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GBT DCR Calibration in GFM

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Abstract

The Green Bank Telescope (GBT) uses a Digital Continuum Receiver (DCR) backend to record continuum data. This data is calibrated by the GBT Fits Monitor (GFM) application. It is the goal of this memo to document how this calibration is performed for the majority of GBT receivers.

1 Introduction

The GFM application plots calibrated DCR data for pointing and focus scans. It is the purpose of this document to give a high-level description of how this is done, along with some kind of scientific justification.

This document is not an attempt to justify what GFM is doing, nor will it get into the weeds of what all the alternatives may be. Instead, this is a recognition of the fact that the methods described here have been used for the last 14 years on the GBT. It's about time we documented it.

We hope to present a sufficiently clear enough explanation such that the reader could write their own DCR calibration code from the description.

2 Scope

Here we will discuss the methods used by GFM for only heterodyne receivers, excluding receivers such as W-band, Argus, and the Ka-band receiver. Also, the fitting that GFM performs is out of scope for this memo.

3 Overview

Below we break down the calibration of DCR data into these general steps:

- **Decoding the Data:** using the raw engineering FITS files, how to we find the raw counts recorded by the DCR for a given set of physical attributes, such as polarization, feed (or 'beam'), frequency, and phase.
- **Calibrating the Data:** how to take the 'decoded' DCR data, along with the receiver calibration information, and produce the result according to the desired calibration mode.

4 Decoding DCR Data

To map the raw counts recorded by the DCR to physical attributes, one needs to combine the contents of the DCR FITS file, which holds the raw counts and which input ports and phases those counts map to, and the contents of the IF FITS file, which describe the physical attributes that apply to each backend input port.

The physical attributes which must be specified in order to retrieve a time-series set of raw counts from the DCR are:

- **Polarization:** these are presented as options to the user in GFM: 'XL', 'YR', or 'Both'. In this case 'Both' means the average of the other two polarizations. These are generic choices, ignoring the difference between circular and linear polarization (i.e. X vs. L).
- **Feed:** also referred to as 'beam'; Instead of offering this as a choice, for multi-feed receivers, GFM attempts to use the feed specified by the Antenna as the 'tracking beam'.
- **Frequency:** the center sky column from the IF FITS table
- **Phase:** these are derived from the DCR STATE table, and map to the four possible states: 'Sig / Cal On', 'Sig / Cal Off', 'Ref / Cal On', 'Ref / Cal Off'. There are 3 possible combinations of these phases found in DCR data:
 - : 1 Phase - 'Sig / Cal Off'
 - : 2 Phases - 'Sig / Cal Off', 'Sig / Cal On'

– : all 4 Phases - 'Sig / Cal On', 'Sig / Cal Off', 'Ref / Cal On', 'Ref / Cal Off'

For further details see:

- <https://safe.nrao.edu/wiki/bin/view/GB/Software/SparrowDataProcessing>
- IF FITS documentation: <http://www.gb.nrao.edu/GBT/MC/doc/dataproc/gbtIFFits/gbtIFFits/gbtIFFits.html>
- DCR FITS documentation: <https://safe.nrao.edu/wiki/pub/GB/Software/ProjectNotes/gbtDCRFits.pdf>

5 Calibrating DCR Data

Once one can map physical attributes to raw counts ('decoding'), one can derive various calibration results. We will cover 3 specific GFM calibration modes:

- Raw: for most cases, this is not a calibration mode, since it is literally the raw counts, but we will cover the exception here.
- Total Power: for a given pair of cal on and off phases, and using the receiver calibration information, computes the antenna temperature
- Dual Beam: for a given pair of beams, or feeds, calculates the TotalPower for each and finds the difference

Note: the 'TBSwitchedOnly' calibration mode is out of scope here, since it only applies to the Ka-band receiver.

5.1 Raw

In most cases, this is simply the raw counts from the DCR, and thus is not really a calibration. Specifically, the 'Sig / Cal Off' phase of the data for the given polarization and tracking beam are used.

There may be concern that not including the 'Sig / Cal On' phase (when present) is throwing away half the data. However, throwing out half the integrations at a high cadence will not have a significant bad effect, and may have a good effect. The noise level in continuum data is not generally set by thermal noise, but rather by gain fluctuations (or atmospheric emission fluctuations). Having the cal ON adds more variables to that limiting dimension. If the cal varies at a very low level (depending on integration time and bandwidth) these fluctuations will introduce an added noise or systematic effect to the cal ON phases. Similarly if the cal is very bright of order the system temperature the impact of system gain fluctuations will be amplified commensurately.

However, when all four phases are present ('Sig / Cal On', 'Sig / Cal Off', 'Ref / Cal On', 'Ref / Cal Off'), things are done differently. In this case, the calibration is simply, for the given polarization and tracking beam:

$$raw = sigCalOff - refCalOff \quad (1)$$

Where *sigCalOff* and *refCalOff* are the data (in counts) from the 'Sig / Cal Off' and 'Ref / Cal Off' phases respectively. Note that DCR data with 4 phases only seem to be used with the Ka receiver, and thus may be treated as out of scope for this memo.

5.2 Total Power

For this calibration result, for a given polarization, we will need to know:

- feed - this is the tracking beam as specified by TRCKBEAM in the Antenna FITS file.
- cal on and cal off counts - for the given polarization, feed, and frequency. This is trivial once the data has been 'decoded'
- 'tcal' - derived from receiver calibration information found in the calibration FITS file.

5.2.1 Tcal

In general, we need to find the average receiver temperature over the frequency range of the data taken.

From the receiver calibration information, and the *centersky* and *bandwidth* values of our cal on and cal off data (IF FITS), we derive the 'tcal'. First the frequency range (Hz) is derived from:

$$freqStart = centersky - (bandwidth/2.) \quad (2)$$

$$freqEnd = centersky + (bandwidth/2.) \quad (3)$$

Then, we use the 'highcal' IF FITS value to determine which set of recorded temperatures (in Kelvin) to use in the receiver calibration FITS file. We finally look this up using the given polarization and feed we are calibrating for.

Finally, our value of *tcal*, in Kelvin, is the integration of the recorded temperature (K), *temp*, over our frequency range (from frequency start to end), divided by this same frequency range (Hz). This can be done simply treating this as a histogram and taking the area.

$$tcal = \left(\sum_{f=freqStart}^{freqEnd} (temp(f) * df) \right) / (freqEnd - freqStart) \quad (4)$$

5.2.2 Antenna Temperature

The final result of the Total Power calibration is the Antenna Temperature, in Kelvin. Once *tcal* is derived, the Antenna Temperature, *Ta* is simply given by:

$$countsPerK = sum(on - off) / tcal / len(on) \quad (5)$$

$$Ta = 0.5 * (on + off) / countsPerK - 0.5 * tcal \quad (6)$$

Where: *on* is the data from 'Sig / Cal On' phase, and *off* is from the 'Sig / Cal Off' phase, all for the given polarization and tracking beam.

5.3 Dual Beam

This calibration is simply derived from the Total Power calibration using multiple beams:

$$DualBeam = TaSig - TaRef \quad (7)$$

Where *TaSig* is the TotalPower for the tracking beam, as specified by the antenna, and *TaRef* is the TotalPower for the other reference beam (the other beam, if simply a dual beam receiver).

6 Summary

We have reviewed how the various types of calibrated GBT DCR results are derived by the GFM application.

Here are some Greek letters, because a scientific memo doesn't seem complete without them: α, ω