Temperature Scale Calibration

Robert Lucas

Commissioning Scientist, ALMA / ESO

2012-06-08

Outline

Goals

Basic Formulae

Methods
- Traditional, single-load
- Using two loads
- Improved, dual-load

Current implementation

Some results

Issues

Outline

Goals

Basic Formulae

Methods

- Traditional, single-load
- Using two loads
- Improved, dual-load

Current implementation

Some results

Issues

Goals

- Establish the amplitude scale to T_{A}^{*} (interferometry and single dish). Advantages:
  - Main effects of atmosphere absorption are corrected for.
  - Take out time variations of absorption: not essential as a secondary calibrator is regularly observed.
  - Enable comparing the emission of sources at different elevations. This is essential in order to establish the flux scale.
  - Give an 'approximate absolute scale': useful to detect efficiency losses due to e.g., bad pointing, bad focus, or poor coherence on a particular antenna, e.g. due to residual delay, LO jitter, or poorly corrected atmosphere path fluctuations
  - Do this in a spectral mode: wide bandwidths, frequency dependence of atmospheric absorption
- Use the most appropriate method to do this, which may depend on receiver band and atmosphere conditions.

Outline

Goals

Basic Formulae

Methods
- Traditional, single-load
- Using two loads
- Improved, dual-load

Current implementation

Some results

Issues

Notations

- $\eta_{\rm F}$: Forward efficiency (coupling to sky)
- g_s, g_i sideband gains ($g_s + g_i = 1$)
- $J_{\rm L}$ is the Rayleigh-Jeans equivalent temperature of the load.
$$J_{\rm L} = \frac{h\nu/k}{exp(h\nu/kT_{\rm L}) - 1}$$
- $J_{{\rm SKY}\,s}, J_{{\rm SKY}\,i}$: Rayleigh-Jeans equivalent temperature seen by the receiver when looking at the sky,
- $J_{{\rm M}\,s}$: atmosphere source function (signal band)
- $J_{{\rm SP}\,s}$: Spillover RJ-equivalent temperature (signal band)

Formulae

$$V_{\mathrm{SKY}} = G \times (T_{\mathrm{REC}} + g_s J_{\mathrm{SKY}\,s} + g_i J_{\mathrm{SKY}\,i})$$

$$J_{\mathrm{SKY}\,s} = \eta_{\mathrm{F}}(J_{\mathrm{M}\,s}(1 - e^{-\tau_s}) + J_{\mathrm{BG}} e^{-\tau_s}) + (1 - \eta_{\mathrm{F}}) J_{\mathrm{SP}\,s}$$

$$J_{\mathrm{SKY}\,i} = \eta_{\mathrm{F}}(J_{\mathrm{M}\,i}(1 - e^{-\tau_i}) + J_{\mathrm{BG}} e^{-\tau_i}) + (1 - \eta_{\mathrm{F}}) J_{\mathrm{SP}\,i}$$

$$V_{\mathrm{L}} = G \times (T_{\mathrm{REC}} + g_s J_{\mathrm{L}\,s} + g_i J_{\mathrm{L}\,i})$$

$$\Delta V_{\mathrm{A}} = G \times (g_s \eta_{\mathrm{F}} e^{-\tau_s} \Delta T_{\mathrm{A}})$$

System noise:

$$V_{\mathrm{SKY}} + \Delta V_{\mathrm{A}} = G' \times (T_{\mathrm{SYS}} + \Delta T_{\mathrm{A}})$$

$$T_{\mathrm{SYS}} = \frac{e^{\tau_s}}{g_s \eta_{\mathrm{F}}} (T_{\mathrm{REC}} + g_s J_{\mathrm{SKY}\,s} + g_i J_{\mathrm{SKY}\,i})$$

Outline

Traditional, single-load

- Single-load "chopper-wheel" (Penzias & Burrus 1973): rewrite the equations:

$$\begin{aligned} T_{\mathrm{CAL}} = & (J_{\mathrm{M}s} - J_{\mathrm{BG}s}) + g_i/g_s e^{\tau_s - \tau_i}(J_{\mathrm{M}i} - J_{\mathrm{BG}i}) \\ & + \frac{e^{\tau_s}}{g_s \eta_{\mathrm{F}}}[(g_s J_{\mathrm{L}s} + g_i J_{\mathrm{L}i}) - \eta_{\mathrm{F}}(g_s J_{\mathrm{M}s} + g_i J_{\mathrm{M}i}) \\ & - (1 - \eta_{\mathrm{F}})(g_s J_{\mathrm{SP}s} + g_i J_{\mathrm{SP}i})] \end{aligned}$$

$$\Delta T_{\mathrm{A}} = T_{\mathrm{CAL}} \frac{\Delta V_{\mathrm{A}}}{V_{\mathrm{L}} - V_{\mathrm{SKY}}} = T_{\mathrm{SYS}} \frac{\Delta V_{\mathrm{A}}}{V_{\mathrm{SKY}}} \qquad T_{\mathrm{SYS}} = T_{\mathrm{CAL}} \frac{V_{\mathrm{SKY}}}{V_{\mathrm{L}} - V_{\mathrm{SKY}}}$$

- Note: τ terms intervene only as a correction in T_{CAL}, because J_{L}, J_{SP} and J_{M} are all of order 273 K.
- This does not rely on T_{REC} which is not measured.
- The atmosphere emission is used to measure T_{CAL} and T_{SYS} and calibrate out the absorption.

Using two loads

- We have two loads to measure and monitor T_{REC} independently of the atmosphere.
- Using only the loads:

$$T_{\mathrm{CAL}} = \frac{(1 + g_i/g_s)e^{\tau_s}}{\eta_{\mathrm{F}}}(J_2 - J_1)$$

  which gives directly the temperature scale for the signal band. T_{REC} is also derived.
- Drawbacks:
  - For ALMA the two load temperatures are very similar: $\sim$ 290 and 360 K, compared to the sky brightness, around 30K
  - Then absorption correction and T_{SYS} derivation are totally model dependent : use τ from ATM model, using the water content based on WVR data.

Improved millimetre wave (dual-load)

- The single load method works best if the load temperature matches the temperature of the atmosphere.
- Replace the single load measurement by a linear combination of the two load measurements:

$$J_{\mathrm{L}} = \alpha J_1 + (1-\alpha) J_2 \qquad (1)$$

- choose α to zero the τ dependent term in the expression of T_{CAL}.

$$\alpha = \frac{\eta_{\mathrm{F}} J_{\mathrm{M}} + (1-\eta_{\mathrm{F}}) J_{\mathrm{SP}} - J_{\mathrm{L}2}}{J_{\mathrm{L}1} - J_{\mathrm{L}2}} \qquad (2)$$

with:

$$J_{\mathrm{M}} = g_s J_{\mathrm{M}s} + g_i J_{\mathrm{M}i};\, J_{\mathrm{SP}} = g_s J_{\mathrm{SP}s} + g_i J_{\mathrm{SP}i}$$

Improved millimetre wave (dual-load) (2)

- The calibration temperature becomes:

$$T_{\mathrm{CAL}} = (J_{\mathrm{M}s} - J_{\mathrm{BG}s}) + g e^{\tau_s - \tau_i} (J_{\mathrm{M}i} - J_{\mathrm{BG}i})$$

  and the system temperature:

$$T_{\mathrm{SYS}} = T_{\mathrm{CAL}} \frac{V_{\mathrm{SKY}}}{V_{\mathrm{L}} - V_{\mathrm{SKY}}}$$

  with: $V_{\mathrm{L}} = \alpha V_1 + (1 - \alpha) V_2$
- The scaling of spectra obtained by :

$$\Delta T_{\mathrm{A}} = T_{\mathrm{CAL}} \frac{\Delta V_{\mathrm{A}}}{V_{\mathrm{L}} - V_{\mathrm{SKY}}} = T_{\mathrm{SYS}} \frac{\Delta V_{\mathrm{A}}}{V_{\mathrm{SKY}}}$$

Outline

Goals

Basic Formulae

Methods
- Traditional, single-load
- Using two loads
- Improved, dual-load

Current implementation

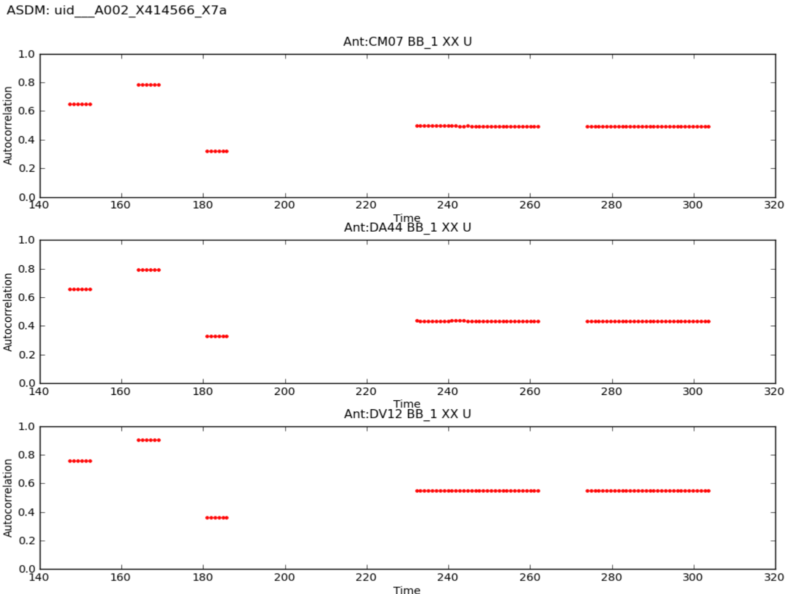
Some results

Issues

Current implementation

- We measure T_{SYS} using Atmosphere Calibration scans
- 3 subscans: ambient load, hot load, sky
- A specific attenuation setting (common to the 3 subscans) is used to ensure that the input power suits the correlator's range of digitization correction.
- After the scan the attenuation level suitable for the sky is restored.
- Observing is done in TDM mode (digitization correction for FDM needs work).
- TelCal publishes on-line detailed results in CalAtmosphere table (asdm) and T_{SYS} for each spectral window in SysCal Table.
- T_{REC} also calculated (using loads only)
- Baseband averaged system temperatures and receiver temperatures are displayed by Quick Look.

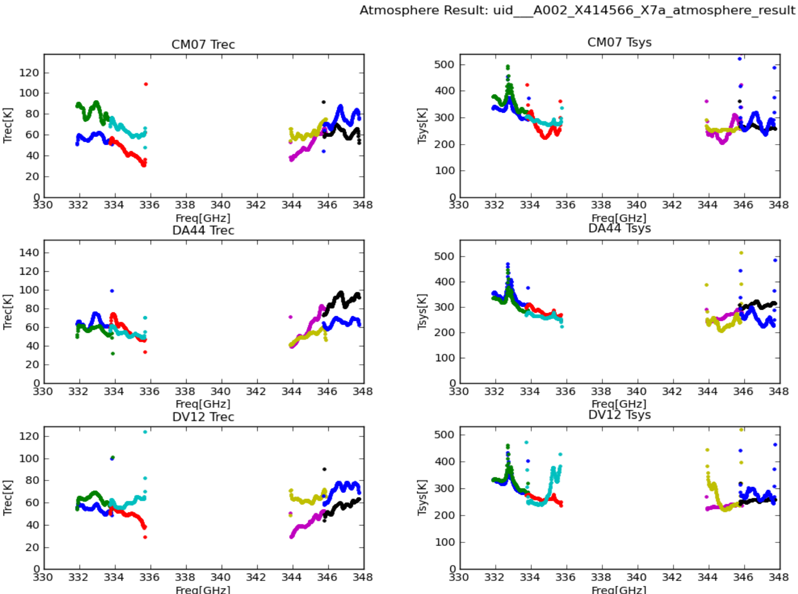
Autocorrelation plot



Off-line execution: **tc_atmosphere**

- Use task **tc_atmosphere** (from **casapy-telcal** in OSF/SCO data reduction machines). This will recalculate the on-line results, and display both T_{REC} and T_{SYS} for 4 basebands and two polarizations
- Parameters:
  - **asdm** : input dataset name
  - **dataorigin** : set this to **"specauto"**
  - **scans** : give the scan number for atm cal; if empty, will loop over the atm cals, processing them independently
  - **antennas** : use this to plot only results for selected antennas
  - **calresult** : should be equal to **asdm** to append the results to the SysCal table in input data set.
  - for others, use default.

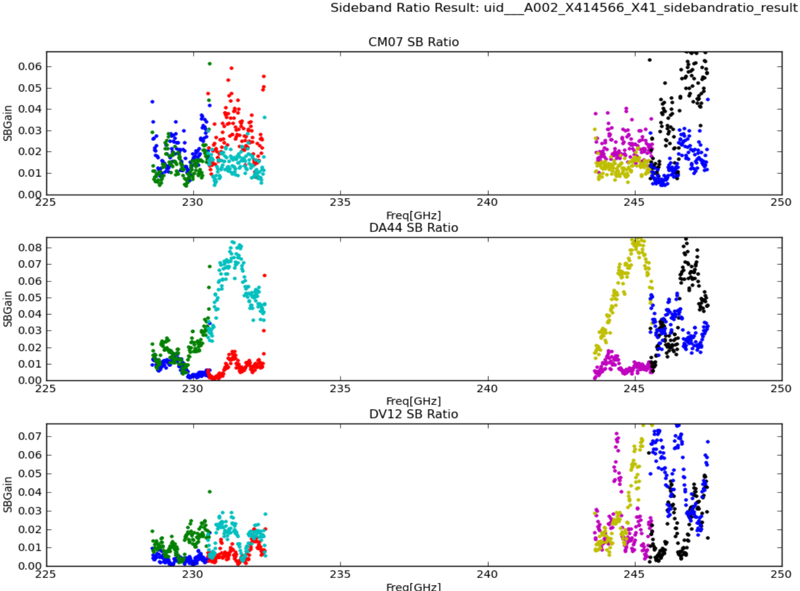
tc_atmosphere plot



Side band gain ratio

- The ratio of sideband gains enter the calculation of Tsys.
- For bands 3, 6, 7, the image side band gain is small, it is only a corrective gain
- Band 9 is very close to DSB, so the image side band contribution is large; we measure it using a specific scan
- Using 2-LO offsetting we measure the signals in the signal then image band, using a strong point source (the passband calibrator)
- off-line: use task **tc_sidebandratio**

tc_sidebandratio plot



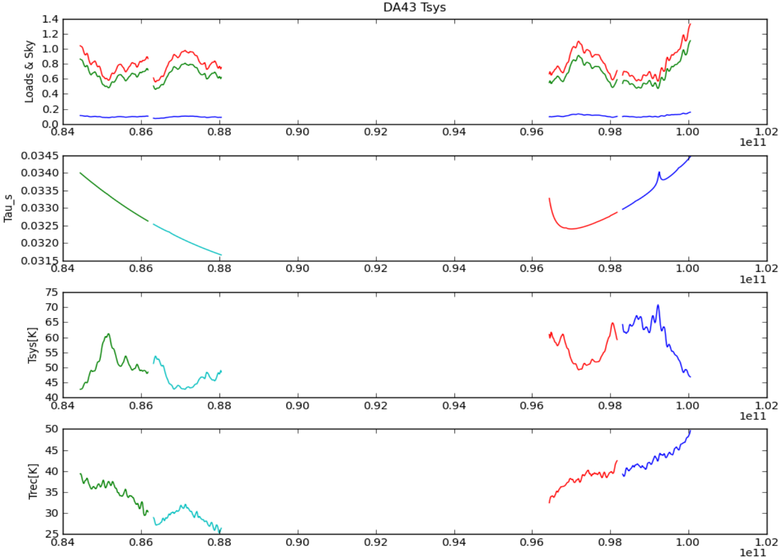
Offline Processing into Casa

The main functionalities are:

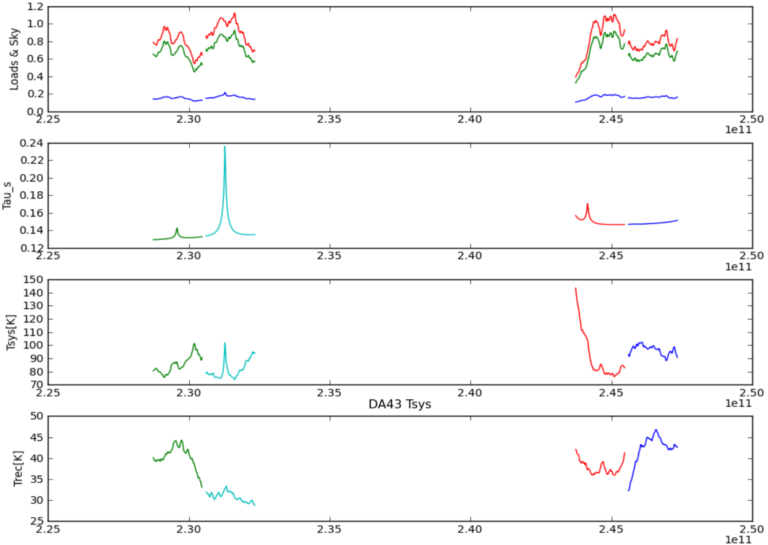
- The T_{SYS} measurements from the SysCal table are associated to the relevant scans and fields in the measurement set.
- The measurements are interpolated in time to the relevant data in the ms
- When the system temperatures needs to be applied to a FDM spectral window, they are interpolated into a new gain table.
- The final table is applied to the data column
- Will be even more straightforward in casa 3.4
- Ask Stuartt for details!

Outline

Band 3 T_{SYS}

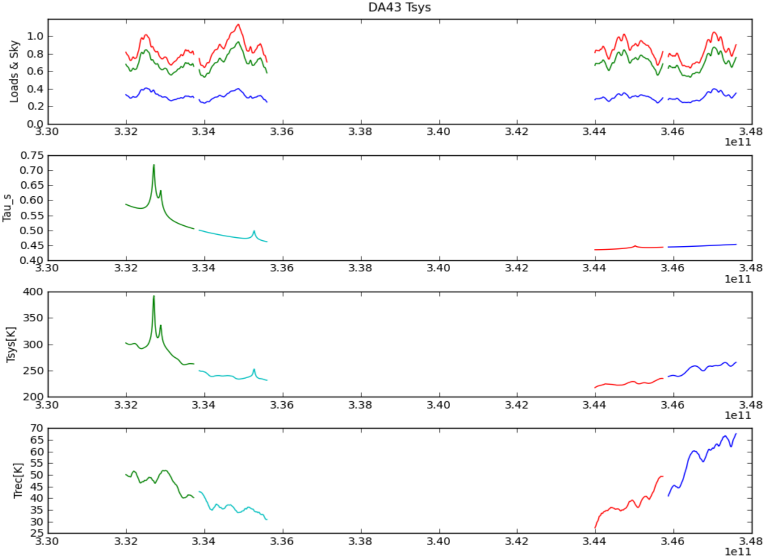

DA43 Tsys
Loads & Sky
Tau_s
Tsys[K]
Trec[K]
1e11
0.84
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.0315
0.0320
0.0325
0.0330
0.0335
0.0340
0.0345
40
45
50
55
60
65
70
75
25
30
35
40
45
50

Band 6 T_{SYS}

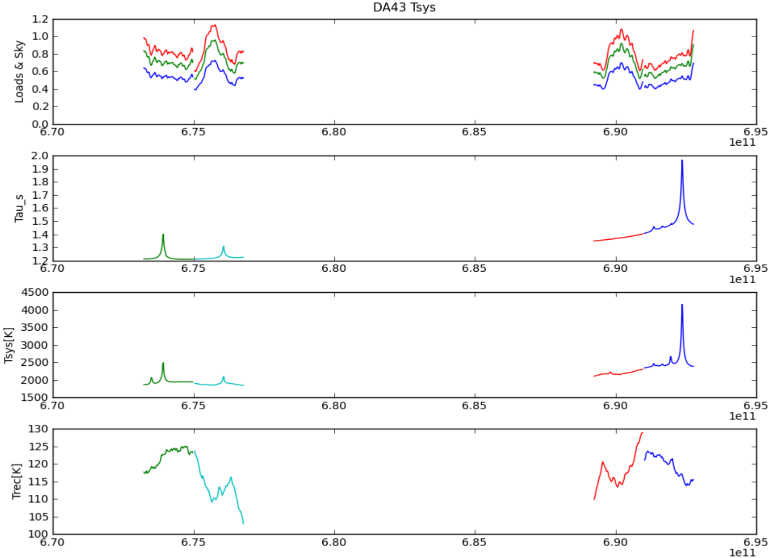


Loads & Sky
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Tau_s
0.24
0.22
0.20
0.18
0.16
0.14
0.12
Tsys[K]
150
140
130
120
110
100
90
80
70
DA43 Tsys
Trec[K]
50
45
40
35
30
25
2.25
2.30
2.35
2.40
2.45
2.50
1e11

Band 7 T_{SYS}

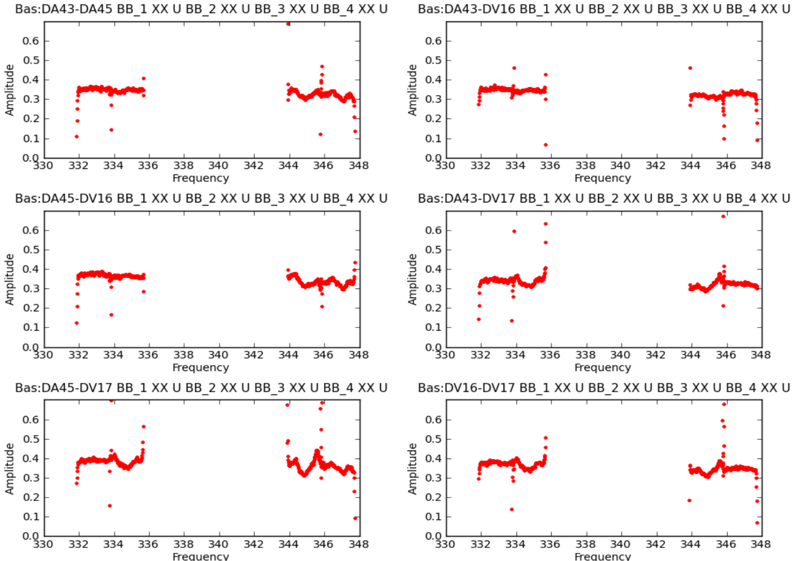

DA43 Tsys
Loads & Sky
Tau_s
Tsys[K]
Trec[K]
1e11
3.30
3.32
3.34
3.36
3.38
3.40
3.42
3.44
3.46
3.48

Band 9 T_{SYS}

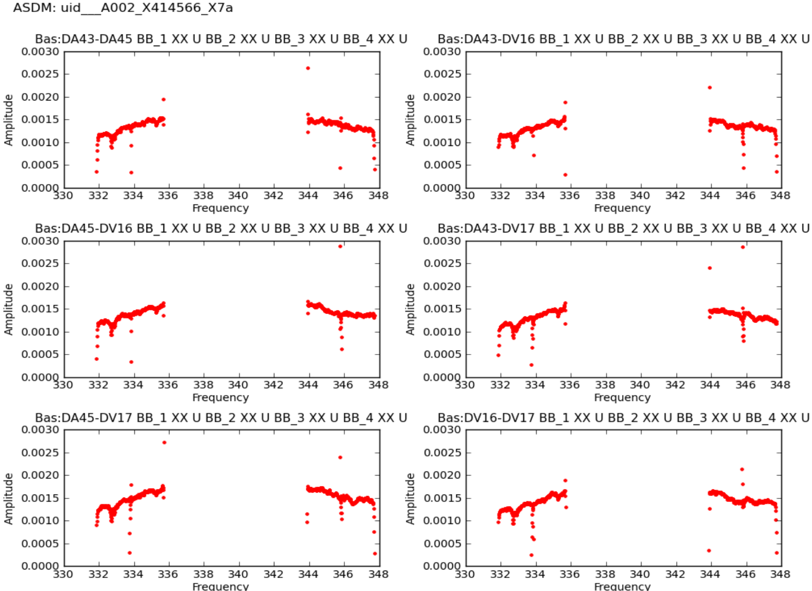


Spectra Band 7 - T_{SYS} applied

ASDM: uid___A002_X414566_X7a



Spectra Band 7 - no T_{SYS} applied



Outline

- Goals
- Basic Formulae
- Methods
  - Traditional, single-load
  - Using two loads
  - Improved, dual-load
- Current implementation
- Some results
- Issues

0-th order Issues

Conspired to compromise the execution, or to produce totally wrong results (like negative T_{REC} or T_{SYS})

- ACD hardware control issues: now solved
- Observing mode control, e.g. like sending the ACD to the wrong band: believed to be solved
- Timing issues, e.g. correlator synchronization : should be detected beforehand.
- Sideband gain ratio errors leading to wrong result, like: source too weak, or too short integration time, for high frequency band.
- ... or other possible software bugs

1st order Issues (1)

- *on source* V_{SKY} is used in correlator sw to scale correlations
  - instead of multiplying by T_{SYS}, we should multiply by: $T_{\text{SYS}} \times \frac{V_{\text{SKY}}}{V_{\text{SKY}\,ATM}}$
- T_{REC} errors seen in bandpass
  - poorly join when basebands overlap , seen also in B9, for which T_{REC} in conjugate base bands should be equal.
  - this possibly affects T_{SYS} as well : T_{SYS} - applied spectra show small bandpass features
- Not addressing so far saturation effects at a few % level in SIS mixers

1st order Issues (2)

- Measurement takes time (> 30s).
- Should ideally be done more frequently than every 10 minutes, really tracking elevation changes, and atmosphere changes.
- We interpolate T_{SYS} while T_{CAL} is better behaved (nearly constant for SSB systems). This requires having V_{L} available with T_{CAL}.

Plans for improvement

- Check whether new, lower sideband IF level setting improves accuracy.
- Accelerate measurement by insertion in scan sequences, removing the scan start overhead
  - *in progress*
- Keep the load measurements in memory for a while, only re-observing the sky.
  - *available in TelCal, need CSV testing to determine timescales*
- Use 90-degree switching for side band gain ratio measurement
  - *coming soon...*

Summary

- Works but could really be improved, still needing more investigation
- Caveat: very little real-world experience with band 9, which:
  - needs very good conditions,
  - exercises the algorithm in a different domain (DSB) which is more complex.