreases with decreasing DC bias. For the lowest line in the left panel, obtained at a high DC bias of 20 mV, no heterodyne response is measurable. The explanation being that at a very high bias the HEB mixer conversion gain $\rightarrow 0$, and thus we measure the IF response of our setup. At about 5 seconds of integration time we see the 20 mV bias line deviate from the radiometer equation (Eqn. 11) which is indicated by the dotted line. This deviation is due to gain instability of the GaAs LNA and warm IF amplifier chain ($\approx$ 45 seconds in a 1 MHz resolution BW). Being so far out, it does not effect the HEB mixer stability measurements.

The plateau after reaching the system's Allan time indicates that short term gain fluctuations (1/f noise) are limiting the stability of the HEB mixer. The strong bias dependence of the gain fluctuations is another indication that we are observing a property of the HEB, and not some spurious noise sources in the system. Especially so since the expected LO-mixer standing wave is only 3%, and that short time scale mechanical path length changes of up to ± 5 μm are allowed (Fig. 5). Other measurements, where the DC bias voltage is kept constant but the LO power is increased indicate that an increase in LO power has the same effect as an increase in DC voltage; i.e. an increase in stability [8]. This indicates that fluctuations in the LO output power are very likely not influencing these measurements as well. Therefore we conclude that the mixer gain fluctuations observed are a fundamental property of NbN phonon cooled HEB mixers. The physical cause of the gain instability is likely related to stochastic modulation, due to for example heat or quantum noise, of the "hot spot" mixing area internal to the mixer. It is not inconceivable that device geometry and/or magnetic field can play an important role in minimizing HEB gain fluctuation noise. As such, small differences in the Allan time minima maybe expected between the different

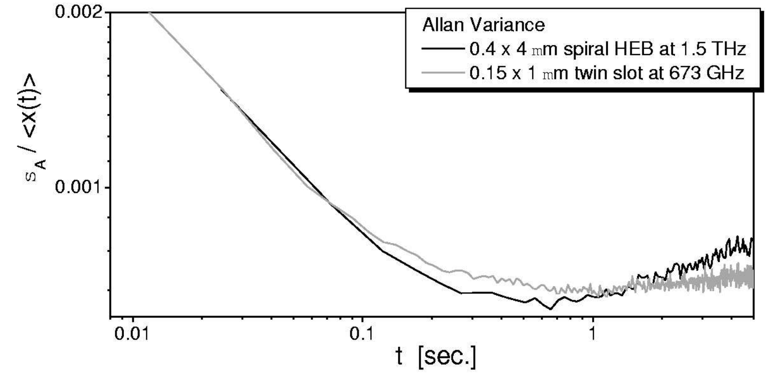

Fig. 10. Allan variance stability measurements with two different HEB mixers measured at 1.5 and at 673 GHz

mixer groups. The reported measurements are in good agreement with other reported stability measurements (these proceedings) on similar devices, taking into account variations in (noise) bandwidth[9], [10].

In addition to the discussed measurements, we have also performed similar measurements using a large volume (4 x 4 μm) spiral antenna HEB mixer at 1.52 THz, at its optimal operating point. The $T_{N,DSB}$ of this mixer is 750 K at 1.89 THz and 950 K at 2.5 THz, and estimated to be of the order of 700 K at 1.52 THz [7]. The result of this measurement is shown in Fig. 10. In the same graph we reproduce the result obtained at 673 GHz using the small volume twin slot HEB. From the figure it is clear that the stability is roughly identical for both devices, indicating again that the observed stability is a device property and not something in our setup. However, looking at longer integration times it is obvious that for the black line representing the data taken at 1.52 THz, no 1/f plateau is observed. Instead, we see an increase in the variance, associated with drift, which we believe can be attributed to mechanical and/or atmospheric instability in the setup. At 1.52 THz, due to available LO power, the LO was injected directly into the mixer. This being the case of a Martin-Pupplet LO injection scheme (Fig. 7). Interestingly, because of the relatively short time scale gain fluctuations, the measured Allan variance stability time does not appear to be limited by mechanical or atmospheric fluctuations at 1.52 THz. However at the 1.63 THz CH_2F_2 FIR laser line, when using more stable mixers, or by measuring at higher terahertz frequencies, the receiver stability will almost certainly be dominated by the setup. Thus a proper design approach should be taken to minimize atmospheric and mechanical fluctuations in the terahertz regime.

VIII. Conclusion

In this paper we have studied the effect of atmospheric and mechanical stability on terahertz mixers from the point of view of the LO - mixer "cavity" standing wave. There are of course many other mechanisms that can cause a mixer to behave unstable or erratic, such as temperature drifts of the mixer/LNA and low frequency noise on bias lines [5] [4]. As far as the LO standing wave is concerned; mechanical, thermal, and atmospheric tolerances for mixers operating in the terahertz regime have been found to be much more stringent than for mixers operating in the submillimeter. Even with proper mechanical engineering principles in mind, it will be difficult to use terahertz heterodyne (LO pumped) receivers in continuum mode.

As a direct result of the analyses, it has been found that phonon cooled HEB's have significant short term (mixer) gain fluctuations, and that up to at least 1.5 THz they tend to dominate the mixer stability budget. The physical origin of the gain fluctuation noise is unclear, however it conjectured that it maybe related to thermal and/or quantum hot-spot modulation inside the mixer. For this reason it maybe advisable to establish stability, and possibly sensitivity, of terahertz mixers via spectroscopic, rather than continuum means.

The level of improvement that can be gained from using the spectroscopic measurement (statistically differencing two or more uncorrelated IF channels) will depend on how correlated the noise is across the HEB IF band. If science goals call for the receiver to be used in continuum mode, than spectroscopic stability measurements may mask actual performance. Whatever method is relevant thus will depend on the science objectives of the instrument.

In regards to the use of a Martin-Pupplet LO injection scheme, one should be very careful to only tune to the peak of the LO power standing wave. If the mixer-LO cavity length is fixed (LO and Mixer cannot be moved) than one should tune the LO at discrete frequencies such that $\beta n z$ is a multiple of π radians. This is the free spectral range, which is for z=1 meters 150 MHz.

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