GBT Memo #275

Comparison of Methods of Focal Plane Array Gain Measurements

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Abstract

We describe a time sequence of GBT K-band Focal Plane (KFPA) array calibration measurements. We deduce gain factors required to scale the laboratory measured noise diode effective temperatures, based on On/Off scans of the Planets, the Moon and selected 3C reference sources. These measurements are compared with results obtained by Peak observations and by mapping these sources.

The spectral line observations were reduced using GBTIDL, and were facilitated by calibration scripts to compute the expected source brightness temperatures at the time of the observations. We summarizes the observing steps, data reduction scripts and application of the measurements to the KFPA pipeline.

We find that each of the calibration methods can determine the scale factors to improve observational accuracy, but with differing accuracy. Repetition of measurements can improve the calibration accuracy, but care must be taken to reject measurements taken if pointing offsets are detected. Comparison of Peak, Nod and Map observations show that pointing accuracy can strongly effect Nod measurements. Peak observations are time consuming when they must be repeated for each beam. Mapping observations produce the most consistent results but require significant processing time. We prefer gain calibration by observations of the Moon, but care must be taken that the IF-rack and Spectrometer have the input power levels properly balanced, otherwise gain compression may corrupt the measurements.

Change Record

Revision	Date	Author	Sections/Pages Affected
	Remarks		
1.0	2011-May-11	G. Langston	All
	Initial version		
1.1	2011-May-17	G. Langston	All
	Describe time sequence		
1.2	2011-May-22	G. Langston	All
	Short note on TKFPA_30		
1.3	2011-May-23	G. Langston	Summary
	Clean up results		

1. Introduction

We describe a time sequence of GBT K-band Focal Plane (KFPA) array calibration measurements. We deduce gain factors required to scale the laboratory measured noise diode effective temperatures, based on On/Off scans of the Planets, the Moon and selected 3C reference sources. These measurements are compared with results obtained by Peak observations and by mapping these sources.

The spectral line observations were reduced using GBTIDL, and were facilitated by calibration scripts to compute the expected source brightness temperatures at the time of the observations. We summarizes the observing steps, data reduction scripts and application of the measurements to the KFPA pipeline.

The KFPA has been used to observe a large number of galactic star forming regions, using the 7 beam, 50 MHz mode. An important aspect of these observations is accurate calibration of the measured intensities. We present a time series of measurements of the antenna temperature of the moon, and use a moon brightness temperature model to deduce gain factors appropriate for each observing session. Moon observations and data reduction are described in GBT Memo 273 by Glen Langston. In GBT Memo 274, we presented a time series of Moon observations. Here we compare observations of planets Venus, Mars and Jupiter, plus observations of 3C48, 3C123.

During the initial KFPA commissioning observations, in April 2010, we found reasonably good consistency between laboratory measurements of calibration noise diode values and astronomical observations of reference radio sources. During summer 2010, the receiver was improved in the lab and restored to the telescope in late August 2010. Astronomical observations began in September 2010, with first "shared risk" observations in October 2010. All the first observations had a target of galactic NH_3 emission and we focus on calibration of this frequency range, 23700±100 MHz.

The first images of galactic NH_3 had low noise and clear detections of emission was possible in only a few seconds of observations. A large number of galactic images were observed and images were quickly produced using the data pipeline. In January 2011, we found that the measurements of reference radio sources were showing low peak intensities. When the receiver was restored to the telescope in mid February, 2011, we conducted a series of calibration tests and found that the calibration noise diodes associated with the data had too low of values.

We corrected the calibration noise diode file and ran a number of tests on February 17, 2011. We also adjusted the cal control hardware current settings. We report on pointing tests made during this observing session and its implications for Nod-based gain calibration.

We summarize the observations in §2 and compare different methods of extracting the calibration factors. In §3 we summarize the measurements.

For more information on the KFPA development project, see links from the page:
https://safe.nrao.edu/wiki/bin/view/Kbandfpa/WebHome

2. Observations

The KFPA 7-beam commissioning observations began in early 2010. During this time the software for recording the frequency axis formation was under development. The first session containing all valid frequency information was obtained on 2010 April 19 (TKFPA_16). During this session we observed 3C48 and the Moon, so have good calibration measurements.

We analyze a number of GBT observations in the interval 2010 April through 2011 May. The telescope was configured in the standard manner for galactic NH_3 (1,1) and (2,2) transitions, using Astrid. The observations were carried out using the 7 beam+1, 50 MHz bandwidth, centered on frequency 23706 MHz. The extra spectrometer band was used for observation of the NH_3 (3,3) transition. This configuration is called the NH_3 7+1 Mode.

2.1. 2010 April 17: TKFPA_16

This observation session's goal was tests of different mapping modes and comparison of gain calibration using NOD observations of 3C48 and On/Off observations of the Moon. The observations discussed here were made with the NH_3 7+1 mode.

Table 1 lists selected scans and measured 3C48 intensities. A GBT Peak observation consists of 4 antenna motions, back and forth in the cross elevation direction (XEL), followed by adjustment of the XEL pointing offset, then up and down in the elevation (EL) direction. The values in Table 1 are the two peaks measured in the EL direction, so should have minimum decrease in intensity due to pointing errors in the XEL direction. Notice that the R and L polarization values agree well for the within a single scan, but successive scans have significantly different intensities. This is believed to be due to small random pointing offsets in the XEL direction during the time the EL scans are taken. Care must be taken to confirm proper pointing when making sensitive comparison of the gains of the different beams.

Based on a sequence of NOD observations of 3C48, we measure the relative gain of the different beams and polarizations. Table 2 lists the relative gains, which are computed using the GBTIDL script `sourcecalget.pro`. These calibration scripts are summarized in the appendix. This script includes a model for the flux density of selected calibration sources. Note that the Moon-based gain factors agree with laboratory measurements of the calibration noise diode values to with ±9%. Also note that the gain corrections are generally higher for the values based on observations of 3C48 and 3C123.

Table 1. Intensities from Selected Scans of TKFPA_16

Scan Numbers	Type Obs.	Beam/Pol	Peak (K)	Peak (K)	ΔXEL ($'$)	ΔEL ($'$)	Source Name
10-11	Peak	1/R	1.64	1.74	+0.032	+0.053	3C48
		1/L	1.66	1.74	+0.019	+0.027	
17-20	Nod	1/R	1.56	1.94			3C48
		1/L	1.56	1.77			
30-31	Peak	1/R	3.66	3.38	-0.006	-0.016	3C123
		1/L	3.44	3.15	-0.008	-0.032	
66-67	Peak	1/R	3.69	3.77	-0.008	-0.031	3C123
		1/L	3.41	3.49	-0.008	-0.018	
101-102	Peak	1/R	1.60	1.61	-0.029	+0.106	3C48
		1/L	1.70	1.68	-0.035	+0.084	
114-117	Nod	1/R	1.55	1.38			3C48
		1/L	1.67	1.53			
152-153	Peak	1/R	1.52	1.37	+0.096	+0.306	3C48
		1/L	1.57	1.39	+0.087	+0.291	

Table 2. Gain Factors from Selected Scans of TKFPA_16

Scan Numbers	Type Obs.	Pol	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 6	Beam 7	Source Name
13-20	Nod	R	1.103	0.981	1.138	1.115	-	1.084	1.257	3C48
		L	1.149	0.983	1.175	1.091	1.105	1.132	1.108	$T_A = 1.91K$
21-22	OnOff	R	0.911	0.930	1.048	0.988	-	1.020	1.079	Moon
		L	1.007	0.872	1.084	0.981	1.005	1.039	0.967	$T_A = 137K$
26-27	OnOff	R	0.896	0.873	1.012	0.960	-	0.955	1.015	Moon
		L	0.987	0.842	1.055	0.959	0.960	0.981	0.922	$T_A = 142K$
94-95	OnOff	R	0.951	0.910	1.075	1.007	-	1.040	1.128	Moon
		L	1.055	0.890	1.143	1.017	1.037	1.086	1.005	$T_A = 161K$
97-98	OnOff	R	0.947	0.908	1.095	1.002	-	1.031	1.110	Moon
		L	1.046	0.886	1.135	1.010	1.026	1.073	0.994	$T_A = 162K$
111-117	Nod	R	1.206	1.189	1.084	1.284	-	1.465	1.290	3C48
		L	1.317	1.150	1.246	1.242	1.304	1.501	1.168	$T_A = 1.92K$

2.2. 2010 September 6: TKFPA_30

On the date of TKFPA_30 observations, we observed the Moon and 3C48. On this date the On/Off Moon scans were made at 24.3 GHz and the zenith opacity was relatively high, $\tau = 0.067$. These observations used a relatively distant off-Moon location, so that direct comparison of gain correction factors between this session and other later observations have some uncertainty. During this observation the average measured gain correction factor was 1.73±0.14, significantly higher than the values obtained from observing session TKFPA_16.

These data were examined after discovery of anomalously low measured source intensities during observations in late December 2010.

2.3. 2010 December 15: TKFPA_40

On the date of TKFPA_40 observations, we performed On/Off moon observations with more optimum signal strength settings for the IF Rack and Spectrometer. These observations are described in GBT Memo 273, and include a check of the application of the calibration gain factors to maps of 3C48 and 3C123.

The pipeline gain calibration values listed in Table 3 are slightly different than those reported in GBT Memo 73. Here we include an improvement application of atmospheric opacity to the measurements. These values should be applied to all mapping observations obtained in the interval between Sept 6, 2010 and January 16, 2011.

2.4. 2011 February 17: TKFPA_47

The KFPA was restored to the GBT and on this date we ran a number of tests of gain calibration. The system was configured for NH_3 7 Beam + 1 mode, but we only observed continuum source

Table 3. Gain Factors from Selected Scans of TKFPA_40

Scan Numbers	Type Obs.	Pol	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 6	Beam 7	Source Name
25-26	OnOff	R	2.161	2.073	2.070	-	2.286	2.367	2.709	Moon
		L	1.955	1.851	2.035	2.159	2.344	2.283	2.629	$T_A = 174K$
30-31	OnOff	R	2.168	2.070	2.079	-	2.306	2.369	2.724	Moon
		L	1.965	1.857	2.043	1.913	2.349	2.289	2.634	$T_A = 175K$
AVE		R	2.164	2.071	2.075	-	2.296	2.368	2.716	Moon
AVE		L	1.960	1.853	2.038	2.036	2.346	2.286	2.632	

3C48. The test goals were to determine gain stability by a sequence of peak observations, followed by a set of Nod and Map observations.

The first set of 9 peak observations had a total 36 minute duration. During that time we measured only the beam 1 R and L polarization gain time stability. Table 4 shows measurements of the peak antenna and coordinate offsets of the location of peak emission. At higher frequencies, pointing accuracy is more critical to gain calibration. For these observations we find the RMS XEL pointing offset is $0.055'(3.3'')$ and the RMS EL offset is smaller, $0.027'(1.6'')$. The consistency of the L and R polarization values suggest that the pointing errors are not due to measurement, but rather random motions of the telescope on short time scales. Assuming these errors add in quadrature the 1 σ error is $0.061'(3.7'')$. The FWHM telescope beam width is $32''$, so a 1σ pointing error corresponds to 3.8% gain error (14% for 2σ and 29% for 3σ). In Table 4 note that the largest source intensities are not at the location of average offset, suggesting the RMS may be an underestimate of the pointing error.

Since 2σ errors occur $\sim$30% of the time (ie 2 out of 7 beams), care must be taken to repeat NOD observations, in order to confirm that pointing errors are not falsely indicating gain differences in the beams. Since at least 4 Nod observations would be required to confirm gain measurements for each beam, we suggest that relative gains might be more effectively determined by mapping observations, where the pointing offsets can be determined simultaneously with gain measurements.

2.5. 2011 April 8: TKFPA_62

After correcting the calibration noise diode values, we performed On/Off Moon observations on two dates. The resulting gain factors, listed in Table 5, show the good agreement between deduced gain factors and laboratory measurements.

The average and RMS gain factors for the 14 values in Table 5 is 0.99 ± 0.06. This value suggests the lab calibration is very good in this frequency range. The deviation from 1 is smaller than the expected systematic errors in the Moon based intensity calibration. The similarity of the values for the orthogonal polarizations suggest measurement accuracy is small for these values and that the relative gains of the different beams are reliably measured.

2.6. 2011 May 6: TKFPA_66

The gain factors measured from observations in session TKFPA_62 were applied to Daisy mapping scans of 3C48, obtained on May 10, 2011. Two sets of 7 scans were obtained. For these map scans the integrated intensity of 3C48 was 1.30 ± 0.11 Jy, in reasonable agreement with the Ott *et al.* 1993 model.

Table 4. Intensities from Selected Scans of TKFPA_47

Scan Numbers	Type Obs.	Beam/Pol	Peak (K)	Peak (K)	ΔXEL ($'$)	ΔEL ($'$)	Source Name
66-69	Peak	1/R	3.093	2.652	-0.011	0.018	3C48
		1/L	3.210	2.634	-0.012	0.012	
71-74	Peak	1/R	2.329	3.077	-0.113	0.019	3C48
		1/L	2.376	3.077	-0.113	0.019	
76-79	Peak	1/R	2.564	2.198	-0.164	0.007	3C48
		1/L	2.551	2.184	-0.164	0.000	
81-84	Peak	1/R	2.074	2.521	-0.033	0.037	3C48
		1/L	2.021	2.510	-0.028	0.030	
86-89	Peak	1/R	3.107	3.176	-0.063	-0.033	3C48
		1/L	3.217	3.264	-0.057	-0.041	
91-94	Peak	1/R	3.001	3.237	-0.018	-0.012	3C48
		1/L	3.212	3.296	-0.017	-0.021	
95-98	Peak	1/R	2.642	3.002	-0.032	-0.017	3C48
		1/L	2.674	3.020	-0.027	-0.028	
100-103	Peak	1/R	3.166	3.090	-0.117	-0.005	3C48
		1/L	3.282	3.125	-0.117	-0.010	
105-108	Peak	1/R	3.338	3.355	-0.105	-0.047	3C48
		1/L	3.436	3.430	-0.102	-0.050	
AVE		1/R	2.81	2.92	-0.073	-0.004	3C48
RMS		1/R	±0.43	±0.38	±0.054	±0.027	
AVE		1/L	2.89	2.95	-0.071	-0.010	3C48
RMS		1/L	±0.49	±0.042	±0.055	±0.027	

Table 5. Gain Factors from Selected Scans of TKFPA_62

Scan Numbers	Type Obs.	Pol	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 6	Beam 7	Source Name
105-106	OnOff	R	1.032	1.017	0.946	0.933	1.041	0.915	1.054	Moon
		L	1.041	1.015	0.930	0.950	1.065	0.905	0.988	$T_A = 142K$

3. Summary

We presented a series of calibration measurements with the KFPA. Comparison of laboratory measurements of the calibration noise diode values with values deduced from observations of the Moon and 3C48 are now consistent.

During the interval Sept 6, 2010 to January 16, 2011, the calibration values associated with the data are too low, and images produced from the observations should be scaled with the gain values listed in Table 3.

Pointing accuracy is critical for calibration measurements made using Nod observations. Observations made in December 2010 confirmed good GBT pointing accuracy, with typical 1 σ radial angular offset of $3.7''$. This angular offset would result in an over estimate of the gain correction factor of 3.8 %. For gaussian distributed pointing errors, NOD observations would yield gain errors as large as 14 %. Therefore we recommend mapping observations to determine calibration gain factors, or use of the Moon, where sensitivity to pointing errors is greatly reduced.

After 2011 February 17, the calibration values deduced from astronomical observations closely match the laboratory values. The gain correction factors in Table 5 are consistent with unity to with the absolute temperature scale uncertainty. The relative intensity differences in the gain factors are significant, as other observations show that the intensities measured with beams 3 and 4 are always higher than for the other beams.

The gain calibration factors should be periodically checked by astronomical observations either by On/Off observations of the Moon or by mapping observations of compact reference radio sources.

A. Example Execution of a GBTIDL script to extract Gain Factors

The observations were reduced using a contributed set of GBTIDL scripts. The scripts were placed in directory:

/home/astro-util/gbtidl/contrib

These scripts are available for general use. Others are encouraged to place useful data reduction scripts in this location as well. Below is a listing of an execution of these scripts. The observer needs only execute two commands inside GBTIDL, a setup command and a command to extract the data from the archive and compute the gain factors:

```
@/home/astro-util/gbtidl/contrib/calsetup.pro
mooncalget,'TKFPA_51',29,30
```

The script finds the data in the archive, in this case for project TKFPA_51, and converts two scan numbers for On and Off Moon observations (29,30) to the required format. After execution of this script, the observer should copy the gain factor values into their gbtpipeline input parameter file.

A.1. GBTIDL procedures for Gain Calibration

To facilitate reduction of gain calibration observations, we created a set of GBTDL procedures to compute opacity, gain and source model brightness temperatures. These procedures are listed below:

`gainel` - Compute the GBT elevation dependance of telescope efficiency.

`taudate` - Retrieve a set of zenith opacities from the weather database

`dateToMjd` - Convert an ascii string date to Modified Julian Date.

`endfix` - Replace the spectral band edges with the median value, to improve autoscaling of plots.

`opacity` - Compute the opacity correction based on zenith opacity and elevation of the observation.

`natm` - Compute the number of atmospheres for a given elevation of observation.

`tatm` - Compute the atmospheric contribution to the system temperature.

`tsystau` - Call other GBTIDL routines to compute the atmospheric system temperature

`gettau` - Retrieve a single zenith opacity from the weather database.

`etagbt` - Return the GBT efficiencies as a function of system temperature

`showtsys` - Utility function to show all tsys values for a scan.

`showsigref` - Utility function to show all tsource values for a pair of signal and reference scans

`humidityToTDew` - Compute the dew point temperature from humidity.

`densityWater` - Compute the density of water in air for specific weather conditions

`opacityO2` - Compute the opacity of O2 for a specified frequency

`partialPressureWater` - Compute the partial pressure of water for specified weather conditions

`liebeTau` - Compute the model zenith opacity for specified weather conditions

`linereject` - Utility function to remove narrow band RFI from spectra for plotting.

`goodbeam` - Utility function called by the calibration routines to identify good beams for reference temperature estimates. This function should be replaced by the observer if some beams are not performing correctly.

`mooncal` - Function to compute gain corrections based on Moon On/Off observations.

`mooncalget` - Function to get archive data, then call `mooncal` to compute gain corrections.

`venusmodel` - Function to estimate the Venus equivalent brightness temperature on a date of observations.

`venuscal` - Function to compute gain corrections based on a series of NOD observations of Venus.

`venuscalget` - Function to get archive data, then call `venuscal` to compute gain corrections.

`marsmodel` - Function to model the Mars equivalent brightness temperate on a date of observations.

`marscal` - Function to compute gain corrections based on a series of NOD observations of Mars.

`marscalget` - Function to get archive data, then call `marscal` to compute gain corrections. We note that Mars is often too weak for use as a calibration source.

`jupitermodel` - Function to model the Jupiter equivalent brightness temperature on a date of observations.

`jupitercal` - Function to compute gain corrections based on a series of NOD observations of Jupiter.

`ott3C123` - Function to model the 3C123 equivalent brightness temperature.

`ott3C48` - Function to model the 3C48 equivalent brightness temperature.

`ott3C147` - Function to model the 3C147 equivalent brightness temperature.

`ott3C286` - Function to model the 3C286 equivalent brightness temperature.

`ottTaurus` - Function to model the Taurus A equivalent brightness temperature.

`sourcemodel` - Function to equivalent brightness temperatures from point sources.

`sourcecal` - Function to compute gain corrections based on a series of NOD observations.

`sourcecalget` - Function to get archive data, then call `sourcecal` to compute gain corrections.

A.2. Moon Calibration Example

Log of a GBTIDL session for computing gain factors:

```
GBTIDL -> @/home/astro-util/gbtidl/contrib/calsetup.pro
% Compiled module: GAINEL.
...
% Compiled module: MOONCAL.
% Compiled module: MOONCALGET.
% Compiled module: VENUSMODEL.
% Compiled module: VENUSCAL.
% Compiled module: VENUSCALGET.
GBTIDL -> mooncalget,'TKFPA_62',105,106
Scan:   105   Tsys: 194.65
Scan:   106   Tsys:  83.87
2011_04_08_20:22:03 ->        55659.849
zenithOpacity    :   0.152 +/-   0.025
Opacity Factor(M):   1.174+/-  0.032
Opacity Factor(R):   1.174+/-  0.032
Model Number of Atmospheres:        1.0586094 at elevation        70.845198
Freq, etaA, etaB :        23703.448      0.64378678      0.82469088
Moon Illumination:      0.23855309 (fraction) for MJD        55659.849
Moon Phase Angle :       58.581610 (degrees)  for Date
Moon Phase Offset:      40.0000 (degrees)
Moon Model: tAve :       239.18601 tVariation:        28.719860 K
Moon Temp (K)    :        211.96329 +/-        8.7000375
Opacity factor :        0.85164028
All Corrections:        0.67722399
Predicted On-Off Moon Temp K:        141.64754
Predicted On Moon Temp(-Trx):        143.54662
Predicted Off Moon CMB Temp :        1.8949679
Predicted Elevation Change K:    -0.0041173741
#IF 1L    1R    2L    2R    3L    3R    4L    4R    5L    5R    6L    6R    7L    7R        MHz     Az(
 0 136.1 137.3 139.5 139.2 152.3 149.7 149.1 151.8 133.0 136.1 156.5 154.8 143.4 134.4   23703.455  138
 1                         160.3 155.0                                                   22341.193  138
SigScan:   105  RefScan:   106  units: Ta (K)  Tsys:  81.43
SigScan:   105  RefScan:   106  units: Ta (K)  Tsys:  83.87
Calibration Factors
--gain-factors-left  1.041,1.015,0.930,0.950,1.065,0.905,0.988
--gain-factors-right 1.032,1.017,0.946,0.933,1.041,0.915,1.054
Summary in :MoonTemp.log
```

After computing the gain factors, these should be applied using the KFPA pipeline input file. Below is an example input parameter file `tkfpa51.par`:

```
#KFPA pipeline arguments for KFPA observations; RR Polarizations, no beam 4
--clobber
-v 4
-a 20
# make a map of an On/Off moon observation
-m 29
--refscan1 30
#--refscan2 35
--gain-factors-left  1.041,1.015,0.930,0.950,1.065,0.905,0.988
--gain-factors-right 1.032,1.017,0.946,0.933,1.041,0.915,1.054
#--imaging-off
#--allmaps
#-m 31:33
#Limit noise range to 4 K RMS
-n 4.0
#The following allows selecting all beams, but 4
#-f 1,2,3,5,6,7
#Potentially select only RR or LL polarization
#-p LL
#Select the maximum number of processors
#--max-processors 14
#--no-map-scans-for-scale
-i ./TKFPA_51.raw.acs.fits
-u Tmb
```
