Heterodyne Calibration

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(With a great deal of help from all at EAO, especially Jan Wouterloot and Per Friberg)
Overview

1) Calibration applied **while observing**:
   - Carried out by telescope while taking an observation.
   - Included in raw files.

2) Calibration applied **after observing**:
   - Conversion from $T_A^*$ to scientifically useful temperature or flux scale.
   - Done by PI/scientists based on telescope provided values/obs.

3) Additional post-observation **calibration fixes** sometimes required:
   - HARP: corrections for total power variation between receptors.
   - RxA3m: currently requires corrections for sideband ratio issues.

4) Recommended **work flow** for heterodyne calibration.
1) While observing

- Already applied to your raw data.
- Calibration combines measurements of ambient loads, sky measurements and a load of known temperate (heated for HARP, cooled for RxA3).
- Calibrates all ACSIS spectra into **corrected antenna temperature** ($T_A^*$), in Kelvin.
- Corrected for:
  - Atmospheric attenuation.
  - Scattering.
  - Rearward spillover (portion of beam not looking at sky).
1) While observing

Monitoring performance

- Spectral standard observations done every night @ appropriate freq.
- TSS checks performance of JCMT heterodyne instruments during night.
  - Expect standards to be within \(\approx 10\%\) of nominal.
- Results monitored to keep track of long term performance.
- Pointing offsets will tend to skew distribution below 'true' value.
  - Spectral standards observed as stares, so offset reduces the flux.
  - JCMT RMS pointing offset: 2” in x & y, giving 2.8” radial RMS offset
- Average spectra available online for spectral standards at many transitions.
1) While observing HARP CRL 2688 CO 3-2
1) While Observing

HARP CRL 618 CO 3-2
1) While Observing

HARP IRC+ 10216 CO 3-2

HARP: IRC+10216 (Peak intensity)

HARP: IRC+10216 Peak intensity
1) While Observing

RXA3 CRL 2688 CO 2-1
1) While observing RxA3 CRL 618 CO 2-1

![Graph of RxA3: CRL618 (Peak intensity)](chart1)

![Graph of RxA3: CRL618 Peak intensity](chart2)
1) While Observing

**RxA3 IRC+ 10216 CO 2-1**
1) While Observing

### Heterodyne Standard Uncertainties

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Source</th>
<th>Type</th>
<th>mean</th>
<th>std</th>
<th>% error</th>
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<td>INTEGINT</td>
<td>463.7</td>
<td>26.5</td>
<td>5.7</td>
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</table>
1) While Observing

Heterodyne Calibration Observations

- We recommend checking the spectral standard and heterodyne planetary observations from the same night to see if they are reasonable.
  - Look at shift comments and obslog comments on JCMTCAL observations, along with the ORAC-DR logs.
  - For archival data, you can download proposal=JCMTCAL observations from that night.
  - If you see issues please contact your support scientist directly, or the observatory via: helpdesk@eaobservatory.org
2) After observing

- After observing, it is usually necessary to convert from the telescope/instrument dependent $T_A^*$ scale into a scientific scale; $T_{MB}$ or $T_R^*$.
- Done by using the appropriate efficiencies.
  - $\eta_{MB}$ for $T_{MB}$
  - $\eta_{FSS}$ for $T_R^*$
- Note that different telescopes/papers may use different nomenclature or slightly different definitions.
- See e.g. Kutner & Ulich, 1981
2) After observing

Heterodyne Temperature Scales

- **Main beam temperature:** \( T_{MB} = T_A^* / \eta_{MB} \).
  - \( \eta_{MB} \) is the efficiency of the main beam of the instrument/telescope combination, as found by measuring a source of similar size to the beam (Jupiter, Uranus or Mars).
  - Most appropriate for point sources.

- **Radiation Temperature:** \( T_{R}^* = T_A^* / \eta_{FSS} \).
  - \( \eta_{FSS} \) is the efficiency of the entire telescope beam, including the sidelobes, as found by measuring the intensity from a source much larger than the beam (e.g. the moon).
  - Most appropriate for large sources filling the whole beam, otherwise a correction for source filling factor should be applied.

- Many sources are intermediate between these two extremes (e.g. clumpy molecular clouds), so the **best choice of calibration is a decision by the scientist.**
2) After observing

**Flux density**

- To convert to point source flux density:
  - (e.g. equivalent of $T_{MB}$)
  - Conversion uses the aperture efficiency $\eta_A$.
  - $\eta_A$ is calculated from the same data as $\eta_{FSS}$.
- For a 15m dish, the conversion factor is:
  $$S(\text{Jy}) = 15.6 \frac{T_A \, (\text{K})}{\eta_A}.$$
2) After observing

**Efficiency Measurements**

- Observatory regularly measures $\eta_{MB}$ (and $\eta_A$) with HARP and RxA towards the planets to monitor the main beam efficiency.
  - RxA3: 230.538 GHz (CO 2-1)
  - HARP: 345.796 GHz (CO 3-2) @ tracking receptor H05
- canonical telescope values are
  - **HARP**: $\eta_{MB} = 0.64$ and $\eta_A/\eta_{MB} = 0.812$ (Uranus), 0.814 (Mars)
  - **RxA3**: $\eta_{MB} = 0.65$ and $\eta_A/\eta_{MB} = 0.867$
  - **RxA3m**: $\eta_{MB} = 0.6$ and $\eta_A/\eta_{MB} = 0.867
2) After Observing $\eta_{MB}$ for HARP

(Daytime observations are shown in orange)
2) After Observing $\eta_{MB}$ for HARP: variation with hour and $\tau$
2) After Observing $\eta_{MB}$ for RxA3
2) After Observing $\eta_{MB}$ for RxA3: variation with hour


2) After Observing

(Some) sources of uncertainty

- Uncertainty in the known brightness of the standards.
- Pointing offsets.
- Varying efficiencies:
  - Variation due to variation in beam (e.g. surface accuracy, temperature deformation of dish etc.).
  - Systematic issues: e.g. periods where RxA3 has a different calibration value due to misalignment, time where HARP pointing could be affected by K-mirror flips.
- RxA3m: issues from sideband ratios.
- HARP only: receptor to receptor variation.

  All calibration observations by the telescope are only analysed for the tracking receptor (normally H05).
2) After Observing

$\eta_{\text{FSS}}$ for HARP and RxA3

- We also have observed the Moon to determine $\eta_{\text{FSS}}$.
- $\eta_{\text{FSS}}$ includes entire beam.
  - $\Rightarrow$ Not expected to be as variable as $\eta_{\text{MB}}$.
- HARP: measured as 0.77 (2006) & 0.75 (2015) @ 345 GHz.
- RxA3: 0.72 (measured prior to 2006).
2) After Observing

Applying calibration to data files

• How to apply calibration, using KAPPA commands and an SDF file:
  1) Divide the data file by the correct value using `cdiv`.
  2) Update the 'label' attribute using `setlabel`.
  3) If changing units (e.g. to flux density), also update the `unit` attribute: `setunits`.

• Example commands to calibrate to $T_{MB}$:
  ```
  cdiv in=harpreduced.sdf scalar=0.64
  out=harptmb.sdf
  setlabel ndf=harptmb.sdf label='T_{MB}'
  ```
3) Additional calibration fixes

Sometimes it is necessary to apply additional fixes to correct specific instrumental problems.

Two specific cases addressed here:

- RxA3m: sideband ratio.
- HARP: detector-to-detector total power variation.
3) Additional Calibration Fixes

**RxA3m**

- December 2015: ASIAA mixer installed in RxA3.
- Now called RxA3m.
- Main change for users:
  - Intensity of lines are currently different when observed in the upper and lower sideband.
  - Intensity of lines will not match those found with RxA3.
  - Slight change in main beam efficiency.
  - From June/July 2016 until Jan 2017, receiver temperature at high frequencies was degrading (i.e. there is a higher noise than expected).
3) Additional Calibration Fixes

**RxA3m Side Band Ratios**

- Line intensities differ depending on which side band they are observed in, and differ from RxA3.
- Effect depends on the Local Oscillator (LO) frequency.
- It's not possible to measure the sideband ratios directly, therefore they have been inferred by examining the difference in intensities observed with RxA3 and RxA3m, in each sideband.
  - Estimated as a function of LO using an empirical 5th order polynomial fit.
- Relative error below 20% for LO frequency < 240 GHz and > 265 GHz.
- 240 to 265 GHz: relative errors up to almost 40% (including error from RxA3 problems at these frequencies).
- Uncertainty in line intensities ~ 15%.

3) Additional Calibration Fixes

Flow chart for RxA3m analysis.

For more details on the side band issue, see:
https://www.eaobservatory.org/jcmt/instrumentation/heterodyne/rxa

This contains at the end a look up table of sideband ratio correction factors $R$ for different LO values.

Please note: this correction is a bit of a simplification and may be updated in the future.
3) Additional Calibration Fixes

Commands to apply correction

1. Find LO frequency of observation:

   $\text{fitslist examplereduced.sdf |grep LOFREQ}$
   
   LOFREQS = 234.5281306285 / [GHz] LO Frequency at start of obs.
   LOFREQE = 234.5281269598 / [GHz] LO Frequency at end of obs.

   Find sideband of observation:
   $\text{fitslist examplereduced.sdf |grep OBS_SB}$
   
   OBS_SB = 'LSB' / The observed sideband

2. Look this up in look up table:
   
   http://www.eaobservatory.org/jcmt/instrumentation/heterodyne/rxa/

   \[
   \begin{array}{cccc}
   \text{LO (GHz)} & G_t/G_a & (1 + G_t/G_a)/2 & (1 + G_a/G_t)/2 \\
   \hline
   234.0 & 0.96 & 0.98 & 1.02 \\
   234.5 & 0.96 & 0.98 & 1.02 \\
   235.0 & 0.96 & 0.98 & 1.02 \\
   \end{array}
   \]

3. Apply correction and efficiency with KAPPA (here for T_{mb}):

   $\text{cmult in=examplereduced.sdf scalar=1.02 out=example_sbrcorr.sdf}$
   $\text{cdiv in=example_srcorr.sdf scalar=0.6 out=example_tmb.sdf}$
3) Additional Calibration Fixes

HARP detector-to-detector variation

- Visible as gridlines in raster-maps, due to variation in total power response per detector.
- This variation is not directly measured, but appears to vary on a ~nightly basis.
- Fixable for some raster maps by comparing total intensity across a map in each detector from observations in a single night.
  - Calculate relative power across whole map for each detector and derive normalisation constant relative to reference receptor.
  - Apply normalisation constant to ungridded files for each detector.
  - Regrid/re-reduce the corrected raw files.
  - Assumes each detector sees ~ same emission in the map. Not valid for point sources.
- ORAC-DR has an optional flatfield recpar option in heterodyne recipes.
  - Note this can degrade quality sometimes, so not turned on by default; please inspect results carefully.
  - Add FLATFIELD=1 to your recipe parameter file to turn this on in heterodyne recipes.
3) Additional Calibration Fixes

HARP detector-to-detector variation

Jenness et al 2015: Automated reduction of submillimetre single-dish heterodyne data from the James Clerk Maxwell Telescope using ORAC-DR
4) Recommended heterodyne workflow.

1) Get observations and calibrations, reduce all with ORAC-DR.

2) Check data quality & fix/consult as necessary.
   - RxA3m: correct sideband ratio problem and/or $^{13}$CO issue.
   - RxA3: check if observations taken during period of misalignment.
   - HARP rasters: check if flat-field fix required/possible.

3) Check calibration result is within expected value +/- scatter.
   - If answer is NO: read obslogs and consult observatory for further help!

4) Select final temperature/flux scale ($T_{MB}$, $T_R^*$, Flux density).

5) Look up and apply appropriate efficiency.
   - Remember to include uncertainty in calibration to your overall uncertainty estimation, if required.
Links and references

- Heterodyne calibration pages on JCMT website:
  http://www.eaobservatory.org/jcmt/instrumentation/heterodyne/calibration/

- Spectral standard average spectra:

- PI/CoIs of projects: see OMP project pages for access to obslogs, especially TSS comments on heterodyne calibration observations.

- If required, email either your Friend of Project, or the observatory directly (helpdesk@eaobservatory.org).
  - Dr Per Friberg is head of instrumentation, and Dr Jan Wouterloot monitors the heterodyne calibration performance.