Heterodyne Calibration

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

Overview

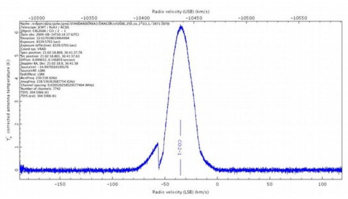
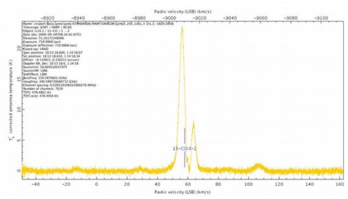
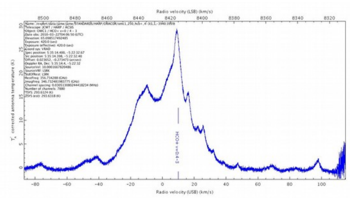
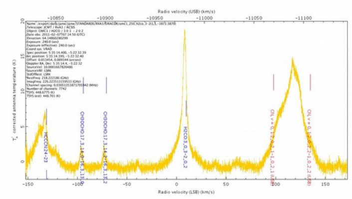
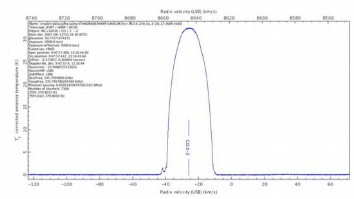
1) Calibration applied **while observing**:
   - Carried out by telescope while taking an observation.
   - Included in raw files.
2) Calibration applied **after observing**:
   - Conversion from T_A^* to scientifically useful temperature or flux scale.
   - Done by PI/scientists based on telescope provided 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

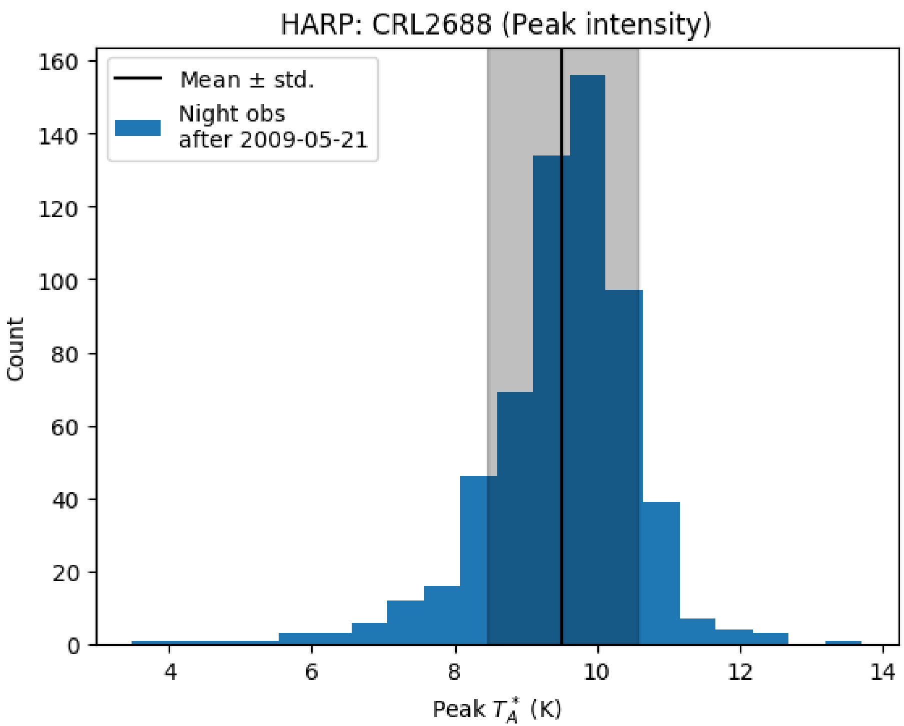
- Already applied to your raw data.
- Calibration combines measurements of ambient loads, sky measurements and a load of known temperate (heated for HARP, cooled for RxA3).
- Calibrates all ACSIS spectra into **corrected antenna temperature** (T_A*), in Kelvin.
- Corrected for:
  - Atmospheric attenuation.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

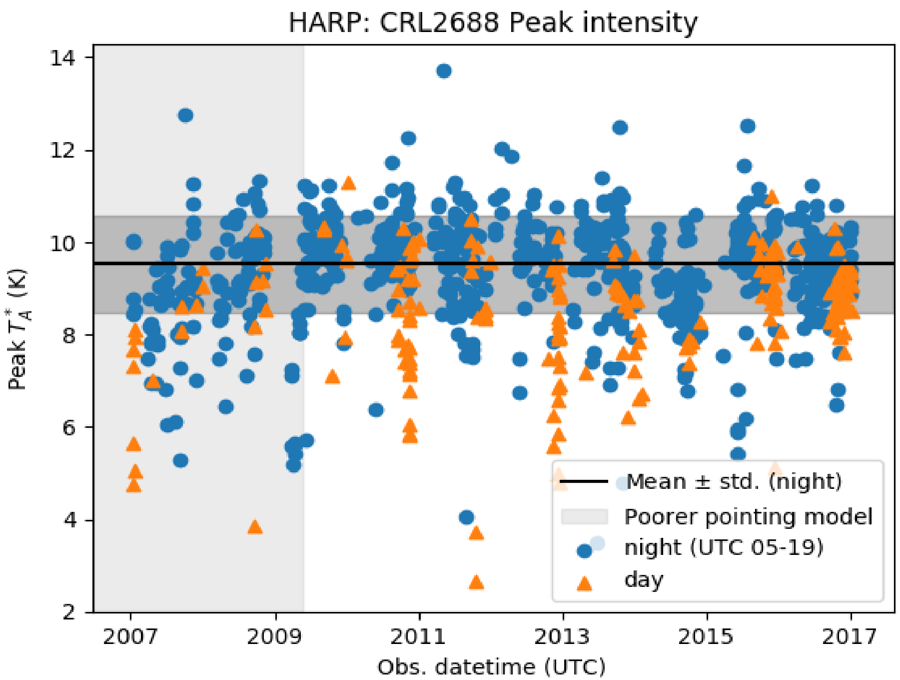
Monitoring performance

- Spectral standard observations done every night @ appropriate freq.
- TSS checks performance of JCMT heterodyne instruments during night.
  - Expect standards to be within ≃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.

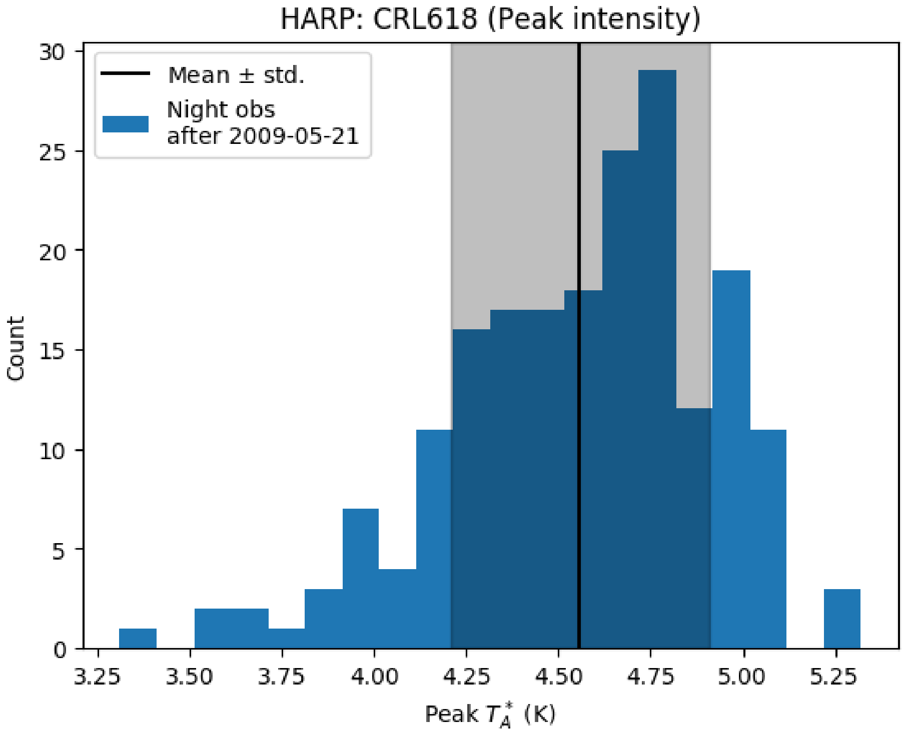






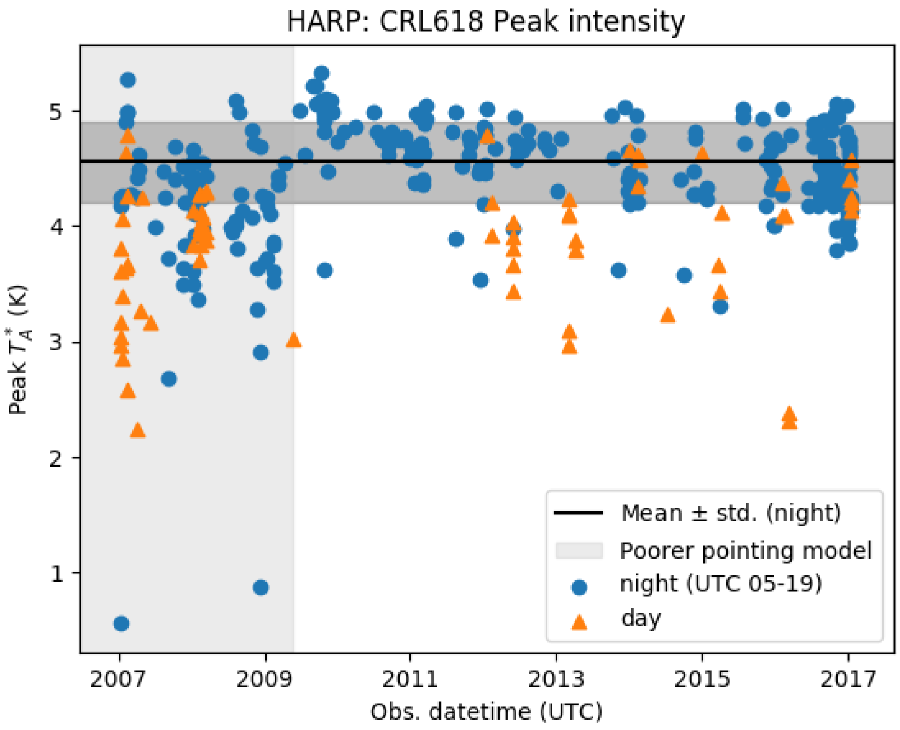
1)While Observing
HARP CRL 2688 CO 3-2



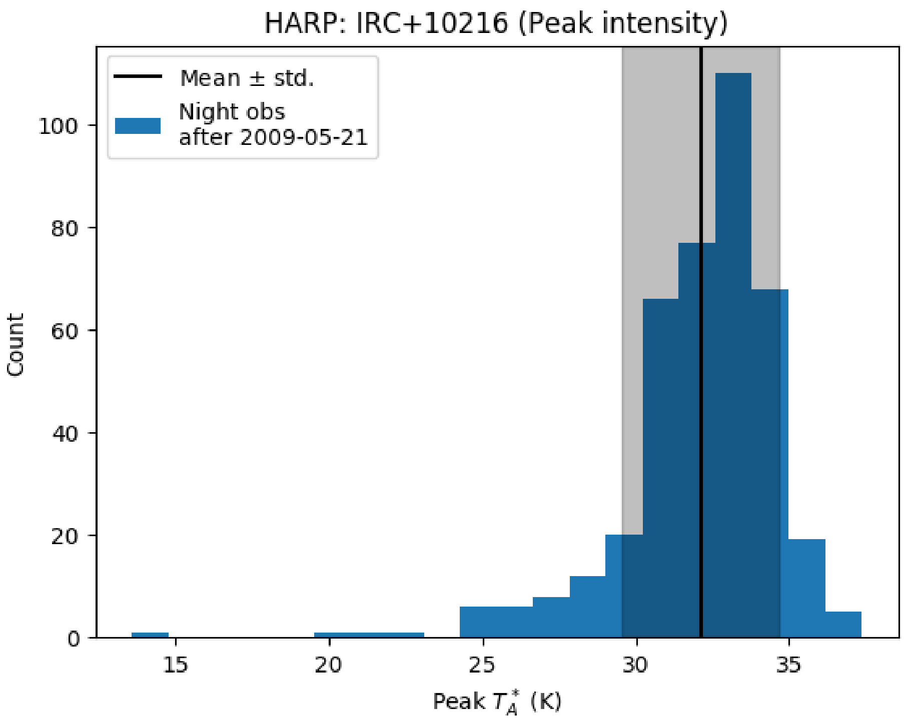


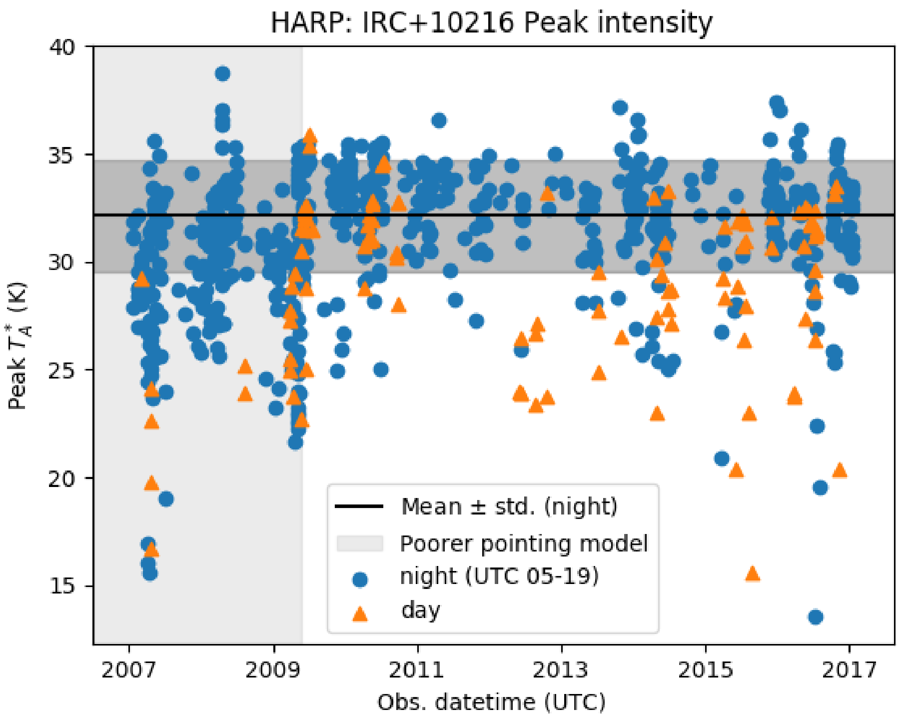
1)While Observing
HARP CRL 618 CO 3-2





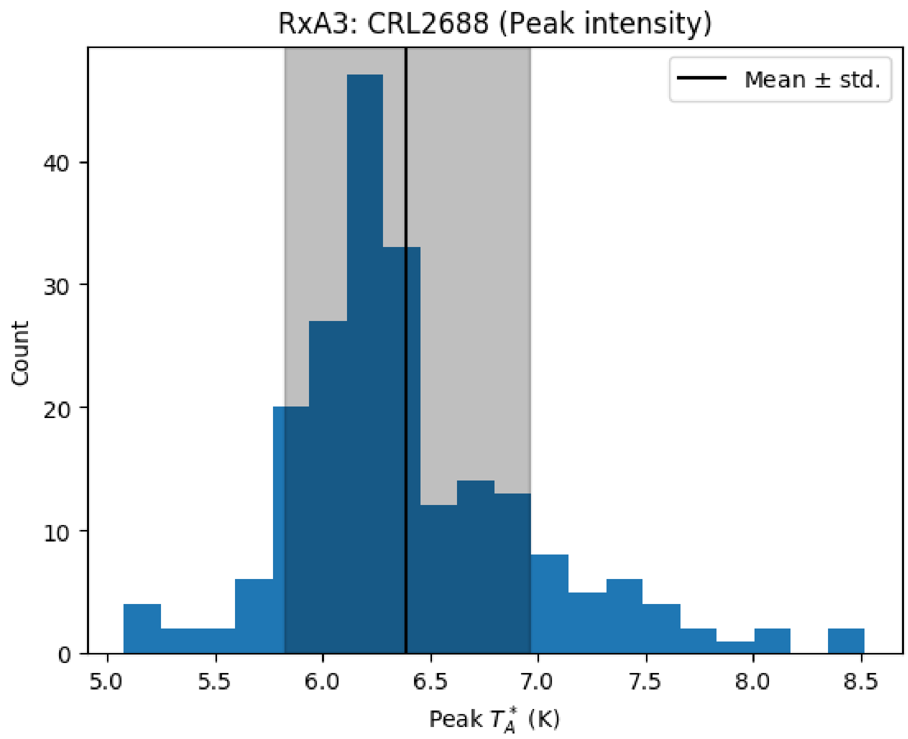
1)While Observing
HARP IRC+ 10216 CO 3-2

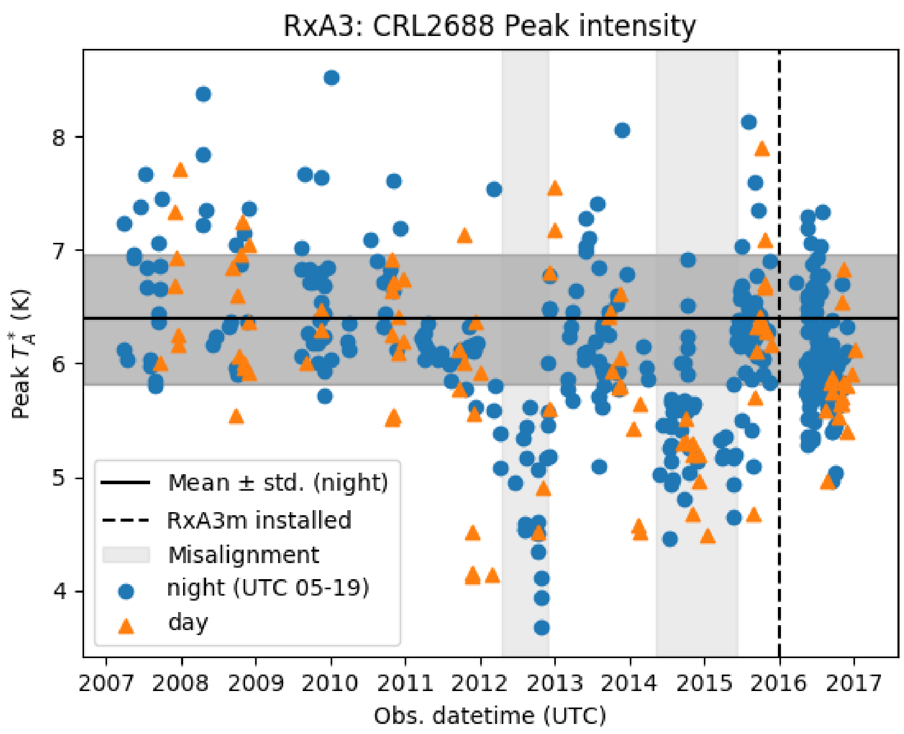




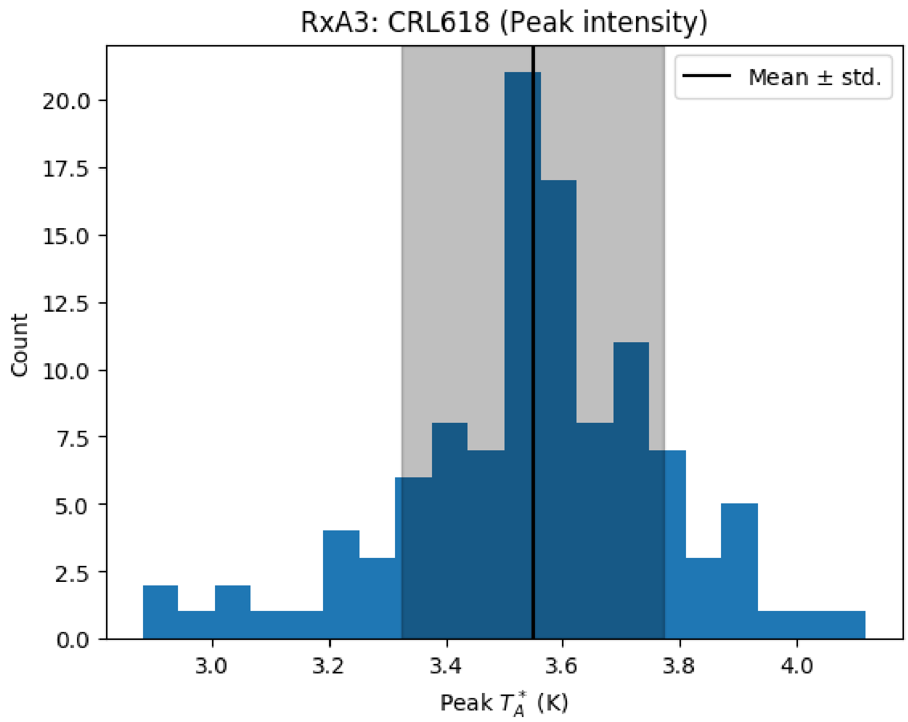
1)While Observing

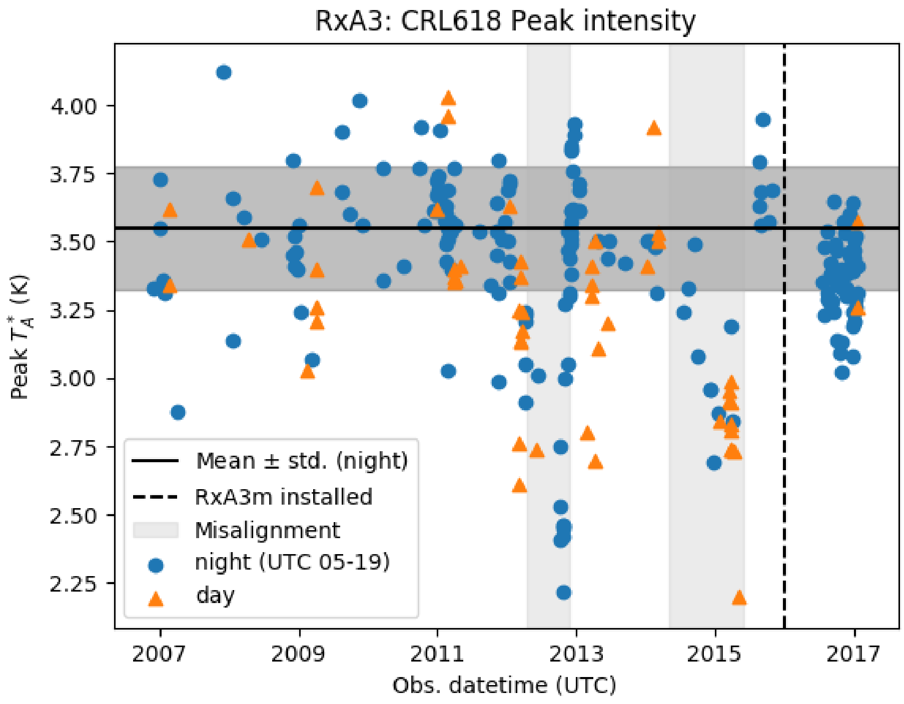
RxA3 CRL 2688 CO 2-1



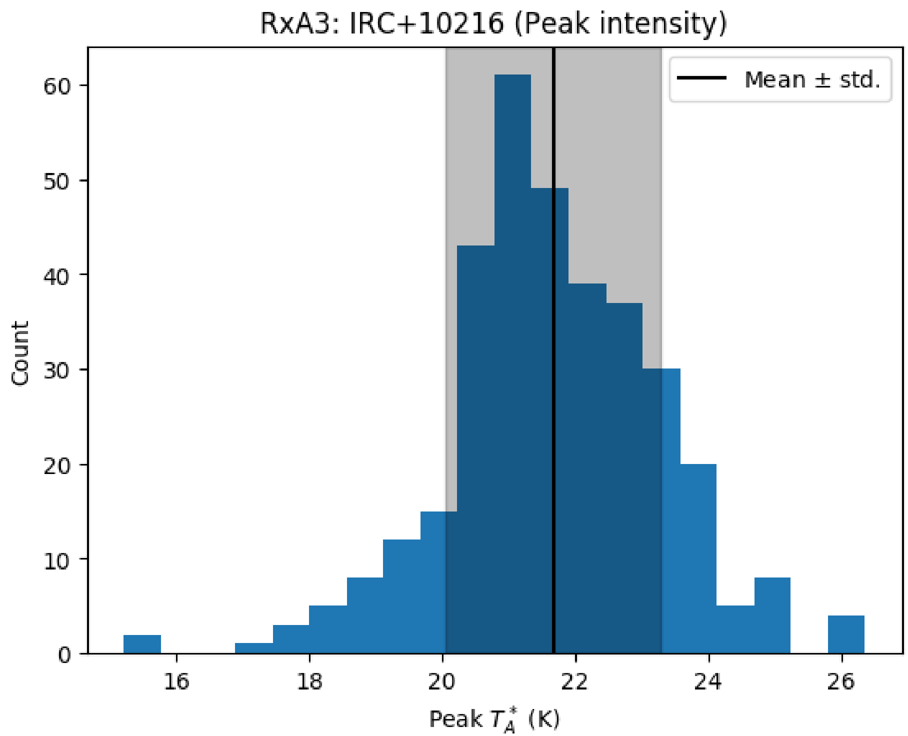


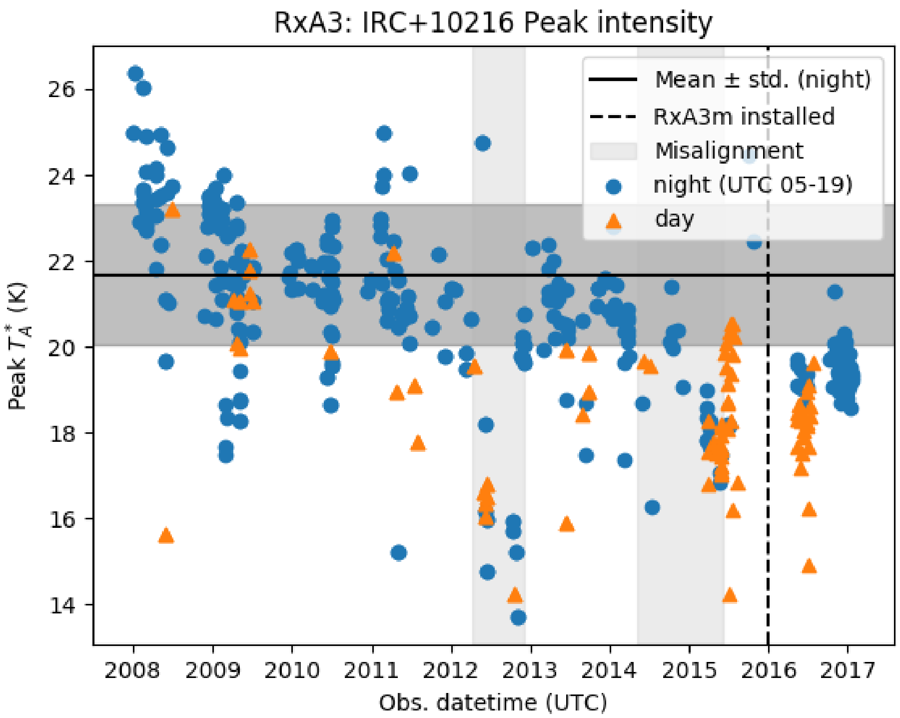
RxA3 CRL 618 CO 2-1





RxA3 IRC+ 10216 CO 2-1





1)While Observing

Heterodyne Standard Uncertainties

Instrument	Source	Type	mean	std	% error
HARP	CRL2688	PEAK	9.4	1.1	12.1
HARP	CRL2688	INTEGINT	237.2	28.3	11.9
HARP	CRL618	PEAK	4.4	0.5	11.9
HARP	CRL618	INTEGINT	139.8	19.3	13.8
HARP	IRC+10216	PEAK	31.2	3.2	10.2
HARP	IRC+10216	INTEGINT	672.0	70.4	10.5
RxA3	CRL2688	PEAK	6.4	0.6	8.9
RxA3	CRL2688	INTEGINT	155.4	9.3	6.0
RxA3	CRL618	PEAK	3.5	0.2	6.3
RxA3	CRL618	INTEGINT	99.9	7.4	7.4
RxA3	IRC+10216	PEAK	21.7	1.6	7.5
RxA3	IRC+10216	INTEGINT	463.7	26.5	5.7

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.
  - η_{MB} for T_{MB}
  - η_{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:** $T_{MB} = T_A^* / \eta_{MB}$.
  - η_{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:** $T_R^* = T_A^* / \eta_{FSS}$.
  - η_{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.**

Flux density

- To convert to point source flux density:
  - (e.g. equivalent of T_{MB})
  - Conversion uses the aperture efficiency η_A .
  - η_A is calculated from the same data as η_{FSS}.
- For a 15m dish, the conversion factor is:

$$S(Jy) = 15.6\ T_A^*(K)\ /\ \eta_A.$$

Efficiency Measurements

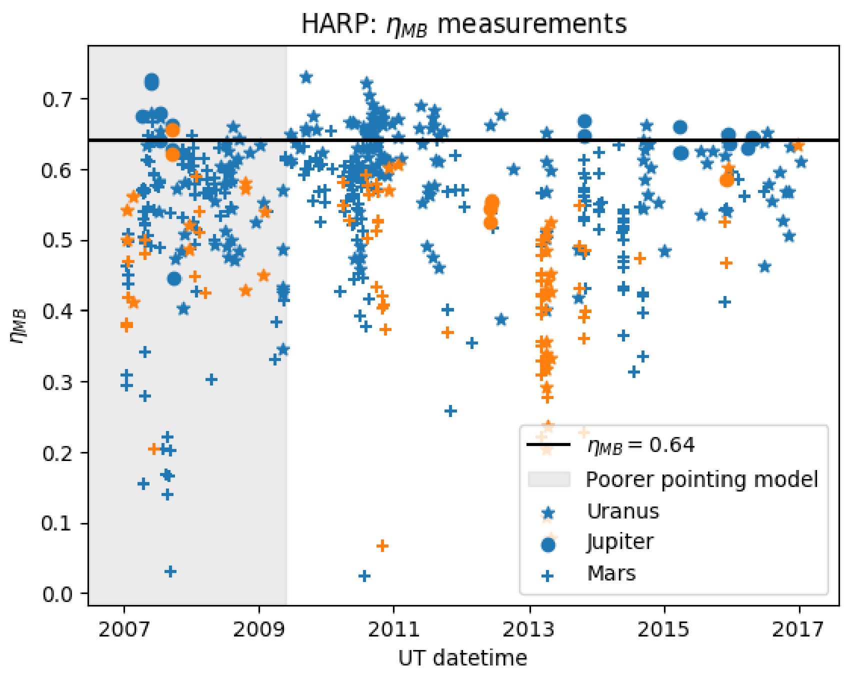
- Observatory regularly measures η_{MB} (and η_A) with HARP and RxA towards the planets to monitor the main beam efficiency.
  - RxA3: 230.538 GHz (CO 2-1)
  - HARP: 345.796 GHz (CO 3-2) @ tracking receptor H05
- canonical telescope values are

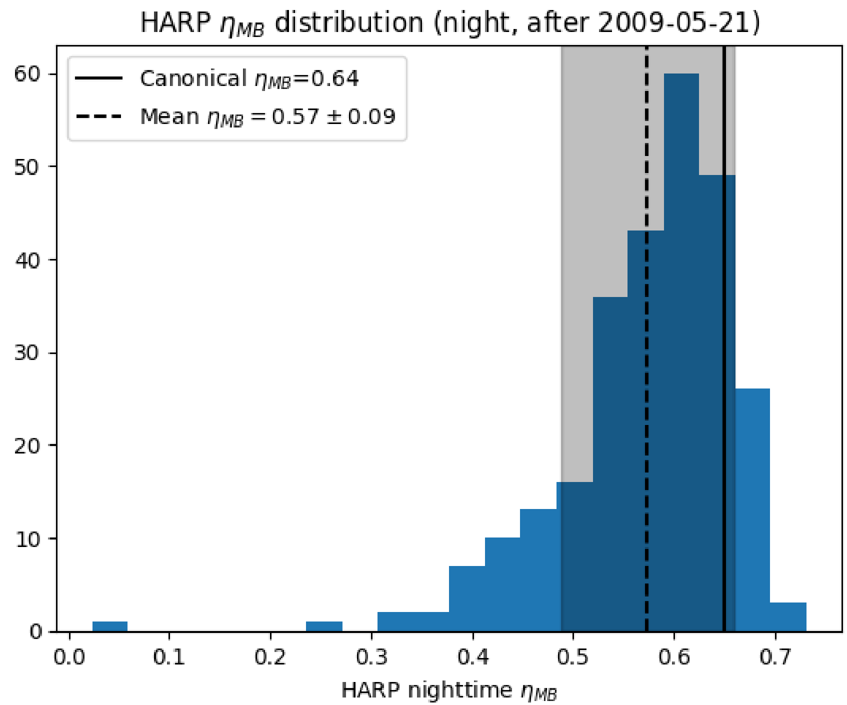
  HARP: $\eta_{MB} = 0.64$ and $\eta_A / \eta_{MB} = 0.812$ (Uranus), 0.814 (Mars)

  RxA3: $\eta_{MB} = 0.65$ and $\eta_A / \eta_{MB} = 0.867$

  RxA3m: $\eta_{MB} = 0.6$ and $\eta_A / \eta_{MB} = 0.867$

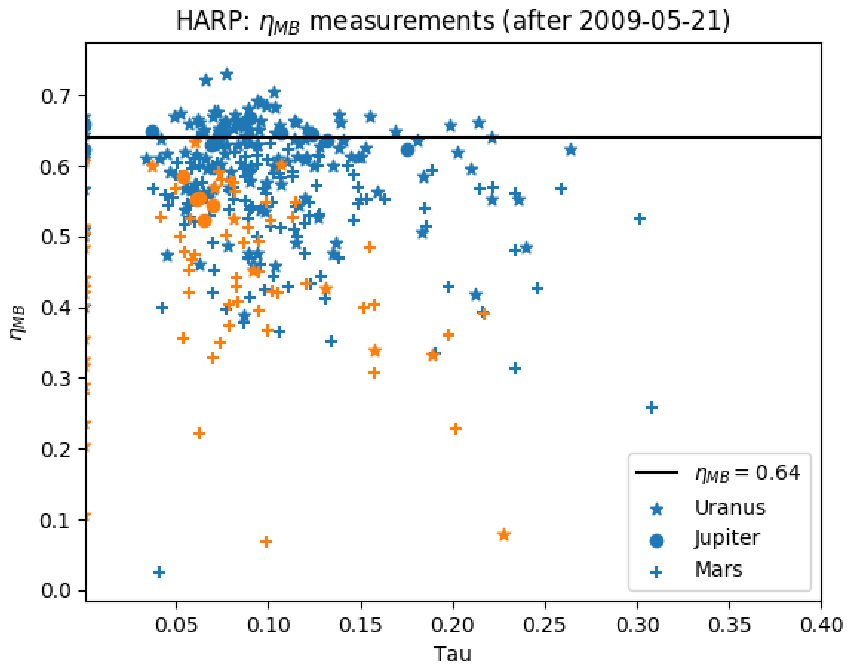
η_{MB} for HARP

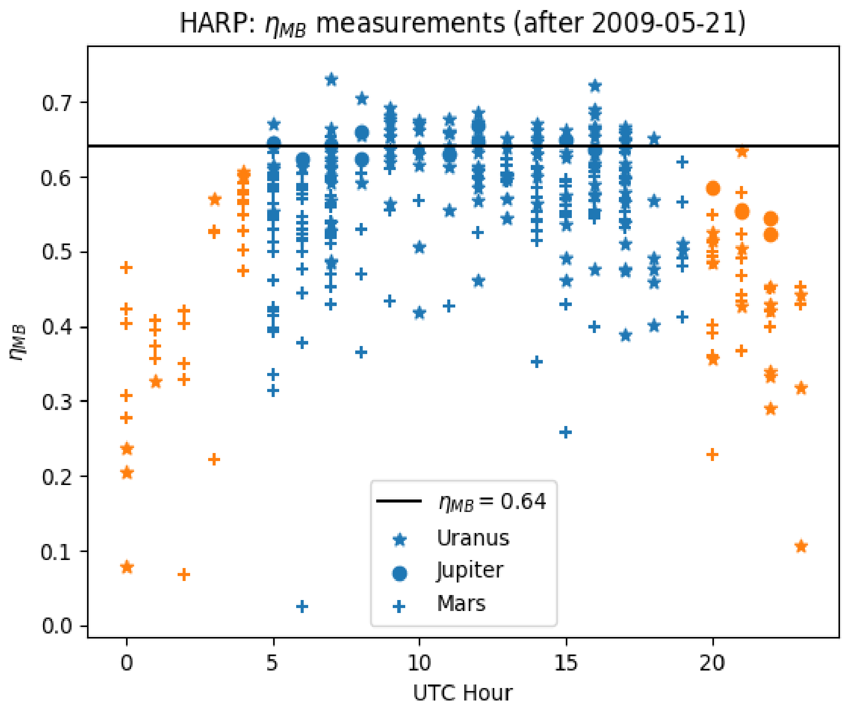




(Daytime observations are shown in orange)

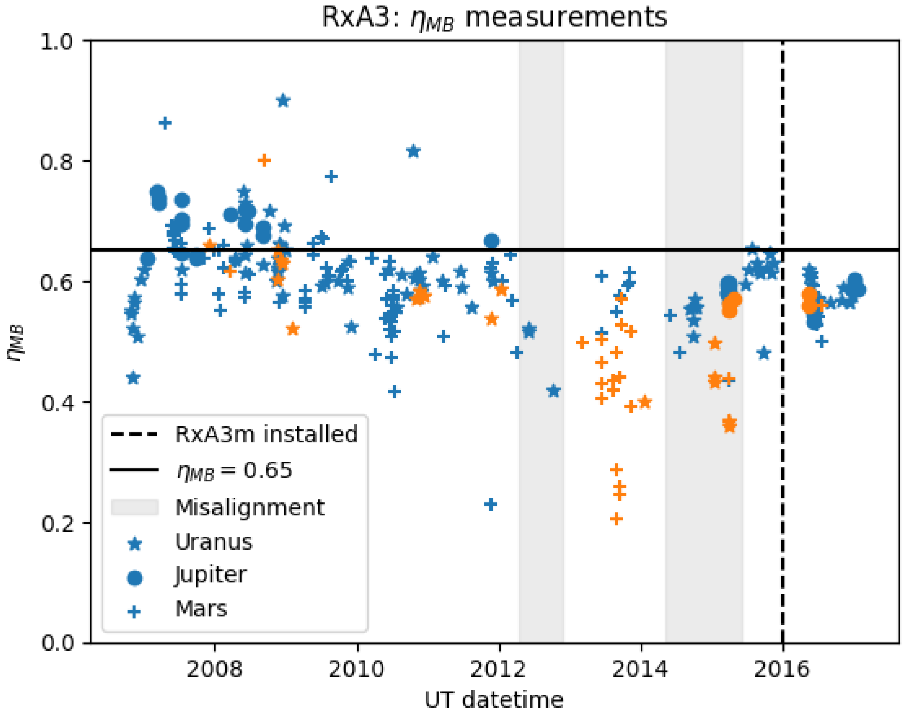
η_{MB} for HARP: variation with hour and τ

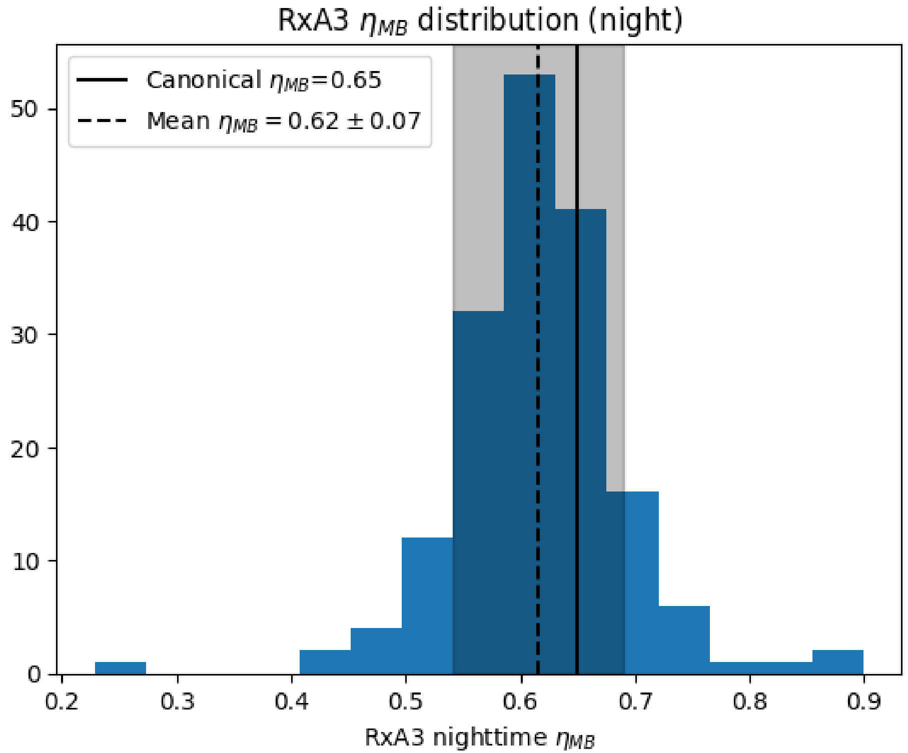




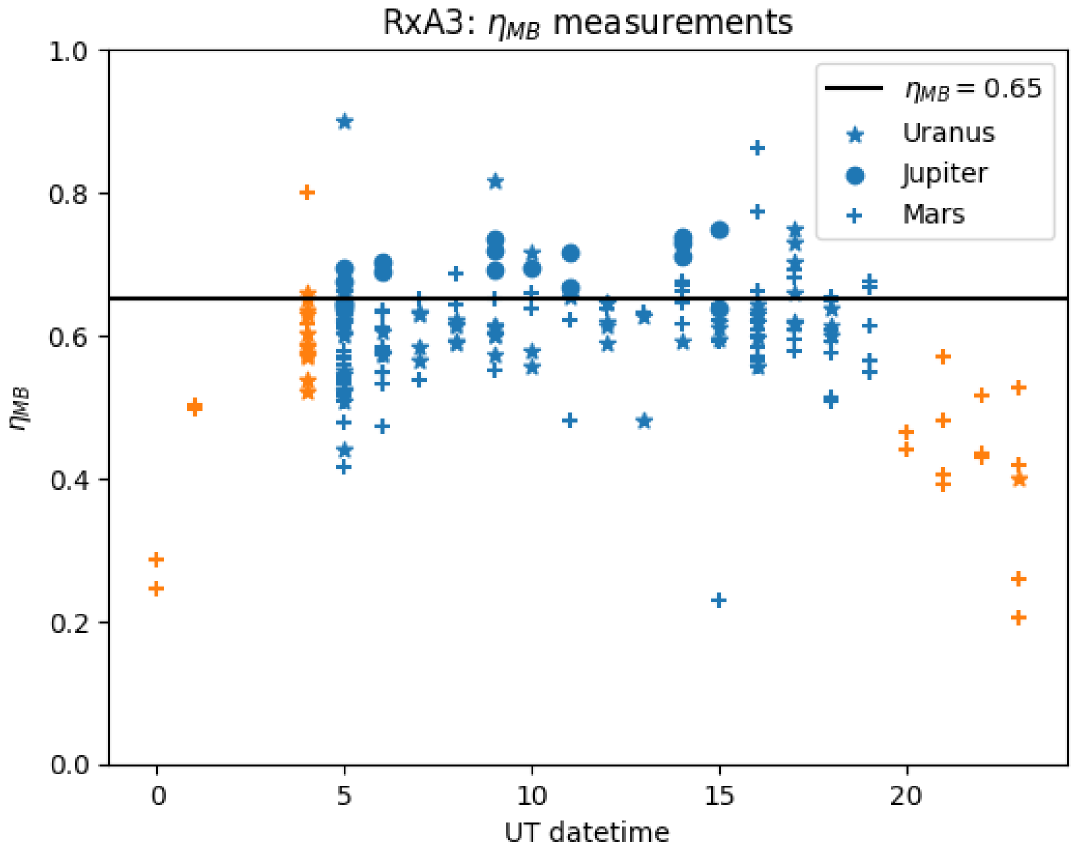
2) After Observing

η_{MB} for RxA3





η_{MB} for RxA3: variation with hour



(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

η_{FSS} for HARP and RxA3

- We also have observed the Moon to determine η_{FSS}.
- η_{FSS} includes entire beam.
  - ➔ Not expected to be as variable as η_{MB}.
- HARP: measured as 0.77 (2006) & 0.75 (2015) @ 345 GHz.
  http://www.eaobservatory.org/jcmt/instrumentation/heterodyne/harp/
- RxA3: 0.72 (measured prior to 2006).
  http://www.eaobservatory.org/jcmt/instrumentation/heterodyne/rxa/

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.

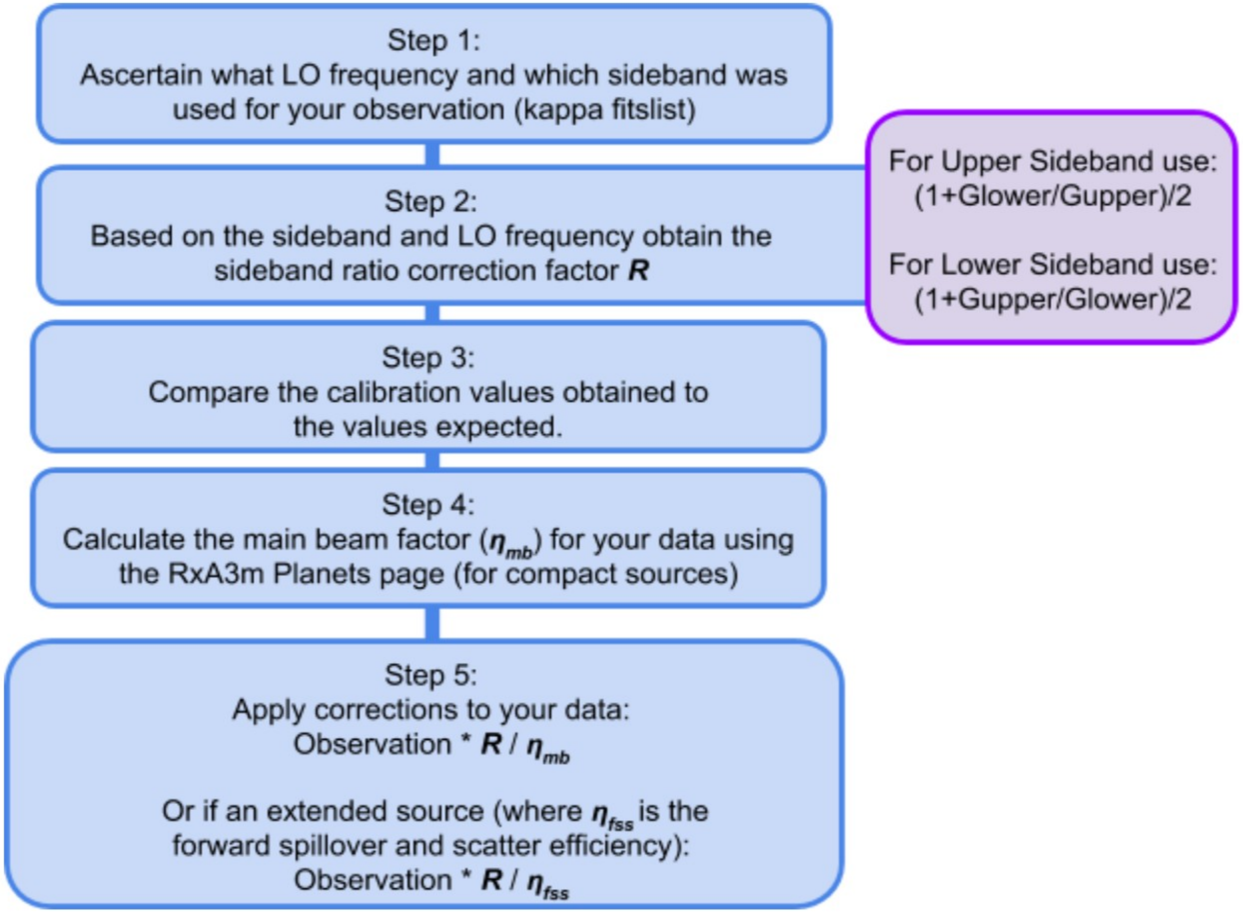
RxA3m

- 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).

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.
- Its 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%.
- https://www.eaobservatory.org/jcmt/wp-content/uploads/sites/2/2014/11/RxA3m-SB-Notes-updated.pdf

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.

Commands to apply correction

1. Find LO frequency of observation:

```
$ 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:

```
$ 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/

LO (GHz)	G_l/G_u	$(1+G_l/G_u)/2$	$(1+G_u/G_l)/2$
[illegible]	[illegible]	[illegible]	[illegible]
234.0	0.96	0.98	1.02
234.5	0.96	0.98	1.02
235.0	0.96	0.98	1.02

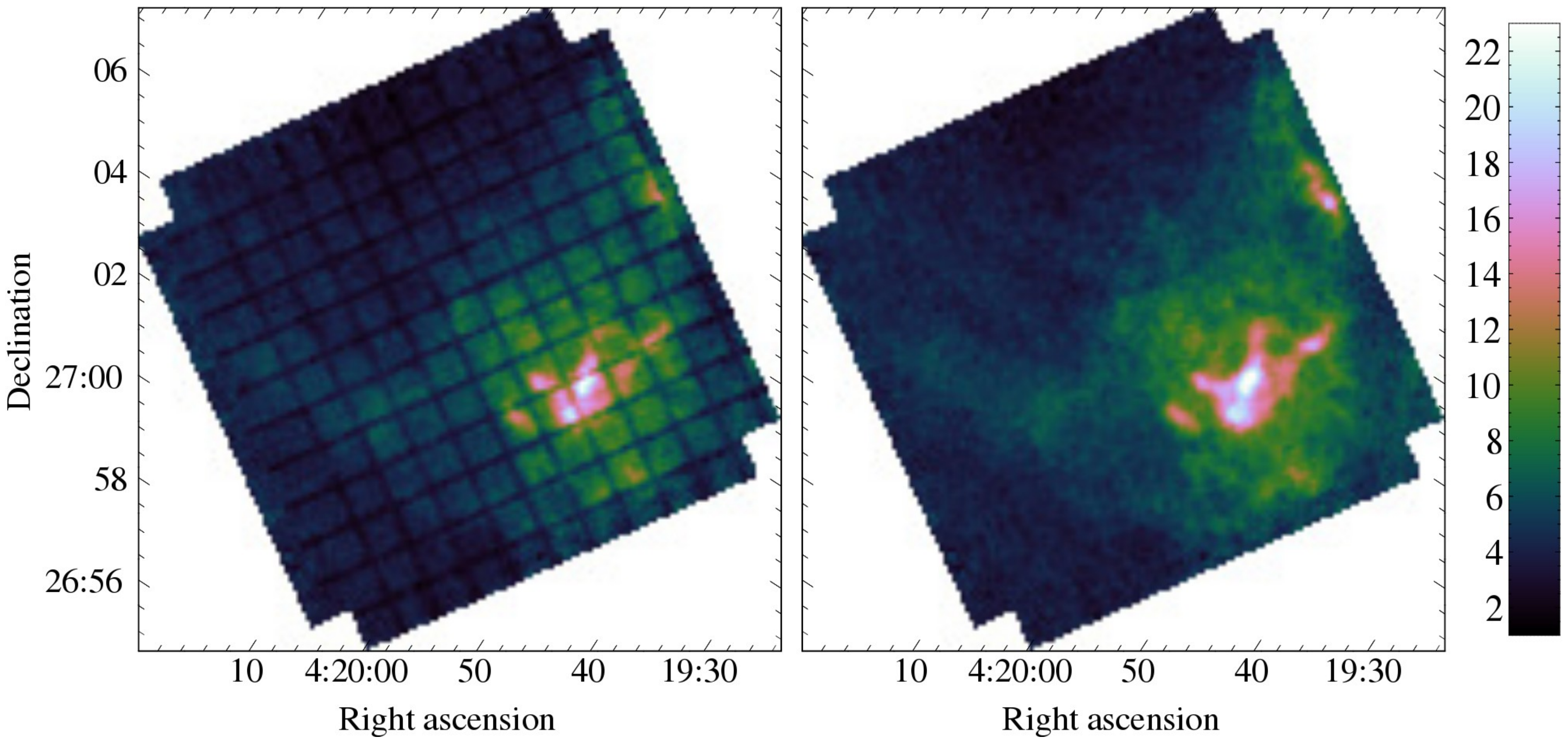
3. Apply correction and efficiency with KAPPA (here for T_{mb}):

```
cmult in=examplereduced.sdf scalar=1.02 out=example_sbrcorr.sdf
cdiv in=example_srcorr.sdf scalar=0.6 out=example_tmb.sdf
```

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.

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:
  - http://www.eaobservatory.org/jcmt/instrumentation/heterodyne/calibration/rxa3-standards/
  - http://www.eaobservatory.org/jcmt/instrumentation/heterodyne/calibration/harp-standards/
- 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.