Pointing & Single-Dish Amplitude Calibration

Bob Campbell, JIVE

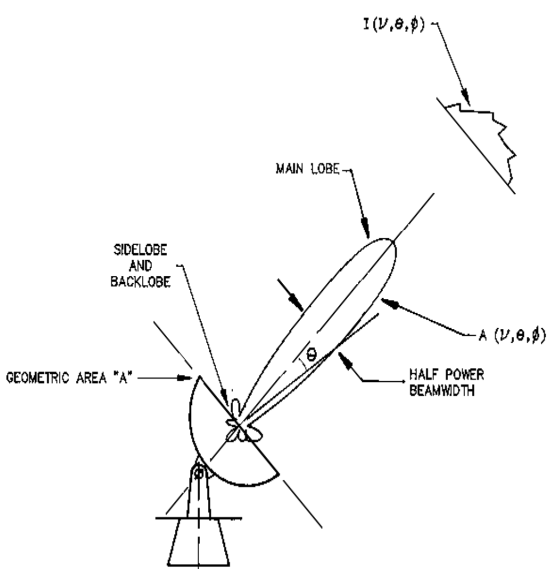
- Beams & Pointing
- Antenna Efficiency, Antenna Temperature
- SEFD as the key for calibration
- System Temperature & Gain
- rxg & ANTABFS files

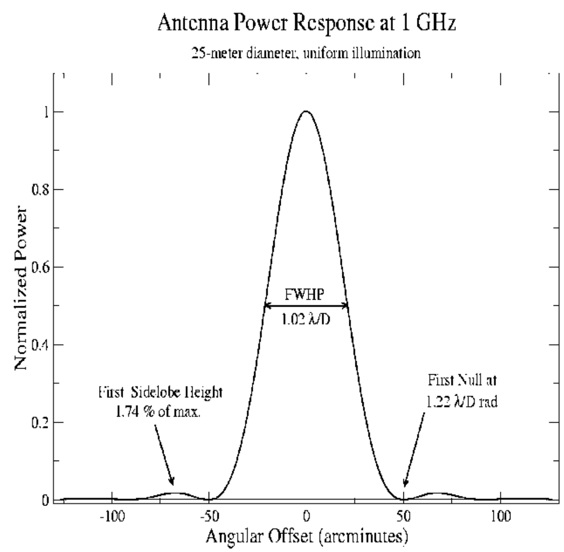
Why Calibrate?

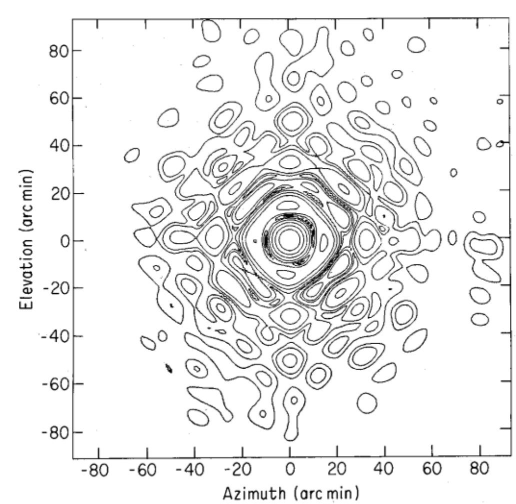
- Scientific quality:
  - geodesy — best SNR per scan to improve delay precision
  - astronomy — source brightness on absolute physical scale
  - Regular checks of calibration → help notice problems
- You can measure/calibrate:
  - the focus & pointing
  - the aperture efficiency (η_A)
  - the system 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
  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 <λ mostly biases pointing, with less loss of gain

Antenna Efficiency

- Power received from an unpolarized source by a perfect antenna: $P = ½ S A_{geom} \Delta\nu$
  - 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

- 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:

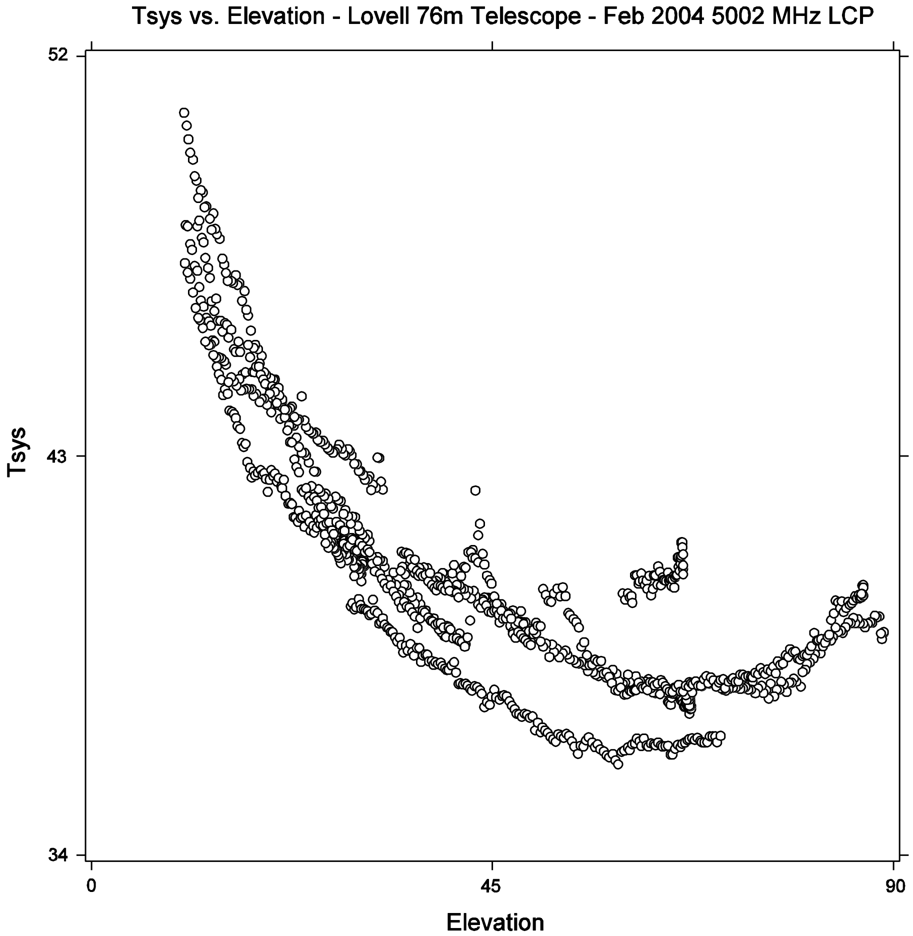
$$T_{sys} = T_{rcvr} + T_{struct} + T_{sky}$$

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

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

- T_{sys} itself can have an elevation dependence
- Note: T_{sys} is almost always >> T_A

T_{sys} vs. elevation



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

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:

$$\Gamma = \eta_A \pi D^2 / (8k)$$

$$\approx 3 \times 10^{-4}\, \eta_A D^2$$

Importance of SEFD

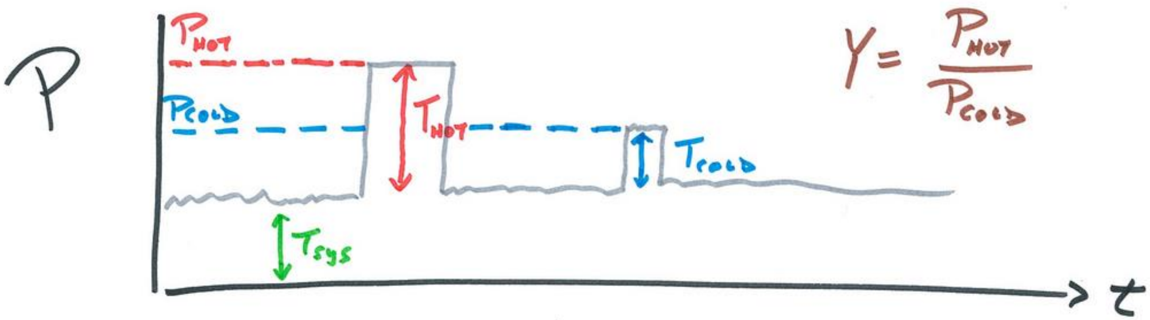
- Invariably in radio astronomy, system noise dominates over power from the source in the beam.
  - Nominal X-band SEFDs in [Jy] (see, e.g., EVN status table):

    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}:

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

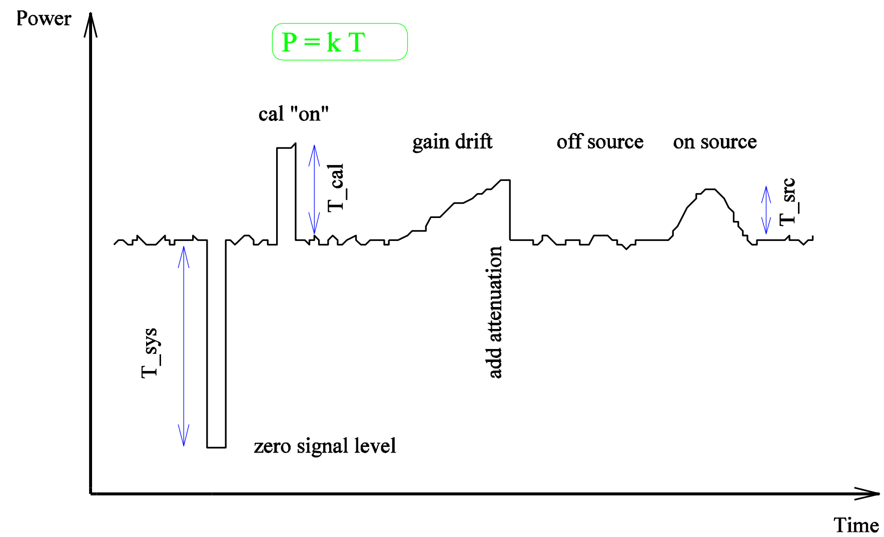
  - Assumptions: receiver remains in linear regime; g, T_{sys} constant

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:

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

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

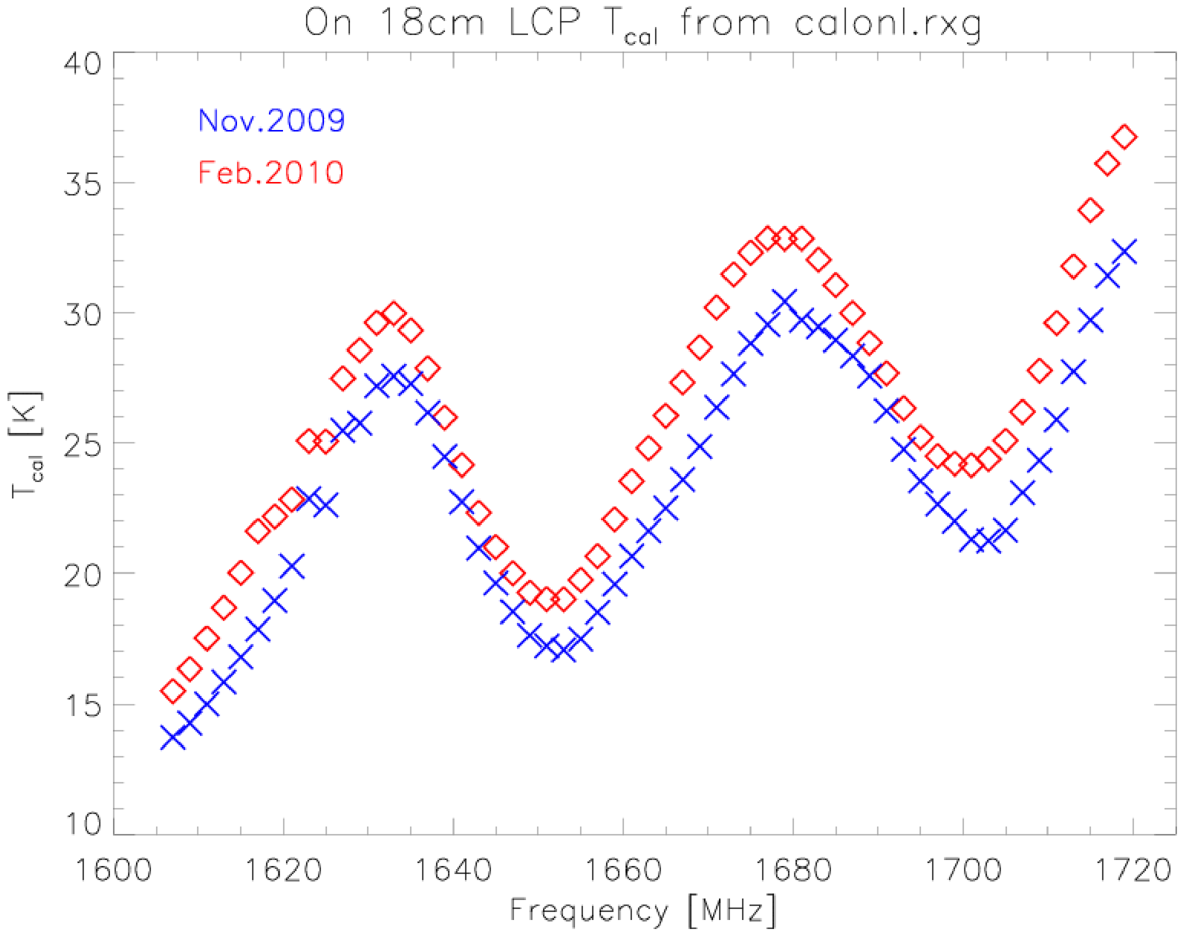
- Forming ratios & solving for T_{cal} gives:

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

- 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 18cm



► "Amplitude Gain Calibration" Workshop (Lindqvist)

Gain parameterization

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

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

- 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:

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

$$P_{\rm on.src} - P_{\rm off.src} = g\,(T_A + T_{\rm sys}) - gT_{\rm sys} = gT_A$$

- Forming the ratio gives: $T_{\rm cal} / T_A$, where T_A can further be written as $GAIN \cdot S$ (S = source flux density)

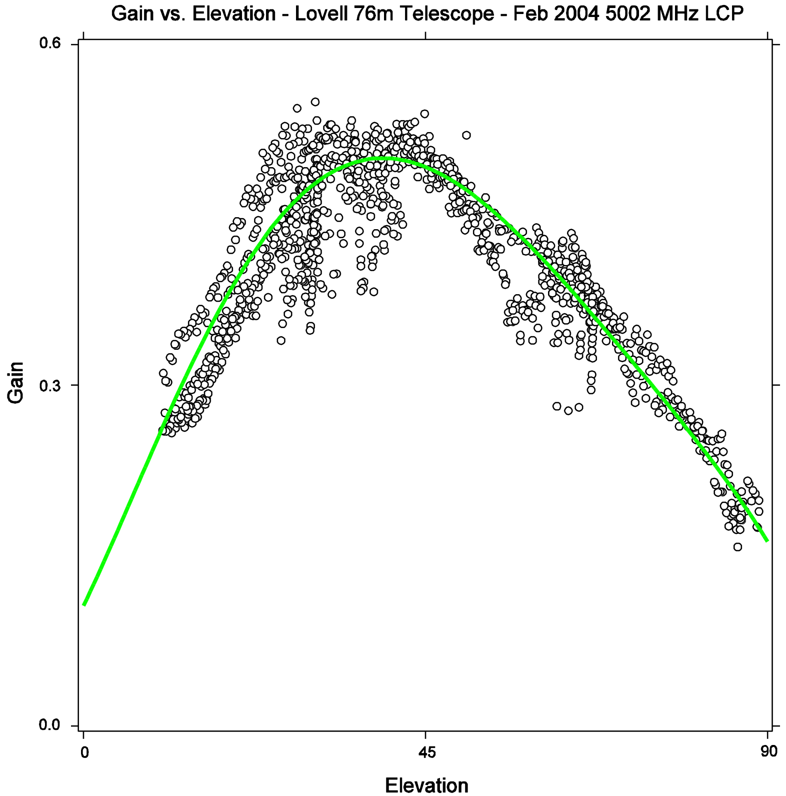
$$GAIN = \frac{P_{\rm on.src} - P_{\rm off.src}}{P_{\rm cal.on} - P_{\rm cal.off}} \frac{T_{\rm cal}}{S}$$

- FS program aquir to collect gain-calibration data

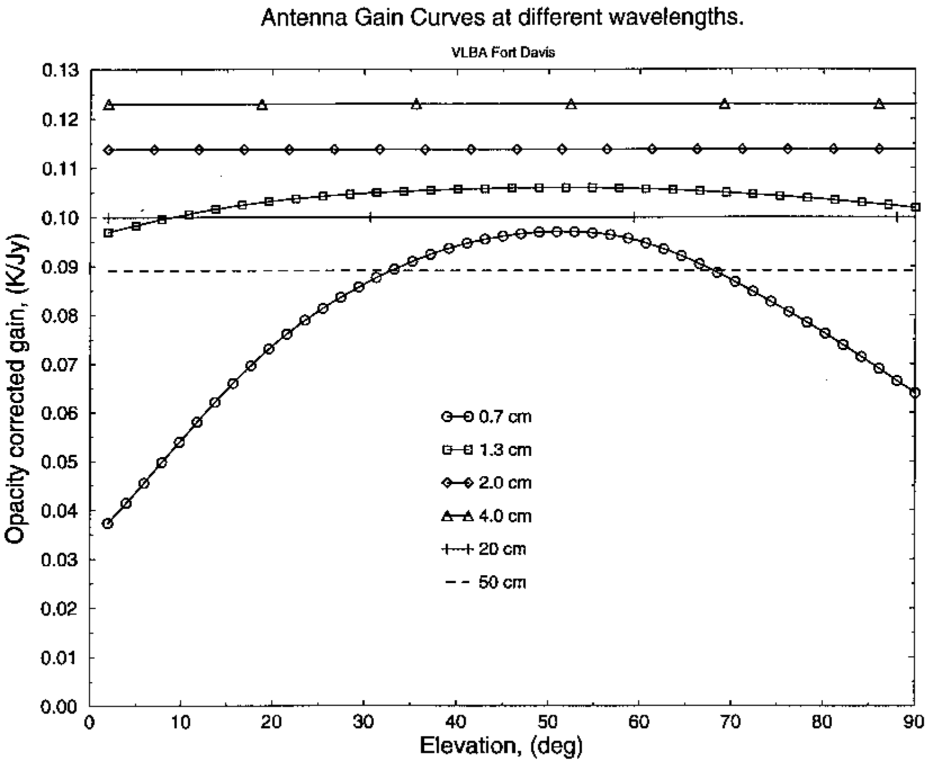
Gain Curves

- Gain vs. elevation:

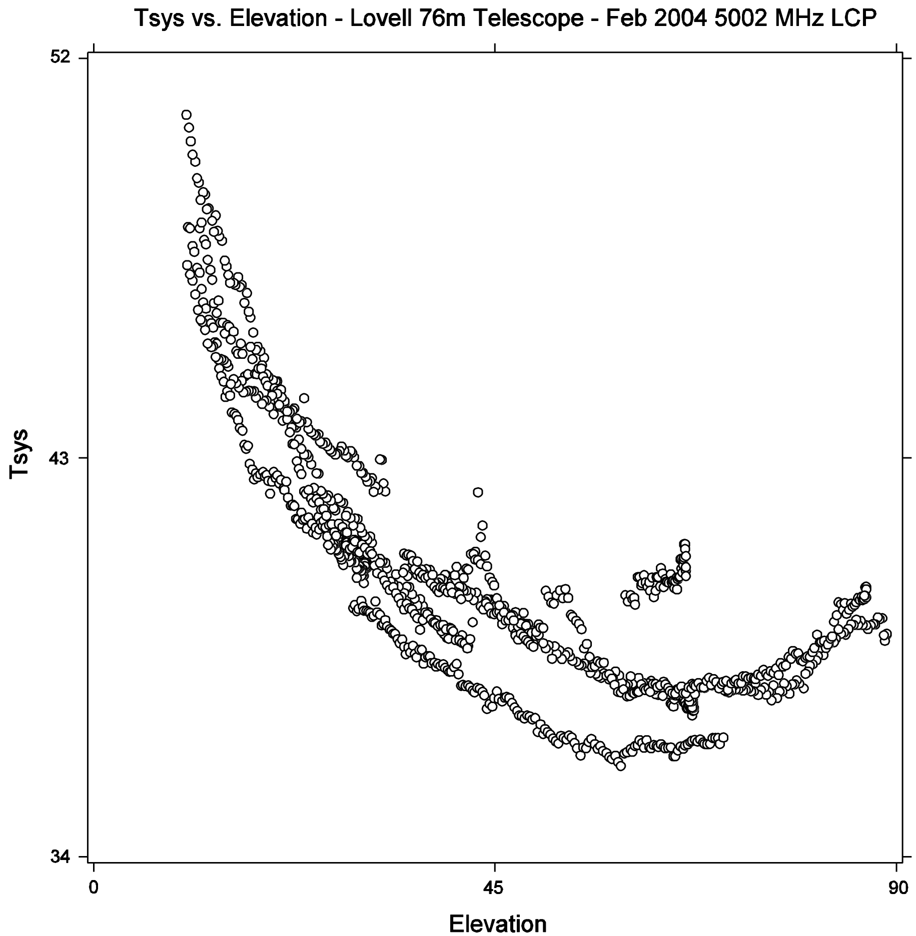
Old/big antenna



VLBA antenna (25m)



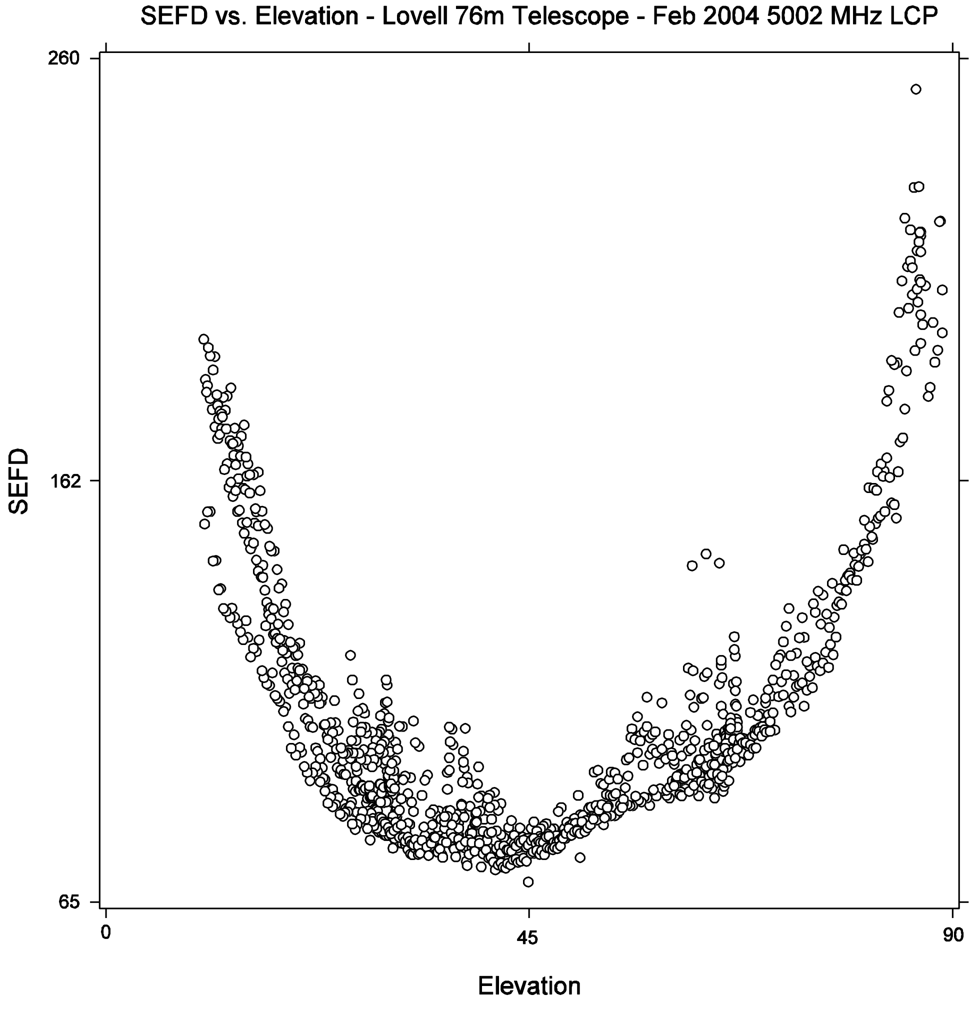
Reminder of T_{sys}(elevation)



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

SEFD example for Lovell

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



Summary (of "theory")

- 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:

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

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

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

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

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

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

  - *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

```
2019.060.12:16:01.79#tpicd#tpi/1l,16204,1u,15889,2l,15761,2u,16031,3l,15888,3u,15712,4l,15905,4u,16174
2019.060.12:16:01.79#tpicd#tpi/9l,16008,9u,16055,al,15897,au,15610,bl,16043,bu,16289,cl,15778,cu,15727
2019.060.12:16:16.81#tpicd#tpi/1l,16205,1u,15878,2l,15765,2u,16030,3l,15884,3u,15688,4l,15901,4u,16166
2019.060.12:16:16.81#tpicd#tpi/9l,16012,9u,16050,al,15897,au,15608,bl,16029,bu,16259,cl,15759,cu,15707
```

- 2: tpicd monitors both tpi and tpi’ continuously

```
2019.060.12:01:20.35#tpicd#tpcont/1l,7351,6724,1u,7283,6672,2l,7340,6736,2u,7377,6776,3l,7242,6642
2019.060.12:01:20.35#tpicd#tpcont/3u,7301,6711,4l,7258,6682,4u,7275,6698,ia,1437.72
2019.060.12:01:20.35#tpicd#tpcont/9l,8677,8002,9u,8630,7959,al,8597,7936,au,8504,7859,bl,8618,7950
2019.060.12:01:20.35#tpicd#tpcont/bu,8587,7919,cl,8531,7883,cu,8562,7929,ic,1634.08
2019.060.12:01:30.36#tpicd#tpcont/1l,7344,6730,1u,7285,6676,2l,7345,6737,2u,7368,6765,3l,7230,6634
2019.060.12:01:30.36#tpicd#tpcont/3u,7296,6709,4l,7265,6678,4u,7275,6699,ia,1428.26
2019.060.12:01:30.36#tpicd#tpcont/9l,8668,8005,9u,8622,7962,al,8601,7940,au,8504,7866,bl,8621,7951
2019.060.12:01:30.36#tpicd#tpcont/bu,8591,7922,cl,8528,7881,cu,8577,7930,ic,1654.27
2019.060.12:01:30.36#tpicd#tsys/1l,43.2,1u,42.8,2l,43.3,2u,44.4,3l,43.8,3u,43.2,4l,44.5,4u,44.1
2019.060.12:01:30.36#tpicd#tsys/9l,48.4,9u,48.0,al,48.3,au,49.8,bl,48.7,bu,48.0,cl,49.3,cu,49.2
```

  - 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)

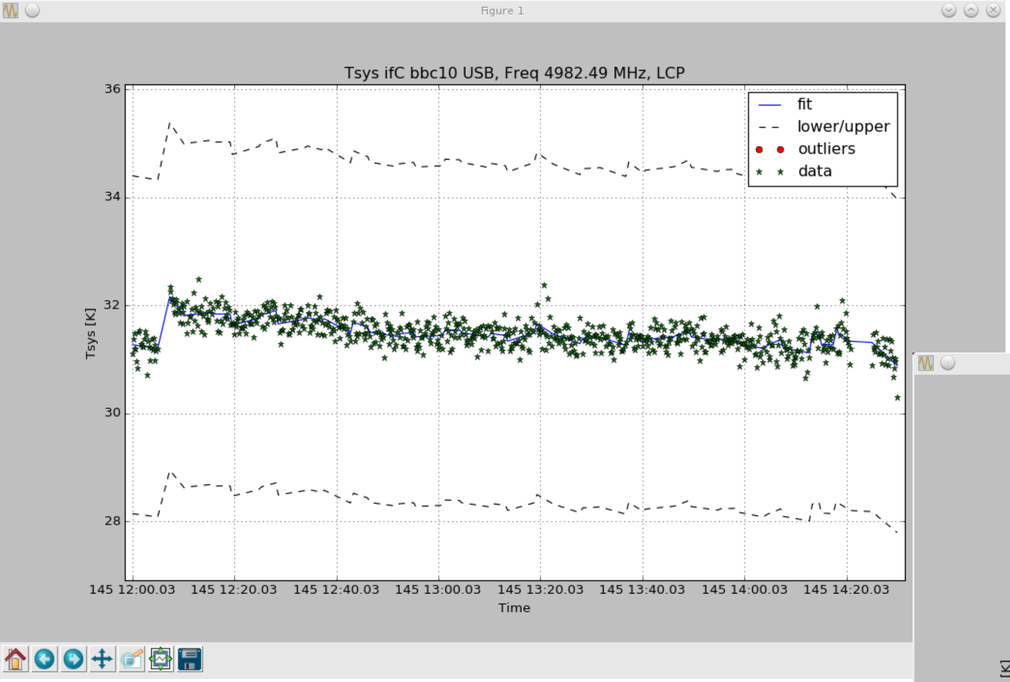
```
! Amplitude calibration data for EF in rg005b.
! For use with AIPS task ANTAB.
! Waveband(s) = c.
! RXG files used for each LO:
!       LO= 4840.00 MHz lcp: calefC.rxg 2010 10 27
!       LO= 4840.00 MHz rcp: calefC.rxg 2010 10 27
! Produced on 2011-04-27 using antabfs.pl version:  file:///export/jive/reynolds
/svnroot/repos/antabfs/tags/ANTABFS-4-2/antabfs/antabfs.pl   305   2008-01-30 17
:42:39 +0100  .
GAIN EF  ELEV DPFU=1.55,1.55       FREQ=4290,5390
POLY=1.0434E+00,-1.9066E-03,2.7559E-05,-2.1536E-07
/
TSYS EF FT=1.0 TIMEOFF=0
INDEX= 'L1:2', 'R1:2', 'L3:4', 'R3:4', 'L5:6', 'R5:6', 'L7:8', 'R7:8'
/
!Column 1 = L1: bbc01, 4956.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.7 K
!Column 1 = L2: bbc01, 4956.49 MHz, BW=16.000 MHz, USB, Tcal= 1.7 K
!Column 2 = R1: bbc02, 4956.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.7 K
!Column 2 = R2: bbc02, 4956.49 MHz, BW=16.000 MHz, USB, Tcal= 1.7 K
!Column 3 = L3: bbc03, 4988.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.7 K
!Column 3 = L4: bbc03, 4988.49 MHz, BW=16.000 MHz, USB, Tcal= 1.7 K
!Column 4 = R3: bbc04, 4988.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.7 K
!Column 4 = R4: bbc04, 4988.49 MHz, BW=16.000 MHz, USB, Tcal= 1.7 K
!Column 5 = L5: bbc05, 5020.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.7 K
!Column 5 = L6: bbc05, 5020.49 MHz, BW=16.000 MHz, USB, Tcal= 1.7 K
!Column 6 = R5: bbc06, 5020.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.7 K
!Column 6 = R6: bbc06, 5020.49 MHz, BW=16.000 MHz, USB, Tcal= 1.7 K
!Column 7 = L7: bbc07, 5052.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.8 K
!Column 7 = L8: bbc07, 5052.49 MHz, BW=16.000 MHz, USB, Tcal= 1.8 K
!Column 8 = R7: bbc08, 5052.49 MHz, BW=16.000 MHz, LSB, Tcal= 1.8 K
!Column 8 = R8: bbc08, 5052.49 MHz, BW=16.000 MHz, USB, Tcal= 1.8 K
! 165 10:49.20, scan=0001, source=0039+230
165 11:13.00  34.4  34.8  33.9  34.3  35.3  35.7  35.0  34.9
!165 11:13.06  -2.0  -2.0  -2.0  -2.0  -2.0  -2.0  -2.0  -2.0 ! Tsys from log
165 11:13.06  34.3  34.8  33.8  34.3  35.3  35.7  34.9  34.8
165 11:13.40  34.4  34.8  33.9  34.4  35.3  35.7  35.0  34.9
165 11:13.48  34.4  34.8  33.9  34.4  35.3  35.7  35.0  34.9
!165 11:13.56 7619.8 6084.6  -2.0  -2.0  -2.0  -2.0  -2.0  -2.0 ! Tsys from log
165 11:13.73  34.4  34.9  33.9  34.4  35.3  35.7  35.0  34.9
165 11:14.06  34.4  34.9  33.9  34.4  35.3  35.7  35.0  34.9
165 11:14.16  34.4  34.9  33.9  34.4  35.4  35.7  35.0  34.9
!165 11:14.25  -2.0  -2.0  -2.0  -2.0  -2.0  -2.0  -2.0  -2.0 ! Tsys from log
! 165 11:14.35, scan=0002, source=0039+230
165 11:14.83  34.4  34.9  33.9  34.4  35.4  35.8  35.0  34.9
!165 11:14.90  -2.0  -2.0  -2.0  -2.0  -2.0 17119.0  -2.0  -2.0 ! Tsys from log
165 11:15.00  33.9  34.2  33.3  33.7  34.7  35.1  34.3  34.2
165 11:15.33  34.5  34.9  34.0  34.4  35.4  35.8  35.0  35.0
165 11:15.66  34.5  34.9  34.0  34.5  35.4  35.8  35.1  35.0
165 11:16.00  34.5  35.0  34.0  34.5  35.4  35.8  35.1  35.0
```

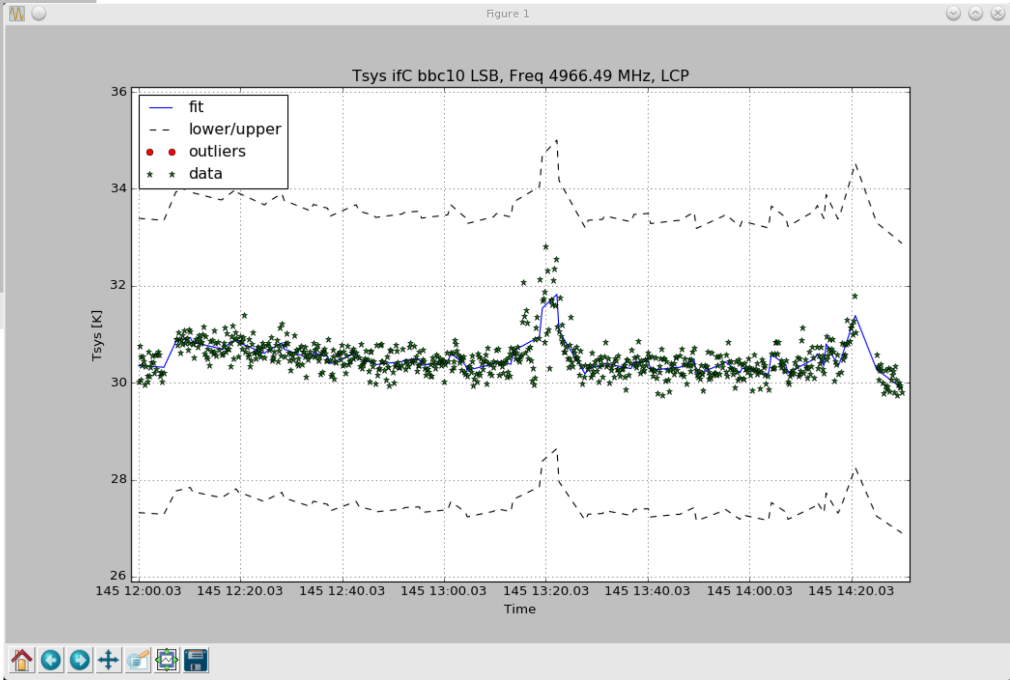
Running antabfs.py

- Syntax:
  - antabfs.py [-f rxg file] FS.logfile
  - 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

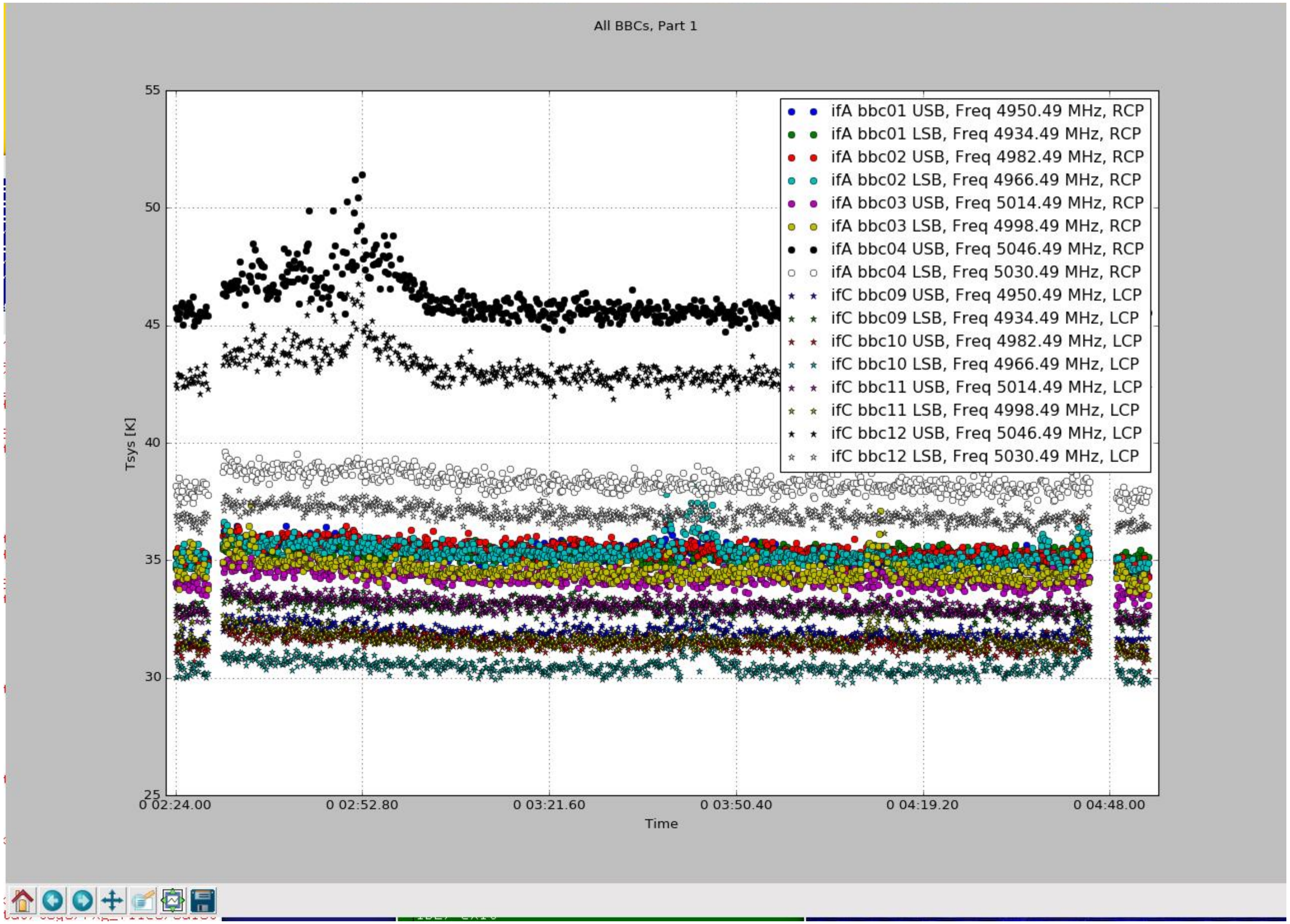
- On (continuous cal), 6cm, EVN session 2/2018





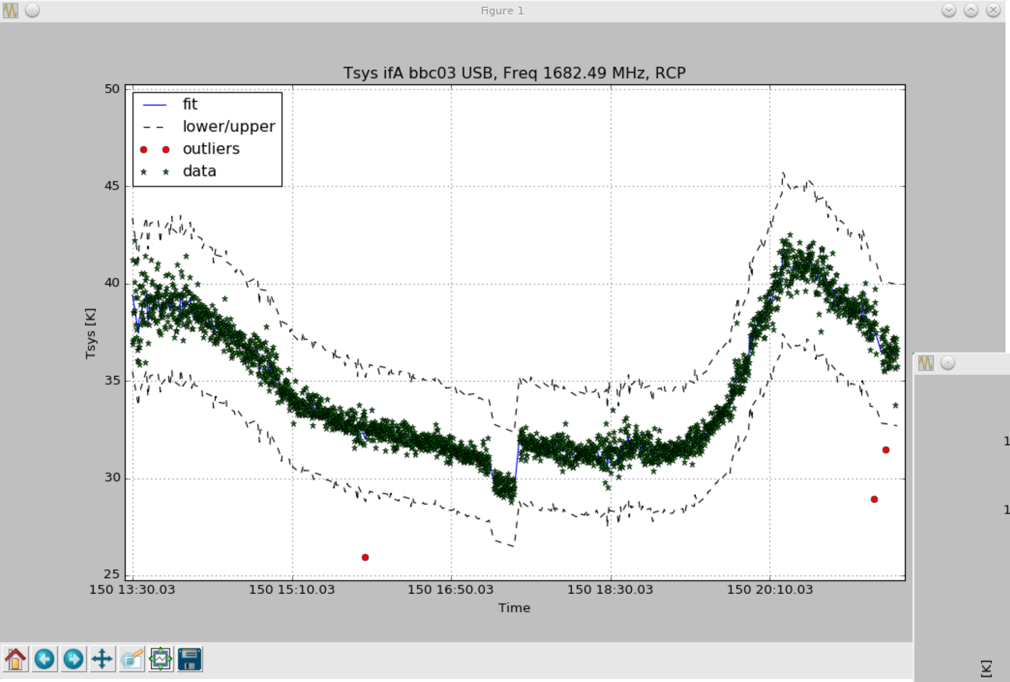
antabfs.py: final plot

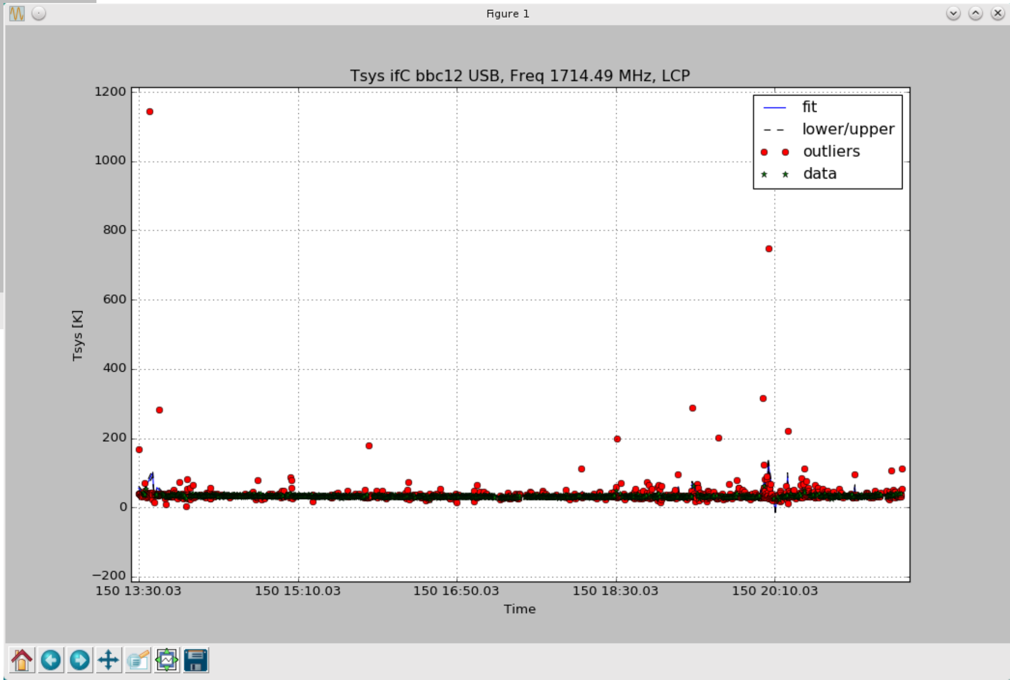
- On (continuous cal), 6cm, EVN session 2/2018



antabfs.py: case needing edits

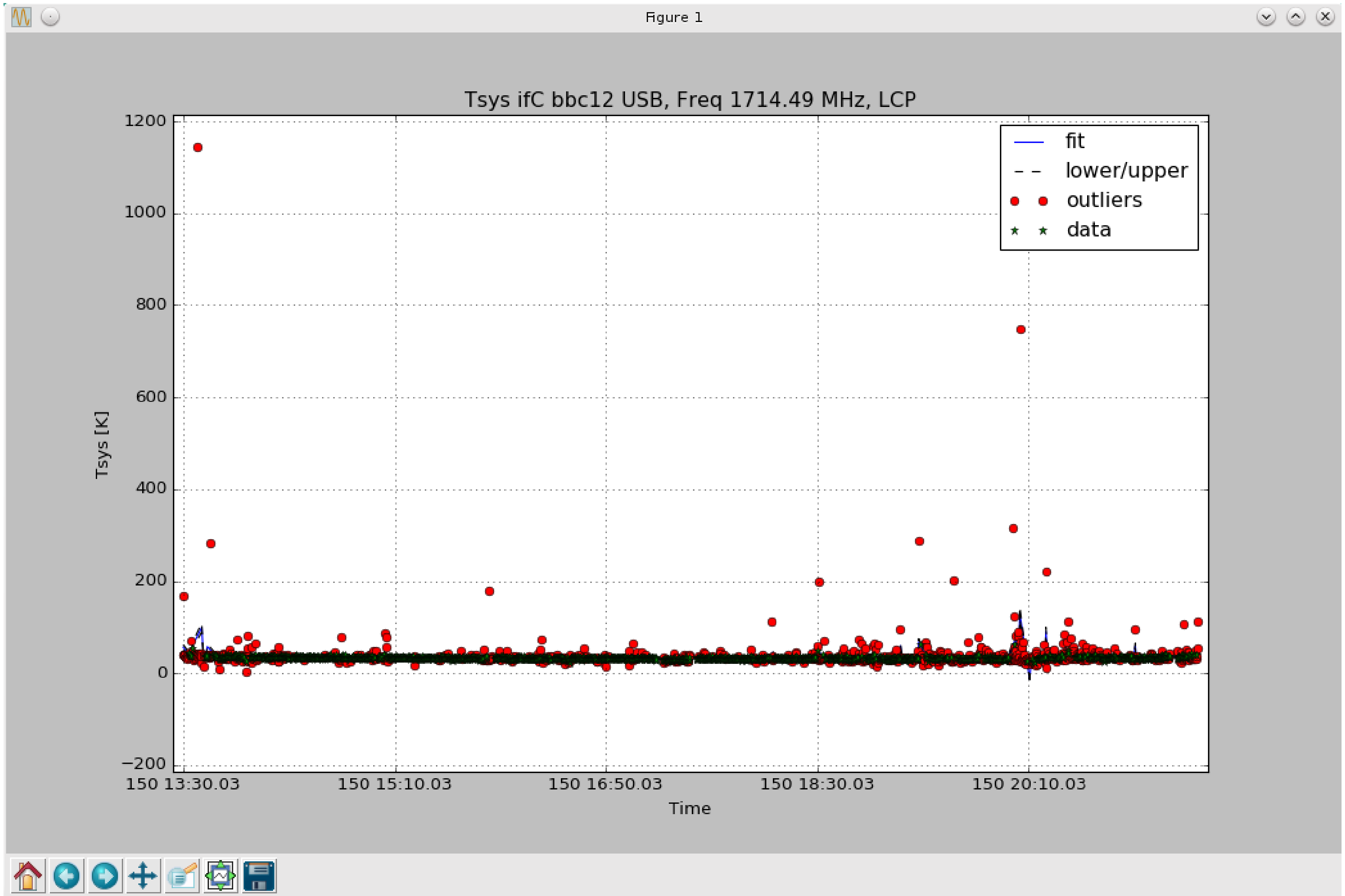
- On (continuous cal), 18cm, EVN session 2/2018





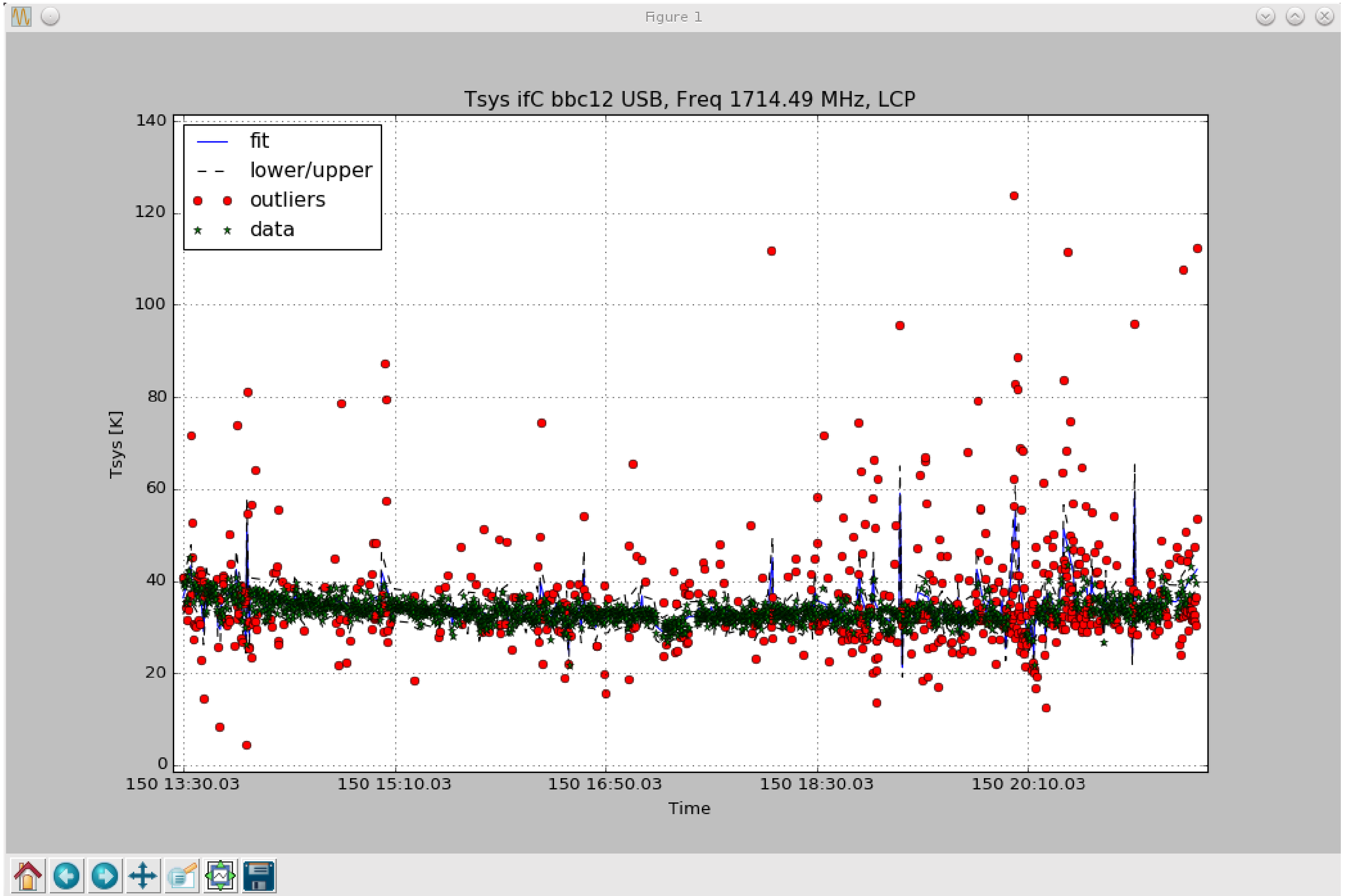
antabfs.py: edit iter.0

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



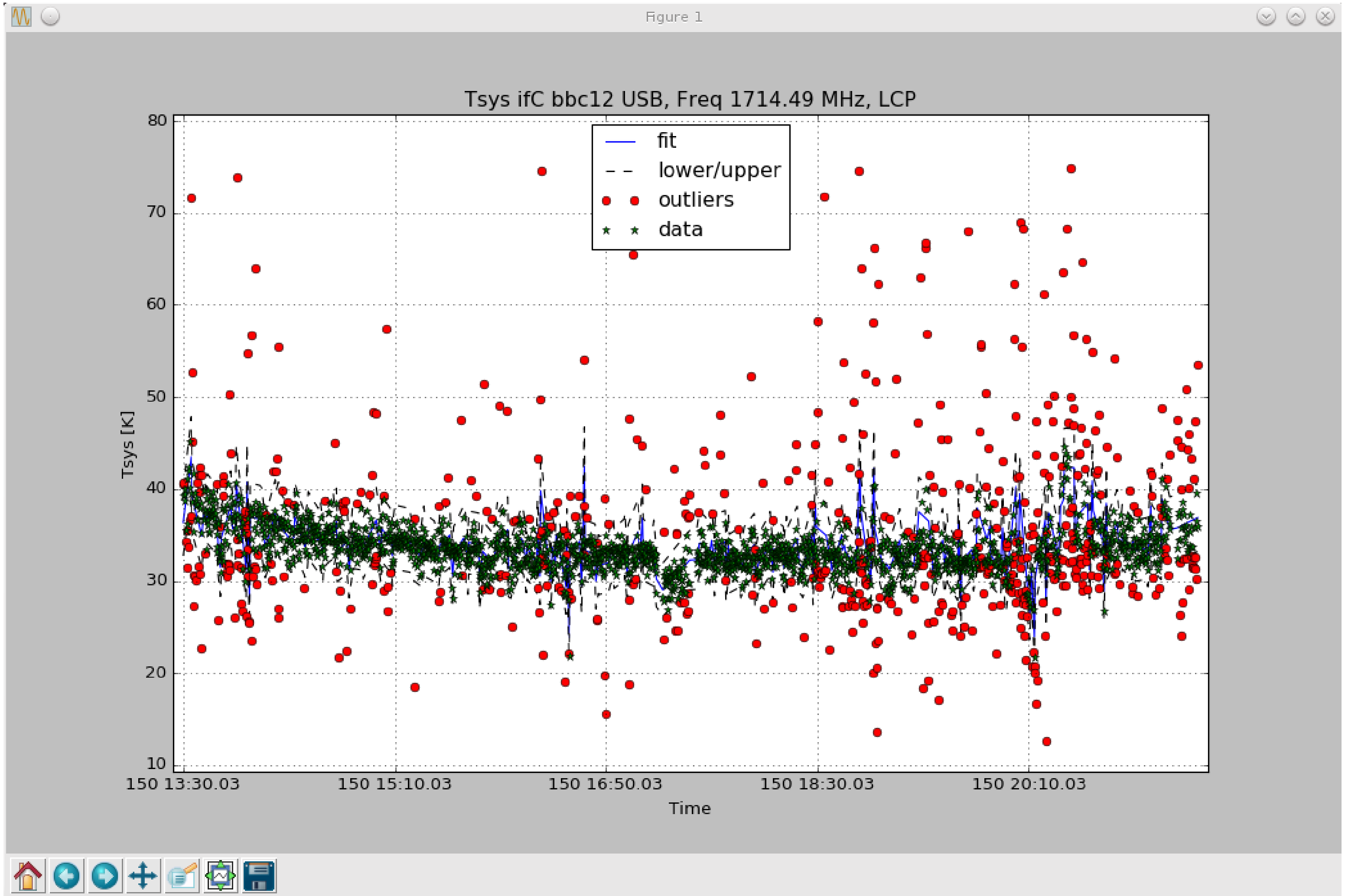
antabfs.py: edit iter.1

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



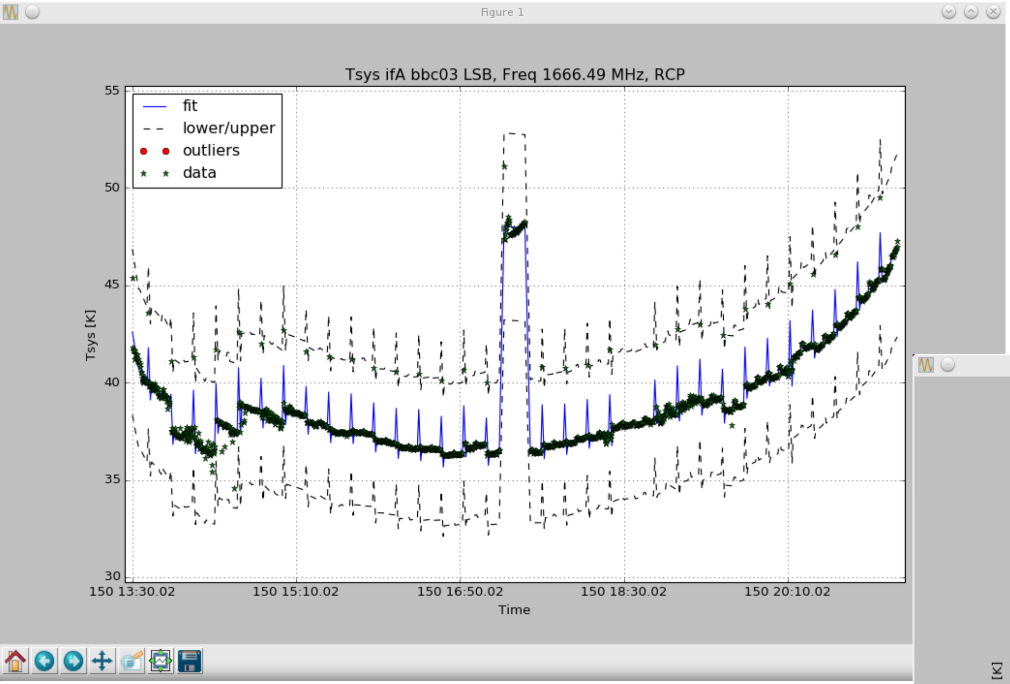
antabfs.py: edit iter.2

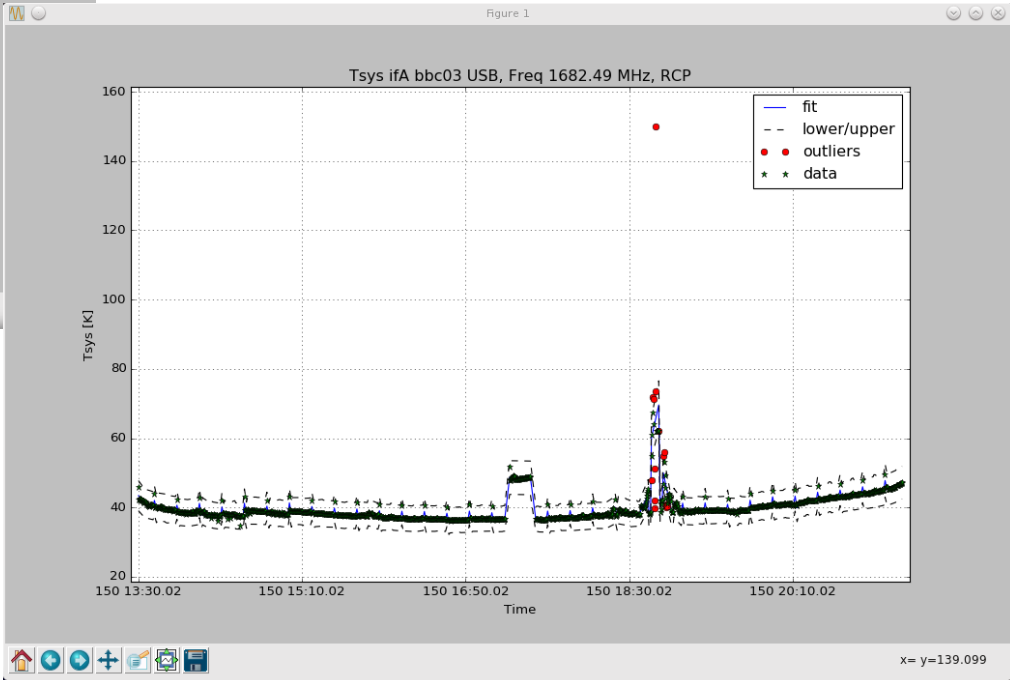
- On (continuous cal), 18cm, EVN session 2/2018



antabfs.py: not continuous cal.

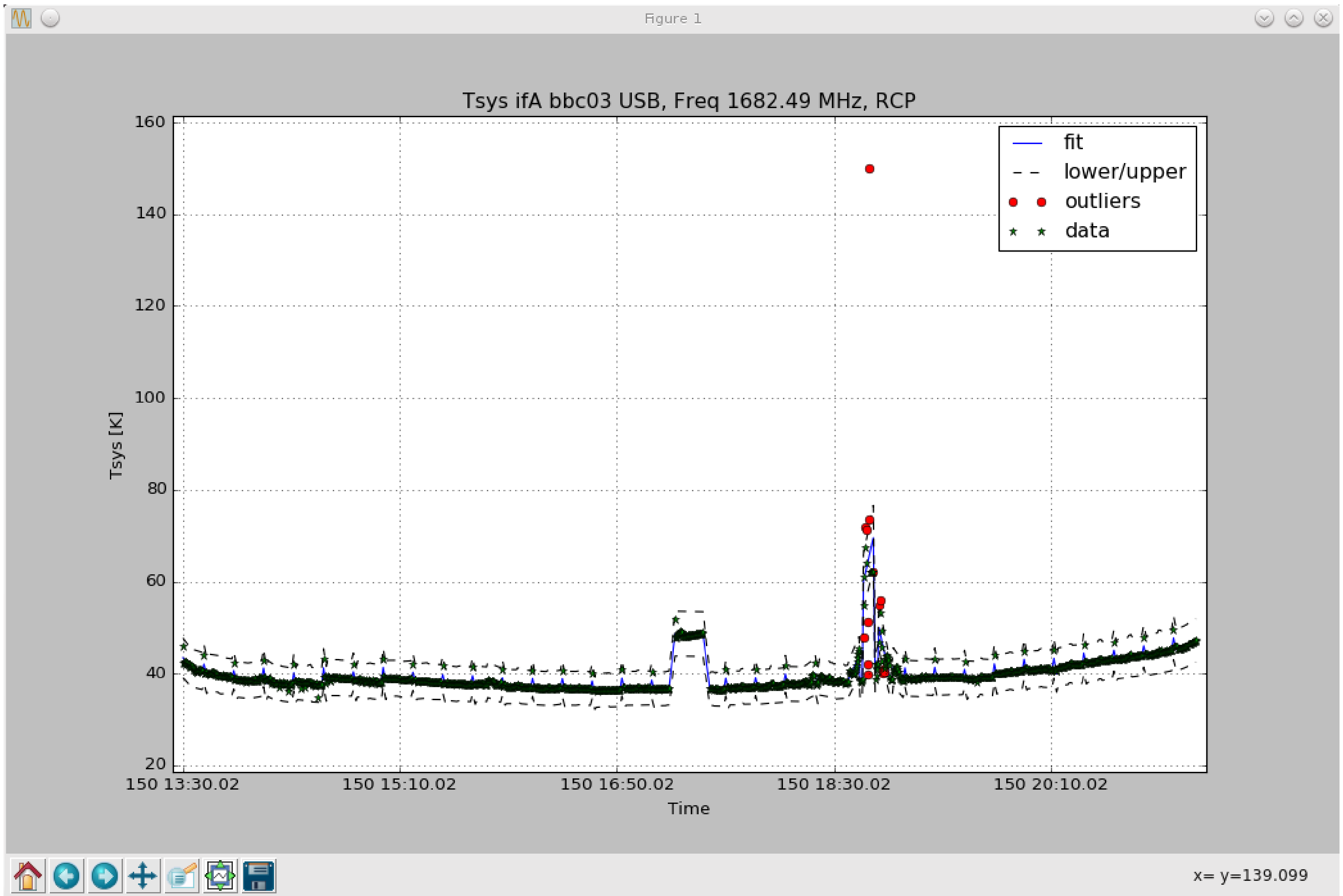
- Hh (gap-based cal-diode), 18cm, EVN session 2/2018





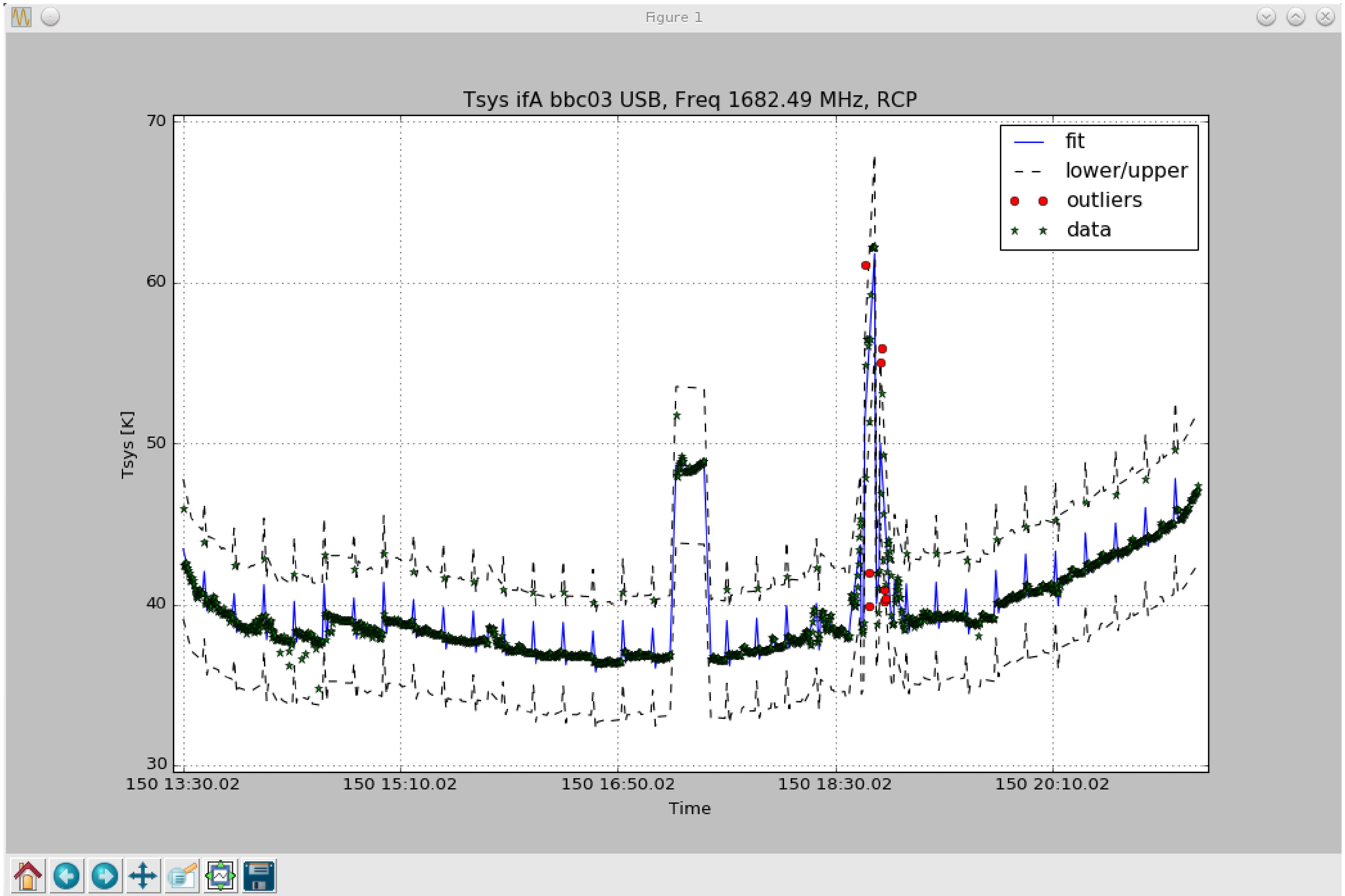
antabfs.py: edit iter.0

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



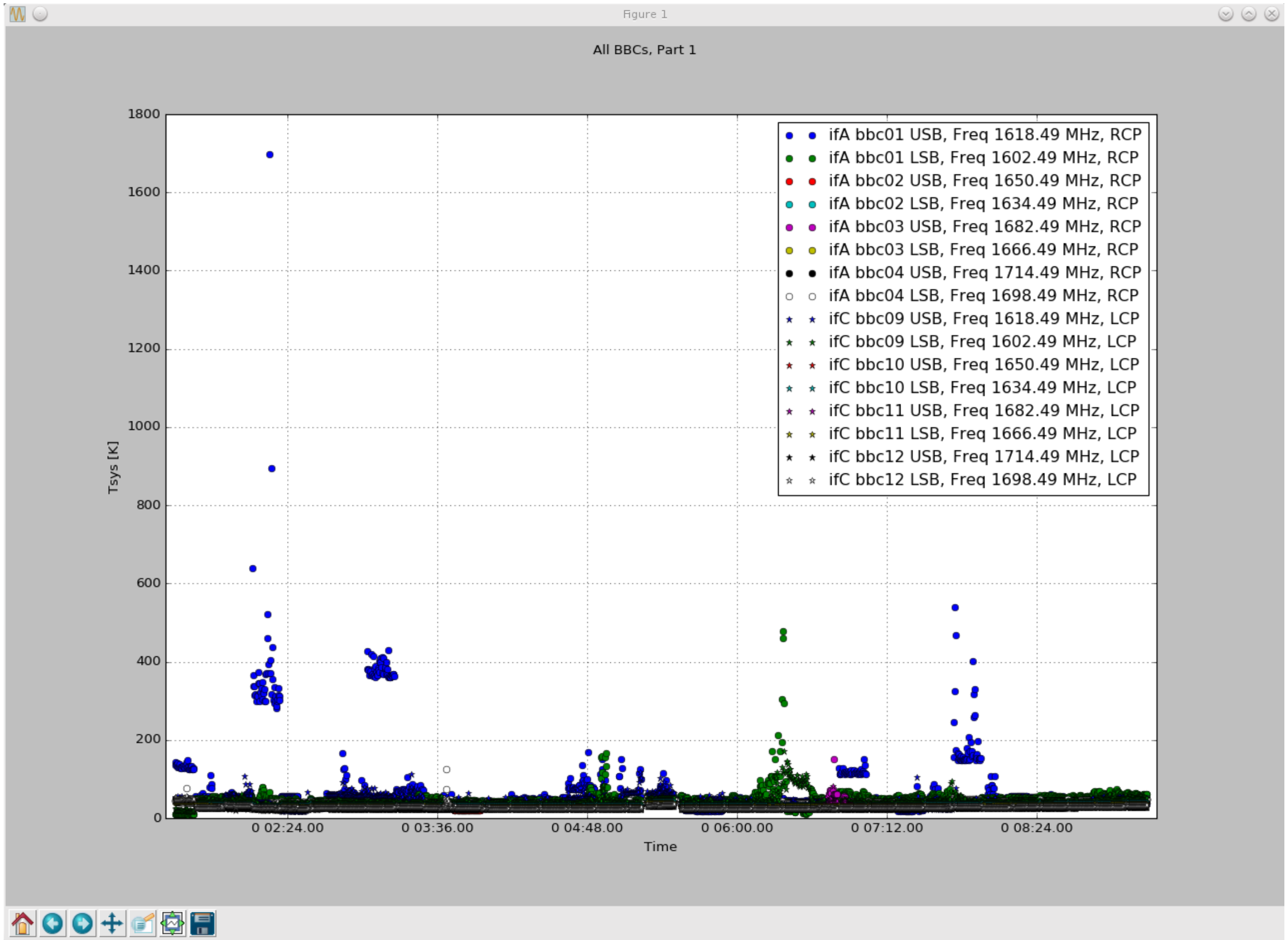
antabfs.py: edit iter.1

- 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

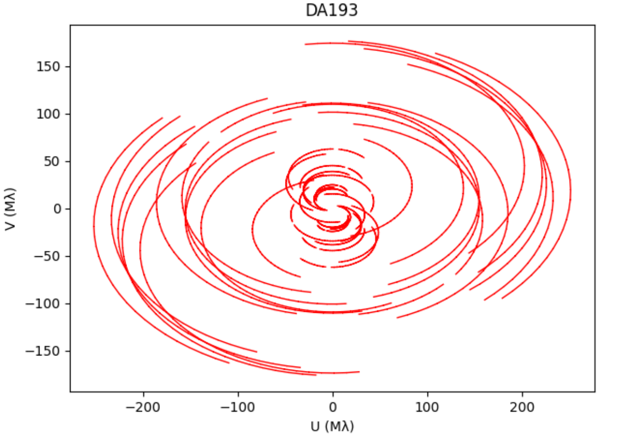


Summary (of "antabfs")

- 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
  - Javier González (jgonzalez@oan.es)
  - Fran Beltrán (franciso.beltran@oan.es)

Calibration affects imaging

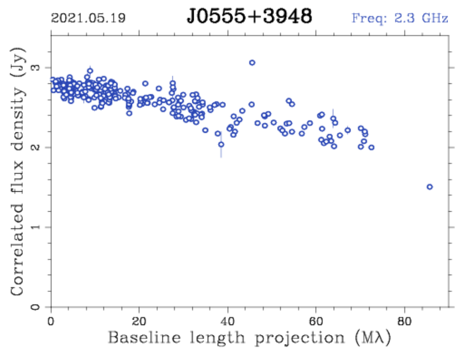
- Building up u-v coverage
  - Points = projections of baselines onto plane of sky
  - Earth rotation “draws” ellipses

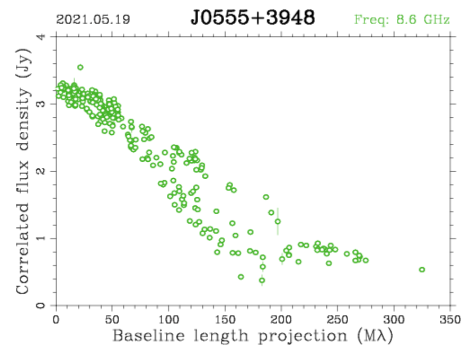


- Each point (“visibility”) has an amplitude and a phase
  - Source images = Fourier inversion of assembled points
  - u-v sampling can limit the kind of structure sensitive to
- u-v crossing
  - Different baselines at same u-v location should yield same ampl.

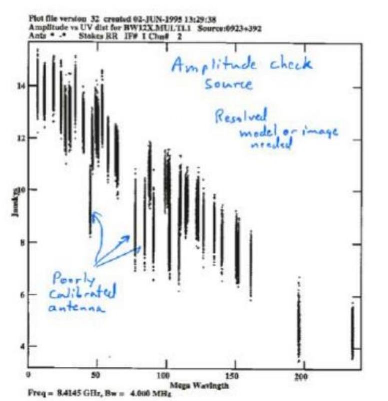
Amp(|uv|) plots

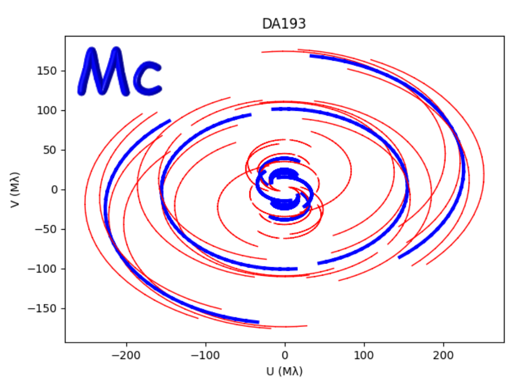
- Visibility amplitudes plotted against "u-v distance"

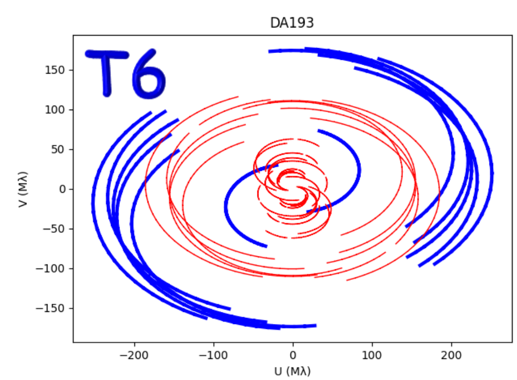




- Fall-off with |uv| → insights into source strucutre
  - Large |uv| "resolves out" less compact structure
- Signs of a station with remaining calibration issue:







Closures

- Station-based gains vs. baseline-based visibilities
  - Both things complex → Amps & Phases
- Observed bsln-based combinations that are invariant to station-based effects
  - Closure phase (non-0 → source structure):

    $$\varphi_{AB} + \varphi_{BC} + \varphi_{CA}$$

  - Closure amplitude (non-1 → source structure):

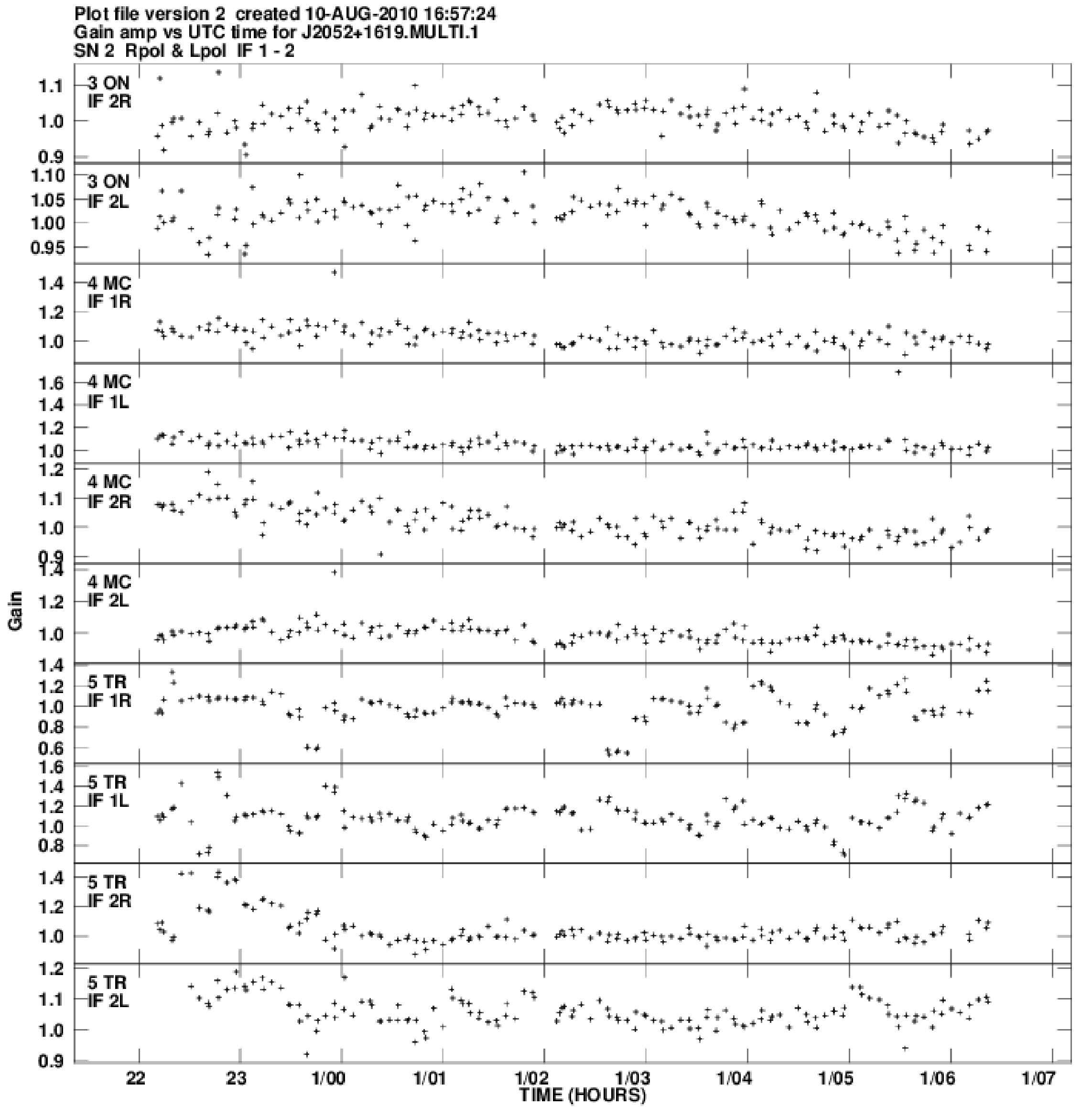
    $$(A_{AB} * A_{CD}) \ / \ (A_{AC} * A_{BD})$$

- But closures aren't a panacea
  - Fewer such constraints
  - More affected by missing data / non-detections

EVN Archive Calib. Feedback

- JIVE-correlated experiments get "pipelined"
  - Includes self-calibration on bright-enough sources
    - "Amplitude corrections applied to apriori calibration" within "Pipeline plots"
- pdf plot: amplitude correction factors (ACFs) by station, sideband, polarization (1 = no correction needed)
- Statistical summary: median ACF & related stats per sta/SB/pol
- Text file: sta/SB/pol ACF, time-resolution ~ 1 scan

EVN pipeline: Amp. Corr. Plot



EVN pipeline: Amp. Corr. Text

```
File = J2052+1619   .MULTI .    1 Vol = 1  Userid = 2194    IF =  2
FQID IF#       Freq(GHz)        BW(kHz)    Ch.Sep(kHz)  Sideband
   1   1        1.60444000      8000.0005      15.6250       1
       2        1.65671000      8000.0005      15.6250       1

station=2(EF)
IF  median  med.err  stderr  med.err-(med-1)  ndata
L1  0.9927  0.0180  0.00280  0.0107            148
L2  0.9890  0.0135  0.00164  0.0025            149
R1  0.9899  0.0150  0.00417  0.0049            147
R2  0.9954  0.0100  0.00151  0.0054            149
All:  0.9913  0.01425  0.00145  0.0056         4

station=3(ON)
IF  median  med.err  stderr  med.err-(med-1)  ndata
L1  0.9972  0.0233  0.00546  0.0205            146
L2  1.0163  0.0253  0.00279  0.0090            147
R1  1.0107  0.0258  0.00401  0.0151            146
R2  1.0087  0.0241  0.00303  0.0154            147
All:  1.0097  0.02470  0.00401  0.0150         4

station=4(MC)
IF  median  med.err  stderr  med.err-(med-1)  ndata
L1  1.0400  0.0400  0.00580  -0.0000            147
L2  0.9852  0.0391  0.00488  0.0243            149
R1  1.0279  0.0409  0.00539  0.0130            147
R2  1.0079  0.0330  0.00414  0.0251            149
All:  1.0179  0.03955  0.01201  0.0216         4

station=7(UR)
IF  median  med.err  stderr  med.err-(med-1)  ndata
L1  1.0441  0.0577  0.00650  0.0136            115
L2  1.0874  0.0874  0.00501  0.0000            115
R1  1.1800  0.1827  0.01977  0.0027            110
R2  0.6861  0.3139  0.00320  0.0000            115
All:  1.0657  0.13505  0.10821  0.0693         4
```

```
File = J2052+1619   .MULTI .    1 Vol = 1  Userid = 2194    IF =  1
Freq=  1.608432188 GHz    Ncor=  2    No. vis=     35648
Polarization = R    Subarray =    0
Listing SN table, version   2
SN table has already been applied to a CL table

Gain amplitudes, 1000 =      0.100000
Stokes = R     IF =  1 Freq =  1.608432188 GHz

  Time    Source  -- 1---- 2---- 3---- 4---- 5---- 6---- 7---- 8--

Day #    0
22:10:51 J2052+16  9007 10001 10104 10741  9339 11356 11307 10546
22:12:17 J2052+16  9066  9963 11346 11296  9630 10421 11338 10476
22:13:41 J2052+16  9159  9871  9673 10627  9336 11539 11333 10619
22:14:45 J2052+16  8985  9965  9357 10275 10616 11548 11061 10609
22:19:41 J2052+16  8951 10071 10161 10870 13321 11174 11497 10203
22:20:25 J2052+16  9016  9967 10215 10611 12334 10731 10752 10009
22:25:05 J2052+16        9905 10400 10306 10532 10183 11466 10510
22:30:43 J2052+16  9042  9872  9919 10255 10725 11651 10527 10367
22:35:45 J2052+16       11532  9994 10885 10950 11435 11398 10015
22:40:49 J2052+16  8879  9841  9932 10729 10930 10760 10658 10169
22:41:33 J2052+16  9092  9961 10060 11146 10515 10356 10621  9118
22:46:21 J2052+16        9512 10088 10614 10668 12515 11493  8888
22:46:59 J2052+16        9192 11347 11548 10831 12591 10995 10403
22:52:03 J2052+16  9038 10012  9516 11059 10781 11064 11077 10271
22:56:49 J2052+16        9733 10266 10740 10658 11635 11253 10492
22:57:27 J2052+16        9787  9494 10955 10654 10762 11203 10500
23:02:31 J2052+16  8932  9978  9803 10749 10641 11009 11630 10165
23:03:15 J2052+16  8807 10188  9272  9831 10861 10133 11357 10259
23:07:15 J2052+16        9559 10841  9437        9771 11972
23:07:53 J2052+16        9736 10221 10656 10812 12677 12248 10466
23:12:55 J2052+16  8968  9939  9656 11440 10459 11264 11212 10283
23:13:39 J2052+16  8936  9940 10048 10210 10204 11051 10576 10294
23:18:25 J2052+16        9712 10402 10969 11379 11259 11141 10554
23:24:03 J2052+16  9010  9945 10031 10338 11139 10978 10730 10298
```

EVN Amp. Cal. Feedback

- Created a centralized database structure (SQL)
  - Searchable by various quantities e.g., station, session, freq.band
  - Graphical interface: Grafana (provides dashboard for…)
  - Stations can create their own custom plots and tables
  - Historical series → possible to evaluate trends
    - Amplitude calibration back-loaded to 2006
- Similar tools for databasing station feedback
    - Feedback comments back-loaded to 2002
- Arose from the JUMPING JIVE project

Horizon 2020
#730884

Amp. Cal. Feedback: Grafana

old.evlbi.org/feedbackplots/