Tests on Q-band Components
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Setup

This report describes measurements and analysis made on a test arrangement consisting of a cooled LNA and mixer, IF filter, and IF amplifier taken from the Q-band receiver and placed in one of our test dewars. The LNA input port was connected to a cooled isolator and a cooled rectangular waveguide load. The load was thermally separated from the isolator with a 13 cm length of stainless waveguide. A small heater and temperature sensor allowed the load temperature to be adjusted. VNA measurements on the ss waveguide and the load show that the load has a return loss of 34 dB or better, and that the ss waveguide flanges also have return losses of about 34dB. The combination of the ss waveguide and the load have peak return loss of 27dB, with ripple period of about 1.16GHz.

The test dewar was located in the Equipment Room and the IF output (centered at 6GHz) was connected into OR1 via heliax cable. Converter Module 1, Sampler/Filter 1, and the spectrometer were then configured for a 800 MHz bandwidth measurement of the spectrum. A 83620 synthesizer was used to provide a LO signal to the cooled mixer via a 4X multiplier, just as in the Q-band receiver.

Results

Several scans were taken with one to six minute duration. Analysis of these indicate the system was reasonably stable, and that the noise integrated down with root time at least to 5-6 minute durations. The analysis herein will concentrate on a sequence of six minute scans taken about a step in the LNA input load temperature. A description of the scans of interest and related conditions is given in Table 1.

It is probably obvious that the reason for using a heated load on the LNA input is to simulate a situation for which the GBT suffers particularly poor

Table 1: Scan Descriptions

Scan	f_{cen}	Load Temp	Notes
23,24	42GHz	21.8K	System Stable
25	42	Increasing	Load Heating
26,27	42	32.8	System Stable
51,52	43GHz	21.4K	System Stable
53	43	Increasing	Load Heating
54,55	43	32.6	System Stable

baseline performance, namely spectroscopy on continuum sources. The usual way to perform these observations is to do two scans - one (Ref) on cold sky, and a second (Sig) on the source of interest. The baseline, BL, is then calculated by:

$$BL = T_{sys}(Sig - Ref)/Ref \tag{1}$$

Figure 1 shows the $(Sig - Ref)/Ref$ results taking a scan with low load temperature (Scans 24 and 52) as Ref, and a scan with higher load temperature (Scans 27 and 55) as Sig. To understand why these quantities exhibit so much structure, it is useful to analyze a simple model of the receiver system.

Let us model the receiver chain with a power gain transfer function $G(f)$ and noise temperature $T_{rx}(f)$. As indicated, both of these quantities are functions of frequency and summarize the cascade of many active and passive components. Our test system consists of the receiver, input terminated by a thermal noise source having effective source temperature T_L, and the spectrometer at the receiver output to measure the output power spectrum. The equation for the receiver output power spectrum is well-known:

$$S_o(f) = (T_L + T_{rx}(f))k_B G(f) \tag{2}$$

where k_B is the product of Boltzmann's constant and the effective bandwidth of each spectrometer frequency channel. (From this point on I will omit the (f) except when it seems important to emphasize certain quantities are functions of frequency.) Let us now write down the equations for output spectra for two values of T_L. Call the lower load temperature T_{cold}, and the corresponding spectrum S_r. Call the higher load temperature T_{hot}, and the corresponding spectrum S_s. The receiver gain and noise temperature are in general functions of time, if not signal level, so we will also distinguish the values with s and r subscripts.

$$S_r = (T_{cold} + T_{rx,r})k_B G_r \tag{3}$$

$$S_s = (T_{hot} + T_{rx,s})k_B G_s \tag{4}$$

So,

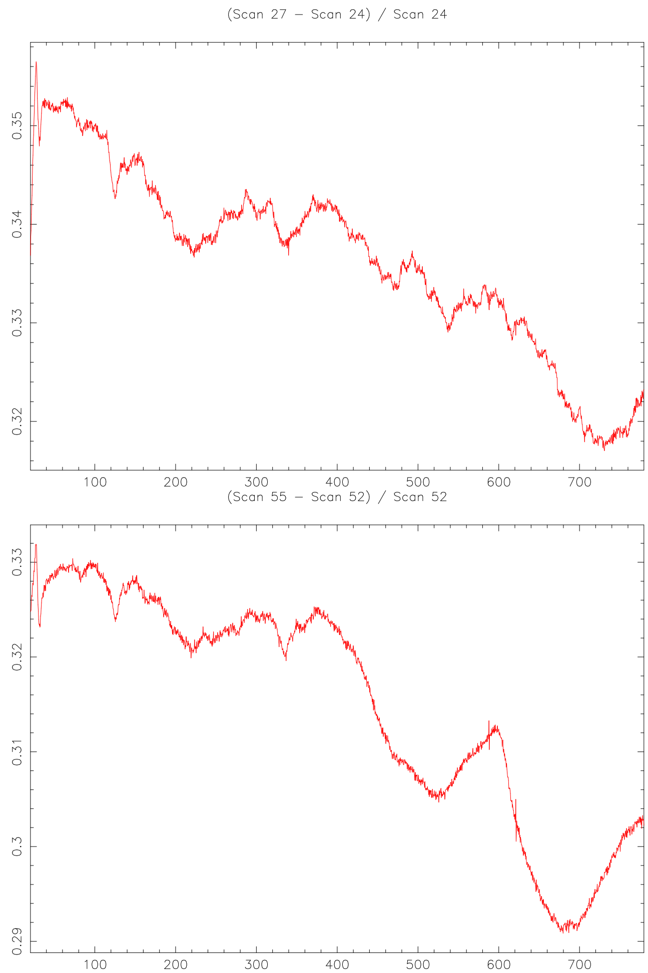

Figure 1: The quantities $(Sig - Ref)/Ref$ at 42 GHz (upper panel) and 43GHz (lower panel), using the scans indicated. The horizontal axis of this plot (and all plots in this report) is in MHz at the spectrometer IF input frequency. The IF spectrum is inverted; front-end frequency increases to the left.

$$\frac{S_s - S_r}{S_r} = \frac{(T_{hot} + T_{rx,s})G_s - (T_{cold} + T_{rx,r})G_r}{(T_{cold} + T_{rx,r})G_r} \tag{5}$$

regrouping we obtain,

$$\frac{S_s - S_r}{S_r} = \frac{(T_{hot}G_s - T_{cold}G_r) + (T_{rx,s}G_s - T_{rx,r}G_r)}{(T_{cold} + T_{rx,r})G_r} \tag{6}$$

If we take the optimistic view that the receiver gain and noise temperature are completely stable over the measurement period, that is $G_s = G_r$ and $T_{rx,s} = T_{rx,r}$, then equation 6 becomes:

$$\frac{S_s - S_r}{S_r} = \frac{T_{hot} - T_{cold}}{T_{cold} + T_{rx,r}(f)} \tag{7}$$

This equation shows that the quantity $(Sig - Ref)/Ref$ will only be flat with frequency if $T_{rx,r}$ is flat, or $T_{hot} - T_{cold}$ is very small over most of the frequency range. The denominator of equation 7 is just $T_{sys}(f)$ during the reference scan, so multiplying by that value will retrieve the desired quantity $T_{hot} - T_{cold}$. T_{sys} is usually determined by using a small injected noise cal, but for flat baselines T_{sys}, and hence T_{cal}, must be determined to a high accuracy at every frequency in the passband. Another possible means to determine $T_{sys}(f)$ is to use the Y-factor method.

The most common engineering method of determining a receiver's noise temperature is to measure its output power with two known input source temperatures, T_{hot} and T_{cold}. The ratio of the two powers is termed the Y-factor. Equations 3 and 4 define these two quantities for our model:

$$Y(f) = \frac{S_s}{S_r} = \frac{(T_{hot} + T_{rx,s}(f))k_B G_s}{(T_{cold} + T_{rx,r}(f))k_B G_r} \tag{8}$$

Again assuming receiver stability, and solving for T_{rx}, we obtain the familiar equation:

$$T_{rx}(f) = \frac{T_{hot} - Y(f)T_{cold}}{Y(f) - 1} \tag{9}$$

Using equations 8 and 9, we can calculate T_{rx} at 42GHz using, say, scan 24 as the reference and scan 26 as the signal, $T_{cold} = 21.8$, and $T_{hot} = 32.8$. A similar calculation at 43GHz can be done using scans 52 and 54, $T_{cold} = 21.4$, and $T_{hot} = 32.6$. The results are shown in Figure 2. Compared with Figure 1, the shapes are obviously similar but inverted and scaled as expected from the model and equation 7.

The next step is to use T_{rx} determined in this fashion in equation 1. Figure 3 shows the results at 42 GHz. The red trace was obtained for Scan 27 (Sig) and 24 (Ref) by using $T_{sys} = T_{cold} + T_{rx}$ with $T_{cold} = 21.8$ and T_{rx} as plotted in Figure 2. The green trace uses $T_{sys} = T_{cold} + mean(T_{rx})$. It is clear that using a constant T_{sys} across the band is a bad idea. Figure 4 shows the results of a similar procedure at 43 GHz using scans 55 and 52. Note that in this procedure,

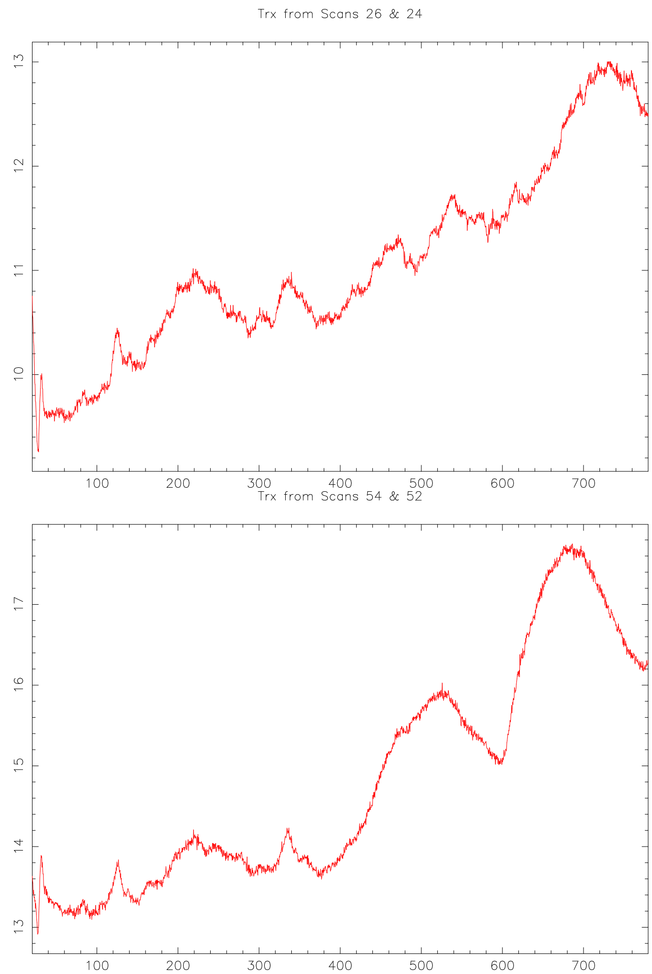

Figure 2: T_{rx} at 42 GHz (upper panel)and 43 GHz (lower panel), calculated with equations 8 and 9.

one "hot" scan was used with the "cold" scan to calculate T_{rx}, and this was used to process a subsequent "hot" scan. The scans were 6 minutes long, and since the change in load temperature occupied 6 minutes, there was a 6 minute gap between the end of the "cold" scan and the beginning of the "hot" scan used for the calculation of T_{rx}. The Sig scans used in Figures 3 and 4 began 12 minutes after the end of the "cold" (Ref) scans.

Summary

It seems that the simple test described here proves that the spectral baselines seen in $(Sig - Ref)/Ref$ was largely due to structure in T_{rx}. I strongly suspect the same is true for most GBT measurements on continuum sources. It is not known exactly why the receiver temperature shows such uneven frequency structure. Additional lab tests may shed light on this question.

In the meantime, it might be profitable to consider if an adaptation of the Y-factor technique used here would be useful for astronomical measurements. Would it be possible to use flat-spectrum astronomical calibration sources to accomplish a "hot-cold" T_{rx} measurement in conjunction with the usual position switched observations? An absolute knowledge of the hot and cold source temperatures might not be critical to achieve flat baselines, although of course it is certainly critical for absolute calibration.

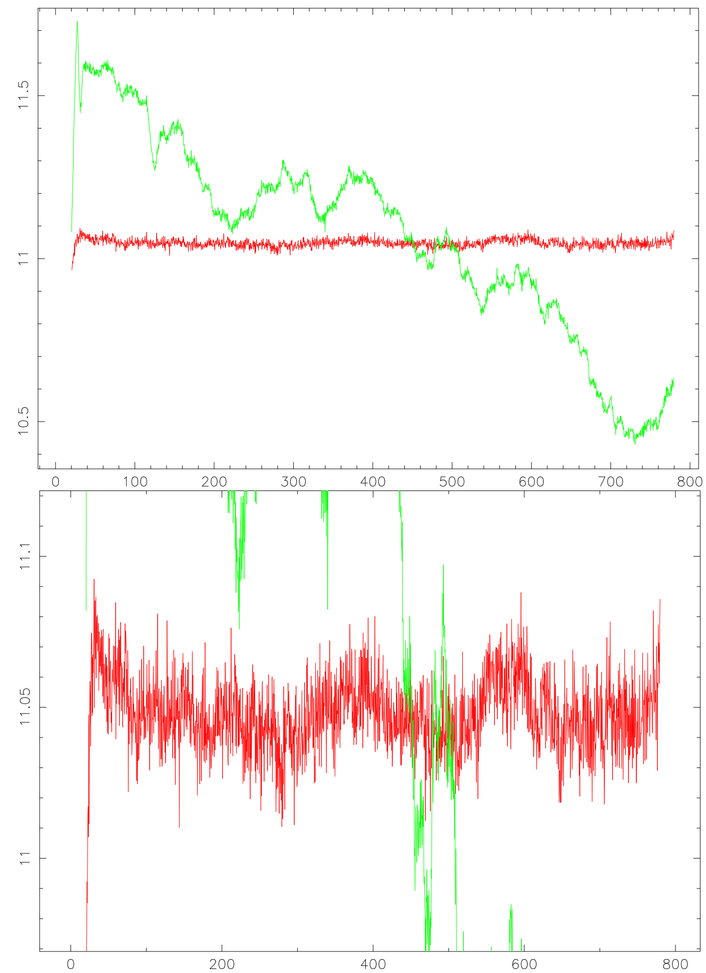

Figure 3: The upper panel shows the baseline at 42GHz, and the lower panel a zoomed portion. The quantity plotted is $T_{sys}(Sig - Ref)/Ref$, which reduces to $(T_{hot} - T_{cold})$. For the green trace, T_{sys} was constant versus frequency, while for the red trace T_{sys} was determined by the Y-factor method. The vertical scale is Kelvin.

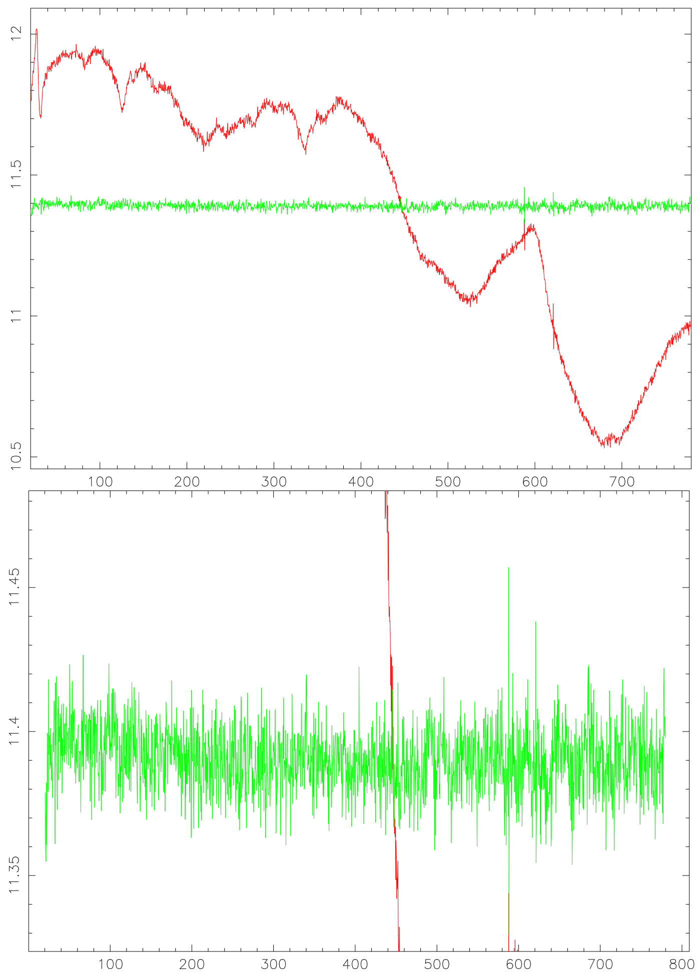

Figure 4: The upper panel shows the baseline at 43GHz, and the lower panel a zoomed portion. The quantity plotted is $T_{sys}(Sig - Ref)/Ref$, which reduces to $(T_{hot} - T_{cold})$. For the red trace, T_{sys} was constant versus frequency, while for the green trace T_{sys} was determined by the Y-factor method. The vertical scale is Kelvin.