IF amplifier stability for the Heterodyne Instrument for FIRST (HIFI)

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ABSTRACT

The Heterodyne Instrument for FIRST (HIFI) is a heterodyne receiver system which has an intermediate frequency (IF) amplifier that will likely exhibit 1/f-type gain fluctuations. Although the level of fluctuation is very small, wideband spectral observations require exceptional stability. A methodology for measuring 1/f fluctuations is described along with measurements of two amplifiers. Comparisons are made with previous 1/f measurements of HEMT amplifiers. The implications for HIFI are described.

Keywords: FIRST, HIFI, heterodyne instrument, amplifier stability

1. INTRODUCTION

The 'Far-Infrared and Submillimeter Telescope', (FIRST), is the fourth European Space Agency (ESA) cornerstone mission in the current 'Horizon 2000' science program.[1] FIRST will be an exciting new space-based observatory that will revolutionize astrophysics in this important wavelength regime. It will allow detailed investigations of the formation and evolution of galaxies in the early universe, the cycling of gas and dust between stars and the interstellar medium, and many others.

One of three instruments, the Heterodyne Instrument for FIRST (HIFI) is designed to provide continuous frequency coverage of the 480 - 1250 GHz range; additional bands cover 1410 - 1910 GHz and 2400 - 2700 GHz. HIFI has the exceptional spectral resolution available with heterodyne receivers and the low system noise achievable with Superconducting-Insulating-Superconducting (SIS) mixers and Hot Electron Bolometer (HEB) mixers.[2]

HIFI's high spectral resolution is particularly well suited to the study of molecular and atomic fine structure line emission. Many of the most interesting lines, including those from water and HD, are only accessible from space.

One of the HIFI goals is the observation of [CII] 158 μm emission from the interstellar medium of galaxies. This atomic fine structure line is a primary cooling line and therefore an important probe of the physical conditions of the interstellar medium. Observations of this line in highly redshifted galaxies will allow an investigation of the physical properties of galaxies near the time of their formation. Because these galaxies will be spatially unresolved, the emission will be broadened by the contribution from many different parts of the galaxy. Observations of very broad lines pose special instrumental challenges, in particular greater gain and baseline stability.

One of the critical items in the receiver chain is the IF amplifier. HIFI has one cryogenically-cooled IF amplifier after each mixer. Low noise in these amplifiers is important in minimizing the overall system temperature of the receiver. Such amplifiers are known to have 1/f - type gain fluctuations.[3–5] These fluctuations can adversely affect wide bandwidth observations unless there is some form of sufficiently fast instrument chopping.

Below, we examine the connection between transistor fluctations and amplifier fluctuations, make predictions for the amplitude vs. frequency for such fluctuations, and make a preliminary attempt to assess the impact on wide bandwith observations.

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2. MATHEMATICAL DESCRIPTION

There are several useful scaling arguments that we can apply to understand how the gain fluctuations in a single transistor are related to the dimensions of the transistor. We can also relate this to the fluctuations in the amplifier as a whole based on the type and number of devices. We can then relate this to the instrument stability.

Fluctuations in the transconductance of individual high-electron-mobility-transistors (HEMTs) can lead to gain fluctuations in an amplifier built from these HEMTs.[3,4] In order to minimize noise figure, very low noise cryogenic amplfiers typically do not make extensive use of feedback to minimize these fluctuations. We will use a semi-empirical approach to characterize the effect. We can describe the gain fluctuations in an amplifier according to

$$\left[\frac{\Delta G(f)}{G}\right]^2 = \frac{C^2 N_s}{A_{\rm gate}/5\mu{\rm m}^2}\frac{1}{f}. \tag{1}$$

Here, $\Delta G(f)/G$ is the fractional gain fluctuation as a function of post-detection frequency, f. The amplifier is assumed to have N_s stages, each of area A. The constant, C, describes the amplitude of fractional gain fluctuation of individual HEMTs, normalized to a gate area of $5\mu{\rm m}^2$ (corresponding to a device with dimensions of 50 μm $\times\, 0.1\mu$m.) These fluctuations are frequently referred to as "1/f" - type fluctuations because the spectral power is appoximately of this form. This spectral form is consistent with the measurements described below over the interval from 0.1 Hz to 10 Hz, and is also consistent with measurements described in the literature.[3] Some reported measurements, however, have shown lower spectral indicies of approximately 0.85.[6] As one progresses to lower and lower frequency, the gain fluctuations do not increase without limit (or the device would break!), so some softening with and eventual flattening of the spectral index is expected at low frequencies. We will scale from fluctuation measurements near 1 Hz. For instrument chopping frequencies near 1 Hz, the exact spectral behavior of the fluctuations is not critical, and we'll adopt an index of 1.00 for the remainder of the discussion.

For radiometeric applications, it is useful to compare the level of gain fluctuations to the white noise level of the system. We'll examine the impact on spectroscopic applications in the next section. First, we define the post-dectection frequency at which the gain fluctations have the same spectral power as white noise as the knee frequency, $f_{\rm knee}$. We can calculate the equivalent rms noise, $\Delta T_{\rm equiv}$ of the gain fluctuation,

$$G\Delta T_{\rm equiv} = T_{\rm sys}\Delta G(f), \tag{2}$$

where $T_{\rm sys}$ is the system noise temperature. As we noted above, the knee frequency occurs where the gain fluctations equal the white noise. To calculate this frequency, we substitute the white noise level,

$$\Delta T_{\rm equiv} = \frac{T_{\rm sys}}{\sqrt{\beta/2}}, \tag{3}$$

where β is the predetection bandwidth of the system; the units here are ${\rm K}/\sqrt{\rm Hz}$. To determine the knee frequency, we have used the white noise level appropriate for a total power receiver. One can then use the knee frequency to inform decisions about the chopping frequency. The factor of 2 under the square-root in the denominator is a separate issue; its presence is necessary for the units to be $/\sqrt{\rm Hz}$ rather than $\sqrt{\rm sec}$. Substituting Eqn. (3) into Eqn. (2) yields

$$\frac{\Delta G(f_{\rm knee})}{G} = \frac{1}{\sqrt{\beta/2}}. \tag{4}$$

We can now use Eqn. (1) and solve for $f_{\rm knee}$,

$$f_{\rm knee} = \frac{C^2 N_s \beta}{2(A_{\rm gate}/5\mu{\rm m}^2)}. \tag{5}$$

The knee frequency is useful as an indicator of how fast to chop the instrument for continuum observations. We note that there could well be other important sources of instrument instability.

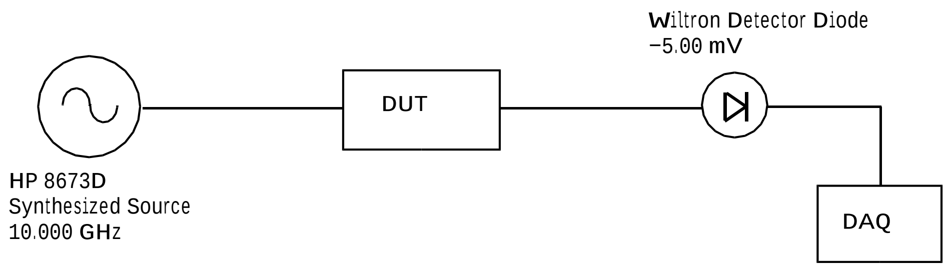

Figure 1. Experimental setup. A synthesized source was used to provide an input signal to the device under test (DUT), in this case, an IF amplfier. Gain fluctuations in the DUT cause fluctuations in the level detected by the detector diode. The RF signal was set so that there was approximately -5 mV on the detector.

3. MEASUREMENTS

In order to assess the level of gain fluctuations in IF amplifiers, we have made measurements of two 8-12 GHz amplifiers built by a group at the Centro Astronomica de Yebes, Spain. The first amplifier was built with a first stage InP HEMT from TRW with gate dimensions of 0.1×160 μm. The second amplifier was built with a first stage InP HEMT from the Swiss Federal Institute of Technology (ETH) with gate dimensions of 0.2×200 μm. Each amplifier consists of two transitor stages; the second stage on each was a Fujitsu GaAs HEMT (FHX 13X) with gate dimensions of 0.25×200 μm.

To measure gain fluctuations, we use the setup depicted in Fig. 1. A synthesized source (HP 8673D) provides a stable signal at 10.000 GHz. This signal is passed to the device under test (DUT) and then detected with a Wiltron detector diode. The synthesized source RF level was adjusted to produce a DC level of -5.00 mV on the detector diode. The diode was sampled at 6250 Hz with a very low noise, high gain data acquisition system. After the time series data is collected, the power spectrum can be computed and compared to the measurement baseline which is established with no device under test. Figure 2 shows the results for the amplifier built with TRW devices. The amplitude of fractional gain fluctuation at 1 Hz is approximately $2.5 \times 10^{-5}/\sqrt{\mathrm{Hz}}$. Figure 3 shows the results of a similar test of an amplifier constructed with the ETH devices. This amplifier appears to have a slightly lower level of gain fluctuation; we'll take the level to be approximately $2.3 \times 10^{-5}/\sqrt{\mathrm{Hz}}$. More data is clearly required to precisely quantify the difference between the two amplifiers.

The data described above were collected at room temperature. Previous experience with InP HEMTs suggests that at cryogenic temperatures the level of gain fluctuation will increase by a factor of 2 - 3. Taking a factor of 2.5 as typical and using the preceeding results with Eqn. (5), we can estimate a knee frequency contributed by the IF amplifier. We also need to scale from the number of stages in the measured amplifiers (2) to the amplfiers that are expected for the final instrument (5). We do not include any contribution from warm IF amplifiers. An important factor in Eqn. (5) is the RF bandwidth. We'll make two estimates using different bandwidths: the full RF bandwidth of 4 GHz in the wide bandwidth receiver mode, and a fiducial bandwidth of 100 MHz. The results are shown in Table 1.

	RF Bandwidth	
	100 MHz	4 GHz
ETH devices	0.45	18
TRW devices	0.5	19.5

Table 1. Estimated 1/f knee frequencies (in Hz) for 100 MHz and 4 GHz bandwidths. The gain fluctuation amplitude measured for the two amplifiers and the form of Eqn. (5) has been used. An additional scaling of $(2.5)^2$ has been used to account for the increase in fluctuation level expected from cryogenic operation, and a factor of (5/2) has been applied to scale from the number of stages in the tested amplifiers (2) to the number of stages the are expected for the final instrument amplifiers (5).

The 4 GHz bandwidth is appropriate for an observation where the instrument is used as a radiometer in which the entire bandpass is compared between an on-source and off-source position. For such continuum observations, we see that the chop speed should be faster than about 20 Hz. For observations of broad lines, however, one can use the part of the RF spectrum that has no line in it as an additional reference for chopping. The effectiveness of this depends upon the bandwidth of the line and the degree to which the gain fluctutations are correlated across the band. This is the subject of the next section. Again, we stress that the IF amplifier may not be the only source of instability in the receiver system.

The gain fluctuation measurements could have benefited from a better measurement baseline. From previous experience with some of the components, we believe that the synthesized source is the dominant source of flucutations in the baseline data. A significant improvement may be obtainable with a cavity stabilized, temperature stabilized Gunn oscillator.

4. IMPLICATIONS FOR WIDE BANDWIDTH OBSERVING

We now turn to the implications of the measurements described in the previous section for observing broad spectral lines with HIFI. Of key importance is the degree to which the gain fluctuations are correlated with frequency. If the IF amplifier has gain fluctuations that are perfectly correlated with frequency, then we can easily remove the effect: we simply subtract from the region of spectral interest a nearby signal-free portion of the spectrum. Another way to look at this is that gain fluctuations that are perfectly correlated across frequency produce flat baselines (in the absence of other systematic effects, of course). If the gain fluctuations are not perfectly correlated with frequency, there will be some impact on the baseline.

To assess this impact, we performed the following simulation. The amplifier is assumed to have gain fluctuations that are correlated with frequency according to the curve shown in Figure 4. We stress that this correlation is merely an educated guess. This function describes the degree to which gain fluctuations in nearby predetection frequencies are correlated. We expect that as the difference between two frequencies of interest diminish, the fluctuations must become more correlated; the extreme limit is reached with no frequency difference and perfect correlation. A number of attempts have been made to measure and regress gain fluctuations using a nearby "pilot signal".[7–9] These efforts have generally been only partially successful, apparently because of the lack of perfect correlation between fluctuations present in the pilot signal and the band of interest. We have little information as to the precise functional form of the correlation. We'll assume a linear relationship with frequency as a simple form. From these considerations we make the educated guess shown in Fig. 4.

It is also worth noting that the results of the simulation depend strongly on this correlation function. For example, if the gain fluctuations were perfectly correlated with frequency, the result would be a baseline offset, but there would be no peculiar structure in the resulting spectrum. If the fluctuations were perfectly uncorrelated, there would be added white noise in the resulting spectrum, but again there would be no peculiar structure. We are, however, in the intermediate case: there is some correlation that will result in concern about spurious structure in the observed spectra. The simulations presented here are a preliminary attempt to assess the magnitude of such structure relative to the white noise.

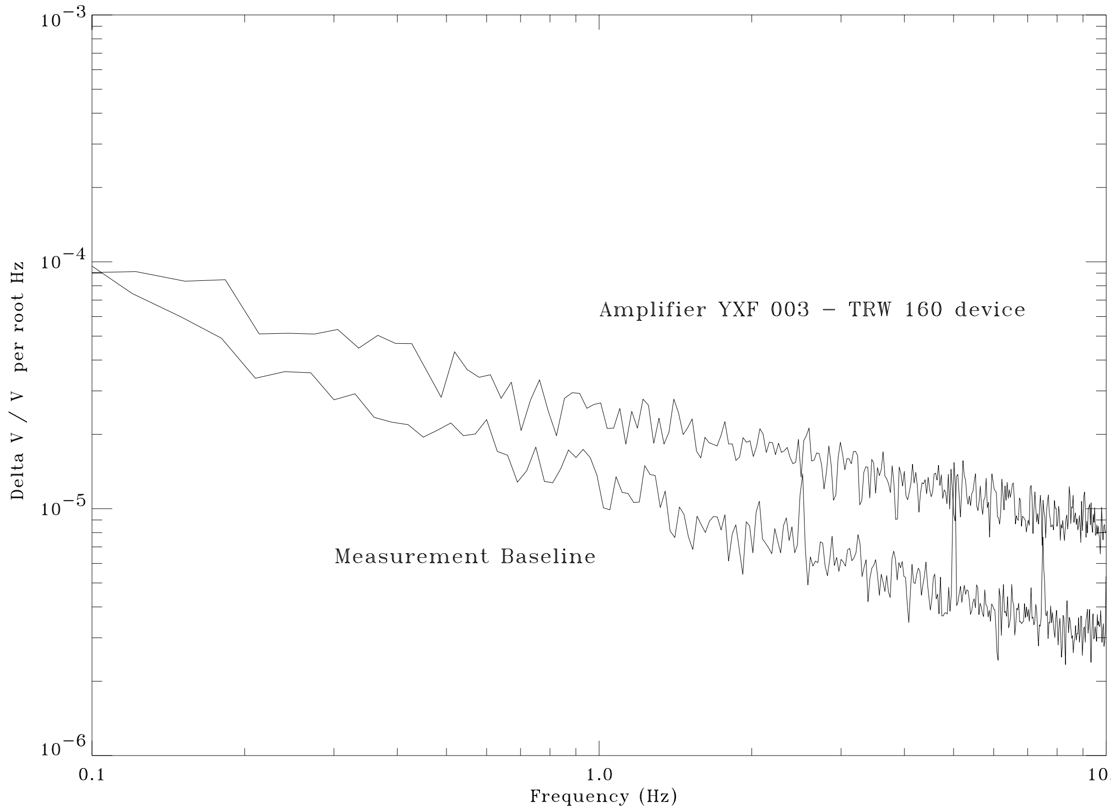

Figure 2. Measurement of amplifier gain fluctuations. The upper curve is the fluctuation level for a two-stage amplifier built with a TRW 160 micron gate width device for the first stage and a Fujitsu 200 micron gate width device for the second stage. The lower curve is the measurement baseline established with no device under test.

Figure 5 shows a simulated observational wide-bandwidth spectrum. The correlation function shown in Fig. 4 has been used along with the level of gain fluctuations implied from the measurements of the amplifier built with a TRW first stage, scaled appropriately as described earlier. A 1 Hz chop has been assumed. The 4 GHz total bandwidth was divided into 400 bins of 10 MHz each for the purposes of the simulation. Each bin contains a white noise contribution and a 1/f gain fluctuation contribution. The 1/f contribution is correlated from bin to bin according to the previous figure. The relative level of the white noise to the 1/f noise is set by the chopping frequency relative to the knee frequency in one simulation bin. No baseline offset has been removed from the resulting spectrum. We are interested in investigating the level of spurious structure relative to the white noise in the spectrum. The y-axis has arbitrary units because we have not specified the total observing time or the noise figure of the instrument system. The relative level of structure is *independent* of these and depends only on the level of gain fluctuation, the bandwidth of interest, the chopping speed, and the degree of correlation. With 1 Hz chopping, we can see in Fig. 5 that there is almost no additional structure above the white noise due to correlated gain fluctuations.

Figure 6 shows the results of a similar simulation where the chopping period has been extended to 60 seconds. A baseline offset of 6.6 units has been subtracted from the displayed spectrum. Because the chopping frequency is lower, the relative contribution of 1/f gain fluctuations is larger. This results in correlated structure in the spectrum that is now significant compared to the white noise level. This in turn implies that chopping periods in excess of 1 minute may not be adequate for observations of wide lines with low signal to noise ratios. We caution that these results are dependent upon the educated guess for the shape and level of the gain fluctuation correlation function.

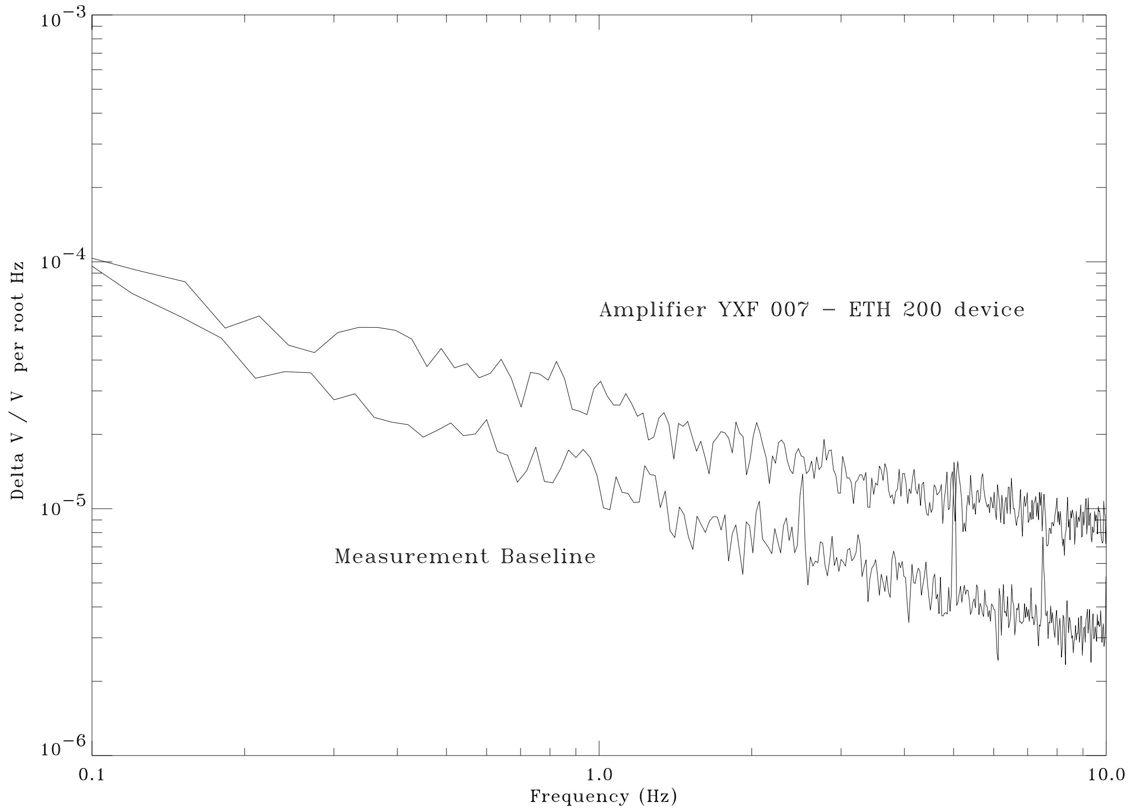

Figure 3. Measurement of amplifier gain fluctuations. The upper curve is the fluctuation level for a two-stage amplifier built with a ETH 200 micron gate width device for the first stage and a Fujitsu 200 micron gate width device for the second stage. The lower curve is the measurement baseline established with no device under test.

5. CONCLUSION

Wide bandwidth observations with an instrument that possesses 1/f type gain fluctuations are possible, but special attention must be paid to the chopping speed, the line width of interest and the level of fluctuation. For the IF amplifiers for HIFI, a chopping period of approximately 1 second suffices for moderately wide lines. If the chopping period is in excess of 1 minute, there is the potential for spurious structure in the spectra. For full continuum sensitivity, however, a chopping speed in excess of 15 Hz is probably necessary. A lower chopping speed would still provide useful information, although at degraded sensitivity.

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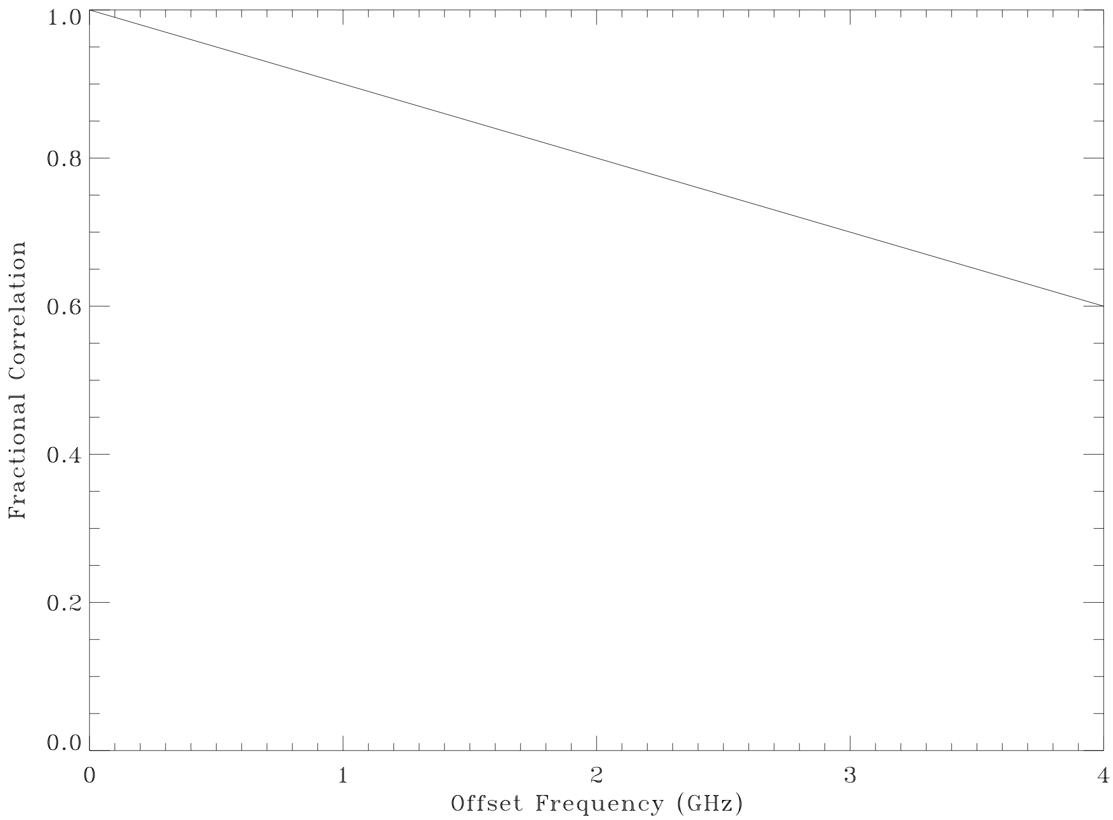

Figure 4. Fractional amplifier gain fluctuation correlation vs. offset frequency used in simulation.

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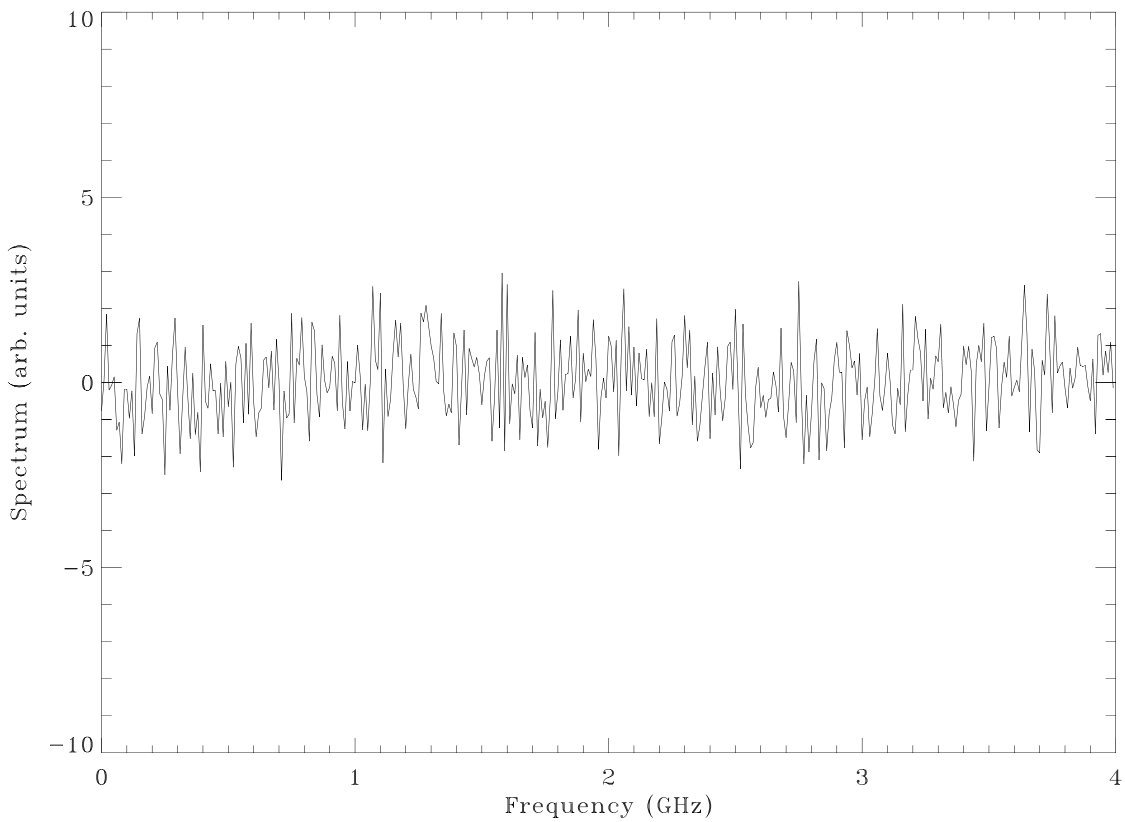

Figure 5. Sample simulated spectrum of wide bandwidth observation with 1/f gain fluctuation contribution from the IF amplifier. A spectrum has been simulated assuming that there is no source signal and that the gain fluctuation noise from the IF amplifier has a correlation function described in Fig. 4. There is little resulting structure in the spectrum due to these gain fluctuations. A gain fluctuation level consistent with the measurements described earlier was used. A chopping speed of 1 Hz has been assumed. The simulation was performed with a 10 MHz spectral bin size and 400 specral bins.

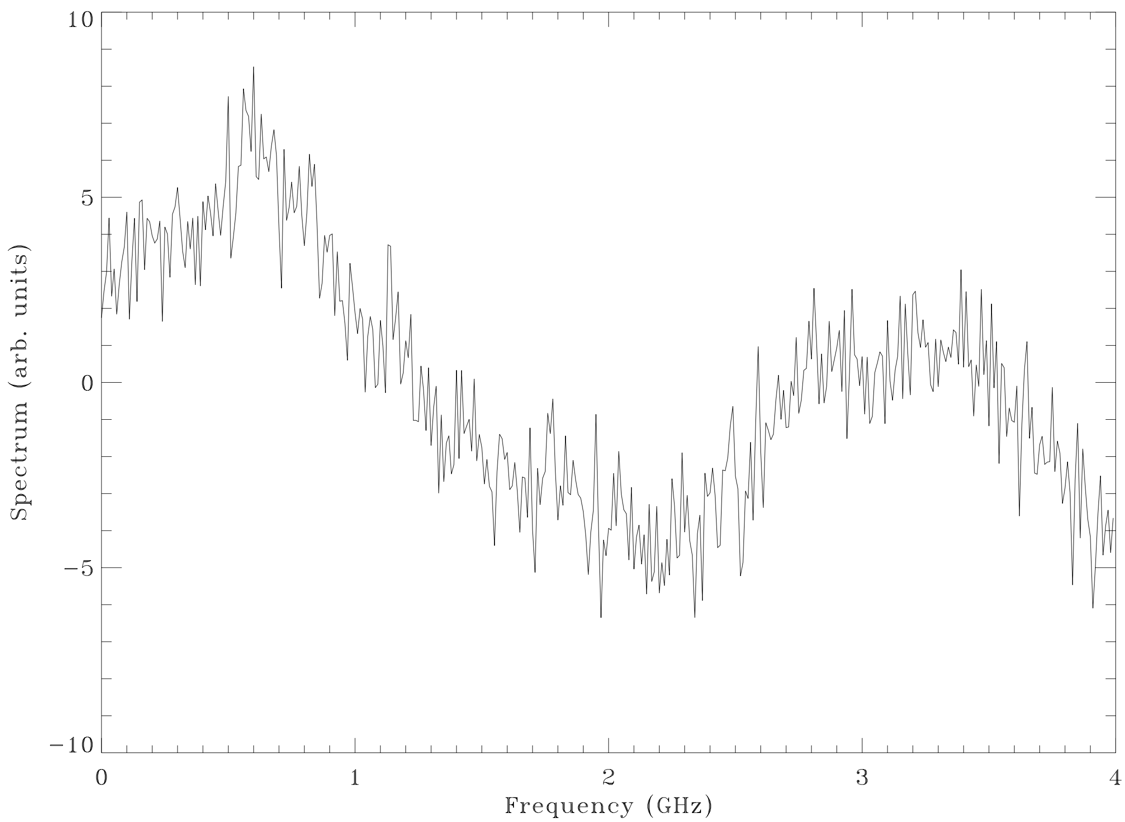

Figure 6. Sample simulated spectrum of wide bandwidth observation with a much larger 1/f gain contribution from the IF amplifier. A spectrum similar to that in the previous figure has been simulated, but now with the assumption that the chopping speed is 60 seconds. The 1/f gain fluctuation contribution is therefore larger relative to the white noise. Again, it is assumed that the IF amplifier has a correlation function described in Fig. 4. A gain fluctuation level consistent with the measurements described earlier was used. Structure in the spectrum that results from gain fluctuations is now readily apparent. A baseline offset of 6.6 units has been subtracted.