GBT IF System Non-Linearity

April 4 and 8, 2004 Tests Results

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1 Introduction

The GBT IF system was know to have a non-linear response in the presence of strong continuum sources when data was obtained with the spectrometer. This non-linearity may be responsible for the strong continuum induced baseline structures. (For more information see the reports of the GBT Spectral Baseline Investigation Group[2].)

In the course of checking out the GBT01A_004 proposal the cause of the baseline structure was isolated to be between the LO1 mix with the RF signal in the X-band receiver and the LO2 mix with the IF signal in the Converter Rack. (See Toney Minter's document "GBT01A_004 Observation Checkout Report – March 31, 2004"[3].)

Test observations were performed on April 4 and April 8, 2004 in an attempt to further isolate where the non-linear response occurs in the IF system. We also wanted to determine if the non-linearity could be seen by all GBT backends. We report on the results of these observations in this note.

2 April 4, 2004 Observations

2.1 Setup

The IF system was setup to observe four spectral windows with the spectrometer. Each spectral window was 800 MHz wide with center frequencies of 9900, 9875, 9925 and 9950 MHz. The first two spectral windows used Optical Drivers 2 and 3 and then proceeded through Converter Modules 1, 2, 5, and 6. The second two spectral windows usedOptical Drivers 6 and 8 and then proceeded through Converter Modules 11, 12, 15, and 16.

2.2 Optical Driver Comparison

Data was obtained using double position switching between NGC 7027 and 2202+422. See "GBT01A_004 Observation Checkout Report – March 31, 2004"[3] for information on double position switching and its data reduction. If everything is behaving linearly – there are no gain changes and bandpasses are constant – then the resulting data should just be the ratio of the source fluxes. For example, if the target source has a spectrum given

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[1] http://www.gb.nrao.edu/ tminter/1A4/nonlinear/nonlinear.html

[2] Found at http://www.gb.nrao.edu/gbt/baseline/index.html

[3] Found at http://www.gb.nrao.edu/ tminter/1A4/1A4obscheckout.shtml

by $S^{target}(\nu) = A\nu^{\alpha}$ and the calibration source has a spectrum given by $S^{calibration}(\nu) = B\nu^{\beta}$ then the double position switching would result in a spectrum that goes as

$$\frac{S^{target}(\nu)}{S^{calibration}(\nu)} = \frac{A}{B}\nu^{\alpha-\beta}. \tag{1}$$

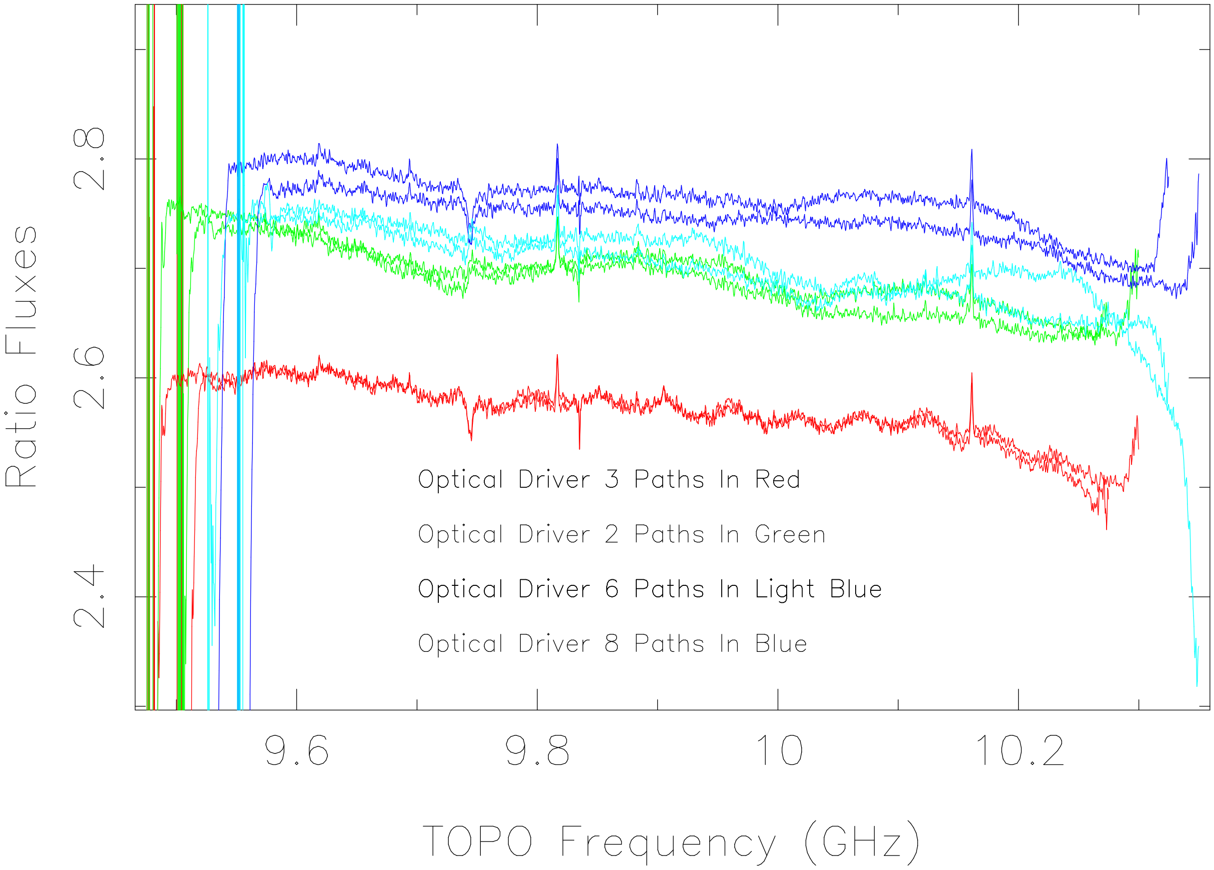


Figure 1: Double position switch observation of NGC 7027 and 2202+422 using different Optical Drivers with data taken at the same time.

The resulting data are shown in Figure 1. The plot consists of four spectral windows with two polarizations in each window. The plot is color coded as to which signals used common Optical Drivers. As can be seen from Figure 1 a constant flux ratio is not achieved. The flux ratio depends on which set of Optical Drivers was used. The variation in flux ratio is greater than could be expected due to measurement noise. Furthermore it was found that the flux ratio varies in time. This means that you can not convert GBT double position switch results onto a scale with known flux units.

Given the previous results that the non-linearities arise between LO1 and LO2, the results of Figure 1 suggest that the non-linearities arise in components associated with a particular Optical Driver path. Data coming down the same Optical Driver has about the same flux ratio so this suggests that the largest non-linearities are before the LO2 mixes and after the IF splitter in the receiver.

In Figure 2 we compare the flux ratios found from double position switching using data only when the noise diodes are off compared to using data only when the noise diodes are on. It is easily seen that the $\sim$ 2.6 Kelvins that the noise diodes add to the total power in the system are enough to excite a non-linear response. This suggests that the problem may be such that the IF system always has some degree of non-linearity.

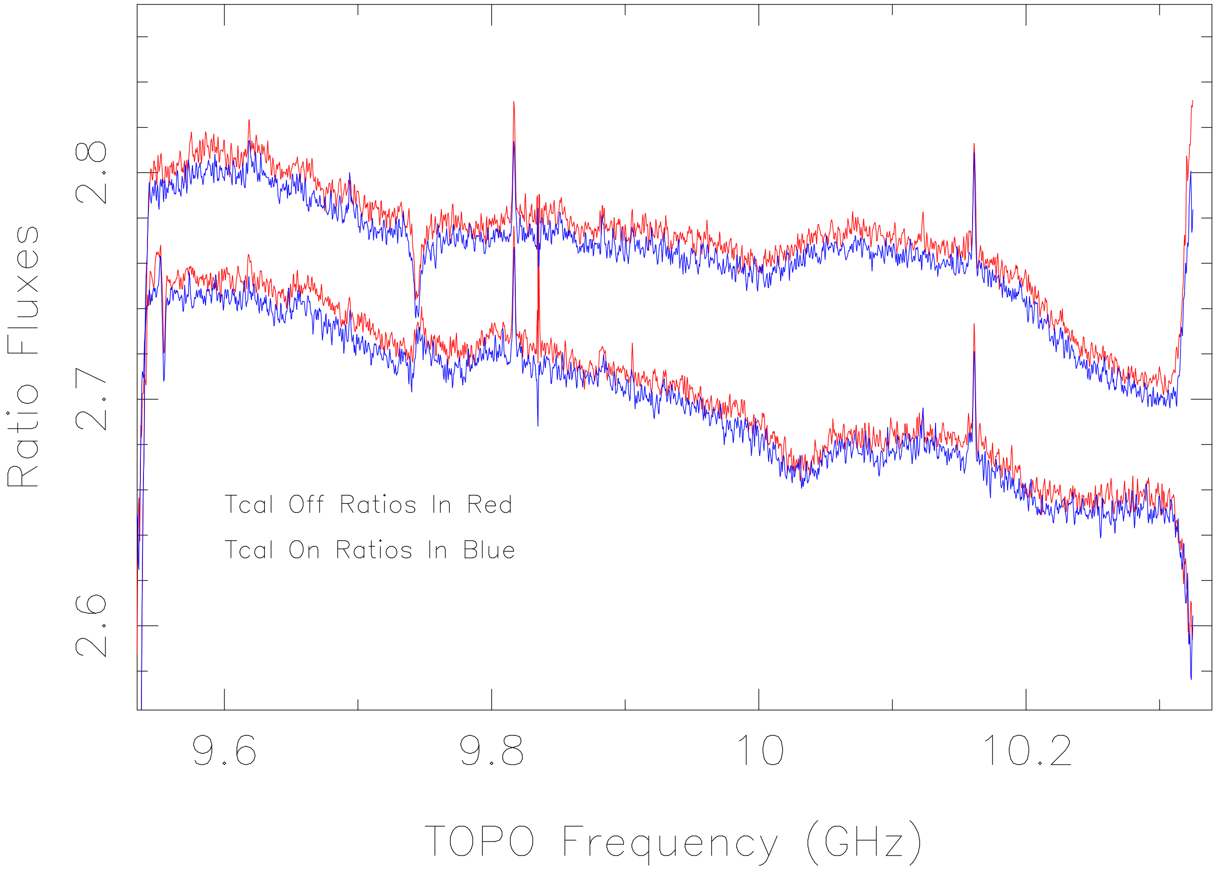


Figure 2: Double position switch observation of NGC 7027 and 2202+422 using $\mathrm{T_{cal}(off)}$ only data in red and $\mathrm{T_{cal}(on)}$ only data in blue. Data from two polarizations are shown. It is easily seen that a power change of $\sim$ 2.6 Kelvins from firing the low noise diode is enough to see a non-linearity in the results.

2.3 Using the Cal Signals To Find Gain Non-linearity

At this point we desired a better method to diagnose the non-linear response of the IF system. Since it would seem that the noise diodes can excite a non-linear response (see Figure 2) we thought that comparing the two states with the noise diode on and off could provide some insight.

We can define the gain, G, of the IF system as follows:

$$G = \frac{P_{\mathrm{out}}(\mathrm{counts})}{\mathrm{P_{in}(K)}} \tag{2}$$

where P_{in} is the input power to the system (i.e. total system temperature), and P_{out} is the raw output counts of one of the backends. If the IF system response is linear then G = constant. We can use the first derivative of Equation 2 to check for non-linearities. The first derivative is

$$\frac{\partial P_{\mathrm{out}}(\mathrm{counts})}{\partial \mathrm{K}} = \frac{\partial\,(G\ P_{\mathrm{in}}(\mathrm{K}))}{\partial K} = \frac{\partial G}{\partial K} P_{\mathrm{in}}(\mathrm{K}) + \mathrm{G}\frac{\partial \mathrm{P_{in}(K)}}{\partial \mathrm{K}} \tag{3}$$

which can be approximated as

$$\frac{\partial P_{\mathrm{out}}(\mathrm{counts})}{\partial \mathrm{K}} \sim \frac{P_{\mathrm{out}}^{\mathrm{cal\ on}}(\mathrm{counts}) - \mathrm{P_{out}^{cal\ off}(counts)}}{\mathrm{T_{cal}(K)}} \sim G + \frac{\Delta G\ P_{\mathrm{in}}^{\mathrm{cal\ off}}}{T_{cal}(\mathrm{K})} \tag{4}$$

for two power levels that are separated by firing only the noise diode. ΔG is the change in the gain between the two power levels. Now by taking the data with the cals firing on two different sources with different input power levels (or on a single source and changing the level of attenuation in the IF system) we can look for non-linearities. Taking the ratio (we will refer to this as the gain ratio hereafter)

$$R_{gain} = \frac{(P_{\rm out}^{\rm cal\ on} - P_{\rm out}^{\rm cal\ off})\,|_{\rm src1}}{(P_{\rm out}^{\rm cal\ on} - P_{\rm out}^{\rm cal\ off})\,|_{\rm src2}} = \frac{(G\,T_{cal} + \Delta G\,P_{\rm in}^{\rm cal\ off})\,|_{\rm src1}}{(G\,T_{cal} + \Delta G\,P_{\rm in}^{\rm cal\ off})\,|_{\rm src2}} \tag{5}$$

it can be seen that if the gain is linear then $\Delta G = 0$ and $R = 1$. If the system gain is non-linear then $R \neq 1$ and $\Delta G \neq 0$.

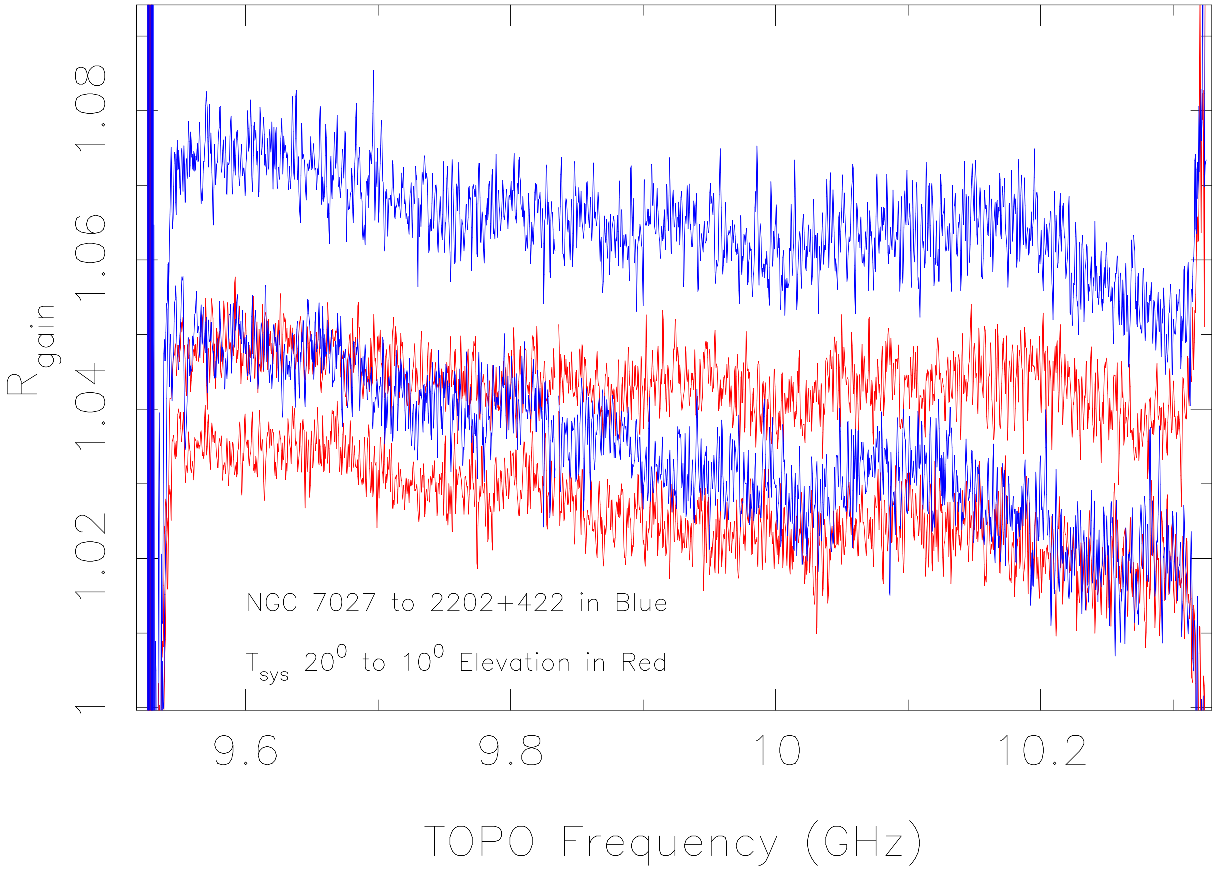


Figure 3: Gain ratios plotted for two polarizations. The red lines compare R_{gain} for the sources NGC 7027 and 2202+422. The blue lines compare R_{gain} for blank sky between 20° and 10° elevation (the off positions for the double position switch observations of NGC 7027 and 2202+422.

In Figure 3 we plot R_{gain} for part of the double position switch observations of NGC 7027 and 2202+422. We considered the gain ratio for the NGC 7027 and 2202+422 on source data and for the NGC 7027 and 2202+422 off source data. The off source data differ in T_{sys} slightly since the off positions are at elevations of 20° and 10° for these observations.

Figure 3 shows us that the GBT IF system gain is non-linear even for changes of input power of $\sim 5\%$ on blank sky. It should also be noted that the frequency dependence of the gain ratio is approximately the shape of the residual baselines in the results of the double position switching data.

Although most Optical Drivers exhibit symptoms of gain supression there is some indication that some Optical Drivers exhibit anti-compression (i.e. the Gain Ratio is less than one). Further tests are needed to isolate which Optical Drivers exhibit this feature – currently Optical Driver 3 is suspect.

3 April 8, 2004 Observations

We performed follow-up tests observations on April 8, 2004 to try to confirm the findings from the April 4, 2004 tests. We decided to use the C-band receiver to test whether the non-linearities are common to all the receivers. We took data with the DCR with signals coming from the V/F output of the IF Rack and then from the Analog Filter Rack V/F outputs. This was to test that the problem existed for the DCR as well as the spectrometer and to try to isolate whether or not the optical fibers had a non-linear response. While the DCR was being run from the Analog Filter Rack we also ran the Spectrometer simultaneously.

3.1 DCR Through The IF Rack

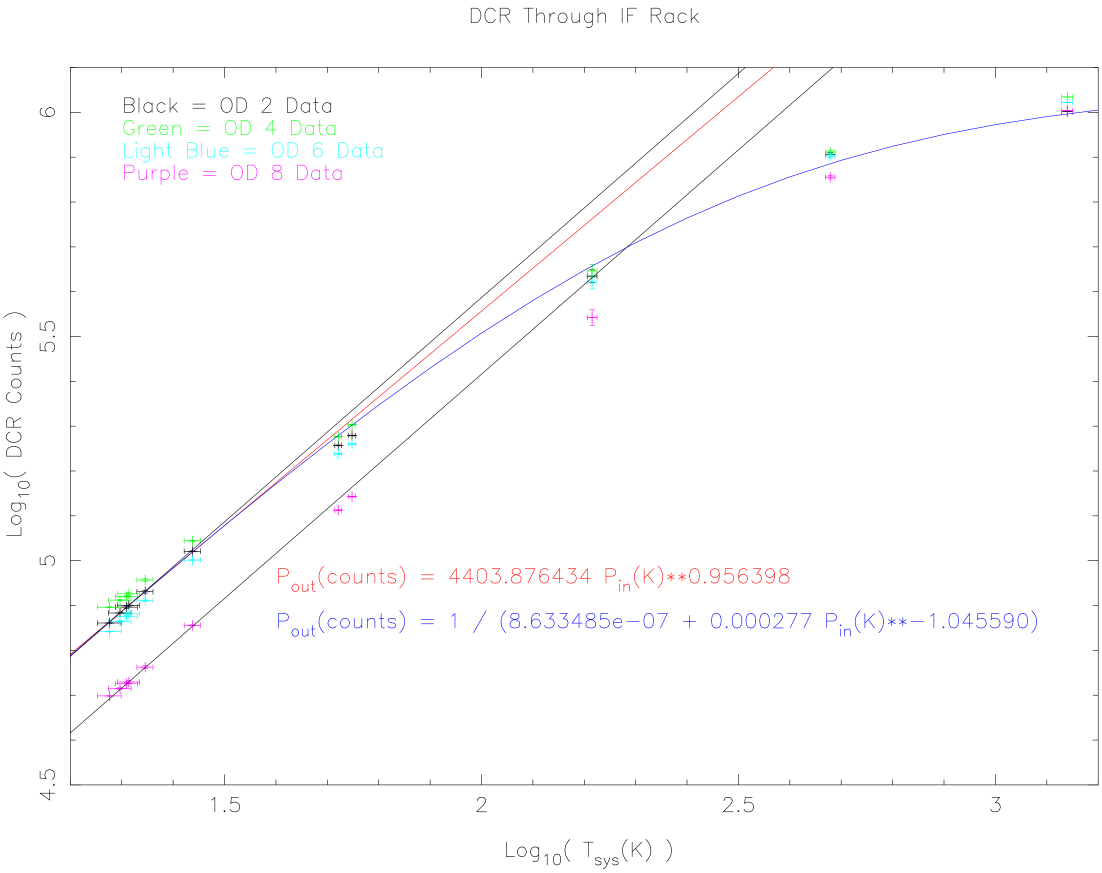


Figure 4: Log-Log plot of DCR counts versus various source's fluxes in Kelvins. The black line is the result expected for a linear gain. The red line is determined from the DCR results of W3(OH) and 3C 84 + 1° Dec for the Optical Driver 2 data. **Note that the red line is not linear.** The blue line is a "χ-by-eye" fit to the same data.

Our first test was to see if the DCR exhibited a non-linear response when observing sources of varying strength. We took data at the positions listed in Table 1. The results are shown in Figure 4. As can be seen from Figure 4 the slope of the DCR counts vs. input power does not have a slope of one as would be expected for a constant gain. **This indicates that the gain is indeed non-linear even for changes of a few Kelvin at the system temperature of even our best receivers ($\sim$ 20 K).** This also indicates that the non-linearity does not arise in the receivers since it is seen from both the X-band and the C-band receivers.

Another test that we did was to observe one source continually while we varied the attenuation in the IF Rack. This was done to see if the DCR responded linearly with the change in power coming through the IF Rack attenuators. We tracked 3C 274 (Virgo A) and balanced the IF Rack to 1 Volt in each of the RF power samplers for Optical

Source Name	5.0 GHz Flux (Jy)	$T_{ant} = T_{src} + T_{sys}$ (K)
M1 (Crab Nebula)	$680 \pm 34\ Jy$	1360 ± 69
M1 + 1° Dec	–	20.4 ± 1
3C 123	16.32 ± 0.816	52.6 ± 2.7
3C 123 + 1° Dec	–	18.9 ± 1
3C 84	18.0 ± 0.9	56.0 ± 2.8
3C 84 + 1° Dec	–	19.8 ± 1
W3(OH)	1.1 ± 0.8	22.2 ± 2.7
W3(OH) + 1° Dec	–	20.6 ± 1
Orion A	457 ± 10	934 ± 21
3C 274 (Virgo A)	72.1 ± 3.6	164.2 ± 8.2
3C 274 + 1° Dec	–	27.4 ± 1

Table 1: Source Fluxes. The Off source fluxes were determined from the DCR Tool which does not take into account any non-linearity. An artificial error of 1 K is thus assumed for these values. A system temperature of 20 K was assumed for the on source T_{ant} values.

	IF Rack Attenuation			
Scan	OD 2	OD 4	OD 6	OD 8
19	13	12	10	15
20	10	9	7	12
21	7	6	4	9
22	4	3	1	6
23	1	0	0	3

Table 2: Attenuation settings for optical drivers during TGBT01A_004_08 tests with the DCR signals coming from the IF Rack.

Driver paths 2, 4, 6 and 8. We then added 3 dB to all IF Rack attenuators (bringing each RF power sampler down to about 0.5 Volts). We then fired the hi cal (~ 32 K) and took data with the DCR being input from the IF Rack at several different attenuator settings which are listed in Table 2.

The results are plotted in Figure 5. We have plotted the gain ratio from Equation 5 versus the relative change in input power (i.e. $dB(scan\ n) - dB(scan\ 19)$). As can be seen in Figure 5 the gain ratios are not one – indicating that the DCR response is non-linear with the change in attenuation setting. **This suggests that the observed non-linearity in the system comes after the IF Rack attenuators.**

We can also see from Figure 5 that we have sent the DCR into strong gain compression for the last sets of values. Further investigations are warranted to determine exactly when the DCR goes into gain compression. This is critical when observing very bright continuum sources.

3.2 DCR Through The Analog Filter Rack

Next we decided to repeat the above experiment of changing the IF Rack attenuation with the DCR signals coming from the Analog Filter Rack (AFR). If the same non-linearities are seen as when the DCR signals come from the IF Rack then we can narrow down where the non-linearities enter the system to be between the IF Rack attenuators and the directional coupler between the IF Rack DCR V/F path and the Optical Fibers.

The signals were sent down Optical Drivers 2, 4, 6 and 8. Each signal was split in the Converter Rack into two exact copies. These eight signals were then feed to the DCR and the spectrometer at the same time. Splitting the signals in this way will allow us to determine if there are any non-linearities after the Converter Rack splitter.

The DCR was feed eight signals into ports 9 – 16 in its Rack B input. The spectrometer was feed the same

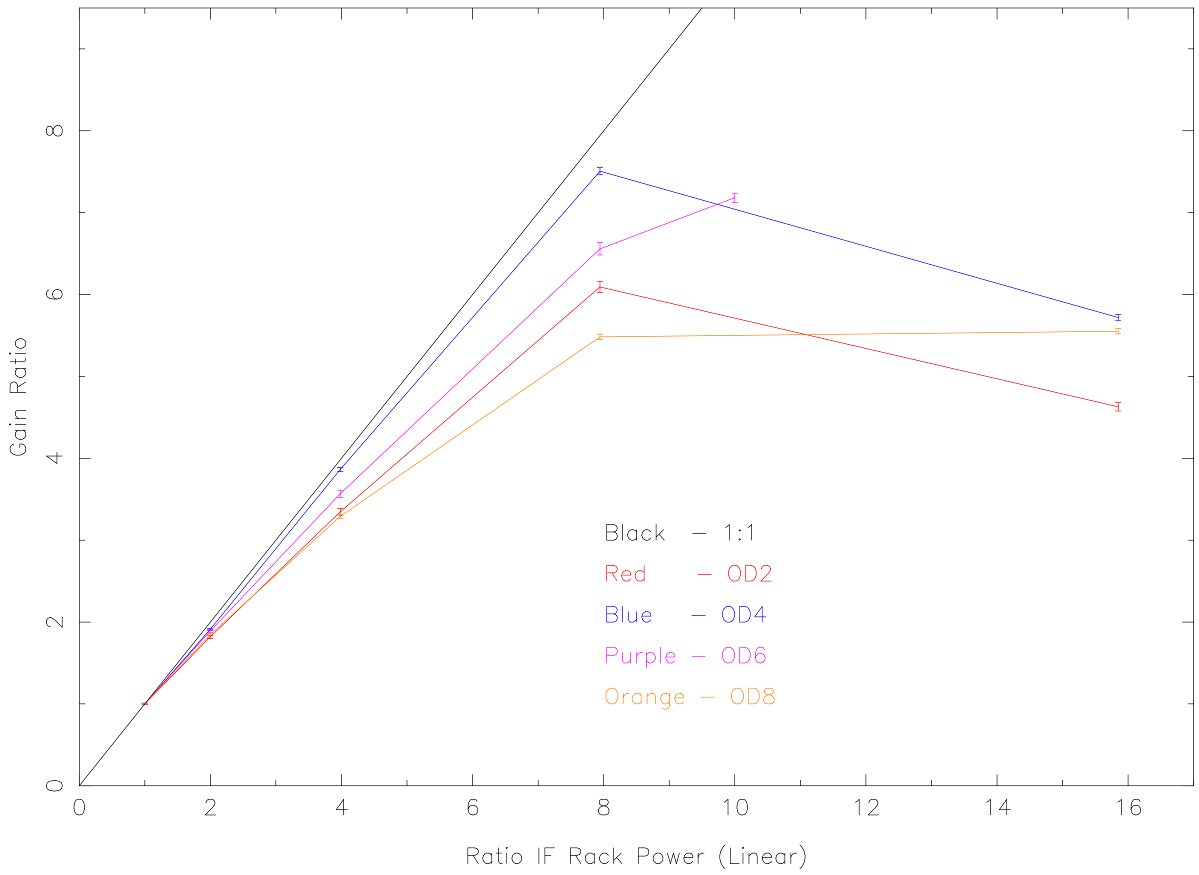


Figure 5: Gain ratios versus relative input power for the DCR signals coming from the IF Rack. 3σ errors are shown. The black line is the expected result for a linear system response.

	IF Rack Attenuation			
Scan	OD 2	OD 4	OD 6	OD 8
28	12	12	10	17
29	15	15	13	20
30	18	18	16	23
31	9	9	7	14
32	6	6	4	11

Table 3: Attenuation settings for optical drivers during TGBT01A_004_08 tests with the DCR signals coming from the Analog Filter Rack.

8 signals and was setup in its A1B1C1D1 mode with 50 MHz bandwidth, 2 samplers per bank, and 9–level sampling (1N2-XX-50-9 modes). The relative data paths are shown in Table 4.

We tracked 3C 274 (Virgo A) and balanced the IF Rack to 3 Volts in each RF power samplers for Optical Driver paths 2, 4, 6 and 8. After the IF Rack was balanced to 3 Volts the Spectrometer was balanced. Again the hi cal was used and data was taken at several different attenuator settings which are listed in Table 3.

The results are plotted in Figure 6 where we have again plotted the gain ratio from Equation 5 versus the relative change in input power (i.e. $dB(scan\ n) - dB(scan\ 30)$). As can be seen in Figure 6 the gain ratios are not one – indicating that the DCR response is again non-linear. In this case we have not driven the DCR into gain compression. This is likely due to the extra attenuation that was provided in going through the Optical Fiber system, the Converter Rack and the Analog Filter Rack (i.e. the real input power to the DCR was less than

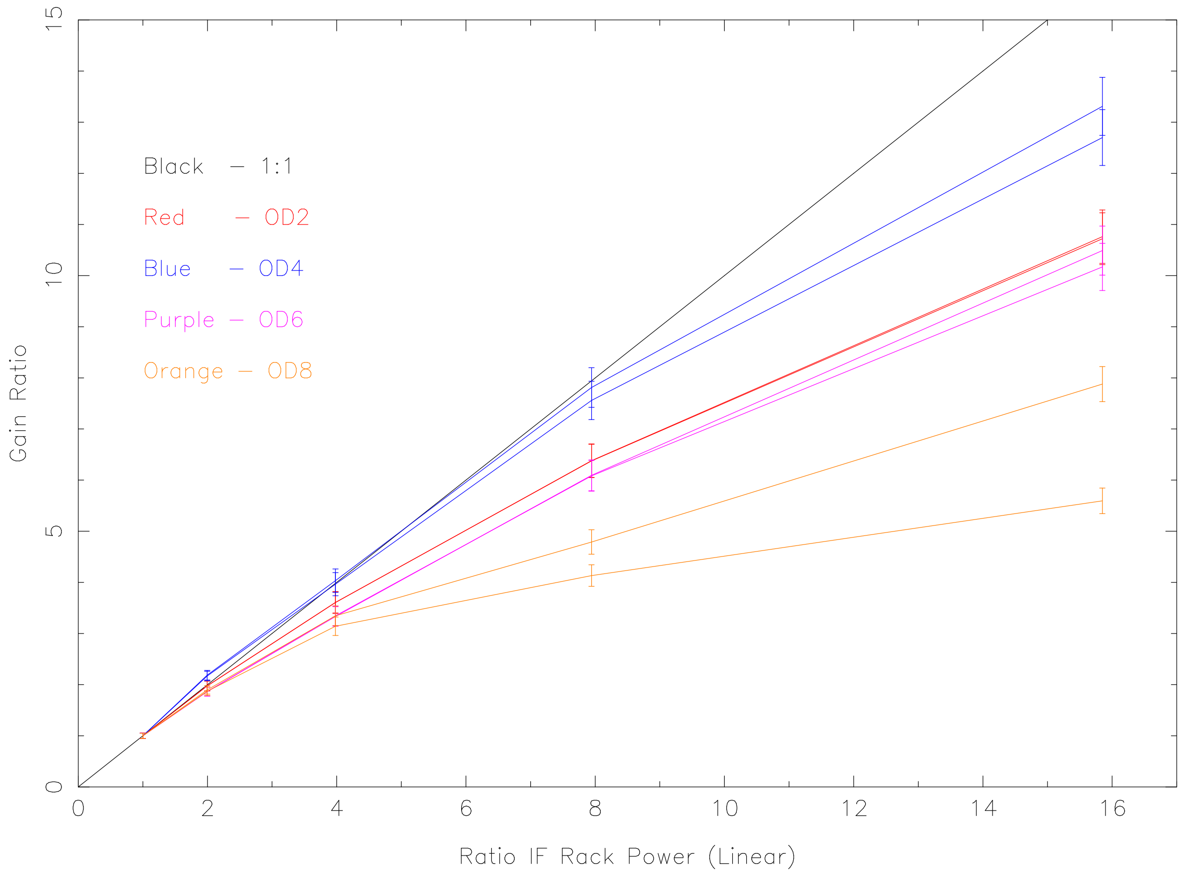


Figure 6: Gain ratios versus relative input power for the DCR signals coming from the Analog Filter Rack. 3σ errors are shown. The black line is the expected result for a linear system response.

Receiver Polarization	Optical Driver	DCR_IF Sampler	Converter Module/Filter	DCR_AFR Sampler	Spectrometer Sampler
XL:1	2	A 2	1	B 9	J9
YR:1	4	A 4	5	B 11	J13
XL:1	2	–	3	B 10	J17
YR:1	4	–	7	B 12	J21
XL:2	6	A 6	9	B 13	J25
YR:2	8	A 8	13	B 15	J29
XL:2	6	–	11	B 14	J33
YR:2	8	–	15	B 16	J37

Table 4: IF Paths for the Spectrometer and the DCR_ACF tests.

before).

From Figure 6 we see that the data match within the error bars for signals split in the Converter Rack that came down Optical Drivers 2, 4, and 6. This suggests that these paths are not adding any dominant non-linearities to the system. Since the lines are separated in the same direction for the different paths after the Converter Rack split we suggest further tests to obtain lower error bars to check for smaller non-linearities.

However, From Figure 6 we see that the data that came down Optical Driver 8 do show significant differences. This suggests that some significant non-linearity exists in one of the following components: CM13, CM15, CF13, CF15, DCR B 15, and DCR B 16. We can rule out the LO2 and LO3 mixes as the source of this non-linearity since they are not seen in the data from Optical Driver 6 which were mixed with the same LO2 and LO3 signals.

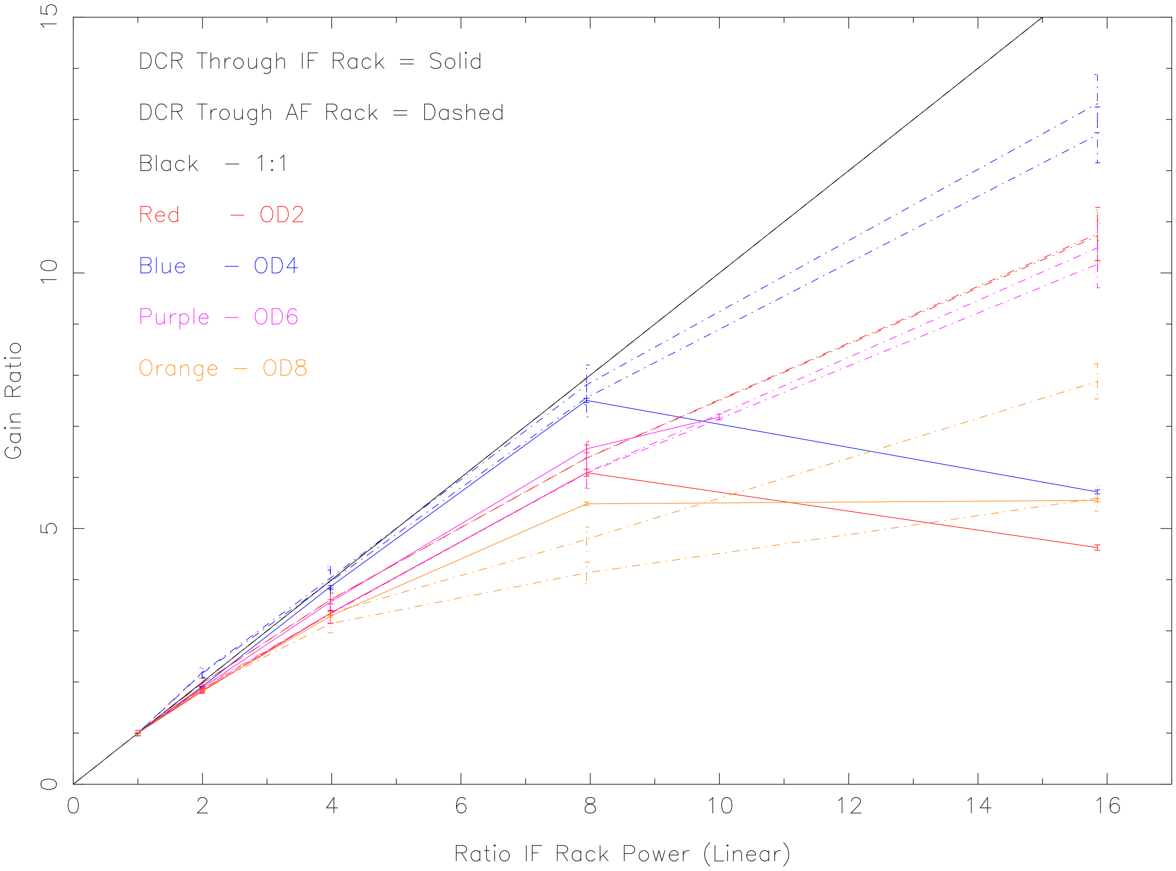


Figure 7: Gain ratios versus relative input power for the DCR signals coming from the IF Rack and the Analog Filter Rack. 3σ errors are shown. The black line is the expected result for a linear system response.

In Figure 7 the gain ratios from the DCR through the IF Rack are compared with the DCR through the Analog Filter Rack. For signals going down Optical Drivers 2, 4 and 6 we see that the data agree fairly well. (Recall that the AFR data has more attenuation and does not put the DCR into gain compression.) This suggests that the major contribution to the non-linearities is generated before the directional coupler in the Optical Drivers in the IF Rack and after the attenuators in the IF Rack.

However, we see from Figure 7 that the Optical Driver 8 data do not agree very well between the DCR through the IF Rack and the Analog Filter Rack. This suggests that Optical Driver 8 may contribute to the non-linearity of the system. However, from Figure 4 we note that the data from the DCR coming from Optical Driver 8 in the IF Rack does not have the same shape as for the other Optical Drivers. The problem may well lie ahead of the optical fibers.

If we take the ratio of the gain ratio for data coming down Optical Drivers 2 and 6 with the DCR signals coming from the IF Rack and then the Analog Filter Rack we can check to see if there is any possible non-linearity in the IF system after the IF Rack directional couplers (i.e. the optical fiber and downstream). These ratios are shown in Figure 8. Although the error bars overlap, it would appear that there could be some non-linearity in and downstream of the optical fibers. This is based on the fact that every data point is less than one for the DCR through the IF Rack and is greater than one for the DCR through the Analog Filter Rack. Further tests are obviously needed.

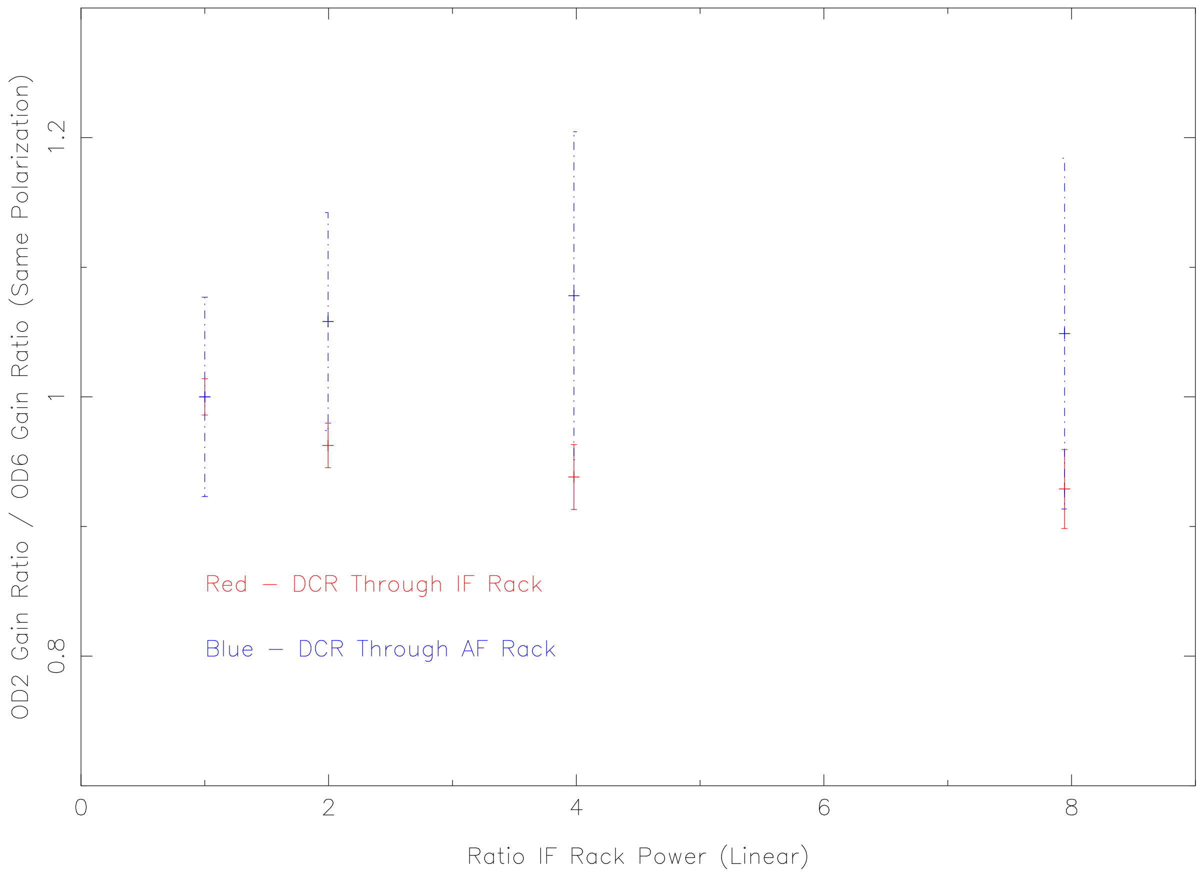


Figure 8: Comparison of DCR IF Rack non-linearity with DCR AFR non-linearity. 3σ errors are shown.

3.3 DCR-AFR Spectrometer Comparison

In order to check that the non-linearities were not occurring in the DCR only, we ran the spectrometer at the same time that we took data with the DCR signals coming from the Analog Filter Rack. In Figures 9, 10, 11, and 12 we plot the gain ratio measured in the spectrometer versus the gain ratio found in the DCR. Recall that the DCR values should be considered averages over frequency of the spectrometer results. We see that the spectrometer gain ratios agree extremely well with the DCR gain ratios. The spectral response of the non-linearities is flat for all but the highest input powers. It thus appears that the DCR is not responsible for the observed non-linearities.

4 A Possible Non-Linear Calibration Scheme

From Figure 4 we see that the DCR counts are tending to approach an asymptotic value as the source strength increases. The gain curve can then be approximated as

$$P_{\mathrm{out}}(\mathrm{counts}) \sim \frac{1}{\epsilon + \beta\,[\mathrm{P_{in}(K)}]^{-\delta}} \tag{6}$$

or

$$P_{\mathrm{in}}(\mathrm{K}) \sim \frac{1}{\mathrm{B}\,[\mathrm{P_{out}(counts)}]^{-\gamma} - \mathrm{A}} \tag{7}$$

where ϵ,β,δ,A,B,and γ are assumed to be greater than or equal to zero. Normal Sig/Ref observations are reduced – assuming a constant gain – using

$$\begin{aligned} T_{src}(K) &= \left(\frac{G\ Sig^{cal\ off}(counts) - G\ Ref^{cal\ off}(counts)}{G\ Ref^{cal\ off}(counts)}\right) T_{sys}^{Ref}(K) \\ &= \left(\frac{Sig^{cal\ off}(K) - Ref^{cal\ off}(K)}{Ref^{cal\ off}(K)}\right) T_{sys}^{Ref}(K) \end{aligned} \qquad (8)$$

where

$$\begin{aligned} T_{sys}^{Ref}(K) &= \frac{T_{cal}}{2}\left(\frac{G\ Ref^{cal\ on}(counts) + G\ Ref^{cal\ off}(counts)}{G\ Ref^{cal\ on}(counts) - G\ Ref^{cal\ off}(counts)}\right) \\ &= \frac{T_{cal}}{2}\left(\frac{Ref^{cal\ on}(K) + Ref^{cal\ off}(K)}{Ref^{cal\ on}(K) - Ref^{cal\ off}(K)}\right). \end{aligned} \qquad (9)$$

Equations 8 and 9 assume $Sig(counts) = G\ T_{Sig}(K)$ and $Ref(counts) = G\ T_{Ref}(K)$ with $G =$ constant.

If we use Equation 7 then Equation 8 becomes

$$T_{src}(K) = \left(\frac{\frac{1}{B[Sig^{cal\ off}(\text{counts})]^{-\gamma} - A} - \frac{1}{B[Ref^{cal\ off}(\text{counts})]^{-\gamma} - A}}{\frac{1}{B[Ref^{cal\ off}(\text{counts})]^{-\gamma} - A}}\right) T_{sys}^{Ref}(K) \qquad (10)$$

which with a little algebra can be shown to be

$$T_{src}(K) = \left(\frac{\left[Ref^{cal\ off}(\text{counts})\right]^{-\gamma} - \left[Sig^{cal\ off}(\text{counts})\right]^{-\gamma}}{[Sig^{cal\ off}(\text{counts})]^{-\gamma} - C}\right) T_{sys}^{Ref}(K) \qquad (11)$$

where $C = A/B$. Putting Equation 7 into Equation 9 and doing little algebra results in

$$T_{sys}^{Ref}(K) = \left(\frac{\left[Ref^{cal\ off}(counts)\right]^{-\gamma} + \left[Ref^{cal\ on}(counts)\right]^{-\gamma} - 2C}{[Ref^{cal\ off}(counts)]^{-\gamma} - [Ref^{cal\ on}(counts)]^{-\gamma}}\right) \frac{T_{cal}}{2} \qquad (12)$$

A fit could be done to Equations 11 and 12 to determine C and γ while allowing the source strength to be $T_{src}(K) = T_o\nu^{\alpha}$.

This scheme has the potential to provide calibrated data on a known temperature scale if γ and C are stable or slowly varying. The data could then be further processed using the "Solomon scheme" to provide good baselines.

If γ and C are stable or slowly varying then it may be possible to periodically observe well known calibration sources – with well defined $T_o\nu^{\alpha}$ to determine γ and C. The values for γ and C determined from the calibrators could then be "blindly" applied to the target observations.

5 Summary

- Optical Drivers 2, 4, 6, and 8 show non-linearities.
- Optical Drivers 2, 4, 6, and 8 show evidence of gain compression.
- Gain compression sets in when using high target levels in the IF Rack.
- The DCR saturates sooner when using the detectors in the IF rack.
- Some Optical Drivers may exhibit gain expansion.
- Non-linearities seem to have common causes of than backends and receivers.

- The most significant non-linearities arise after the IF Rack Attenuators.
- The most significant non-linearities arise before optical fiber – DCR V/F directional coupler in IF Rack.
- Optical Drivers 3 and 8 appear to behave differently than the other Optical Drivers.
- We may be able to calibrate the data with a non-linear calibration fitting scheme.

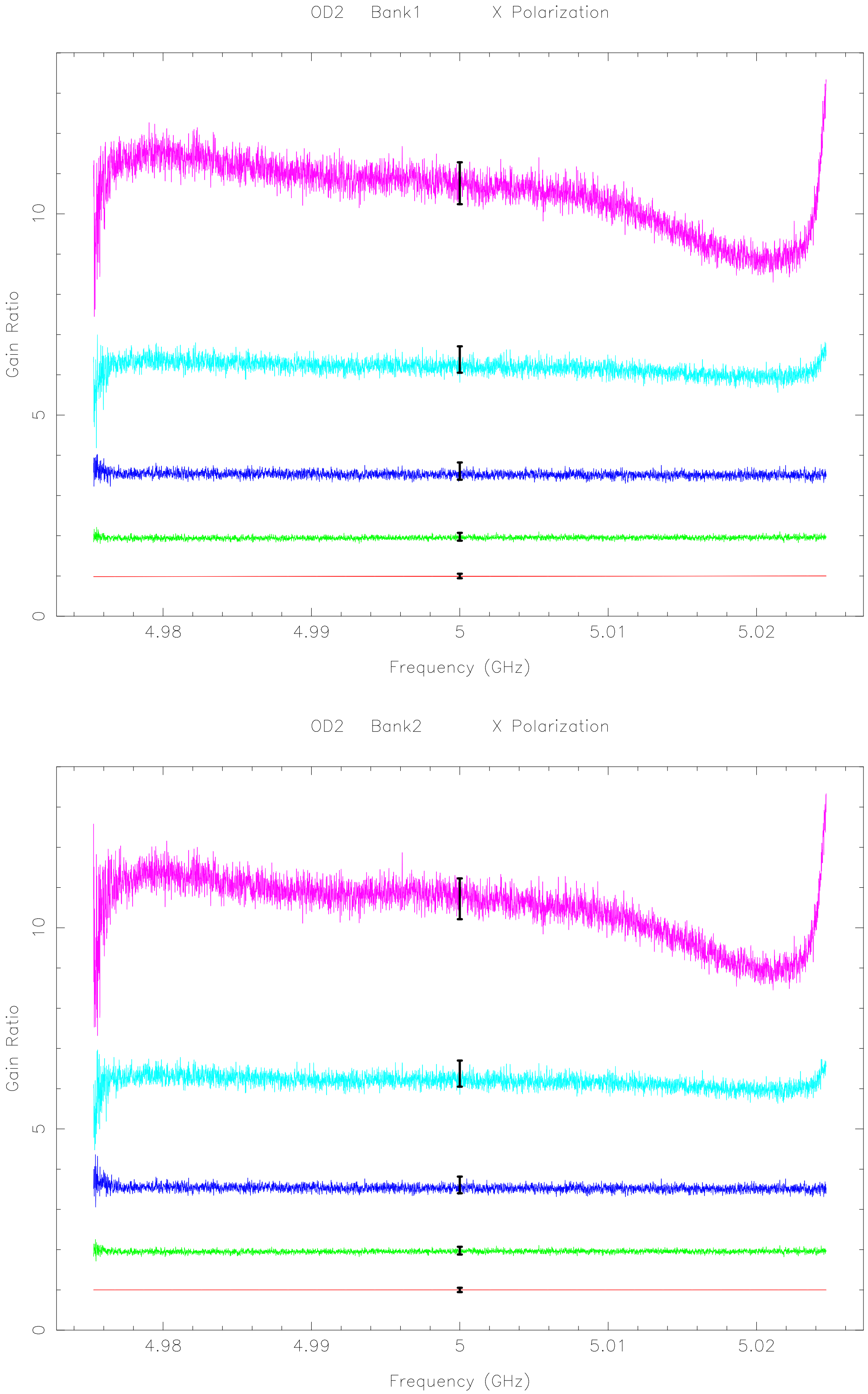
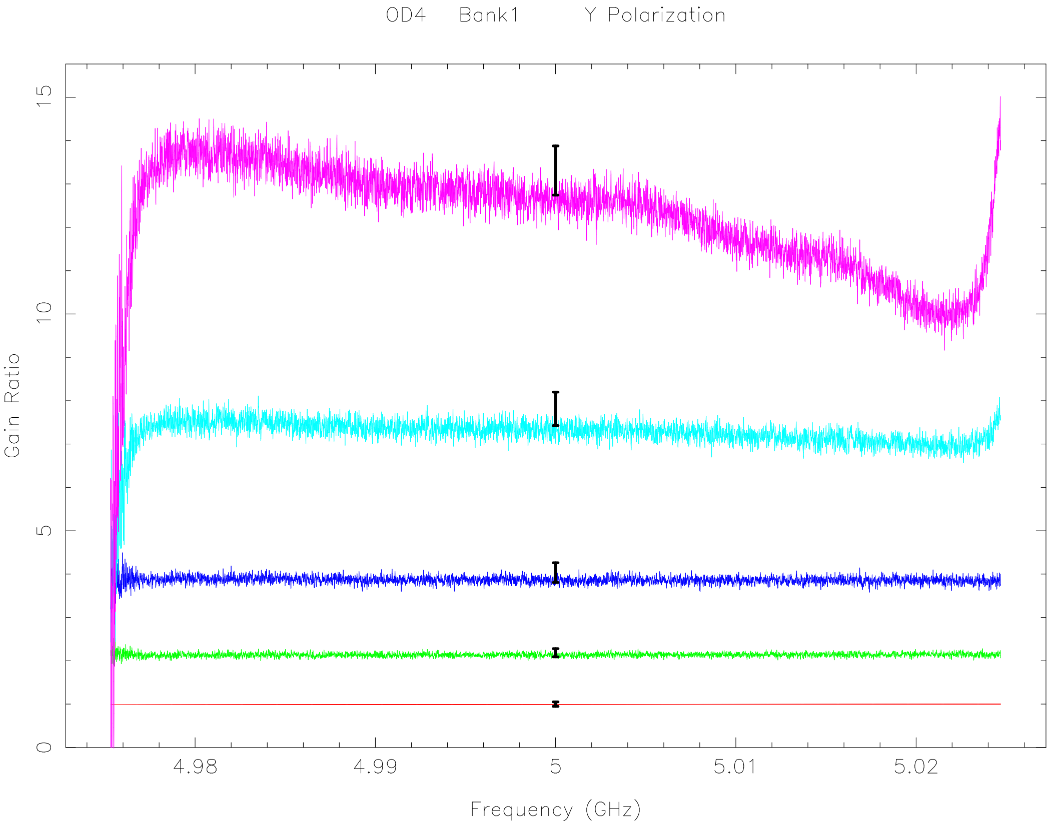


Figure 9: Comparison of Spectrometer gain ratios with DCR AFR gain ratios for data coming down Optical Driver 2. The DCR results with 3σ errors are shown as the black data points. Each colored line represents a different set of attenuation levels (see Table **??**) used to determine the gain ratios. The DCR result should be compared with an average over frequency of the spectrometer results.



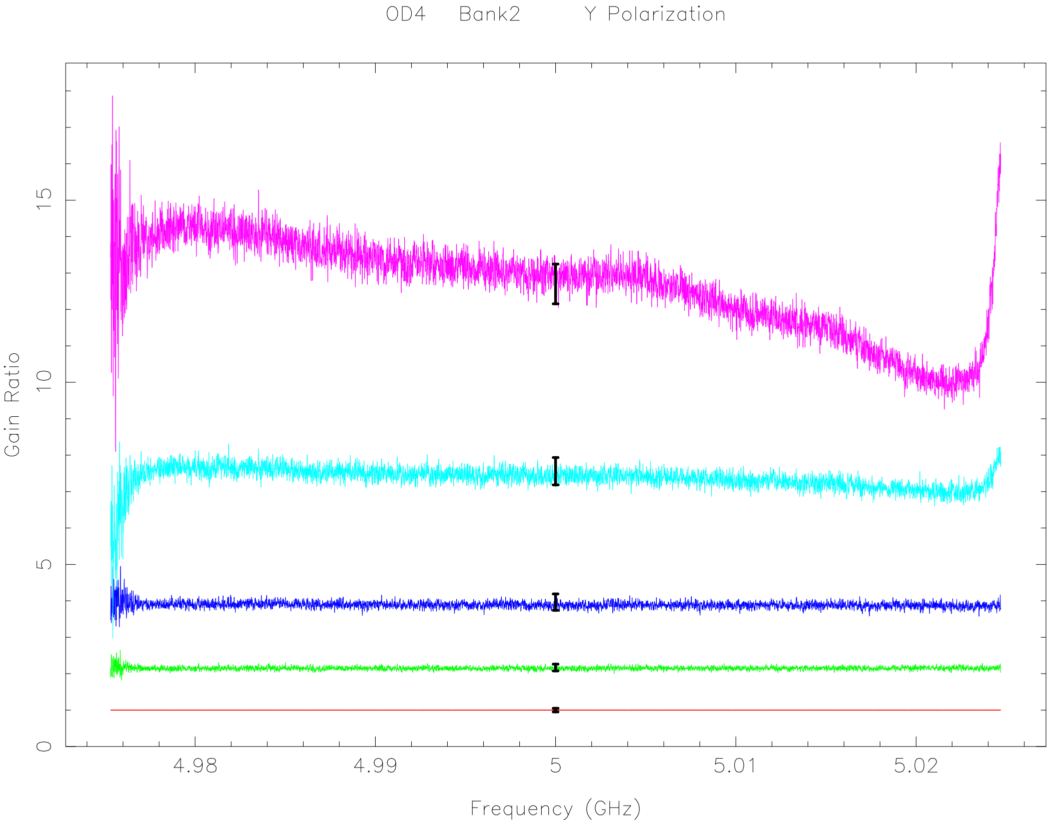


Figure 10: Comparison of Spectrometer gain ratios with DCR AFR gain ratios for data coming down Optical Driver 4. The DCR results with 3σ errors are shown as the black data points. Each colored line represents a different set of attenuation levels (see Table **??**) used to determine the gain ratios. The DCR result should be compared with an average over frequency of the spectrometer results.

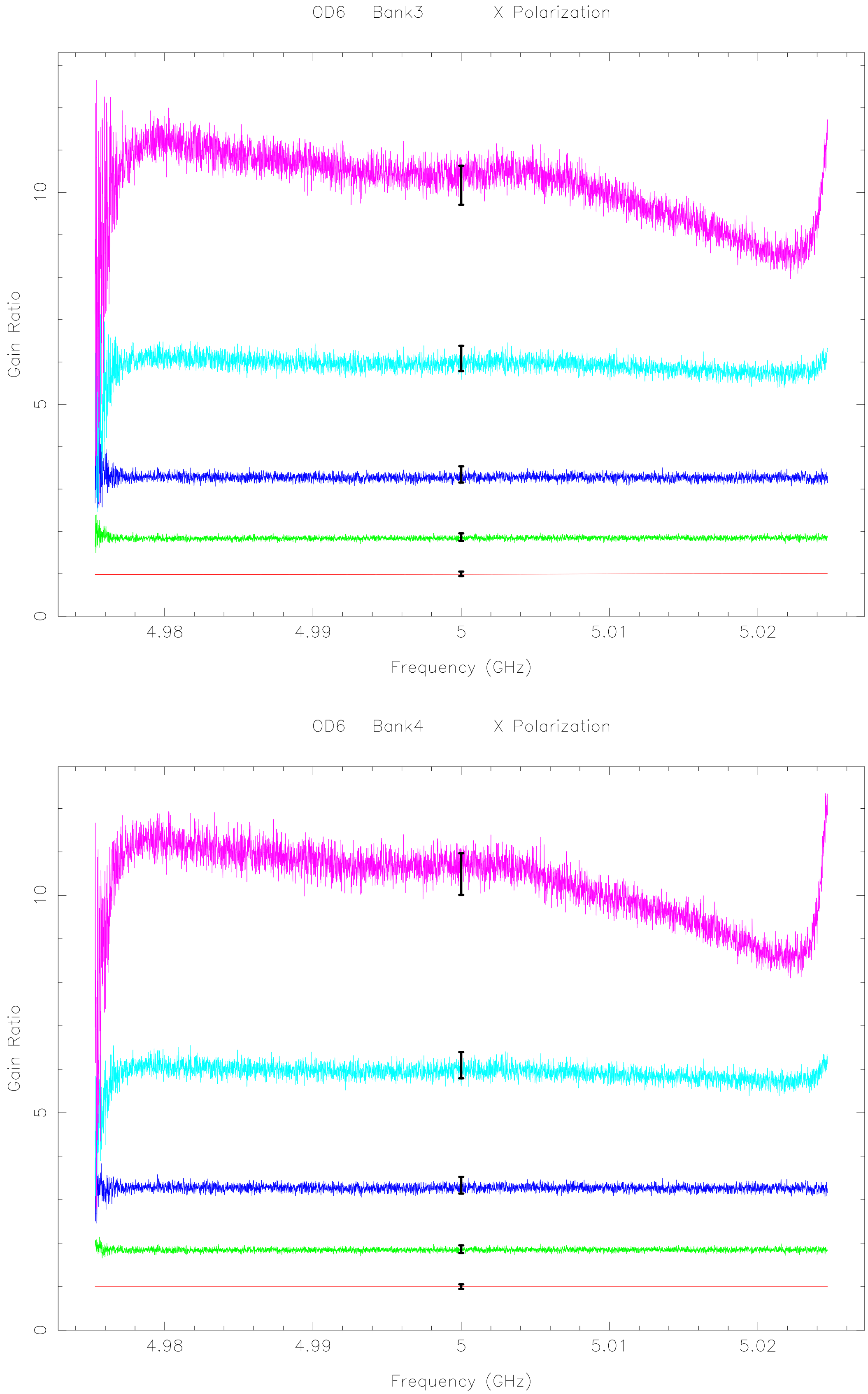
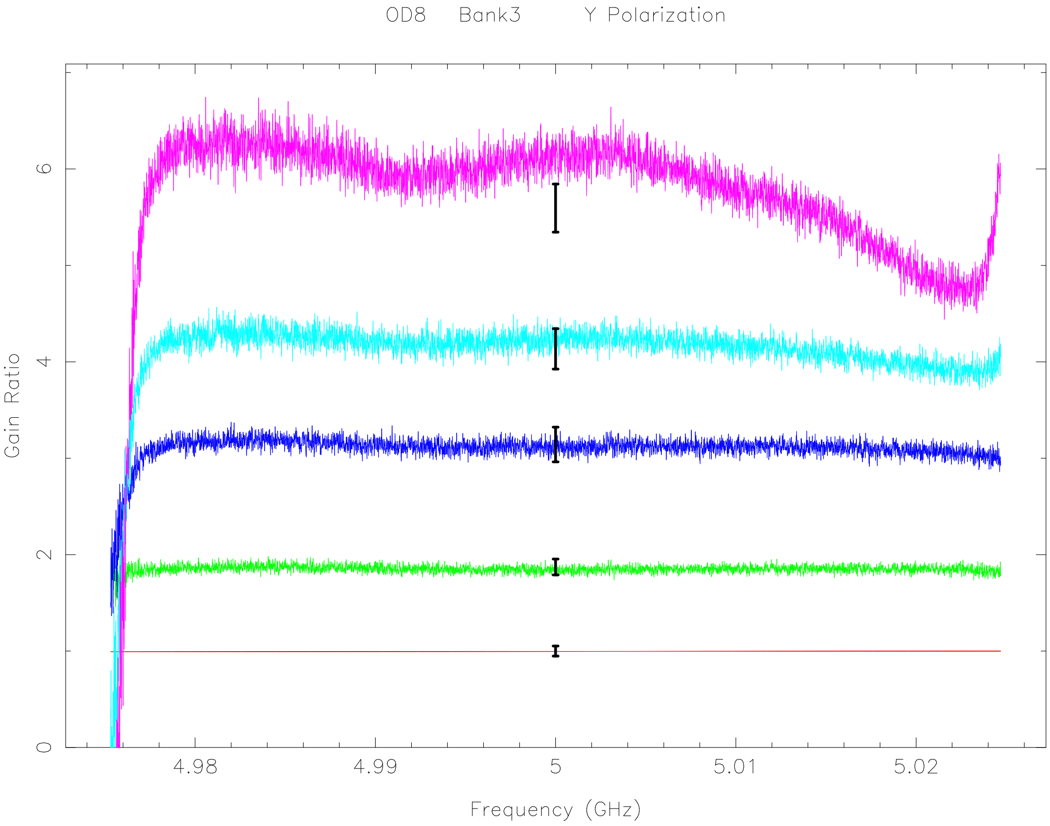


Figure 11: Comparison of Spectrometer gain ratios with DCR AFR gain ratios for data coming down Optical Driver 6. The DCR results with 3σ errors are shown as the black data points. Each colored line represents a different set of attenuation levels (see Table **??**) used to determine the gain ratios. The DCR result should be compared with an average over frequency of the spectrometer results.



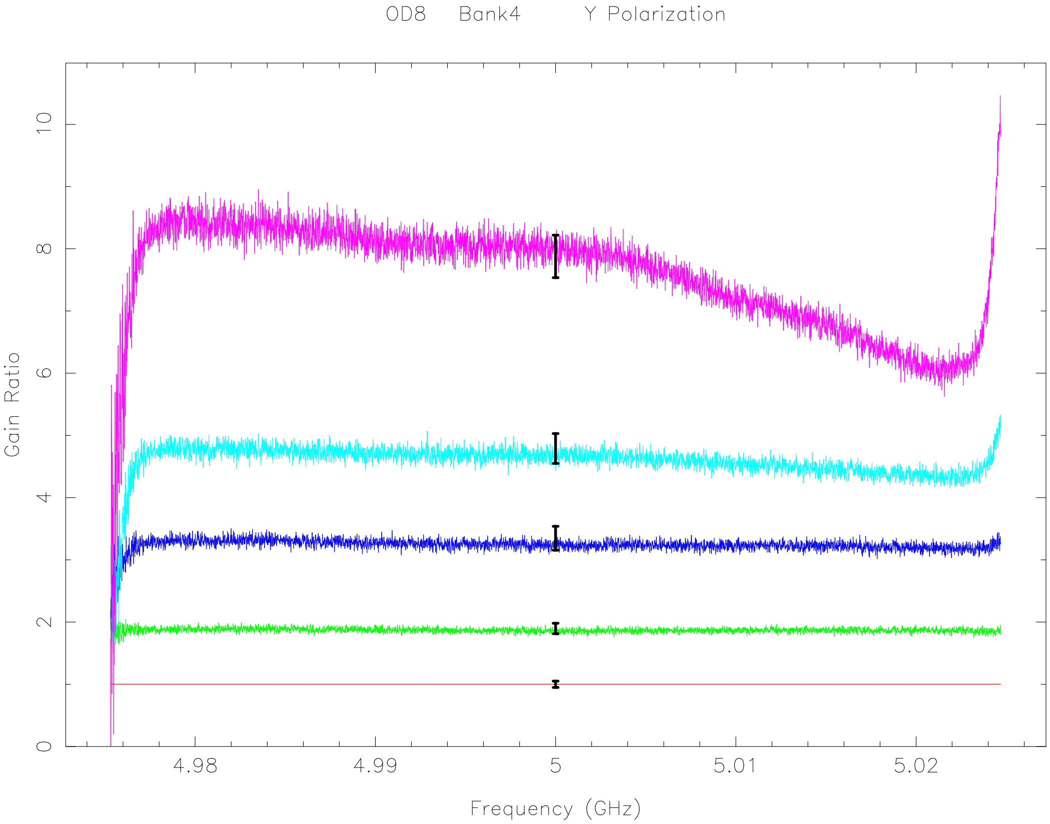


Figure 12: Comparison of Spectrometer gain ratios with DCR AFR gain ratios for data coming down Optical Driver 8. The DCR results with 3σ errors are shown as the black data points. Each colored line represents a different set of attenuation levels (see Table **??**) used to determine the gain ratios. The DCR result should be compared with an average over frequency of the spectrometer results.