GBT Memo 261: Ka-band/CCB Instrumental Calibration

v1. 31mar08 Brian S. Mason: first draft (formalism only).

v2. 20feb09 bsm: document existing calibration FITS files.

Contents

1 Formalism

The Caltech Continuum Backend, currently in use with the Ka-band receiver, provides sensitive, beamswitched, broadband continuum measurements over the entirety of the 26 - 40 GHz receiver band. The architecture of the Ka-band receiver, in addition to allowing rapid beamswitching, gives rise to some unusual properties, for instance, a low-level (few to 10%) "cross-talk" between output channels which nominally measure different beams on the sky. This needs to be accounted for in determining T_{cal} values from hot/cold load calibration measurements. In this memo we outline a strategy for deriving a Ka-band receiver calibration from hot/cold load data and applying it to astronomical data. We also document the existing CCB calibrations and provide pointers on how to generate future calibrations, and how the scheme presented maps to the terminology used by the GBT Measurements database for calibration. We do not address astronomical calibration.

We assume that the receiver and backend are linear, and that the gains, leakages, and offsets (the latter corresponding roughly to receiver temperature contributions) depend only on beamswitch state. The data from one one of the receiver output channels (a single frequency channel from one polarization from one beam, as labeled in a nominal SIG beamswitch state) can then be represented as

$$\begin{pmatrix} d_s \\ d_r \end{pmatrix} = \begin{pmatrix} G_s & \delta_s \\ \delta_r & G_r \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \end{pmatrix} + \begin{pmatrix} O_s \\ O_r \end{pmatrix} \quad (1)$$

where for a given beamsiwtch state[1] SIG (s) or REF (r) G is the gain with respect to the noimnal input feed, δ is the leakage from the other feed, and

[1] For the Ka-band receiver there are two phase switch states the correpond to SIG and two that correpond to REF. These can be averaged to obtain an average SIG and average REF datastream.

O is the offset (in practice, mostly due to the receiver noise temperature). T_1 and T_2 represent the inputs to the two feeds. For a single channel, there are then six calibration parameters that need to be determined: a gain, a leakage, and an offset in each of the SIG and REF states. In addition there are the two calibration diode[2] equivalent temperatures T_A and T_B, for a total of eight parameters. Solutions for the astronomically important terms can be obtained without reference to the offsets.

Consider that data are collected against each of a hot and cold load, and against one load, data are collected both with cal A firing and cal A not firing, and with cal B firing and cal B not firing as well. We then have four measurements (Hot, Cold, Cal A on, Cal B on) for a total of eight equations so it may be possible to determine all eight parameters. The eight equations are:

$$d_s^{Hot} = (G_s + \delta_s) T_h + O_s \tag{2}$$
$$d_r^{Hot} = (G_r + \delta_r) T_h + O_r \tag{3}$$
$$d_s^{Cold} = (G_s + \delta_s) T_c + O_s \tag{4}$$
$$d_r^{Cold} = (G_r + \delta_r) T_c + O_r \tag{5}$$
$$d_s^{Cold,A} = (G_s + \delta_s) T_c + G_s \, T_A + O_s \tag{6}$$
$$d_r^{Cold,A} = (G_r + \delta_r) T_c + \delta_r \, T_A + O_r \tag{7}$$
$$d_s^{Cold,B} = (G_s + \delta_s) T_c + \delta_s \, T_B + O_s \tag{8}$$
$$d_r^{Cold,B} = (G_r + \delta_r) T_c + G_r \, T_B + O_r \tag{9}$$

Here we denote the cal-on data by a superscript A or B and assume it is collected against the cold load. We have also assumed a particular correpondence between cal diodes (A and B) and feeds; if the other correspondence pertains, then equations 6 - 9 will have A replaced with B. In practice, which association pertains can be determined by comparing the cal signals; for the case assumed here, one will have $d_s^{Cold,A} - d_s^{Cold} > d_r^{Cold,A} - d_r^{Cold}$.

In order to solve for the gains, leakages, and T_{cal} values, these can be rewritten as:

$$d_s^{Hot} - d_s^{Cold} = (G_s + \delta_s)(T_h - T_c) \tag{10}$$
$$d_r^{Hot} - d_r^{Cold} = (G_r + \delta_r)(T_h - T_c) \tag{11}$$
$$d_s^{Cold,A} - d_s^{Cold} = G_s T_A \tag{12}$$
$$d_r^{Cold,A} - d_r^{Cold} = \delta_r T_A \tag{13}$$
$$d_s^{Cold,B} - d_s^{Cold} = \delta_s T_B \tag{14}$$
$$d_r^{Cold,B} - d_r^{Cold} = G_r T_B \tag{15}$$

Note that owing to the $\delta \times T_{cal}$ terms this is not a system of linear equations. In practice $\delta / G << 1$ so it can be solved iteratively starting with $\delta = 0$. For

[2] The CCB independently controls the Ka band receivers two calibration noise diodes and labels them A and B.

given values of $\delta_{s,r}$ we have

$$G_s = \frac{d_s^{Hot} - d_s^{Cold}}{T_h - T_c} - \delta_s \quad (16)$$

$$G_r = \frac{d_r^{Hot} - d_r^{Cold}}{T_h - T_c} - \delta_r \quad (17)$$

$$T_A = \frac{d_s^{Cold,A} - d_s^{Cold}}{G_s} \quad (18)$$

$$T_B = \frac{d_r^{Cold,B} - d_r^{Cold}}{G_r} \quad (19)$$

then improved δ values are found by

$$\delta_s = \frac{d_s^{cold,B} - d_s^{cold}}{T_B} \quad (20)$$

$$\delta_r = \frac{d_r^{cold,A} - d_r^{cold}}{T_A} \quad (21)$$

This scheme is iterated until the solutions are stable. Usually a few iterations will converge to a fraction of a percent.

Given these parameters, the timestreams d_s and d_r can be calibrated from counts to kelvin by

$$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix} = \begin{pmatrix} \frac{1}{G_s} & -\frac{\delta_s}{G_s G_r} \\ -\frac{\delta_r}{G_s G_r} & \frac{1}{G_r} \end{pmatrix} \begin{pmatrix} d_s \\ d_r \end{pmatrix} \quad (22)$$

to first order in δ/G. One can then determine effective receiver temperatures for each feed (or beamswitch state) as $T_{rx,1} = T_1 - T_c$ for the feed 1 data that were collected against the cold load, for instance. This assumes that any difference in receiver temperatures comes from before the first hybrids, which is reasonable since in principle the dominant terms of the receiver noise come from the HEMT amplifiers and do not depend on beamswitch state. However, owing to bandpass effects and imperfections in the hybrids it is only an indicative figure, and further analysis would be needed to precisely separate receiver temperature contributions of various parts of the system.

It is interesting to note that the "raw" beamswitched measurement $d_s - d_r$ has the form

$$d_s - d_r = (G_s - \delta_r)(T_1 - r\,T_2) + (O_s - O_r) \quad (23)$$

with

$$r = \frac{G_r - \delta_s}{G_s - \delta_r} \quad (24)$$

expressing the response of the REF beam relative to that of the SIG beam. This shows how differences in gain and leakage give rise to differences in the individual beam responses in uncalibrated difference data.

Once temperatures for the calibration diode are derived from hot/cold load measurements, these can be used to determine the system gains at subsequent points in time, *e.g.*, for a given observing session. By rearranging eqs. 18 - 21 we have

$$G_s = \frac{d_s^A - d_s}{T_A} \quad (25)$$

$$G_r = \frac{d_r^B - d_r}{T_B} \quad (26)$$

$$\delta_s = \frac{d_s^B - d_s}{T_B} \quad (27)$$

$$\delta_r = \frac{d_r^A - d_r}{T_A} \quad (28)$$

Again, if the other cal-to-feed association pertains these expressions will have A replaced with B. All data quantities are averages over the scan; one trick which improves the stability of the estimate in the presence of astronomical signals, when subtracting cal-off integrations from cal-on integrations, is to use only the cal-off integrations immediately preceding and following the cal-on integrations in time.

Note that in order to derive the full calibration, some data are needed with neither cal firing; some data are needed with the A cal only firing; and some data are needed with the B cal only firing.

IDL routines have been implement to apply this calibration to CCB data. The main routine is `~bmason/ccbidlbin/calibtokelvin.pro`; it depends on T_{cal} information (or previously derived gains and leakages) which are stored in independent calibration FITS files described in the next section.

2 Calibration Data

The per-port CCB calibrations used by IDL are contained in FITS files. The table called CCBCALIB contains the necessary information:

- Keywords MJDSTART and MJDSTOP specifying the period over which the calibration in the table is nominally valid.
- Keyword CCBCALV denoting the calibration version (2 for the formalism presented here in v2 of this document).
- Comments in the header describing the origin of the data.
- Columns GSIG, GREF, DSIG, and DREF containing the gains and leakages (both in counts per kelvin) in each beamswitch state.
- Columns TA and TB, containing the cal diode equivalent brightness temperatures in Kelvin for the diodes controlled by CCB cal outputs A and B.
- Columns TRXSIG and TRXREF containing the system temperature in Kelvin in the sig and ref beamswitch states.

- Column ACALISSIG indicating whether the A cal is brighter in the sig (1) or ref (0) states.
- Column VALID indicating whether the hot/cold measurement for the given port was good or not. In cases where it was not, typically this was due to overflow on the hot load scans; efforts have been made to infer the correct values of TA and TB even in these cases.

Other tables in these FITS files are present for historical completeness and backward compatibility reasons only.

2.1 Existing CCB Calibration Files

All files are kept in `~bmason/ccbPub/calibDat`. The calibration FITS files are produced by the IDL routine `~bmason/ccbidlbin/reg/reduceCcbHotCold.pro` which makes use of other routines in `~bmason/ccbidlbin/` and its subdirectories. The code allows inclusion of a zero-level file as well. This would be data collected with all HEMTs turned off in order to measure the RF detector zero levels, and provides a more accurate T_{rx} value. Often this underflows the CCB's analog-to-digital converter resulting in usless data for many ports, so has not been done in any of the following.

Note that the reciprocals of the gain values that follow are the calibration factors needed by the CCB ygor manager to convert counts into approximate antenna temperatures in Kelvin for the calibrated data samplers. The values go in the file
`/home/gbt/etc/config/CCB26_40.conf`

kaCcbCalibSep06.fits:

PORT	Ta	Tb	Trxsig	TrxRef	Gsig	Dsig	Gref	Dref	AcalIsSig	Valid
1	7.93	9.11	22.75	26.17	37.90	0.78	35.58	0.82	1	1
2	5.32	3.62	25.28	28.88	36.24	2.51	33.75	2.60	1	1
3	6.69	5.48	27.88	31.68	21.39	2.12	20.07	1.97	1	1
4	3.47	2.25	29.60	31.87	23.92	8.01	22.20	8.54	1	1
5	5.48	3.59	30.86	27.11	31.94	2.30	34.06	2.33	0	1
6	7.99	9.03	25.07	21.50	33.43	0.93	35.90	0.79	0	1
7	6.40	4.89	29.65	26.63	30.81	3.19	31.83	3.71	0	1
8	3.82	2.24	31.41	29.10	20.67	6.75	21.22	7.29	0	1
9	3.66	1.36	31.70	33.34	35.07	2.53	34.61	1.97	1	1
10	8.39	4.14	28.55	27.56	36.10	1.14	37.99	0.81	1	1
11	9.53	4.87	23.69	24.81	34.56	2.40	34.13	2.36	1	1
12	7.22	3.66	27.31	28.52	34.67	1.06	33.61	1.46	1	1
13	3.48	1.35	31.80	30.43	34.47	2.01	34.48	2.58	0	1
14	8.50	4.21	26.30	27.00	39.07	1.00	37.75	1.26	0	1
15	9.67	4.79	25.78	24.58	34.08	2.36	34.45	2.58	0	1
16	7.17	3.64	29.43	28.25	34.29	1.21	34.64	1.43	0	1

Above: Calibration data derived from December 2005 lab measurements.

kaCcbCalibMar06.fits:

PORT	Ta	Tb	Trxsig	TrxRef	Gsig	Dsig	Gref	Dref	AcalIsSig	Valid
1	4.57	3.91	37.00	27.00	1.00	0.09	1.00	0.09	0	1
2	5.86	5.44	25.00	21.00	1.00	0.05	1.00	0.05	0	1
3	3.87	4.62	29.00	24.00	1.00	0.07	1.00	0.07	0	1
4	1.71	1.92	34.00	28.00	1.00	0.07	1.00	0.07	0	1
5	4.44	3.69	30.00	40.00	1.00	0.08	1.00	0.08	1	1
6	6.04	5.62	20.00	24.00	1.00	0.06	1.00	0.06	1	1
7	4.32	4.85	24.00	29.00	1.00	0.05	1.00	0.05	1	1
8	1.72	1.94	30.00	35.00	1.00	0.08	1.00	0.08	1	1
9	1.33	1.43	33.00	31.00	1.00	0.02	1.00	0.02	1	1
10	6.22	3.77	30.00	26.00	1.00	0.02	1.00	0.02	1	1
11	5.07	5.58	23.00	22.00	1.00	0.01	1.00	0.01	1	1
12	6.12	3.38	37.00	35.00	1.00	0.06	1.00	0.06	1	1
13	1.33	1.43	29.00	31.00	1.00	0.02	1.00	0.02	0	1
14	6.32	3.88	24.00	28.00	1.00	0.02	1.00	0.02	0	1
15	5.20	5.50	21.00	21.00	1.00	0.02	1.00	0.02	0	1
16	6.15	3.39	32.00	34.00	1.00	0.06	1.00	0.06	0	1

Above: calibration data for Mar06, collected in the lab. Absence of the original data files, prevented derivation of direct gains for this dataset.

kaCcbCalibNov06d.fits:

PORT	Ta	Tb	Trxsig	TrxRef	Gsig	Dsig	Gref	Dref	AcalIsSig	Valid
1	4.89	3.30	24.39	20.92	1.00	0.09	1.00	0.09	0	1
2	7.76	8.96	27.06	23.38	1.00	0.05	1.00	0.05	0	1
3	6.25	5.03	29.92	25.34	1.00	0.07	1.00	0.07	0	1
4	2.68	1.59	29.52	27.45	1.00	0.07	1.00	0.07	0	1
5	5.29	3.44	25.15	28.75	1.00	0.08	1.00	0.08	1	1
6	7.80	8.71	19.83	23.13	1.00	0.06	1.00	0.06	1	1
7	5.49	4.26	24.85	27.49	1.00	0.05	1.00	0.05	1	1
8	2.86	1.76	27.01	29.23	1.00	0.08	1.00	0.08	1	1
9	3.31	1.25	31.29	29.51	1.00	0.02	1.00	0.02	0	1
10	7.66	3.74	25.68	26.59	1.00	0.02	1.00	0.02	0	1
11	8.40	4.29	23.03	21.86	1.00	0.01	1.00	0.01	0	1
12	7.03	3.52	26.50	25.23	1.00	0.06	1.00	0.06	0	1
13	3.16	1.27	28.50	29.63	1.00	0.02	1.00	0.02	1	1
14	7.76	3.95	25.09	24.37	1.00	0.02	1.00	0.02	1	1
15	8.54	4.26	22.80	23.87	1.00	0.02	1.00	0.02	1	1
16	6.78	3.50	26.24	27.42	1.00	0.06	1.00	0.06	1	1

Above: Nov06 calibration from data collected on the telescope. Absence of the original data files prevented derivation of direct gains for this dataset.

kaCcbCalibLabAug07.fits:

PORT	Ta	Tb	Trxsig	TrxRef	Gsig	Dsig	Gref	Dref	AcalIsSig	Valid
9	35.38	28.48	32.77	31.65	34.88	3.00	35.44	2.65	1	1
10	50.91	36.45	28.28	26.49	34.86	2.36	35.67	2.11	1	1
11	52.17	39.72	24.91	24.13	38.60	1.58	38.71	1.61	1	1
12	40.87	25.30	36.50	29.39	36.53	1.46	38.84	1.58	1	1
13	35.63	28.94	33.98	34.83	35.03	2.56	34.65	2.81	0	1
14	50.90	36.70	27.14	28.90	35.64	2.04	34.92	2.20	0	1
15	52.82	39.75	25.73	26.33	38.77	1.41	38.45	1.60	0	1
16	40.71	25.50	33.68	38.92	37.81	1.21	35.61	1.67	0	1

Above: calibration from the first dataset after the modifications to the Ka band receiver for ZPECtrometer, which eliminated one polarization (half the channels). These data were collected in the lab and the cal diodes were not padded down as much as they had been before, which was fixed when installing on the telescope.

```
IDL> dumpcalibtbl,'kaCcbCalibAug07.fits',1
MRDFITS: Binary table.  13 columns by  8 rows.
PORT Ta    Tb Trxsig TrxRef  Gsig Dsig Gref   Dref AcalIsSig  Valid
 9  7.70  7.12  1.00  1.00  1.00  0.00  1.00  0.00   1        0
10 11.97 10.13 40.98 48.93 36.87  1.69 34.48  1.57   1        1
11 13.20 10.05  1.00  1.00  1.00  0.00  1.00  0.00   1        0
12 11.14  6.33 51.10 41.48 35.31  1.22 37.92  1.32   1        1
13  7.70  7.12 39.43 38.20 30.87  2.40 31.17  2.55   0        1
14 12.77  8.87 33.56 48.12 38.40  1.43 33.52  1.77   0        1
15 13.22 10.05 30.93 29.73 39.22  0.97 39.36  1.18   0        1
16 10.07  6.89 56.48 42.94 34.66  1.16 38.56  1.41   0        1
```

Above: Aug07 on-telescope calibration.

```
IDL> dumpcalibtbl,'kaCcbCalibOct08hotColdA.fits',1
MRDFITS: Binary table.  13 columns by  8 rows.
PORT Ta    Tb Trxsig TrxRef  Gsig Dsig Gref   Dref AcalIsSig  Valid
 9  6.98  6.48  1.00  1.00  1.00  0.00  1.00  0.00   1        0
10 10.91  9.18 32.52 39.38 38.34  1.72 36.09  1.55   1        1
11 12.60  9.60  1.00  1.00  1.00  0.00  1.00  0.00   1        0
12 10.13  5.85 42.03 34.95 37.48  1.29 39.60  1.49   1        1
13  6.98  6.48 31.81 30.52 32.67  3.13 32.93  3.31   0        1
14 11.61  8.68 33.16 39.41 37.90  1.44 35.55  1.71   0        1
15 12.58  9.59 28.65 26.42 40.20  0.94 40.86  1.11   0        1
16 10.10  5.85  1.00  1.00  1.00  0.00  1.00  0.00   0        0
```

Above: oct08 on-telescope calibration.

Two features of the recent (Aug 07 & Oct 08) data stand out. First, the T_{rx} at the lowest frequencies (channels 12 and 16) tends to be high (40-55 K) and possibly variable. Second, the offset is substantially different in the two beamswitch states (5 - 7 K). This doesn't appear to be due to imbalances before the first hybrid since its sign is not consistent.

Also worth noting is the fact that since, in practice, the δ_{sig}/G_{sig} values are very close to the δ_{ref}/G_{ref} values, and always positive, a conventional total power calibration would do a reasonable job. The absolute temperature scale would be wrong by a few to 10% (δ/G) but the relative beam scalings would be accurate to significantly better than this.

3 Relation to the GBT Measurements Database

Since the CCB is a hard-wired, direct detection system, the per-port calibration described above is simpler and more robust than a calibration scheme based on physical labels such as feed number and polarization which require astronomical verification. Other GBT receivers' calibrations are described in the Measurements Database and the FITS files generated by the Measurements manager.

These calibrations are labeled by receptor[3]. We briefly describe how to relate the calibration information above to receptor names; most of this mapping is standard, *i.e.*, the same as for all other GBT receivers and backends. The main differences are

1. The cal signals that can be injected into feed 1 and feed 2 are controlled indvidually by CCB;

2. In order to minimize cross-coupling between the HEMT amplifiers, the Ka band receiver's beamswitch switches between orthogonal polarizations.

The latter fact breaks the GBT's scheme for inferring the receptor names in the beamswitched state. This could be fixed by replacing the IF manager's SRFEED1/SRFEED2 keyword pair (denoting which two feeds are switched between for a given port) with an SRRECEPT1/SRRECEPT2 keyword pair explicitly designating the receptors that are seen.

To associate a receptor with a given CCB port with the beamswitch in the SIG state, simply look up the values of FEED and POLARIZE in the row of the IF manager FITS file that corresponds to the desired PORT and BACKEND. With the beamswitch in the REF state the same procedure can be used, but use the polarization orthogonal to POLARIZE.

To label the Tcal values in the IDL CCB FITS calibration files by receptor for a given PORT:

1. If ACALISSIG=1 in the CCB FITS calibration file, follow the same prescription used to map a CCB PORT to a RECEPTOR and apply the label to the A diode Tcal.

2. If ACALISSIG=0 in the CCB FITS calibration file, follow the same prescription used to map a CCB PORT to a RECEPTOR and apply the label to the B diode Tcal.

The information deduced from this exercise can be stored in the CCB YGOR manager FITS file keyword AISXL. The Tcal values can be stored in the standard Measurements manager fields LOW_CAL_TEMP for A and HIGH_CAL_TEMP for B. The other calibration quantities (Gsig, Dsig, Gref, Dref) could also be added to the calibration database and measurements FITS files.

For more information refer to GBT SPN 4.2, "Device and Log FITS files for the GBT"; GBT SPN 10.6, "GBT IF Manager FITS File Specification"; and GBT SPN 27.0, "GBT Caltech Continuum Backend FITS File Specification". All are available at

`http://wiki.gb.nrao.edu/bin/view/Software/ProjectNotes`.

[3]A receptor is a physical label for a receiver's distinct signal outputs, usually constructed from POLARIZE+FEED. The continuum outputs of the Ka band receiver that go to the CCB have "_C" appended. Consistent with the practice for other receivers the different Ka band continuum frequency channels for a given feed and polarization are not given different receptor labels.

4 Calibration Checklist

The following should be done each time the Ka band receiver is installed on the telescope.

1. On-telescope hot, cold, and zero level measuremnts. Collect data to FITS files and ensure that there are at least 2 integrations with each of A cal on, B cal on, both cals on, and no cals on.

2. Generate IDL FITS calibration files and place in the calibDat area. Update MJDSTOP value for the preceding calibration file.

3. Update CCB manager config file to have the new counts to kelvins conversion.

4. Update CCB manager AISXL value based on what polarization cal A maps to. This is also in the manager config file.

5. Update the T_{cal} entries in the measurements database.