Influence of Temperature Variations on the Stability of a Submm Wave Receiver

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Abstract

Radio astronomy requires SIS mixers and receivers with very high stability. The goal for the total power stability of the ALMA receivers is $1x10^{-4}$ over 1 second. The SIS mixer is one of the most critical components in the receiver signal chain determining stability. Most changes in mixer noise and gain are due to variations of its operating conditions.

In this paper we present accurate measurements of SIS mixer noise and gain variations with respect to physical temperature, operating point and local oscillator power changes. We use an ALMA band 9 prototype waveguide mixer – developed at NOVA-SRON – working in the 600-720 GHz frequency range. Intermediate frequency coverage of this mixer is 4-11 GHz. A 4-12 GHz isolator was used between the mixer and IF amplifier. The physical temperature of the mixer was varied from 2.5 K to 6 K in steps of 0.05 K and the mixer parameters were measured. Based on our measurement data we provide an estimate (derivatives) of the influence of mixer operating temperature on gain and noise temperature for different LO frequencies.

Introduction

Normal mode of operation of a radiostronomical receiver is improving signal to noise ratio by integrating the output signal for a given time (integration time). If the noise sources in the receiver and in front of receiver are uncorrelated (white noise) the relative fluctuations of the receiver output scales with integration time and receiver bandwidth according to well known radiometer equation:

$$\frac{dP}{P} = \frac{1}{\sqrt{Bt}} \qquad (1),$$

where B is detection bandwidth and t is integration time. Provisions are usually made to make receiver system as wide band as possible and allow for as long integration time as possible in order to be able to observe weak astronomical signals. For instance ALMA receivers will have at least 8 GHz Intermediate Frequency (IF) bandwidth. With such a bandwidth a relative stability of order of 10^{-5} can be achieved in theory by integrating only for one second.

A receiver output power is determined not only by receiver input signal, gain and noise but it is also determined by a receiver operating conditions. For SIS receiver such conditions are: bias point, Local Oscillator (LO) input power, magnetic field strength and receiver physical temperature. Variation of receiver output power due to change in operating conditions may exceed variations due to noise signals given by equation (1) for a certain integration time. If that is the case further increasing of integration time will not lead to a signal to noise ratio improvement. More sophisticated techniques like correlation receiver or chopper calibrator are required for further improvement of quality of observations. These techniques allow to calibrate receiver parameters faster than change of a receiver environment and take this change into account. Receiver gain and noise temperature can have different sensitivity for change of different receiver operating conditions. It is instrumental to know this dependence in order to be able to design a receiver that could reach a required stability specification.

One of important operating condition of an SIS receiver is physical temperature. Since SIS technology is based on superconductivity one can intuitively expect that SIS mixer should be quite sensitive to temperature variations. One can also expect temperature variations of mixer block in modern cryogenic systems based on closed cycle refrigerators. By the nature of operation these systems produce a temperature variations on the tame scale of several Hertz. In this work we investigate experimentally how gain and noise of SIS receiver change with respect to small variations of the mixer block temperature. For doing this, mixer parameters were measured while mixer temperature was varied with small steps of 0.05 K from 2.6 K to 6.4 K in our laboratory system. This allows us to determine differential sensitivity of output power P, dP/dT for any given operating temperature T with high accuracy. Measurements were done for Nb-AlOx-Nb type SIS mixer in the frequency range of 600-720 GHz.

Experimental setup and mixer block

A photograph of an experimental setup used in experiment is shown in figure 1. An

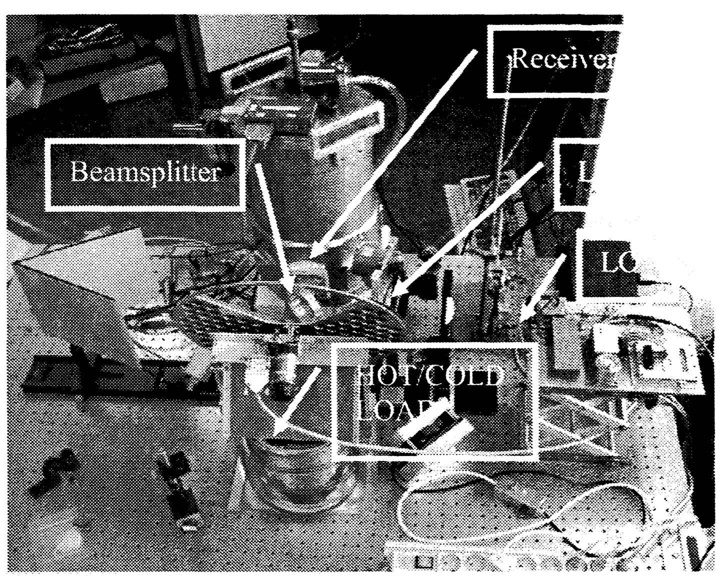

Figure 1. Photograph of experimental setup.

ALMA prototype local oscillator was used to pump an SIS mixer. This LO includes: several high frequency amplifier and multiplier components which result in approx 50 micro watts output power in 600-680 GHz frequency range with total multiplication of 45. A Rohde & Schwartz SR20 synthesizer in the range of 13-15 GHz was used ath the input of this LO chain. LO power level was regulated by means of changing the angle of rotation of a wire grid inserted into LO beam. Grid was rotated under angle of 30 degrees to avoid standing waves in LO path. The position of the grid with respect an LO polarization vector was controlled by an encoder allowing for automatic adjustment of SIS mixer pumping level.

LO power was coupled into receiver signal path by means of 12 micron thick Mylar film beam splitter. It provides about -10 dB LO power coupling to a mixer.

A two level: liquid nitrogen cold load (80 K) and 300 K warm loads were used in the signal path for measuring receiver gain and noise. These loads can be switched also by means of computer allowing fully automated operation.

A standard Infrared Laboratories liquid helium cryostat was used to provide a cryogenic environment. Since liquid helium was used as cryogen the temperature stability of this cryostat was expected to be much better than stability of close cycle refrigerator.

An SIS mixer block (see figure 2) was mounted on 4 K plate of cryostat. Stainless steal washers were used between dewar bottom and mixer block to increase heat resistance to allow temperature regulation. In addition stainless teal bolts were used to attach mixer to a cold stage. A 500 Ohm resistive heater was mounted close to the bottom of the mixer block to be able to heat mixer block up. A semiconductor diode thermometer from Lake Shore was mounted on top of the mixer block for accurate temperature measurement. A temperature constant of order of 2 seconds was observed when mixer was heated and then cooled by switching voltage through heater resistor. Temperature of the dewar cold plate can be decreased by pumping on He bath. The typical end pressure of helium vepour was about 20 mBar. Lake Shore temperature controller type 330 was used for temperature read out and stabilization. Note that this PID type controller allows for high temperature stability. The temperature resolution of this controller is 0.01 K. It was possible to reach any temperature in the range of 2.5..20 K under conditions of this experiment.

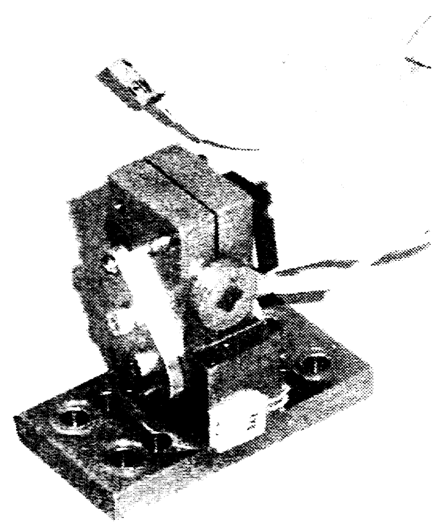

Figure 2. Photograph of SIS mixer block

An NRAO 4-12 GHz three stage HEMT amplifier [1] in combination with 4-12 GHz Pamtech isolator [2] was used in this measurement as an IF chain. Amplifier and isolator were firmly connected to the dewar cold plate keeping the temperature constant

throughout whole experiment. Outside of the dewar thic chain was followed by two MITEQ wide band amplifiers followed by an electronically tunable YIG filter (50 MHz band pass). The central frequency of that filter was also controlled by a computer.
An ALMA band 9 mixer prototype was used in this experiment. This is a waveguide type mixer based on standard Nb-AlOx-Nb tunnel junction technology. Junctions were produced at DIMES laboratories in TU Delft. RnA product for this junction is about 35 and normal state resistance is about 36 Ohm. Junctions quality factor is about 20 and depends on physical temperature. An integrated microstripline tuner was used to compensate junction's capacitance at the frequency of operation and match it to an input waveguide. Nb was used as conduction material and SiO2 was used as insulator. Note that gap frequency of Nb (~690 GHz) is close to the frequency of operation of the receiver. Since this frequency scales with gap energy of Nb which depends on the temperature we expect that mixer can be more sensitive for physical temperature variations at higher part of the band. Details of the mixer design can be found in [3-4].

Measurement results and discussions

Measurements were performed for several LO frequencies in 600-720 GHz range. For each LO frequency optimum parameters of receiver were determined giving the best noise temperature. These parameters are: bias point, LO power and intermediate frequency. The Josephson current noise was suppressed for the lowest temperature of operation if 2.6 K. After optimization the temperature of mixer block was varied with the steps of 0.05 K while keeping LO power level and magnetic field current and intermediate frequency constant. A mixer current/voltage and mixer output power/voltage dependences were recorded for both ambient (300 K) and liquid nitrogen (80 K) loads. This was automatically repeated for each temperature steps till 6.5 K temperature was reached. In addition, an "unpumped" I-V characteristics were measured for each temperature as well.

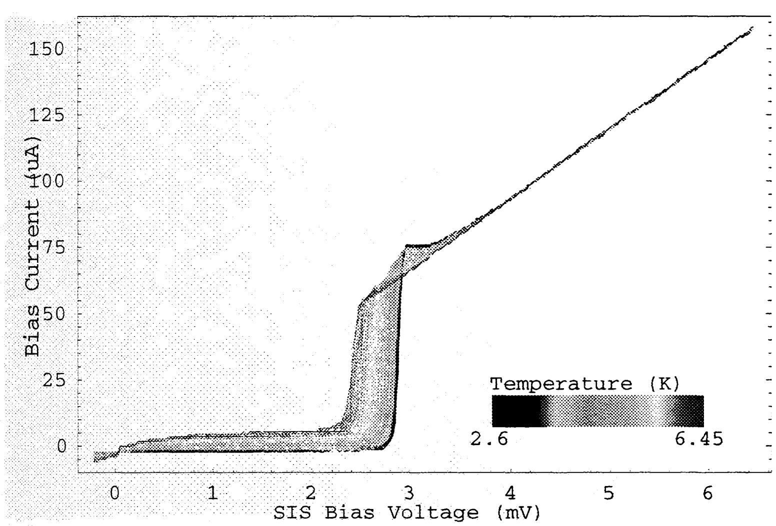

Figure 3, Measured unpumped SIS junction I-V characteristics for different mixer block temperatures

Measured "unpumped" I-V characteristics are shown in figure 3 for different ambient temperatures. One can see that both junction's gap voltage and quality factor decreases when temperature increase. One can expect from mixer theory that mixer gain will decrease and mixer noise will increase when ambient temperature is higher. One can also observe significant increase of leakage current. The junctions critical current, that was suppressed to zero at 2.6 K, becomes visible for higher temperatures. In contrast, the normal resistance of the junction stays independent on temperature for a given temperature range.

The typical data set for LO frequency of 630 GHz is shown in figure 4 for 300 K input and in figure 5 for 80 K receiver input respectively. As expected the receiver output power decreases when temperature increases.

A strong dependence of Josephson noise peak at approximately 1.15 mV bias voltage is observed. Despite of the good suppression at lower temperature one can observe a strong Shapiro step at higher temperatures. This creates additional temperature instability of receiver parameters in vicinity of Josephson steps.

Mixer gain can be obtained from the data in figure 4,5 by subtracting curves corresponding to the same physical temperature. The receiver noise temperature can be calculated from the same data by using Y-factor method. Resulting graphs are presented in figure 6,7 for receiver gain and noise temperatures respectively.

The observed mixer gain variation is quite strong especially in the range 5..6 K operating

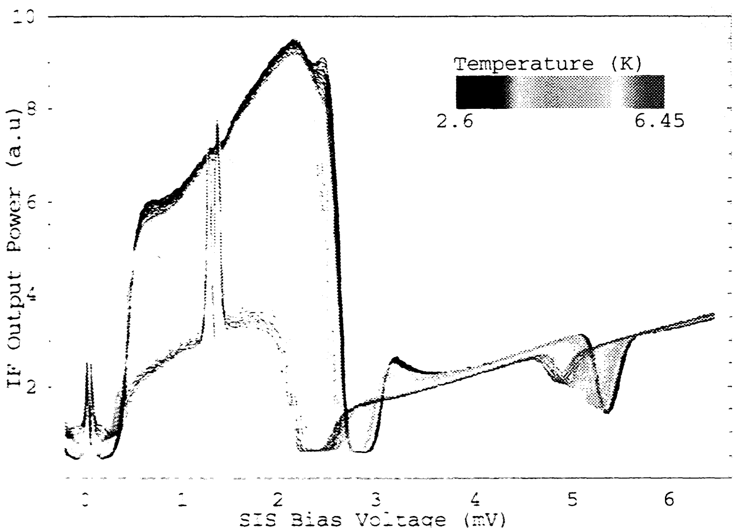

Figure 4. Measured Pumped SIS junction IF output powers for different mixer block temperatures. LO Frequency is 630 GHz. Input signal is 300 K

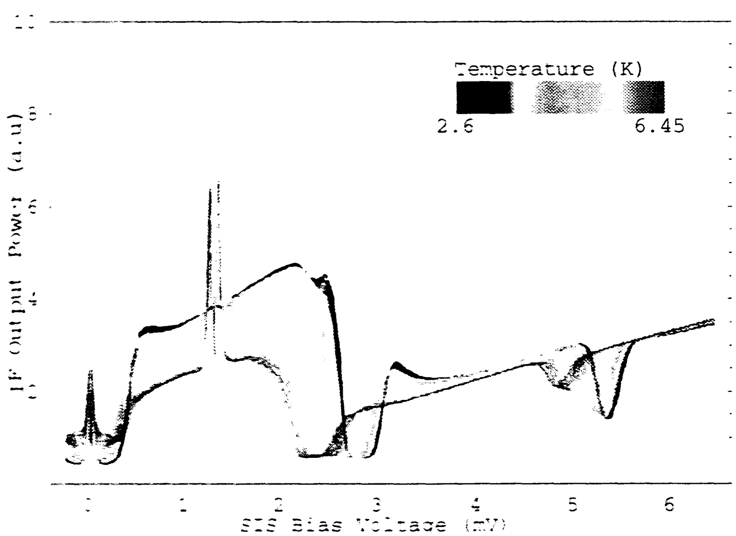

Figure 5. Measured Pumped SIS junction IF output powers for different mixer block temperatures. LO Frequency is 630 GHz. Input signal is 80 K

temperatures. The same is true for receiver noise temperatures. By fixing a certain bias voltage we can obtain dependences of receiver gain and noise temperatures from physical temperature at different bias conditions. This data is presented in figure 8 a).b). Note that at 4 K physical temperature (ALMA receiver operating point) the bias point of 2.4 mV is the most unstable point both for gain and for noise temperature. However, at the same bias point receiver has the best noise temperature. We can conclude that for the most stable operation of receiver we can not choose bias points close to the gap voltage of SIS junction due to strong temperature dependence. For real operation a compromise should be made between receiver noise temperature and receiver stability.

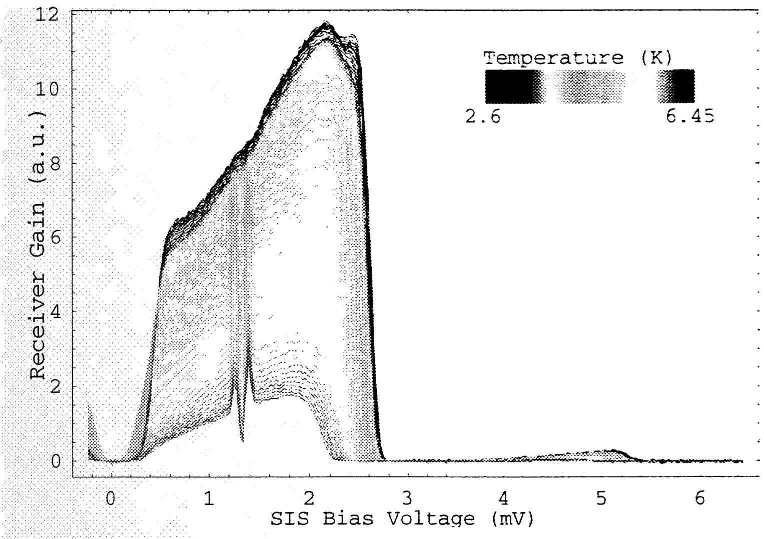

Figure 6, Measured SIS receiver gain for different mixer block temperatures. LO Frequency is 630 GHz

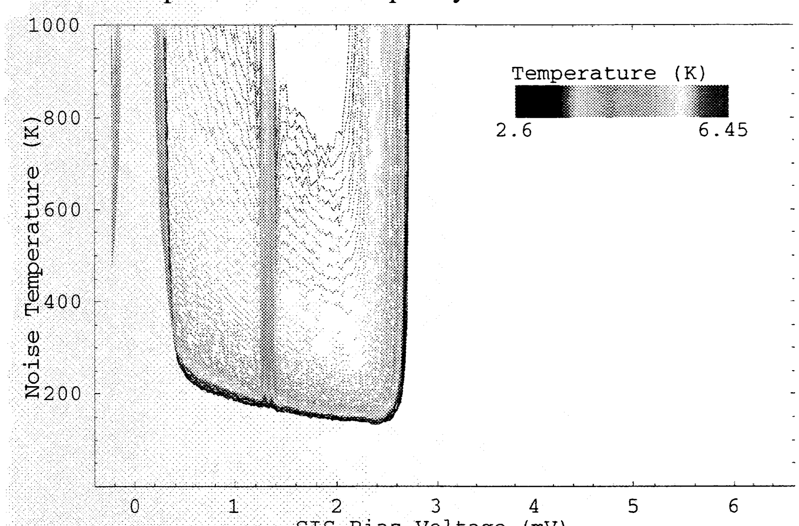

Figure 7, Measured SIS receiver noise temperature for different mixer block temperatures. LO Frequency is 630 GHz

The most interesting parameter for receiver operation is total power stability. It can be given by following equation:

$$P = (Ts + Ti) \cdot G \qquad (2)$$

where Ts is system noise temperature, Ti is receiver input signal and G is receiver gain. We assume further that typical value of input signal $Ti = 80$ K corresponds to an approximate value of atmospheric noise for a 600 - 720 GHz atmospheric window at ALMA site. We also assume that Ti does not depend on receiver temperature when taking derivatives.

Total output power dependencies are presented in figure 8 c). It demonstrates the same principle behavior as noise temperature and gain curves.

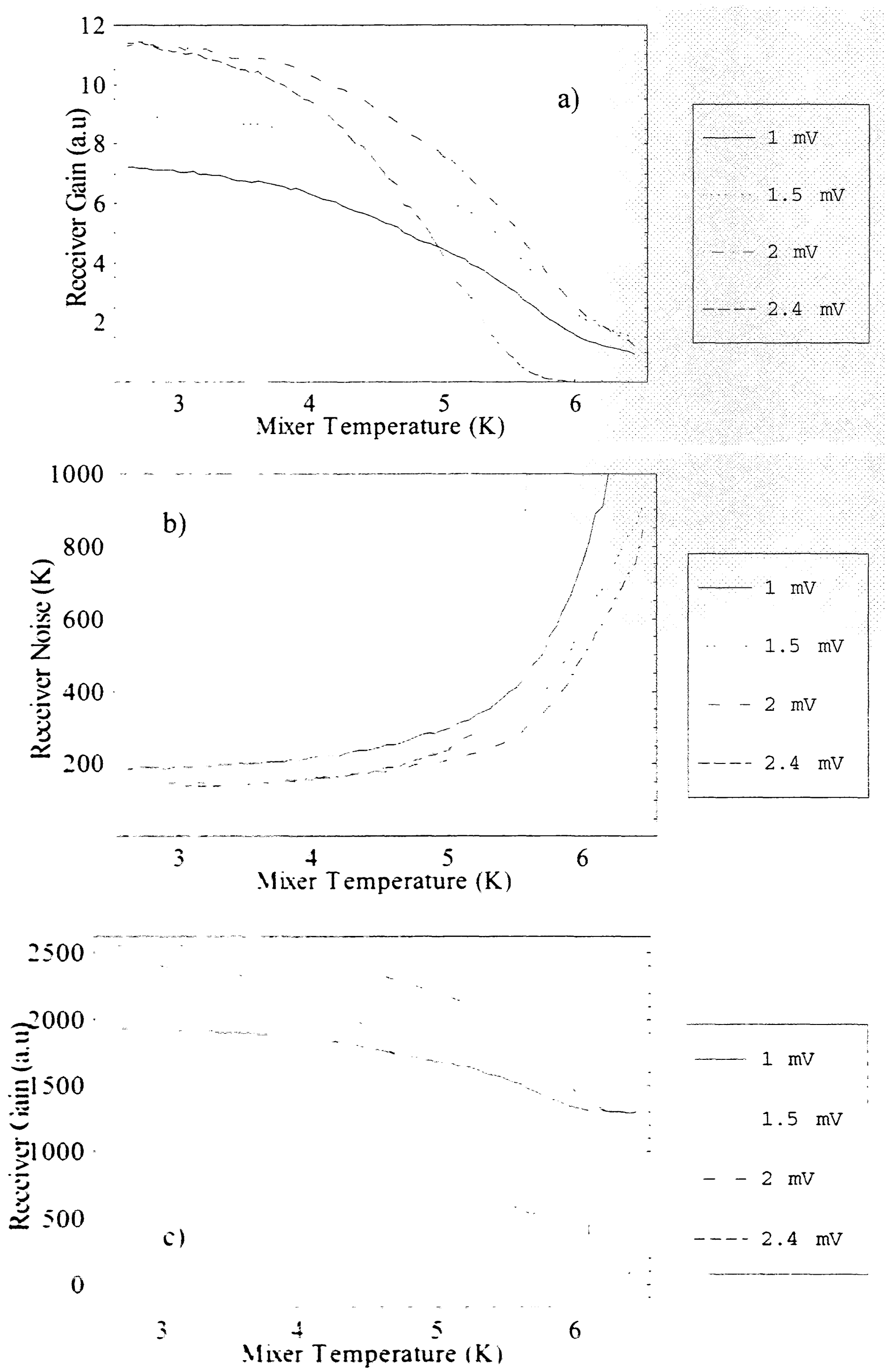

Figure 8. Receiver gain a), receiver noise temperature b) and total output power c) dependence for different bias voltages. LO frequency is 630 GHz. Input signal 80 K.

In order to represent how relative total power stability $\Delta P/P$ relates with the mixer's physical temperature stability ΔT we calculate the following quantity $S(Ti,T) = \frac{dP}{dT} \Big/ P$. The relative receiver stability that we can expect for physical temperature stability ΔT can be expressed as: $\Delta P/P = S(Ti,T)\ \Delta T$. Graphs for parameter S calculated assuming different bias voltages and input signal Ti = 80 K are presented in figure 9. Using this graph we can estimate, that, for reaching relative stability of 10^{-4} over 1 second, absolute temperature stabilities of 2 mK and 0.5 mK are required for bias points of 2 mV and 2.4 mV respectively (mixer temperature is 4 K).

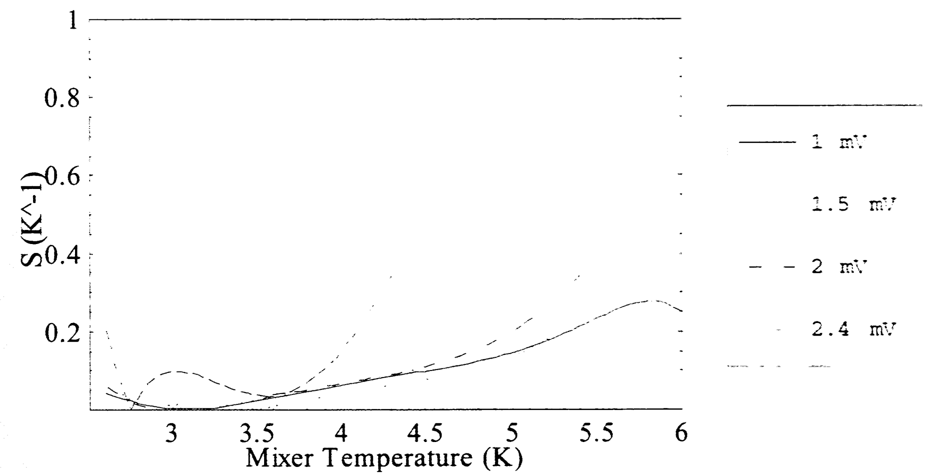

Figure 9. Parameter $S(Ti,T) = \frac{dP}{dT} \Big/ P$ calculated for different bias voltages assuming Ti = 80 K. LO frequency 630 GHz.

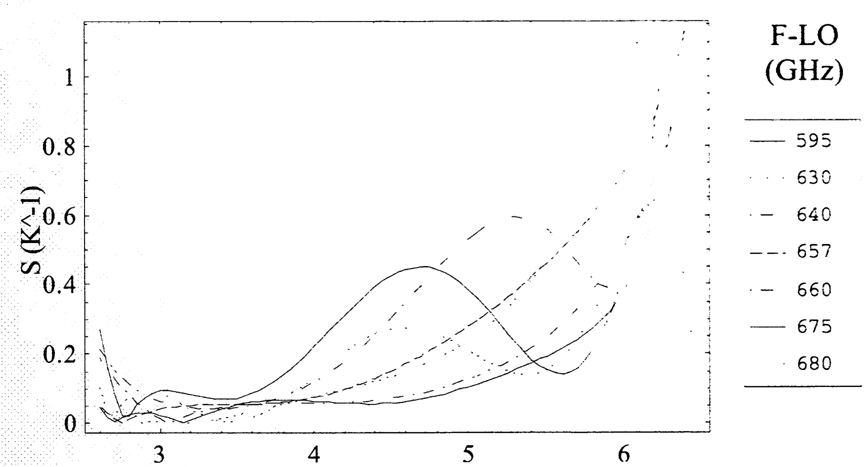

Figure 10. Parameter $S(Ti,T) = \frac{dP}{dT} \Big/ P$ calculated for bias voltage of 2.1 mV, assuming Ti = 80 K. for different LO frequencies.

The same general trends in receiver stability were observed at different LO frequencies as data was taken. To summarize these measurements, we present parameter S calculated for bias voltage 2.1 mV for different LO frequencies in figure 10. Mixer sensitivity to temperature variations increases as the LO frequency approaches Nb gap frequency (for temperatures 4-5 K).

Conclusion

We have performed detailed measurements of receiver noise and gain with respect to SIS mixer physical temperature for several LO frequencies in ALMA band 9 (600-720 GHz). It was found experimentally that bias point, corresponding the best noise temperature, is about 4 times less stable assuming the same mixer physical temperature variations. A parameter $S(Ti,T) = \frac{dP}{dT} \Big/ P$ was estimated from measurements. This parameter allows to connect relative total power stability with absolute temperature stability by following formula: $\Delta P/P = S(Ti,T)\ \Delta T$. It was found , that, for reaching relative stability of 10^{-4} over 1 second, absolute temperature stabilities of 2 mK ... 0.5 mK are required for bias points 2.1 mV for different LO frequencies at physical temperature of 4 K.

Acknowlegement

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