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SIS Receiver Noise Stability

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Abstract— **There is a strong interest in the submillimeter astronomy community to increase the IF bandwidth of SIS receivers in order to better facilitate broad spectral linewidth and continuum observations of extragalactic sources. However, with an increase in receiver IF bandwidth there is a decrease in the mixer stability. This in turn effects the integration efficiency and quality of the measurement. In order to better understand the noise mechanisms responsible for reducing the receiver stability, we employed a technique first described by D.W. Allan and later elaborated upon by Schieder *et. al.* In this paper we address a variety of factors that degrade the noise stability of SIS receivers. The goal of this exercise is to make recommendations aimed at maximizing SIS receiver stability.**

Keywords— **"Allan" Variance, SIS mixer stability, low noise amplifier, gain stability, bias noise, temperature fluctuation noise, acoustic vibrations, Josephson noise.**

I. Introduction

RA dio astronomy receivers in general look at very weak signals deeply embedded in noise. To extract the weak signals, synchronous detection (signal on - signal off) is typically employed. This is done by either slewing the whole telescope back and forth so as to get the beam on/off the source, or by moving the secondary mirror (subreflector) of the telescope at a certain rate. The problem in both these cases is the dead time between observations, i.e., chopping efficiency. A practical lower limit for slewing the whole telescope is typically 15 seconds, while chopping the secondary mirror can perhaps be as fast as 0.2 seconds (5 Hz). Frequency switching is possible and can be at a much higher rate, but suffers from a separate set of problems not discussed here.

If the noise in the receiver system is completely uncorrelated (white), it turns out that the rate of chopping (modulation frequency) has no effect on the final signal to noise ratio. This can be deduced from the well known radiometer equation (1) which states that the noise integrates down with the square root of integration time:

$$\sigma = \frac{< x(t) >}{\sqrt{(B * \tau_{int})}} \tag{1}$$

Here σ is the standard deviation (rms voltage) of the signal, $< x(t) >$ the signal mean, B the effective fluctuation bandwidth, and τ_{int} is the total integration time of the data set.

However, in practice the noise in radiometers, and in particular superconductor-insulator-superconductor (SIS) receivers, appears to be a combination of low frequency drift (correlated noise), 1/f electronic noise and white (uncorrelated) noise. Hence, there is an optimum integration time, known as the "Allan" stability time (T_A), after which observing efficiency is lost. In actual synchronous detection measurements "n" samples of difference data (signal on - signal off) are taken, each with a period T. These differences are then averaged so that the total observed time equals $n * (2T)$. If the period T is larger than the "Allan" stability time (T_A) of the system, then apart from loss in integration efficiency, there will be a problem with proper baseline subtraction. This manifests itself in baseline ripples at the output of the spectrometer which severely limits how well the noise integrates down with time.

In this paper an effort has been made to understand the de-stabilizing effects on a radiometer output due to:

- LNA bias noise and gain fluctuations of the cryogenic low noise amplifier (LNA) immediately following the mixer.
- Temperature modulation of the SIS mixer and low noise amplifier.
- Acoustic noise pickup by the LNA and the local oscillator (LO).
- LO pumping of the SIS mixer.
- SIS mixer bias noise and the effectiveness of suppressing the Josephson effect [5] by means of a magnetic field applied across the SIS junction.

The goal of this paper is to focus attention to the output noise stability of radiometers and SIS receivers in particular. This work is especially pertinent in light of the present trend to construct very large IF bandwidth SIS and HEB receivers for spectroscopic and continuum observations of very weak extragalactic sources.

II. Theoretical Considerations

To optimize observation efficiency, it is important to find the best secondary mirror (subreflector) chopping rate. This requires a knowledge of the nature of the receiver noise fluctuations. In practice, we have employed a method developed by Allan [2], Barnes [3], and further elaborated on by Schieder *et al.* [4].

Following Schieder's analyses of synchronous detection, two sets of contiguous data samples are taking, each with the same integration time (T). The first measurement is the signal s(t), and the second measurement is the off-source reference signal r(t). In the analysis, it is assumed that there is no dead time between the data samples. If we define the first measurement as:

$$S(T) = \int_0^T s(t)\ dt, \tag{2}$$

and the second measurement as:

$$R(T) = \int_T^{2T} r(t)\ dt, \tag{3}$$

then difference of the two measurements is

$$D(T) = S(T)\ -\ R(T). \tag{4}$$

Because we look at signals deeply embedded in the noise and are only interested in how the noise integrates down with time, we can make the simplification that there is essentially no signal present in s(t). This means that on average D(T) = 0, and s(t) = r(t).
If μ is defined as the mean of D(T) and σ^2 the variance of D(T) then

$$\sigma^2(T) =< [D(T) - \mu]^2 >=< D(T)^2 > - < D(T) >^2 \tag{5}$$

Here $< D(T)^2 >$ is the mean (expectation value) of the difference squared and $< D(T) >^2$ is the squared mean of the difference. But since $< D(T) >$ equals zero we get

$$\sigma^2(T) =< [R_1(T) - R_2(T)]^2 > . \tag{6}$$

From [2] we find that the "Allan" Variance is defined as:

$$\sigma_A^2(T) = 1/2\sigma^2(T) \tag{7}$$

The mathematical treatment of the above expression can be found in [3] for different types of noise spectra. If the noise spectral density is represented by a power law, then

$$S(f) = f^{-\alpha}, \quad \alpha = [-1, 3] \tag{8}$$

and one finds that

$$\sigma_A^2(T)\ \propto\ T^{\ \alpha - 1} \tag{9}$$

where $\alpha = 0$ stands for white (uncorrelated) noise, $\alpha = 1$ for "1/f" noise, and $\alpha \geq 2$ for correlated low frequency (drift) noise. Using a simple power law to characterize low frequency drift noise might not be correct. A more accurate representation would be to describe the noise by a correlation function, given by:

$$g(\tau)\ =\ < r(t) * r(t + \tau) > . \tag{10}$$

The "Allan" variance can then be expressed as:

$$\sigma_A^2(T)\ =\ \frac{1}{T^2}\int_{-T}^{T}(T - |\tau|)(g(\tau) - g(T + \tau))\ d\tau. \tag{11}$$

Because we are interested only in integration times less than the correlated (drift) noise time scale, the correlation function can be expanded in a power series with only a few terms:

$$g(\tau)\ =\ g(0) - a\tau^\beta\ \pm\ \ldots, \quad \beta = 1, 2, ... \tag{12}$$

From equation (11) we get

$$\sigma_A^2(T)\ \propto\ T^\beta. \tag{13}$$

Combining equation (9) and equation (13) we find that for a noise spectrum that contains drift, white noise, and 1/f noise that the "Allan" variance takes the form:

$$\sigma_A^2(T)\ =\ aT^\beta + \frac{b}{T} + c, \tag{14}$$

where a, b, and c are appropriate constants. For short integration times, the variance decreases as $\frac{1}{T}$, as expected from the radiometer equation (1). For longer integration times, the drift will dominate as shown by the term aT^β. In that case, the variance starts to increase with a slope β which is experimentally found to be between 1 and 2. On certain occasions, it is observed that the variance plateaus at some constant level. This is attributed to the constant factor and is representative of flicker or 1/f noise in the electronics.

Plotting $\sigma_A^2(T)$ on a log-log plot demonstrates the usefulness of this approach in analyzing the radiometer noise statistics. For reference, a slope of $(\frac{1}{T})$ has been drawn in all figures. This represents the uncorrelated (white) noise part of the spectrum. The minima in the plot gives the "Allan" time (T_A), the crossover from white noise to 1/f or drift noise. For the sake of optimum integration efficiency, one is advised to keep the integration time well below the system's "Allan" time.

Finally, it is often of interest to estimate what happens to the "Allan" stability time if the IF bandwidth of the radiometer is increased. Solving equation (14) for T as a function of receiver IF bandwidth we get:

$$T_A\ \propto\ B_{IF}^{-(\frac{1}{\beta + 1})}, \quad \beta = 1 - 2. \tag{15}$$

B_{IF} presents the IF bandwidth and β the slope of the drift noise as discussed above. As the uncorrelated (white) noise component of the mixer spectral output power is reduced, the intersect between radiometric (1) and drift noise (13) equations occurs at an earlier time. Where exactly the two curves intersect depends on the statistical nature of the long term drift. It should be noted that all data presented in this paper have been taken with a 100 MHz bandpass filter.

III. Measurement Setup and Calibration

The measurement configuration is shown in Fig. 1 and consists of a variable 0-10 dB step attenuator, a 100 MHz bandwidth filter, centered at 1.5 GHz, and a Schottky power detector. RF signal power on the detector has been kept constant to within 1 dB throughout the measurements. The whole unit is bolted to a 1 cm thick aluminum between positions than actually taking data. On the other hand, if integrations longer than 10 seconds are allowed, baseline subtraction suffers and integration efficiency is expected to be poor. An alternative observing mode is 'on-the-fly' (OTF) mapping. Here the telescope is allowed to scan through the source while averaging the data in short (typically $\sim$ 3 sec) bins. When atmospheric conditions are good ($\leq$ 1 mm of precipitable water vapor) 'on' scans can last for upwards of 120 seconds before a single 'off' scan is taken, thereby minimizing the loss in time associated with slewing the telescope between 'on' and 'off' positions. However, even when the 'OTF' mapping technique is used observing efficiency and proper baseline subtraction will improve if the receiver stability is increased.

When SIS receivers are used for large continuum or low resolution extragalactic observations only fast 'beam switching' operation seems appropriate.

Finally, it should be noted that interferometers (multiple telescope's used together to synthesize a single large diameter telescope) are by their nature much more tolerant of gain fluctuations than single dish receivers. This because only correlated signals will appear at the output of the spectrometer while uncorrelated signals such as receiver instabilities will not. Note however that this does not negate the importance of high integration efficiency, and hence having receivers with suitable long stability ("Allan" variance) times.

XII. Conclusion

A detailed study on the output noise stability of SIS receivers is presented. We have investigated the destabilizing effects of acoustic vibrations on a low noise amplifier (LNA) and local oscillator (LO) chain , micro-phonic noise on the LNA and SIS mixer bias lines, SIS constant voltage feedback bias noise, Josephson oscillation noise, and finally thermal drift noise of the SIS mixer and low noise amplifier.

In the process we found that fundamentally the SIS mixer is stable to at least 6 seconds in a 100 MHz bandwidth. This limit is set by how well one is able to suppress the Josephson effect in the superconducting tunnel junction and possibly also by SIS mixer bias noise, which modulates the mixer gain. In practice though the Josephson effect does not limit the stability of SIS receivers, rather the stability of the receiver is set by numerous external factors.

In a passive cooled dewar we have measured "Allan" variance stability times up to 9 seconds with an above the energy gap biased SIS mixer (IF bandwidth = 100 MHz). The "Allan" variance time in this case is limited by the room temperature IF total power amplifier and measurement setup.

In an active cooled hybrid style dewar the situation was much worse. With the low noise amplifier mounted on the 15K active cooled stage we measure an "Allan" variance time of 1.5 seconds, both at the observatory and in the laboratory. Vibration isolating the low noise amplifier gives a significant stability improvement, however the exact amount of improvement is very much dependent on the amplifier design and employed mounting scheme.

In the lab we did not observe a difference in the "Allan" variance stability time of the receiver when the junction was biased in closed feedback, or open loop mode. At the observatory, due to the large EMI/RFI noise environment, we did in fact notice a significant change.

The mixer gain of a Local Oscillator pumped SIS junction has been measured and is observed to be a strong and negative function of temperature. The mixer's peak sensitivity to temperature change appears to be at approximately 4.9 Kelvin. The low noise amplifier (GaAs HEMT's) in contrast has a small, linearly varying, and positive temperature dependence. Cooling the mixer below 3K improves the mixer gain by 10%, but even more importantly reduces the mixer's susceptibility to LHe bath temperature fluctuations. In high resolution spectrometer mode with a channel bandwidth of 100 KHz, 1 second of "Allan" stability time and an high altitude Helium bath temperature of 3.6 Kelvin, we find a maximum allowed temperature fluctuation of 106 mK/second for the LNA and 48 mK/second for the SIS mixer. At 4.2 Kelvin the allowed SIS mixer temperature fluctuation has been reduced to 13.8 mK/second. These numbers are upper limits, and for wide bandwidth continuum or course resolution extragalactic observations the result is much more stringent.

Finally, high mobility transistor (HEMT) gain fluctuations, if any, appear to be at least an order of magnitude below such noise sources as acoustic vibrations, bias line noise due to high EMI/RFI noise environment, and problems with Josephson noise suppression.

It is recommended that special attention be given to minimize microphonic pickup in the LNA and Local Oscillator chain. Temperature fluctuations should be kept at a minimum, especially so when the mixer is operated at a Helium bath temperature of 4.2 Kelvin. In a high noise environment such as an observatory, it may be advisable to use several different feedback loop time constants, depending on the mode of operation. And finally a resistive divider network in the SIS and LNA bias line should at all cost be implemented.

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