

Submillimeter SIS Receiver Gain Stabilization

James Battat, Raymond Blundell, Todd R. Hunter, Robert Kimberk, Patrick S. Leiker, Cheuk-yu Edward Tong
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA USA

ABSTRACT

We have designed a system to stabilize the gain of a submillimeter heterodyne receiver against thermal fluctuations of the mixing element. In the most sensitive heterodyne receivers, the mixer is usually cooled to 4 K using a closed-cycle cryocooler, which can introduce $\sim 1\%$ fluctuations in the physical temperature of the receiver components. We compensate for the resulting mixer conversion gain fluctuations by monitoring the physical temperature of the mixer and adjusting the gain of the intermediate frequency (IF) amplifier that immediately follows the mixer.

This IF power stabilization scheme, developed for use at the Submillimeter Array (SMA), a submillimeter interferometer telescope on Mauna Kea in Hawaii, routinely achieves a receiver gain stability of 1 part in 6,000 (rms to mean). This is an order of magnitude improvement over the typical uncorrected stability of 1 part in a few hundred. Our gain stabilization scheme is a useful addition to SIS heterodyne receivers that are cooled using closed-cycle cryocoolers in which the 4 K temperature fluctuations tend to be the leading cause of IF power fluctuations.

1. Introduction

Superconductor insulator superconductor (SIS) receivers are in use on many millimeter and submillimeter telescopes because of their good spectral line sensitivity. Their continuum sensitivity, however, does not usually reach the theoretical limit because of receiver gain fluctuations. These arise predominantly from changes in mixer conversion gain, which result from physical temperature changes and local oscillator (LO) power changes. Here we describe a technique to reduce the impact of physical temperature changes on mixer conversion gain variations by changing the intermediate frequency (IF) gain of the receiver in proportion to fluctuations of the physical temperature of the SIS junction used as a mixing element.

A number of radio observatories make use of liquid Helium filled cryostats so that temperature induced receiver gain fluctuations are minimized. However, due to their lower degree of maintenance and upkeep, closed-cycle Helium cryocooler systems may be preferred. For example multi-receiver systems with high heat loads, such as those in use at the 8-element Submillimeter Array (SMA) (Moran 1998) or the upcoming 64-element Atacama Large Millimeter Array (ALMA) (Wootten 2003), are dependent on the use of cryocoolers. For these applications it is necessary to develop techniques to reconcile the need for highly stable receivers with the practical benefits of cryocoolers. An obvious approach is to design more stable cryocoolers, another is to compensate for the fluctuations in the mixer's conversion gain.

In some systems it is possible to stabilize the physical temperature of the mixer in a cryocooler system to 1-2 mK by using a heating resistor or a pot of liquid helium (Plambeck 1998; Sekimoto *et al.* 2001; Orłowska 2004). At the SMA these options are not feasible, so we take a different approach to receiver stabilization. While monitoring the physical temperature of the mixer we actively vary the gain of the third stage of the low noise HEMT amplifier to compensate for mixer conversion gain variations. We achieve nearly an order of magnitude improvement in receiver gain stability from 1 part in ~ 800 to 1 part in 6,000 (rms to mean ratio) using a 33 ms integration time over 10 minutes. This corresponds to an effective temperature stability of < 2 mK. Such a scheme is straightforward to implement and can be applied to existing systems without redesigning the cryocooler.

2. Theoretical Considerations

The conversion gain of an SIS mixer has a negative temperature coefficient (Baryshev *et al.* 2003; Kooi *et al.* 2000). In simple terms, as the physical temperature, T_{phy} , of the mixer increases, the leakage current increases and the current-voltage relationship near the gap voltage becomes less sharp causing the mixer conversion gain, G , to decrease. For small temperature changes we may write

$$\frac{\Delta G}{G} \propto -\frac{\Delta T}{T_{phy}} \quad (1)$$

where ΔG and ΔT represent small fluctuations in the conversion gain and physical temperature of the mixer, respectively, and the minus sign reflects the anti-correlation between physical temperature and conversion gain.

At the SMA a two stage Gifford-McMahon (G-M) and a single Joule-Thomson (J-T) stage closed-cycle cryocooler maintain the SIS mixer at a nominal operating temperature of 4.2 K. In our system, cryocooler-induced temperature swings of about 1% (10-60 mK) result in mixer gain fluctuations of about 0.5%. Under the assumption that the $1/\sqrt{B\tau}$ fundamental gaussian radiometer noise and the instrumental gain fluctuations are statistically independent, (Tiuri and Räsänen 1986) show that they contribute to the fractional error in the system temperature by adding in quadrature to give:

$$\frac{\Delta T}{T_{sys}} = \sqrt{\left(\frac{1}{\sqrt{B\tau}}\right)^2 + \left(\frac{\Delta A}{A}\right)^2} \quad (2)$$

where $\Delta T/T_{sys}$ is the fractional error in the measured system noise temperature, B and τ are the IF bandwidth and integration time, respectively, and $\Delta A/A$ is the fractional gain fluctuation in the entire receiver chain.

The SMA receivers have a 2.5 GHz IF bandwidth and the digital correlator has a minimum integration time of 1 second, so the fundamental radiometer noise is $\lesssim 2 \times 10^{-5}$. Therefore fractional instrumental gain fluctuations, typically of order 10^{-2} - 10^{-3} , dominate the system temperature fluctuations. In order to approach the fundamental noise limit of the receiver, the instrumental gain stability must be significantly improved.

Ignoring losses at the receiver input, the power output of an SIS receiver, shown schematically in Figure 1, can be written in the Rayleigh-Jeans limit ($h\nu \ll kT$) as

$$P_{IF} = k_B B G H \left(T_S + T_M + \frac{T_H}{G} \right) \quad (3)$$

where k_B is Boltzmann's constant, B is the IF bandwidth, G is the conversion gain of the mixer, H is the total HEMT amplification, T_S is the noise temperature of the source, T_M is the mixer noise temperature and T_H is the HEMT amplifier noise temperature.

If we assume that mixer conversion gain fluctuations are the dominant source of receiver gain fluctuations, and that T_M and T_H are independent of the physical temperature of the mixer and IF amplifier, then we can compute the necessary change in IF gain required to maintain a constant IF power from the following condition

$$\Delta P_{IF} = \frac{\partial P_{IF}}{\partial G} \Delta G + \frac{\partial P_{IF}}{\partial H} \Delta H = 0. \quad (4)$$

Using Equations 3 and 4, we find that the necessary fractional change in IF amplification is related to the fractional change in mixer conversion gain by

$$\frac{\Delta H}{H} = -\left(1 - \frac{P_H}{P_{IF}}\right) \frac{\Delta G}{G}. \quad (5)$$

where we have introduced $P_H \equiv k_B B H T_H$, the output noise power of the HEMT amplifier.

The observed physical temperature fluctuations, ΔT , are small compared to the nominal operating temperature, T_0 (generally $\Delta T/T_0 \lesssim 5\%$). Thus for linear perturbations, and under the assumption that the conversion gain of the mixer is only a function of its physical temperature, T_{phy} , we can write

$$\Delta G \equiv G(T_{phy}) - G(T_0) \approx g_T \Delta T. \quad (6)$$

where g_T is equal to the first derivative of the curve of mixer conversion gain versus physical temperature, evaluated at T_0 . Over a broad temperature range, g_T is well approximated by the derivative of the Fermi function (Kooi *et al.* 2000).

Over temperatures relevant to this work, $G(T_{phy})$ is approximately quadratic so g_T varies linearly with physical temperature as confirmed by our measurements described in Section 4.1.

In our system, we alter the IF gain by changing the bias current of the final stage of the low noise 3 stage HEMT amplifier immediately following the mixer. The HEMT gain, H , is a linear function of its bias current, I_B , as shown in Section 4.2. With the assumption that the HEMT gain depends only on its bias current, in other words, by ignoring its dependence on physical temperature (in practice, temperature induced HEMT amplifier gain fluctuations are much smaller than mixer gain variations, as shown in Figure 2), we have

$$\Delta H \equiv H(I_B) - H(I_0) \approx h_I \Delta I \quad (7)$$

where h_I is the slope of the HEMT gain versus bias current curve evaluated at current I_0 and ΔI is a small change in the HEMT bias current.

Thus, from Equations 5, 6 and 7, we see that the necessary change in HEMT bias current for a given change in the physical temperature of the mixer is given by

$$\Delta I = -\frac{g_T}{h_I} \frac{H}{G} \left(1 - \frac{P_H}{P_{IF}}\right) \Delta T \quad (8)$$

In order to change the HEMT third stage bias current, we generate a voltage with a digital to analog converter, V_{DAC} , and feed it through a series resistor, R . Therefore the required DAC voltage is

$$\begin{aligned} V_{DAC} &= -R \left[\frac{g_T}{h_I} \frac{H}{G} \left(1 - \frac{P_H}{P_{IF}}\right) \right] \Delta T \quad (9) \\ &= -f \Delta T \quad (10) \end{aligned}$$

where f is the proportional gain of the open-loop servo system, an experimentally determined value, with units of $V K^{-1}$, that relates changes in the physical temperature of the mixer to the DAC voltage necessary to stabilize the receiver. By changing the third stage of HEMT gain, we introduce negligible receiver noise temperature changes.

Because f is not known ahead of time and it changes with operating conditions, we have a training period of 5-10 minutes during which we place a fixed temperature load in the receiver beam and select a value of f to minimize dP_{IF}/dT_{phy} . Then the calibration load is removed from the beam and the value of f is maintained during the astronomical observation. We routinely achieve a stability of a part in 6,000 during the training period, and the derived value of f is typically valid over many hours.

3. Experimental Setup

We have made stability measurements using a 230 GHz SIS heterodyne receiver designed for the SMA (Blundell *et al.* 1995). A schematic of the receiver and the open-loop gain stabilization system is shown in Figure 1. The horn, mixer, isolator and 3 stage low noise HEMT IF amplifier with ~ 30 dB gain are maintained at a nominal temperature of 4.2 K, and an additional gain of 20 dB is provided by an amplifier maintained at 20 K (not shown in Figure 1). The receiver output, 2.5 GHz wide centered at 5 GHz, is measured with a Herotek DT-4080 tunnel diode that is temperature stabilized near room temperature to 1 part in 10^5 (rms to mean ratio). The rms stability of this continuum detector was measured at 1 part in 8,000 over 600 seconds with a 33 ms integration time. This value is $\sim 15\%$ larger than the $1/\sqrt{B\tau}$ fundamental radiometer noise and sets a noise floor for our gain stabilization system. The detected signal is digitized by an Analog Devices AD7716 22-bit, 4 channel sigma-delta analog to digital converter (ADC) at 230 Hz and averaged down to a ~ 30 Hz sampling rate (33 millisecond integration time) in software. The physical temperature of the mixer is measured with a Lakeshore DT-470 silicon diode and recorded simultaneously with the first temperature measurement of the time series. The microprocessor then instructs the digital to analog converter (DAC) to output a voltage proportional to ΔT , as described in Equation 10. The analog voltage from the DAC, V_{DAC} , is fed through the resistor, R , to generate an excess bias current for the third stage of the HEMT IF amplifier. This excess current is used to change the HEMT gain (see Section 4.2) to compensate for the physical temperature induced conversion gain fluctuations in the mixer.

During a servo system training period, the receiver observes a constant temperature source, for which we used a microwave absorber immersed in liquid nitrogen. The proportional loop gain factor, f , is selected to minimize the correlation between the physical temperature of the mixer and the detected IF power.

4. Measurements and Discussions

4.1. Mixer Conversion Gain

By adjusting the J-T valve on the cryocooler, we varied the physical temperature of the mixer from 4 K to 6 K. From this data, we then determined the conversion gain of the mixer and the gain of the IF chain as functions of the physical temperature, using the technique described in (1). We sampled this temperature range in steps of ~ 0.2 K. Figure 2 shows that over the entire 2 K temperature range, the data are well fit by a quadratic and that the gain of the mixing element is more sensitive to physical temperature fluctuations than is the IF gain. At the SMA, the amplitude of cryocooler-induced temperature fluctuations is typically 50-200 mK. Over such a small fractional temperature range (1-5% of 4.2 K), the temperature dependence of the mixer conversion gain is well modeled by a straight line and the linear approximation to the Taylor series expansion of $G(T_{phy})$ (Equation 6) is sufficient. From the quadratic fit to $G(T_{phy})$, we compute that g_T , the derivative of the gain curve, increases in magnitude with temperature from -0.322 K^{-1} at 4 K to -0.504 K^{-1} at 6 K.

4.2. HEMT Amplifier Gain

The majority of the SMA receivers incorporate three stage HEMT amplifiers fabricated by the National Radio Astronomy Observatory (NRAO) with a total gain of ~ 30 dB. Using an 8510 HP network analyzer, the total HEMT gain at 4 GHz, 5 GHz and 6 GHz (IF band center and edges) was measured at room temperature while we varied the bias current of the third stage from 9.0 mA to 10.5 mA. As shown in Figure 3, the gain is well fit by a straight line over the entire range of bias currents for all measured frequencies, so h_I is nearly constant over the entire range of bias currents at a given frequency. When the gain stabilization scheme is active, the bias current changes by $\lesssim 0.1$ mA and over this range, h_I is sufficiently constant. We note that h_I has a frequency dependence that may ultimately limit the usefulness of this gain stabilization technique.

4.3. IF Phase

At the same time that we measured the effect of bias current on the gain of the HEMT amplifier (see previous section), we also measured the effect of the bias current on the signal phase. Figure 3 shows that the phase changes linearly with the bias current and that the slope of the phase error versus bias current increases with frequency. The maximal phase gradient ($d\phi/dI_B$) is -1.3 degree mA^{-1} . During normal servo operation, the bias current is changed by $\lesssim 0.1$ mA, and therefore the servo system will introduce $\ll 1$ degree of phase error in the IF signal. Using data from (Masson 1994), we find that under median weather conditions on Mauna Kea on a 100 meter baseline, one expects 0.12 degrees of atmosphere induced phase fluctuations per GHz of observing frequency (27 degrees at 230 GHz).

4.4. The Gain Stabilization System Performance

Figure 4(a) shows the response of a 230 GHz receiver observing an absorber immersed in liquid nitrogen. The cryocooler in use during these tests had a very stable 4 K stage temperature compared to a typical SMA cryocooler. To simulate temperature instabilities more typical of SMA cryocoolers, we manually adjusted the J-T valve of the cryocooler to induce periodic ~ 50 mK peak to peak fluctuations in the physical temperature of the mixer. Figure 4(a) shows the time variation of V_{DAC} , which generates the bias current correction for the third stage of the HEMT amplifier, T_{phy} , the physical temperature of the mixer and P_{IF} , the detected IF power. P_{IF} is normalized to its mean during the time when the gain stabilization system is inactive.

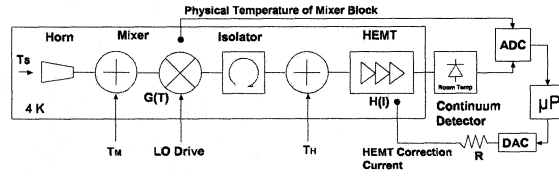


Fig. 1.— A schematic of the SIS receiver and gain stabilization servo system. The horn, mixer, isolator and HEMT amplifier are maintained at cryogenic temperatures by a cryocooler. The physical temperature of the mixer, T_{phy} , is monitored by a diode thermometer. The continuum detector measures the IF power. An ADC records the mixer temperature and the detected continuum power simultaneously. The microprocessor (μP) directs the DAC to generate a voltage, V_{DAC} , in direct proportion to measured mixer temperature fluctuations (see Equation 9). This voltage is converted to a correction bias current for the third stage of the HEMT IF amplifier by the resistor, R . The symbols, G , H , T_S , T_M and T_H are described in the text after Equation 3.

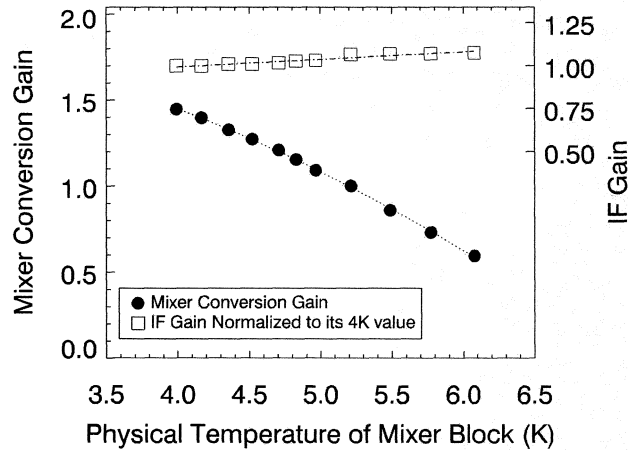


Fig. 2.— The conversion gain of the 230 GHz SIS mixer and the normalized IF gain as a function of the mixer physical temperature. The mixer data are well fit by the displayed quadratic $2.006 + 0.042 * T_{phy} - 0.045 * T_{phy}^2$ over entire temperature range. The slope of this curve, g_T , increases in magnitude from -0.322 K^{-1} at 4 K to -0.504 K^{-1} at 6 K. The IF gain is a weaker function of temperature, with less than an 8% change over the full temperature range. It is well fit by the linear function $0.820 + 0.0435 * T_{phy}$. Over a typical operating temperature swing of 50-100 mK, the IF gain would vary by 0.22-0.44%.

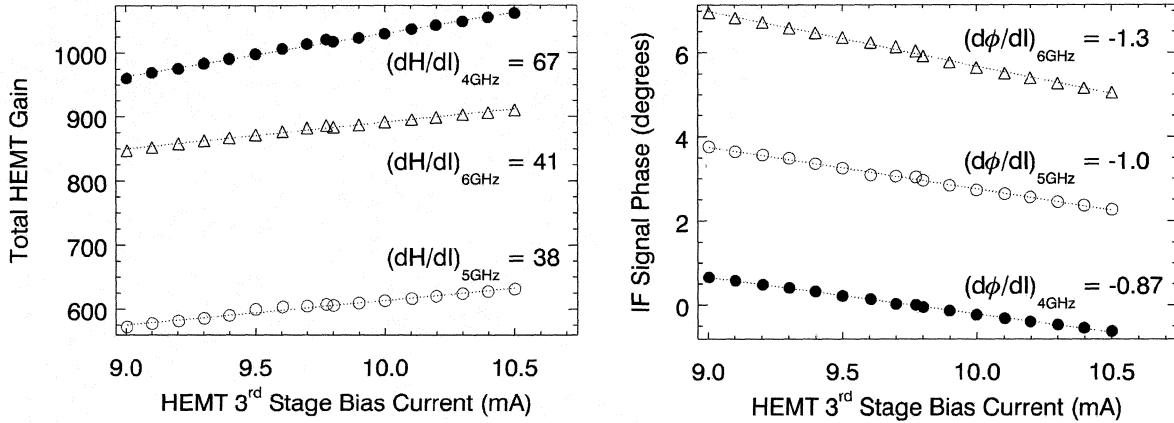


Fig. 3.— **Left** - The gain of the HEMT IF amplifier at room temperature as a function of its the third stage bias current at 4, 5 and 6 GHz, and corresponding linear fits. The slope of the gain curve, h_I , is frequency dependent. Nevertheless, we can achieve a receiver gain stability of 1 part in 6,000 using this technique. **Right** - The phase, ϕ , of the IF signal out of the HEMT amplifier as a function of its the third stage bias current at 4, 5 and 6 GHz, and corresponding linear fits. The phase data has been mean subtracted and offset for clarity.

During the first 311 seconds of the data set, V_{DAC} is held constant so that the servo system is inactive. The direct correlation (with negative proportional factor) between the physical temperature of the mixer and the receiver output is observed. When the physical temperature of the mixer increases, its conversion gain decreases and the receiver output decreases. As seen in the bottom plot of Figure 4(a), the resulting instrumental gain fluctuations limit the receiver stability to 1 part in 780 (rms to mean ratio).

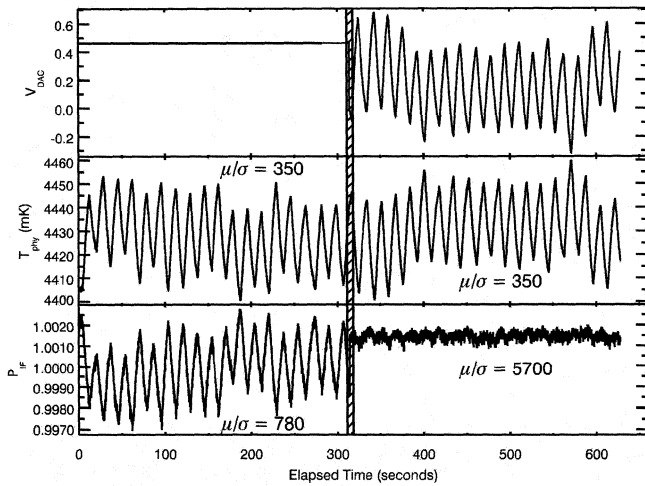
From 318 seconds onward, when the gain stabilization system is activated, V_{DAC} is set in proportion to fluctuations in the physical temperature of the mixer. The resulting gain change in the third stage of the HEMT amplifier reduces the fluctuations in IF power caused by mixer conversion gain fluctuations, and the IF power stability improves by a factor of ~ 7.3 from 1 part in 780 to 1 part in 5,700.

Figure 4(b) demonstrates that the IF power depends linearly on the physical temperature of the mixer without the servo loop. A linear fit to the correlation between the IF power and physical temperature of the mixer is shown and it has a slope of -10^{-4} mK^{-1} with a negative sign indicating that an increase in the physical temperature of the mixer corresponds to a decrease in receiver output.

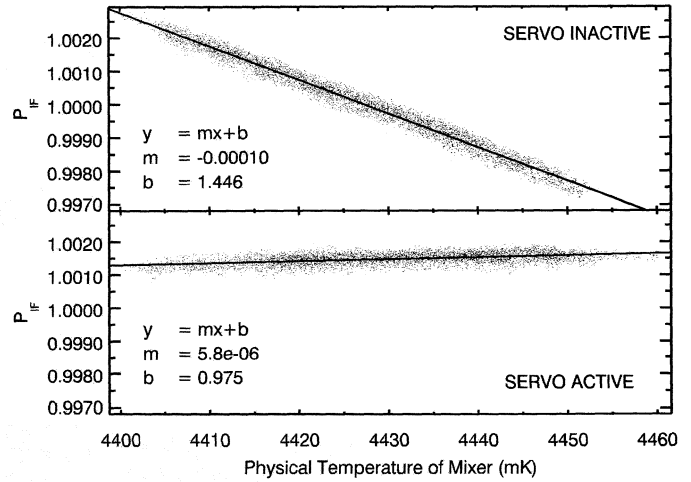
Figure 4(b) also demonstrates that the gain stabilization servo system decreases the slope of the correlation between the IF power and the physical temperature of the mixer. The data for 318 seconds onward are plotted along with the best-fit line with slope $5.8 \times 10^{-6} \text{ mK}^{-1}$. The positive slope indicates that the servo system has slightly over-corrected for the mixer conversion gain fluctuations. Nevertheless, the receiver output power has been significantly decorrelated from the temperature of the mixer.

In Figure 5 we present the results of the same tests performed with a freely running cryocooler (i.e. with no J-T adjustment). The order of the plots are the same as in Figure 4. Fluctuations in the physical temperature of the mixer are largely due to the G-M cycle of the cryocooler on about a one second time scale, and a larger amplitude, ~ 60 second semi-periodic fluctuation of unknown origin. In addition, there is a low frequency drift (~ 5 minute period) in the physical temperature of the mixer. Here, the intrinsic temperature stability of the cryostat and thus the IF power is very good even before activating the servo system. Still, the gain stabilization servo loop improves the receiver stability from 1 part in 2,600 to 1 part in 6,000. Figure 5(b) shows that the proportional coefficient between IF power and mixer temperature has been reduced to $1.7 \times 10^{-5} \text{ mK}^{-1}$.

The effective temperature fluctuations, $\Delta\tilde{T}$, that would generate the observed residual IF power fluctuations in the absence of any receiver stabilization can be written $\Delta\tilde{T} = |(dP/dT)^{-1} \Delta P|$ where dP/dT is the slope of the IF power versus mixer temperature plot and ΔP is the residual fluctuation in continuum power when the servo is active.

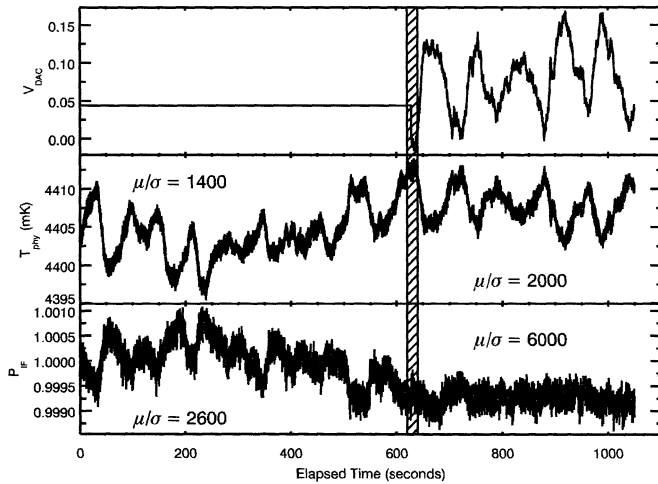


(a) Time Series Data

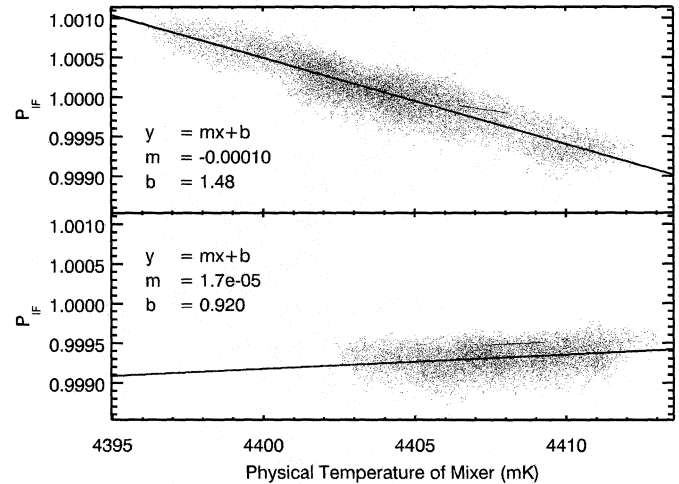


(b) Correlation Between Continuum Power and Mixer Temperature

Fig. 4.— **At left:** The middle and bottom plots are the physical temperature of the mixer and the detected continuum power. In the top plot, V_{DAC} is proportional to the correction current applied to the third stage of the HEMT amplifier. Here the J-T valve is continuously manually adjusted. The gain stabilization servo system improves the receiver stability by a factor of ~ 7.3 from 1 part in 780 to 1 part in 5,700 (rms to mean ratio). **At right:** The correlation plots show that the activation of the gain stabilization servo system reduces the slope of the correlation between the IF power and the temperature of the mixer.



(a) Time Series Data



(b) Correlation Between Continuum Power and Mixer Temperature

Fig. 5.— Same as Figure 4, but this time with a freely running cryocooler (i.e. the J-T Valve was not adjusted). The temperature stability of the 4 K stage of this cryocooler is significantly better than a typical SMA cryocooler, with 4 K temperature fluctuations of only 3-5 mK rms. Even with such a stable operating temperature, we improve the receiver stability by a factor of ~ 2.4 with our gain stabilization servo system.

From the top part of Figure 4(b) we find that $dP/dT = -10^{-4} \text{ mK}^{-1}$. The bottom part of Figure 4(b) shows that $\Delta P = 0.0013$ peak to peak or $\Delta P = 1.7 \times 10^{-4}$ rms (in normalized units). Therefore the gain stabilization servo system achieves an effective peak to peak temperature stability of $\Delta \tilde{T} = 13 \text{ mK}$ or an effective rms temperature stability of $\sigma_{\tilde{T}} = 1.7 \text{ mK}$.

5. Conclusion

We have developed a system that stabilizes the gain of a 230 GHz SIS heterodyne receiver to 1 part in 6,000 (rms to mean). With the use of an open-loop proportional servo system, we monitor the physical temperature of the mixer block and adjust the gain of the third and final stage of a low noise HEMT IF amplifier in order to compensate for the subsequent variations in the conversion gain of the mixer. We have shown that the conversion gain of the mixer varies linearly over the range of typical cryocooler-induced physical temperature fluctuations, and that the gain of the HEMT amplifier varies linearly with its third stage bias current. Using our gain stabilization system, we routinely achieve a total receiver gain stability of 1 part in 6,000 (rms to mean ratio) for a 0.033 second integration time over 10 minutes, which corresponds to an effective rms temperature fluctuation of 1.7 mK. In comparison, the typical fluctuations in the physical temperature of the mixer at the SMA are on the order of 50-100 mK, and the corresponding power fluctuations are 1 part in several hundred. Therefore, our gain stabilization servo system can provide more than an order of magnitude improvement over a typical unstabilized system. Our technique introduces a negligible level of instrumental phase error into the source signal. This gain stability system can be implemented on any heterodyne receiver system in which the physical temperature of the mixer can be monitored and the IF amplification can be adjusted in real time.

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