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Calibration Plan of the GBT 4mm Receiver

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ABSTRACT

The memo discusses the calibration plan for the GBT 4 mm receiver. The specification to maintain better than about 3% relative calibration of the instrument drives the calibration strategies and design of the instrument. We plan to adopt a three load calibration system (cold, ambient, and sky). By using the cold and ambient loads we can accurately calibrate the system gains and expect relative calibration uncertainties on the derived T_A^* antenna temperature scale of order 1–3%. With the addition of the sky-load, we can monitor the weather conditions and verify the self-consitency of the calibration solution with the adopted opacity and astmospheric temperature.

1. Background

Historically, noise diodes have been used to calibrate data taken at cm wavelengths, while the chopper-wheel/vane method (e.g., Kutner & Ulich 1981) has been used at mm wavelengths. The 4 mm receiver working group has decided to use the chopper-wheel/vane method of calibration and avoid the use of a noise diode. This significantly simplifies the design of the system. The VLBA group has concurred that a noise diode is not required, but there will be additional overheads required to calibrate the data with the chopper-wheel/vane method (a calibration scan of length 40-50 s [TBD] is expected every 10-60 minutes [TBD]). We follow the nomenclature of Kutner & Ulich (1981) [KU81] for consistency.

2. Calibration Specifications

We provide four specifications related to the calibration of the receiver output voltage into a physical temperature on the sky. The first two specifications are on the receiver gain stability. Assuming the long-term and short-term stability of the receiver gains are well behaved, the 3% specification for the relative antenna temperature scale will drive the design and the choice of calibration techniques. The 15% absolute calibration specification is more dependent on the amount of engineering and observing time available for measurements than the details of the system design.

1. **Short-term gain stability** – A short-term gain stability of the receiver output in volts shall be better than 1% over times of less than 10 seconds.

2. **Long-term gain stability** – The receiver drifts shall be well behaved such that one can calibrate out the drift for time scales of at least 10 minutes from a simple linear interpolation between two measurements to better than 1%. The long-term gain stability of the instrument will determine how often calibration scans are needed.

3. **Relative antenna temperature scale** – The conversion of measured instrumental volts into the antenna temperature scale corrected for atmospheric attenuation ($T'_A = \eta_l T^*_A$) shall be measured to 3% accuracy. This specification reflects the repeatability of making relative measurements with the instrument. The output temperature scale of the GBT data taken with the 4 mm receiver shall be in units of T^*_A, but this 3% accuracy specification is explicitly for T'_A (i.e., does not include our ability to measure η_l [ohmic losses and rearward spillover and scattering]).

4. **Absolute temperature scale** – The derivation of the telescope-independent absolute temperature scale depends on measurements of planets of known brightness and the derivations of several telescope efficiencies. The calibration goal is to provide absolute calibration at the 15% level. This specification implies that we need to measure the effective main-beam efficiency ($\eta_{mb} = \eta_c * \eta_{fss}$) with an accuracy of 15%; $T_{mb} = T^*_A/\eta_{mb}$.

3. One Load Versus Two Loads

The chopper-load/vane calibration method chopping between an ambient load and the sky ("one load") technique has been adopted by many observatories since the measurement of T^*_A is nearly independent of airmass, opacity, and η_l, assuming the atmosphere temperature is similar to the ambient and spillover temperatures. The main uncertainty in this method is the estimation of the effective atmospheric temperature. An additional complication is that for observations with significant opacity, the differences between the ambient temperature and the effective sky temperature are small enough such that the fractional calibration errors on the gain factors can be significant. A two load (cold + ambient) calibration method has the advantage of more accurate calibration of the gains that are independent of the atmosphere. The disadvantage of the method is that the opacity needs to be applied in computation of T^*_A, so errors in opacity directly effect the calibration scale.

To test the relative merits of the one-load versus two-load systems, we have computed the expected errors on the resulting T^*_A scale. The relationship for T^*_A is given by

$$T^*_A = g(V_{\rm on} - V_{\rm off})\exp(\tau_o A)\eta_l^{-1}, \quad (1)$$

where the gain g is the scaling factor between the measured temperature scale and measured voltages, τ_o is the zenith opacity, and A is the airmass. The relationship assumes the Raleigh-Jeans approximation (sufficient for the discussion here) and is for a single-sideband instrument (the 4 mm instrument is single side-band only). Equation A12 of KU81 provides a more general relationship for T_A^*.

The gain is given by

$$g = (T_1 - T_{2)})/(V_1 - V_2), \tag{2}$$

where the index 1 refers to the ambient load. For the two-load system, index 2 refers to the cold load, while 2 corresponds to the load from the sky for the one-load system. We assume the gain errors are dominated by the measurement of the temperature differences (and any instabilities of the receiver voltages are negligible).

For the one-load system, the errors on the gains represent the errors in measuring $(T_{\rm amb} - T_{\rm sky})$, where "amb" is the ambient load and "sky" is the sky load. The temperature of the sky is

$$T_{\rm sky} = T_{\rm atm}[1 - \exp(-\tau_o A)] + T_{bg} \exp(-\tau_o A) \tag{3}$$

where the $T_{\rm atm}$ is the effective temperature of the atmosphere and T_{bg} is the microwave background temperature of 2.73 K. Ignoring the microwave background and assuming the spillover is at the ambient temperature, then

$$T_A^* \propto T_C \simeq T_{\rm atm} + (T_{\rm amb} - T_{\rm atm}) \exp(\tau_o A). \tag{4}$$

This represents equation A9 of KU81 and has been rewritten to show the dependency on $T_{\rm atm}$. The uncertainty of T_A^* is given by

$$\sigma^2(T_A^*) \simeq \sigma^2(T_{\rm atm}) + ([\sigma^2(T_{\rm amb}) + \sigma^2(T_{\rm atm})]/[T_{\rm amb} - T_{\rm atm}]^2 + [\sigma(\tau_o)A]^2)[(T_{\rm amb} - T_{\rm atm}) \exp(\tau_o A)]^2. \tag{5}$$

For the two-load system the error in T_A^* is dominated by the errors in the gain as well as the additional error in τ_o (equation 1), yielding an error relationship of [two-load]:

$$\sigma(T_A^*)/T_A^* \simeq ([\sigma(\tau_o)A]^2 + [\sigma^2(T_{\rm amb}) + \sigma^2(T_{\rm cold})]/[T_{\rm amb} - T_{\rm cold}]^2)^{0.5} \tag{6}$$

Figure 1 shows the calibration errors on T_A^* as a function of opacity and airmass for the two different calibration techniques. Based on Ron Maddalena's models and monitoring of the weather at Green Bank, we adopt $\sigma(T_{\rm atm}) = 5$ K and $\sigma(\tau_o)$ =0.006. We assume the temperature sensors are accurate to 1 K ($\sigma(T_{\rm amb}) = \sigma(T_{\rm cold}) = 1.0$ K, but the results are not that sensitive to the accuracy of the sensors). We adopt an effective atmospheric temperature of 270 K, an ambient temperature of 285 K, and a cold load temperature of 20 K. The accuracy of the two-load solution is very dependent $\sigma(\tau_o)$, while the accuracy of the one-load temperature depends significantly on $\sigma(T_{\rm atm})$. At high airmass and moderate

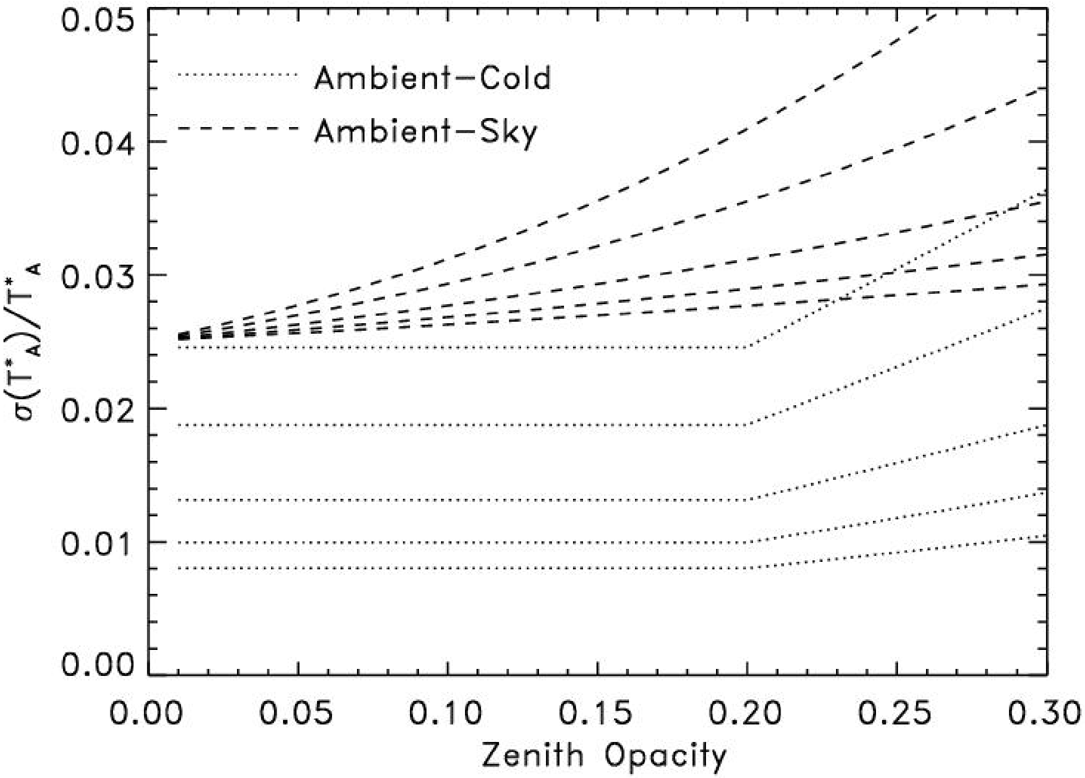

Fig. 1.— The fractional errors on $\sigma(T_A^*)$ as a function of zenith opacity for the two-load (Ambient-Cold) calibration system (dotted-lines) and the one-load (Ambient-Sky) calibration system (dashed-lines). The curves are plotted for airmasses of 1.0, 1.4, 2, 3, and 4, from bottom to top, respectively. This assumes the nominal errors of $\sigma(T_{\rm atm}) = 5\,{\rm K}$ and $\sigma(\tau_o) = 0.006$ (for $\tau_o < 0.2$), based on estimates of the Green Bank weather models.

zenith opacities, the one-load system exceeds the 3% accuracy specification. These conditions would occur for observations at low declinations, such as the Galactic Center. Given that one of the primary science targets will be the Galactic Center, we need to consider a cold-load calibration system.

Figure 2 shows the errors for slightly higher uncertainty values for $\sigma(T_{\rm atm})$ and $\sigma(\tau_o)$. To meet the specification with the cold load system, we need to be able to estimate the opacity better than $\sigma(\tau_o) < 0.01$ for elevations greater than 20-25°. The one-load system requires an estimation of $T_{\rm atm}$ to better than 1.7% at elevations greater than 20° to meet the specification over moderate opacities.

By taking calibration data with all three loads (cold, ambient, and sky), we can potentially back out constraints on the atmospheric conditions. Without a cold load, we have limited calibration options and may not be able to meet our desired calibration specifications.

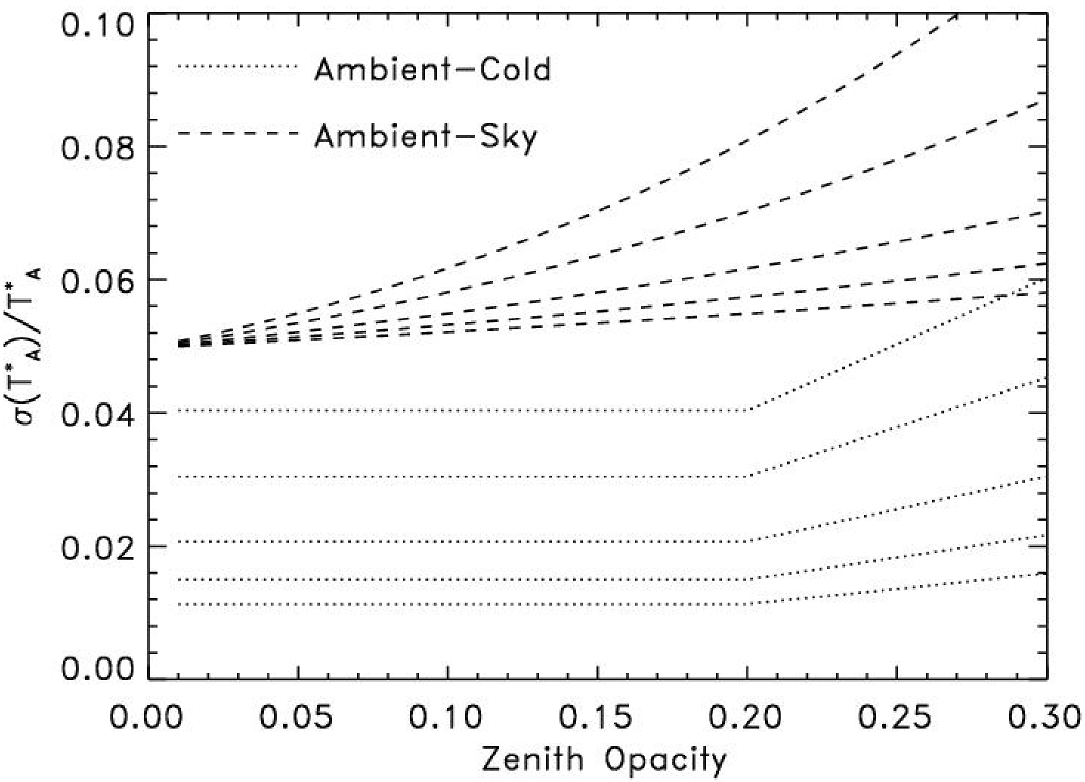

Fig. 2.— The fractional errors on $\sigma(T_A^*)$ as a function of zenith opacity for the Ambient-Cold (dotted-lines) and Ambient-Sky (dashed-lines) calibration systems. Lines are for the same airmasses given in Figure 1, but the curves represent larger uncertainties of $\sigma(T_{\rm atm}) = 10\,{\rm K}$ and $\sigma(\tau_o) = 0.01$.

4. Receiver Temperature

Using the cold load the receiver temperature can be estimated in the lab. An additional cold load absorber at liquid nitrogen temperature could be used to help constrain the effective temperature of the cold load, including losses through the window and spill-over. The receiver temperature is

$$T_{\rm rx} = (T_{\rm amb} - YT_{\rm cold})/(Y - 1), \tag{7}$$

where the "Y"-factor is

$$Y = (V_{\rm amb} - V_{\rm DCoff})/(V_{\rm cold} - V_{\rm DCoff}). \tag{8}$$

The voltage $V_{\rm DCoff}$ represents the DC-offset voltage which can arise from the backend even when there is no frontend signal (i.e., "zero"-level voltage).

5. System Temperature

The system temperature for the signal side-band is simply

$$T_{sys} = T_A^* V_{\rm off}/(V_{\rm on} - V_{\rm off}), \tag{9}$$

where T_A^* is given by equation 1.

6. Software System Specifications

The 4 mm system needs to support the DCR, spectrometer, GUPPI, and VLB backends. Most continuum science observations at 4 mm are expected to be carried out with Mustang. The DCR backend will be used for pointing, focus, and occasional tipping observations. Only one beam of the 4 mm system will be used for VLB observations.

The optical table of the 4 mm system will be able to place the sky, a cold load, and an ambient load into each of the two beams. The cold and ambient loads are 180 degrees apart on the table and can be alternated between the two beams. A typical calibration sequence will consist of the following:

1. Sky observations in both beams (off source)
2. Ambient-load observations in beam 1 and cold-load observations in beam 2
3. Ambient-load observations in beam 2 and cold-load observations in beam 1

The system shall be able to collect the data from the calibration sequence for each of the supported backends. Most observations will be done with the spectrometer. In addition to the observations provided by the calibration sequence, proper calibration requires real-time estimates of the current weather conditions (τ_o and T_{atm}) and system parameters such as telescope efficiencies.

6.1. Spectral Line Calibration with the Spectrometer

The spectral line data will be calibrated based on the calibration sequence taken with the spectrometer. With the minimum bandwidth of 12.5 MHz of the spectrometer, sufficient S/N is obtained with even short observations (< 10 s).

$$\sigma_T = T_{\rm sys}/\sqrt{\Delta\nu t}. \tag{10}$$

For system temperatures of 100 K, σ_T will be will less than 10 mK for integrations longer than 10 s. For 10 s of observations for each of the three sets of integrations within the calibration sequence (sky, cold, and ambient loads) and allowing time for movement and settling of the calibration wheel, the nominal calibration sequence will take about 40-50 s. Additional overheads related to recording the data and saving the data as GBT sdfits files shall be less than 10 s per calibration sequence. The calibration sequence will measure the voltage signals for each of the loads ($V_{\rm amb}$, $V_{\rm cold}$, and $V_{\rm sky}$) across the available bandpass. The measurements of the temperature sensors on the ambient-load and cold-load shall be recorded for each calibration sequence to better than 1 K.

The gain of the system shall be derived for each calibration sequence and saved.

$$g = (T_{\rm amb} - T_{\rm cold)}/(V_{\rm amb} - V_{\rm cold}). \tag{11}$$

The gain should be computed as a function of frequency across the available bandwidth per 1 MHz [TBD] interval. For high-resolution data, the average gain should be used across the bandwidth.

The effective receiver temperature shall be derived and saved for each calibration sequence (equation 7), where the Y-factor is a system parameter derived by lab measurements. For online data reduction, the gain factors derived from the last calibration sequence shall be used to derive the temperature scale of the current spectral line scan. For offline data reduction, the software system should be able to support the linear interpolation of the gains between two calibration sequences.

The software system shall support the T_A, T'_A, and T^*_A, and T_{mb} temperature scales.

$$T^*_A = T'_A \eta_l^{-1} = T_A \exp(\tau_o A) \eta_l^{-1} = \eta_{mb} T_{mb}. \tag{12}$$

The default temperature scale shall be T^*_A. To derive T^*_A, the system needs an estimate of the zenith opacity from the weather database. The system shall support the conversion of the temperature scales into Jansky units appropriate for point sources using, e.g.,:

$$S_\nu = \frac{2kT^*_A \eta_l}{\eta_a A_{\rm geom}}, \tag{13}$$

where k is the Boltzmann constant, η_a is the aperture efficiency, and the geometric area of the telescope area is $A_{\rm geom}$.

The following parameters need to be saved within the sdfits file of every spectral line scan.

- $T_{\rm amb}$ derived from the ambient-load sensor during the calibration sequence.
- $T_{\rm cold}$ derived from the cold-load sensor during the calibration sequence.
- $V_{\rm amb}$ measured during the calibration sequence.

- V_{cold} measured during the calibration sequence.
- V_{sky} measured during the calibration sequence.
- T_{rx} – receiver temperature calculated by equation 7 for the calibration sequence.
- T_{sys} – system temperature calculated from equation 9.
- g_{avg} – the average gain across the bandwidth measured from the calibration sequence (equation 11).
- g_{ν} – the gain as a function of frequency measured per 1 MHz [TBD] interval across the bandwidth from the calibration sequence (equation 11).
- A – airmass using the appropriate relationship as function of elevation.
- τ_o – zenith opacity from the weather database.
- T_{atm} – effective atmospheric temperature from the weather database.
- The outside temperature near the telescope measured by one of the weather stations or another sensor.

The following set of parameters need to be saved for each session.

- Y – Y-factor measured in the lab.
- A_{geom} – system parameter for the area of the GBT.
- η_l – system parameter for ohmic losses and rearward spillover.
- η_a – aperture efficiency giving the effective area of the GBT ($A_{\mathrm{effective}} = \eta_a A_{\mathrm{geom}}$).
- η_{mb} – system parameter for the main-beam efficiency appropriate for extended sources larger than the beam ($T_{mb} = T_A^*/\eta_{mb}$).

6.2. Continuum Calibration

The instrument shall support the calibration of continuum data for the VLB, DCR and GUPPI backends. The bandwidths available for continuum data provide sufficient S/N for the calibration sequence. The continuum data containers should contain the same information stored in the sdfits files for the spectral-line data.

For VLB observations the T_{sys}, gains, and opacity values should be tabulated a function of time [TBD].

7. Weather Quality

The T_A^* scale can be derive both using the two-load system (equation 1) and the one-load system. For the one load system,

$$T_A^* = T_C * (V_{\rm on} - V_{\rm off})/(V_{\rm amb} - V_{\rm sky}), \tag{14}$$

where T_C is given by equation 4. Equating these expressions for T_A^*, one can test whether the parameters from the weather database are consistent with the measured voltages and temperatures.

REFERENCES

Kutner, M. L. & Ulich, B. L. 1981, ApJ, 250, 341

8. Appendix A

TBD = To Be Determined

This preprint was prepared with the AAS LaTeX macros v5.2.