# Response to Change Request ALMA-40.00.00.00-200 on Band 6 IF Frequencies

This CRE has been discussed by both the ASAC and at a recent Science IPT meeting. In both meetings there were strong views expressed that this CRE represents a significant loss of capability and that it should be resisted. As is clearly stated in the System Requirements, an IF frequency extending below 5 GHz is required in order to make simultaneous observations of the main CO line at 230 GHz and the isotopes near 220 GHz. Making these observations simultaneously not only increases the efficiency but will also reduce errors in comparing the structures seen in the different lines since many forms of error will cancel in that case. The view from scientific perspective therefore is that this capability should not be sacrificed.

In its present form, the CRE mixes together several issues:
1) the actual noise performance of the mixer-preamplifier combination
2) the slope on the IF output.
3) the excess noise generated in the LO system.

In summary, the Science IPT recommendation is that the noise requirements should continue to extend down to 4.5GHz, but that a relaxation on the slope requirement should be accepted.

The logic is that, since the use of the low end of the band is focused on spectral line observations, the slope is not so critical as it is for broad-band measurements. The digitization is of course always over a 2 GHz band, so digitization noise will be the main problem. The slope in power is always upwards as a function of frequency so that implies we should put the center IF frequency as low as possible so that there is plenty of power in the part of the spectrum that we are interested in (the two CO lines will be close to 5GHz in the IF). It is likely that we would be using the Tunable Filter Bank for these cases so we have 3 bits, which also reduce this effect.

I suggest that the criterion on slope should be no more than 6dB more power at 6GHz than at 5GHz. I think that even the worst case shown in figure 5 of the CRE would meet this. If the band 6 people can accept a limit of 5dB so much the better. (We should try to check what the effects really are for these cases where there is a big slope right across the band and we are interested in a relatively narrow section in the middle.)

As far as the noise temperature is concerned, I suggest that the specification should should be for an SSB receiver temperature (averaged over both sidebands) of 83K at an IF frequency of 5GHz and an LO frequency of 225GHz. (I think these frequencies are close enough to those required for the 12CO and 13CO rest frequencies of 230.54 and 220.40 and allow for some red-shift.)

It appears from Figure 2 of the CRE that a small fraction of the mixer-preamps will fail this, but it is not stated whether the histogram is for all LO frequencies or just 225GHz, which is the relevant one here, and whether or not these plots include cases where there is excess LO noise. Going back to John Effland's memo, which is RD3 of the CRE, it appears that noise from the preamplifiers should not be a problem and there is no obvious reason why different SIS mixers would change the noise as a function of IF frequency much.

Turning to the excess LO noise, this seems to be a different class of problem. From the noise temperature plot, Fig 1 of the CRE, it is clear that a small fraction of the WCA's are adding a great deal of excess noise at 4 to 5 GHz for some LO settings. Figures 3 and 4 show that, for that particular WCA at least, this problem is unfortunately worst at just the relevant LO frequency of 225GHz.

I would argue that WCA's with such a large amount of excess noise should not be accepted and that this should be done quite independent of issue raised in the CRE. There are at least three reasons why one would be extremely concerned about operating with an LO that generates so much excess noise:

1) Although the noise has the appearance of being broad-band, since it is being produced in a series of amplifiers and multipliers which are operating in a non-linear regime there is at least the possibility that is contains coherent components that are products of frequencies in the LO system.

2) Even if we are operating with an IF of say 6 to 10GHz, this noise is of course seen by the SIS mixer and the IF preamplifier. It will therefore contribute to any non-linearities in those parts of the system and it could well have an effect on stability.

3) The presence of noise on the LO implies a loss of coherence when doing interferometry.

Just to spell out this last point, one can think of the action of the mixer as being, to first order, a convolution of the spectrum of the incoming astronomical signal with the spectrum of the LO. I think this means that noise at on the LO at say 1 GHz moves signal from its proper place in the IF to places that are +/- 1 GHz away. Obviously this produces loss of coherence which is proportional to the power in the noise sidebands on the LO. Now it may be that the noise power on the LO is in fact negligible in the relevant region (essentially from 0 to 4GHz) despite the appearance of the plots, but at the very least this needs to be checked.

Even if all three of these points are non-issues, the question of whether or not we can and should build Band 6 WCA's that meet the excess noise requirements at 4.5GHz and above is quite separate from the ones that are associated with the performance of the cold cartridges. The cost and schedule implications keeping the WCA requirement at the level necessary to meet the noise specification proposed above should be considered separately from the cartridge issues.

Finally, the question was very reasonably raised at the ASAC as to why on earth we being asked about this now (and in terms that more or less say that we have no choice but to accept this CRE) instead of when the problem was identified. It appears that FE has proceeded for the last several years with specifications on the Band 6 cartridge that are inconsistent with the FE Spec and the System Spec. It is clear that this issue was understood at least as early as 2006 when John Effland's memo was written. Note that this memo specifically proposed that the cartridge specifications should be tightened "to prevent scheduling and production demands from further degrading performance outside the 6-10 GHz band". That was impressively far-sighted of him and what he was trying to avoid is of course exactly what is now happening.

Richard Hills 18th Sept 2009

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|---|---|---|
| ALMA | **ALMA CHANGE REQUEST** | **Date submitted**: 2009-08-07<br>Revised 2009-09-15<br>**CRE #**: ALMA-40.00.00.00-200-A-CRE |
| | **TITLE: Change the Band 6 Receiver Output IF range in the ALMA Front End Specifications Document** | |

*(To be completed by CR Submitter/Initiator)*

**Description of change (detailed description of change proposed) and Justification:**

Change the Band 6 IF range over which all specifications should be met

*From*: 4.5 – 10 GHz (should perhaps have been 4.3 – 10 GHz)
*To*: 6 – 10 GHz

The existing design fails to meet noise and output spectral power slope/variation requirement when used in the 4.3 – 6 GHz IF range.

1. Noise performance: The cold cartridge assembly (CCA) as well as the warm cartridge assembly (WCA) exhibit extra noise over the 4.3 – 6 GHz IF range. The overall performance specifications are not met in general for the CCA plus WCA combinations.

   For the CCAs, the average noise over 4.3 – 10 GHz IF range does not meet specification. Even more significantly, the noise performance over 4.3 – 6 GHz is significantly worse than that over 6 – 10 GHz IF range. See Figure 1 and Figure 2.

   For the WCAs, in some instances the average noise over the full 4.3 – 10 GHz might meet the required specification or only marginally miss it, yet the noise performance over 4.3 – 6 GHz IF range is significantly poorer. See Figure 3 & Figure 4.

2. Spectral gain/power[1] slope: The CCA is estimated to have a 6 dB gain slope over the 4 – 6 GHz IF range, if the best mixer pre-amps measured to date were to be used [RD1]. See Figure 5. Actual cartridges have been measured to have a gain slope of about 10 dB over the 4 – 6 GHz IF range. Most of the sensitivity loss due to this poor slope could be corrected by incorporating external equalizers, for instance located in the BE IF processor. See [RD2].

Upgrading the existing CCA and WCA designs to be compliant (or screening for good performance) implies a significant negative impact on the production and delivery schedules. Approval of this change request will permit freezing the current designs for production.

A future upgrade could permit use of the region from 4 – 6 GHz by the following means: redesign of the cold IF amplifier, replacement of the IF hybrid, use of a balanced mixer design to eliminate LO sideband noise, and subsequently retrofitting all cartridges.

Referenced Documents:
[RD1] Band 6 Cartridge Gain Slope Analysis, FEND-40.02.06.00-346-A-REP
[RD2] An EVLA-like gain slope correction scheme for ALMA?, FEND-40.00.00.00-192-A-MEM
[RD3] Noise Temperature and Gain Slope Considerations for Band 6 Cartridge Operating over 4-12 GHz IF Band, FEND-40.02.06.00-165-A-REP

**Additional information in attached documents**:

None. Appropriate documents are already referenced above.

**Impact:** ☑Specifications ☑Science ☑Cost ☑Schedule ☐Safety ☐Technical ☐Other (specify):

**Description of impact**:

Relaxation of specification as requested by this CRE would allow manufacture of the Band 6 CCA and the FE LO WCA using the current designs (positive impacts on cost and schedule). But this will have a negative impact on some use cases and the

[1] Although gain and power slope are distinct parameters and the specification is on the spectral power slope with 300 K source, the actual difference between the two quantities is small and measurement of gain slope adequately predicts the spectral power slope, at least for the purpose of this CRE.

science impact should be studied as a part of the review of this CRE. An example use case involving eight spectral lines in the RF range of 219.560 – 230.538 GHz that could have benefitted from the availability of 4.3 – 6 GHz IF range is provided in Appendix-1 of [RD3].

It must also be noted that thus far the plan was for the Band 6 group to keep outputting power in the 4 – 12 GHz range (regardless of the official IF range) since it was thought to be useful for some observations. With this CRE the power outside the 6 – 10 GHz would be considered "out of band power". Since there is conceivable that the IF outside of the 6 – 10 GHz might be used, the out of band specification shall be interpreted to imply the sum of the unwanted signal power that might be present in the 10 MHz – 4 GHz and 12 GHz – 18 GHz ranges.

This will also ensure that the IF processor in the FETMS at the FEICs, would not need to be modified to verify this requirement.

## Affected products to be modified:

“Frequency Band 6 Cartridge” (ALMA Product Tree # 40.02.06.00) and therefore the” Front End Assembly” (ALMA Product Tree # 40.00.00.00).

## Affected documents to be revised:

1. Front-End Sub-System for the 12m Antenna Array – Technical Specifications, ALMA-40.00.00.00-001-A-SPE; Section 3.3.2 in Table-4 under [FEND-40.00.00.00-00070-00 / R and Section 3.3.3, IF output port bandwidth and centre frequency, [FEND-40.00.00.00-0080-00 / R].

NOTE1: The Band 6 Cartridge Technical Specifications, FEND-40.02.06.00-001-A-SPE only requires the specification to be met over and IF range of 6 – 10 GHz, and there is no intent to revise this requirement in the CRE, FEND-40.02.06.00-154-A-CRE, filed to update this document. So this document does not need to be revised, if this CRE is approved.

NOTE2: The Band 6 Warm Cartridge Assembly Technical Specifications, FEND-40.10.06.00-001-C-SPE, and the ICD between the FELO and the cold cartridge, FEND-40.02.06.00-40.10.06.00-C-ICD specify a 10K/μW noise contribution from LO when integrated over the full IF band (without explicitly specifying it), and hence do not need to be modified, if this CRE is approved.

## Remarks:

The proposed change was discussed and recommended for consideration by the NSF schedule review panel.

| **Date Submitted:** 2009-08-07 Revised 2009-09-04 | **Date Decision Required:** 2008-08-21 |
|---|---|
| **CRE Initiator:** Kamaljeet S Saini | |

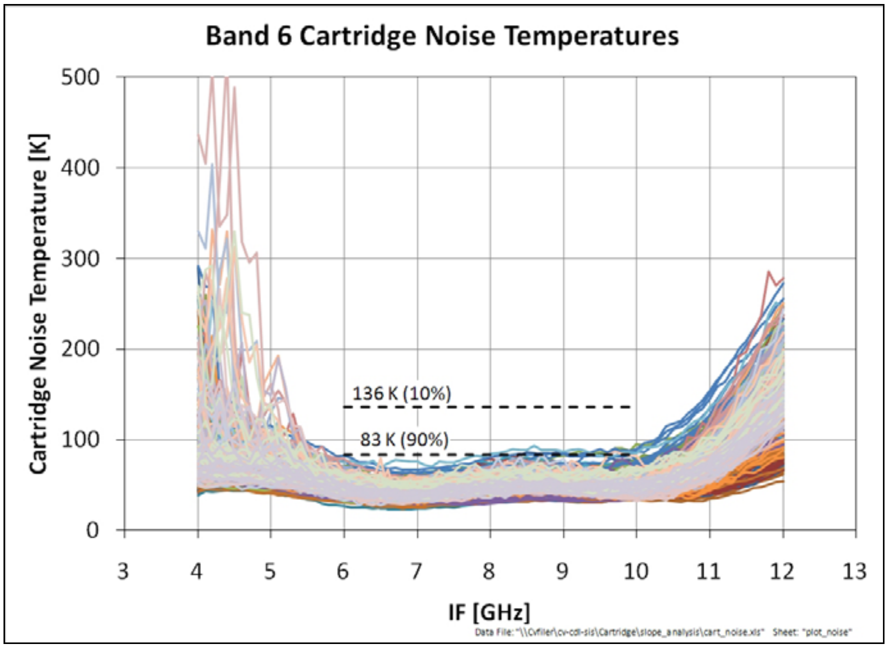


**Figure 1: Band 6 Cartridge Noise Temperatures as a function IF frequency (for 22 different mixer-preamplifier pairs and for several LO settings). The dashed lines are the Band 6 cartridge noise specifications shown here for reference. (Note that, strictly speaking, the specifications are on the average noise over the full IF range and not as a function of IF frequency as shown).**

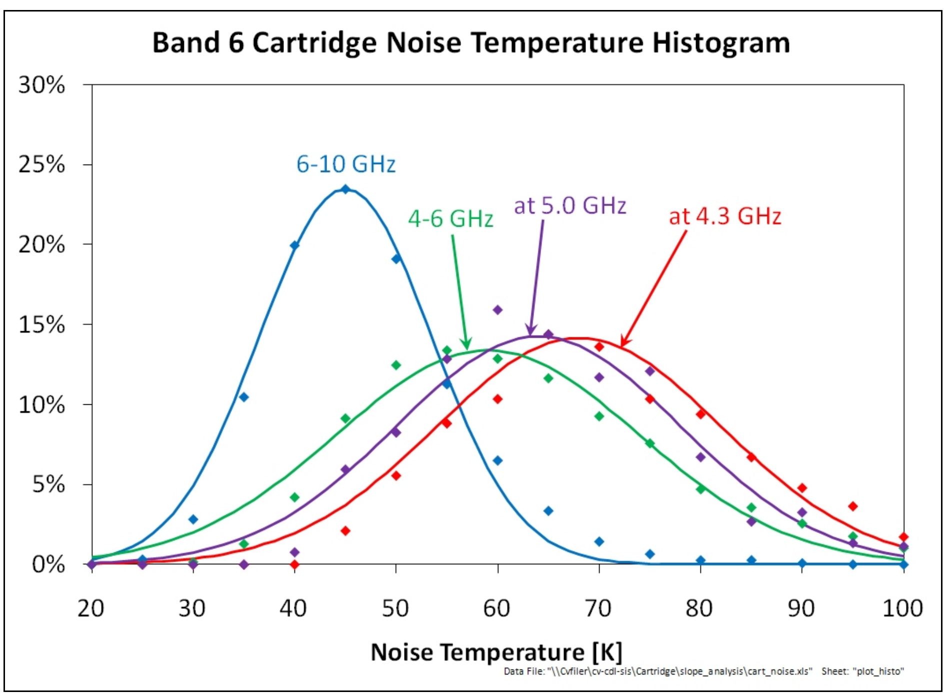


**Figure 2: Histogram showing the distribution of mixer-preamplifier pairs based on their noise performance over 6 – 10 GHz IF range, over 4-6 GHz IF range, and at 4.3 GHz and 5.0 GHz spot IF.**

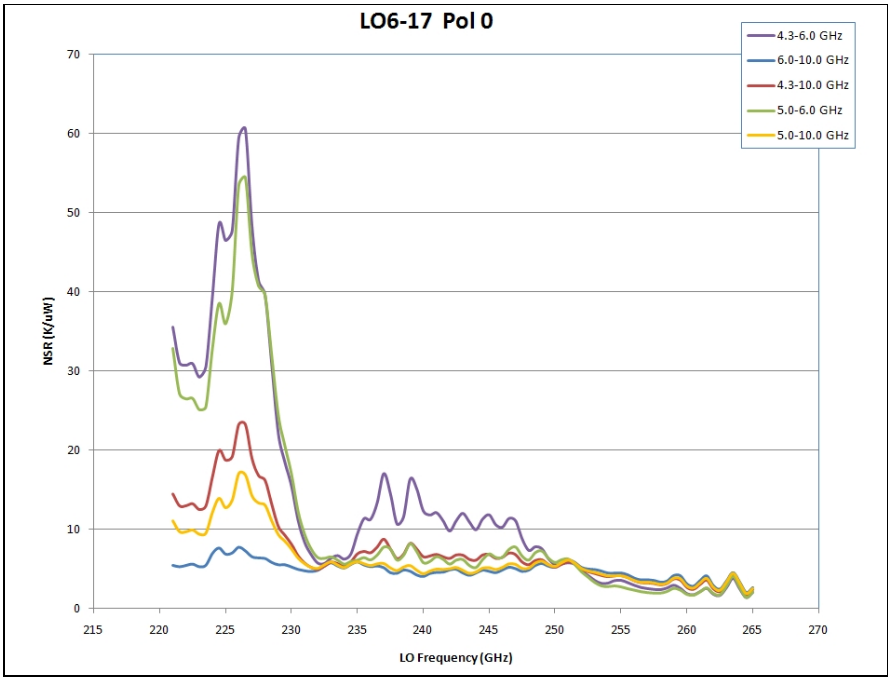


**Figure 3: Noise performance of a Band 6 WCA for various scenarios - averaged over 6 - 10 GHz (meets specification), averaged over the full 4.3 - 10 GHz (meets specification except at the low end of the band) and averaged over 4.3 - 6 GHz showing how much poorer the performance is over the part of the IF. Averages over 5 - 6 GHz and 5 - 10 GHz are also indicated.**

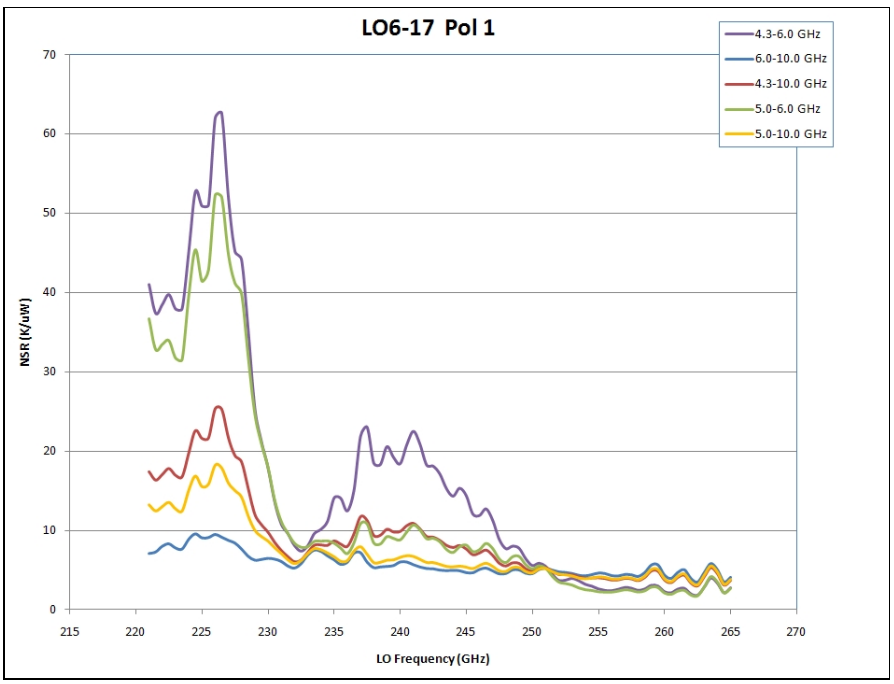


**Figure 4: Noise performance of a Band 6 WCA for various scenarios - averaged over 6 - 10 GHz (meets specification), averaged over the full 4.3 - 10 GHz (meets specification except at the low end of the band) and averaged over 4.3 - 6 GHz showing how much poorer the performance is over the part of the IF. Averages over 5 - 6 GHz and 5 - 10 GHz are also indicated.**

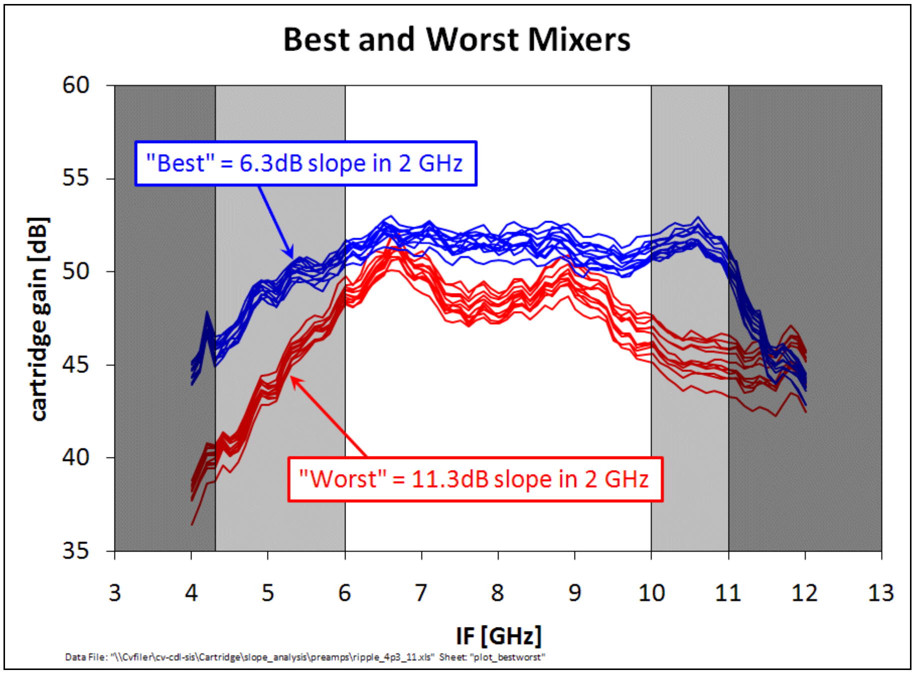


**Figure 5: Predicted cartridge gain for the best and worst mixer-preamps measured to date.**

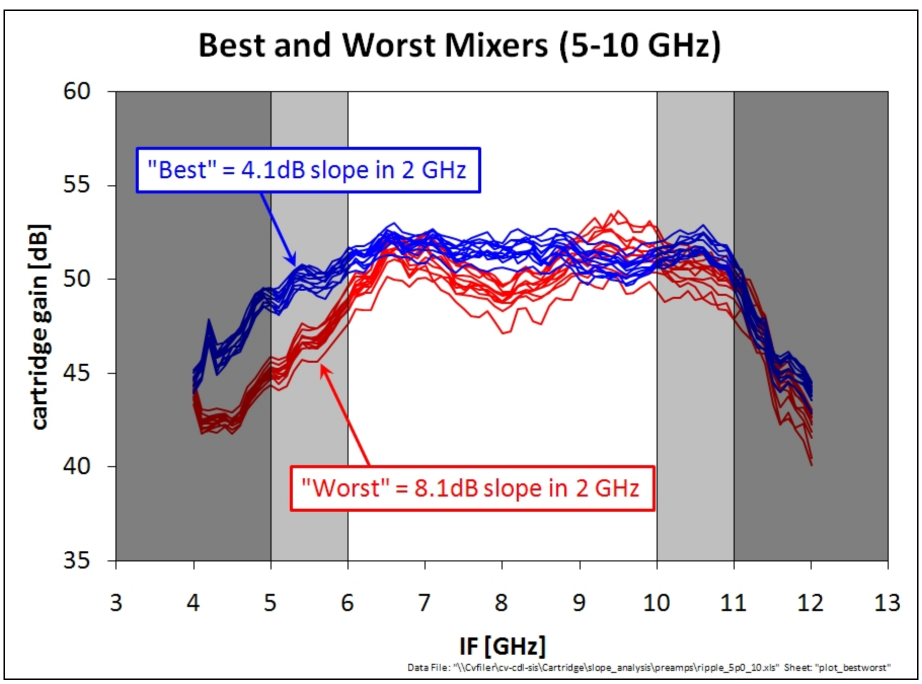


**Figure 6: Predicted cartridge gain for the best and worst mixer-preamps measured to date.**

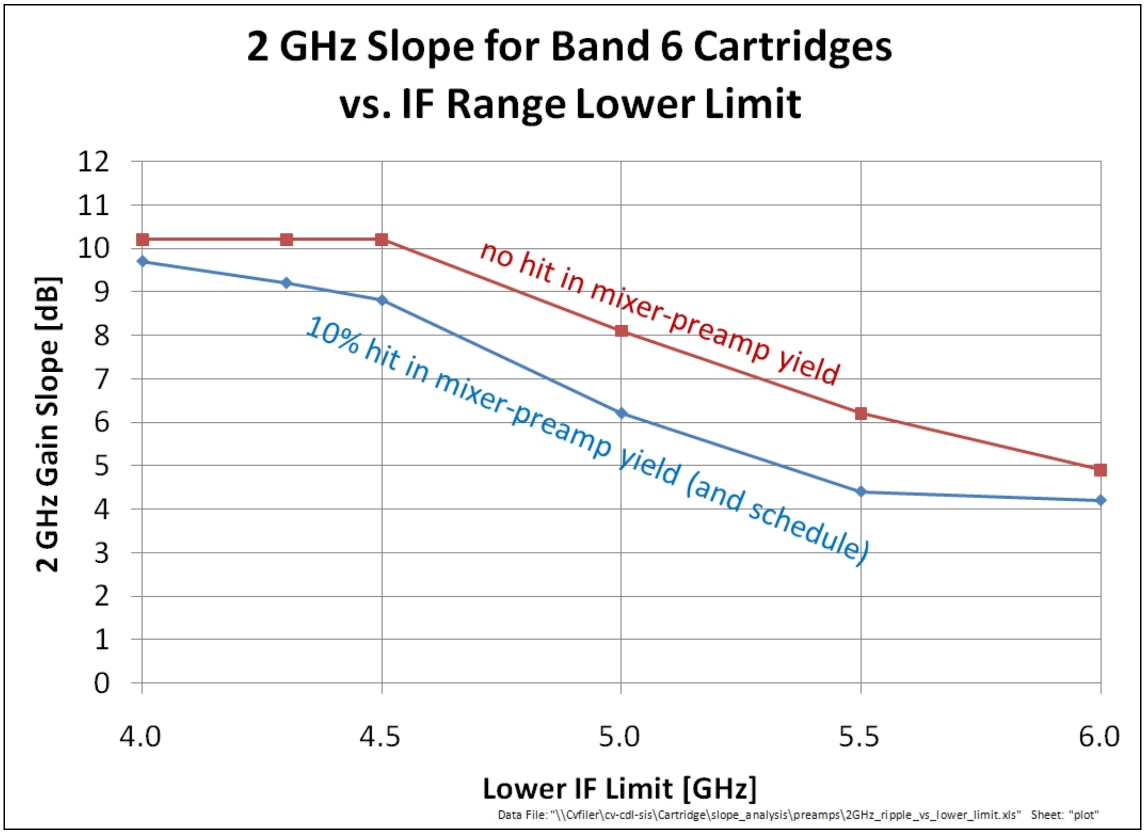


**Figure 7: Plot shows that with the existing design, simply screening to select mixer-preamplifiers / cartridges with better slope performance results in a significant yield hit without a commensurate slope improvement.**

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| | **ALMA CHANGE REQUEST** | **Date submitted**: 2009-08-07<br>Revised 2009-09-15<br>**CRE #**: ALMA-40.00.00.00-200-A-CRE |
| | **TITLE: Change the Band 6 Receiver Output IF range in the ALMA Front End Specifications Document** | |

# SUMMARY STATEMENT

**Summary of Technical Impact (state concerns and/or merit):**

Relaxation of specification as requested by this CRE would allow manufacture of the Band 6 CCA and the FE LO WCA using the current designs (positive impacts on cost and schedule). But this will have a negative impact on some use cases and the science impact should be studied as a part of the review of this CRE.

Upgrading the existing CCA and WCA designs to be compliant (or screening for good performance) implies a significant negative impact on the production and delivery schedules. Approval of this change request will permit freezing the current designs for production.

A future upgrade could permit use of the region from 4 – 6 GHz by the following means: redesign cold IF amplifier, replace IF hybrid, use balanced mixer design to eliminate LO sideband noise, retrofit all cartridges.

**Summary of Schedule Impact:**

Approving this change would help the Band 6 cartridge group and the FE IPT to meet the published schedule.

It must be noted however that thus far the plan was for the Band 6 group to keep outputting power in the 4 – 12 GHz range (regardless of the official IF range) since it was thought to be useful for some observations. With this CRE the power outside the 6 – 10 GHz would be considered "out of band power" and the cartridge will probably miss the corresponding specification limiting the out of band IF power – and require a waiver, unless the cartridge design is altered - a negative cost and schedule hit! Additionally, this will imply a change to the IF processor in the FETMS at the FEICs, if the in -band and out -of -band power requirements are to be verified by test.

**Summary of Budget Impact:**

Approving this change could have some budgetary impact. See explanation above. Disallowing will have both budgetary and schedule impact.

**Remarks**:

The proposed change was discussed and recommended for consideration by the NSF schedule review panel.

| Name | Signature | Date | App | Rej | Name | Signature | Date | App | Rej |
|---|---|---|---|---|---|---|---|---|---|
| **IPT LEAD** | | | ☐ | ☐ | **NRAO CONTROLLER** | | | ☐ | ☐ |
| **IPT LEAD** | | | ☐ | ☐ | **ESO CONTROLLER** | | | ☐ | ☐ |
| **IPT LEAD** | | | ☐ | ☐ | **JAO CONTROLLER** | | | ☐ | ☐ |
| **IPT LEAD** | | | ☐ | ☐ | | | | ☐ | ☐ |
| **SYSTEMS LEAD** | | | ☐ | ☐ | **CCB SECRETARY** | | | ☐ | ☐ |
| **SYSTEMS LEAD** | | | ☐ | ☐ | **JAO PROJECT DIRECTOR** | | | ☐ | ☐ |

# Memorandum

| | |
|---|---|
| **To:** | File |
| **From:** | John Effland<br>John Webber |
| **Date:** | 2006-09-11 |
| **Revisions:** | 00 2006-09-05 jee Initial<br>01 2006-09-06 jee Incorporated Observing Scenario by Webber<br>02 2006-09-11 jee Changed sys temps to refer above atmosphere<br>03 2006-09-11 jcw Updated numbers in Table 1 |
| **Subject:** | Noise Temperature and Gain Slope Considerations for Band 6 Cartridge Operating over 4-12 GHz IF Band |

## 1. Summary, Conclusion, and Recommendations

This memo presents noise temperatures and noise power density slopes for the Band 6 Cartridge measured across the formal IF band from 6-10 GHz and also across the wider 4-12 GHz IF band. Although the number of cartridges measured is small, data measured to date suggests that Band 6 specifications could be met over the 4.5 to 11 GHz IF band. A straw man plan for spectral line observation is included.

It is recommended that formal changes should be made to IF bandwidth specifications for the Band 6 cartridge to prevent scheduling and production demands from further degrading performance outside the 6-10 GHz band.

## 2. Data

### 2.1 Noise Temperatures and Image Rejection

Figure 1 is a graph of noise temperature and image rejection of polarization 0 for Band 6 Cartridge 001 which is now in final acceptance testing. Figure 2 is the same measurements for polarization 1. Noise temperature specifications are easily met over the 6-10 GHz IF band and could likely be met over the 4.5 to 11 GHz IF band. Image rejection meets 10 dB specifications over the entire 4-12 GHz IF band.

IF bandwidth of the cartridge noise temperature is a strong function of the mixer's integrated preamplifier performance. That is, gain and noise temperature of the preamplifier generally determine the IF bandwidth of the mixer-preamplifier. Figure 3 summarizes the performance of all 37 preamplifiers built to date and includes the revised specification that should provide acceptable mixer-preamplifier performance from 4.5 GHz to 11 GHz.

### 2.2 Power Density and Power Density Slope

IF bandwidth of the Band 6 Cartridge is more limited by excessive slope of noise power density than by noise temperature bandwidth. The noise power density output from the cartridge is comprised of a mixer-preamplifier noise temperature term and another term that accounts for amplification of noise power input to the receiver.

Receiver gain amplifies the sky noise and ground pickup from sidelobes, and high gain slope maps directly to excessive slope in noise power density.

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

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

where:

| | |
|---|---|
| $P_{100\mathrm{MHz}}(f)$ | = 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 ($1.38 \times 10^{-23}$ W/K-Hz) |
| B | = equivalent noise bandwidth (approx. 100 MHz) |

The source temperature, $T_{Source}$, is specified in the Band 6 Cartridge ICD to be 300K and consequently that temperature is used when testing the receiver.

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[1].

The power density graphs 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. Reducing the effective temperature viewed by the receiver beam can decrease the slope of the power density. Figure 4 compares noise power density (BW = 100 MHz) for both polarizations when the receiver is viewing:

- a 300K ambient load and
- 35K estimated for cold sky plus ambient terrain through sidelobe spill-over[2].

Note that there's little difference in slope for the two different input temperatures. All noise density slopes shown in this report are corrected by assuming the warm IF amps have integrated equalizers with 12 dB of compensating gain slope. These integrated amplifier-equalizers are on order but not yet delivered from the warm amplifier vendor AML Communications.

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. 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.

[1] "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

[2] System temperatures calculated in Appendix 1: Observing with Band 6 Cartridge 001 include an additional 7% receiver temperature to refer them above the atmosphere.

Noise power density slopes are shown in Figure 5 across a sliding 2-GHz IF bandwidth. Also shown in the figure is the 4 dB specification. The thicker curves are slopes for the 6-10 GHz IF band and the thinner curves show slopes for the entire 4-12 GHz band. Note that the slopes are met across the 6-10 GHz IF band with polarization 0 (assuming the equalizer is used) but exceed specifications for polarization 1. Both polarizations exceed noise power density slope specifications across the 4-12 GHz IF band. Reducing the input temperature from 300K to 35K reduces the maximum slopes by up to 1 dB.

Power density slope over the entire IF band, formally spanning 6-10 GHz, 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.

Figure 6 shows noise power density slopes across the 6-10 GHz IF band. Receiver input temperatures of 35K change these slopes by a maximum of 0.5 dB.

# 3. Appendix 1: Observing with Band 6 Cartridge 001

Figure 7 and Figure 8 are graphs of noise temperature and image rejection for cartridge #1 for both polarizations at an LO frequency of 225 GHz. While we do not have adequate statistics for cartridges, the statistics for mixer-preamps suggest that other cartridges will be similar—but this is not guaranteed!

From these data, we calculate approximate system noise temperatures on the sky, assuming typical observing conditions for Band 6 (tau=0.07) give 35K contribution from sky, spillover, and resistive losses. The system temperatures are referred to above the atmosphere by including an additional 7% receiver noise temperature.

## 3.1 Noise Temperatures on the Sky

The minimum system noise will be in the 6-7 GHz area for both polarizations, and is about 78K for polarization 0 and 67K for polarization 1. In typical line observing, these will simply be averaged to give about 73K average system temperature. The corresponding value at 4.5 GHz IF is about 99K, and at 11 GHz it is about 105K.

## 3.2 Straw Man Observing Plan

A possible observing plan based on a set of lines suggested by Debra Shepherd has been used to generate a table of predicted system noise temperatures for 8 spectral lines in the region 219.945 to 230.538 GHz. We have chosen a first LO frequency of 225.039 GHz, which places $SO_2$ and $CH_3CN$ lines both at 4.309 GHz, one in upper and one in lower sideband. If this overlap is undesirable, a slight shift of the LO frequency by up to 100 MHz either direction would produce essentially the same results.

Table 1 shows the calculated system temperature for each of 8 spectral lines, averaged over the two polarizations, for this choice of first LO, under the assumption of 35K added noise for atmosphere and sidelobes and 7% more receiver noise added to refer the system temperature above the atmosphere.

| Table 1: Predicted System Noise Temperatures for Spectral Line Observations[3] | | | | |
|---|---|---|---|---|
| **Molecule** | **Sky freq (GHz)** | **First IF freq (GHz)** | **Sideband** | **$T_{sys}$ (K)** |
| $^{12}C^{18}O$ | 219.560 | 5.479 | L | 86 |
| SO | 219.945 | 5.094 | L | 97 |
| $CH_3OH$ | 220.079 | 4.960 | L | 99 |
| $^{13}C^{16}O$ | 220.398 | 4.641 | L | 103 |
| $CH_3CN$ | 220.730 | 4.309 | L | 101 |
| $SO_2$ | 229.348 | 4.309 | U | 96 |
| $CH_3OH$ | 229.759 | 4.720 | U | 101 |
| $^{12}C^{16}O$ | 230.538 | 5.499 | U | 84 |

# 4. Acknowledgements

The authors would like to thank Dave Schmitt for measuring the cartridge receiver noise temperatures.

[3] Calculations stored in sheet "StrawManPlan" in \\cvfiler.nrao.edu\cv-cdl-sis\Cartridge\SysEngr\GainSlope\TsysCart001.xls

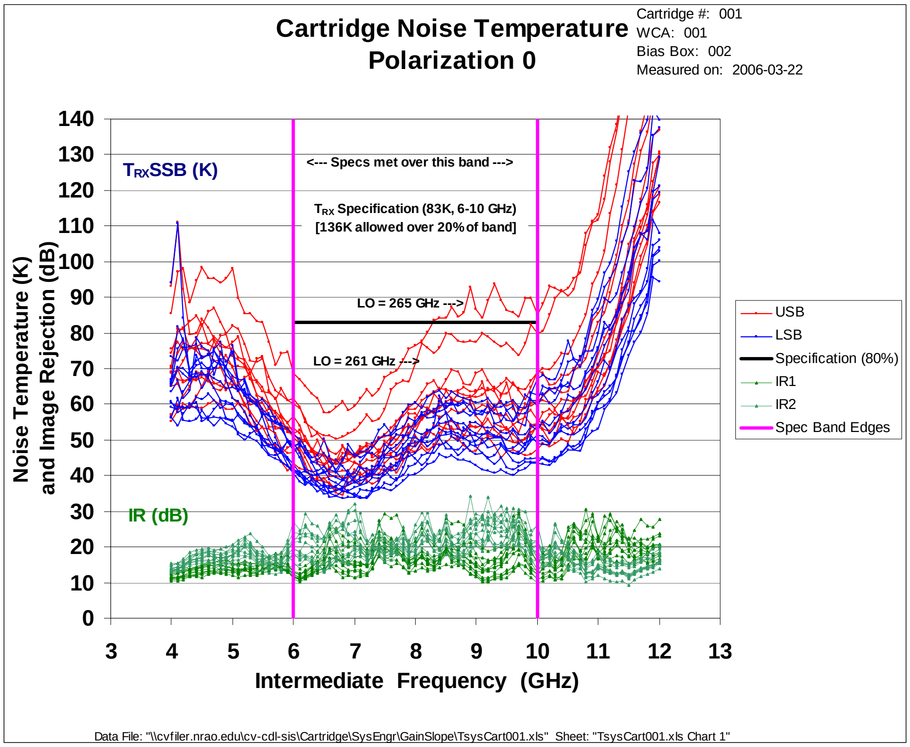


**Figure 1: Receiver Noise Temp and Image Rejection, Pol 0, Band 6 Cartridge 001**

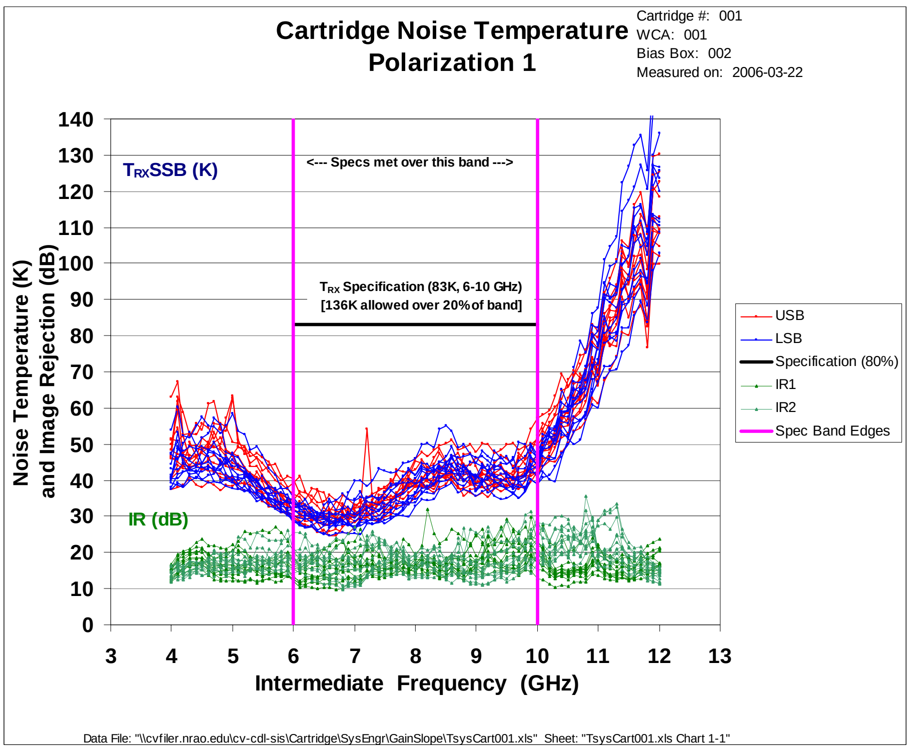


**Figure 2: Receiver Noise Temp and Image Rejection, Pol 1, Band 6 Cartridge 001**

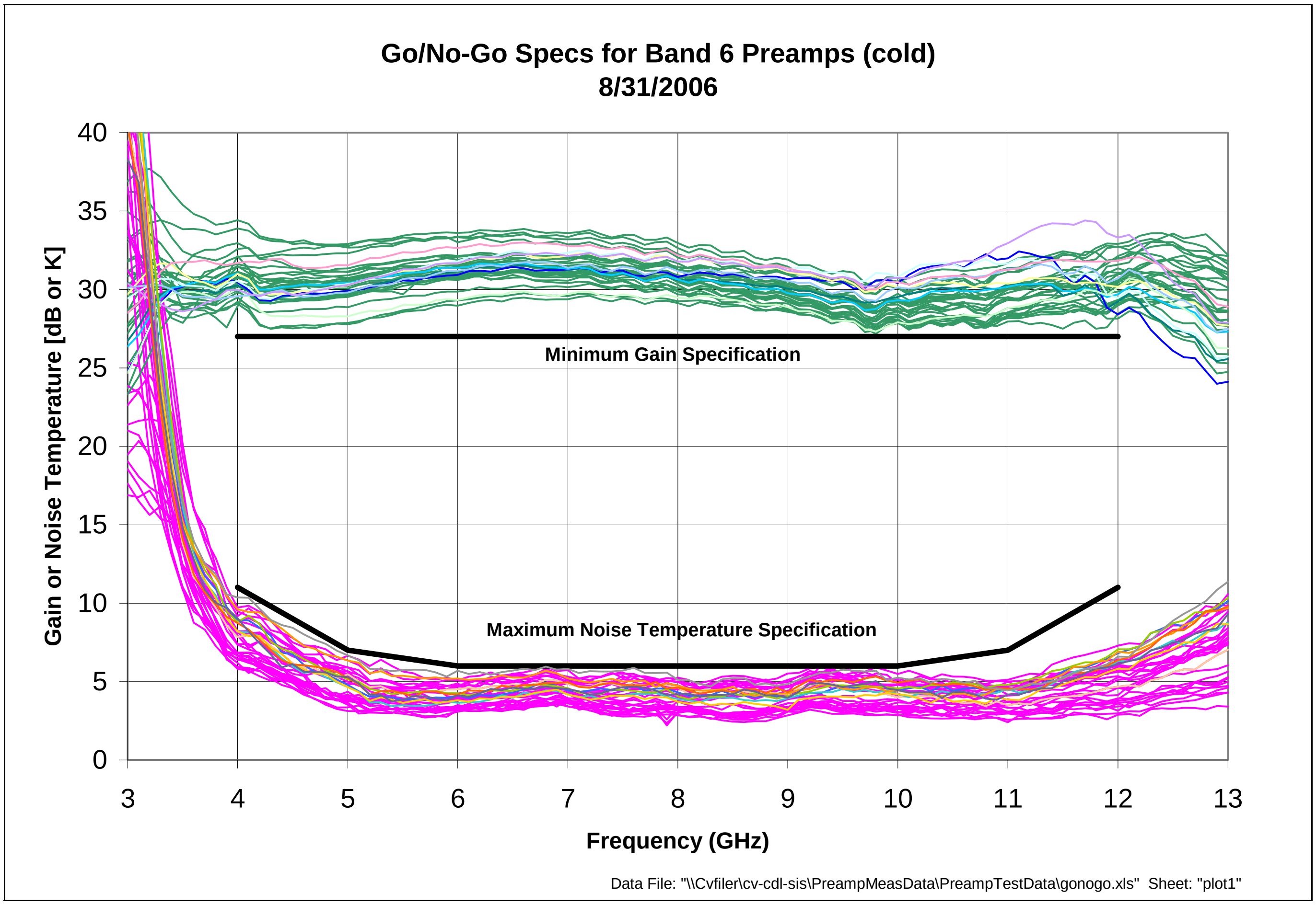


**Figure 3: Widened Spec Masks for IF Amplifiers**

<table>
<tr><th colspan="3">Figure 4: Noise Power Density, Assuming Equalizers in Warm IF Amps</th></tr>
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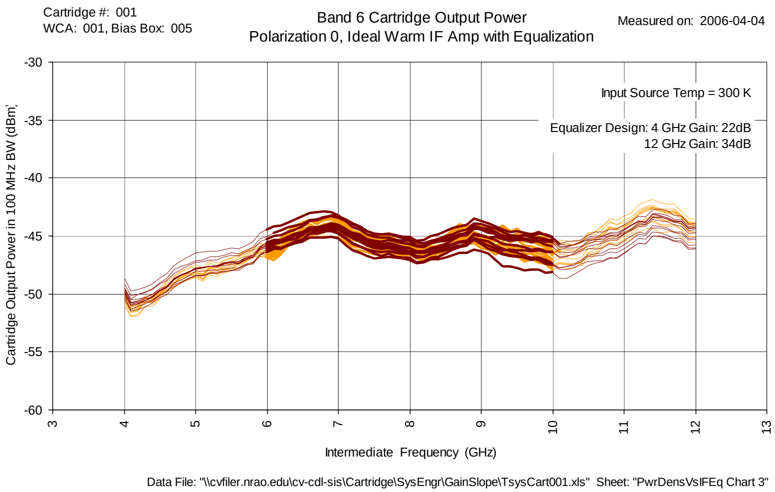
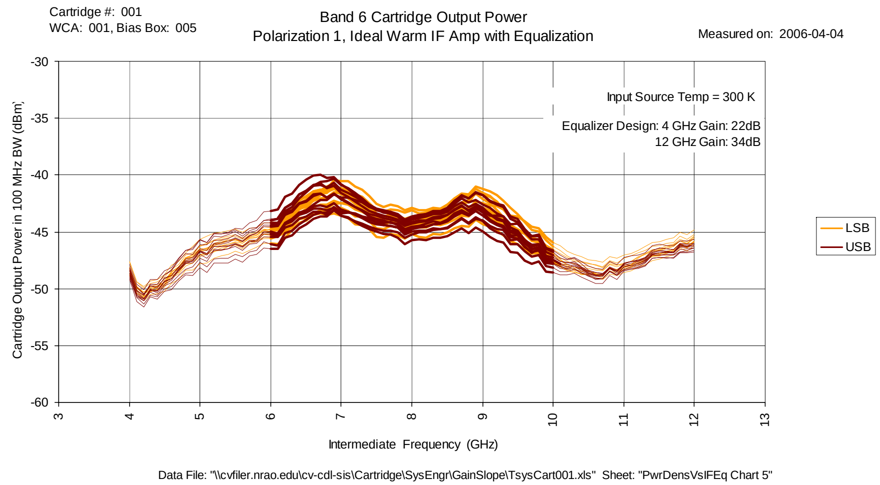
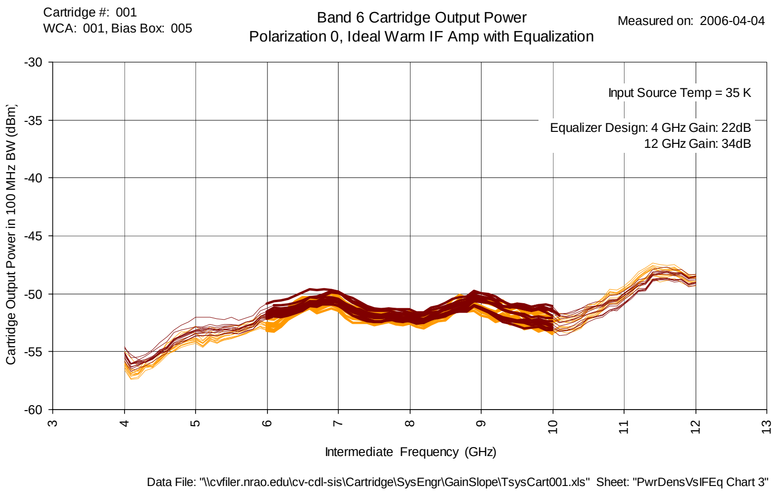
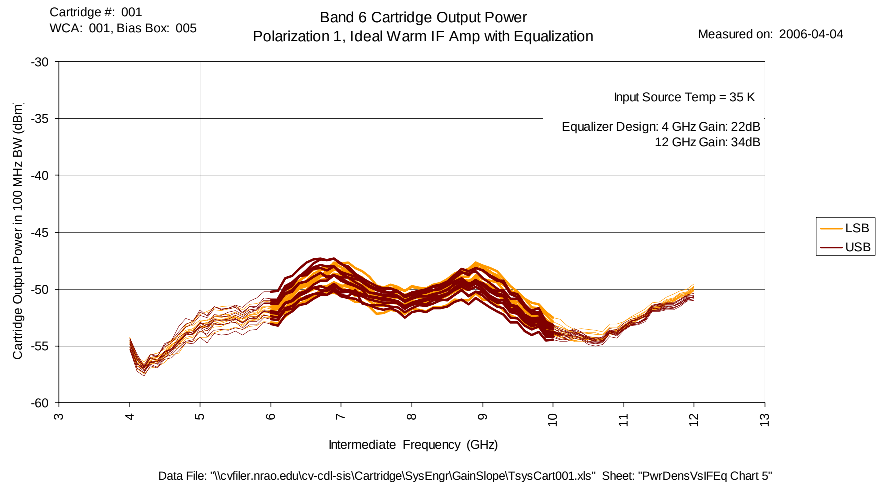
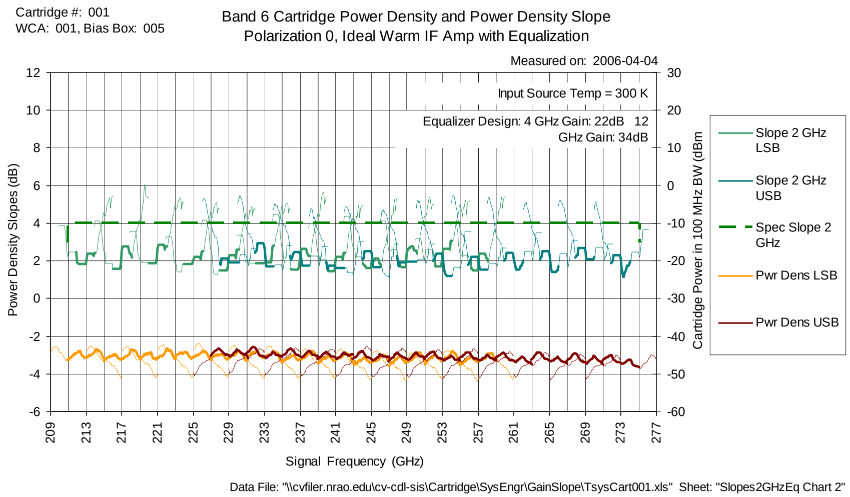
<tr><td>$T_{sky} + T_{spillover} = 300K$</td><td>
</td><td>
</td></tr>
<tr><td>$T_{sky} + T_{spillover} = 35K$</td><td>
</td><td>
</td></tr>
</table>

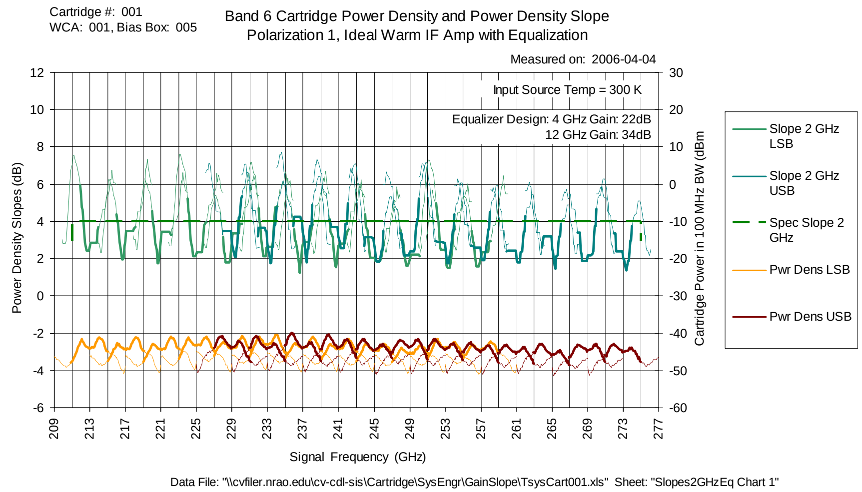
## Figure 5: Gain Slope in 2 GHz IF Bandwidth, Assuming Equalizers in Warm IF Amps

### $T_{sky} + T_{spillover} = 300K$

**Polarization 0**

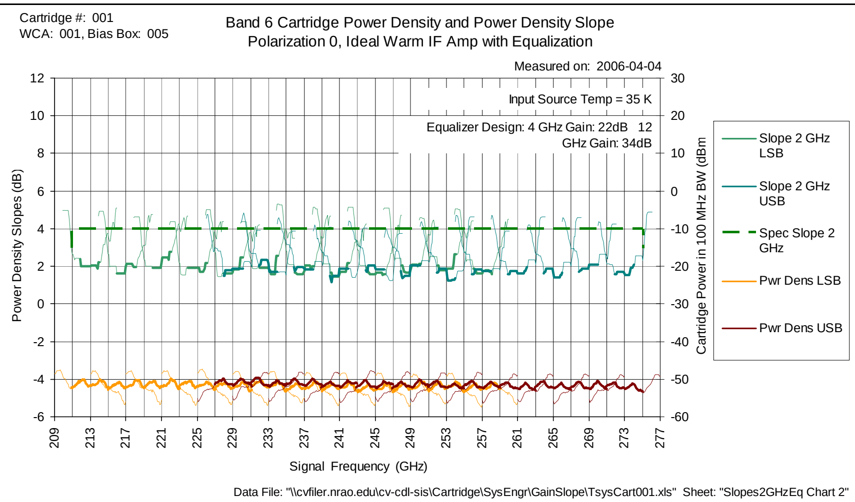



**Polarization 1**

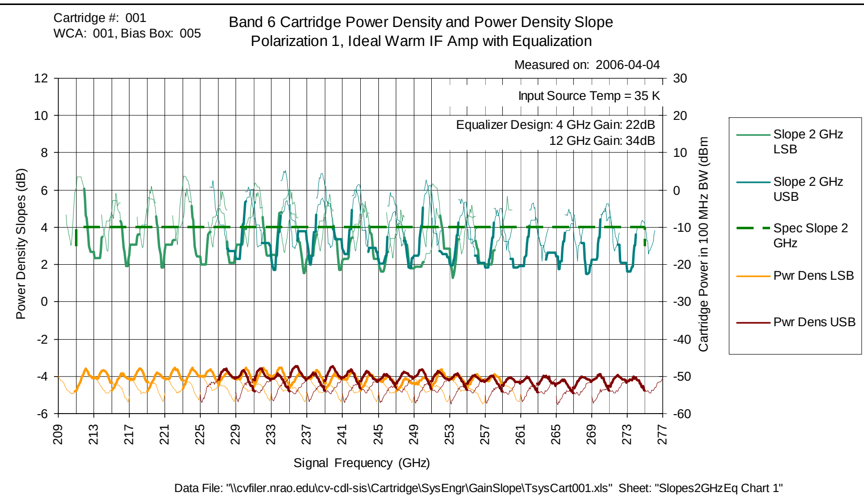



### $T_{sky} + T_{spillover} = 35K$

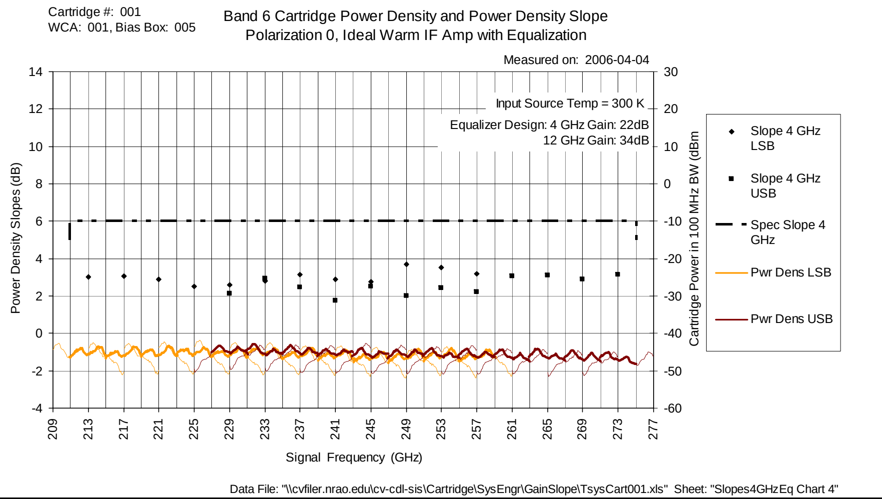
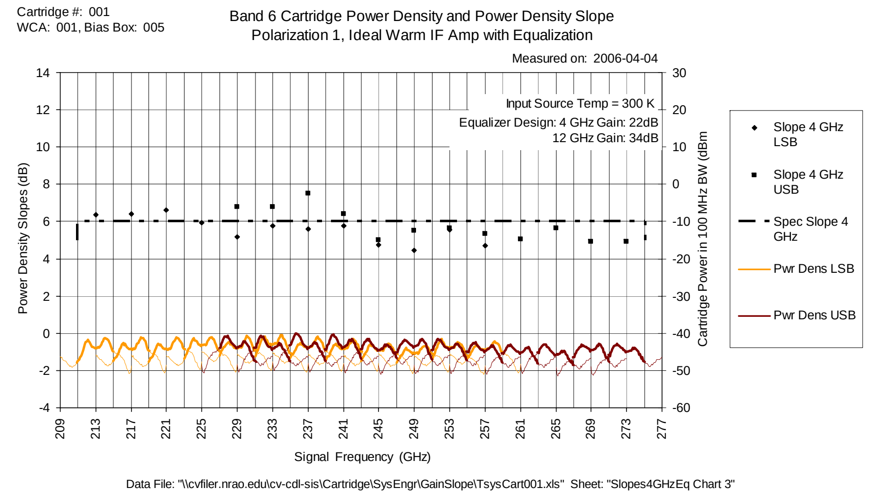
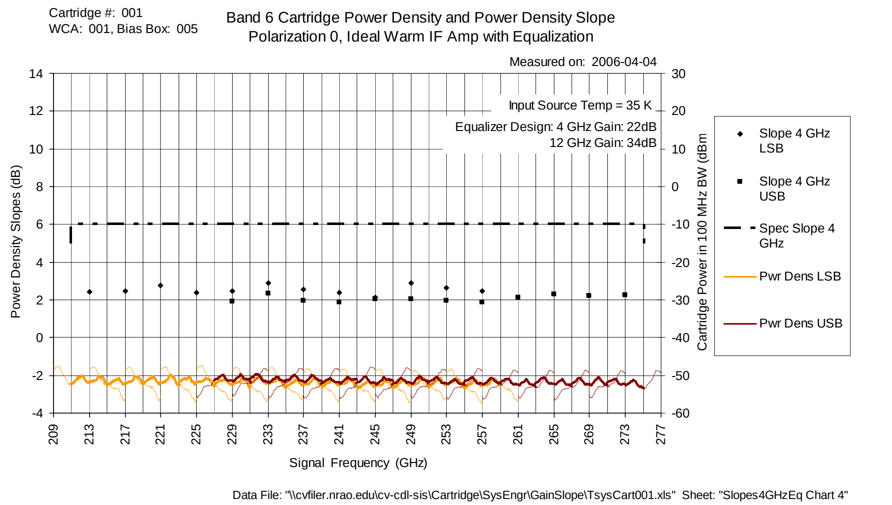
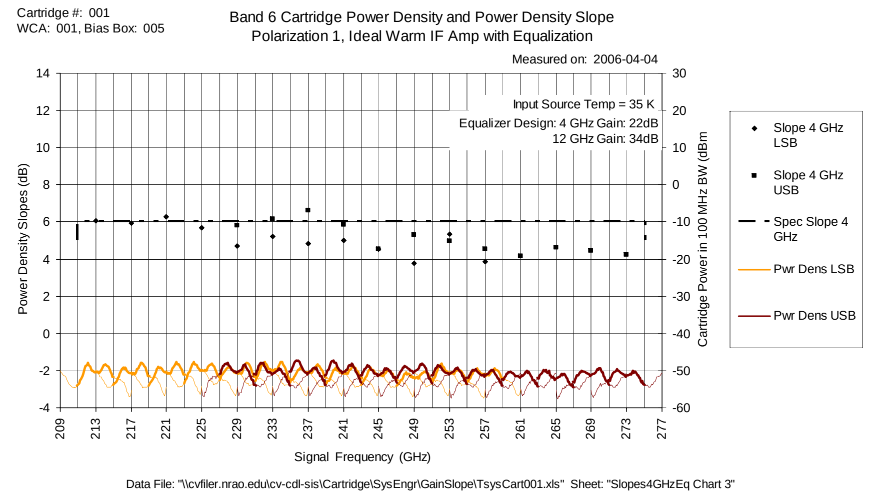
**Polarization 0**




**Polarization 1**



## Figure 6: Gain Slope in 4 GHz IF Bandwidth, Assuming Equalizers in Warm IF Amps

| | Polarization 0 | Polarization 1 |
|---|---|---|
| $T_{sky} + T_{spillover} = 300K$ |  |  |
| $T_{sky} + T_{spillover} = 35K$ |  |  |

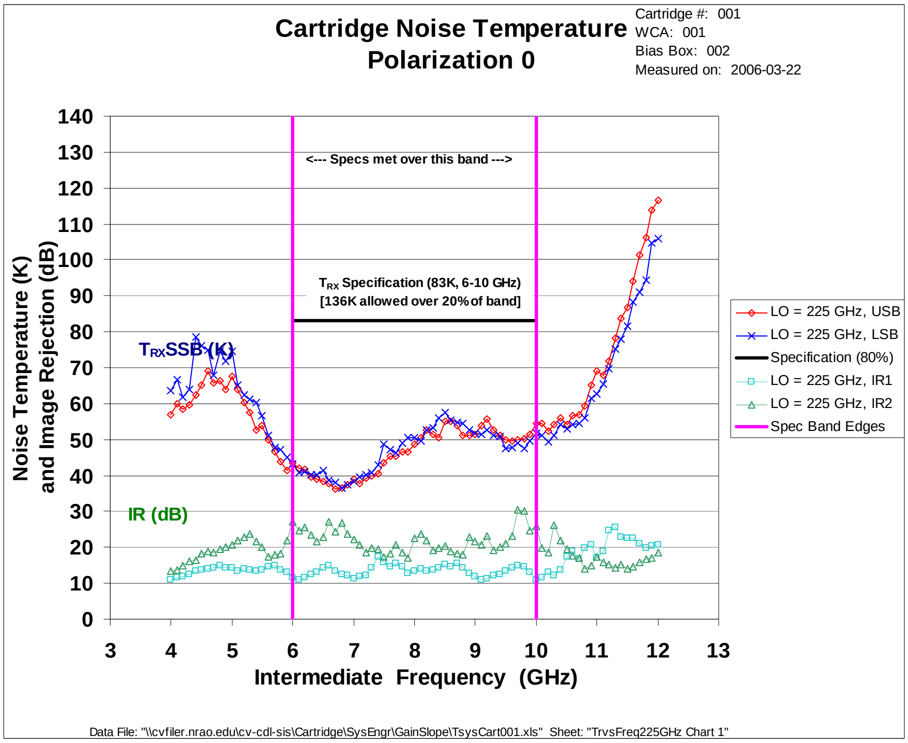



**Figure 7: Receiver Noise Temperature for LO = 225 GHz, Pol 0**

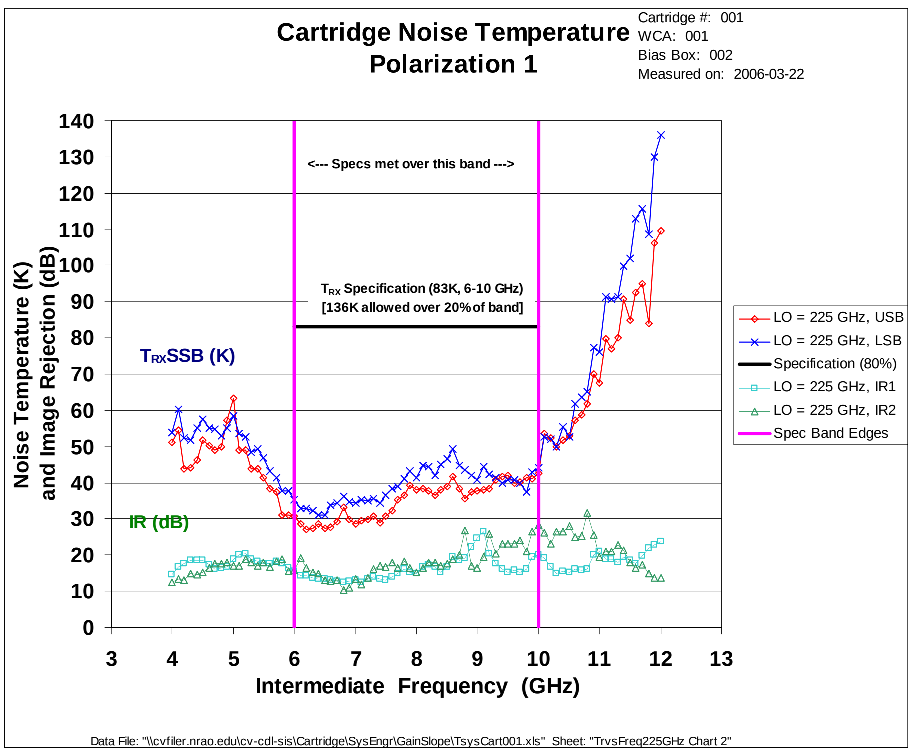



**Figure 8: Receiver Noise Temperature for LO = 225 GHz, Pol 1**