GBT Memo 282
The Continuum Sensitivity of GBT Receivers
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Abstract

I have analyzed the past three semesters of archival GBT data and quantified the limiting sensitivity of the GBT receivers for continuum measurements using the DCR backend. I find typical fractional gain fluctuations of $\Delta G/G \sim 5 \times 10^{-4}$ at 5 Hz. This corresponds to a limiting RF bandwidth, at which gain fluctuation noise equals the radiometer noise in 0.1 sec, of ~ 40 MHz. There is evidence for considerably different levels of gain stability between receivers, with L and Ku band showing the best stability, and X and C-band showing the worst stability. Results for S-band and the prime focus receivers are inconclusive; RFI may be a factor.

1 Introduction

The sensitivity of wide bandwidth radio continuum measurements are usually limited by receiver gain fluctuations unless the receivers are specially designed. Most GBT receivers are designed with spectral line measurements in mind; nevertheless, there are continuum experiments which the GBT is particularly well-suited to perform. With this in mind I have uniformly analyzed a large sample of peak scans obtained with the GBT in order to quantify their sensitivity.

The effect of gain fluctuations on receiver sensitivity can be written (see, for instance, Dicke 1946; Kraus 1986; Jarosik 2003; or Bersanelli 2010) as:

$$\frac{\Delta T}{T_{sys}} = \sqrt{\frac{1}{\Delta\nu\,\tau} + \left(\frac{\Delta G(f)}{G}\right)^2} \tag{1}$$

here τ is the integration time, $f = 1/2\tau$, and $\Delta\nu$ is the RF detection bandwidth of the measurement.

2 Method

Automated analysis scripts were written using the suite of MUSTANG, CCB and DCR analysis tools that have been developed in IDL. These scripts were used to identify all PEAK scans collected during 12A, 12B, and 13A science observing. Essentially all ($> 99\%$) of the data collected had integration periods of 0.1 sec, and none had integration periods longer than 0.2 sec. The analysis procedure was as follows:

1. The noise was estimated as $\sigma_{est.} = MAD(\Delta_i)/0.6745/\sqrt{2}$ where $\Delta_i = d_{i+1} - d_i$. d_i are the raw time-ordered data for a given port. The MAD is the Median Absolute Deviation: $MAD(x_i) = Median(|x_i - Median(x_i)|)$. It is a considerably more robust estimate of the scatter in a distribution than the variance (see, e.g., Hoaglin et al. 1983). The normalization factors (0.6745, $\sqrt{2}$) are chosen so that $\sigma_{est.}$ equals the RMS of the data if the measurement errors are normally distributed and uncorrelated. The quantity $\sigma_{est.}$ is in effect a robust estimate of the Allan standard deviation ($\sqrt{<\sigma^2(2,\tau,\tau)>_{samp.}}$) at 5 Hz.
2. The fractional system noise is then estimated as

$$\Delta T/T_{sys} = \sigma_{est.}/(Median(d_i))$$

   This assumes that DC, non-radiometric offsets are negligible, a point which is discussed below. Only the first 25% of integrations in a given scan are used for these calculations, ignoring the first integration.
3. The fractional gain fluctuation at 5 Hz is then calculated from the excess variance in the observed system noise, compared to what the radiometer equation predicts:

$$\left(\frac{\Delta G(f)}{G}\right)^2 = \left(\frac{\Delta T}{T_{sys}}\right)^2 - \frac{1}{\Delta\nu\,\tau}$$

   where $\Delta\nu$ is the bandwidth reported in the IF manager FITS file for the port in question. τ is the integration time per sample, computed from the sample spacing divided by the number of phases (only cal off, SIG phases were used in the analysis). The estimated distribution of $\Delta G/G$ can have a large dispersion in some cases, particularly where RFI is common. We take our "best estimate" to be the mode of this distribution, and use the MAD to estimate its characteristic dispersion.

4. We also directly compute the ratio of the observed noise to expected radiometer noise:

$$\text{Noise Ratio} = \frac{\Delta T}{T_{sys}}\sqrt{\Delta\nu\tau}$$

   for an ideal (gain-fluctuation free) system this will have a value of unity.

5. For each record, an effective radiometer bandwidth $\Delta\nu_{eff.}$ is computed as

$$\Delta\nu_{eff.} = \left[\left(\frac{\Delta G}{G}\right)^2 \tau\right]^{-1}$$

   This is the bandwidth an ideal (gain-fluctuation free) radiometer would have in order to show noise equal to the observed level of gain fluctuations.

In all there were 26,503 good records in the analysis. A "record" here is one scan's worth of time-ordered data from a single port. About 2% of all records identified were excluded from the analysis due to clearly malformed or anamolous results. The properties of the data are summarized in Table 1.

Receiver	$\Delta\nu_{meas.}$ [MHz]	$N_{records}$
PF(300 MHz)	20	28
PF(850 MHz)	20	412
L	20, 80	4528
S	80	24
C	80	72
X	80, 320	3972
Ku	320	19
K	660, 800	11174
Ka	320	3051
Q	320	607
W	320 , 1280	2616

Table 1: Data summary: number of records and measurement bandwidths for each receiver. One record comprises all integrations from a single port from a single scan.

This analysis assumes that the DC offsets in total power are negligible, *i.e.*, if an infinte attenuator were placed at the receiver output, our measurements would show a mean of zero. Early investigations indicate DC offsets in the DCR of up to 1% (Minter 2006). This would give rise to a 1% fractional error in our estimate of the fractional system noise, which is a negligible effect. The consistency of $\Delta G/G$ estimate for measurements with different bandwidths supports this hypothesis (see Fig. 1 and Fig. 2). To bias our estimate of gain fluctuations high, a consistently negative DC offset in the DCR input would be needed.

3 Results

The results of this analysis are summarized in Table 2. The distribution of estimated gain fluctuations for two different RF bandwidths for the W and X band receivers are shown in Figures 1 and 2, and plots showing more aggregate results for each receiver are shown in Figures 3 through 13. Typical fractional gain fluctuations in the 10 Hz samples are at the level of 5×10^{-4}, the same fractional noise level as would result from an ideal measurement with a bandwidth of ~ 40 MHz. Several features are notable:

- The nature of the distribution of observed noise ratios, as well as prior knowledge, suggests that the results for Pf1 and S band receivers may be strongly affected by RFI. The same may be true for the Pf2 receiver. It is not possible to draw any firm conclusions about gain fluctuations for these receivers from this analysis.
- Most of the high frequency receivers (C, X, K, Ka, Q, and W) clearly and consistently show an elevated noise level consistent with gain fluctuations at the few $\times 10^{-4}$ level in 0.1 sec.
- X and C band receivers clearly show the worst stability of the well-measured receivers; and the Y polarization for C-band is roughly twice as stable as the X polarization.

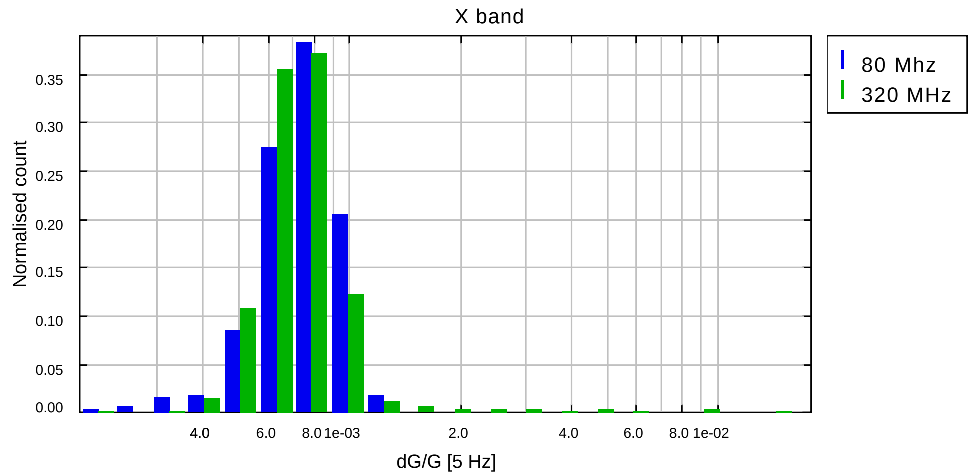

Figure 1: Gain fluctuation levels measured for the X-band receiver for two measurement bandwidths.

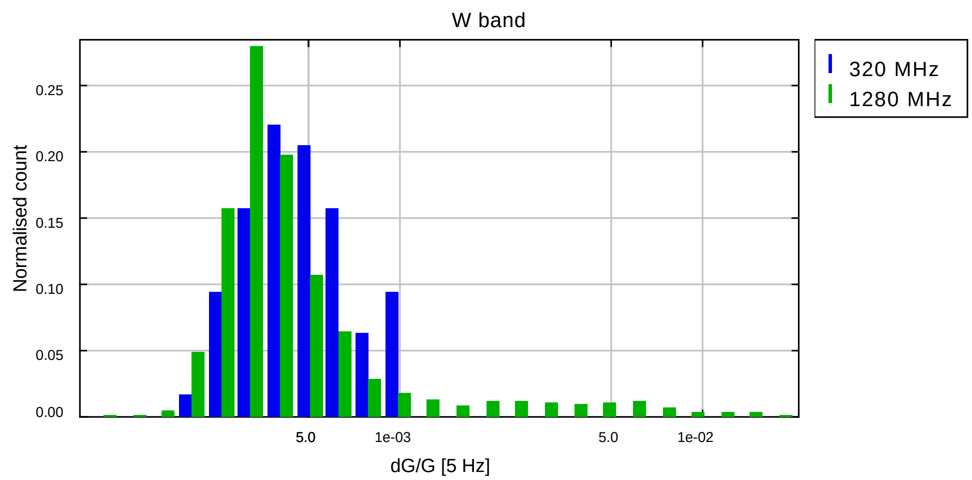

Figure 2: Gain fluctuation levels measured for the W-band receiver for two measurement bandwidths.

- The L band receiver shows some gain instability effects, but has better stability than the high frequency receivers. There are indications the Ku band receiver may also be more gain-stable, though the data are sparse.

These results are a strong function of measurement strategy. So, for example, the Ka band receiver used with the Caltech Continuum Backend (CCB) is known to have an effective measurement bandwidth close to 3.5 GHz, two orders of magnitude better than is seen with the DCR, due to the fast (4 kHz) beam switching it provides. Similarly, for the receivers that may be affected by RFI, better results might be obtained from a set of measurements with sufficient time or frequency resolution to permit RFI flagging or excision. Nevertheless, for receivers other than the Ka-band receiver, these total power results are indicative of the best sensitivity which can be expected in practice with existing receiver architectures and optical signal modulation schemes (scanning, nodding subreflector nodding) on the GBT.

References

Bersanelli et al. 2010, A&A 520, A4
Dicke, R.H. 1946, Rev.Sci.Instr. 17, 268
Hoaglin, D., Mosteller, F., & Tukey, J. 1983, Understanding Robust and Exploratory Data Analysis (New York: Wiley)
Jarosik, N. et al. 2003 ApJ 145, p.413
Kraus, J.D. 1986, Radio Astronomy
Minter, T. 2006, GBT Memo 240.

Receiver	$\frac{\Delta G}{G}(5\,\mathrm{Hz})$	$\Delta\nu_{eff.}$ [MHz]
PF(300 MHz)	$\sim 2.3 \times 10^{-3}$ *	2
PF(850 MHz)	$\sim 1.2 \times 10^{-3}$ *	7
L	$(3.7 \pm 2.4) \times 10^{-4}$	73
S	$(7.9 \pm 2.8) \times 10^{-4}$ *	16
C	$(1.5 \pm 0.8) \times 10^{-3}$	4
X	$(6.9 \pm 1.5) \times 10^{-4}$	21
Ku	$(1.6 \pm 1.2) \times 10^{-4}$	390
K	$(5.2 \pm 2.0) \times 10^{-4}$	37
Ka	$(5.0 \pm 2.1) \times 10^{-4}$	40
Q	$(4.1 \pm 1.1) \times 10^{-4}$	59
W	$(3.6 \pm 1.3) \times 10^{-4}$	77

Table 2: Gain stability results for GBT receivers (12A, 12B, 13A data). Error bars indicate the dispersion in values, not the error in the mean. $\Delta\nu_{eff.}$ shows the bandwidth of an ideal radiometric measurement which will have equal noise as that originating from gain fluctuations. Numbers marked by "*" may be biased by RFI.

A Data for Each Receiver

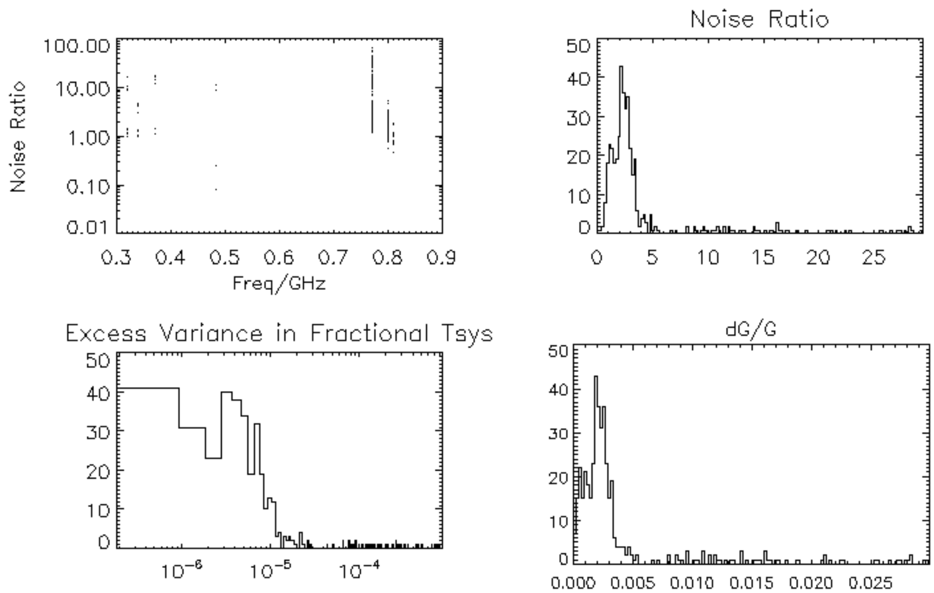

Figure 3: Prime focus 1.

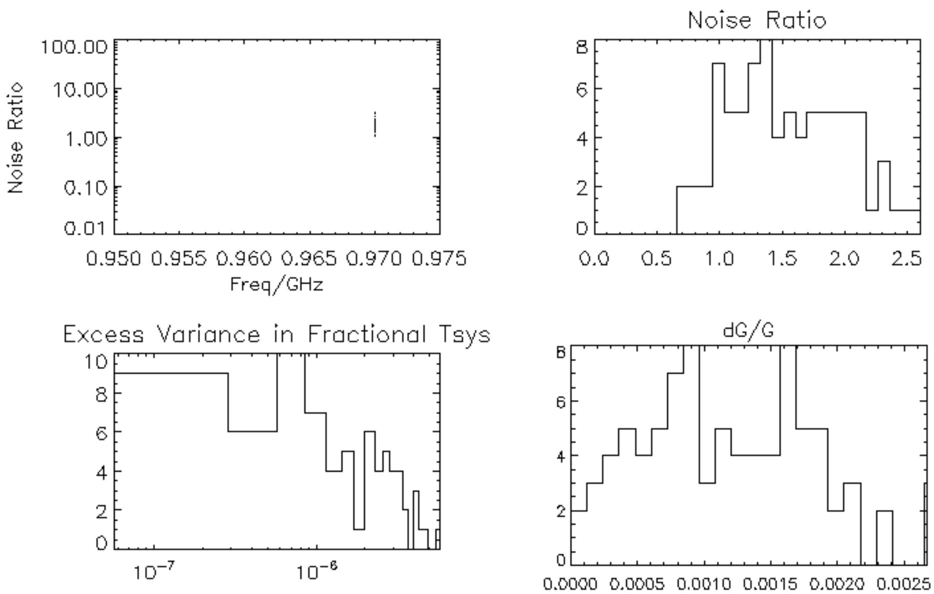

Figure 4: Prime focus 2.

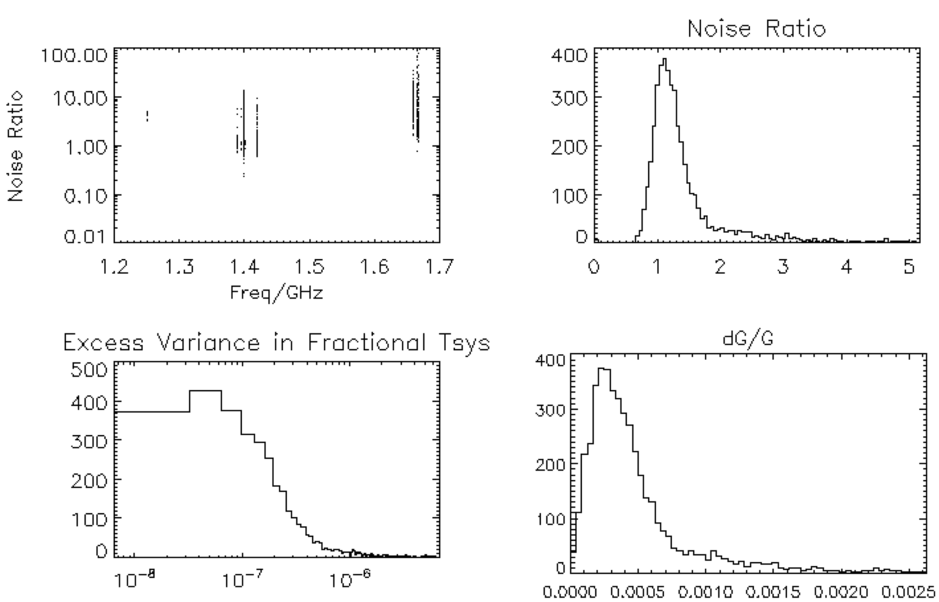

Figure 5: L-band.

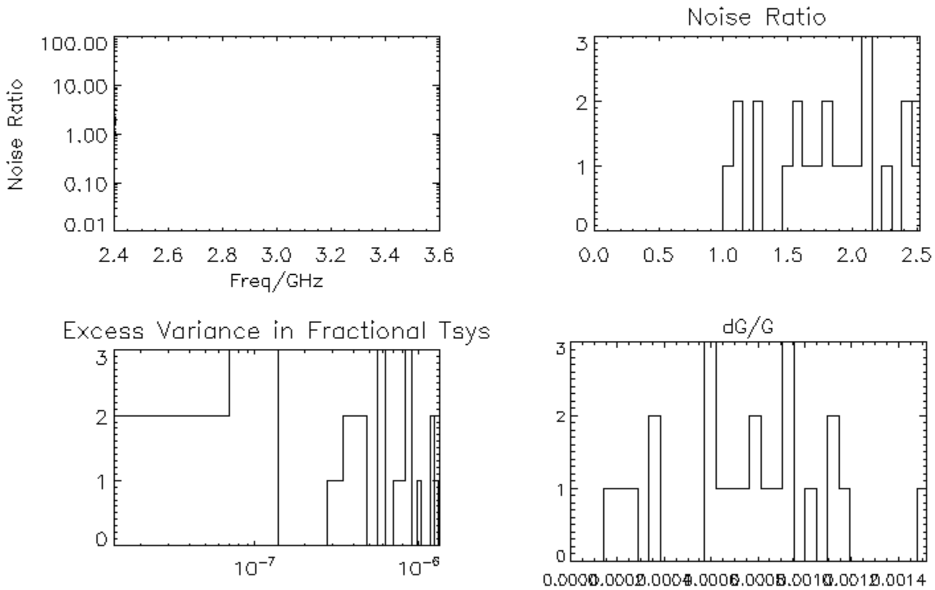

Figure 6: S-band.

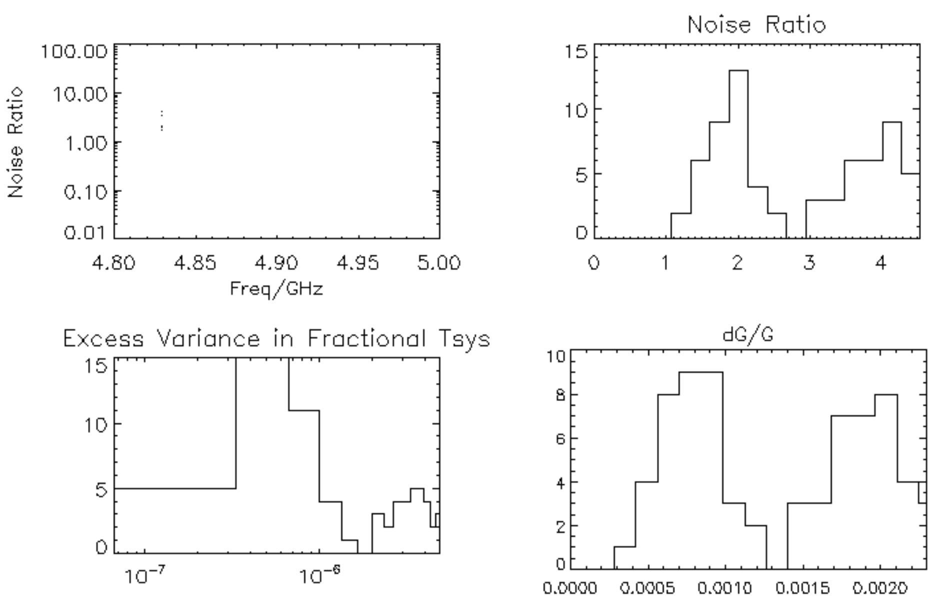

Figure 7: C-band. The bimodality in the gain distribution comes from differing stability in X (less stable) and Y (more stable) polarizations.

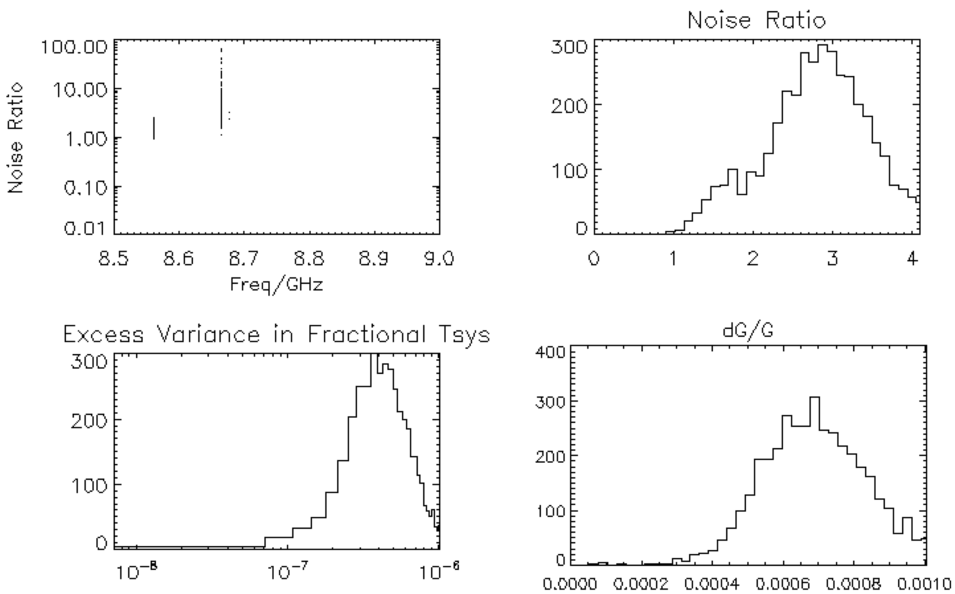

Figure 8: X-band.

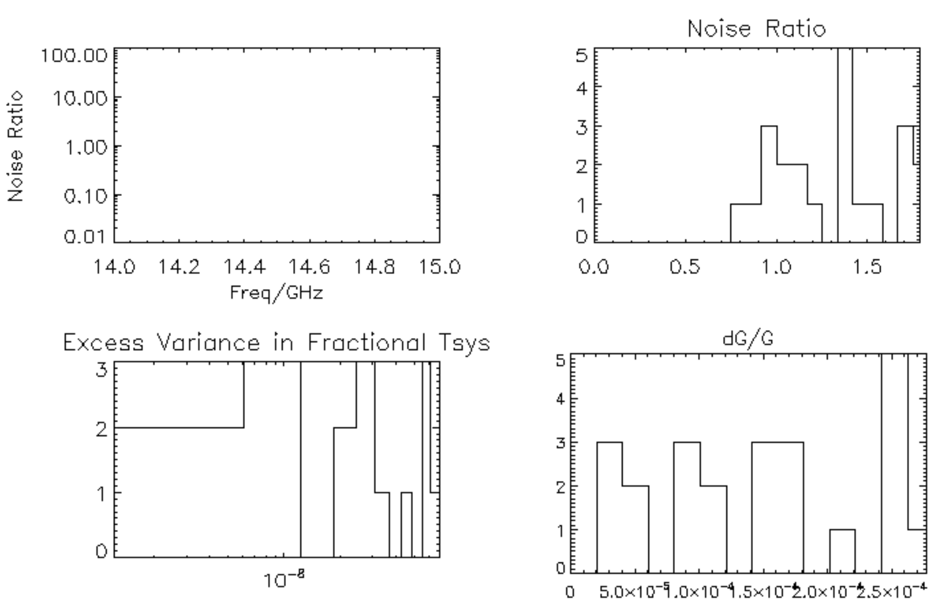

Figure 9: Ku band.

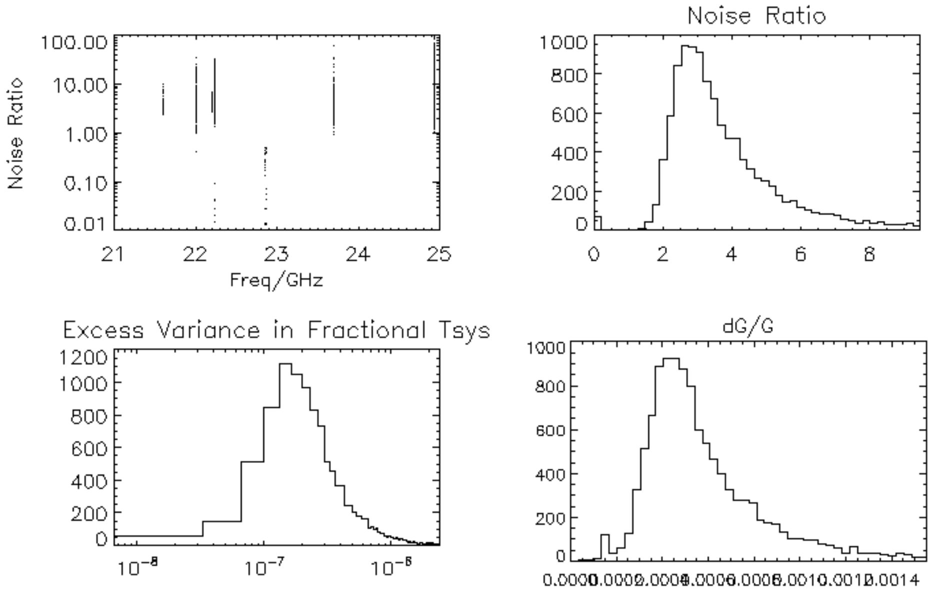

Figure 10: K-band.

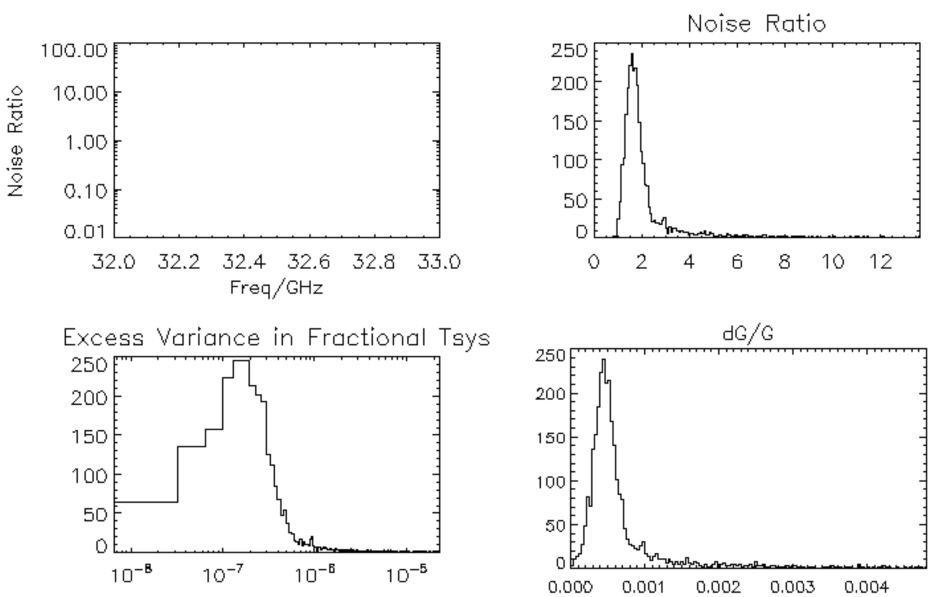

Figure 11: Ka-band.

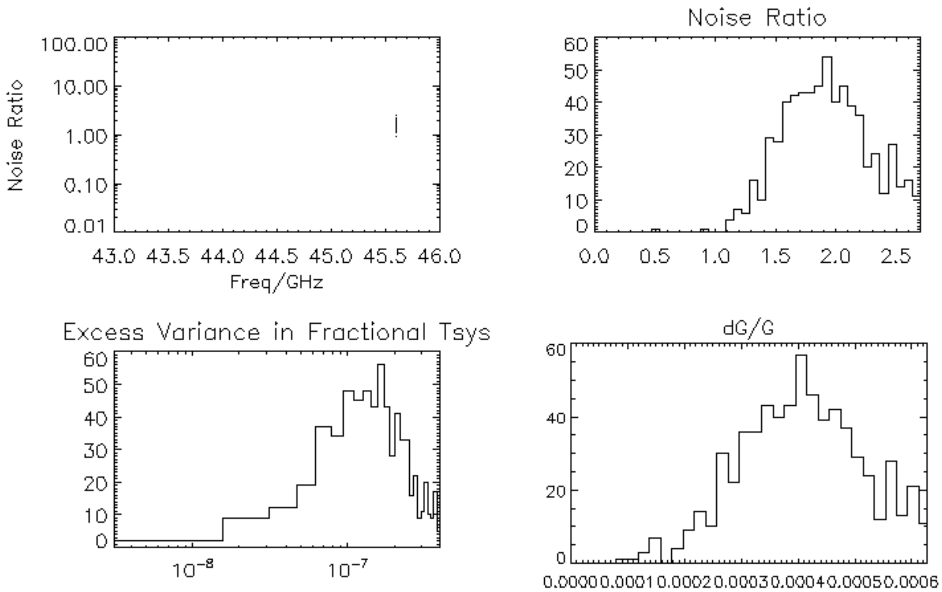

Figure 12: Q-band.

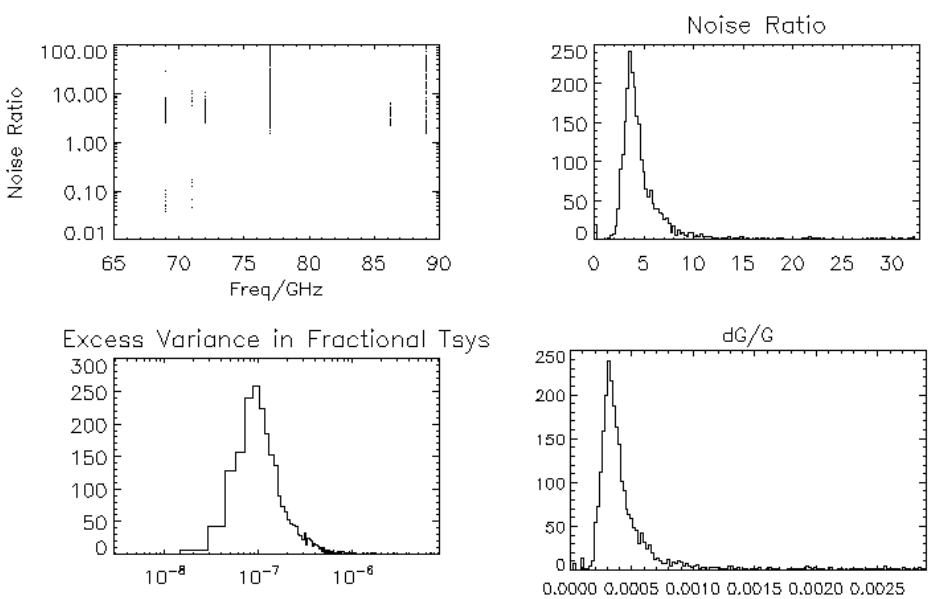

Figure 13: W-band.