

A Cryogenic Integrated Noise Calibration and Coupler Module for the GBT K-Band Focal Plane Array (KFPA): Critical Design Review

**Eric Bryerton
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1. Introduction

Noise calibration on cryogenic radio astronomy receivers has traditionally been performed using noise diodes placed outside the cryostat and routed through an attenuator into the dewar and injected into the signal path before the cold LNA through a coupler (typically ~30 dB). For a focal plane array receiver such as the GBT K-band focal plane array (KFPA), this method of noise injection vastly complicates the cable and waveguide routing inside the cryostat as well as adds extra dewar feedthrough transitions. It is highly desirable to integrate the noise generator with the coupler on the cold stage, eliminating all the associated cabling. Also, integrating the noise source with the noise coupler should result in less frequency structure and therefore more accurate calibrations.

The conceptual design report [1] described results on a noise calibration module test block, which was simply the LNA packaged in a WR-42 housing with no integrated coupler. This test block was measured in a cryogenic test dewar and was shown to produce the necessary noise output within the specified power dissipation.

This critical design report describes the design, construction, and testing of the Noise Calibration Module (NCM) used in the single-pixel prototype of the GBT KFPA (KFPA-1). This module uses the same MMIC LNA as the test block from [1], but integrated with a coupler to inject the specified amount of noise into both channels of a single pixel. Section 2 gives the technical specifications of the NCM. Section 3 describes the design and construction of the NCM. Section 4 reports the measured performance of the NCM both in a cryogenic test dewar and as part of the complete KFPA-1. Section 5 gives the production plan for the seven NCMs needed for the 7-pixel KFPA (KFPA-7), including schedule, test plan, and compliance matrix.

2. Noise Calibration Module Interfaces and Engineering Specifications

Below is a list of the interfaces/engineering specifications for the KFPA NCM.

- RF In/Out: WR42 waveguide, UG595/U Flange Equivalent
- RF Channel Isolation: 40 dB minimum
- Equivalent Injected Noise: 1.5-6.0K (at output of coupler, injected into LNA)
 - Typical system temperature about 40K, want noise cal to be ~5% of that
- Dissipated Power: 15 mW maximum to the refrigerator 15K stage
- Response Time: 100 us maximum rise/fall

- Stability: +/- 3% over 4 hours
- NOT CAL: TTL Low -> Injected Noise ON
- Electrical / Bias Supply Interface: Connector is an ITT Cannon MTB1-5SS (Pin #1,5=Ground; 2,4=VGS; 5=VDS and therefore symmetric and not necessary to be keyed.) NCM bias supply shall be a constant gate voltage supply. Typical bias is VDS=0.71V, VGS=-0.53V, IDS=6mA.
- Monitor and Control Interface: The M/C subsystem shall monitor VDS, VGS, and IDS for each of the seven NCMs. The M/C subsystem shall have the ability to independently vary, for each of the seven NCMs, VDS from 0 to 1.5V and VGS from -1.0 to 0 V. For NOT CAL = TTL Low, M/C subsystem shall set VDS=VDS(ON). For NOT CAL = TTL High, M/C subsystem shall set VDS=0V. VGS shall always remain at nominal value.

3. Design Description

The fundamental noise source is a commercial off-the-shelf (COTS) MMIC LNA from United Monolithic Semiconductor (UMS), part number CHA2092b. The LNA, at 15K ambient temperature, generates a fairly flat noise output over 18-26 GHz. For a bias of approximately 0.7V, 6mA, the output noise of the LNA is about 1000+/-500K over the whole band. The output of the LNA is bonded to an Alumina microstrip to WR-12 transition. The noise is then coupled into the signal path of both channels through a six-port waveguide Bethe hole coupler.

The WR-12 six-port Bethe hole coupler is shown in Fig. 1. The output of the MMIC LNA goes to P1. P4 and P6 are the two receiver channels coming from the OMT. P3 and P5 are the two receiver channels going to the isolator and LNA. P2 goes to a MF-116 waveguide load to absorb the uncoupled power from the noise source. CST Microwave Studio simulation results for the coupler are shown in Figs. 2-4. From 18-26.5 GHz, the coupling (S31 and S51) is -30.5 +/- 0.5 dB. The input match to the noise source and main signal paths is lower than -40 dB, the directivity is greater than 20 dB, and the RF channel isolation is lower than -60dB.

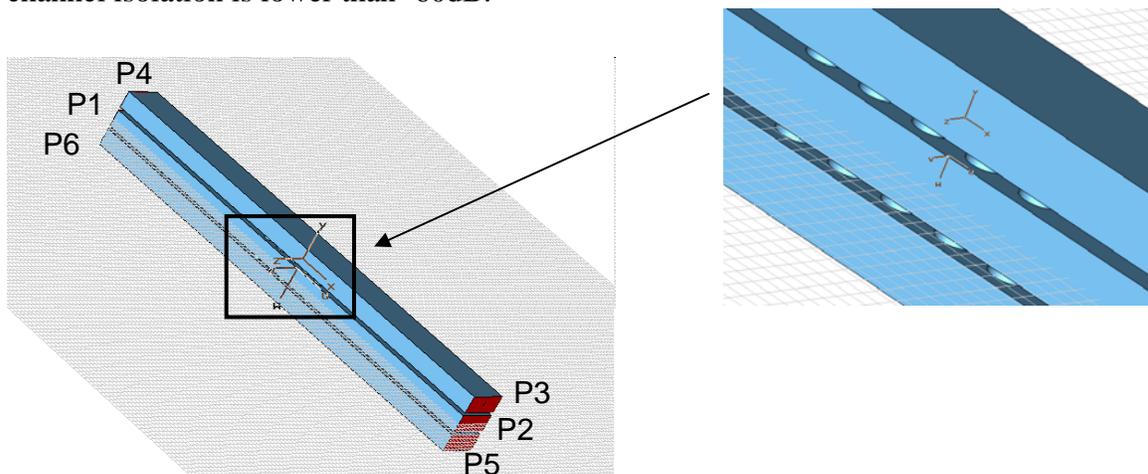


Figure 1 Drawing of Bethe hole coupler geometry simulated in CST Microwave Studio.

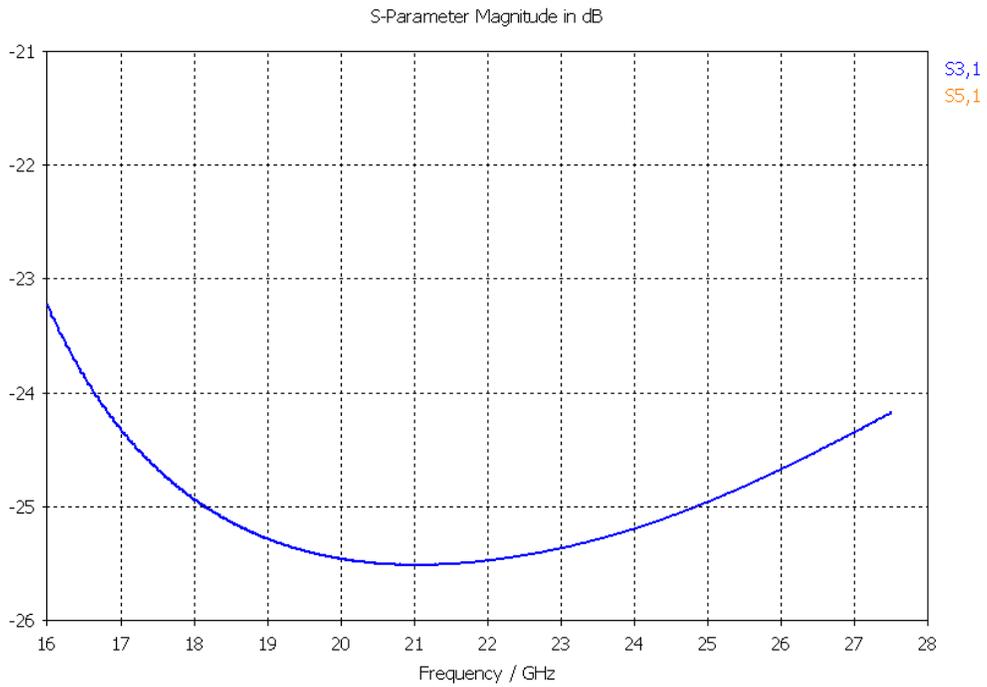


Figure 2 Simulated coupling of noise output to both main signal paths (S31 and S51).

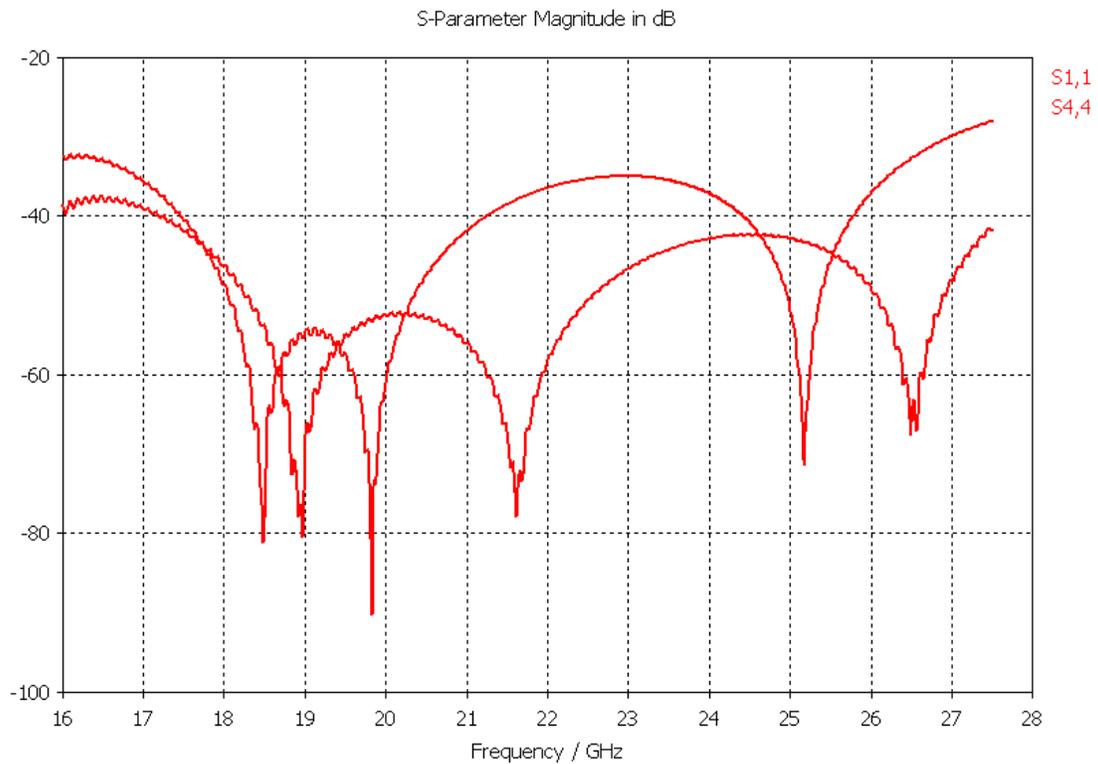


Figure 3 Simulated input match presented to noise source and to main signal path (S11 and S44).

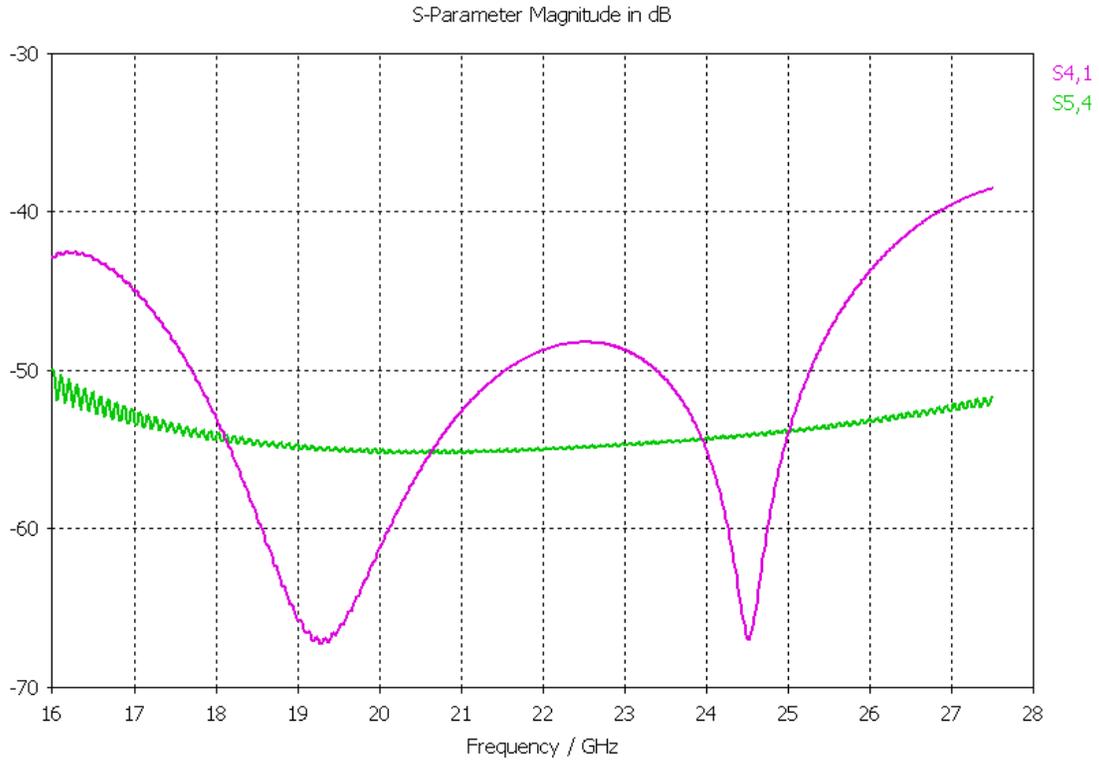


Figure 4 Simulated directivity (S41) and RF channel-to-channel isolation (S54).

A single NCM was fabricated from aluminum as a split-block assembly and gold plated. Photographs of the completed module are shown in Figs. 5-6.

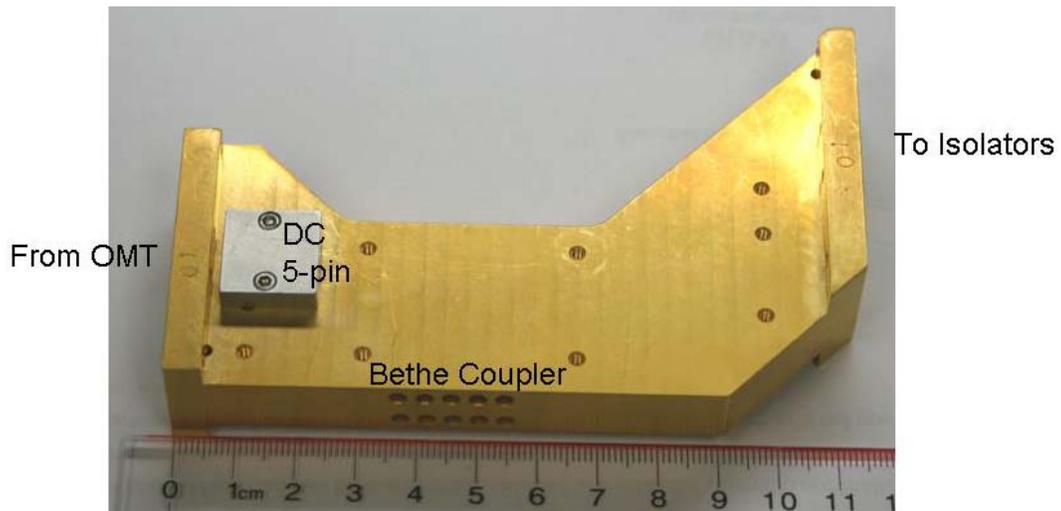


Figure 5 Photograph of KFPA NCM prototype.



Figure 6 Photograph of inside KFPA NCM prototype.

4. Single Pixel Receiver Results

The return loss and insertion loss was measured for the NCM with a network analyzer. Return loss measurements are shown in Fig. 7 for each channel. The return loss of a matched K-band load was also measured and is shown to indicate the quality of the network analyzer calibration. As shown, the return loss for each channel is better than 20dB across the entire band. The measured insertion loss of both channels is shown in Fig. 5. This is measured at room temperature. At cryogenic operating temperature, the insertion loss should be even less.

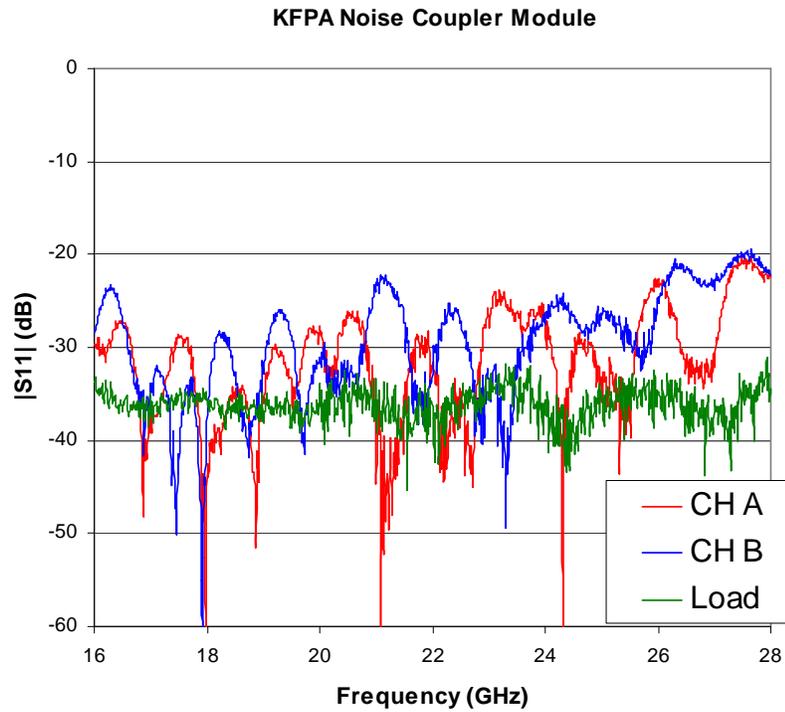


Figure 7 Measured return loss (S11) of KFPA NCM prototype for each channel compared to measured return loss of matched waveguide load.

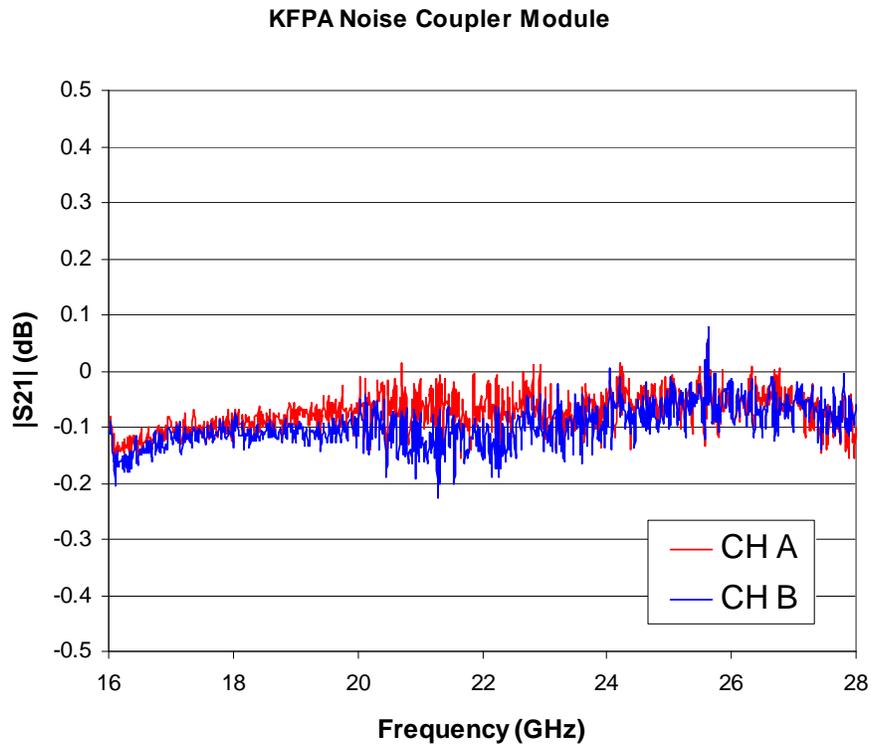


Figure 8 Measured insertion loss (S21) of KFPA NCM prototype for each channel.

The NCM was then placed in an amplifier test dewar for noise measurements. A photograph of the setup is shown in Fig. 9. As indicated in the photo labels, the noise cal module and LNA did not get quite as cold as they will in the actual KFPA receiver due to poor thermal strapping of these modules in the test dewar, but they were cold enough to prove proper noise injection. In this test, the NCM operates in the same manner as the actual receiver—the NCM is placed in front of the LNA and injects noise into the system at this point. By measuring the difference in receiver noise temperature between when the NCM is biased on and when it is biased off, the injected noise can be calculated.

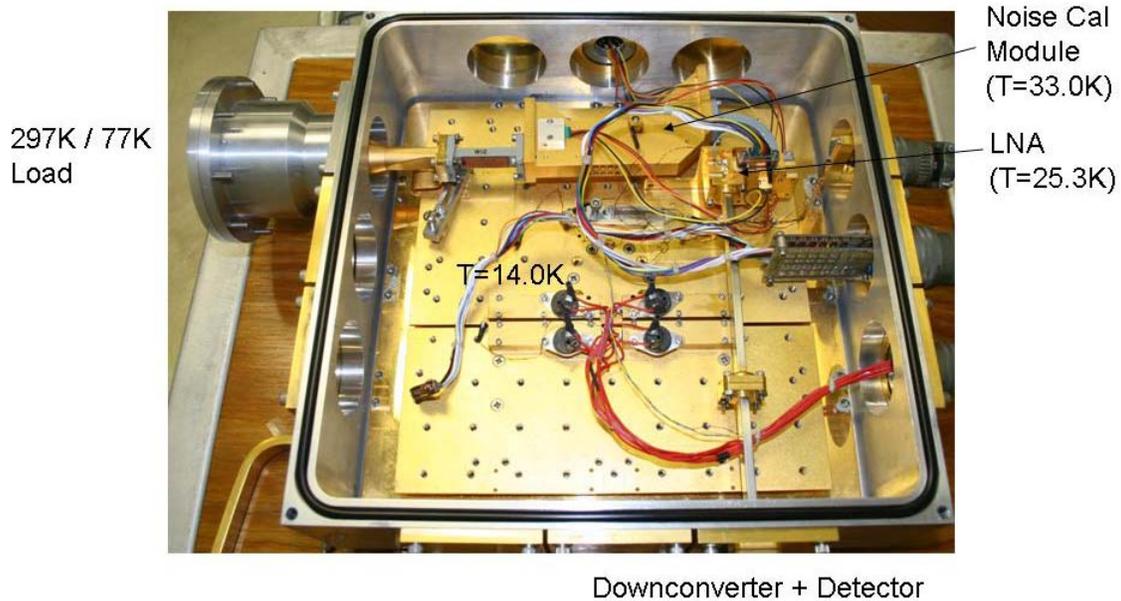


Figure 9 Photograph of amplifier test dewar used to measure injected noise of KFPA NCM prototype.

Fig. 10 shows the measured injected noise from the NCM to be between 2 and 7 K over the entire band. This level of noise is accomplished with a total power dissipation in the NCM of only 4.2mW, much less than the specified 15mW.

**KFPA Noise Cal Module #1
(Noise Cal ON - Noise Cal OFF)**

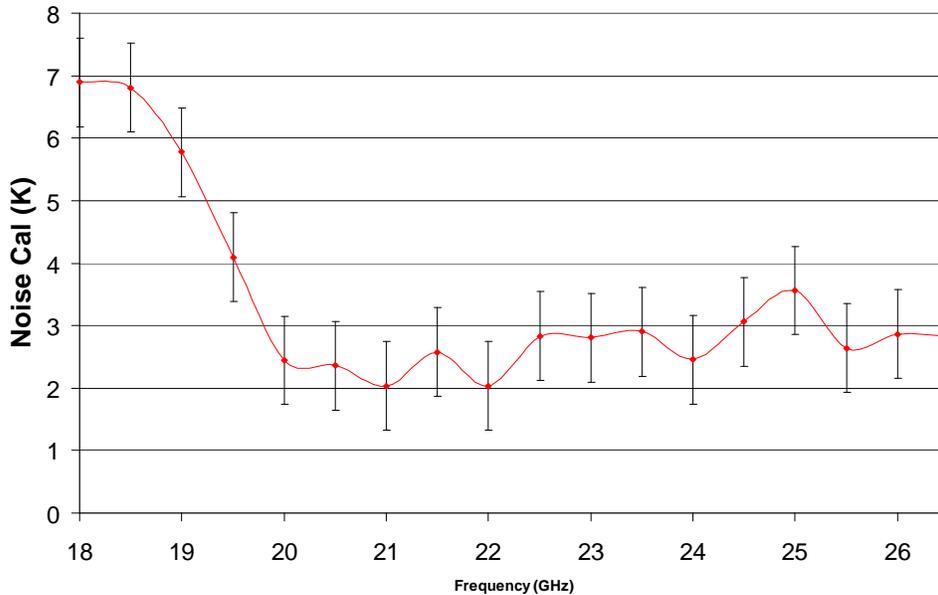


Figure 10 Measured injected noise of KFPA NCM prototype versus frequency. KFPA bias is $V_{DS}=0.71V$, $V_{GS}=-0.53V$, $I_{DS}=6mA$.

This NCM was then integrated into the single-pixel KFPA receiver (KFPA-1) at Green Bank. Receiver noise of the entire single pixel receiver was measured in the lab. The NCM is biased with a constant voltage supply, so V_{GS} stays constant while V_{DS} switched from zero to its nominal value (0.667 V in this case). IF power was recorded with a spectrum analyzer at four different LO frequencies. For each LO frequency, the IF power was measured four times—(1) room temp load, cal ON; (2) room temp load, cal OFF; (3) cold load, cal ON; (4) cold load, cal OFF. A noise temperature was calculated for cal OFF and cal ON at each LO frequency. The difference in these noise temperatures is the injected noise, or T_{cal} , and is plotted in Figs. 11 and 12. The trace shown is for 40 MHz averages. The measured T_{cal} is very similar for both the LCP and RCP channels, as expected from the symmetry of the six-port Bethe coupler. Note that V_{DS} remained constant for all four LO frequencies. To meet the specification of T_{cal} between 1.5-6.0K, V_{DS} can be adjusted as a function of frequency. For any given 2 GHz bandwidth, V_{DS} could most likely be adjusted to give T_{cal} within the specified 1.5-6.0K. Probably only two or three values of V_{DS} need to be characterized to accomplish this. Aside from this, it is actually advantageous to have a few different levels of T_{cal} for different types of astronomical observations.

KFPA LCP

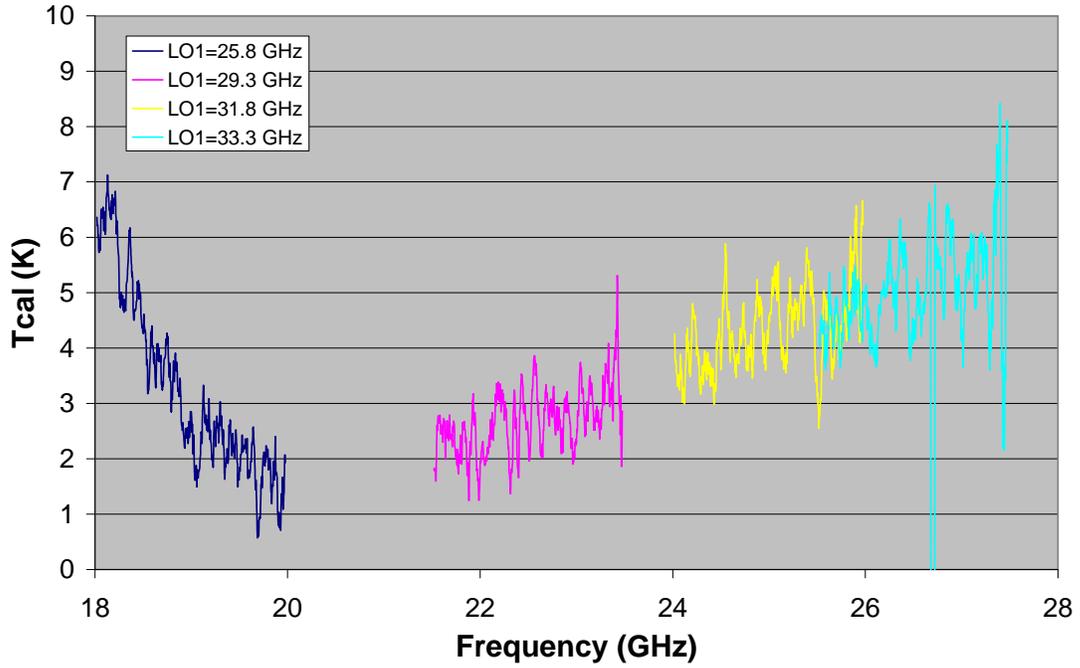


Figure 11 Measured injected noise in LCP channel of KFPA NCM in KFPA single-pixel receiver.

KFPA RCP

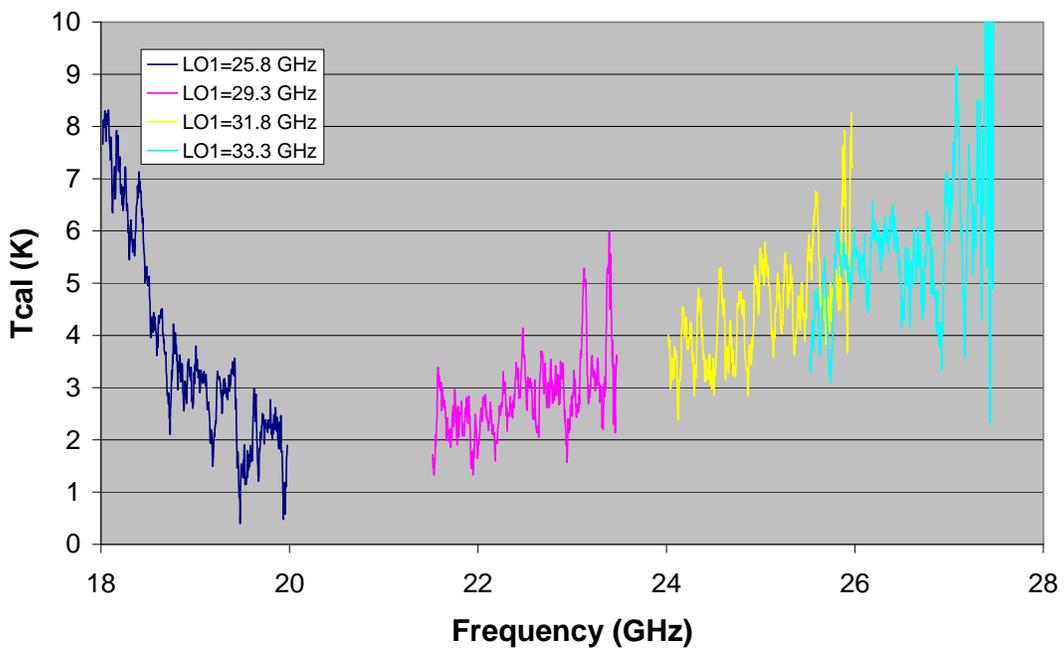


Figure 12 Measured injected noise in RCP channel of KFPA NCM in KFPA single-pixel receiver.

Fig. 13 shows the measured T_{cal} compared to the measured T_{cal} for the exiting GBT K-band receiver (K0). The K0 receiver has a traditional noise calibration architecture, where a noise diode outside the dewar at room temperature is injected into the signal path via a cold coupler inside the dewar. As shown, the KFPA-1 T_{cal} is much smoother and contains less fine frequency structure. Also shown is a fourth degree polynomial fit to the KFPA-1 T_{cal} showing how easily the T_{cal} spectrum can be modeled when it is this smooth. The standard deviation of the difference between the actual measurement and the polynomial fit is 7.5% of the T_{cal} value. This 7.5% is the error one would have in using this polynomial model of T_{cal} rather than using an astronomical calibration to determine T_{cal} versus frequency.

Measured Tcal of Current GBT K-Band Receiver vs. KFPA

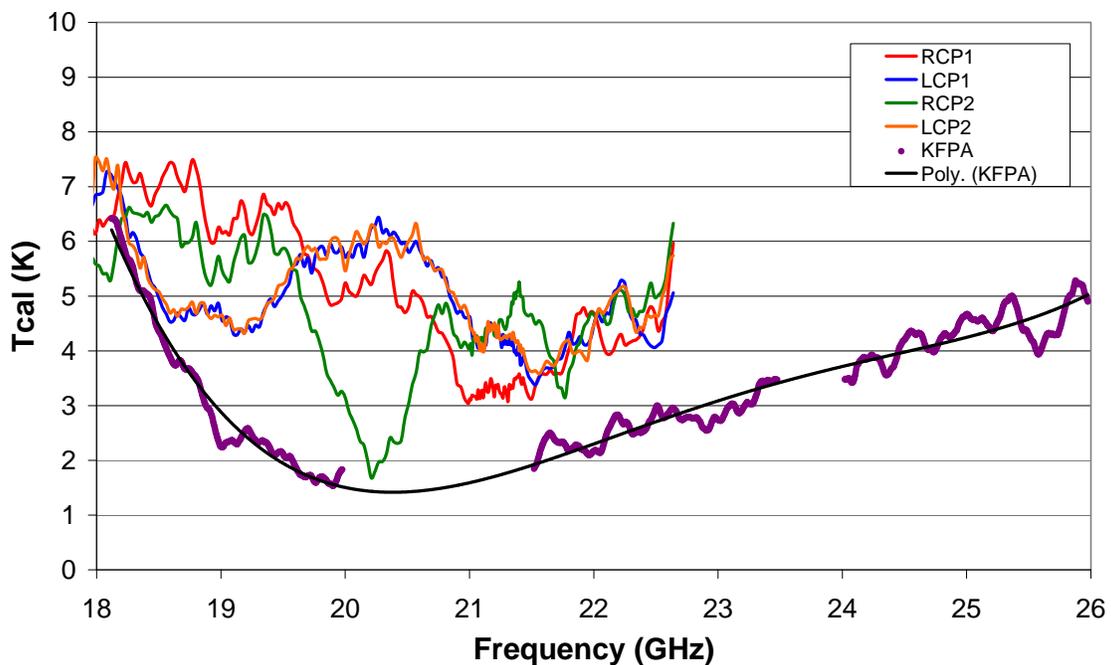


Figure 13 Measured injected noise (200 MHz averages) of the KFPA-1 NCM in the KFPA single-pixel receiver (KFPA-1) versus frequency compared to measured T_{cal} of the existing K-band GBT receiver (K0). Also shown is a fourth degree polynomial fit to the KFPA-1 NCM data.

Fig. 14 shows the NCM T_{cal} measured in the lab on four different dates. Between 9/4/08 and 9/25/08 the nominal value for VDS was increased. For the next three measurements, VDS remained constant. This shows the relative stability of the noise output over a period of one month.

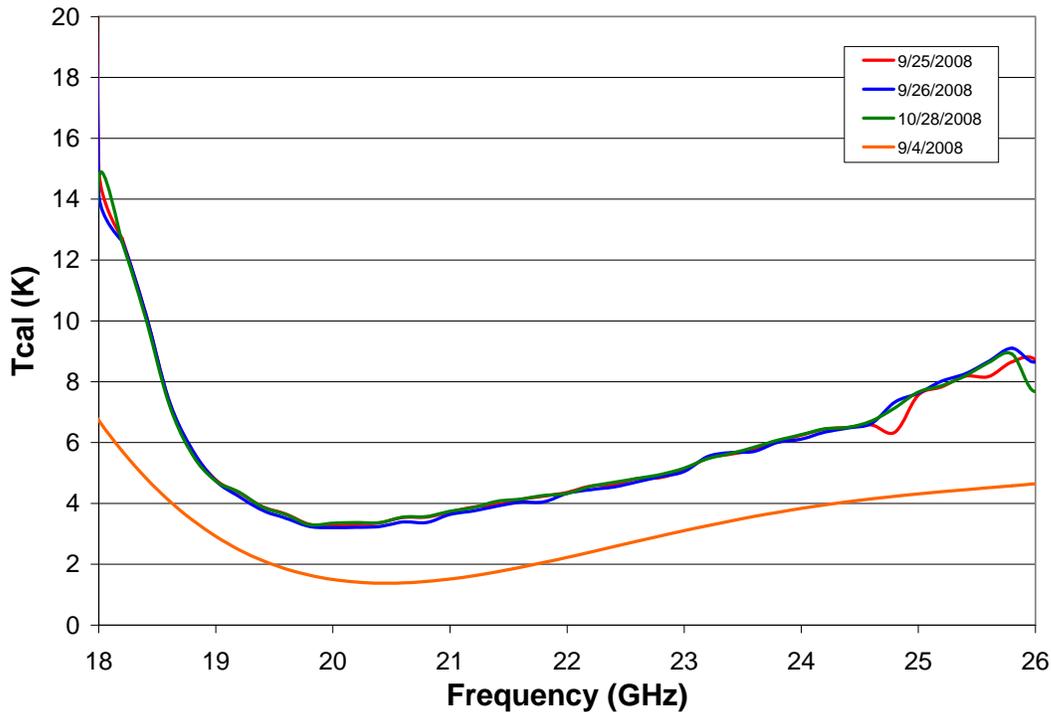


Figure 14 Measured T_{cal} of KFP A NCM in KFP A single-pixel receiver on four different days of laboratory testing. Between 9/4/08 and 9/25/08, NCM VDS bias was increased.

5. Production and Test Plan for Seven Pixel Receiver

5.1. Production Schedule and Resources

According to the schedule, delivery of the seven production NCMs is due in June 2009. After CDR approval of the design, production will begin. Production schedule for the NCMs is as follows:

31-Jan-09	CDR approval, production can begin
13-Mar-09	NCM blocks machined (using NRAO-CV machine shop)
27-Mar-09	NCM blocks plated
17-Apr-09	Units 1-3 assembled
8-May-09	Testing of units 1-3 complete; deliver units 1-3
8-May-09	Units 4-5 assembled
22-May-09	Testing of units 4-5 complete; deliver units 4-5
22-May-09	Units 6-7 assembled
5-June-09	Testing of units 6-7 complete; deliver units 6-7

Machining will be done by the NRAO-NTC machine shop. Plating will also be done at the NRAO-NTC. However, either of these jobs could be sent to outside vendors if the in-

house workload prevents NTC from doing the work. Microassembly will be done by Tod Boyd of NRAO-NTC, who assembled the test block and single pixel unit. Microassembly could also be sent to outside vendors. Two companies have already been qualified for this type of work by the ALMA project. However, the microassembly needed for the NCM is a fairly small effort and should not be a problem to fit into Tod's schedule. All the parts needed for microassembly of all seven units, i.e. MMICs, transitions, loads, have already been procured. Verification testing will be done by Eric Bryerton at the NRAO-NTC.

5.2. Test Plan

Each unit will undergo the following verification tests after assembly:

- (1) Return loss and insertion loss of both channels using network analyzer
- (2) Noise injection in cryogenic test dewar

Both these verification tests are identical to those performed on the single pixel unit described in section 4. Other specifications are considered verified by testing of the single pixel unit or the test block; or by design and/or simulation

5.3. Spares

The seven production units will be identical to the single-pixel prototype described in this report. The single-pixel prototype will therefore serve as a spare.

5.4. Compliance Matrix

Item	Specification	Verification Method / Notes on Compliance
RF In/Out	WR-42, UG595/U Flange Equivalent	By design. See KFPA NCM chassis drawing.
RF Channel Isolation	40dB minimum	By simulation [see Fig. 4]. Level too low to be measured accurately.
Equivalent Injected Noise	1.5-6.0K	Unit testing. Unit #1 was non-compliant below 18.5 GHz, see Figs. 10-12, when constant bias is applied across the entire band. If bias is adjusted, injected noise can be tuned to be between 1.5-6.0K over any 2 GHz bandwidth.
Dissipated Power	15mW maximum	Unit testing. Single-pixel unit was compliant, see Section 4.
Response Time	100us max rise/fall	By design. Test block testing [1] showed response

		time limited by bias supply. RC time constants of bias circuits, both on and off MMIC, are significantly less than this time.
Stability	+/-3% over 4 hours	Testing of test block [1].
NOT CAL	TTL Low -> Injected Noise ON	By design. See Monitor and Control interface specification in section 2.

6. References

[1] E. Bryerton, "A cryogenic integrated noise calibration and coupler module for the GBT K-band focal plane array (KFPA): conceptual design review," Feb. 19, 2008 (https://safe.nrao.edu/wiki/bin/view/Kbandfpa/ConceptualDesignReview/KFPA_Noise_Calibration_-_CoDR_Report.pdf)