Pointing & Single-Dish Amplitude Calibration

Bob Campbell, JIVE

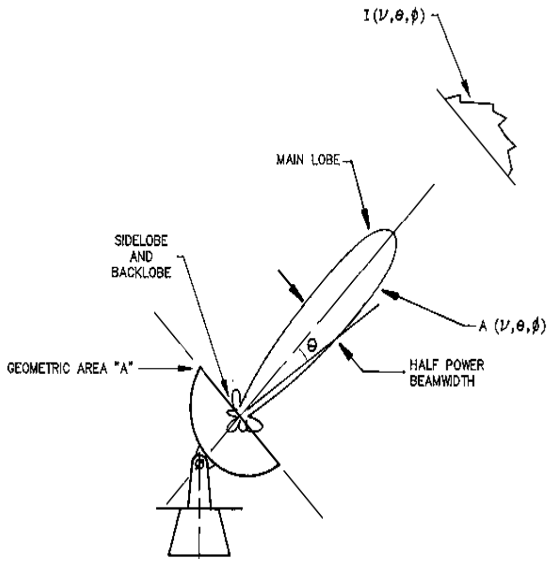
- Beams & Pointing
- Antenna Efficiency, Antenna Temperature
- SEFD as the key for calibration
- System Temperature & Gain
- rxg & antabfs files

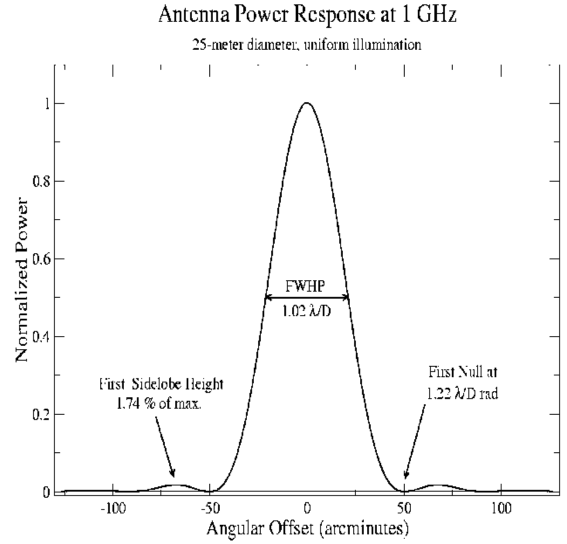
Why Calibrate?

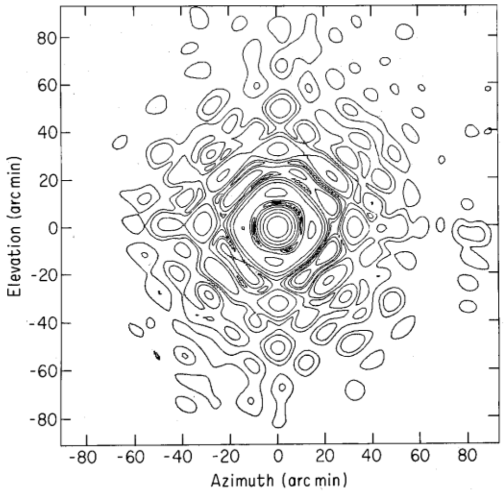
- Scientific quality:
  - geodesy — best SNR per scan to improve delay precision
  - astronomy — source brightness on absolute physical scale
  - Regular checks of calibration → help notice problems
- You can measure/calibrate:
  - the focus & pointing
  - the aperture efficiency (η_A)
  - the system temperature (T_{sys})
  - the gain curve
- Related maintenance workshops:
  - Antenna Gain Calibration (Lindqvist, Varenius) [Tue. 1315UT]
  - Automated Pointing Models Using the FS (Himwich) [previous TOWs]

Antenna Beam-width

- Directivity: power received (or transmitted) should form a small (solid) angle. Roughly: $\theta = \lambda / D$
- 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 Using the FS" workshop
- 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 depend on frequency band & 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.*

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

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

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:

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

$$\sim 3x10^{-4}\ n_A\ D^2$$

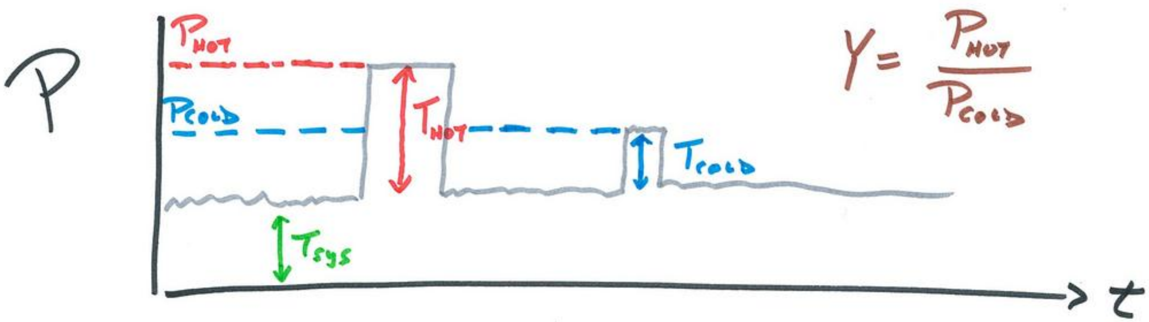
Importance of SEFD

- Invariably in radio astronomy, system noise dominates over power from the source in the beam.
  - Rough X-band SEFDs in [Jy] (see, e.g., EVN status table):
    Ef~20, Ys~200, Mc~320, Nt~840, On~1300, 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 (here, gain now represented by "g"):

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



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

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

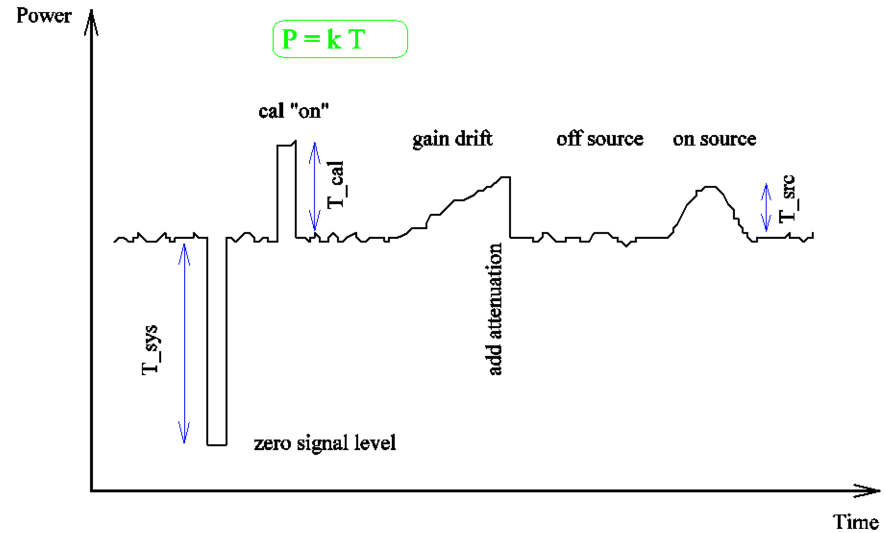
  - Assumptions: receiver remains in linear regime; g, T_{sys} constant

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:

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

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

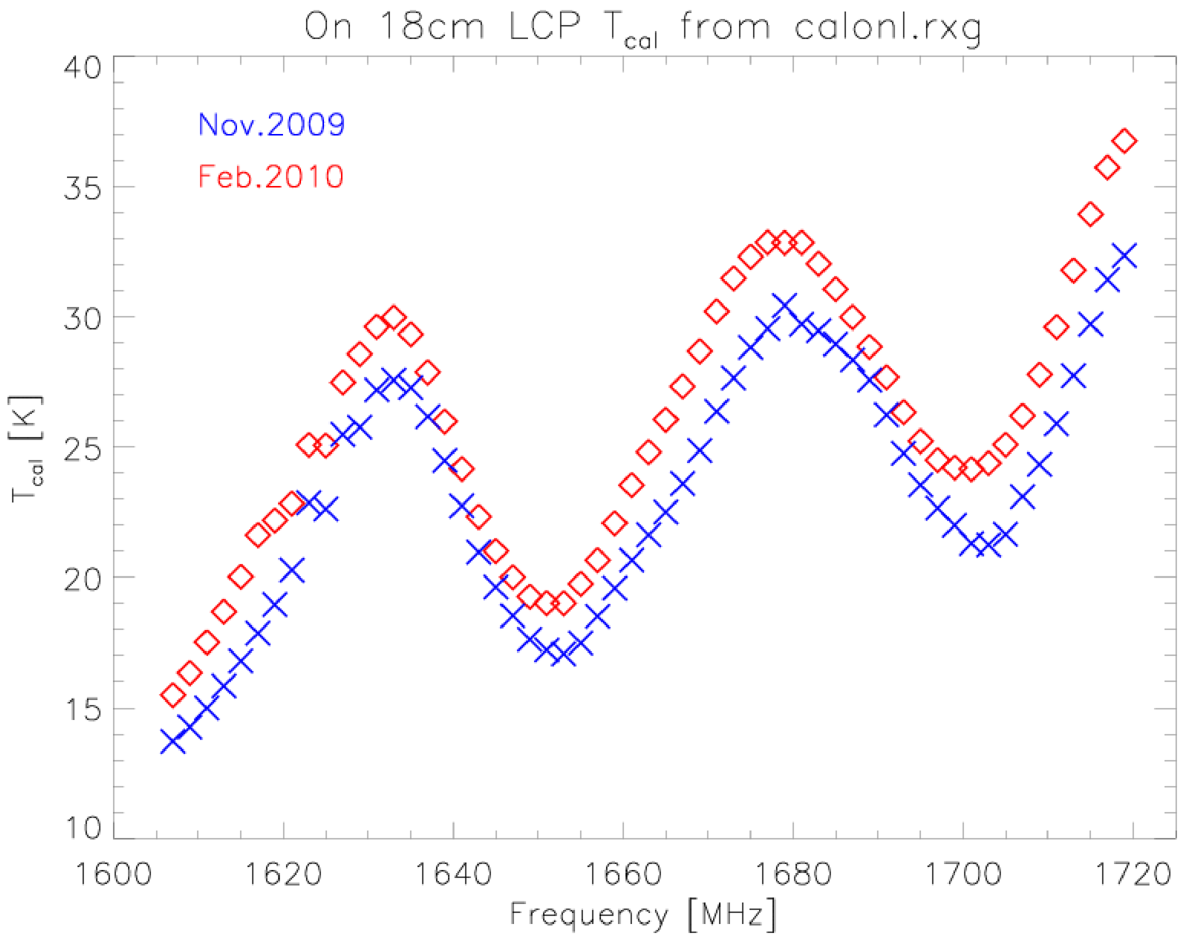
- Forming ratios & solving for T_{cal} gives:

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

- 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 18cm, Nov 2009 – Feb 2010



► "Amplitude Gain Calibration" (Lindqvist, Varenius)

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:

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

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

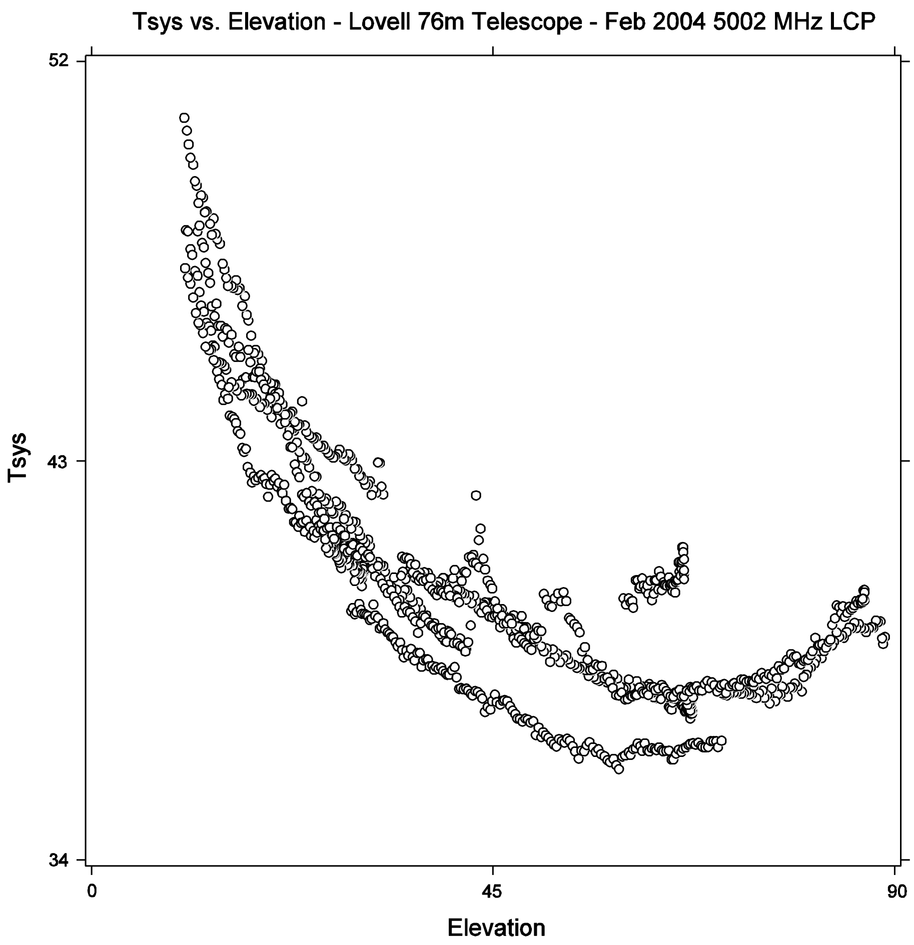
- Forming the ratio gives: T_{cal} / T_A, where T_A can further be written as $GAIN \cdot S$ (S = source flux density)

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

- FS program aquir to collect gain-calibration data

Plots leading to SEFD: T_{sys}

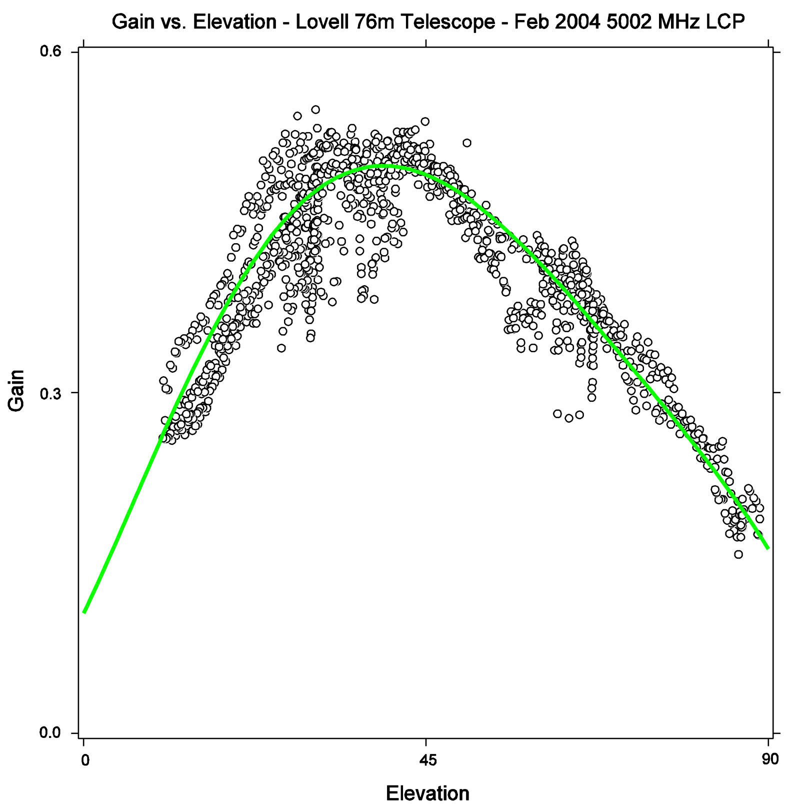
- T_{sys} vs. elevation:

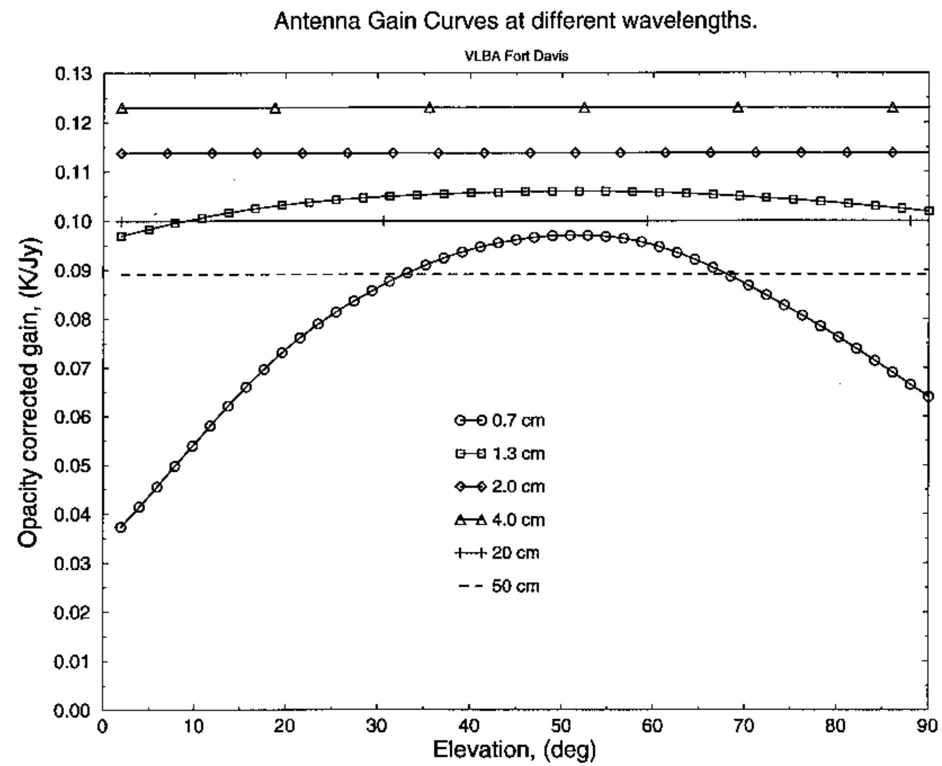


$$T_{\rm atm} = T_{\rm zenith} \left(1 - e^{-\tau / \sin(El)}\right)$$

Plots leading to SEFD: Gain

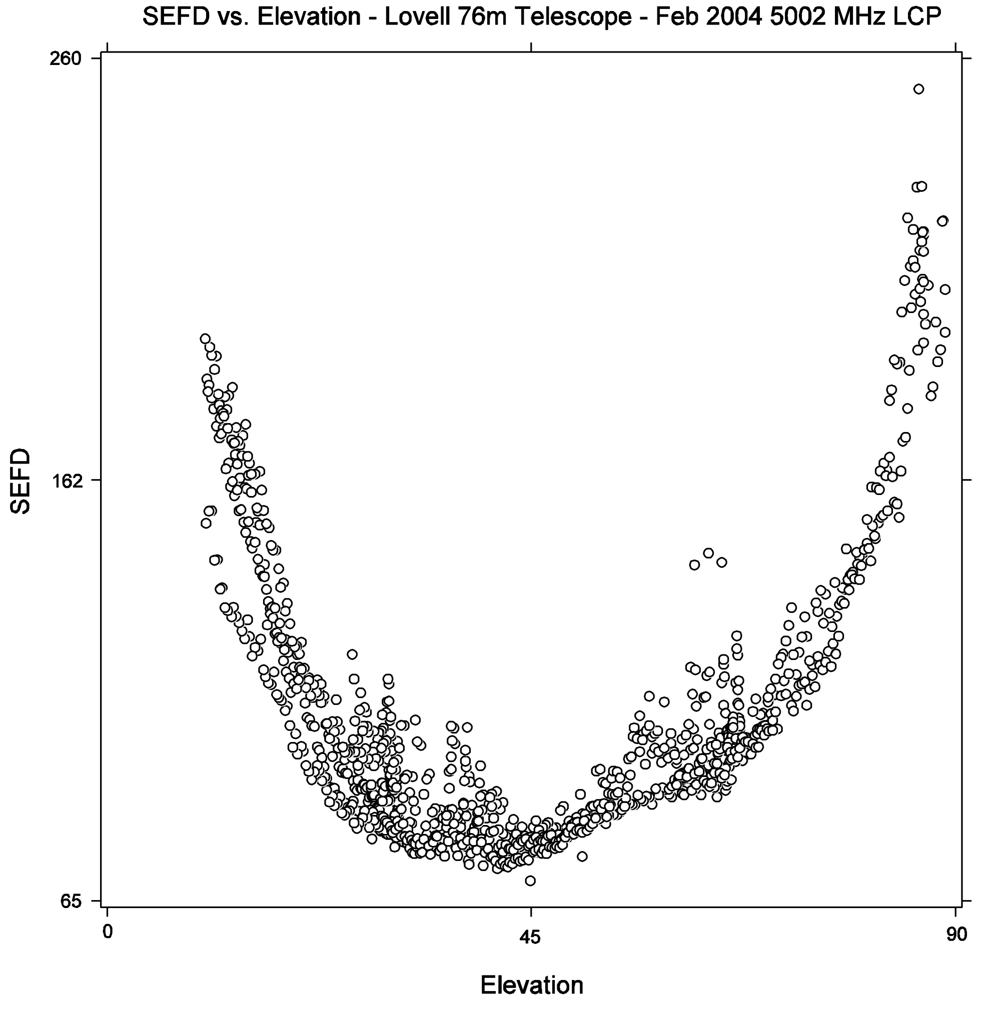
- Gain vs. elevation:





Plots leading to SEFD: SEFD itself

- 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} → T_{sys}
  - DPFU, gain curve → GAIN
  - SEFD = T_{sys} / GAIN
- Other workshops detail their determination:
  - Antenna Gain Calibration (Lindqvist, Varenius)
  - Automated Pointing Models Using the FS (Himwich)

    [in previous TOWs]
- 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-diode is off
  - tpical: measured when cal-diode is on
  - tpzero: zero levels
- Cal-diode "fires" only when not recording
  - tpi': a tpi value measured close in time to a cal-diode 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

- Power readings with the cal-diode 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:

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

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

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-diode 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 FS logs

Continuous Cal: Advantages

- Much less affected by time-variations in gain
- More straightforward scheduling (astronomy)
  - Cal-diode "firing" occurs in preob — last ~10s of gap
  - End of gap defined from the "global" scan start time
  - Cal-diode "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-diode "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 (*e.g.*, for use in AIPS, CASA)
- Originally in perl (C. Reynolds, J. Yang, J. Quick)
- Shifted 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)

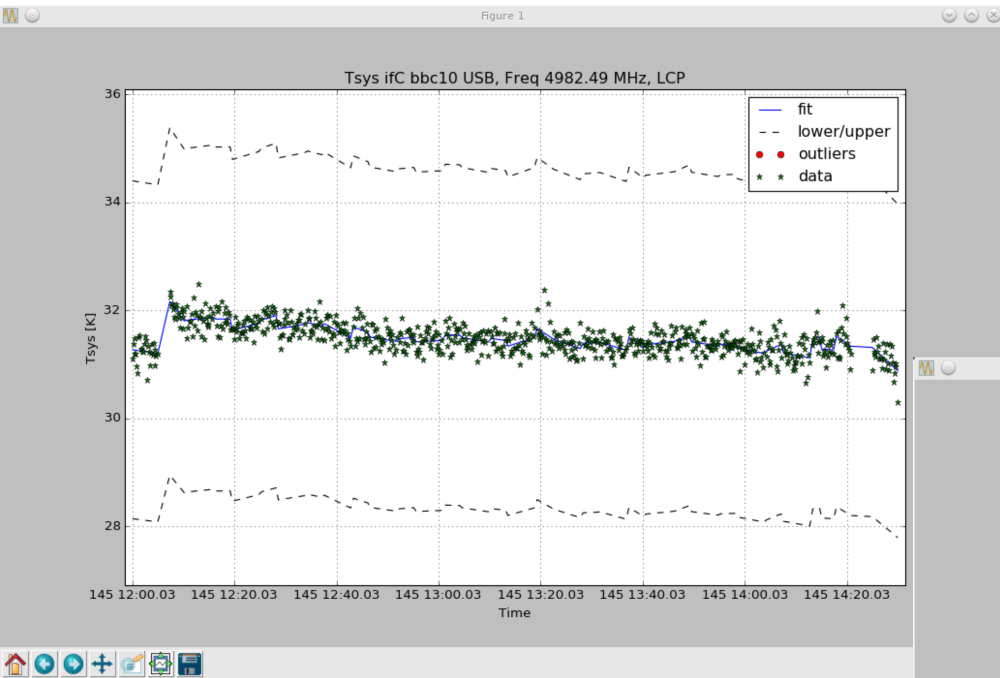
```
! Amplitude calibration data for EF in rg005b.
! For use with AIPS task ANTAB.
! Waveband(s) = c.
! RXG files used for each LO:
!      LO= 4840.00 MHz lcp: calefC.rxg 2010 10 27
!      LO= 4840.00 MHz rcp: calefC.rxg 2010 10 27
! Produced on 2011-04-27 using antabfs.pl version:  file:///export/jive/reynolds
/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
```

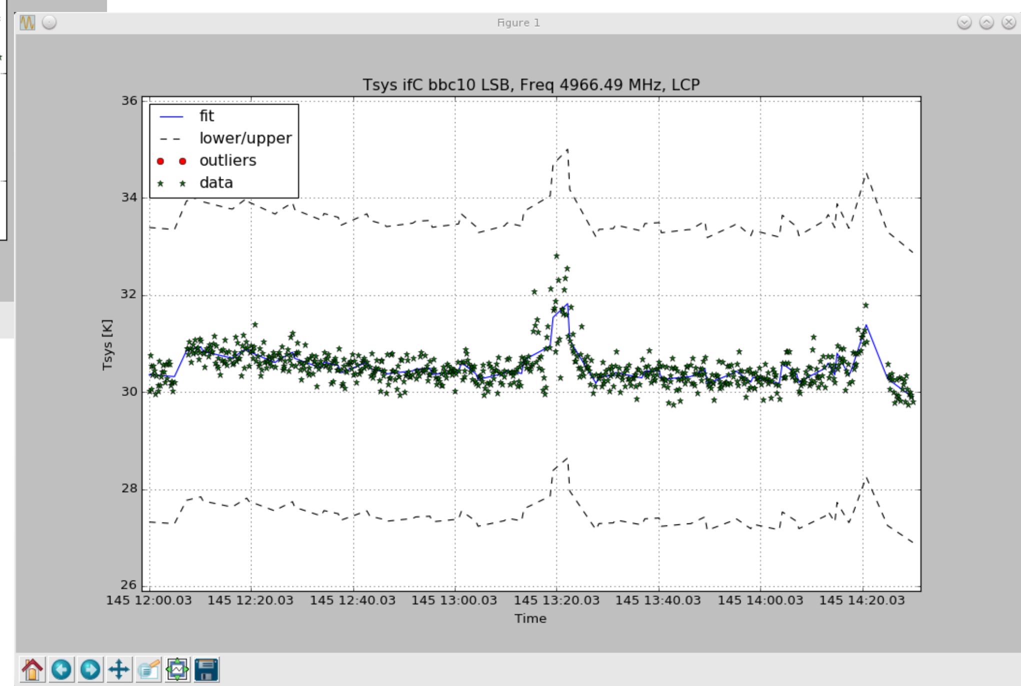
Running antabfs.py

- 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
- 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

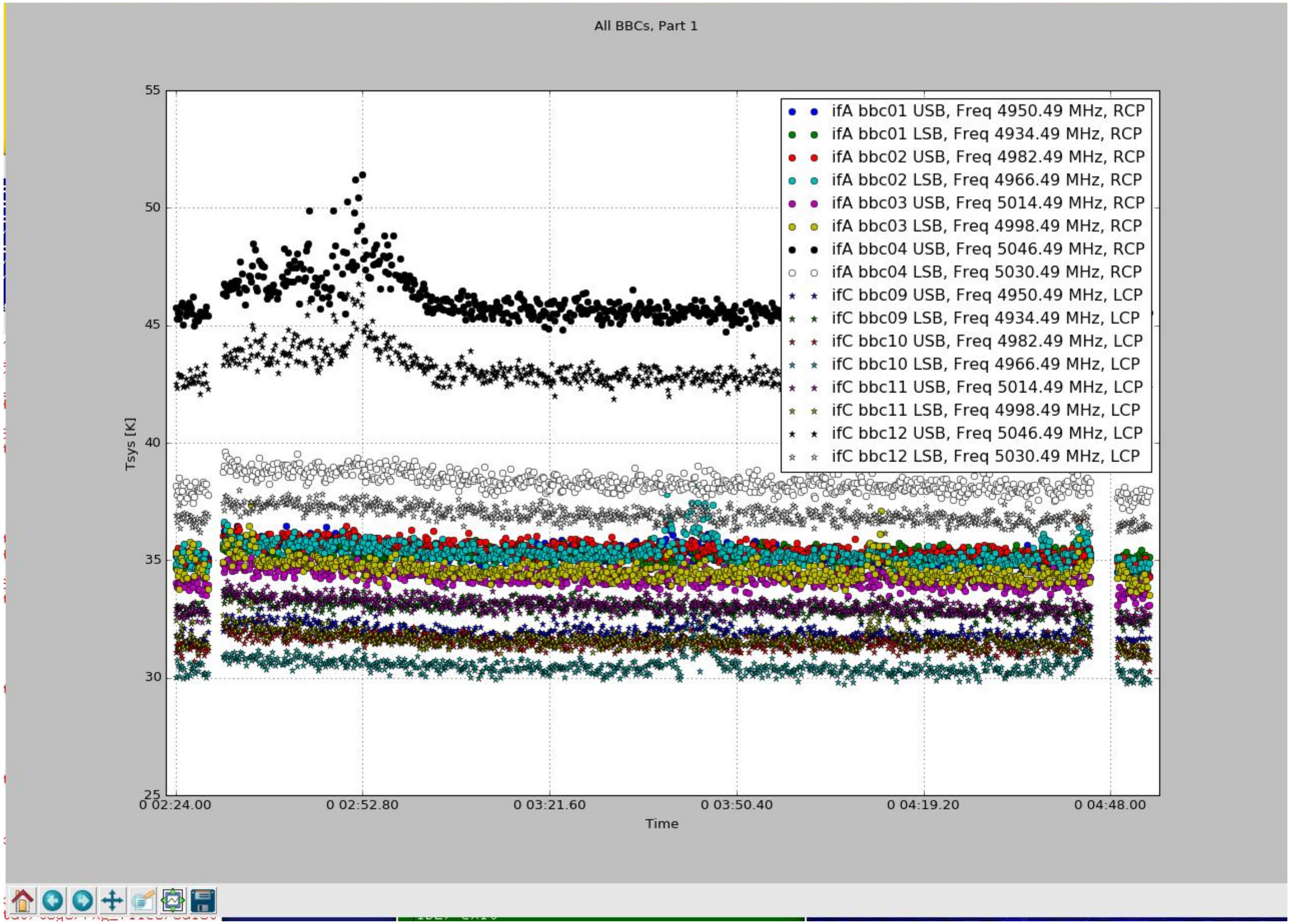
- On (continuous cal), 6cm, EVN session 2/2018





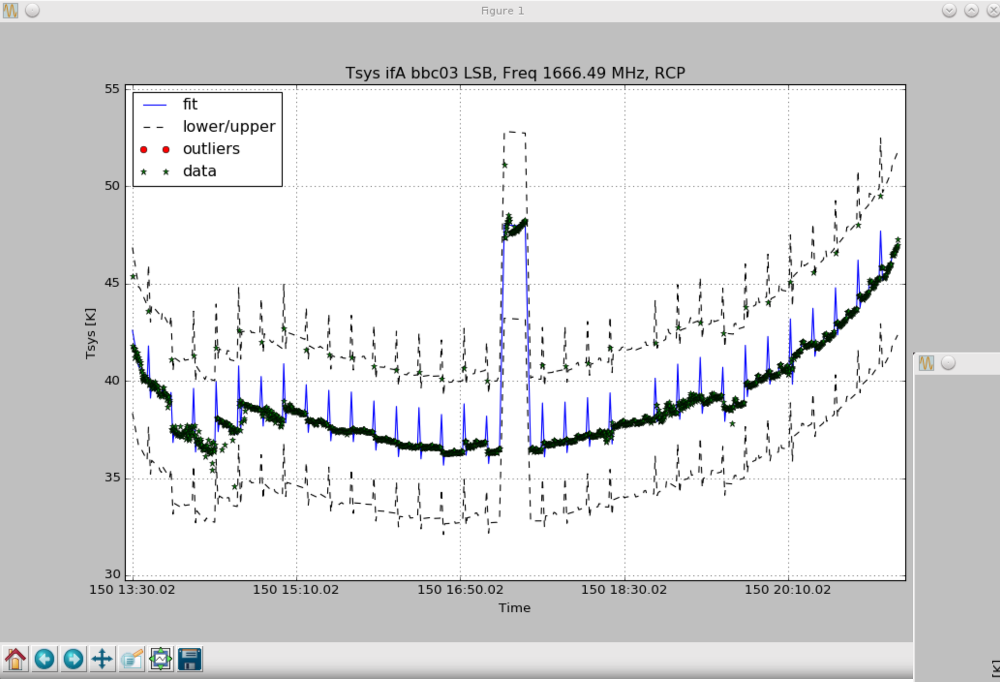
antabfs.py: final plot

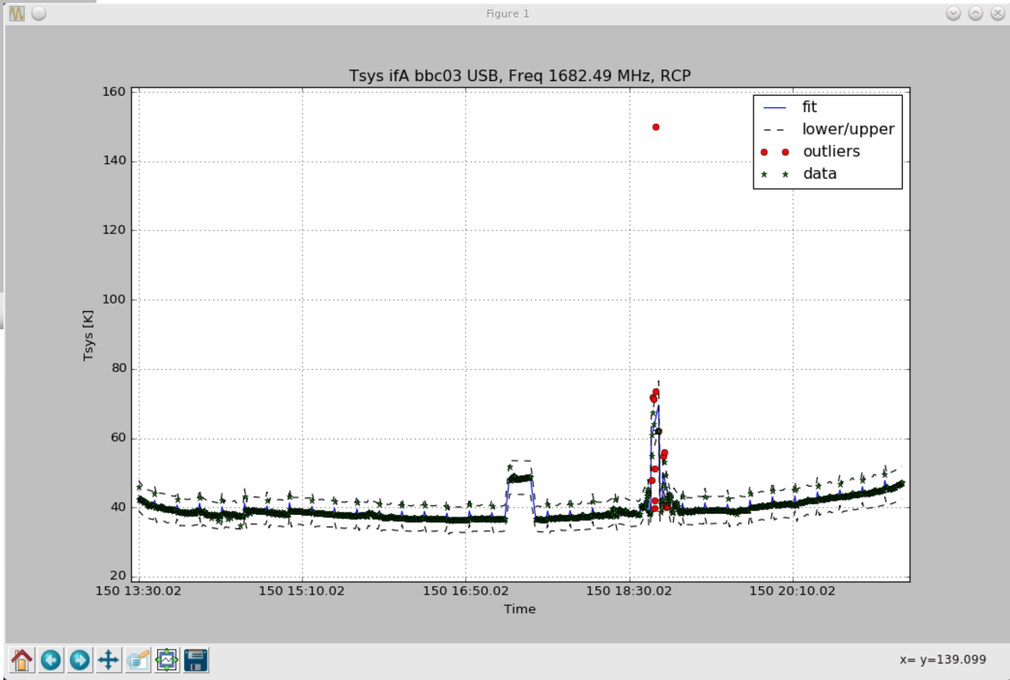
- On (continuous cal), 6cm, EVN session 2/2018



antabfs.py: simple edits

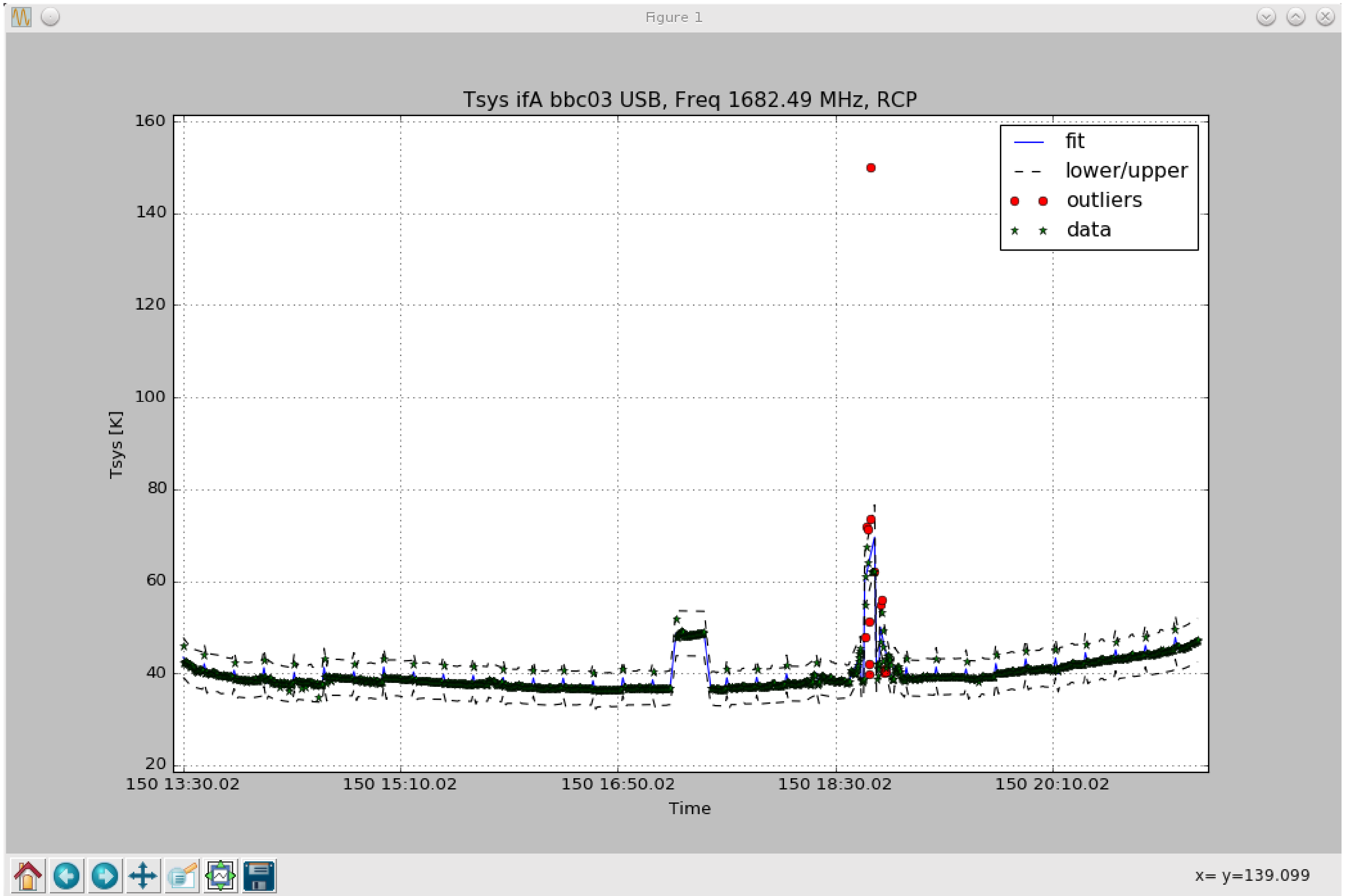
- Hh (gap-based cal), 18cm, EVN session 2/2018





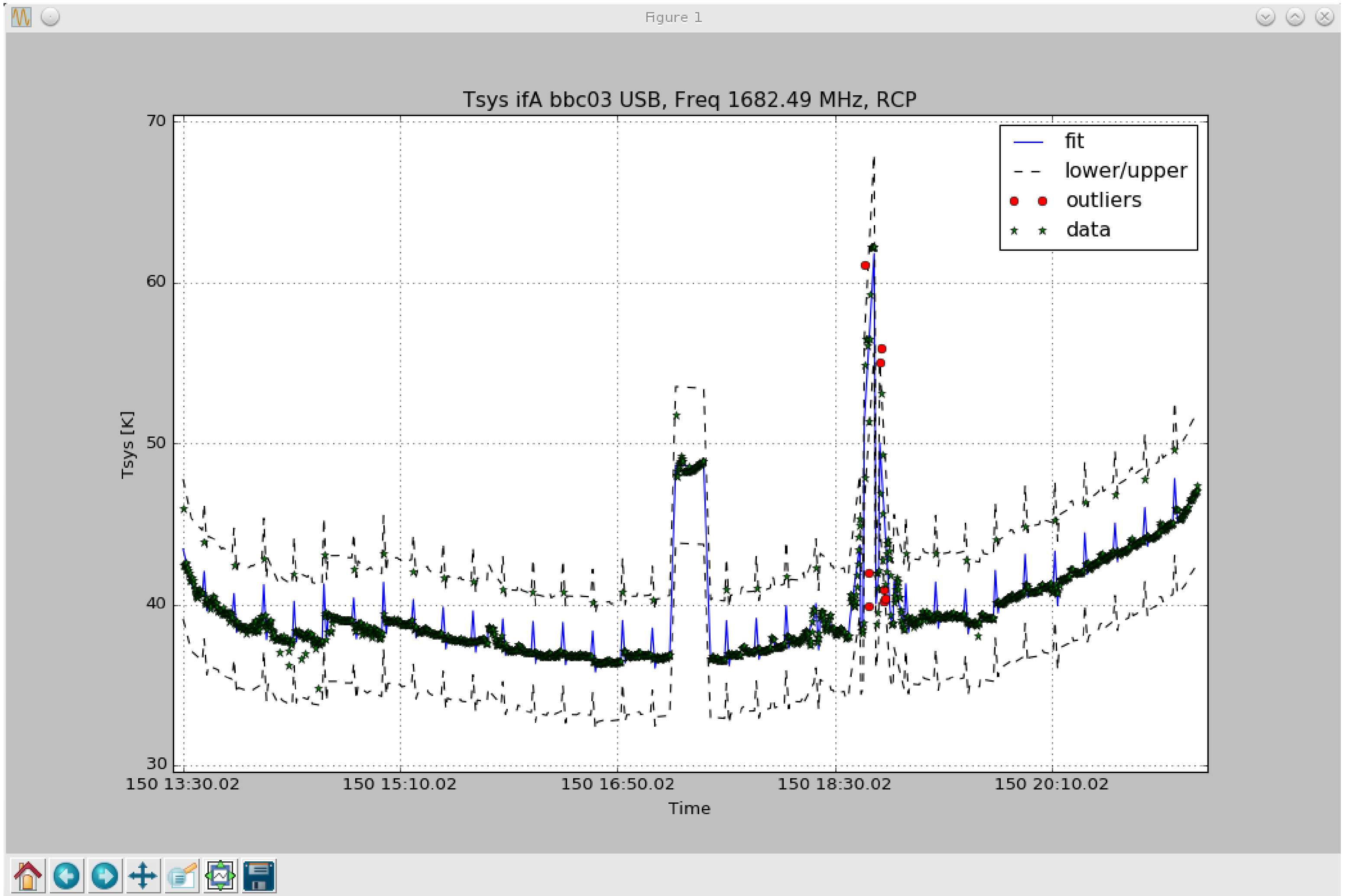
antabfs.py: edit iter.0

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



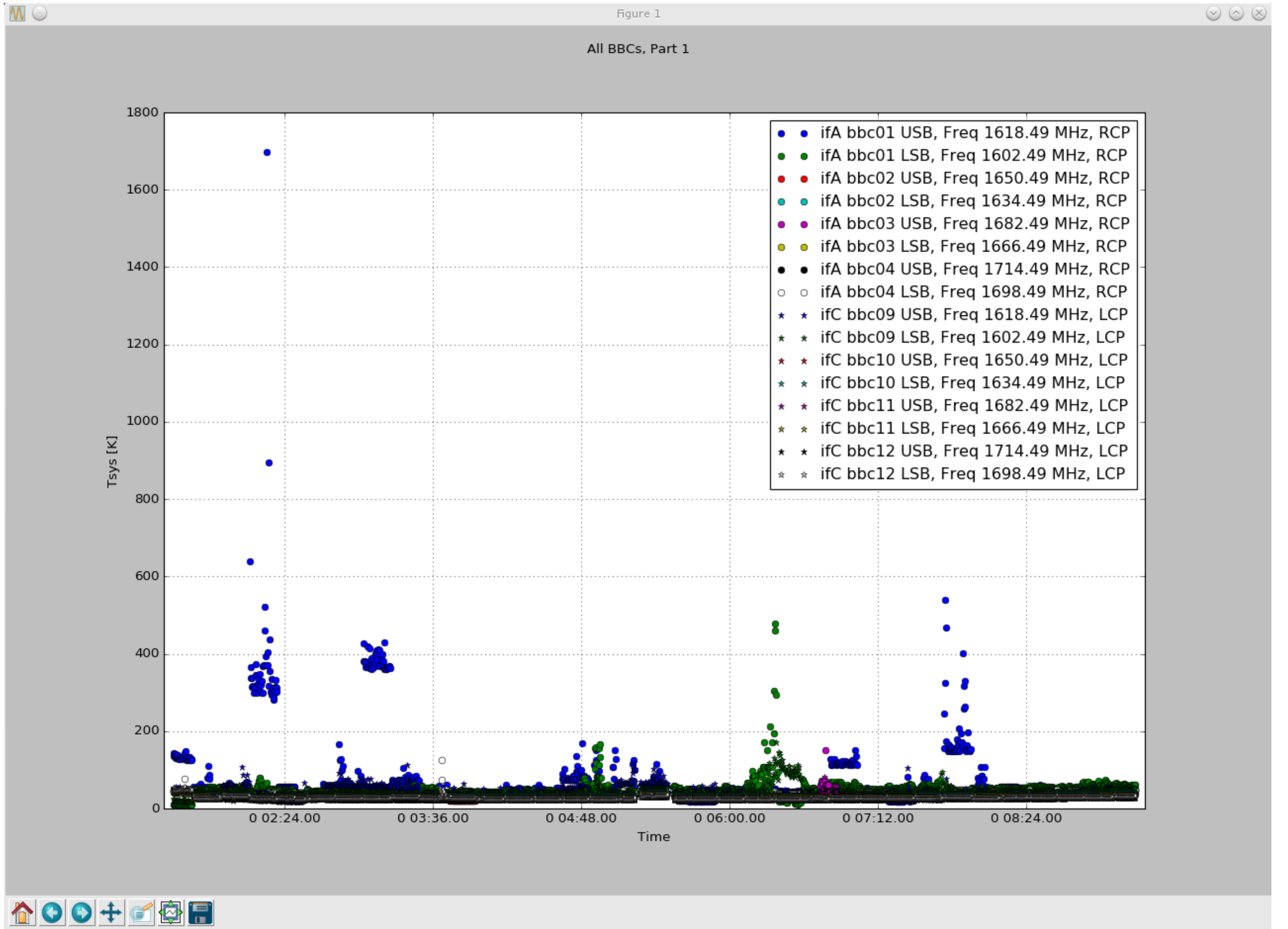
antabfs.py: edit iter.1

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



antabfs.py: *t*-, *ν*-localized RFI

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



Summary (of "antabfs")

- Quality of stations' antabfs file has direct bearing on quality of the subsequent 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
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  - Fran Beltrán (franciso.beltran@oan.es)