

# Calibration of GBT Spectral Line Data in GBTIDL v2.1

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October 30, 2009

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## Purpose of this Document

This document describes the calibration philosophy and algorithms applied to GBT spectral line data in GBTIDL v2.1. GBTIDL provides basic routines that can be used to calibrate and average spectra when the data are taken in standard, predefined observing modes. When applied properly, the calibration routines (called *getnod*, *getfs*, *getps*, and *getsigref*) typically give a flux scale accurate to 10% - 20%, with higher frequencies being the more difficult to calibrate accurately. This document also describes some of the limitations in the current calibration scheme. Observers who use nonstandard observing techniques or require higher precision calibration can apply low-level GBTIDL procedures to build custom calibration routines.

## The Structure of GBT Spectral Line Observations

In this section we describe the structure of GBT spectral line observations and the resulting data products.

Observers generally use one of the GBT “standard observing modes” for spectral line observations. There are five standard observing modes for single pointing spectroscopy. For each one there is a GBTIDL procedure to read and calibrate the data (see Table 1). The calibration philosophy is similar in each of the observing modes, and it is only the sig/ref switching pattern that differs. In addition to these five modes, GBTIDL can also calibrate (but not map) data taken in on-the-fly mapping mode, or in point-map mode. GBT standard observing modes are described fully at

<http://wikio.nrao.edu/bin/view/GB/Observing/StandardObservingModes>.

Table 1. GBT standard observing modes for single pointing spectroscopy observations.

Standard Observing Mode	Astrid Procedure	Scans per procedure	Phases per integration	GBTIDL calibration procedure
Position Switched Single Beam	OnOff, OffOn	2	2	getps
Position Switched Dual Beam	Nod	2	2	getnod
Total Power Track	Track	1	2	getsigref
Frequency Switched Track	Track	1	4	getfs
Beam Switched (not recommended)	Nod	2	4	getbs

GBT spectral line observations are specified using *astrid* observing procedures as outlined in Table 1. Each procedure uses one or two scans, and two or four phases per integration. For example, total power, position switched observations require two scans: one for the “on source” position and one for the “off source” position. Frequency switched observations require only one scan.

No matter which observing procedure is used, each scan may have data for multiple IF’s (i.e. spectral windows), multiple polarizations, and multiple integrations. Most observations collect two polarizations, either LL and RR (circular) or XX and YY (linear). Full polarization observations are also possible, with four polarization products, e.g. LL, RR, LR, and RL for circular feeds, but these data cannot be calibrated using the standard GBTIDL calibration routines. The number of IF’s and integrations are determined by the observer’s configuration. For example, a typical frequency-switched observation might have two-minute scan durations and 10 second integrations, while recording data for two polarizations and two IF’s. For the sake of calibration, each IF and each polarization can be handled independently.

An integration is the smallest unit that can be calibrated to either a temperature or flux density scale. Each integration is subdivided into a number of “phases”, with the number of phases per integration being determined by the observing procedure used. Each phase has a unique set of parameters describing whether the data represents the “signal” or “reference” and describing whether the noise tube calibrator is on or off (*cal\_on* or *cal\_off*). For position-switched observations the signal and reference data are taken from different positions on the sky. For frequency-switched observations, the signal and reference data are taken with different center frequency settings. Beam-switched observations in the context of GBTIDL are similar to position-switched, but there is an additional parameter describing whether the electronic beam switch in the receiver is in the “cross” or “through” position. However, beam-switched observations are not recommended on the GBT except at Ka-band, and beam switching is not discussed further in this document. Ka-band calibration is not yet supported in GBTIDL.

Data are converted from multiple, raw GBT device FITS files into a single SDFITS file using a filler program called *sdfits*. It is possible to apply simple calibration to the data using the filler, but at the present time it is not recommended to do so. The *sdfits* program should be used to generate an uncalibrated SDFITS file (the default) and calibration should then be done within GBTIDL.

The following table gives an example of the data structure of an uncalibrated SDFITS file for a simple GBT observation using dual polarization, one IF, two integrations per scan, and observed using frequency switching. This data structure can be viewed using the *list* command in GBTIDL when the input file is an uncalibrated data set. Note that the calibration code in GBTIDL does not rely on any particular ordering of these records, and future version of the *sdfits* program may write data in a different order.

Table 2. An example of the data structure for an uncalibrated data set.

GBTIDL Record #	Scan	Pol	IF	Integration	Sig/Ref	Cal
0	1001	LL	0	0	Sig	Off
1	1001	LL	0	0	Sig	On
2	1001	LL	0	0	Ref	Off
3	1001	LL	0	0	Ref	On
4	1001	LL	0	1	Sig	Off
5	1001	LL	0	1	Sig	On
6	1001	LL	0	1	Ref	Off
7	1001	LL	0	1	Ref	On
8	1001	RR	0	0	Sig	Off
9	1001	RR	0	0	Sig	On
10	1001	RR	0	0	Ref	Off
11	1001	RR	0	0	Ref	On
12	1001	RR	0	1	Sig	Off
13	1001	RR	0	1	Sig	On
14	1001	RR	0	1	Ref	Off
15	1001	RR	0	1	Ref	On

It is not strictly necessary to observe using the standard observing modes. GBTIDL can be used to analyze data taken in any mode, but the high-level calibration routines are not guaranteed to work unless the standard modes are used.

## GBTIDL Calibration Philosophy and Algorithms

GBTIDL applies a basic  $T_a = T_{sys}^{ref} \times (sig - ref) / ref$  calibration. A noise tube calibrator sets the gain factor used to convert from raw counts to antenna temperature in units of K. The signal and reference observations serve to remove instrumental and atmospheric effects from the spectrum. Once a spectrum is calibrated to antenna temperature, a series of corrections may be applied to obtain calibrated data in corrected antenna temperature ( $T_a^*$  in degrees K) or flux density (Jy).

### Determination of System Temperature

The first step in calibration is the determination of the system temperature ( $T_{sys}$ ). System temperature is calculated separately for each integration, polarization and IF. In GBTIDL the  $T_{sys}$  of a spectrum is calculated as follows:

$$T_{sys} = T_{cal} \times \frac{\langle ref80_{caloff} \rangle}{\langle ref80_{calon} - ref80_{caloff} \rangle} + \frac{T_{cal}}{2}. \quad (1)$$

In order to minimize edge effects in calculating system temperature, 10% of the channels at each edge are eliminated. The notation *ref80* refers to the central 80% of the reference data. The angle brackets represent averaging over channels. A single calibration temperature is applied for the entire bandpass, averaged over the frequencies observed:  $T_{cal} = \langle T_{cal}(v) \rangle_v$ . The calibration temperature used in equation (1) also comes from an average across the central 80% of the bandpass. Future versions of GBTIDL will give a proper vector treatment to  $T_{cal}$  and  $T_{sys}$ . The term  $T_{cal}/2$  in equation (1) accounts for the increase in  $T_{sys}$  caused by the noise tube calibrator, which is on half of the time. Noise tube calibration temperatures  $T_{cal}(v)$  are determined by astronomical measurements of calibrators. There are separate noise tube calibration profiles for each polarization in the GBT receivers. For the multi-beam Ku-, K-, and Q-band receivers, there are also separate noise tube profiles for each beam. Details on improving system temperature measurements are in Appendix II.

## Determination of Antenna Temperature

Once a system temperature is available it is possible to calibrate the data to an antenna temperature. The antenna temperature is calculated by:

$$T_a(\nu) = T_{sys}^{ref} \times \frac{sig(\nu) - ref(\nu)}{ref(\nu)} \quad (2)$$

where  $sig = \frac{1}{2}(sig_{calon} + sig_{caloff})$ ,  $ref = \frac{1}{2}(ref_{calon} + ref_{caloff})$  and the calculation is done on a channel-by-channel basis. The notation  $T_{sys}^{ref}$  indicates that the system temperature calculation comes from the reference data, when the telescope is off source (position switching) or off frequency (frequency switching).

In GBTIDL, the default flux calibration gives (uncorrected) antenna temperature in units of degrees K, so unless the user specifies otherwise, the spectrum will be calibrated according to equation (2). For example, the following GBTIDL command calibrates to  $T_a$  in K:

```
getnod, 10, ifnum=0, plnum=1
```

For scans with multiple integrations, a calibrated spectrum is determined individually for each integration and the calibrated data for the full scan is then an average of the integrations weighted by  $\nu_{res} \times t_{eff} \times T_{sys}^{-2}$ , where the first two terms are the frequency resolution and the effective exposure time for each integration, respectively, and the system temperature is calculated individually for each integration. Under stable conditions the integrations should be weighted nearly equally. The user can enforce equal weighting using the *eqweight* switch available in each calibration procedure.

## A Note on Nod Data

For data taken with the Nod procedure, signal and reference spectra are taken simultaneously in two beams. During the first scan, beam 1 collects *sig* data and beam 2 collects *ref* data, and during the second scan beam 1 collects *ref* data and beam 2 collects *sig* data. The *getnod* procedure treats these data as two sets of total power observations, calibrating the spectra for each beam separately and then combining the two total power spectra in the final result. In averaging the spectra from the individual beams, the data are weighted by  $\nu_{res} \times t_{eff} \times T_{sys}^{-2}$ . The frequency resolution between the two beams will be identical, and the effective integration should be nearly identical, with small differences only possible if the filler has flagged data due to a glitch in the backend. The  $T_{sys}$  can vary significantly between the two beams so it will contribute most to the weighting. If the user wishes to see the calibration for one beam individually, the easiest

way to do so is to use the *getsigref* procedure. To access beam 1 and beam 2 data separately for a nod pair in scans 10 and 11, use:

```
getsigref, 10, 11, fdnum=0  
getsigref, 11, 10, fdnum=1
```

Note that IDL array indices start counting at zero, so `fdnum=0` gives data for the first beam.

## Calibration to Units Beyond $T_a$

When calibrating to units of corrected antenna temperature ( $T_a^*$  in degrees K) or flux density (Jy), the user must supply GBTIDL calibration routines with measured or calculated values of zenith opacity and aperture efficiency to achieve the best calibration. GBTIDL calibration routines will apply defaults if the user does not provide values, but the defaults are valid for quick-look calibration only. Opacity and aperture efficiency can be estimated from NRAO-provided measurements for some observations, or they can be measured as part of the observer's program. Observers requiring high precision calibration must observe flux calibrators, derive calibration parameters, and apply calibration corrections on their own. At frequencies of 18 GHz and above, calibration becomes especially sensitive to weather and telescope efficiencies and it is essential for the observer to pay attention to calibration details. Achieving the best flux calibration at high frequencies requires observing in good weather, including low winds.

## Calibration to $T_a^*$

By setting the keyword *units='Ta\*'* in any of the GBTIDL calibration procedures, the user will get calibration in units of K, corrected for atmospheric attenuation, rear spillover, ohmic loss, and blockage efficiency. In practical terms, GBTIDL first calibrates to standard antenna temperature  $T_a$  and then applies a correction:

$$T_a^* = T_a \times \frac{e^{\tau_0 / \sin(el)}}{\eta_l} \quad (3)$$

GBTIDL uses  $\eta_l = 0.99^1$  as an estimate to correct for rear spillover, ohmic loss, and blockage efficiency. Here  $\tau_0$  is the atmospheric opacity at the zenith, and  $el$  is the elevation of the observation. GBTIDL will provide a default value for the zenith opacity if one is not provided, but *this estimate should be used only for quick-look reduction, not*

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<sup>1</sup> GBTIDL v2.0 was patched on January 8, 2007 to correct a bug in the value of  $\eta_l$ . Prior to this date, the value was stored improperly as  $\eta_l = 1/0.99$  causing a 2% error in data calibrated to  $T_a^*$  or flux density in Jy. This error is less than the advertised precision of the GBTIDL calibration routines.

for final calibration. To obtain the best calibration, the user should provide a value of the zenith opacity using the *tau* keyword in the calibration routines. For example:

```
getnod, 10, ifnum=0, plnum=1, units='Ta*', tau=0.08
```

## Calibration to Flux Density in Jy

By setting the keyword *units='Jy'* in any of the GBTIDL calibration procedures, the user will get flux density calibration in units of Jy via:

$$S_v = \frac{2k \times T_a \times e^{\tau_0 / \sin(el)}}{A_p \times \eta_A \times \eta_l} = \frac{T_a}{2.85} \times \frac{e^{\tau_0 / \sin(el)}}{\eta_A \times \eta_l}. \quad (4)$$

The GBT-specific gain constant 1/2.85 accounts for the Boltzmann constant and collecting area of the telescope ( $2k/A_p$ ), where  $A_p$  is the physical collecting area. Here  $\eta_A$  is the aperture efficiency,  $\eta_l$  is the correction for rear spillover, ohmic loss, and blockage efficiency,  $\tau_0$  is the atmospheric opacity at the zenith, and  $el$  is the elevation of the observation. GBTIDL uses the estimate  $\eta_l = 0.99$ . GBTIDL will provide a default value for the zenith opacity and aperture efficiency if they are not provided, but *these defaults should be used only for quick-look reduction, not for final calibration*. To obtain the best calibration, the user should provide a value of the zenith opacity using the *tau* keyword and a value of aperture efficiency using the *ap\_eff* keyword in the calibration routines. For example:

```
getnod, 10, ifnum=0, plnum=1, units='Jy', tau=0.08, ap_eff=0.575
```

## Calibration to $T_{MB}$ and other units

GBTIDL does not have an option to calibrate to units of main beam brightness temperature or other units, so these must be implemented using scaling factors. The main beam efficiency of the GBT can be approximated by  $1.32 \times \eta_A$  so  $T_{MB} \equiv T_a^* / (1.32 \times \eta_A)$ . The scaling factor can be applied using the *scale* procedure in GBTIDL.

## Customizing Calibration in GBTIDL

### Zenith Opacity

The default atmospheric opacity used for quick-look calibration to  $T_a^*$  and Jy is:

$$\tau_0 = 0.2 \quad \text{for } \nu > 52.0 \text{ GHz}$$

$$\tau_0 = 0.008 + \frac{e^{\sqrt{\nu}}}{8000} + \frac{e^{-(\nu-22.2)^2/2}}{40} \quad \text{for } 18.0 < \nu < 26.0 \text{ GHz}$$

$$\tau_0 = 0.008 + \frac{e^{\sqrt{\nu}}}{8000} \quad \text{for all other values of } \nu.$$

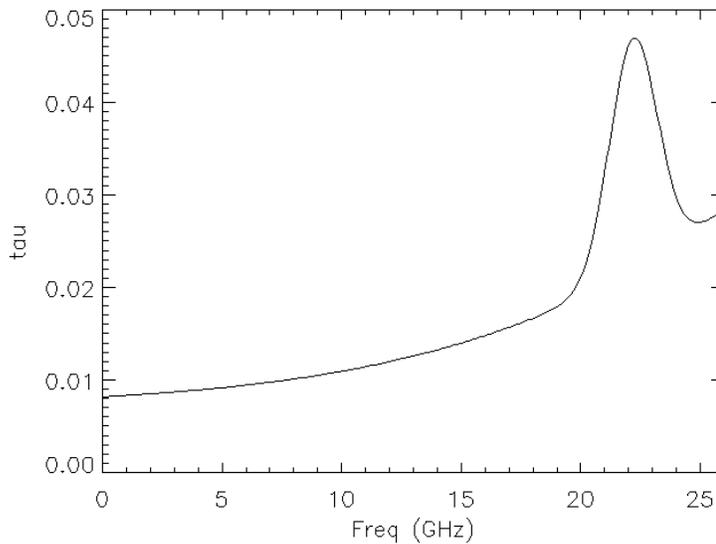


Figure 1. The default zenith opacity applied as the default in the GBTIDL procedures for quick-look calibration. The default opacity applied is an approximation of very cold, dry weather. The user should determine and apply a more accurate value of tau for final analysis.

The observer has two options to improve on the default opacity. The first option is to specify zenith opacity using the *tau* parameter in the calibration routine, as demonstrated above. The second option is to replace the default calculation of zenith opacity with a custom version. The GBTIDL procedure that provides opacity is called `get_tau.pro`. So you can make a personalized `get_tau.pro` routine and place it in your IDL path (e.g. your `~/gbtidlpro` directory). Examine the default `get_tau.pro` (a short, simple IDL function) to see the format required. The file contains a function that returns opacity, given frequency. A simple replacement function might look like:

```
function get_tau,freq
if n_elements(freq) ne 1 then freq = 22.0
if freq gt 18.0 and freq lt 22.5 then tau = 0.1 else tau = 0.02
return, tau
end
```

## Aperture Efficiency

The default aperture efficiency applied by GBTIDL for quick-look calibration to flux density in Jy is:

$$\eta_A = 0.71 \times e^{-\left(\frac{4\pi\varepsilon\nu}{c}\right)^2} \quad \text{for all elevations.}$$

This default is new for GBTIDL version 2.1. The curve comes from the Ruze equation and is applied across all elevations although the gain curve probably drops off above 70 degrees and below 30 degrees elevation. The surface accuracy  $\varepsilon$  is set at 390 microns in GBTIDL, consistent with the measurements by the PTCS group. This curve is a good default for observing under the recommended conditions, but high frequency, daytime observing or other sub-optimal conditions will degrade the effective surface accuracy of the telescope. The observer is strongly recommended to measure aperture efficiency during the observations if flux calibration better than about 20% is necessary.

In December, 2006, the out-of-focus holography measurements (“Zernike polynomials”) began being applied by default to all observations at C-band and higher frequencies. The default aperture efficiency is a reasonable choice for observations made with these corrections turned on, but this curve is not suited to high frequency (especially K-band and higher) observations made prior to December 2006.

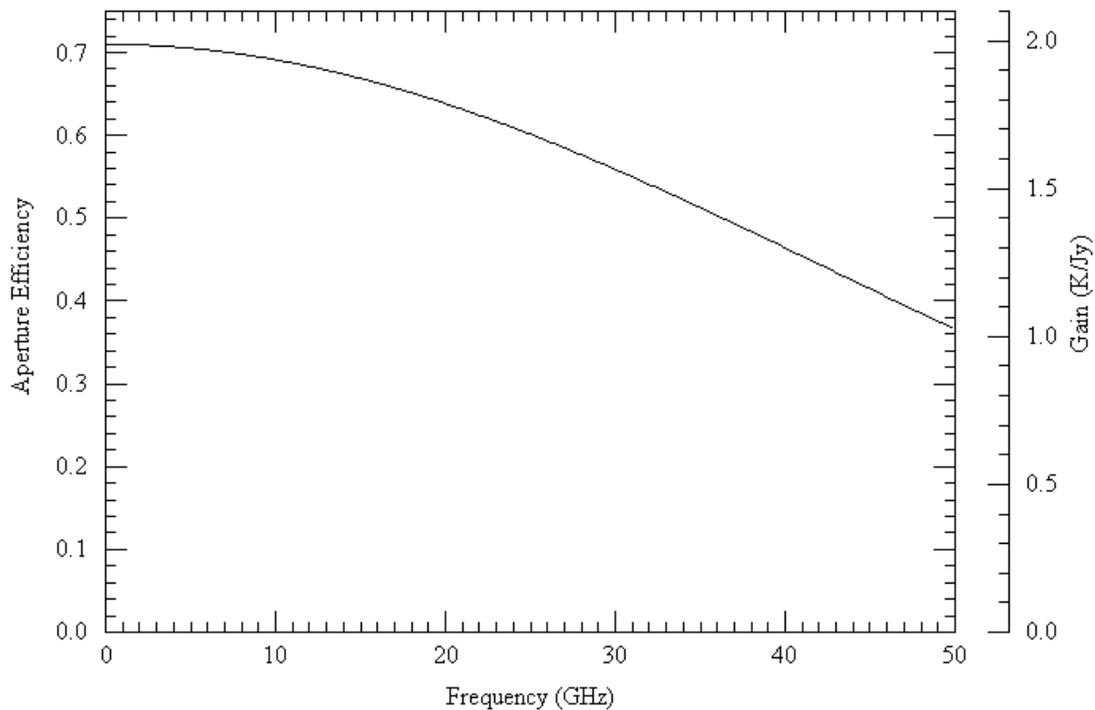


Figure 2. The gain curve applied by GBTIDL for the purpose of quick-look calibration.

The observer has two options for specifying aperture efficiency different than the default. The first is to specify *ap\_eff* as a parameter in the calibration routine. The second is to replace the GBTIDL procedure that provides default aperture efficiency with a custom version. The GBTIDL procedure that provides aperture efficiency is called `get_ap_eff.pro`. So you can place a personalized `get_ap_eff.pro` routine in your IDL path (e.g. your `~/gbtidlpro` directory). The file contains a function that returns *ap\_eff*, given frequency and elevation. The following skeleton function demonstrates the format required for the input parameters and the returned variable. Of course you should base the function on a real, measured gain curve.

```
function get_ap_eff,freq,elev
if n_elements(freq) ne 1 or n_elements(elev) ne 1 then begin
    print,'You must provide frequency and elevation.'
    return, 0.0
end
if freq gt 18.0 and freq lt 22.5 then ap_eff = 0.6 else ap_eff = 0.7
; add appropriate code here for all frequencies and elevations
return, ap_eff
end
```

## Strategies for Improving Calibration Accuracy

### Measuring Zenith Opacity

Historically, tipping observations have been used to determine zenith opacity. Tipping data can be taken with the GBT, but currently there is no NRAO software to measure the opacity based on a tip scan. A basic procedure to reduce tip data will be made available in 2007. An alternative to using tip scans is to use weather-based observations to determine opacity. Ron Maddalena provides opacity calculations determined from weather conditions from three nearby towns. Sounding data is not available directly over Green Bank so local perturbations, such as low-lying fog, are not accounted in the weather-based opacity determination. The address of the weather page is

<http://www.gb.nrao.edu/~rmaddale/Weather/index.html>.

For past observations, these weather-based opacity measurements can be extracted using the `cleo` “Weather Forecast” application, accessible from the menu:  
`cleo` → Utilities/Tools → Observing Tools. Weather data is available back to May 2004.

### Determining Aperture Efficiency

The best way to measure aperture efficiency is to run a `Peak` procedure on a flux calibrator at an elevation equal to that of your target source. The peak should be configured explicitly at the frequency of interest, so it is generally inappropriate to use the `AutoPeakFocus` procedure for this purpose. An example observing script for L-band

is shown in Appendix III. Note that a Peak procedure first scans the source back and forth in azimuth, makes a correction to the azimuth LPC, and then scans up and down in elevation. The elevation scans should therefore pass through the center of the source, so only the peak intensity of the elevation scans should be used to record the source flux.

The procedure, then, is:

1. Measure the antenna temperature of the flux calibrator at the elevation of interest, using the elevation scans in the Peak procedure. The antenna temperature is printed on the GFM display.
2. Determine the appropriate flux density  $S_\nu$  of the calibrator, in Jy, using the parameters from the Ott et al. catalog (see below).
3. Determine aperture efficiency via  $\eta_A = \frac{1}{2.85} \frac{T_a}{S_\nu} e^{\tau_0 / \sin(el)}$ .

Flux calibrators can be found in Ott et al. 1994, A&A, 284, 331. An IDL program to calculate the flux at the frequency of interest is available in Green Bank in the directory `~jbraatz/gbtidlpro/ottflux.pro`. The program can be used as follows:

```
.com /users/jbraatz/gbtidlpro/ottflux
flux = ottflux('3C48',22235.08)
print,flux
```

The first parameter in the `ottflux` function is the name of the calibrator and the second is the frequency in MHz. The valid calibrators are 3C48, 3C123, 3C147, 3C161, 3C218, 3C227, 3C249.1, VirA, 3C286, 3C295, 3C309.1, 3C348, 3C353, CygA, and NGC7027. Not all flux calibrators are valid across all frequencies. See the Ott et al paper for valid frequency ranges.

## Special Topic: Smoothing the Reference Spectrum

Each GBTIDL calibration procedure has a parameter called *smthoff* that can be used in certain circumstances to improve the signal-to-noise in sig/ref observations. The parameter accepts an integer value  $n$ . It then applies a boxcar smoothing with convolution size of  $n$  channels to the reference spectrum. The effect is to reduce the channel-to-channel noise in the reference spectrum and thereby improve the signal-to-noise in the (sig-ref)/ref calculation. The observer should use caution when applying this parameter because it has a number of side effects. It can degrade the baseline, it can emphasize single-channel defects in the spectrometer, and it introduces a correlation in adjacent channels of noise in the final calibration (but adjacent channels in the signal remain uncorrelated). The option can be applied as in this example:

```
getnod, 1001, smthoff=16
```

The optimum value for the *smthoff* value should be determined on an individual basis. Larger values give better signal-to-noise but make the side effects worse. In future

versions of GBTIDL, a Savitsky-Golay smoothing filter may be applied rather than the boxcar.

## Known Deficiencies in Calibration

- As discussed in Appendix II,  $T_{\text{cal}}$  values derived from laboratory measurements have been found to differ considerably over timescales of many months. If not accounted properly, these errors can dominate the uncertainty in the calibration.
- There is currently no GBT software for reducing tip scans. Individual users have personal software to analyze tip scans. Opacities determined from weather data are currently recommended over tip scans in most circumstances.
- Opacity may vary as a function of frequency for very large bandwidth observations. Such variation is not accounted in the GBTIDL calibration scheme.
- A scalar  $T_{\text{sys}}$  is currently applied for the entire spectral window to derive antenna temperature.  $T_{\text{sys}}$  may vary significantly across the band for large bandwidth observations. GBTIDL does not currently incorporate vector  $T_{\text{sys}}$  in the calibration. In addition to the flux scale, baselines are also adversely affected by the current application of a scalar  $T_{\text{sys}}$ .
- Recent, precise gain curves (aperture efficiency vs. elevation) are not currently available for all frequencies.
- When averaging data with flagged channels, the weights are not stored with the averaged spectrum so subsequent averaging operations involving this (intermediate) spectrum will not be weighted properly.

## Appendix I: Parameters Used by Calibration Procedures

The following table shows a number of parameters that are common to most or all of the calibration procedures *getnod*, *getps*, *getfs*, and *getsigref*. For a detailed description of parameters for each procedure, use the *usage* command in GBTIDL, for example:

```
usage, 'getnod', /verbose
```

Parameter	Description
ifnum	Selects an “IF number” (spectral window), counting from 0. Default is 0.
intnum	Selects an integration number, counting from 0. Default is “all”.
plnum	Selects a polarization. Possible values are 0 or 1 for dual polarization data. Default is 0.
fdnum	Selects a feed (i.e. beam) number. Default is 0.
tau	Specifies zenith opacity. Used when calibrating to $T_a^*$ or Jy.
tsys	Specifies zenith system temperature. This parameter is used to override the internal calculation of system temperature.
ap_eff	Sets the aperture efficiency. Used when calibrating to Jy.
smthoff	Specifies the size of a boxcar to be applied to the reference spectrum prior to calibration. This parameter can be used to increase the signal-to-noise under certain circumstances, but should be used with caution because it can also degrade baselines and emphasize spectrometer glitches.
units	Specifies the units of the requested calibration. Default is ‘Ta’ and other possible values are ‘Ta*’ and ‘Jy’
tcal	Overrides the $T_{cal}$ value determined from the receiver FITS file.
/eqweight	Applies equal weights to all integrations when the full scan is calibrated.
/quiet	Suppresses printed messages when set.
/keepints	Stores a spectrum from each integration to the output disk file during the calibration process.
useflag	Allows the user to select specific flag IDs to be applied.
skipflag	Allows the user to ignore specific flag IDs.
instance	If there are multiple instances of a given scan number in the input data file, this parameter can be used to specify which scan is retrieved for calibration.

## Appendix II: $T_{\text{sys}}$ and $T_{\text{cal}}$ Measurements

Under certain circumstances GBTIDL cannot calculate a precise system temperature. For example some of the prime focus receivers do not have  $T_{\text{cal}}$  values stored in the receiver FITS file, so the system temperature cannot be determined. There is a parameter (*tsys*) in each of the GBTIDL calibration routines that allows the user to specify the zenith system temperature to be applied in the calibration, overriding the internal  $T_{\text{sys}}$  calculation.  $T_{\text{sys}}$  at the elevation of the observation is then estimated via  $T_{\text{sys}} = T_{\text{sys}}^{\text{zenith}} \times e^{\tau_0 / \sin(\text{el})}$ . [A better approximation,  $T_{\text{sys}} = T_{\text{rcvr}} + T_{\text{atm}} \times (1 - e^{-\tau_0 / \sin(\text{el})})$ , will be implemented in future versions.] Currently,  $T_{\text{sys}}$  supplied in this manner must be a scalar value and it is applied to all beams that contribute to the calibrated spectrum.

In some data sets the  $T_{\text{cal}}$  data may not have the precision required for 20% or better calibration. Prior to about August 2005, laboratory measurements were used to determine  $T_{\text{cal}}$  as a function of frequency for each receiver. Significant differences in  $T_{\text{cal}}$  measurements for some receivers (notably K-band) taken about a year apart indicate that some GBT data taken prior to August 2005 will not be well calibrated if the GBTIDL defaults are applied. After August 2005,  $T_{\text{cal}}$  values determined from astronomical observations have been applied, and these seem to provide more robust  $T_{\text{sys}}$  measurements so far. Nevertheless, the observer concerned with high-precision calibration should pay attention to the origin and age of  $T_{\text{cal}}$  measurements. The origin of  $T_{\text{cal}}$  measurements for a particular data set is stored in the raw GBT data set, in the Receiver FITS file.

If you suspect erroneous  $T_{\text{cal}}$  values, you can apply the *tsys* parameter in the GBTIDL calibration routines to override the internal calculation of  $T_{\text{sys}}$ . Alternatively, simply scale the offending data after the default calibration is applied.

## Appendix III: Sample Astrid Script for a Peak Observation

The following astrid script demonstrates an appropriate Peak observation on a flux calibrator at L-band for the purpose of determining aperture efficiency.

```
Configure("""
receiver = 'Rcvr1_2'
beam     = 'B1'
obstype  = 'Continuum'
backend  = 'DCR'
nwin     = 1
restfreq = 1400
deltafreq = 0
bandwidth = 80
swmode   = 'tp'
swtype   = 'none'
swper    = 0.2
swfreq   = 0,0
tint     = 0.2
vlow     = 0.0
vhigh    = 0.0
vframe   = 'topo'
vdef     = 'Radio'
noisecal = 'lo'
pol      = 'Linear'
""")

Catalog(fluxcal)
mySource = "3C48"
Slew(mySource)
Balance()
Peak(mySource)
```