Memorandum

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From: John Effland
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Date: 2006-06-01

Rev:

-	2006-05-10	jee	Initial
A	2006-06-01	jee	Changed from gain slope to power density

Subject: Band 6 Cartridge Power Density Slope Correction Using Warm IF Amps

1. Summary

Our previous version of this memo[1] showed cartridge "gain slope" specifications could be met at most frequencies by integrating equalizers into the warm IF amps. Bernard Lazareff reminded us that requirements in the ICD[2] actually apply to the IF power density at the cartridge output, and not overall cartridge gain. Consequently, this version of the memo presents output power density and power density slope when the existing warm IF amps are used and after replacing those with ideal amplifiers with built-in equalizers.

A comparison of specifications to cartridge power density with and without equalization is given in Table 1. Equalization dramatically improves cartridge power density slopes although specifications might not be met at a few frequencies.

Appendix A compares total power calculations to measurements using spectrum analyzers and power meters.

Table 1: Power Density Slope and Output Power Summary

Specifications		**Results (6-10 GHz IF) Entries in bold exceed specs**	
		No Equalizer	**Equalizer in Warm IF Amps**
Power Density Slope, Any 2 GHz	≤ 4 dB P-P	Cart 001: Pol 0: **5.3** dB Pol 1: **9.10** dB Cart 003: Pol 0: **5.2** dB Pol 1: **7.4** dB	Cart 001: Pol 0: 3.1 dB Pol 1: **6.0** dB Cart 003: Pol 0: 2.9 dB Pol 1: **4.4** dB
Power Density Slope, 4 GHz IF band	≤ 6 dB P-P	Cart 001: Pol 0: **9.6** dB Pol 1: **11.7** dB Cart 003: Pol 0: **9.4** dB Pol 1: **11.6** dB	Cart 001: Pol 0: 3.7 dB Pol 1: **7.5** dB Cart 003: Pol 0: 2.9 dB Pol 1: **6.4** dB
IF Power Output (Assumes 300K source)	$P_{min} \geq$ - 40 dBm (min pwr)	Cart 001: Pol 0: -28.4 dBm Pol 1: -24.2 dBm	Cart 001: Pol 0: -30.4 dBm Pol 1: -28.9 dBm
	$P_{max} \leq$ -25 dBm (max pwr)	Cart 001: Pol 0: **-20.7** dBm Pol 1: **-19.5** dBm	Cart 001: Pol 0: -25.9 dBm Pol 1: -25.2 dBm

[1] "Gain Slope Correction Using Warm IF Amps for Band 6 Cartridges," FEND-40.02.06.00-098-A-DSN, Version 2006-05-10.
[2] "Interface Control Document between Band 6 Cartridge and IF Switch Subsystem," FEND-40.02.06.00-40.08.01.00-A-ICD, Version A.v05, 2005-05-04.

2. Calculation of Power Density and Power Density Slope

Cartridge power available in 100 MHz bandwidth was calculated from the following formula:

$$P_{100MHz}(f) = kB[T_{Source} + T_{Rx}(f)]G(f) \qquad \text{Eq. 1}$$

where:

$P_{100\text{MHz}}(f)$	= receiver noise power (W) in 100 MHz bandwidth at cartridge output when observing a load at a temperature of T_{Source} at an RF frequency of *f*.
$T_{Rx}(f)$	= receiver noise temperature (K) at a particular RF
$G(f)$	= cartridge gain at a particular RF
k	= Boltzmann's constant (1.38×10^{-23} W/K-Hz)
B	= equivalent noise bandwidth (approx. 100 MHz)

The source temperature, T_{Source}, is specified in the ICD to be 300K and consequently that temperature is used when testing the receiver. However, the sky temperature is more likely to be ~50K when in operation so analysis below examined the implications of such a lower source temperature.

Cartridge gain, *G(f)*, is calculated by differencing system noise power when the receiver is connected to hot and cold loads and dividing by the difference in the hot and cold load physical temperatures. This is the standard "ΔP/ΔT" technique and implementation details for the Band 6 cartridge are given on ALMA EDM[3].

The power density graphs discussed in Section 5, "Results," plot output power density for each polarization's LSB and USB channels at each LO frequency. Power density calculations span the entire 4–12 GHz IF with bold sections depicting the 6-10 GHz spec band.

As shown in Table 1, the Band 6 cartridge specification has two requirements for gain slope: 1) over any 2 GHz IF sub-band and 2) over the entire 4 GHz IF band. To calculate gain slope over 2 GHz sub-bands, for each LO frequency, absolute values of maximum and minimum gains are subtracted from each other over a 2 GHz bandwidth with sliding center frequency. The result is a locus of gain slope values as the 2-GHz center frequency is slid across the entire IF bandwidth.

The green curves in the gain slope graphs show gain slope calculated over the 2 GHz bandwidth with sliding center frequency. Again, the bold section of each curve identifies the specified 6-10 GHz IF band. The specification for maximum power density over 2 GHz is shown by the green dashed lines at 4 dB.

Power density slope over the entire IF band, formally spanning 6-10 GHz[4], is calculated by subtracting the absolute values of the maximum and minimum gains in this 4 GHz bandwidth. This produces a single power density slope number for each LO frequency as shown by black points in the graphs. Maximum power density specifications over the entire IF band are shown by the black dashed line in the graphs.

3. Total Power Calculations

Total power for the specified bandwidth was calculated for each LO frequency using the following equation:

$$P_{tot} = \sum_{f=6GHz}^{f=10GHz} P_{100MHz}(f) \qquad \text{Eq. 2}$$

[3] "Band 6 Cartridge Test Procedure Noise Performance, Gain, and Gain Slope," FEND-40.02.06.00-076-A-PLA, 2006-04-26, http://edm.alma.cl/forums/alma/dispatch.cgi/iptfedocs/docProfile/101778

[4] Reduced performance is available from 4-12 GHz.

Where: Ptot = total receiver noise power (W) at cartridge output when observing a load at a temperature of T_{Source}

$P_{100MHz}(f)$ = receiver noise power density (W) calculated in Eq. 1

A similar calculation gives total power over the entire 4-12 GHz band. While significant gain exists above 12 GHz and below 4 GHz for the Band 6 cartridge (as shown in Figure 21) measurements described in Appendix A show the power contributions are small.

4. Equalizer Calculations

To predict power density and power density slope when equalizers are built into the warm IF amplifiers, the gain contribution from the warm IF amplifiers installed on the Warm Cartridge Assembly (WCA) was removed from the measured cartridge gain data and the gain of an ideal amplifier with slope correction was added. Table 2 identifies the warm IF amplifiers used with WCA 001, and Figure 1 shows their measured gain.

S-parameters were measured for all warm IF amplifiers so the corresponding s_{21} could be subtracted from the overall cartridge gain for each receiver channel. Afterwards, the gain of an ideal amplifier with gain slope correction was added to each receiver channel. The optimum slope value was determined by minimizing the largest 2-GHz and 4-GHz power density slopes for both polarizations and all intermediate frequencies from 6-10 GHz. The gain of the warm IF amp with integrated equalizer was optimized to meet maximum total power specifications.

The amplifier that minimizes cartridge power density slope has 12 dB of gain slope from 4 to 12 GHz and exhibits the following gain/frequency parameters:

Gain at 4 GHz = 22 dB,
Gain at 12 GHz = 34 dB.

Table 2: Warm IF Amps Installed in WCA 001

Polarization	Sideband	Serial Number
0	USB	0438-104
	LSB	0517-108
1	USB	0523-109
	LSB	0521-110

5. Results

Power density (in 100 MHz bandwidth) *vs*. intermediate frequency for Cartridge 001, polarization 0 is shown in Figure 2 when the existing warm IF amps are used with no equalizers. The IF response for each LO frequency is plotted as overlapping lines in the figures. The darkened lines show gain over the specified 6-10 GHz IF. Figure 3 is the predicted gain response using perfect warm IF amplifiers that include the equalization discussed above. Figure 1 shows that the actual warm IF amplifiers installed in polarization 0 differ in overall gain by about 3 dB. That gain difference is removed when ideal amps are used as shown by the overlapping curves for each sideband in Figure 3. Similar results for polarization 1 are shown in Figure 4 and Figure 5. For polarization 1, the gain of the actual warm IF amps is closely matched.

Power density and slopes for Cartridge 001, polarization 0 are plotted in Figure 6 and the dramatic slope reduction achievable with equalizers is shown in Figure 7. Both 2-GHz and 4-GHz gain slopes meet specifications for this polarization, as shown in Figure 7. However, the power density slope for polarization 1 exceeds specifications by 1.5 dB even with equalizers as shown in Figure 8 and Figure 9, although improvement is significant compared to no equalization.

Power density slopes of a second Band 6 Cartridge, serial number 003, both without and with the same equalizer assumed for Cartridge 001 are shown in Figure 10, Figure 11, Figure 12, and Figure 13. Measurements of that cartridge are limited to course IF frequency spacing, but improvement is similar to the finer-spaced data measured in Cartridge 001.

Total cartridge output power is calculated for polarization 1 in Figure 14 using existing standard warm IF amps and Figure 15 for ideal IF amps with equalization. Figure 16 and Figure 17 show total cartridge power output for polarization 1. The overall gain of the ideal warm IF amplifiers was adjusted to place the Pol 1 power at the maximum power specifications as shown in Figure 17.

Although the total power output specifications assume the receiver looks into a 300K load, the actual temperature on the sky will be closer to 50K. Figure 18 and Figure 19 are the total power output when the source temperature is 50K assuming warm IF amplifiers with equalizers.

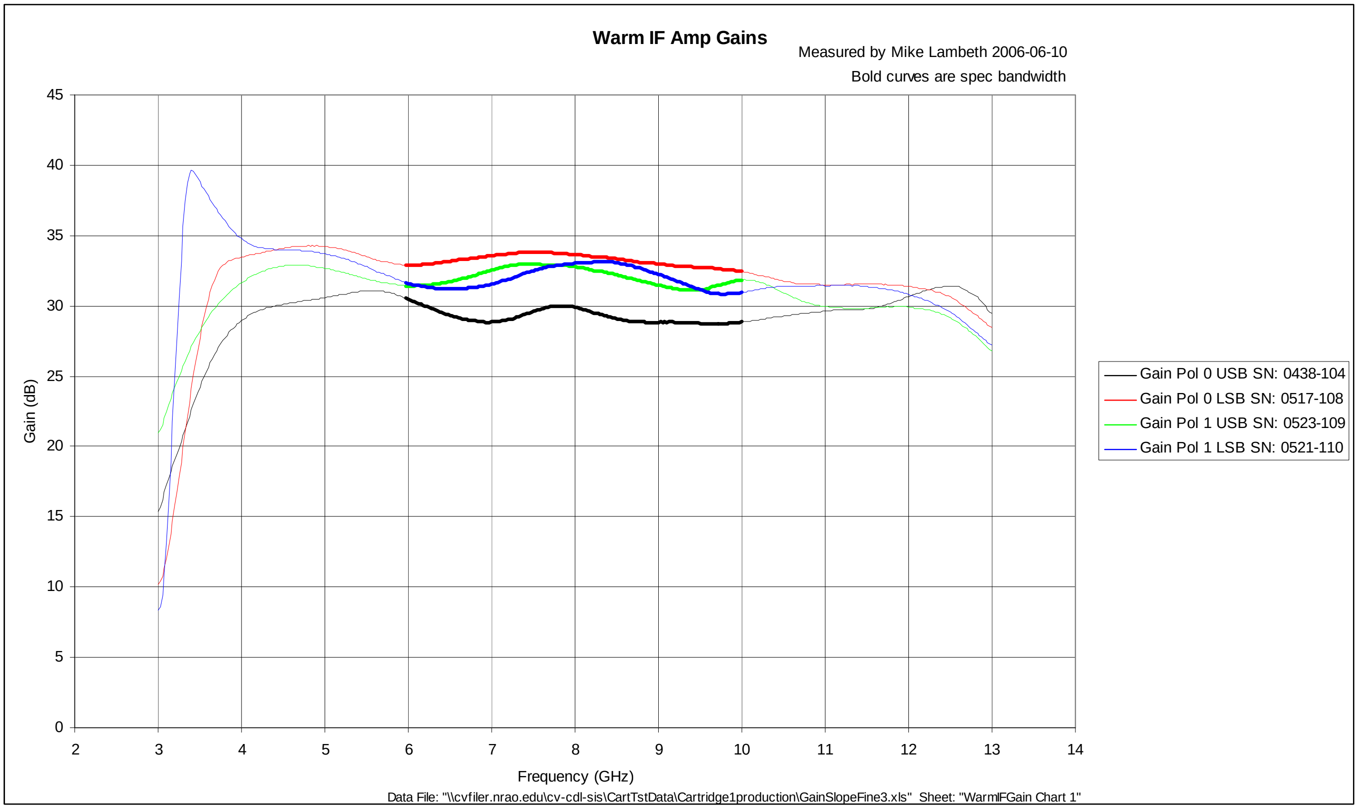

Figure 1: Measured gain of Warm IF amps

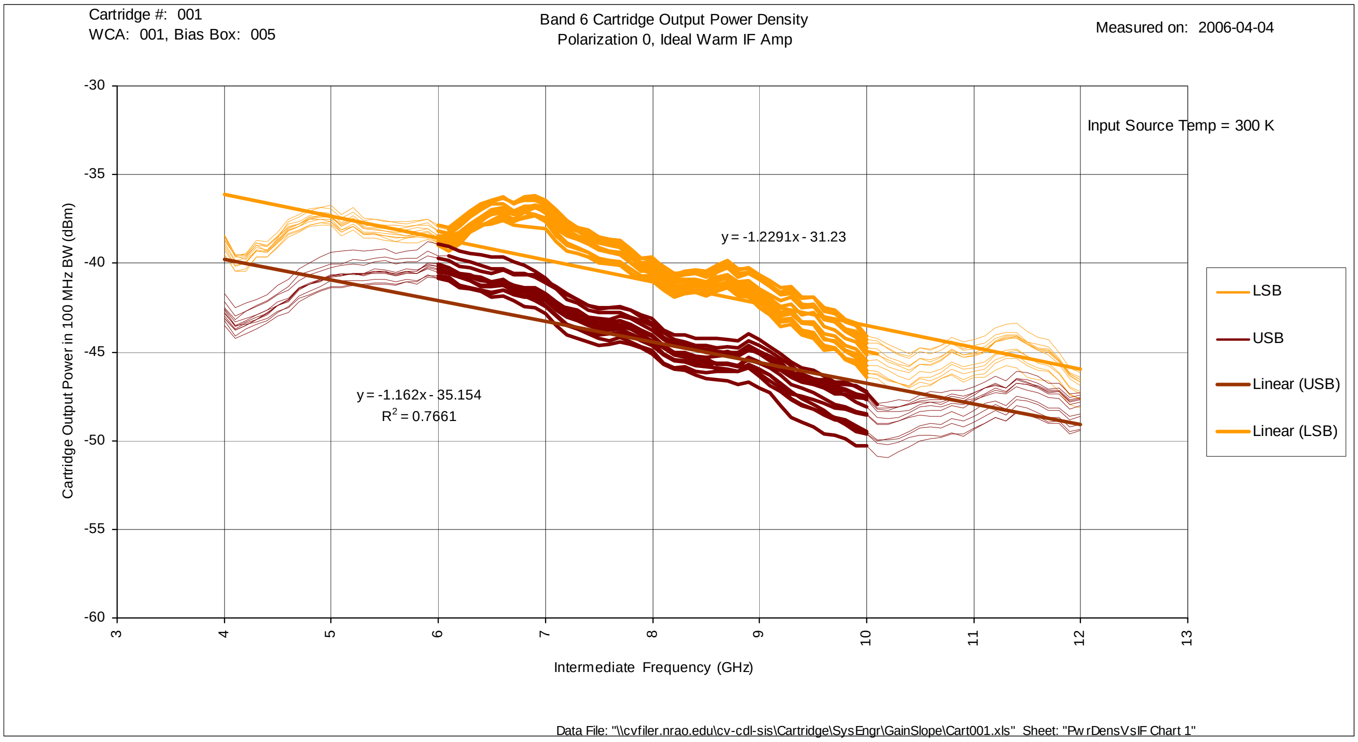

Figure 2: Power Density vs. IF, Cartridge 001, Pol 0 (dark curves are spec bandwidth)

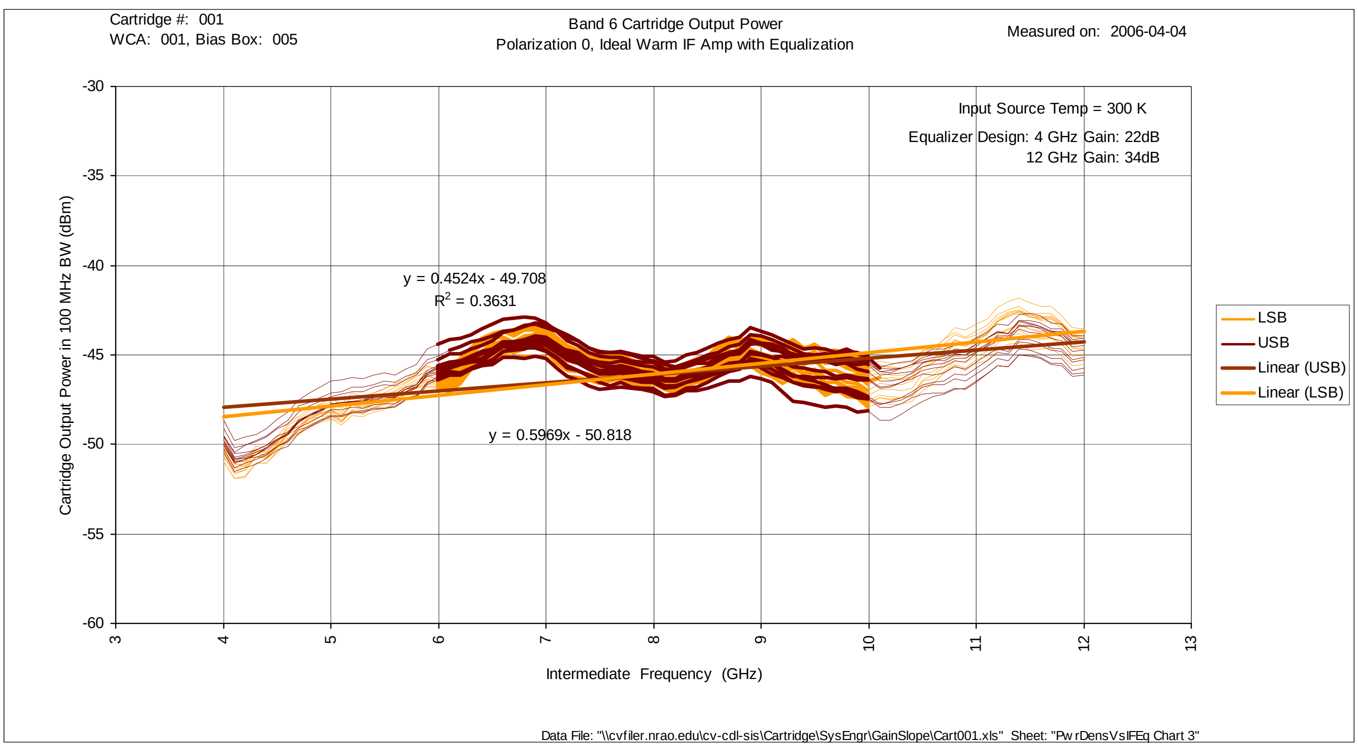

Figure 3: Power Density vs. IF with Equalizer, Cartridge 001, Pol 0

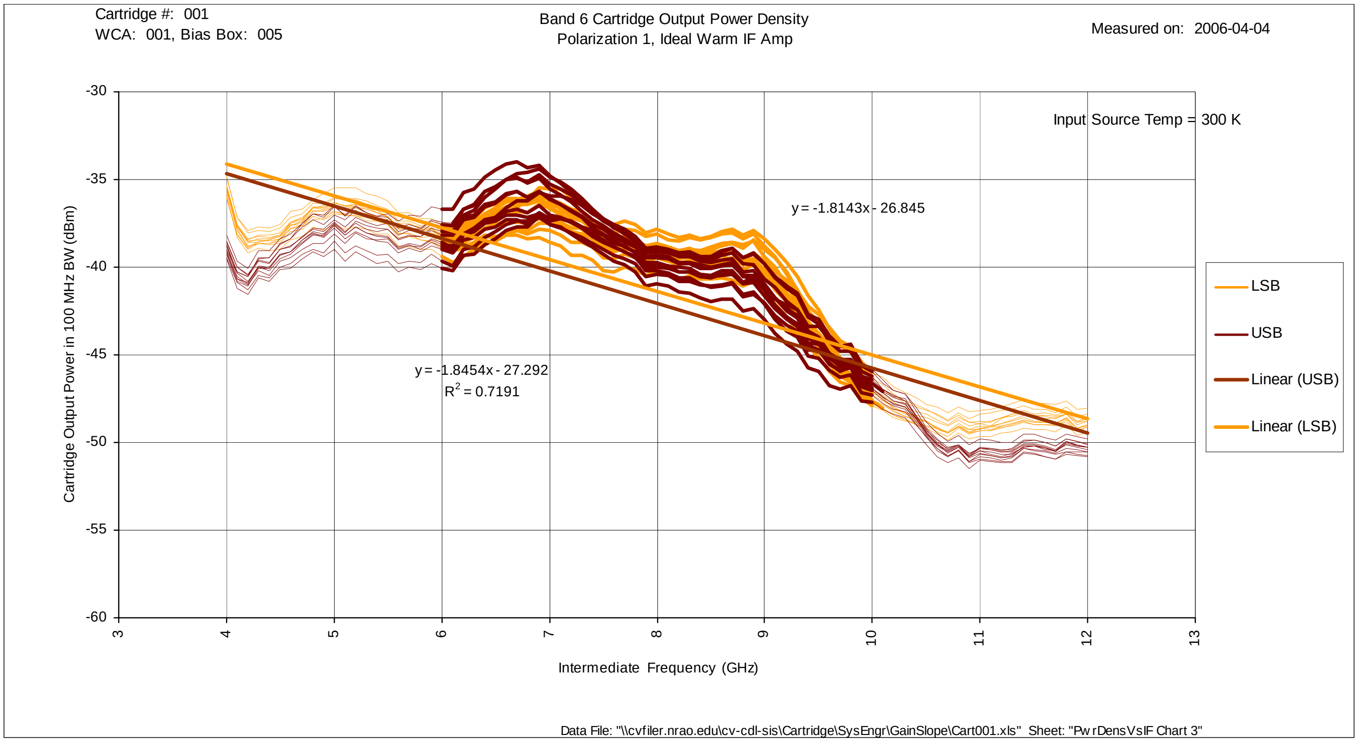

Figure 4: Power Density vs. IF, Cartridge 001 Pol 1

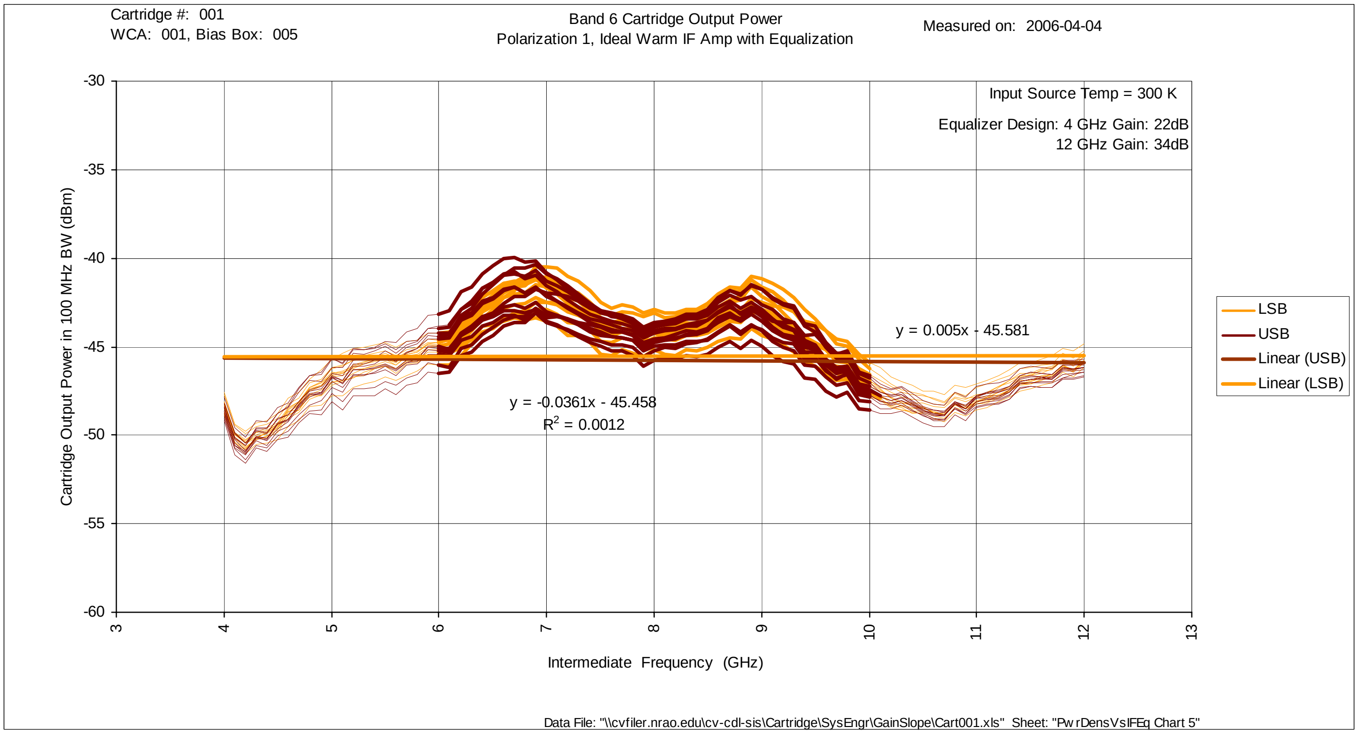

Figure 5: Power Density vs. IF with Equalizer, Cartridge 001, Pol 1

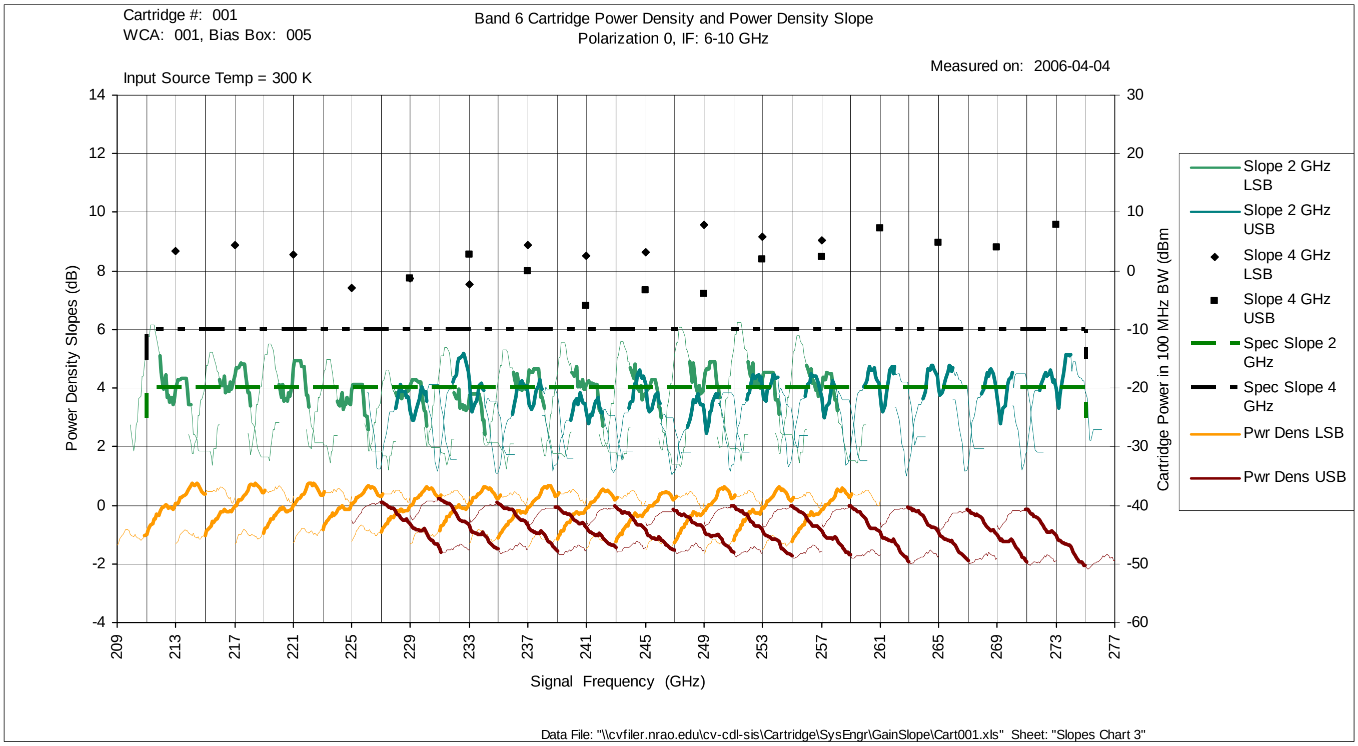

Figure 6: Power Density and Slope, Cartridge 001, Pol 0 (Dark curves are spec bandwidth)

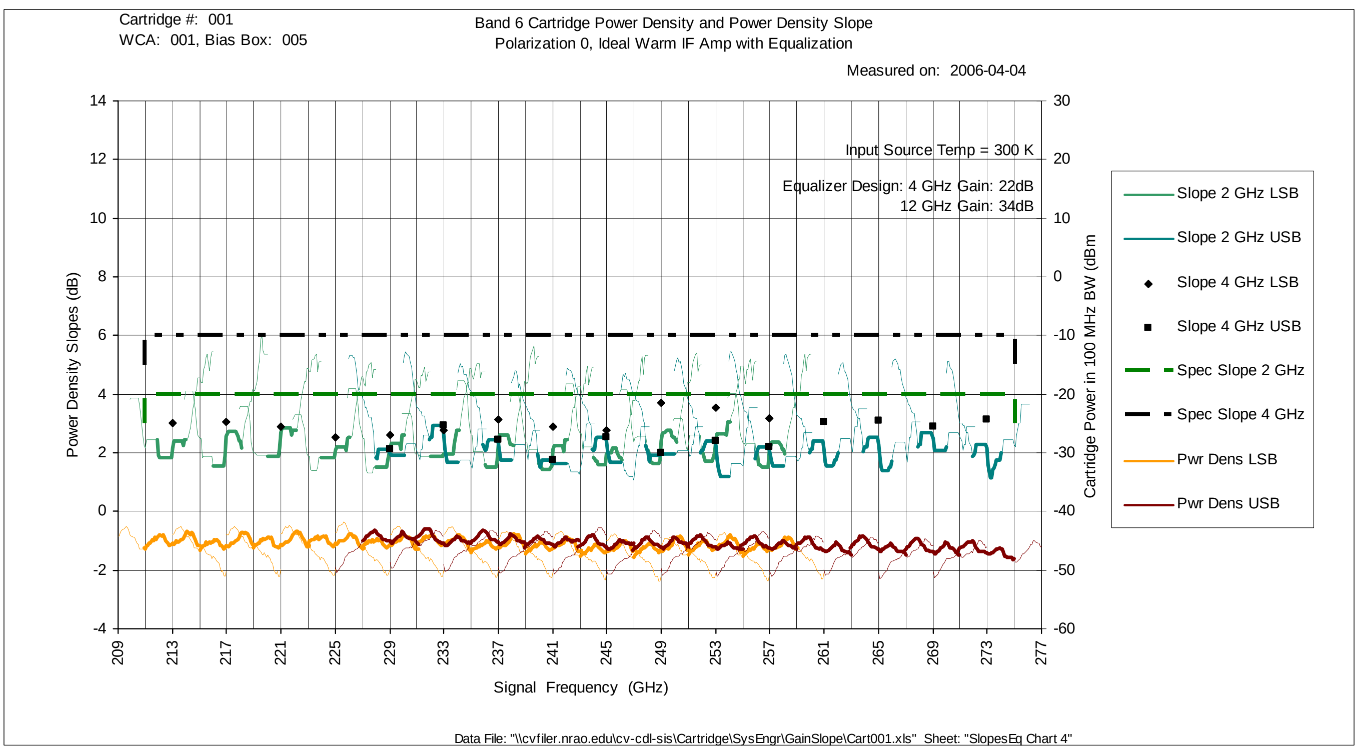

Figure 7: Power Density and Slope with Equalizer, Cartridge 001, Pol 0

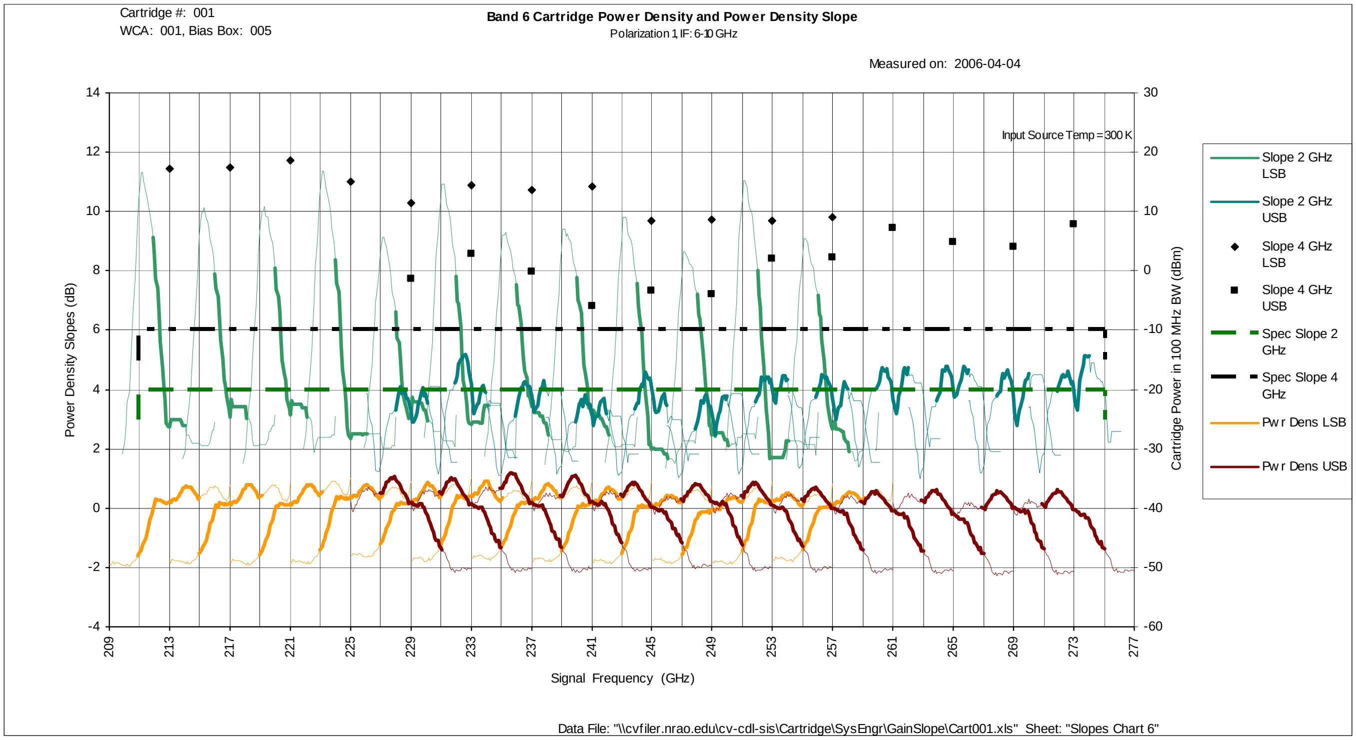

Figure 8: Power Density and Slope, Cartridge 001, Pol 1 (Dark curves are spec bandwidth)

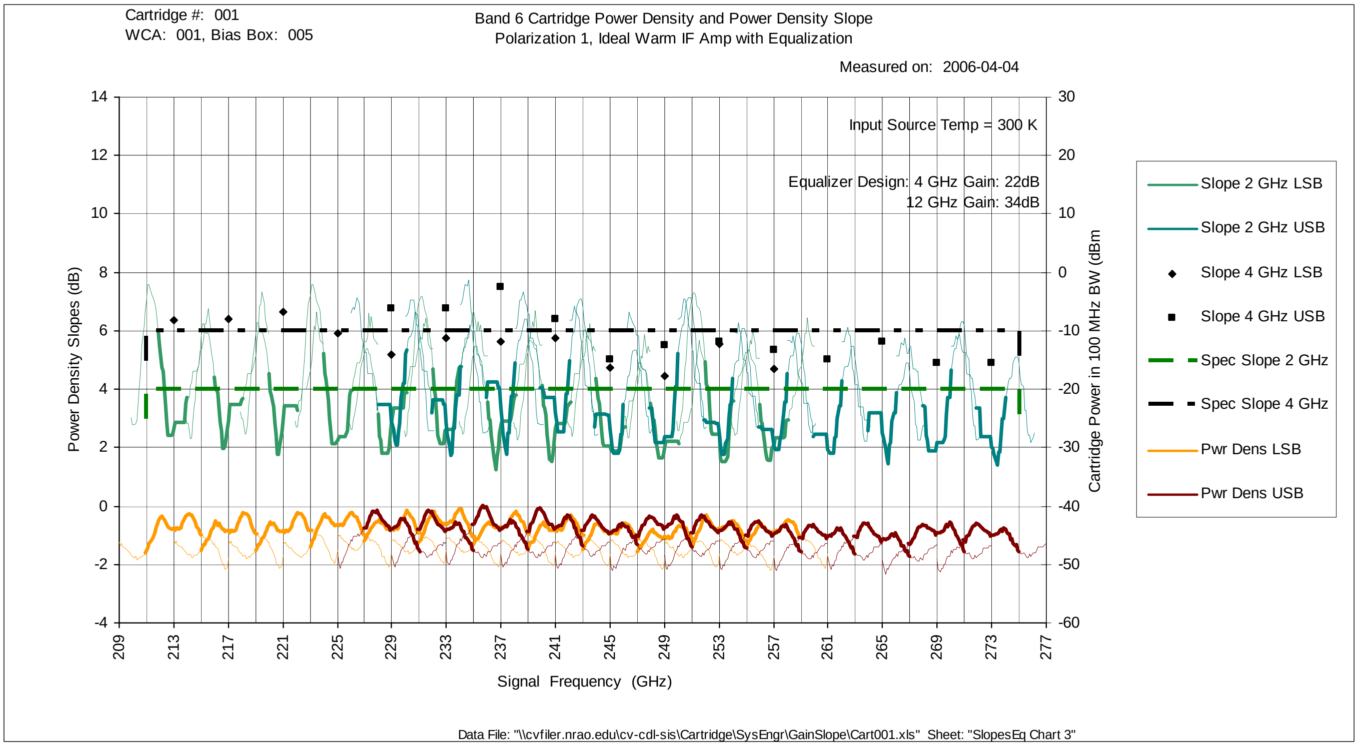

Figure 9: Power Density and Slope with Equalization, Cartridge 001, Pol 1

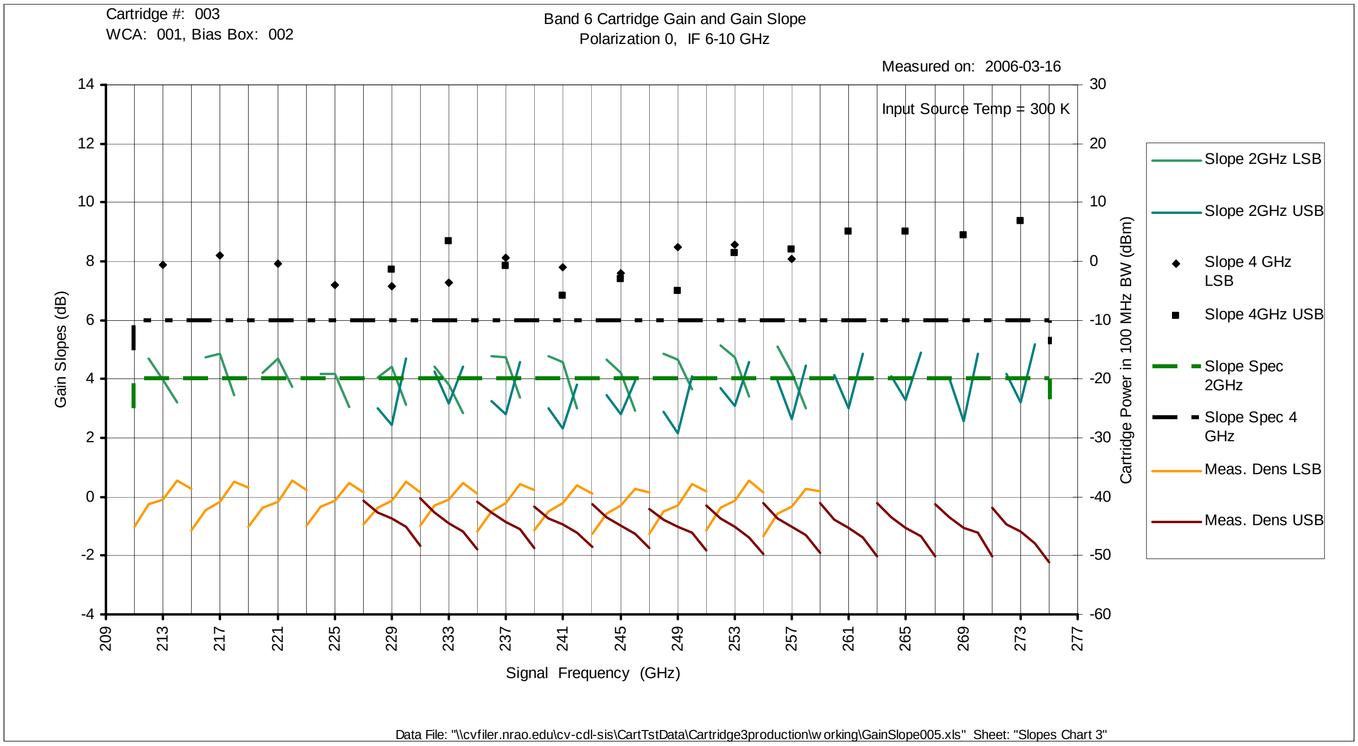

Figure 10: Power Density Slope (6-10 GHz IF), Cartridge 003, Pol 0

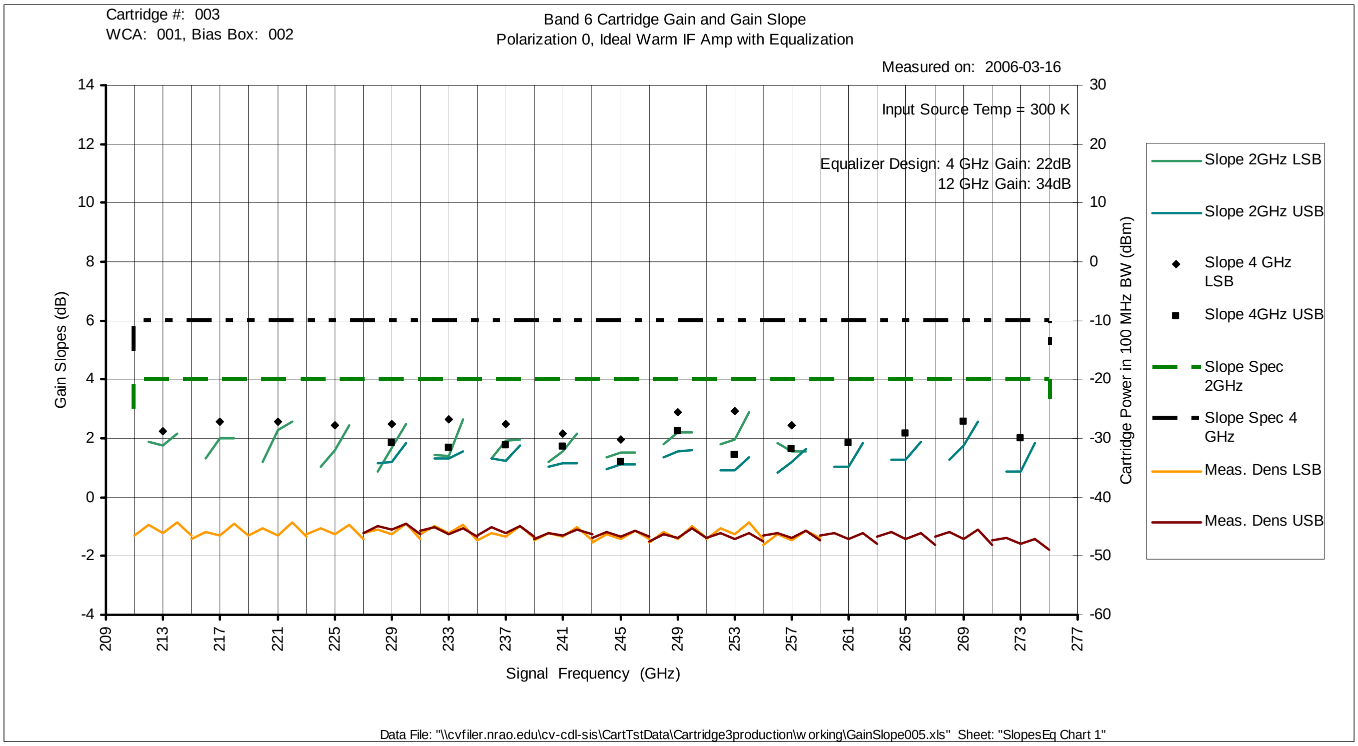

Figure 11: Power Density Slope (6-10 GHz IF) with Equalization, Cartridge 003, Pol 0

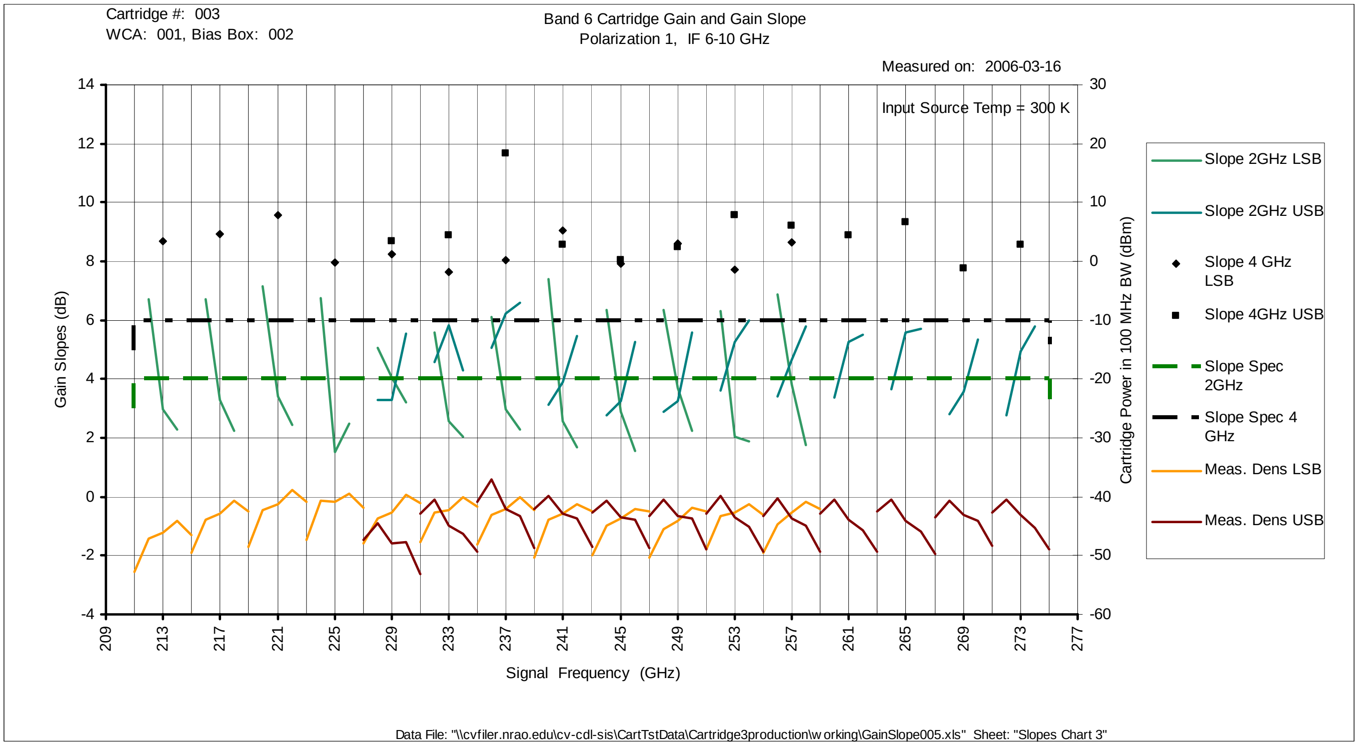

Figure 12: Power Density Slope(6-10 GHz IF), Cartridge 003, Pol 1

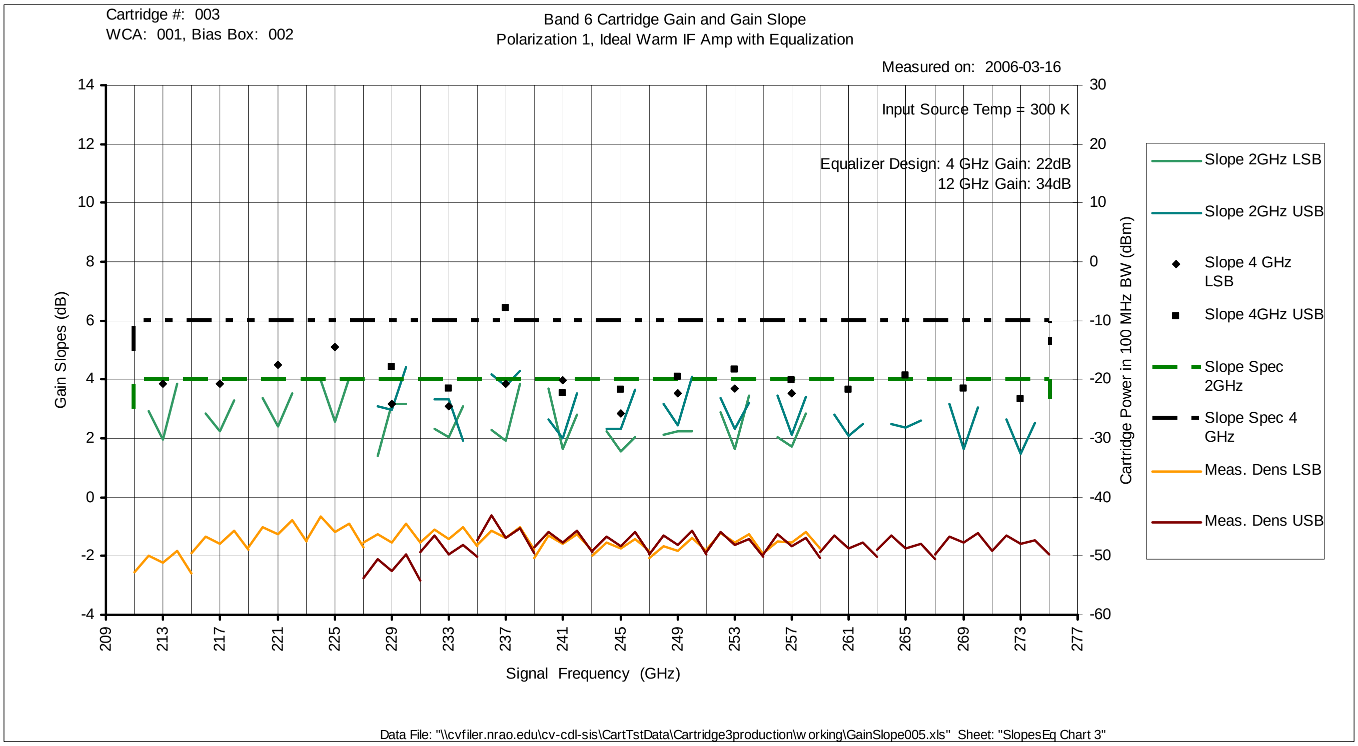

Figure 13: Power Density Slope (6-10 GHz IF) with Equalization, Cartridge 003, Pol 1

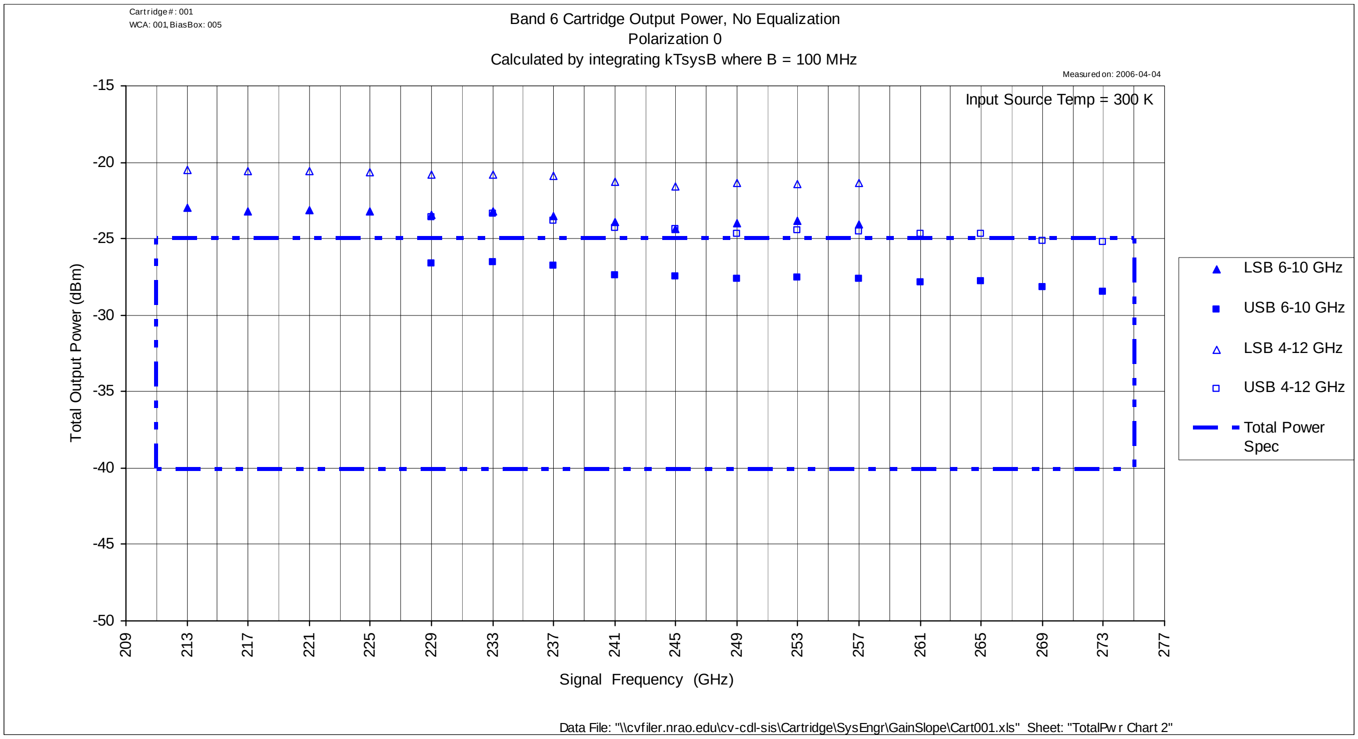

Figure 14: Total Power Calculation, Cartridge 001, Pol 0

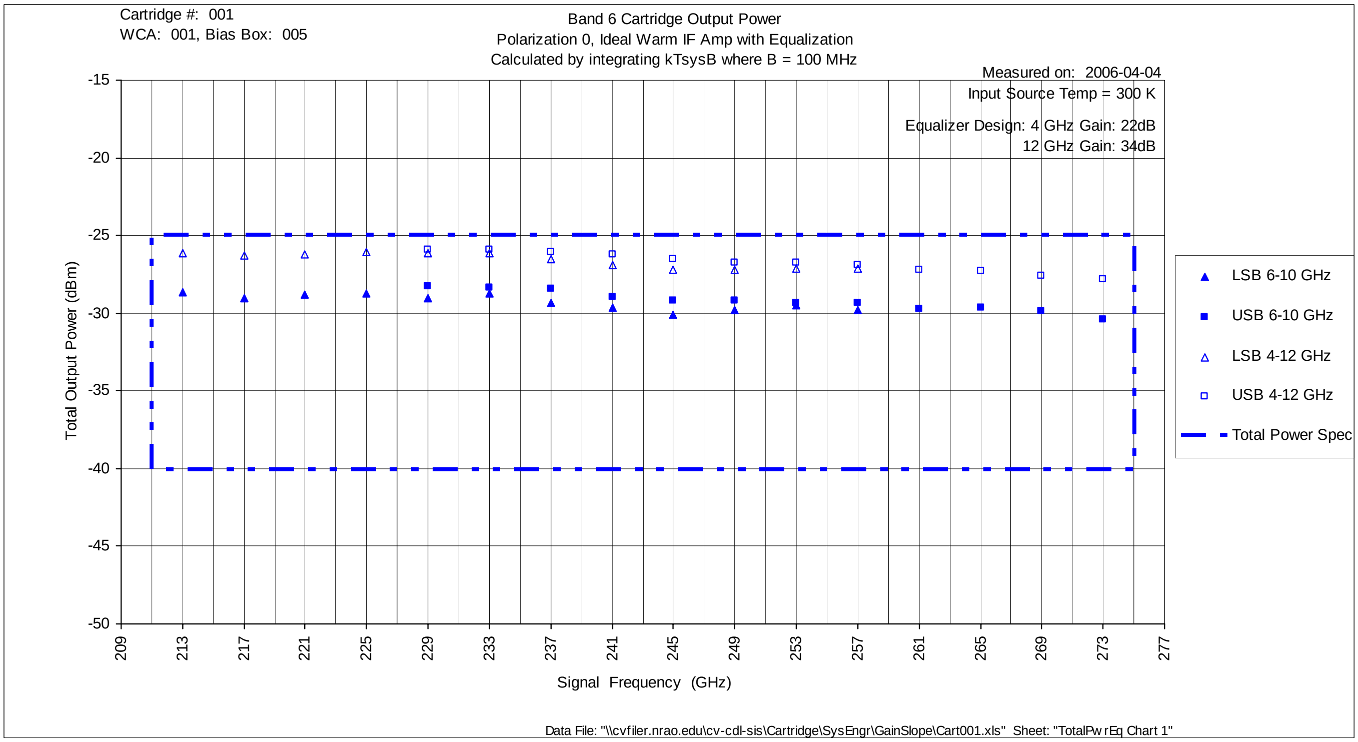

Figure 15: Total Power Calculation with Equalizer, Cartridge 001, Pol 0

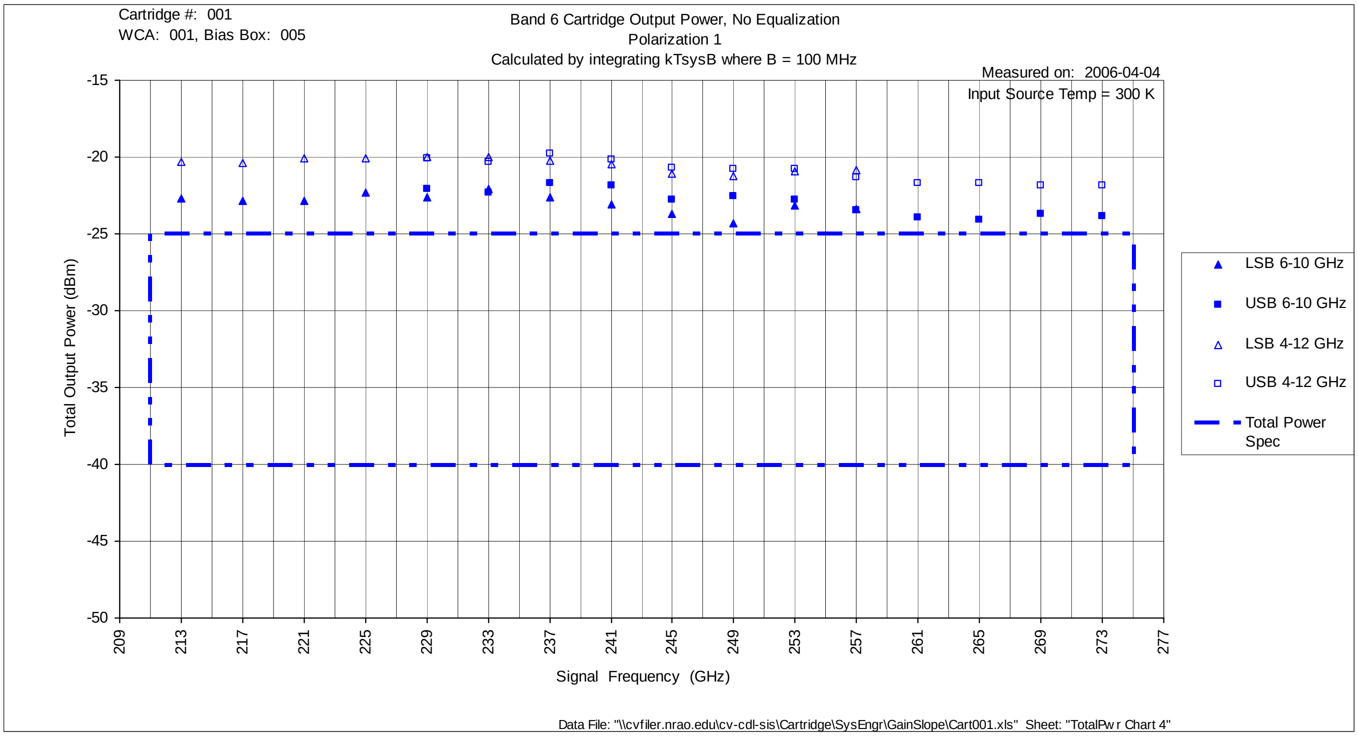

Figure 16: Total Power Calculation, Cartridge 001, Pol 1

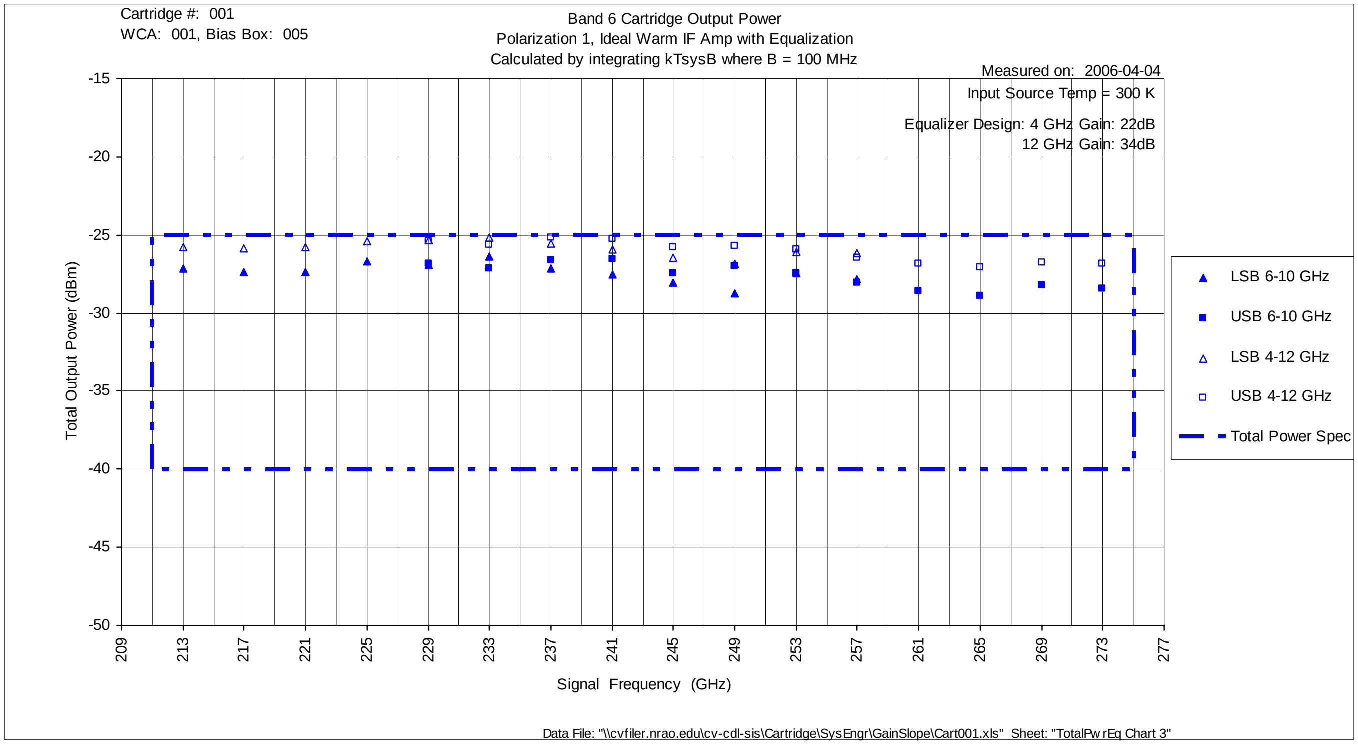

Figure 17: Total Power Calculation with Equalizer, Cartridge 001, Pol 1

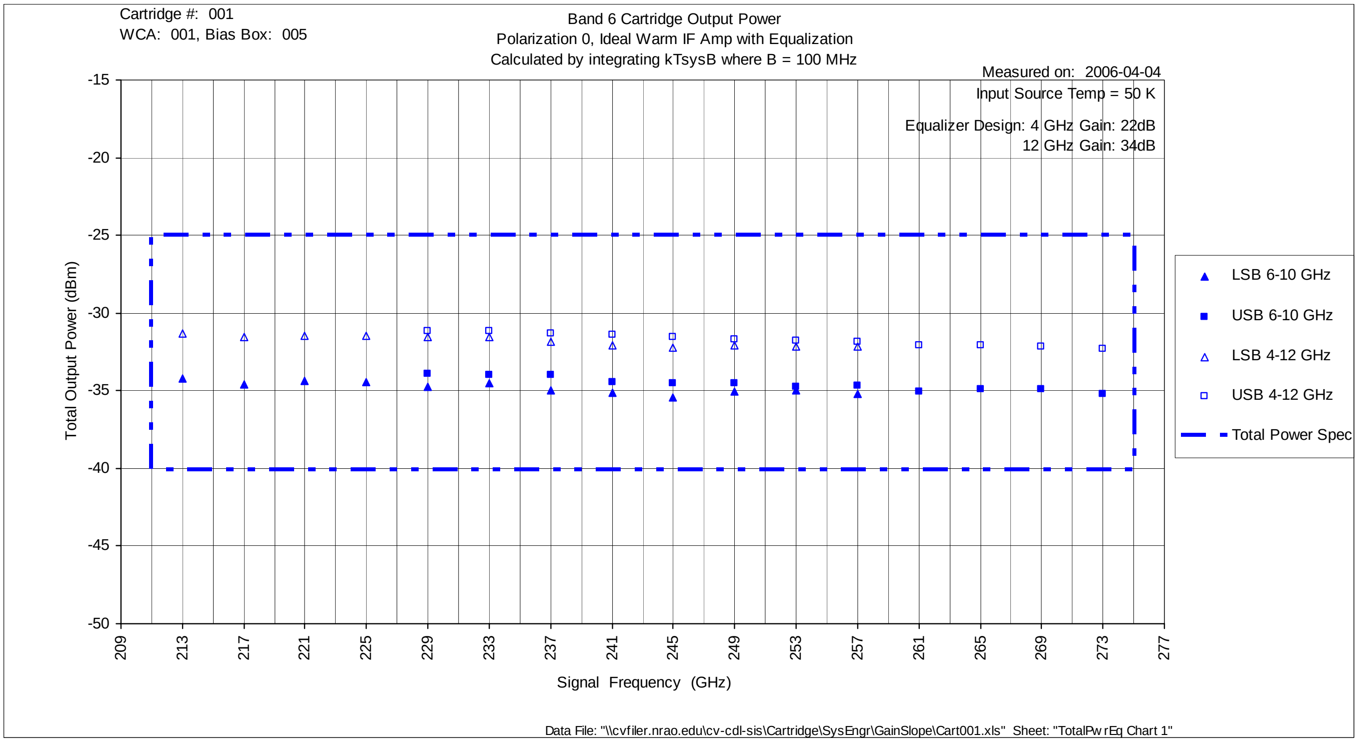

Figure 18: Total Power Calculation with Equalizer, Input source temp = 50K, Cartridge 001, Pol 0

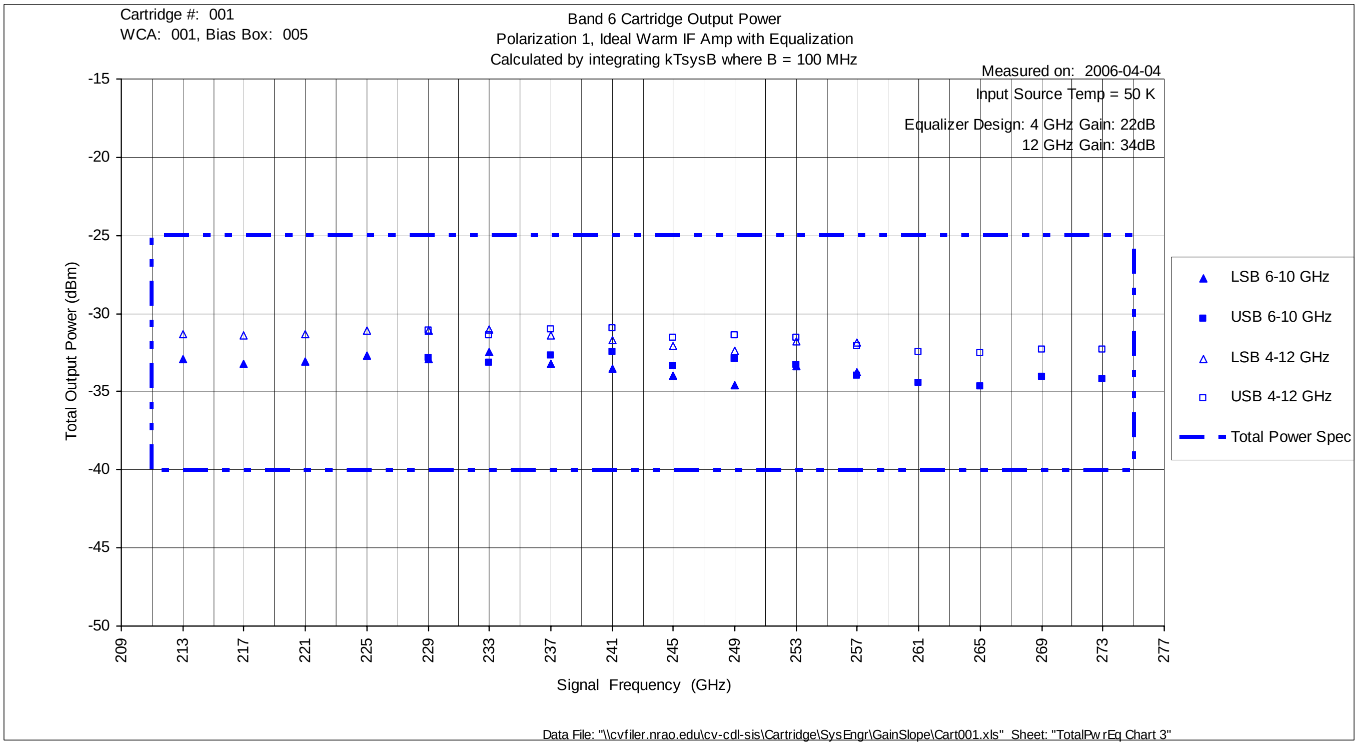

Figure 19: Total Power Calculation with Equalizer, Input source temp = 50K, Cartridge 001, Pol 1

Appendix A: Power from Integration of Spectrum Analyzer Plots Compared to Power Meter

Total power in the main section of this report was calculated from measured cartridge gains and noise temperatures as described in Eq. 1 and Eq. 2. To confirm those calculations, total power was measured in several IF bands using a spectrum analyzer, and the spectrum analyzer was also calibrated using a power meter.

Total power in an IF bandwidth of either 6-10 GHz or 4-12 GHz was calculated by integrating a spectrum analyzer trace. The spectrum analyzer was calibrated by comparing spectrum analyzer integrations to a power meter using filtered noise sources. The spectrum analyzer was an Agilent E4408 and power was measured with an HP 436A power meter and HP 8484A power head (-20 to -70 dBm).

To provide accurate noise power measurements, the spectrum analyzer detector was configured for "Averaging" in lieu of the default "Peak Detection" mode and its attendant detection errors. The spectrum analyzer can also compute noise power density directly at a single frequency using "Marker Noise Mode," which compensates for the effective noise bandwidth of the predetection filters and detector conversion factors.

Noise power was measured by:

1. averaging spectrum analyzer traces at spot frequencies,
2. using the spectrum analyzer's "Marker Noise Mode,"
3. integrating spectrum analyzer traces over IF bands, and by
4. measuring directly with a power meter.

Figure 20 shows the spectrum analyzer plot with a 6 GHz low-pass filter installed between the receiver and spectrum analyzer. Best-fit line segments at 5.5 GHz and 9 GHz were obtained for the spectrum plot and the fit parameters were then used to calculate power at those spot frequencies.

Table 3: Correction factor for Spectrum Analyzer Filter and Detector

Measured by Spec Anal using Marker Pwr Dens (dBm/Hz)		From Spec Anal Spectrum RBW = 3 MHz (dBm)		Differences Spectrum – Density ($dBHz^{-1}$)	
PSD @ 5.5 GHz	PSD @ 9 GHz	Power @ 5.55 GHz	Power @ 9 GHz	@5.55 GHz	@9 GHz
-123	-146	-58.0	-80.9	65.0	65.1

The spectrum analyzer's "Marker Noise Mode" was then used to measure power density at the same frequencies. Power density and spot frequency powers are recorded in Table 3 and their difference, also shown in the table, gives the correction needed to convert from power measured at a single frequency in the spectrum plots to power density at that frequency. This difference, 65 $dBHz^{-1}$, is the expected $10\times\log_{10}$ of the 3 MHz predetection bandwidth. Also note the close agreement between the correction factors at the two different frequencies.

Figure 21 compares spectra measured with the spectrum analyzer, adjusted using the factors discussed above, to spectrum calculated during cartridge noise temperature measurements using Eq. 1. A noise bandwidth of 100 MHz was assumed for the noise temperature data, which is the rough bandwidth of the YIG filter. The power spectrum measured during cartridge noise temperature measurements is about 2 dB greater than the corrected spectrum from the spectrum analyzer.

A comparison of the integrated total power from the spectrum analyzer to that measured using the power meter is tabulated in Table 4.

The total power in a bandwidth B was calculated from power density using the following formula:

$$P_{Total} = \frac{1}{2}\sum_{i=1}^{N-1}\left[\frac{\Psi(f_{i+1})+\Psi(f_i)}{f_{i+1}-f_i}\right] \quad \text{Eq. 3}$$

where:
- P_{Total} = total power (W) in bandwidth spanning f_1 to f_N
- $\psi(f_i)$ = noise power density at frequency f_i (W/Hz)
- f_i = frequency of i^{th} spectrum analyzer bin (Hz)
- N = total number of frequency bins

Total power, calculated by integrating the spectrum analyzer traces shown in Figure 21, corrected using the factors given in Table 3, is compared to power meter measurements in Table 4. Differences between the two techniques is about 1.4 dB, which is sufficiently small to specify the gain of the warm IF amplifiers with equalizers.

As a self-check, the "Deltas" section of Table 4 shows differences between the various measurement configurations for the integrated power and power meter measurements. Agreement between the two approaches is within a few tenths of a dB.

Table 4: Comparison of Power Differences Between Integrating Spectrum Analyzer Traces and Power Meter

Configuration	**Integration of Spectrum (dBm)**	**Power Meter (dBm)**	**Delta (dB)**
No BPF	-25.3	-23.8	**1.5**
6 GHz LPF	-28.2	-26.8	**1.4**
8 GHz BPF	-30.5	-29.3	**1.2**
Deltas (dB)			
No BPF – 6 GHz LPF	2.9	3.0	
No BPF – 8 GHz BPF	5.2	5.5	
6 GHz BPF – 8 GHz BPF	2.3	2.5	

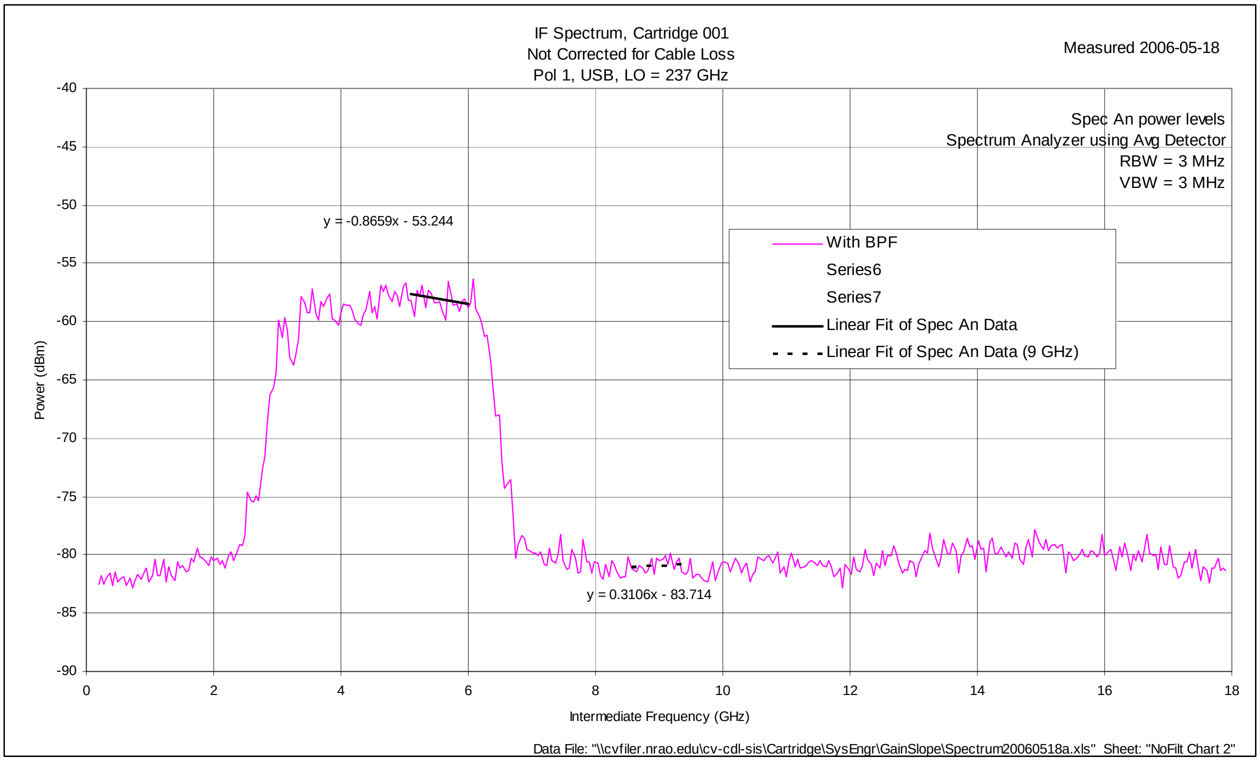

Figure 20: Filtered Cartridge Spectrum showing frequencies used for spectral density calculations. This data was not corrected for cable loss.

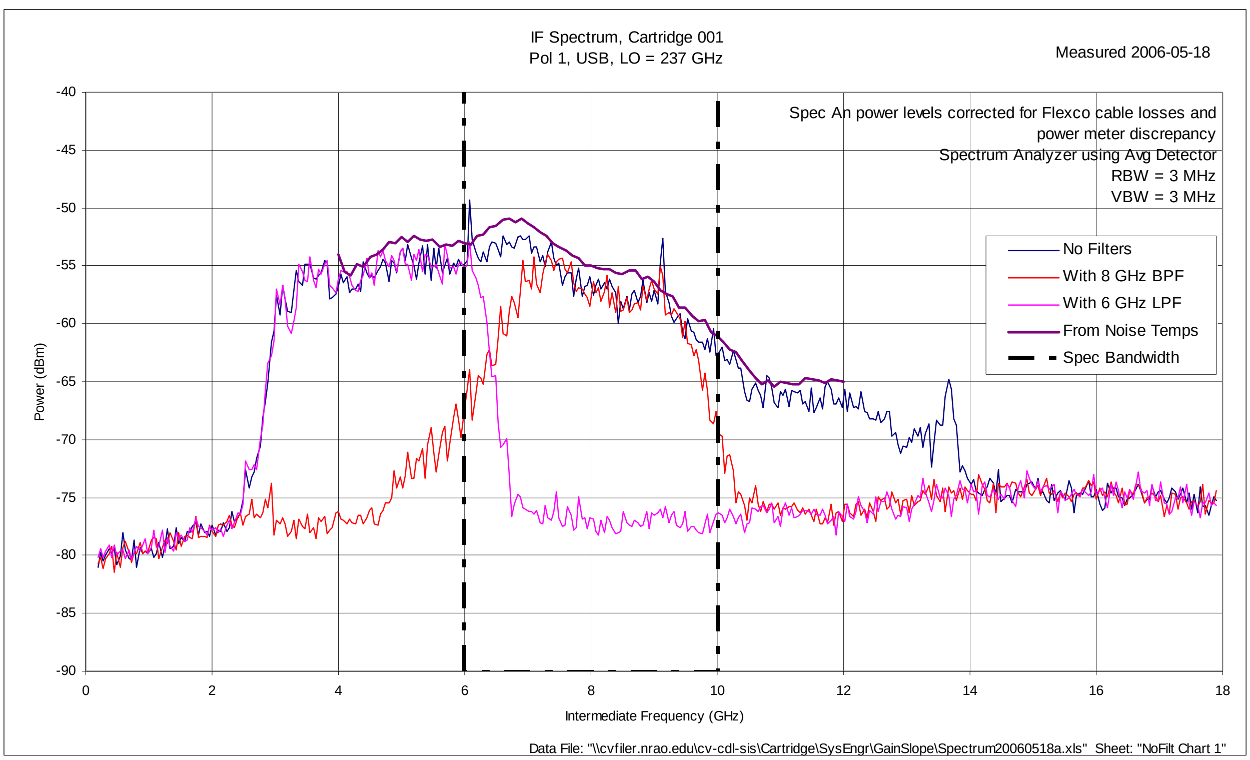

Figure 21: Comparison of full and filtered cartridge spectrum to spectrum calculated from noise temperature measurements. Spikes in the spectrum are from the phase drift measurement system. This data was corrected for cable loss.