Pointing and Amplitude Calibration Concepts

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13th IVS TOW 2025, Haystack Observatory

Outline

- Beams & Pointing
- Antenna Efficiency, Antenna Temperature
- SEFD as the key for calibration
- System Temperature & Gain
- rxg & `antabfs` files

Why Calibrate?

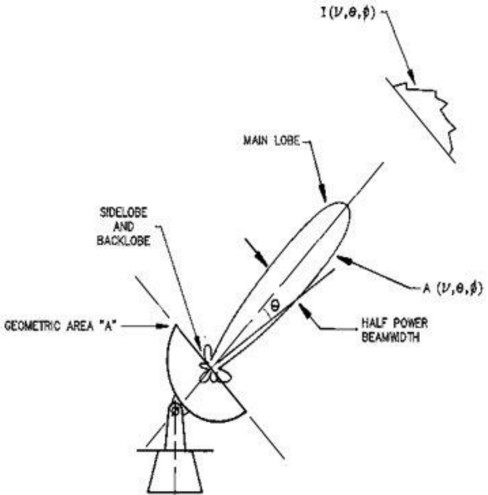
- **Scientific quality:**
  - geodesy — best SNR per scan to improve delay precision
  - astronomy — source brightness on absolute physical scale
  - Regular checks of calibration → help notice problems

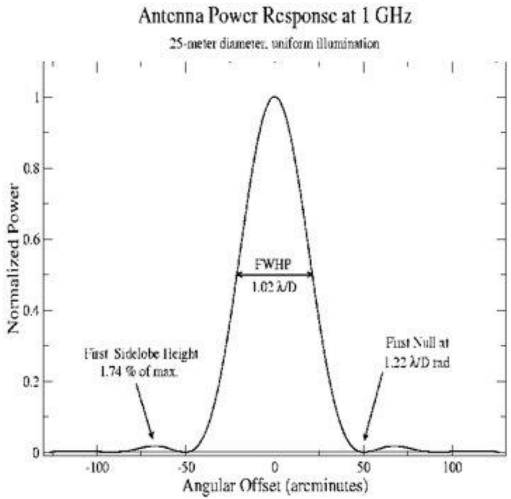
- **You can measure/calibrate:**
  - the focus & pointing
  - the aperture efficiency (η_A)
  - the system temperature (T_{sys})
  - the gain curve

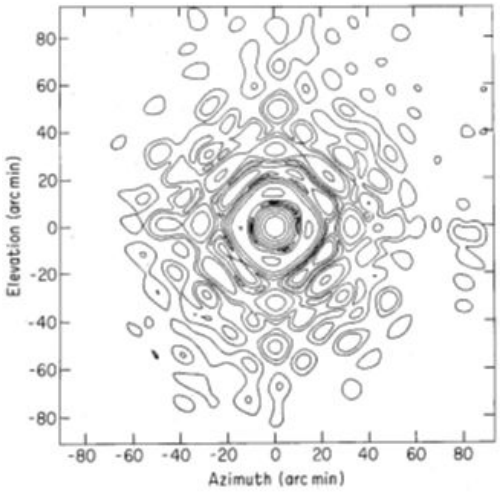
- **Related maintenance workshops:**
  - Antenna Gain Calibration (Lindqvist)
  - Field System Operations (Neidhardt)
  - Automated Pointing Models Using the FS (Himwich) [TOWs ≤ 2019]

Antenna Beam-width

- Directivity: power received (or transmitted) should form a small (solid) angle. Roughly $\theta = \lambda / D$
  - 14 GHz on 12m antenna → ~ 6.1′
- Half-power beam-width (***HPBW***): angle from beam axis such that power falls to one-half of the maximum.







Antenna Pointing Issues

- Ideally, radio source centered in main beam
- Pointing error 10% HPBW causes 3% loss of sensitivity

Pointing error	Loss of sensitivity
10% HPBW	3%
20% HPBW	10%
30% HPBW	22%

- Detailed analysis of pointing errors required to achieve a pointing model good to 10% HPBW across entire sky:
  alignment errors, encoder offsets, antenna deformation
  ► "Automated Pointing Models" workshop from previous TOWs

- Radial feed offset will significantly reduce the gain
  - The feed should be $< \lambda/4$ from the radial focal point
  - The focal length may change with elevation
  - Lateral offest $< \lambda$ mostly biases pointing, with less loss of gain

Antenna Efficiency

- Power received from an unpolarized source by a perfect antenna:

$$P = \tfrac{1}{2}\, S\, A_{geom}\, \Delta\nu$$

  - Units of S = Jansky (10^{-26} Watts per m^2 per Hz)
- Effective aperture: fraction of total power actually picked up by real antenna: $A_{eff} = \eta_A A_{geom}$
- η_A is the aperture efficiency. It depends on:
  - Reflector surface accuracy
  - Feed illumination / spill-over
  - Subreflector / leg blockage
- η_A can be a function of pointing direction

Antenna Temperature

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- A resistive load at temperature T delivers a power of:

$$P = k\,T\,\Delta\nu$$

  - k = Boltzmann constant (1.308x10^{-23} Joules per Kelvin)

- Antenna Temperature: T of a resistive load providing the same power as a source in the antenna beam:

$$T_A = 1/(2k)\,\eta_A\,A_{geom}\,S$$
$$= \pi D^2/(8k)\,\eta_A\,S$$

- Larger, more efficient antennas & brighter sources yield higher T_A

System Temperature (T_{sys})

- T_{sys} is the temperature of a resistive load providing the same power as the system noise:

$$T_{sys} = T_{rcvr} + T_{struct} + T_{sky}$$

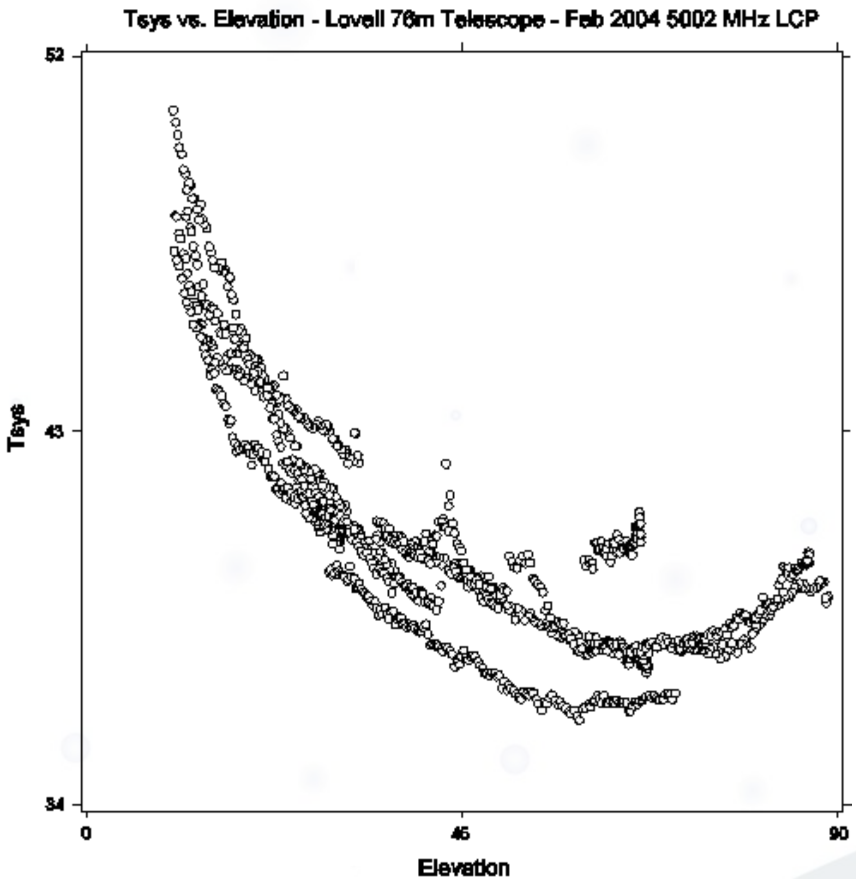
  - rcvr: LNAs, mixers, etc.
  - struct: antenna structure, ground spill-over, sidelobes, etc.
  - sky: atmospheric path-length, cosmic backgrounds, RFI, etc.

$$T_{atm} = T_{zenith} \left(1 - e^{-\tau / \sin(El)}\right)$$

- T_{sys} itself can have an elevation dependence

- Note: T_{sys} is almost always >> T_A

T_{sys} vs. elevation



$$T_{atm} = T_{zenith} \left(1 - e^{-\tau / \sin(El)}\right)$$

System Equivalent Flux Density

- SEFD = flux-density of a fictitious source delivering the same power as the system noise.
- Direct relation between T_{sys} & SEFD:

$$T_{sys}\,[\mathrm{K}] = \Gamma\,[\mathrm{K/Jy}] \cdot SEFD\,[\mathrm{Jy}]$$

- Gain (or sensitivity) Γ gives the increase in the T of the equivalent resistive load for a source of 1 Jy.
    - Thus in a sense the ratio of T_{sys} & T_A sets the sensitivity
- Going back a couple viewgraphs:

$$\Gamma = \eta_A\,\pi\,D^2 / (8k)$$
$$\approx 3x10^{-4}\,\eta_A\,D^2$$

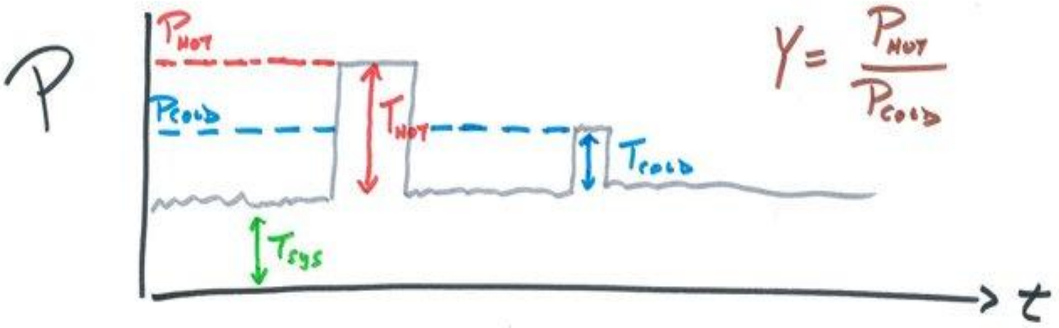
Importance of SEFD

- Invaribly in radio astronomy, system noise dominates over power from the source in the beam.
  - Nominal X-band SEFDs in [Jy] (see, e.g., EVN status table):
    Ef=20, Ys=200, Mc=320, Nt=840, On=785, Tm65=48
- In this case, geometric means of SEFD's at the two stations in a baseline → conversion scale between correlation coefficient and physical amplitude in Jy.
- With $SEFD = T_{sys} / \Gamma$, there are 2 parts to calibrate:
  - System temperature
  - Gain

Y-method for finding T_{sys}

- Put loads at 2 different temperatures "into" antenna:

$$P_{hot} = g\,(T_{hot} + T_{sys})$$
$$P_{cold} = g\,(T_{cold} + T_{sys})$$



- Form ratio of P_{hot} / P_{cold} (= Y) & solve this for T_{sys}:

$$T_{sys} = \frac{T_{hot} - Y\,T_{cold}}{Y - 1}$$

  - Assumptions: receiver remains in linear regime; g, T_{sys} constant

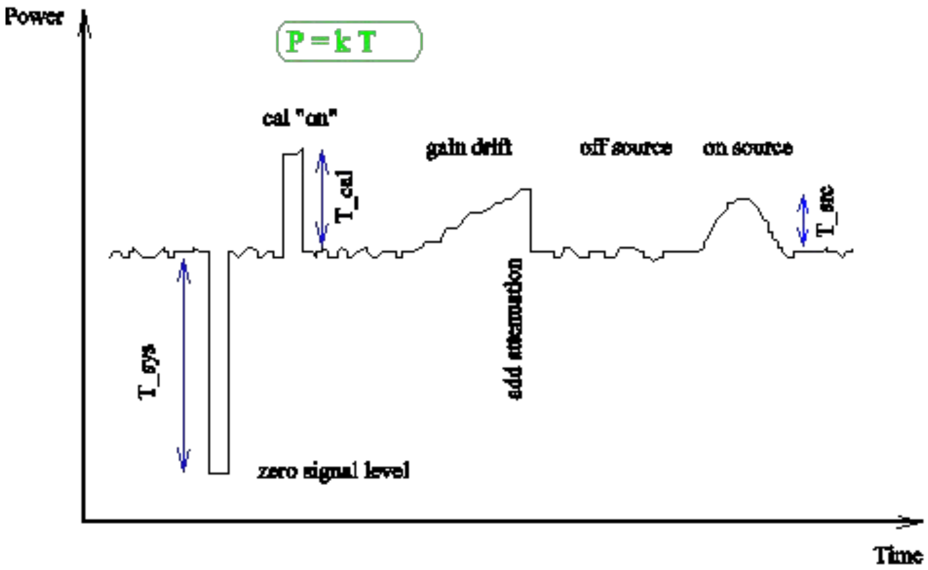
T_{sys} via a cal-diode at T_{cal}

- Noise-cal signal at T_{cal} :

$$P_{on} = g\,(T_{cal} + T_{sys})$$
$$P_{off} = g\,(T_{sys})$$

$$\frac{P_{\rm off}}{P_{\rm on} - P_{\rm off}} = \frac{gT_{\rm sys}}{g(T_{\rm cal} - T_{\rm sys}) - gT_{\rm sys}}$$
$$= \frac{T_{\rm sys}}{T_{\rm cal}}$$

$$T_{\rm sys} = T_{\rm cal}\,\frac{P_{\rm off}}{P_{\rm on} - P_{\rm off}}$$



- T_{sys} needs an accurate measurement of T_{cal}
- Sources for T_{sys} calib.: strong, non-variable, point-like

T_{cal} via hot & cold loads

- A measure of T_{cal} can also come from hot & cold loads:

$$P_{cal.on} - P_{cal.off} = g\,(T_{cal} + T_{sys}) - g\,(T_{sys}) = g\,(T_{cal})$$

$$P_{hot} - P_{cold} = g\,(T_{hot} - T_{cold})$$

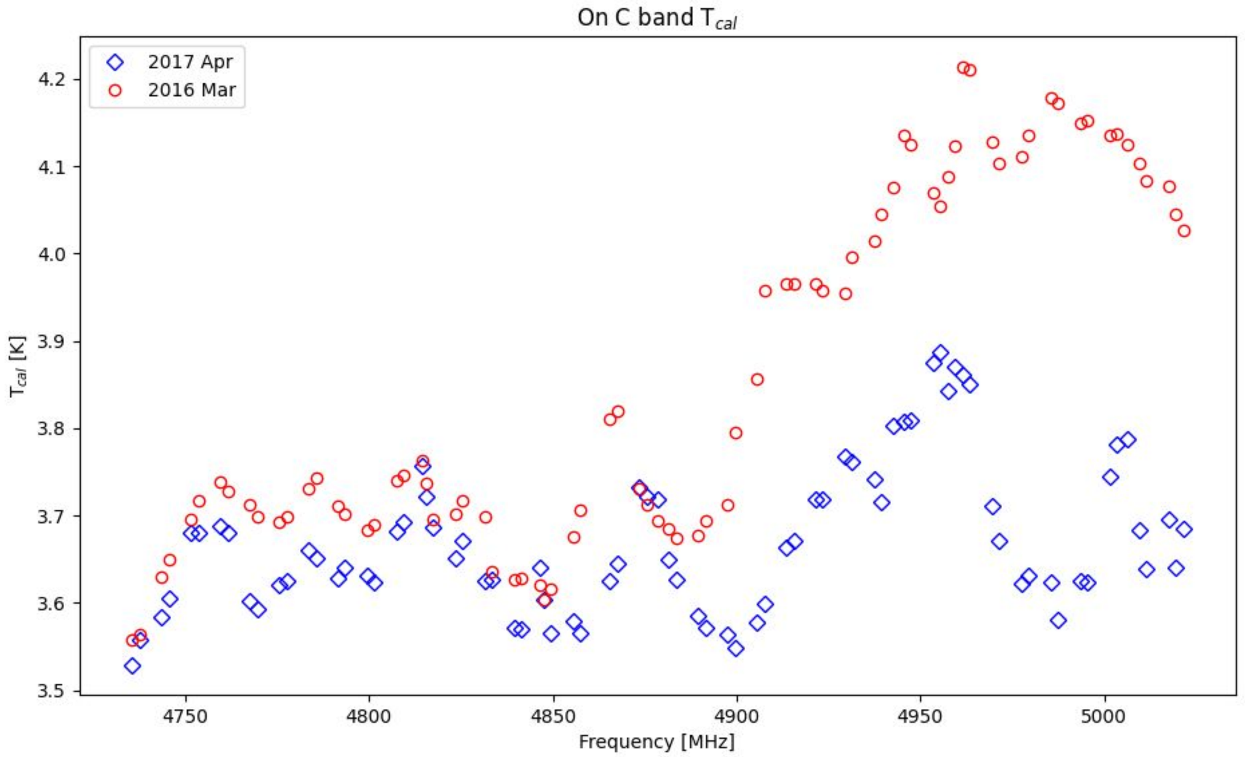
- Forming ratios & solving for T_{cal} gives:

$$T_{cal} = (T_{hot} - T_{cold})\,\frac{P_{cal.on} - P_{cal.off}}{P_{hot} - P_{cold}}$$

- T_{cal} can be a function of time (session to session) and frequency (even within a single IF-sized range)

T_{cal} variations

- Onsala85 at 6cm



► "Amplitude Gain Calibration" Workshop (Lindqvist)

Gain parameterization

- We've seen $T_{sys} = \Gamma \cdot SEFD$
- We can solve this for SEFD:

$$SEFD = \frac{T_{\rm sys}}{GAIN} = \frac{T_{\rm sys}}{DPFU \times g(z)}$$

- DPFU (degrees per flux unit) is an absolute gain
- g(z) is the gain curve as a function of zenith angle (or elevation,...), typically expressed as a polynomial

$$g(z) = c_0 + c_1 z + c_2 z^2 + \ldots + c_n z^n$$

  - g(z) stems mainly from gravitational deformations to the antenna structure (→ aparabolic, focal-length changes, etc.)

Gain Determination

- The gain can be determined from the powers on & off source and the powers with the cal-diode on & off:

$$P_{cal.on} - P_{cal.off} = g\,(T_{cal} + T_{sys}) - g\,T_{sys} = g\,T_{cal}$$

$$P_{on.src} - P_{off.src} = g\,(T_{A} + T_{sys}) - g\,T_{sys} = g\,T_{A}$$

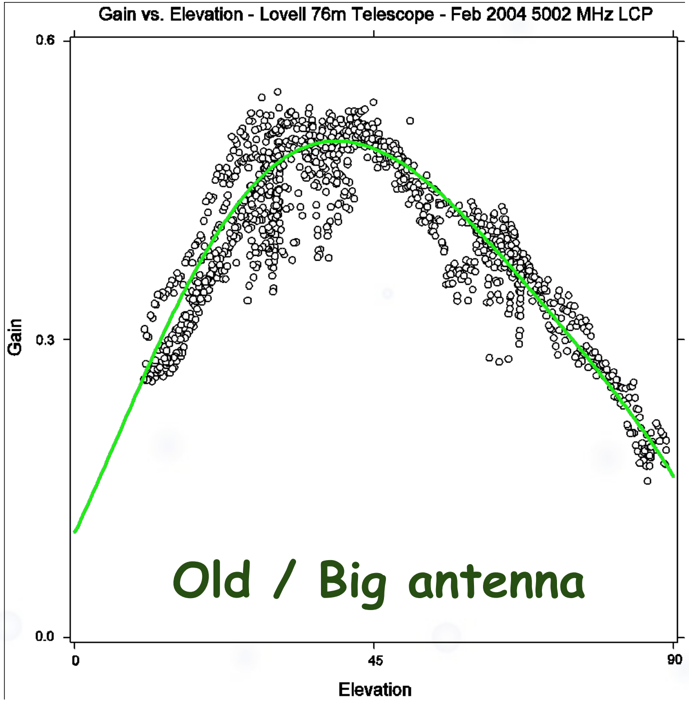
- Forming the ratio gives: T_{cal} / T_{A} , where T_{A} can further be written as GAIN·S (S = source flux density)

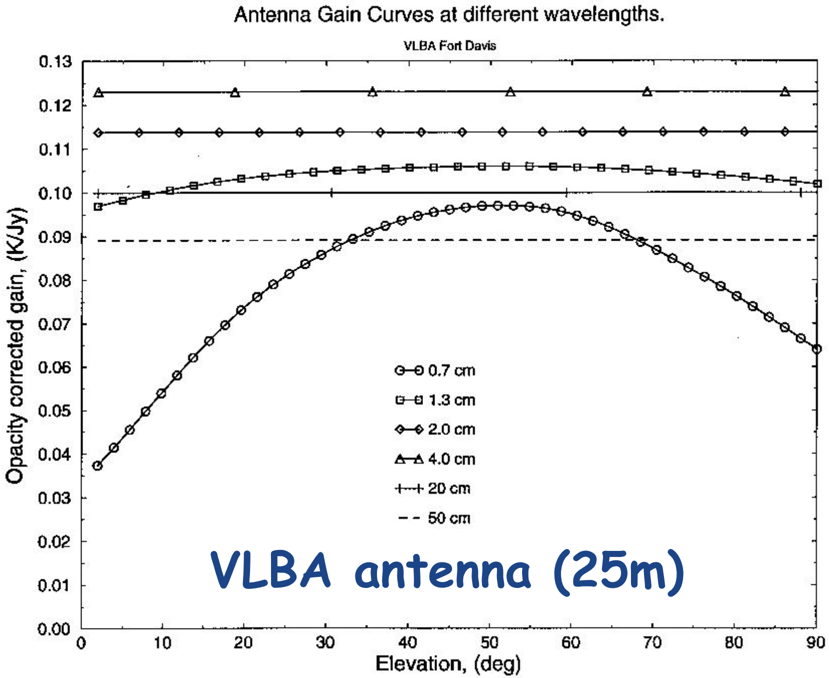
$$GAIN = \frac{P_{on.src} - P_{off.src}}{P_{cal.on} - P_{cal.off}} \frac{T_{cal}}{S}$$

- FS program `aquir` to collect gain-calibration data

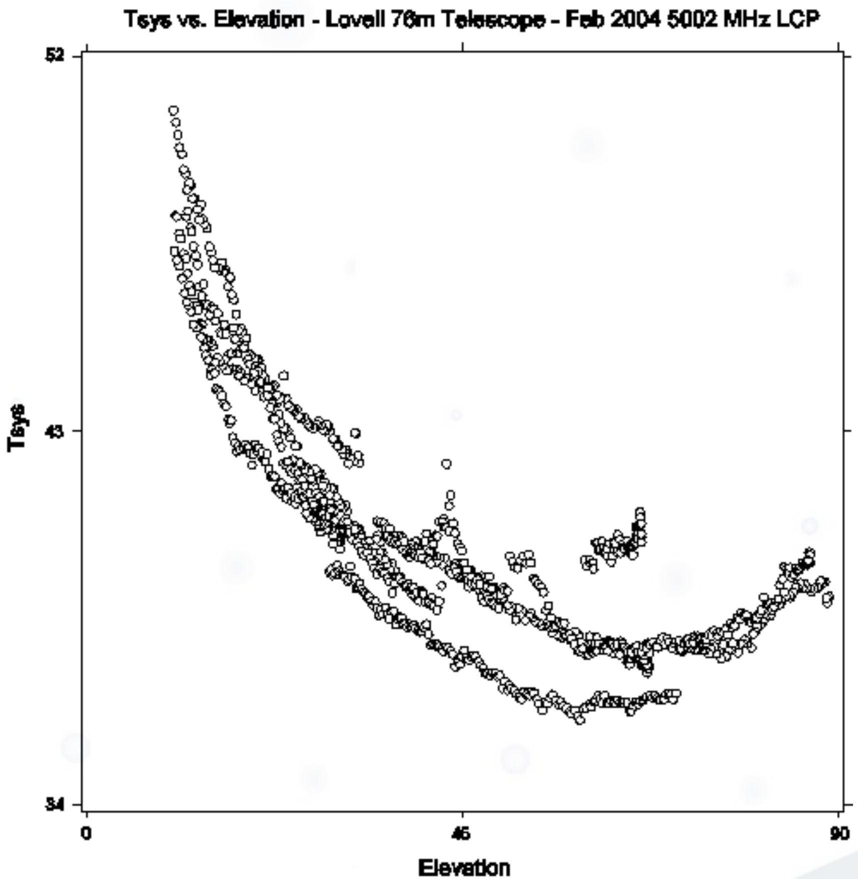
Gain Curve

- Gain vs. Elevation:





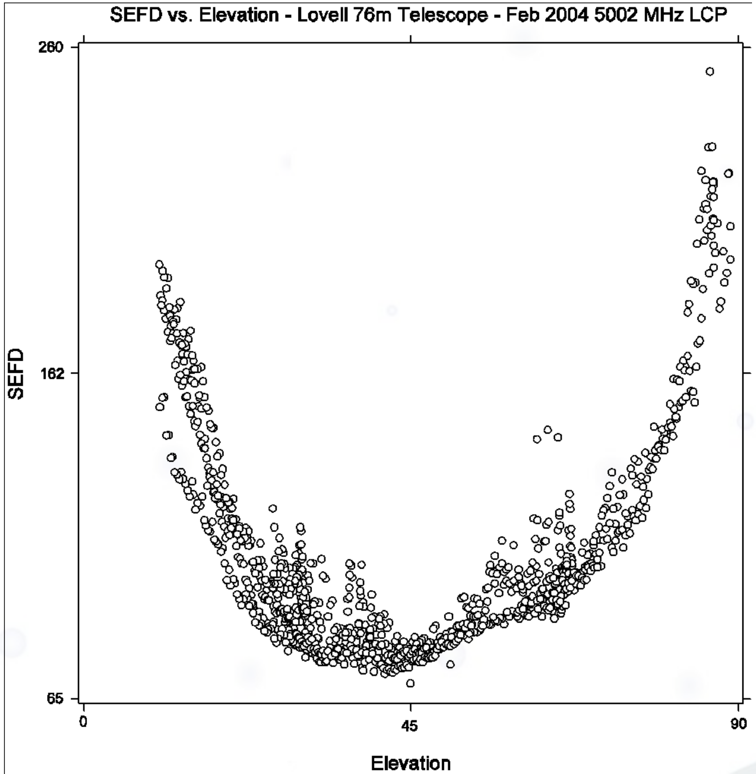
Reminder of T_{sys} vs. elevation



$$T_{atm} = T_{zenith} \left(1 - e^{-\tau / \sin(El)}\right)$$

SEFD example for Lovell

- SEFD vs. elevation: $SEFD = T_{sys} / GAIN$



Summary (of "theory")

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- Combination of DPFU, gain curve, and T_{cal} required to provide accurate calibration (SEFD)
  - $T_{cal} \rightarrow T_{sys}$
  - DPFU, gain curve → GAIN
  - SEFD = T_{sys} / GAIN
- Other workshops detail their determination:
  - "Automated Pointing Models Using the FS" from previous TOWs
  - "Antenna Gain Calibration" (Lindqvist)
- T_{cal} vs. frequency: determine this regularly
- Gain curve: measure at least once per year

FS Power Measurements

- caltemp: broad-band noise source at a specific T
- Total power integrators:
  - `tpi`: measured when cal-source is off
  - `tpical`: measured when cal-source is on
  - `tpzero`: zero levels
- Cal-source "fires" only when not recording
  - `tpi'`: a tpi value measured close in time to a cal-source firing
  - `tpdiff`: (`tpical` - `tpi'`) — essentially sets the scale between TPI counts and the physical temperature
  - "not recording" → long-enough gaps in schedule (>10s)

T_{sys} from FS TPIs

- Output with the cal-source on & off:

  $g\,(T_{cal} + T_{sys}) =$ `tpical` - `tpzero`

  $g\,(T_{sys}) =$ `tpi` - `tpzero`

- Forming the ratio & solving for T_{sys} gives:

$$T_{\mathrm{sys}} = T_{\mathrm{cal}} \frac{\mathrm{tpi} - \mathrm{tpzero}}{\mathrm{tpical} - \mathrm{tpi}'}$$

- Representative `tpical` - `tpi’` value ~ 1000
  - Too low → larger scatter
  - ~ 0 → dead cal-source (?)
  - Jumps → change in attenuation; unstable cal-source

What the Astronomer Wants

- T_{sys} within an experiment
  - `tpical` - `tpi'` : provides a tie to the T_{cal} at gaps
  - `tpi` : provides a relative T scale between gaps
- SEFD : noise (in flux-density units) of telescopes

$$SEFD(t) = \frac{T_{sys}(t)}{GAIN} = \frac{T_{sys}(t)}{DPFU \times POLY(elev)}$$

  - DPFU : an absolute sensitivity (gain) parameter [K/Jy]
  - POLY : the gain curve
- Dimensionless correlation coefficients → physical flux densities via the geometric mean of the SEFD's of the two stations forming a baseline

Continuous Calibration

- FS supports two calibration schemes for DBBCs
  - [1] Non-continuous: as described so far…
  - [2] Continuous: cal-source switched on/off at 80Hz

- [1]: only `tpi` monitored during recording by `tpicd`

```
2024.291.12:00:00.14#tpicd#tpcont/1l,6129,5925,1u,6175,5774,2l,5977,5574,2u,5987,5580,ia,3145.38
2024.291.12:00:00.14#tpicd#tpcont/9l,6282,5970,9u,6045,5777,al,6173,5984,au,6057,5805,ic,3008.89
2024.291.12:00:00.28#tpicd#tpcont/1l,6129,5925,1u,6175,5774,2l,5977,5574,2u,5987,5580,ia,3245.94
2024.291.12:00:00.28#tpicd#tpcont/9l,6282,5970,9u,6045,5777,al,6173,5984,au,6057,5805,ic,2979.93
```

- [2]: `tpicd` monitors both `tpi` and `tpi’` continuously

```
2024.291.12:00:15.37#tpicd#tpi/1l,12922,1u,12114,2l,11929,2u,12385,ia,953.98
2024.291.12:00:15.37#tpicd#tpi/9l,12529,9u,12144,al,11761,au,11897,ib,922.73
2024.291.12:00:30.39#tpicd#tpi/1l,14093,1u,12187,2l,11896,2u,12387,ia,1004.17
2024.291.12:00:30.39#tpicd#tpi/9l,12557,9u,12102,al,11754,au,11892,ib,933.84
2024.291.12:00:45.39#tpicd#tpi/1l,13666,1u,12108,2l,11909,2u,12384,ia,963.25
2024.291.12:00:45.39#tpicd#tpi/9l,14702,9u,12143,al,11729,au,11894,ib,1013.62
```

  - No `tpi/`, `tpical/`, or `tpdiff/` lines in continuous-cal logs

Continuous Cal: Advantages

- Less affected by time-variations in gain
- More straightforward scheduling (astronomy)
  - Cal-source "firing" occurs in `preob` — last ~10s of gap
  - End of gap defined from the "global" scan start time
  - Cal-source "firing" best done while antenna on-source
  - Slower antennas may not yet be on-source at scan start (→ non-zero `data_good` field in the vex-file)
  - Some PIs have made individual-station schedules in order to delay cal-source "firing" for the slower stations, via the essentially "local" scan start-times in each 1-station schedule

rxg Files

- 9 "lines"
  1) Applicable frequency range
  2) Creation date
  3) Beam width
  4) Available polarizations
  5) DPFU for each pol.
  6) Gain curve
  7) Pol. / Freq. / T_{cal} data
  8) Receiver temp / opacity
  9) Spill-over noise T

```
* first line: LO values and ranges, format:
*     type    frequencies [MHz]
* if type is range, the two values: lower and upper frequencies
* if type is fixed, then one or two fixed value
range 1100 1570
*
* 2nd line: creation date
* format:  yyyy ddd or yyyy mm dd (0 is valid for all for intial set-up)
2010 02 02
*
* 3rd line: FWHM beamwidthm format:
*   model value
* if type is frequncy, then fwhm=value*1.05*c/(freq*diameter)
*                          value is 1.0 if omitted
* if type is constant, then fwhm=value (degrees)
frequency 1.0
*
* 4th line polarizations available
lcp rcp
*
* 5th line: DPFU (degrees/Jansky) for polarizations in previous line in order
0.094500 0.09450000
*
* 6th line: gain curve (only one) for ALL polarizations in 4th line
* TYPE FORM COEFFICENTS ...    [max coeffs = 10]
*     FORM = POLY only for now
*     TYPE - ELEV only for now
*     COEFFICENTS - variable number of number values
ELEV POLY 8.69503E-01 2.33055E-03 -1.05562E-05
*
* 7th and following lines: tcal versus frequency
*       Format: POL FREQ TCAL
*           POL     polarization rcp or lcp
*           FREQ    frequency [MHz]
*           TCAL    [K]
*       MAXIMUM ENTRIES 800, group by polarization, then by increasing freq
lcp 1607.0 15.4945
lcp 1609.0 16.3480
lcp 1611.0 17.5200
lcp 1613.0 18.6960
lcp 1615.0 20.0320
rcp 1607.0 22.6755
rcp 1609.0 22.6380
rcp 1611.0 23.0090
rcp 1613.0 23.3990
rcp 1615.0 23.8450
end_tcal_table
*
* Trec - receiver temperature, degrees K
* if value is zero, no opacity corrections are used
 0.0
*
* Spillover table
*       format: elevation temperature
*  elevation is angular degrees above horizon
*  temperature is Kelvin degrees of spillover noise
*spillover table ends with end_spillover_table record
*
end_spillover_table
```

The antabfs Program

- Reads FS logs and rxg files in order to:
  - Compute (`tpical` - `tpi’`) or `tpcont` values for each VC/BBC
  - Compute/edit the resulting T_{sys} values
  - Output an `.antabfs` file (for use in AIPS, CASA)
- Originally in perl (C. Reynolds, J. Yang, J. Quick)
- Shifts to python (Yebes: F. Beltrán, J. González)
  - Fuller DBBC support (e.g., also now form=wastro)
  - Continuous-cal support
  - Download `antabfs.py` from github:

    https://github.com/evn-vlbi/VLBI-utilities

antabfs (output) file

- "GAIN"
  - Gain curve, DPFU, Frequency Range
- INDEX line
- T_{sys} (t, sideband)

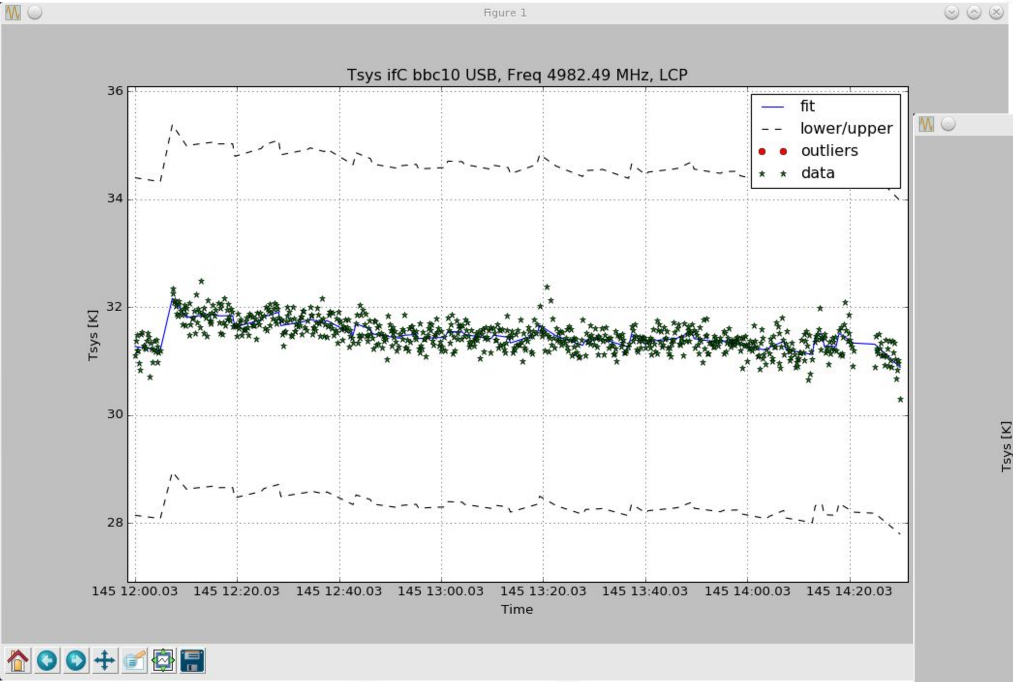
```
! Amplitude calibration data for JB in n24l3.
! For use with AIPS task ANTAB.
! Waveband(s) =  13.2cm.
! RXG files used for each LO:
!   Setup 01
!     LO=2272.00 MHz lcp calJb2272.rxg 2021 11 18
!     LO=2272.00 MHz rcp calJb2272.rxg 2021 11 18
! DBBC used in mode DDC
! Produced on 2024-10-24 using antabfs.py version: 2019-10-11
GAIN JB ELEV DPFU=1.15,1.15 FREQ=1578.49,1738.49
POLY=0.780400926175,0.0121277693428,-0.000212881052904,1.15149509363e-06 /
/
TSYS JB FT = 1.0 TIMEOFF=0
INDEX= 'R1','R2','R3','R4','L1','L2','L3','L4'
/
!
! Setup 01
! Calibration mode: CONT
!
!Column 1 = R1: ifA, bbc01, 1610.49 MHz , LSB, BW= 32.00 MHz, Tcal=17.75 K
!Column 2 = R2: ifA, bbc01, 1642.49 MHz , USB, BW= 32.00 MHz, Tcal=17.36 K
!Column 3 = R3: ifA, bbc02, 1674.49 MHz , LSB, BW= 32.00 MHz, Tcal=20.67 K
!Column 4 = R4: ifA, bbc02, 1706.49 MHz , USB, BW= 32.00 MHz, Tcal=15.97 K
!Column 5 = L1: ifB, bbc09, 1610.49 MHz , LSB, BW= 32.00 MHz, Tcal=14.70 K
!Column 6 = L2: ifB, bbc09, 1642.49 MHz , USB, BW= 32.00 MHz, Tcal=15.59 K
!Column 7 = L3: ifB, bbc10, 1674.49 MHz , LSB, BW= 32.00 MHz, Tcal=20.77 K
!Column 8 = L4: ifB, bbc10, 1706.49 MHz , USB, BW= 32.00 MHz, Tcal=14.47 K
! 291 11:38.87: scanNum=0001 scanName=no0001 source=3c395
291 12:00.09 77.4 78.9 101.9 59.8 64.3 66.9 109.2 58.6
291 12:00.17 74.7 78.4 190.9 51.3 63.8 70.3 108.2 58.6
291 12:00.25 76.7 76.8 101.9 60.0 64.2 67.7 110.5 58.5
291 12:00.34 75.9 77.3 102.0 59.7 63.7 70.9 108.7 58.6
291 12:00.42 75.1 81.9 102.1 59.7 63.5 68.2 108.7 58.6
291 12:00.50 75.4 81.1 103.6 59.8 64.0 68.6 117.2 58.6
```

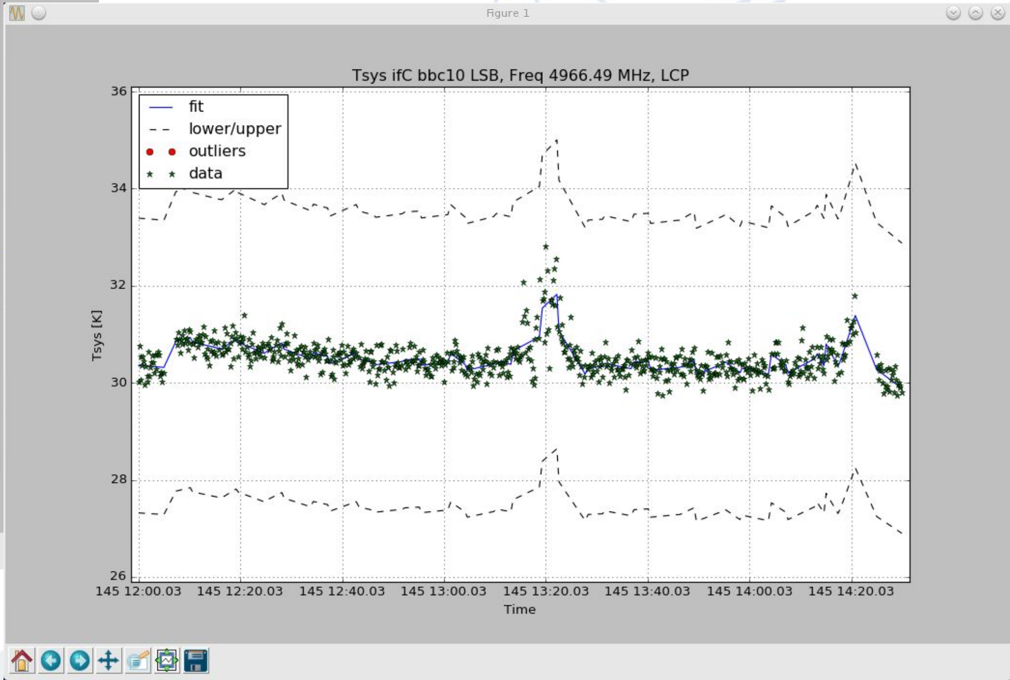
Running `antabfs.py`

- Syntax:
  - `antabfs.py [-f rxg_files_list] fs_log_file`
  - Looks for rxg file in `/usr2/control/rxg_files/` (self.rxgDirectory)
  - `-f`: optionally specify the rxg file explicitly (correct freq.band?)
- Antabfs.py will cycle through the sidebands
  - Opens a plot window showing the derived T_{sys} + fit + bounds
  - "Outlier" points appear in red
  - Interactively edit out T_{sys} points via making drag+click boxes
  - When happy with this sideband, close the plot window
- A final all-sideband plot appears (not editable)
- Closing this window → query to save into an antabfs file

`antabfs.py`: sideband plots

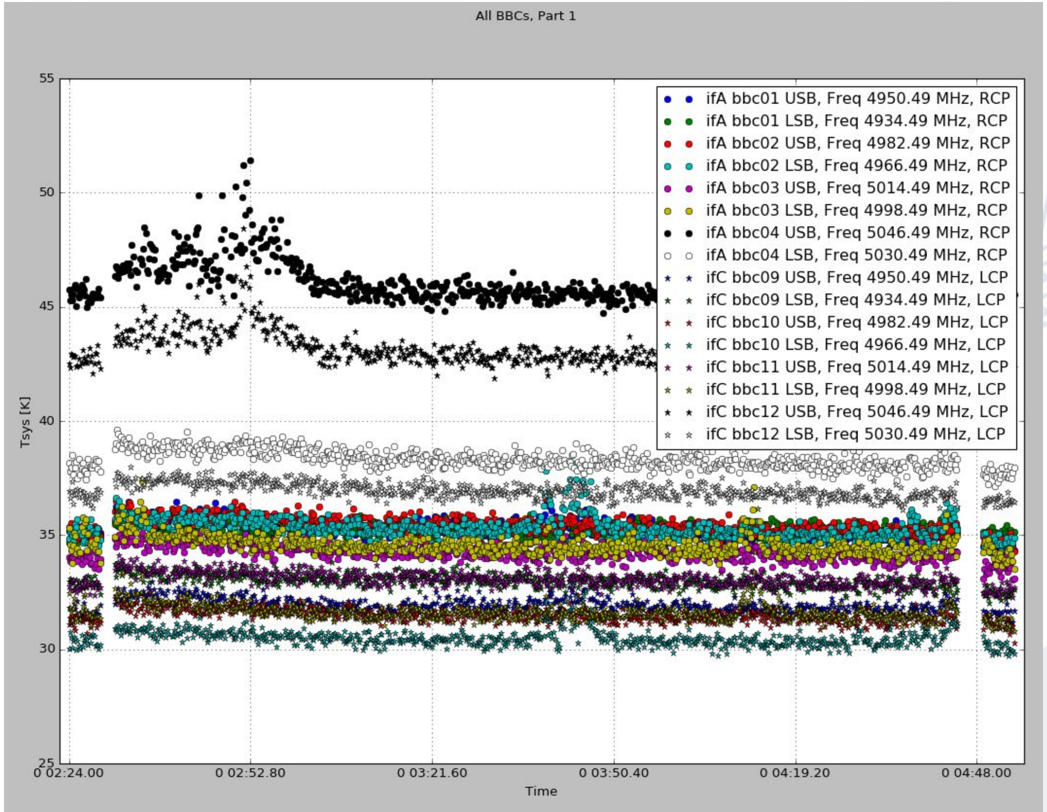
- On (continuous cal), 6cm, EVN session 2/2018





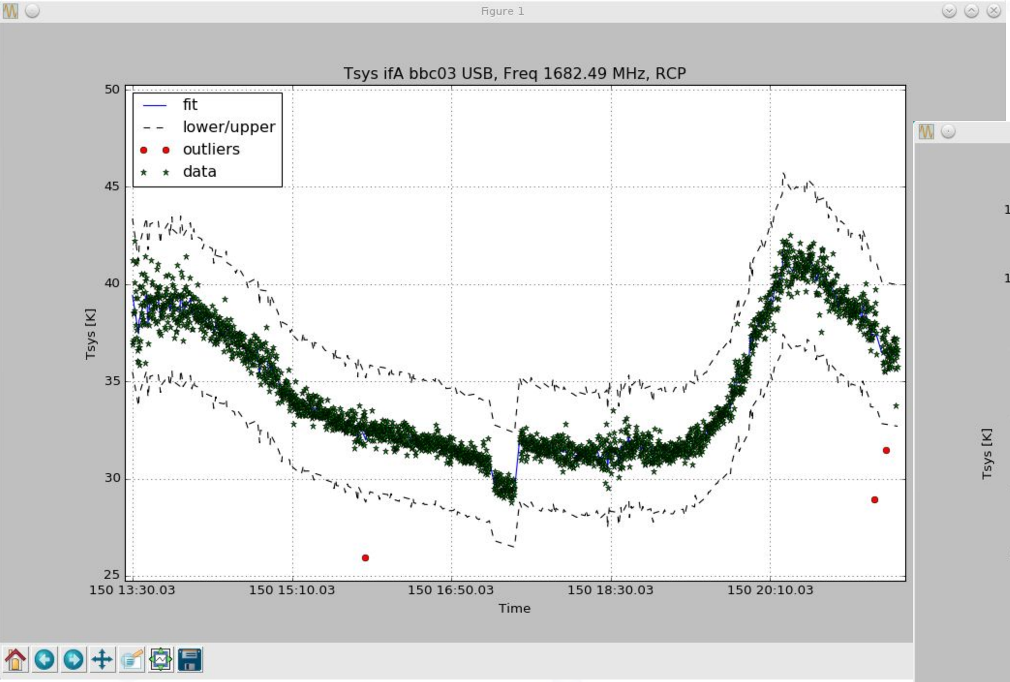
`antabfs.py`: final plots

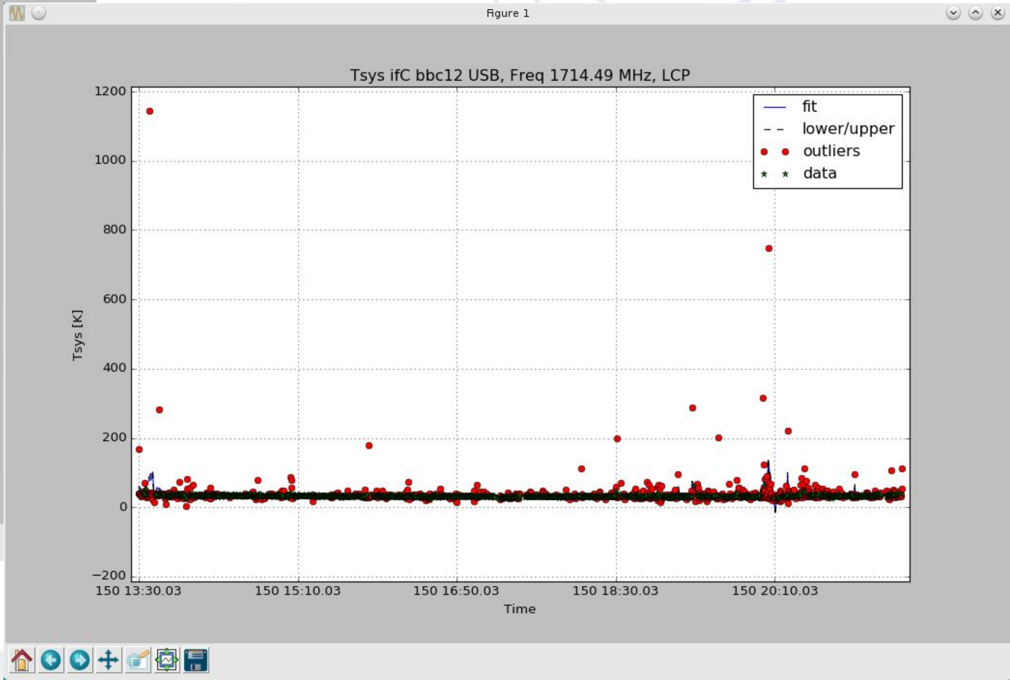
- On (continuous cal), 6cm, EVN session 2/2018



`antabfs.py`: case needing edits

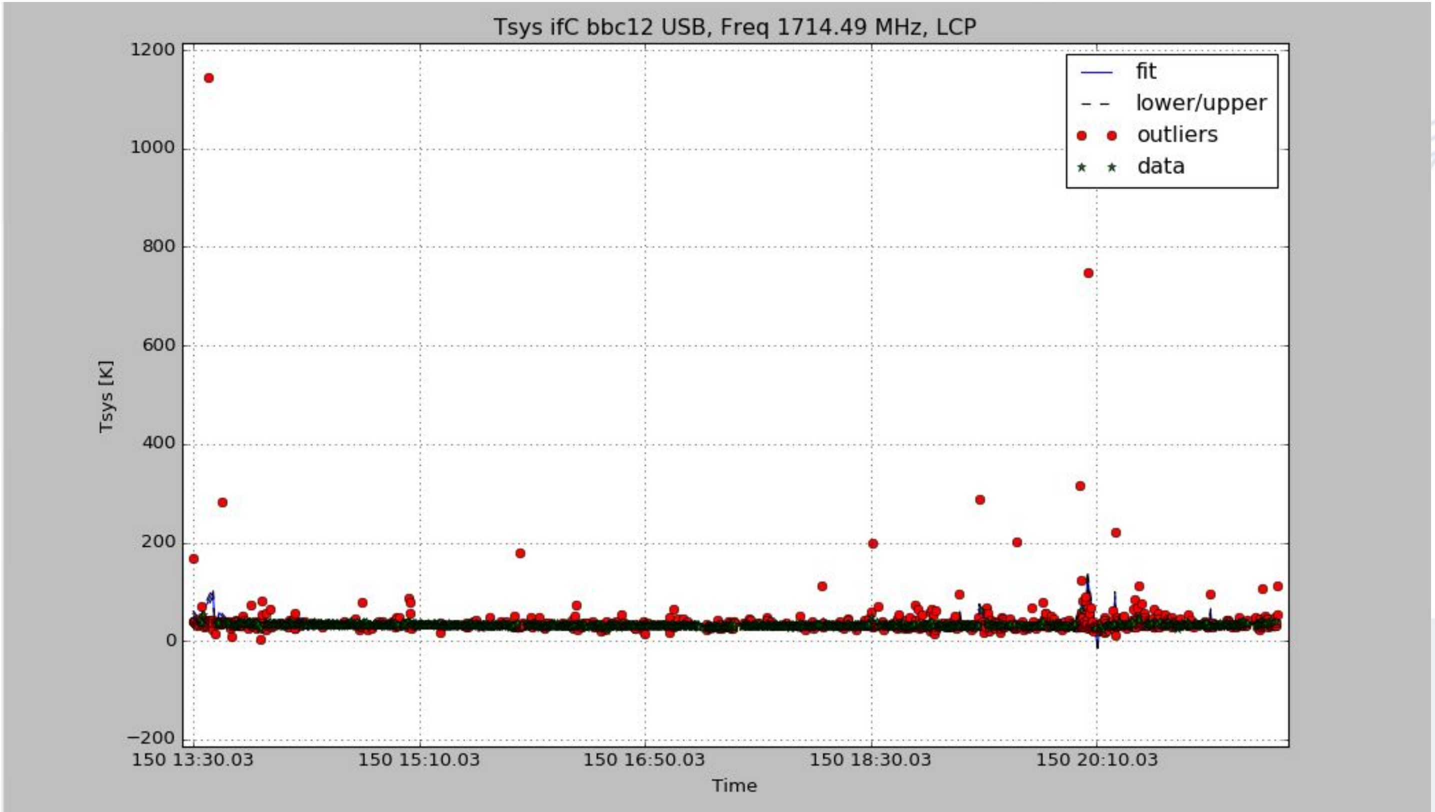
- On (continuous cal), 18cm, EVN session 2/2018





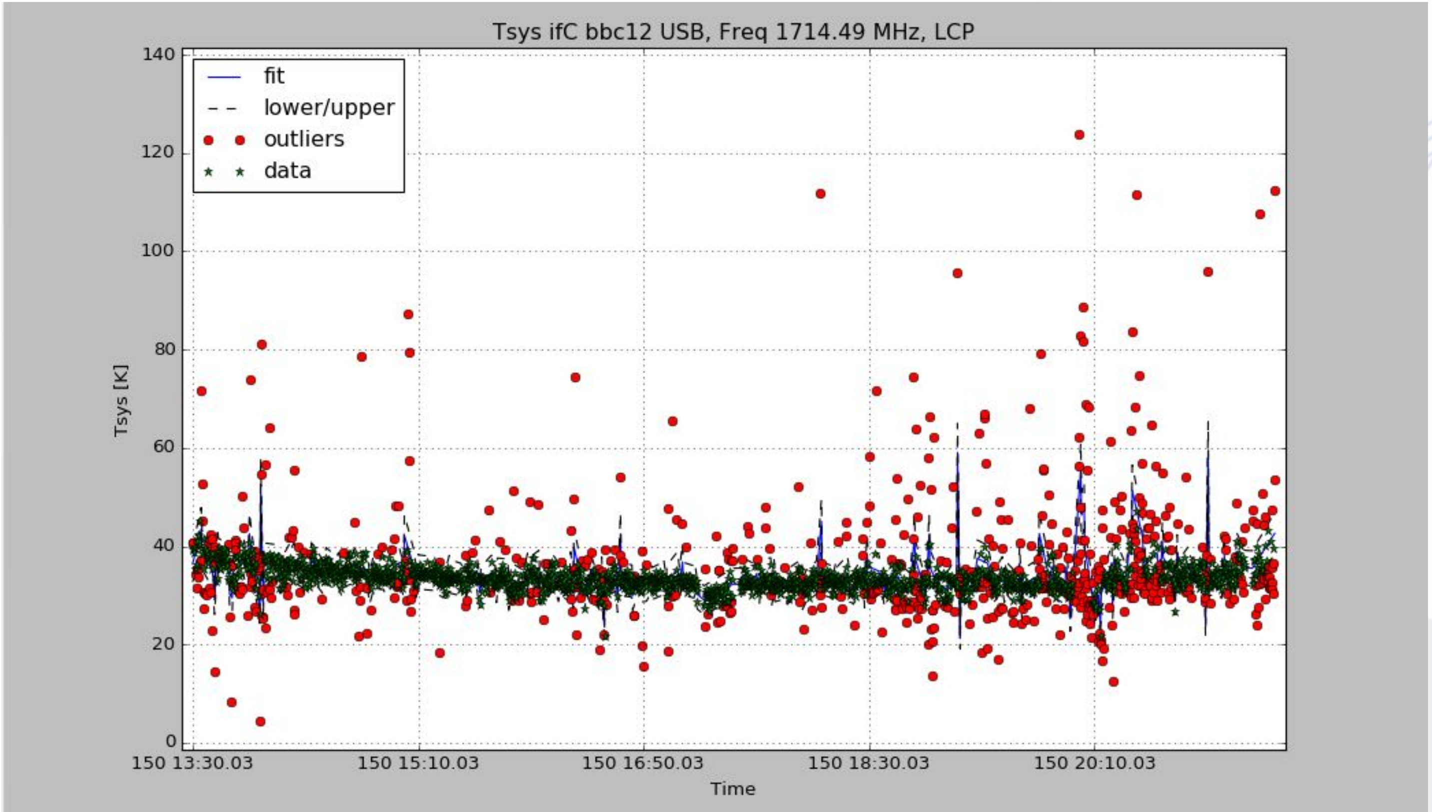
`antabfs.py`: edit iter.0

- On (continuous cal), 18cm, EVN session 2/2018



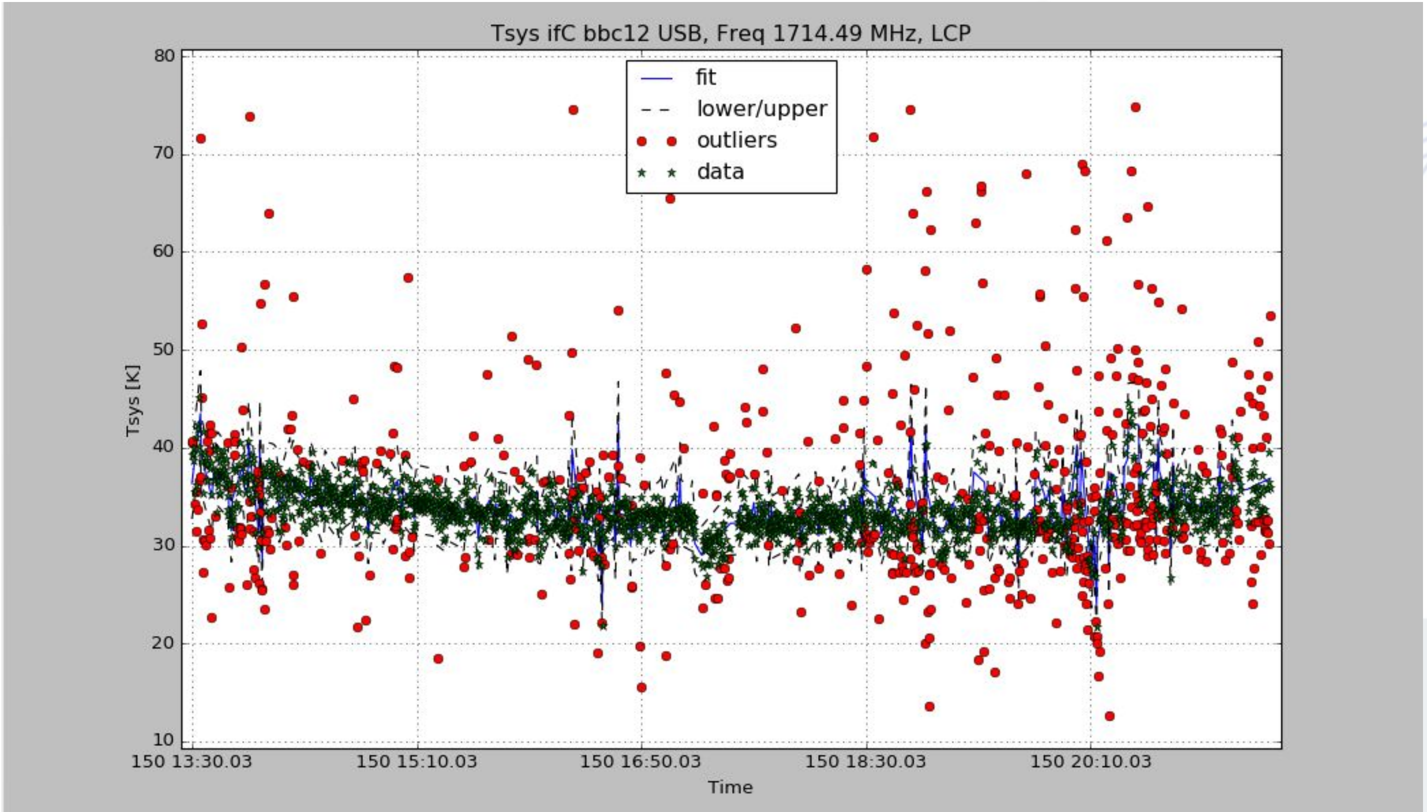
`antabfs.py`: edit iter.1

- *On (continuous cal), 18cm, EVN session 2/2018*



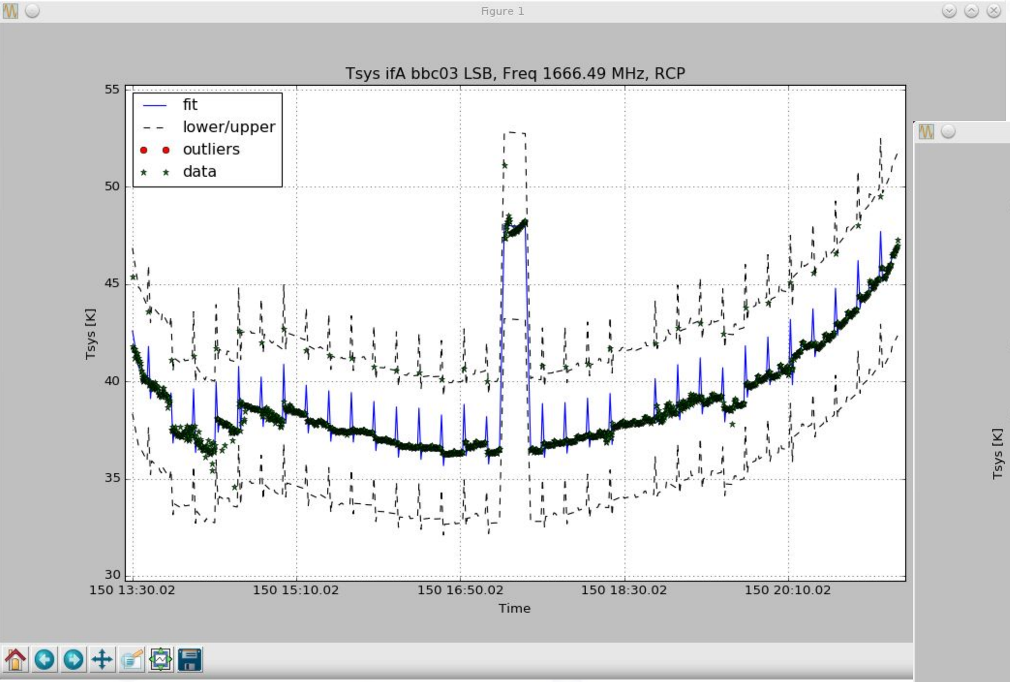
`antabfs.py`: edit iter.2

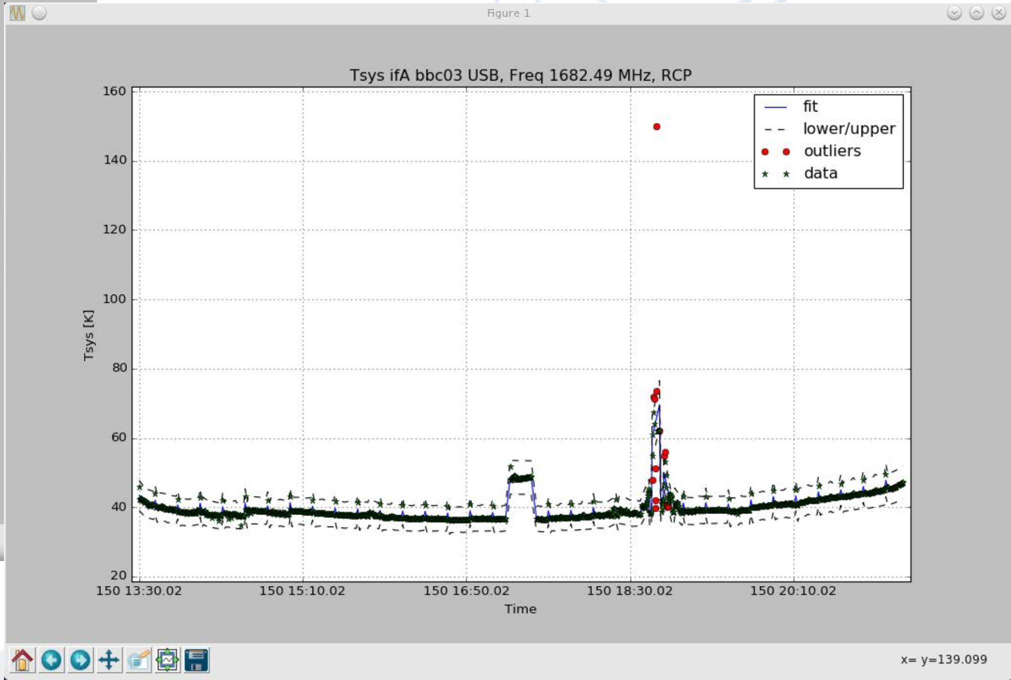
- On (continuous cal), 18cm, EVN session 2/2018



`antabfs.py`: not continuous cal.

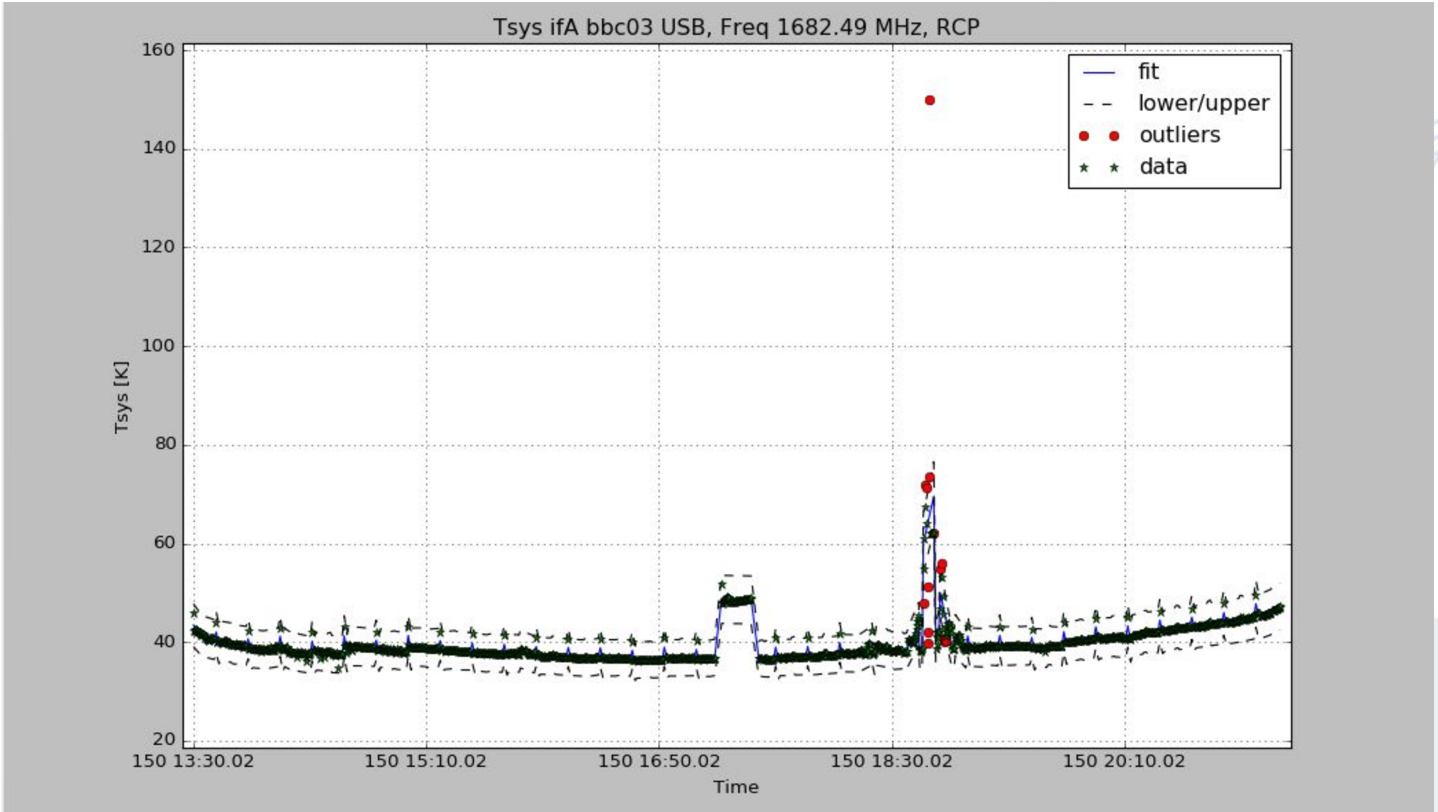
- Hh (gap-based cal-diode), 18cm, EVN session 2/2018





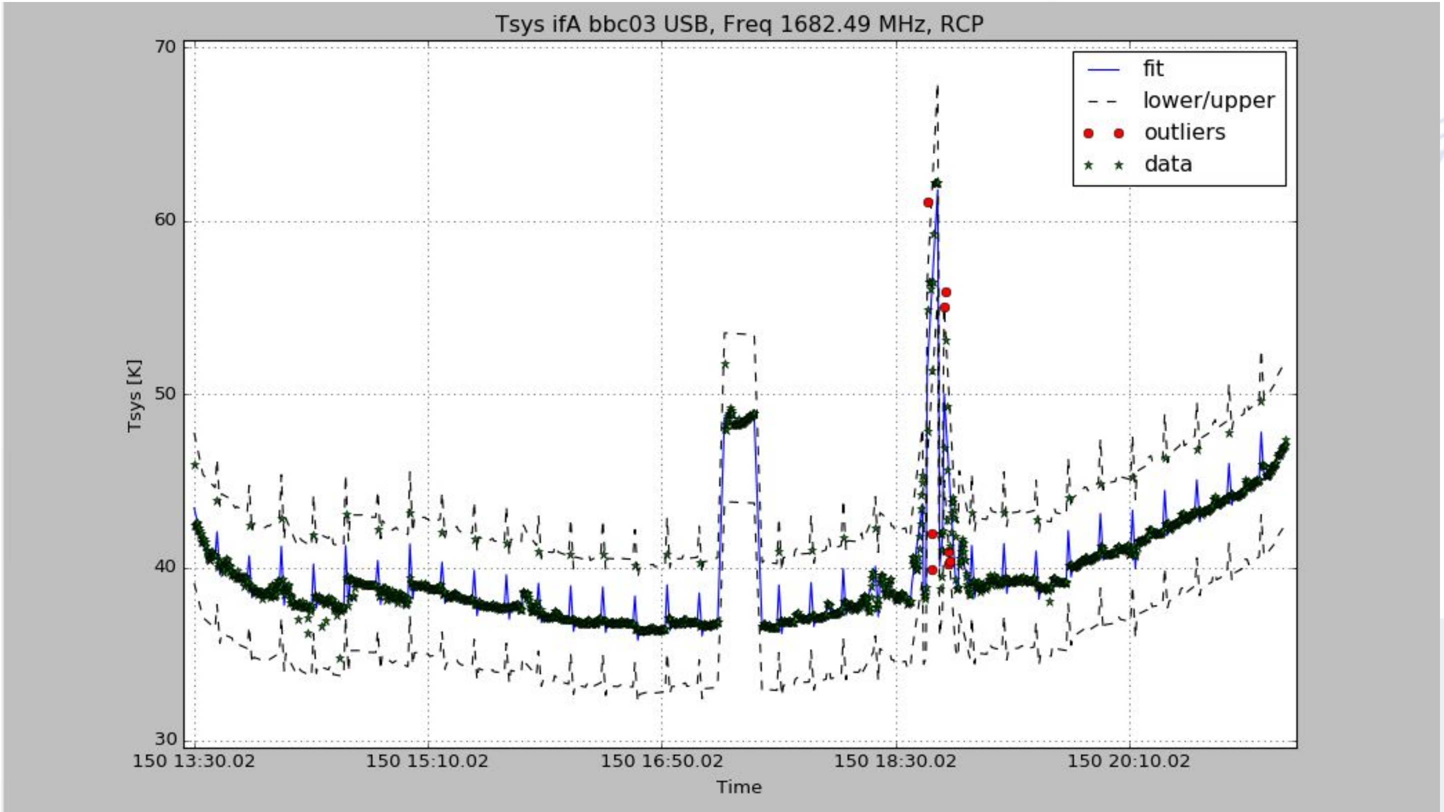
`antabfs.py`: edit iter.0

- Hh (gap-based cal-diode), 18cm, EVN session 2/2018



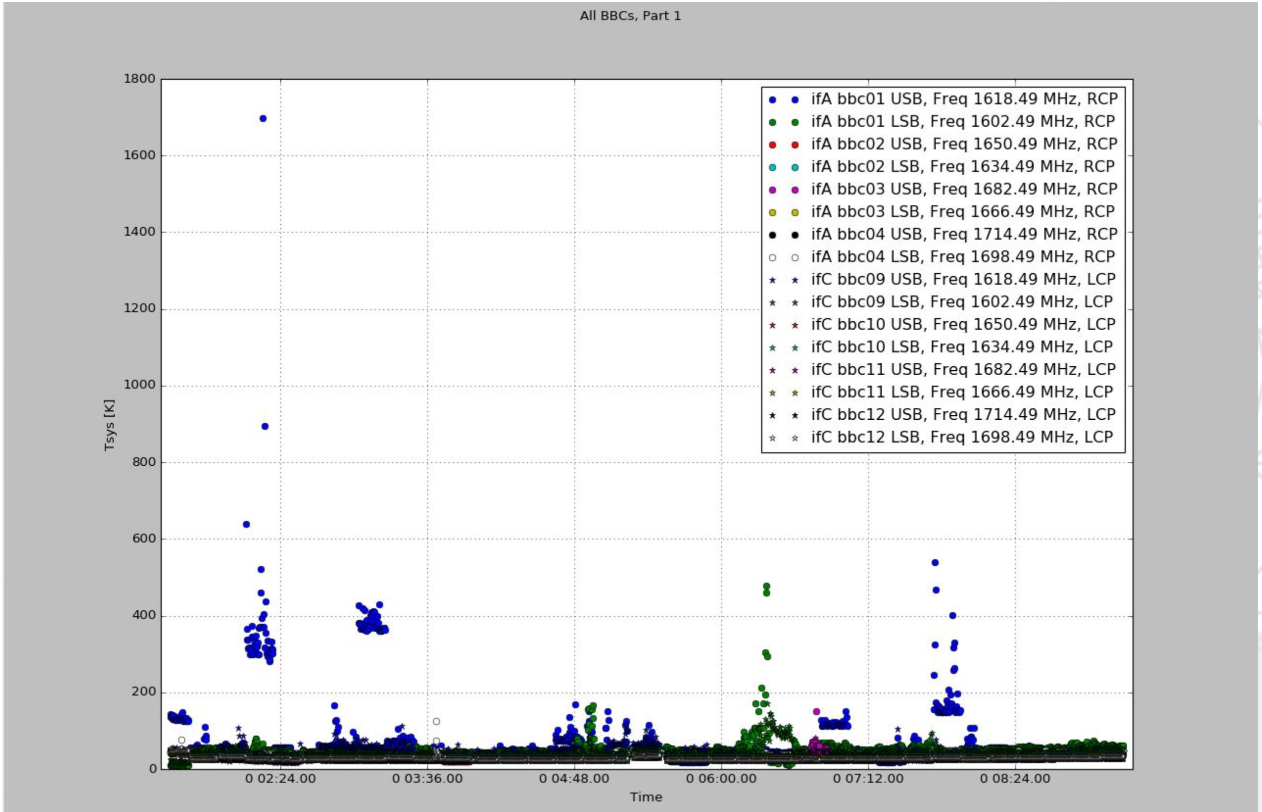
`antabfs.py`: edit iter.1

- Hh (gap-based cal-diode), 18cm, EVN session 2/2018



`antabfs.py`: t-, ν-localized RFI

- Hh (gap-based cal-diode), 18cm, EVN session 2/2018



Summary (of “antabfs”)

- Quality of stations’ `antabfs` file has direct bearing on quality of resulting imaging
  - Keep rxg files up-to-date !
- Provide `antabfs` files in timely fashion
  - They serve as input into pipelining & user analysis
- Stations in a better position to run `antabfs.py` than are the correlators (local knowledge)
- Feedback about `antabfs.py` → Yebes or JIVE
  - Javier González (jgonzalez@oan.es)
  - Fran Beltrán (francisco.beltran@oan.es)