High-Precision Calibration, Baselines and Nonlinearities with the GBT

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Abstract

The traditional methods for calibrating single-dish radio telescopes assume that the system gain is linear: detected power is taken to be proportional to the power incident on the antenna. The assumption is wrong at some low level and noticeably breaks down when observing an object that has a large dynamic range. The high sensitivity, clean beam, and very stable electronics of the Green Bank Telescope (GBT) allow us to detect nonlinearities that would be masked in most other radio telescopes. In particular, the signal processing components of the GBT produce an output power that exhibits at least a quadratic dependence on incident power. Our study indicates that measuring and compensating for the nonlinearity is rather trivial and improves calibration when observing objects with a larger dynamic range. Once measured, the nonlinearity is shown to be stable over a typical observing run (~6-8 hours) with evidence of stability for up to several weeks.

We also investigated ways to improve spectral-line calibration and baseline shape when observing over a band that is many GHz wide, as is typical with many high frequency GBT projects. We have found that baselines are seriously degraded when using the traditional methods of calibration via scalar values for the system temperature and calibration noise diode that are averaged over the entire bandwidth of the observations. System calibration and baselines are shown to be substantially improved when we use noise diode and system temperature values that have a frequency resolution of a few MHz.

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Introduction

Current data reduction techniques used on the Green Bank Telescope (GBT) and elsewhere assume a linear power response curve and use scalar calibration coefficients. The stability of the GBT electronics and large instantaneous bandwidths allow us to investigate the validity of these approximations.

Scalar calibration results in baseline artifacts not associated with the source (Fig. 1). Studies by Johnson et. al. suggested one could easily measure the nonlinearity of the GBT (Fig. 2).

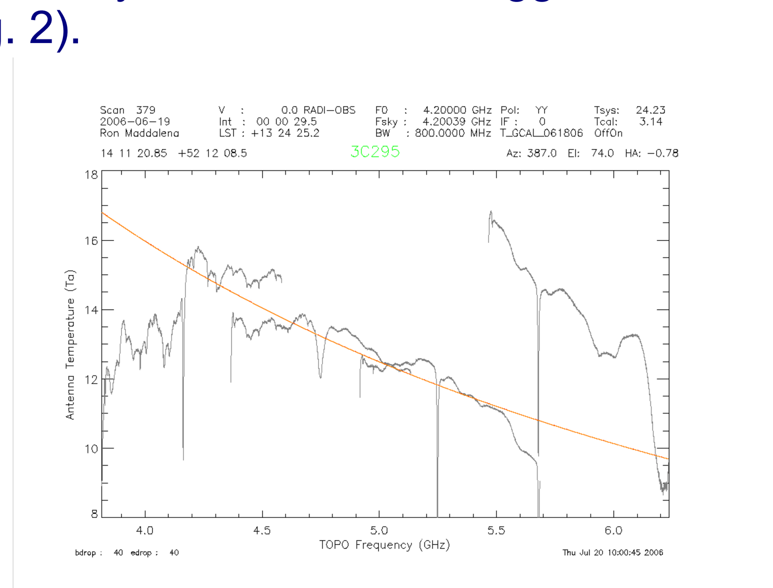

Figure 1: Measured synchrotron spectrum of 3C295 (grey) and catalog spectrum (red)

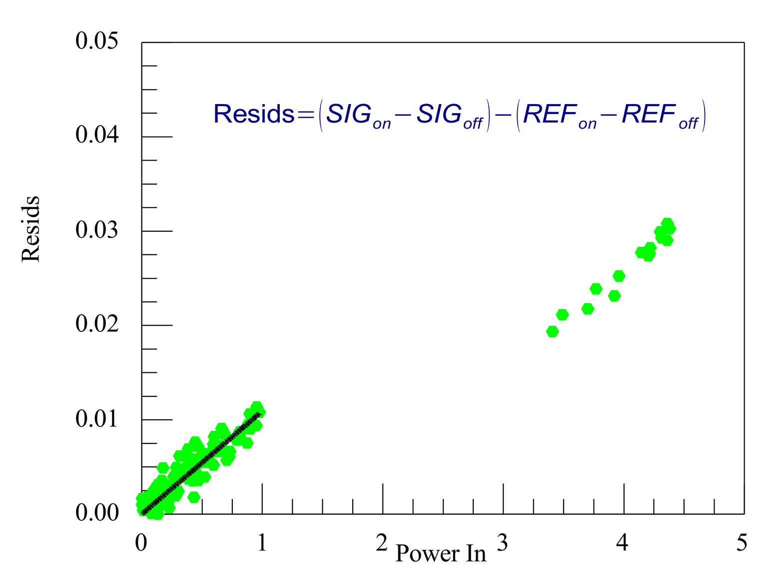

Figure 2: Residuals (Resids) vs. Input Power. Residuals should be constant if the measured power is a linear function of the antenna input power. Discontinuity suggests that higher-order gain terms may be necessary. See below for definitions of quantities

Our study sought to (1) implement a frequency-dependent calibration temperature (*Tcal*) to improve spectral baselines and (2) introduce a nonlinear correction to improve the calibration. In addition, tests were performed to determine calibration stability.

Theory

Calibration coefficients and system temperatures, *Tsys*, are traditionally determined from the detected voltages of measurements of point sources with cataloged intensities (***SIG***) and measurements of nearby blank-sky (***REF***). All GBT receivers have a noise diode whose output power, *Tcal* , is assumed to be extremely stable. We'll use subscripts of ***on*** and ***off*** to indicate the state of the diode. Traditionally, detected voltages are assumed to be linear with source strength.

$$T_{cal}(\nu)=\frac{REF_{on}(\nu)-REF_{off}(\nu)}{SIG_{off}(\nu)-REF_{off}(\nu)}\cdot T_{src}(\nu) \qquad \gamma^{(1)}(\nu)=\frac{T_{cal}(\nu)}{REF_{on}(\nu)-REF_{off}(\nu)}$$

Tcal and $\gamma^{(1)}$ are then be applied to observations of other sources. Calibration coefficients are traditionally averaged over frequency.

$$T_{sys}=\left\langle \gamma^{(1)}(\nu)\cdot REF_{off}(\nu)\right\rangle_{\nu} \qquad T_{src}(\nu)=\frac{SIG_{off}(\nu)-REF_{off}(\nu)}{REF_{off}(\nu)}\cdot T_{sys}$$

However, over the GHz wide bandwidths of the GBT, there might be significant frequency structure in the denominator of the last equation which cannot be cancelled out by a scalar *Tsys*. Instead, for best baselines we need to remove the averaging and employ a frequency-dependent (vector) *Tsys*.

Next, to determine the affects of the known non-linearities (Fig 2), we have added a quadratic gain term to our calibration equations:

$$T_{sys}=\gamma^{(1)}REF_{off}(\nu)+\gamma^{(2)}REF^2_{off}(\nu)$$
$$T_{sys}+T_{cal}=\gamma^{(1)}REF_{on}(\nu)+\gamma^{(2)}REF^2_{on}(\nu)$$
$$T_{sys}+T_{src}=\gamma^{(1)}SIG_{off}(\nu)+\gamma^{(2)}SIG^2_{off}(\nu)$$
$$T_{sys}+T_{src}+T_{cal}=\gamma^{(1)}SIG_{on}(\nu)+\gamma^{(2)}SIG^2_{on}(\nu)$$

As before, $\gamma^{(1)}$, $\gamma^{(2)}$ are determined by observations of an intensity calibrator and then applied to the observer's source:

$$T_{src}=\gamma^{(1)}(\nu)\cdot\left(SIG_{off}(\nu)-REF_{off}(\nu)\right)+\gamma^{(2)}(\nu)\cdot\left(SIG^2_{off}(\nu)-REF^2_{off}(\nu)\right)$$

Analysis/Discussion

Our tests used point sources of moderate strength (~20K). Fig. 3 shows the frequency structure of *Tsys*. Similar plots were derived for *Tcal*. Fig. 4 compares the baseline and calibration accuracy when one uses a linear scalar approximation vs. a linear vector and a 2nd order approximation.

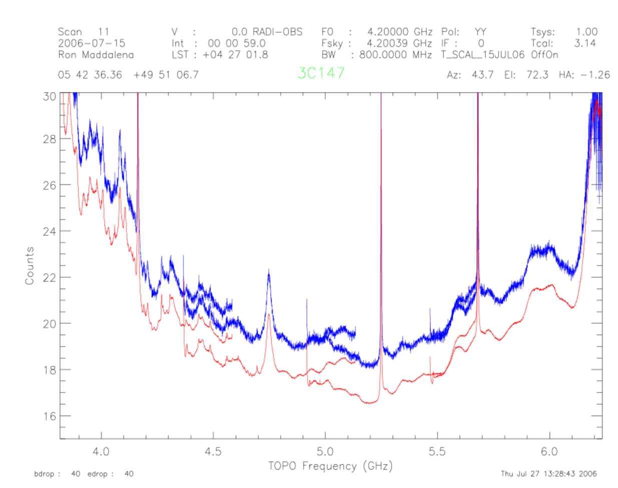

Figure 3: T_{sys} vs. Frequency for 3C147. Nonlinear solution is shown in blue, linear in red.

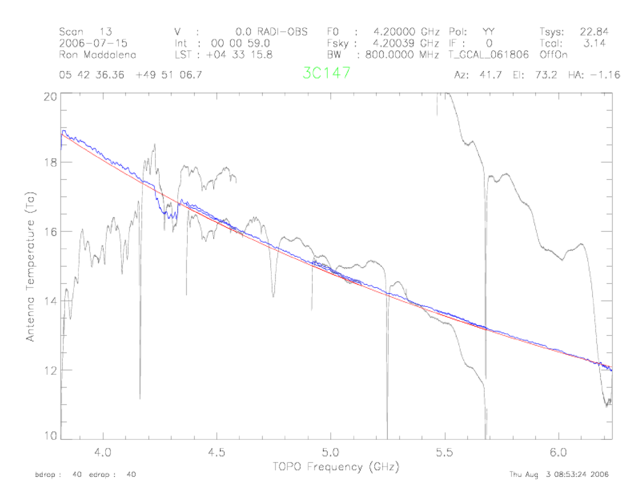

Figure 4: T_A vs. Frequency for 3C147. Scalar-derived value in grey, linear and nonlinear in blue and green, and catalog-derived spectrum is shown in red.

We explored the time span over which one has to re-measure γ. Calibration shifts of 2.5-5% were observed after 4h (Fig 5). Fig 6 shows calibration was unchanged (5%) even after one month.

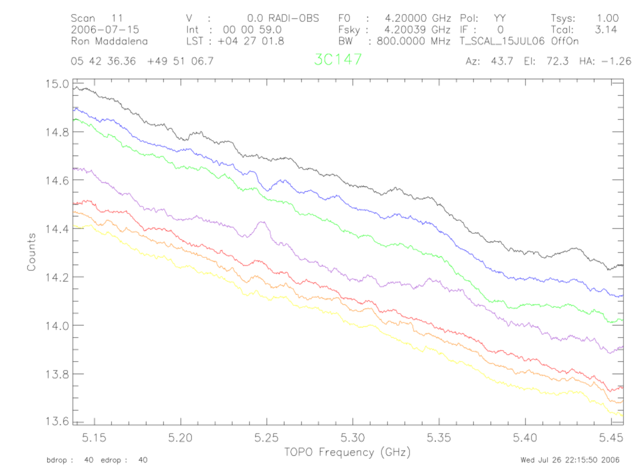

Figure 5: T_{sys} vs. Frequency, varying calibration age. Red represents t = 0h, Black represents 4h.

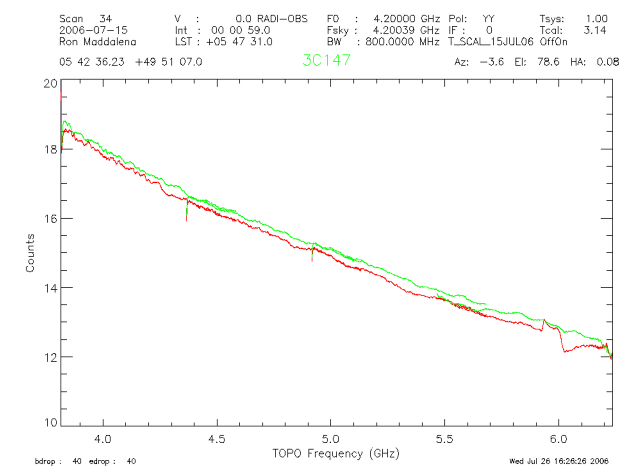

Figure 6: T_{sys} vs Frequency. Two-hour old calibration shown in green, one-month in red.

Figs. 7 and 8 show how changes in input power affect calibration. The changes in *Tsrc* suggest that a 2nd-order approximation holds for up to 3 dB changes in input power.

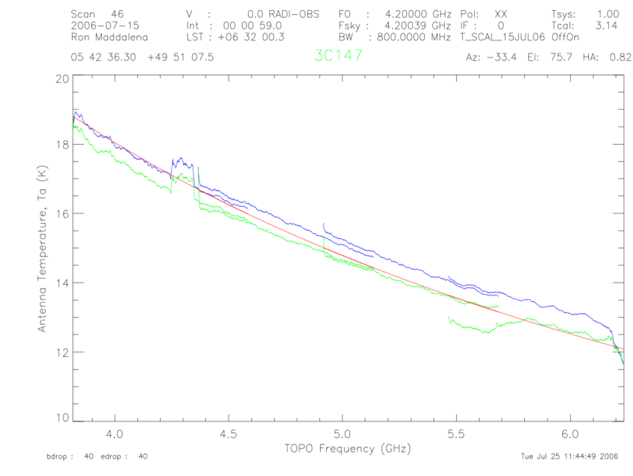

Figure 7: T_A vs Frequency, -3dB attenuation at the IF rack. Nonlinear calibration is in green.

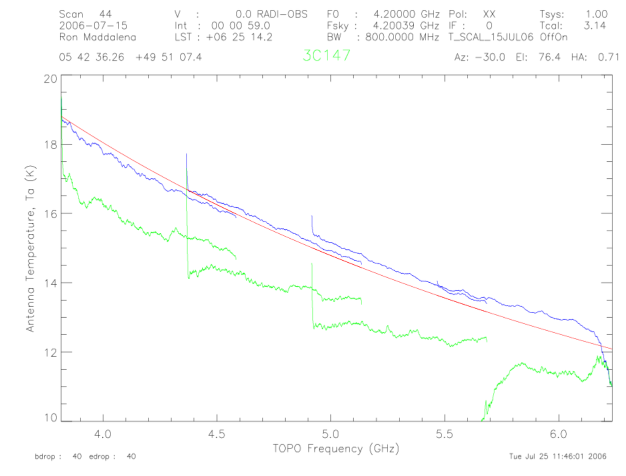

Figure 8: T_A vs. Frequency, -6dB attenuation at IF rack. Nonlinear calibration is in green.

Conclusions

Vector calibration results in substantially improved baseline shapes and calibration accuracy over the traditional scalar approximations

A 2nd-order, nonlinear approximation results in slightly improved calibration over traditional linear approximations. However, 2nd-order is not sufficient for high-dynamic range observations.

Vector calibration and second-order gain coefficients remain fairly constant over a typical observing run, and show very little variation after one month.

Nonlinear gain is produced by many system components and is not easily isolated. However, the affects can be easily measured and removed for most classes of observations.

Use of vector calibration results in increased spectral noise at levels as high as 10x the noise level for the averaged calibration. This may obscure fine/weak spectral lines on the MHz scale

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