Station Amplitude Calibration:

Why we need it and how to do it

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Special thanks to: Ed Himwich, Javier Gonzalez, Bill Petrachenko, Karine le Bail, Leonid Petrov

Outline

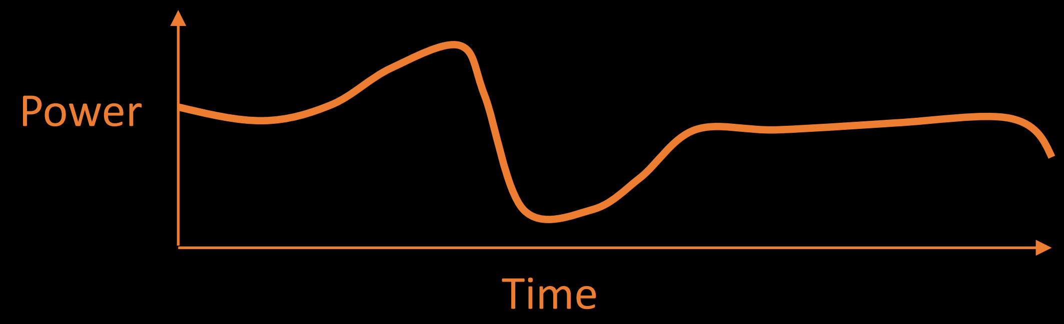
- What is station amplitude calibration?
- Ampcal/Fluxcal/Tsys monitoring?
- Why do we need ampcal for geodesy?
- Acronyms: SEFD, GAIN, TSYS, DPFU, TCAL, RXG, TPI
- Going from TPI+GAIN+DPFU+TSYS to SEFD
- How to measure and verify TPI, TCAL, and GAIN
- Field-system examples: ONOFF, ACQUIR, GNPLT
- Summary
- References and further reading tips

Ow/OSO

What is station amplitude calibration?

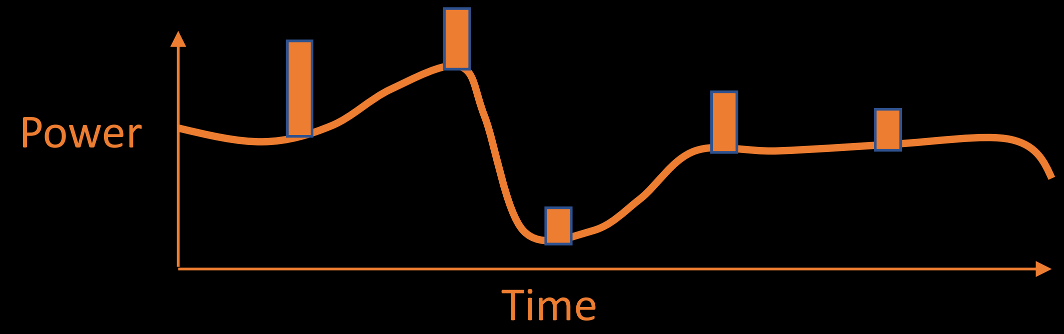
Ho/UTAS

- "Logging the total power every second"



Changes:
Source, receiver temp, atmosphere, LNA gain, backend attenuation,...

- How do we set the scale? Inject known power = noise diode = ▮



- Electronics may vary, noise diode = fixed reference

Ampcal/Fluxcal/Tsys monitoring?

Zv/IAARAS

- Amplitude: how strong is the signal [Volt] ?
- Flux density: how strong is the signal [Jansky] ?
- System temperature (Tsys): how strong is the signal [Kelvin] ? (P=k*T)

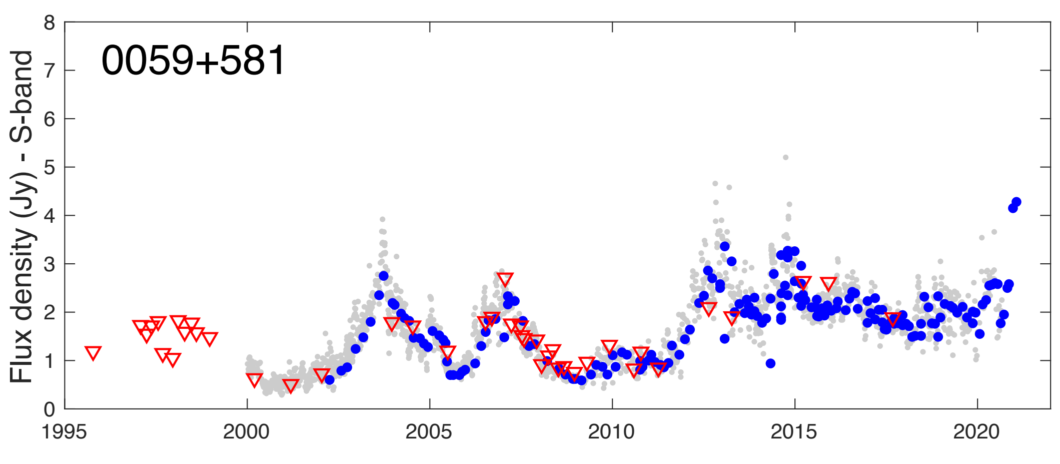
→ “Same thing, different name!”

Why ampcal for geodesy? Scheduling!

Sa/RAGE

- Scan length?

  Source flux density varies...



Le Bail / EVGA

- Surprisingly faint source → No detection → time wasted & bad data

- Surprisingly strong source → "Too good" → time wasted

NOTE: The following equation was wrong in the video and early slides: / now changed to * as it should be.

- *Source flux density = constant* * V_{12} * *sqrt ($SEFD_1$ * $SEFD_2$)*

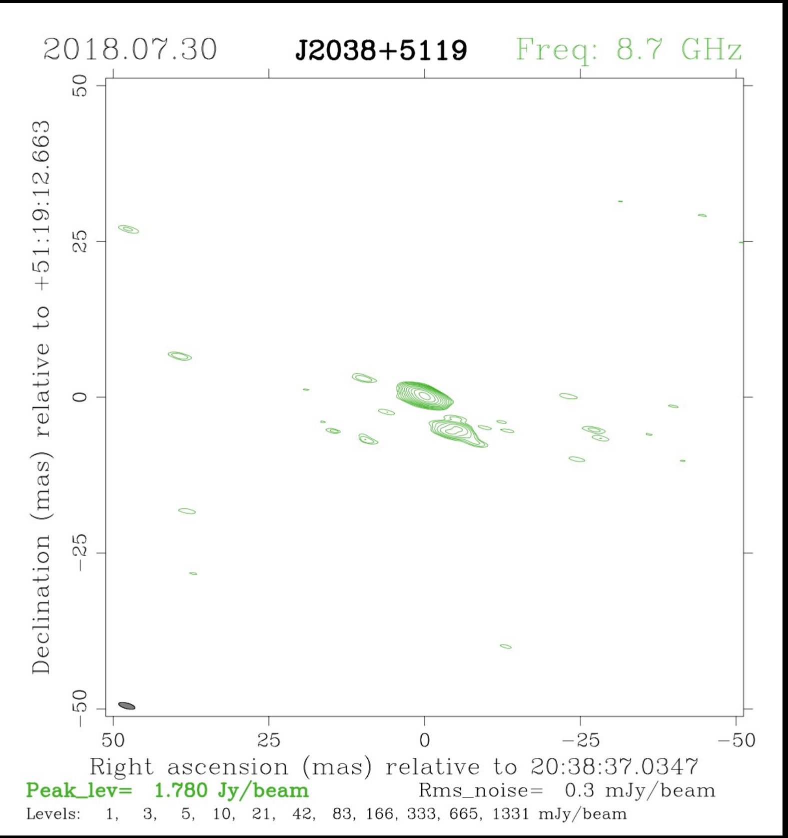
  Corr. amp. — Ampcal ant 1 & 2

- **Ampcal → source flux density → better scheduling → better results!**

Why ampcal for geodesy? Source structure!

Is/GSI

- Source structure affect geodetic results
- Modelling sources = making images
- Imaging is easier with ampcal



astrogeo.org

Why ampcal for geodesy? VGOS → circular

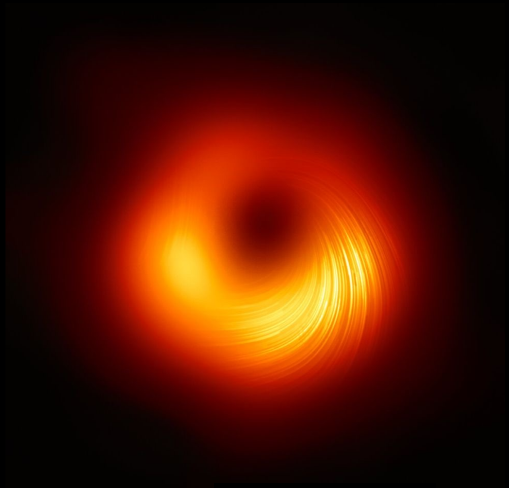
Yj/RAGE

- VGOS observe dual linear (H,V) polarisations
- Geodetic analysis simpler in circular polarisation
- Can convert from linear → circular using e.g. "polconvert"
- Optimal conversion requires ampcal (relative sensitivity of H/V)

Why ampcal for ~~geodesy~~ astronomy?

Mf/NLS

- Monitoring source flux density is interesting for astronomy!
- Regular monitoring is hard to get with astro-VLBI networks.
- With ampcal in IVS, we may get astronomical discoveries “for free”.



M87/EHT

FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

Wz/BKG

- The VLBI Field-System, used to run many VLBI observations.
- FS has tools to measure and check ampcal: ONOFF, ACQUIR, GNPLT.
- ONOFF = Measure ON source, OFF source, with/without diode
- ACQUIR = Run many ONOFFs in sequence
- GNPLT = Plot and analyse ONOFF/ACQUIR data

FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

K2/NASA

- The System Equivalent Flux Density: the flux density of a fictitious source giving the same power at the backend. Unit is Jansky.

- Example:

  - Assume SEFD=2000 Jy at 8 GHz towards empty sky at el=45 deg.

  - If we observe a 2000 Jy source in this direction, RF power doubles.

- Note: SEFD may change with time and direction.

FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

Oe/OSO

- Example:

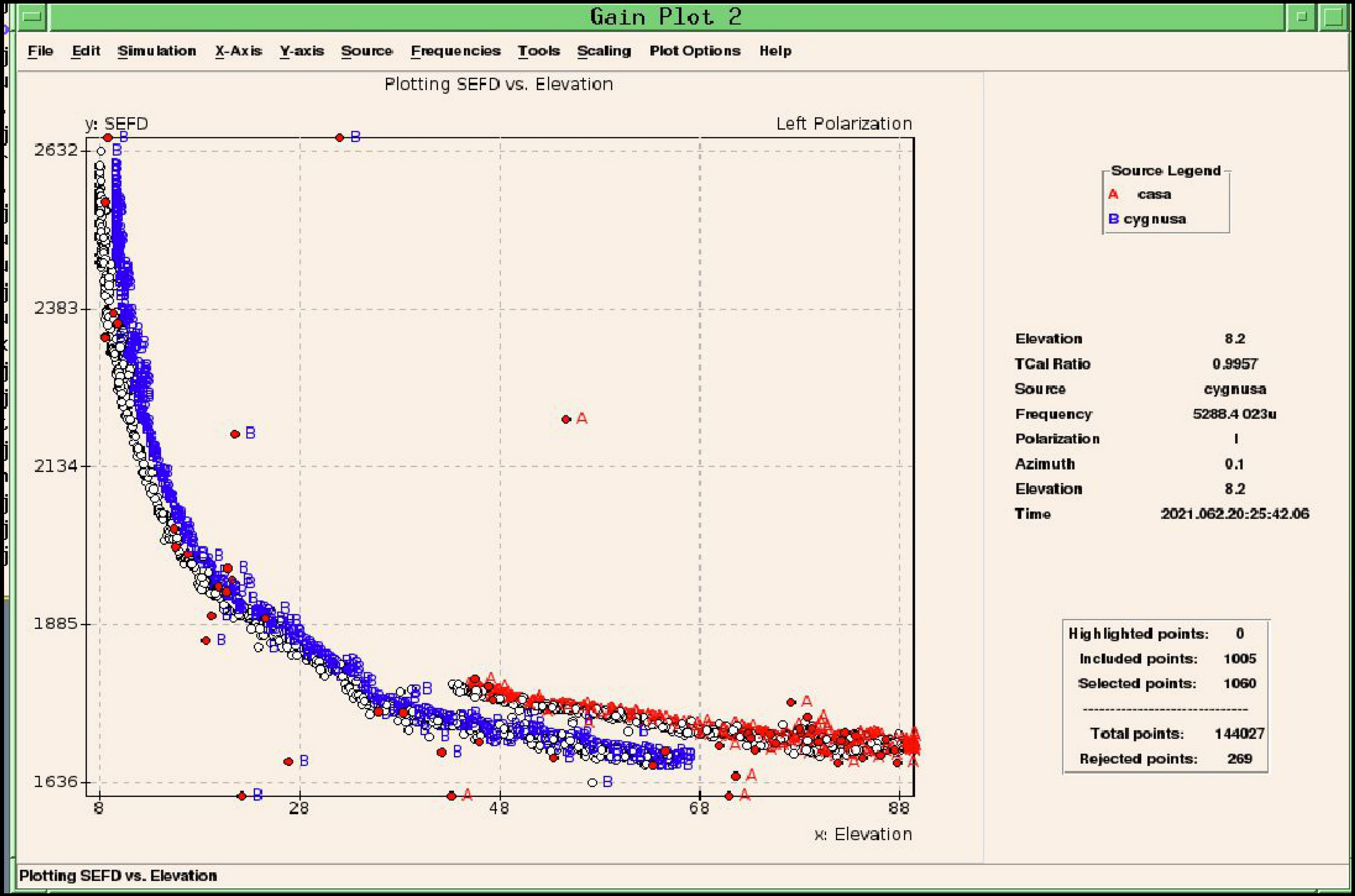
  ONSA13NE

  SEFD vs elevation

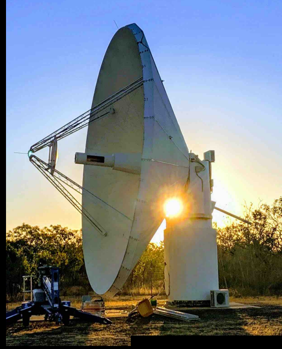
  H-pol

  5.3 GHz

  Cyg A + Cas A



FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI



Ke/UTAS

- The System Temperature is a measure of the total power coming into the backend. Unit is Kelvin.
- It is the equivalent temperature of a resistive load providing the same power (P=k*T).
- Note: TSYS may change with time and direction.

FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

Oe/OSO

- Example:

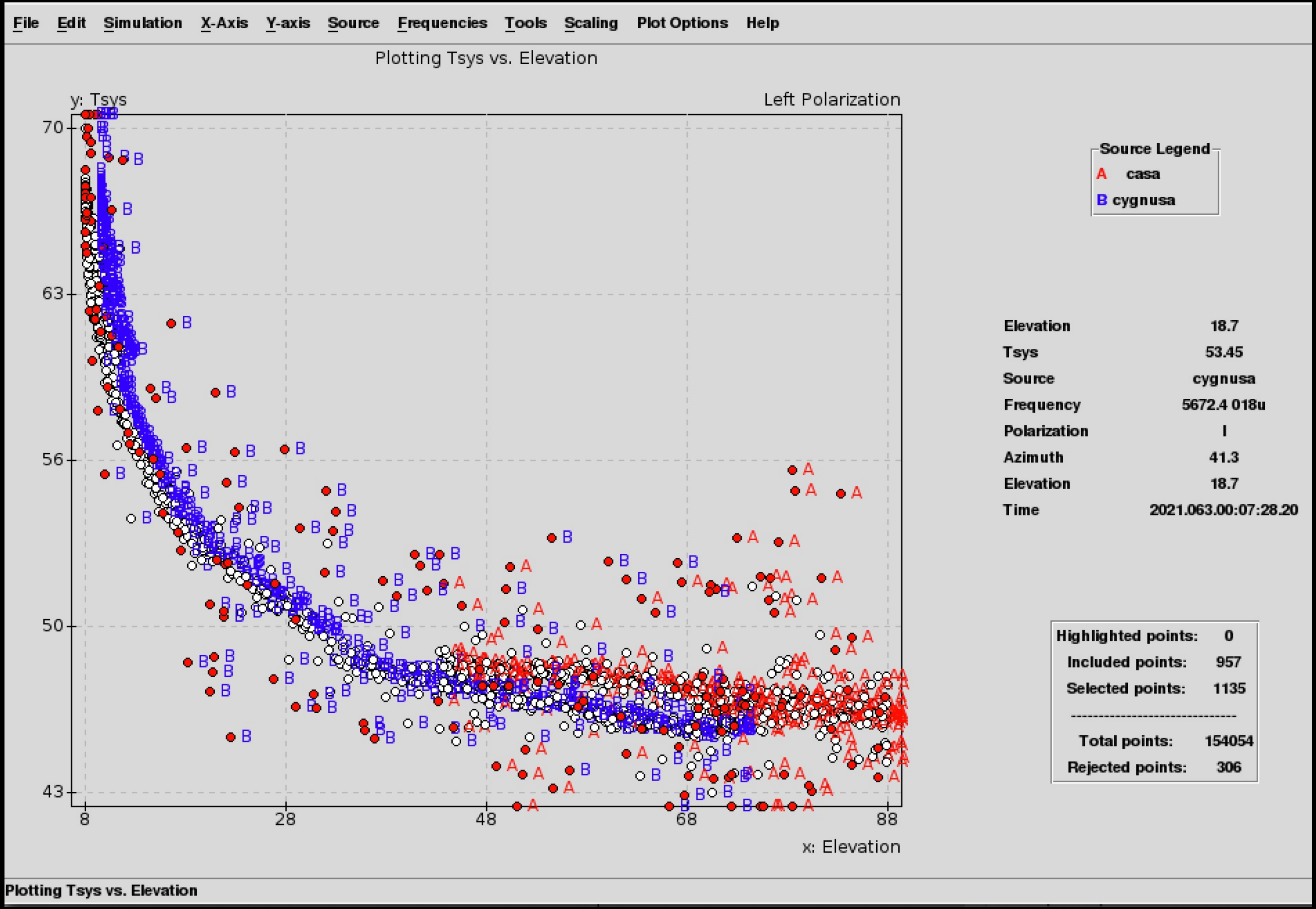
  ONSA13NE

  TSYS vs elevation

  H-pol

  5.7 GHz

  Cyg A + Cas A



FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

Wf/NASA

- The antenna gain usually refers to *The increase in TSYS [K] per unit source flux density [Jy]*. Unit is Kelvin / Jansky.
- Think of this like "How good the antenna is at picking up the source signal". Elevation dependent due to gravitational deformation. Maximum gain usually around 40-60 degrees.
- GAIN = DPFU * polynomial (elevation)

  DPFU = Degrees Per Flux Unit. In theory, DPFU = Area * η / 2k [K/Jy]

FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

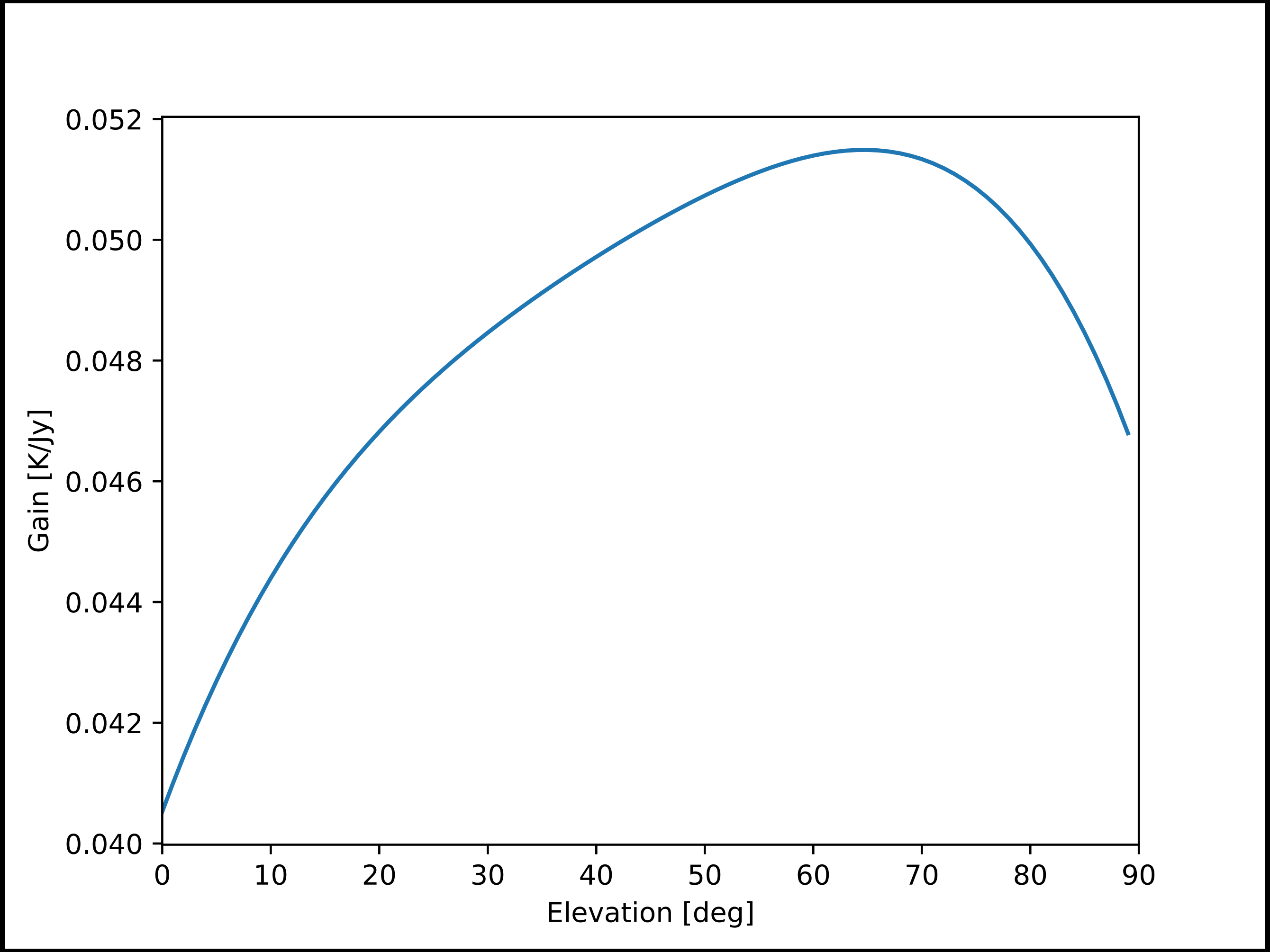
On/OSO

- Example:

  ONSALA60

  X-band

  GAIN=DPFU* POLY(el)



FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

Oe/OSO

- Example:

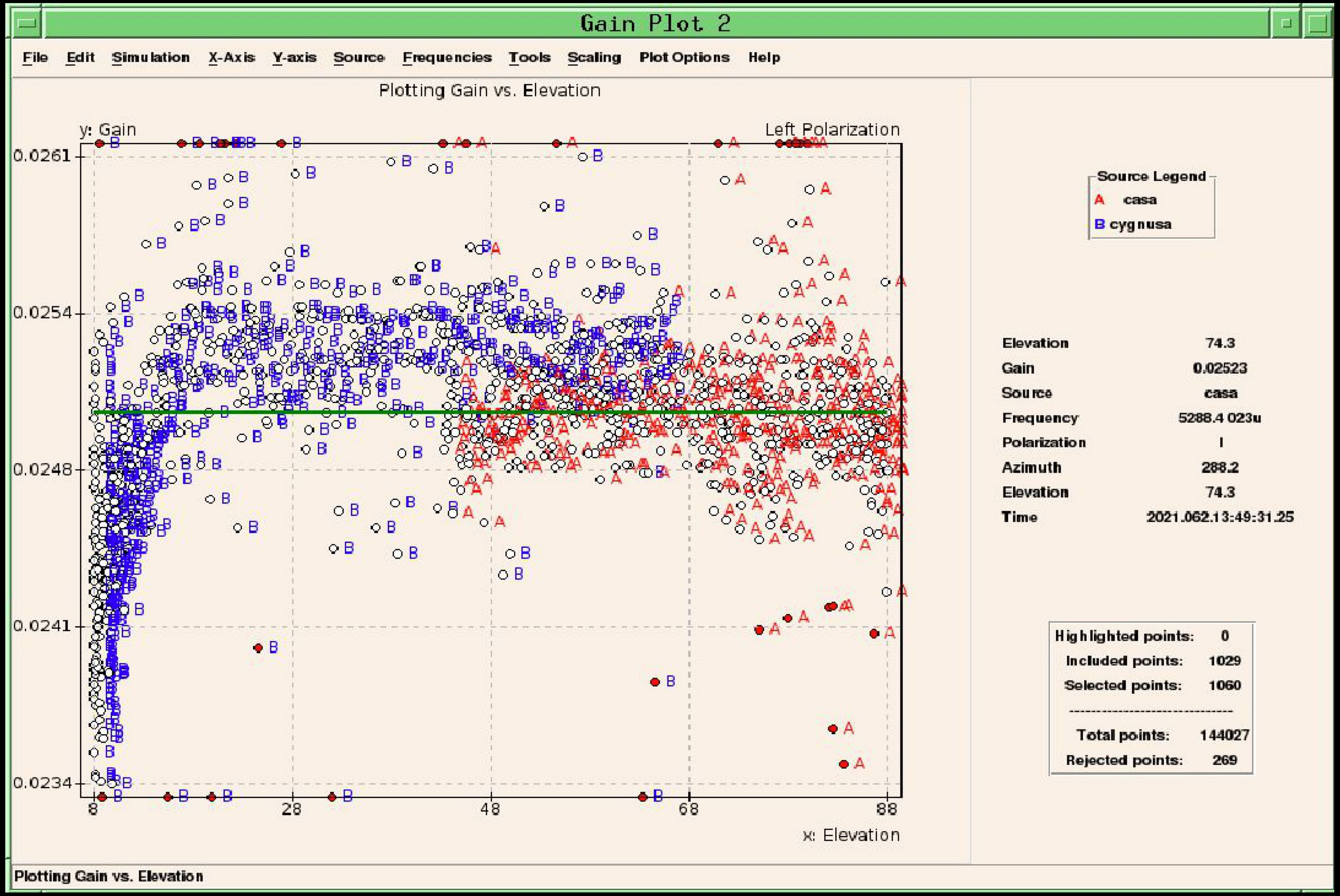
  ONSA13NE

  GAIN vs elevation

  H-pol

  5.3 GHz

  Cyg A + Cas A



FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

Hb/UTAS

- Calibration temperature: The noise diode reference power level.
- How do we know this? We check it against some other reference.

Possible references:

- Bright flux density calibrators (e.g. Cas A) → Diode power in Jansky

- Hot/cold loads of known temperature → Diode power in Kelvin

- Note: Tcal **should** be stable in time (check with ONOFF!).

FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

Cd/UTAS

- The RXG file is a text file on the FS computer.
- Contains a self-consistent set of values for

  TCAL (vs frequency) and

  GAIN (vs elevation; including DPFU).

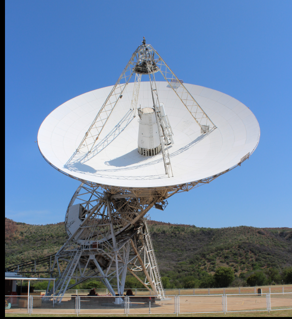
FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI

On/OSO

Example ONSALA60 RXG X-band file:

```
* 1st line: Frequency range
fixed 8080 9080.1

* 2nd line: creation date

2015 06 23

* 3rd line: FWHM beamwidth (calculate from frequency)

frequency 1.0

* 4th line polarizations available

rcp lcp

* 5th line: DPFU (Kelvin/Jansky) for polarizations in previous line in order

0.050 0.050

* 6th line: gain curve (only one) for ALL polarizations in 4th line

ELEV POLY 8.10563E-01 9.74073E-03 -2.33249E-04 3.46868E-06 -2.13463E-08

* 7th and following lines: Pol Frequency [MHz] Tcal [K]

rcp 8116.0 3.812

rcp 8124.0 3.752

rcp 8132.0 3.769

[...]
```

FS, SEFD, TSYS, GAIN, DPFU, TCAL, RXG, TPI



Hh/HartRAO

- Total Power Indicator = total power in arbitrary units.
- Usually seen as TPIon or TPIoff, representing the total power with noise diode ON and OFF respectively.
- Yj RDBE LOG TPI Example: Detector 1, TPIon, TPIoff, Detector 2, ...
  2021.090.18:00:00.22#rdtcd#tpcont/ 00d0, 30661, 29372, 01d0, 25244, 24204, 02d0, 22076, 21240, ...
- Use with TCAL to obtain TSYS vs time:
  TSYS = TCAL * 0.5 *(TPIon + TPIoff)/(TPIon - TPIoff)
- Note: Factor 0.5 since noise diode emits power 50 % of the time.

Going from TPI+GAIN+DPFU+TSYS to SEFD

Yg/UTAS

- We want SEFD vs time for each frequency (BBC).

- SEFD(t) = TSYS(t) / GAIN(el)

  = TSYS(t) / (DPFU [K/Jy] * POLY(el))

  = [(TPIon + TPIoff)/(TPIon - TPIoff)]*TCAL*0.5/ (DPFU [K/Jy]*POLY(el))

Going from TPI+GAIN+DPFU+TSYS to SEFD

Yg/UTAS

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  = TSYS(t) / (DPFU [K/Jy] * POLY(el))

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TPI measured every second by backend (and written to log file)

2021.090.18:00:00.22#rdtcd#tpcont/ 00d0, 30661, 29372, 01d0, 25244, 24204, 02d0, 22076, 21240, ...

Going from TPI+GAIN+DPFU+TSYS to SEFD

Yg/UTAS

- We want SEFD vs time for each frequency (BBC).
- SEFD(t) = TSYS(t) / GAIN(el)

  = TSYS(t) / (DPFU [K/Jy] * POLY(el))

  = [(TPIon + TPIoff)/(TPIon - TPIoff)]*TCAL*0.5/ (DPFU [K/Jy]*POLY(el))

In principle determined once and stable "forever"
Station put this info in RXG file and share with IVS

How to measure TPI, GAIN and TCAL

Bv/IAARAS

- Install noise diode. Normally driven by backend with 80 Hz square wave (turns diode on/off). Noise diode signal is injected as early as possible in RF chain (before LNA). Diode power is usually about 5% of system noise level (on empty sky), but >1% should work.
- Get backend capable of logging Total Power Indicator (TPIon/off) values once every second.
  For VGOS: FS10 supports DBBC2/3 and RDBE-G via multicast.
- Other backends may need FS-mods or external software to log TPI.

How to measure TPI, GAIN and TCAL

Bv/IAARAS

- GAIN = DPFU x POLY (elevation). If not known:
- POLY (el): can be measured (ONOFF+ACQUIR) using e.g. Cas A.
  Normally require a day or so to get full elevation range.
- DPFU: Can be measured if we know POLY and TCAL, else assume.
  In theory, DPFU = Area * η / 2k [K/Jy] $\cong \pi * r^2 * 0.5 / 2760$ [K/Jy]

How to measure TPI, GAIN and TCAL

Bv/IAARAS

FS method, using a bright calibrator source:

- Use ONOFF+ACQUIR+GNPLT with bright calibrator e.g. Cas A. Normally requires an hour or so (to get statistics).
- **Pros:** Simple. Can be done with telescope “as is”.
- **Cons:** If assumed (not measured) DPFU, then derived TSYS may have scale factor error. **BUT**: this error cancels out in SEFD calculation.

How to measure TPI, GAIN and TCAL


Oe/OSO

- Example:

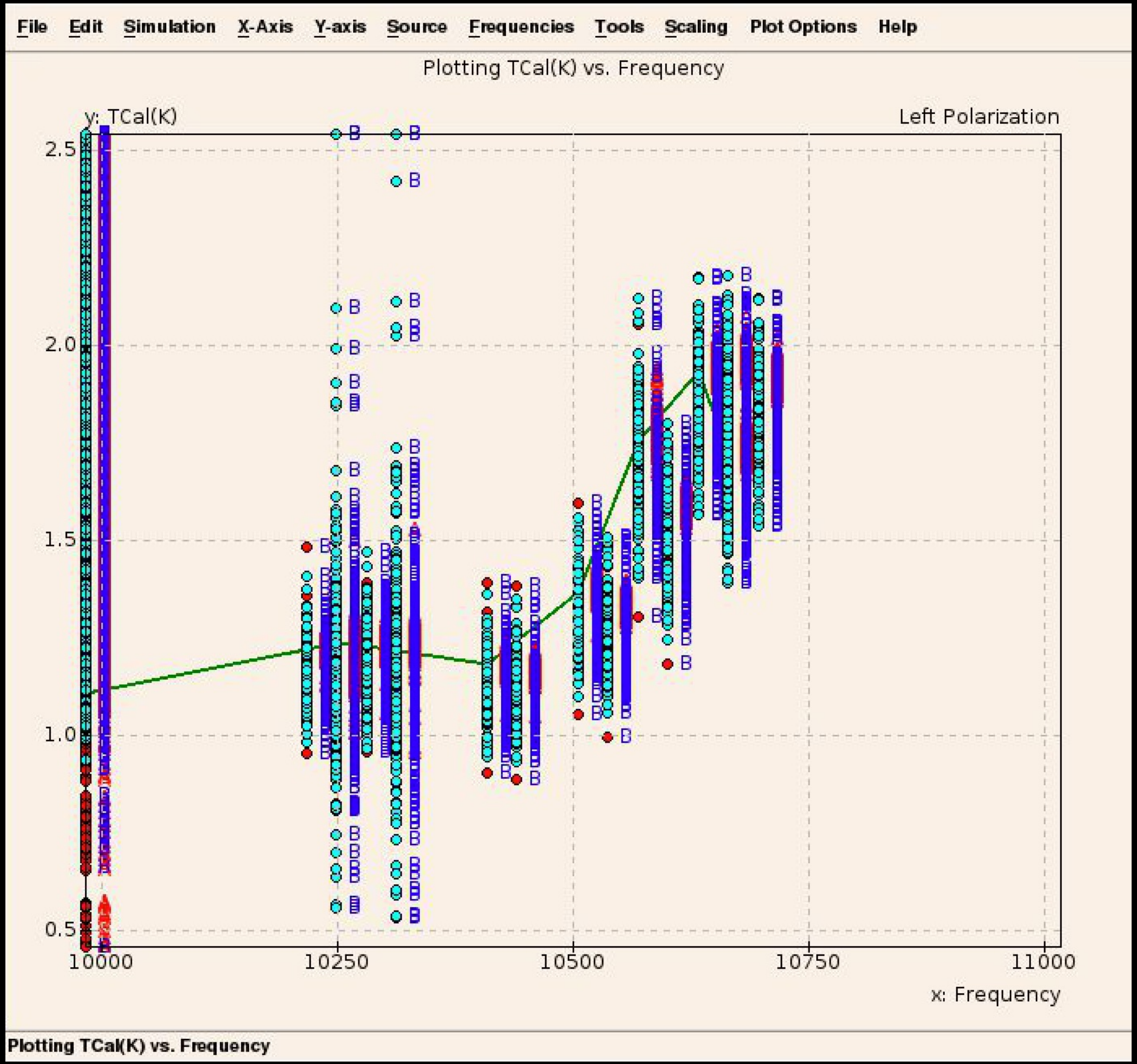
  ONSA13NE

  TCAL vs Frequency

  H-pol

  VGOS Band D

  Cyg A + Cas A



How to measure TPI, GAIN and TCAL


Bv/IAARAS

Y-factor method, with loads of known temperature as input signal:

- Measure diode power vs frequency with spectrum analyser.
- Use hot (e.g. 300 K room) and cold (e.g. 80 K liquid nitrogen) loads.
- TCAL = $(T_{hot} – T_{cold}) * (P_{cal\text{-}on} – P_{cal\text{-}off}) / (P_{hot} – P_{cold})$
- **Pros:** Derived TSYS should be in (actual) Kelvin.
- **Cons:** Tricky without expertise and equipment.

Verify TPI, GAIN and TCAL

Sc/NRAO

- Run ONOFF once before EVERY exp. to verify amp cal.
- Use same LO & BBC setup as experiment
- Normally takes a few minutes (depending on slewing speed).
- If significant (>10%) changes in ampcal: Fix and notify IVS!
- Note: RFI may be an issue for (stability) in some BBCs

FS examples: ONOFF

Ny/NMA

- Setup syntax “onoff=rep,intp,cutoff,step,proc,wait,devices”
  For ONSA13NE I use “onoff=2,2,,,,,all”, where
    2,2 = 2 repetitions, 2 seconds integration time
    all = all detectors, i.e. all BBC channels (USB and LSB)
- Execution: “onoff”
- Results:

```
2021.074.15:59:17.85#onoff#    source       Az   El   De    I P   Center    Comp    Tsys  SEFD  Tcal(j) Tcal(r)
[...]
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 061u 8 r  10408.40 1.0015 54.82 2168.6  89.206  0.99
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 062u 8 r  10280.40 1.0028 50.18 1951.9  92.030  0.97
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 063u 8 r  10248.40 0.9888 48.72 1909.6  89.867  0.98
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 064u 8 r  10216.40 0.9794 49.01 1951.0  78.622  1.00
```

Sv/IAARAS

FS examples: ACQUIR (1/3)

- “A while loop to run ONOFF, and/or other things”
- Setup: Edit /usr2/control/ctlpo.ctl. I use e.g.

```
* Setup procedure etc.
initp  -1 initp -2 91 180 180
* horizon mask
0  5 360
* Sources
cygnusa    195928.4  +404402.  2000 prep    -1 10  5  0 postp    -2
casa       232324.8  +584859.  2000 prep    -1 10  5  0 postp    -2
```

FS examples: ACQUIR (2/3)

Sv/IAARAS

- Setup: Define /usr2/proc/point.prc with content along lines of

```
define  initp         21062181840x
setuppnt
fivept=azel,-2,9,0.4,1,057u
onoff=2,2,,,,,,all
sy=go aquir &
enddef

define  acquire       21062181840
sy=run aquir /usr2/control/ctlpo.ctl $ &
log=acquir
enddef

define  kill          21063081106
sy=brk aquir &
sy=brk fivpt &
sy=brk onoff &
log=station
enddef
```

- where “setuppnt” defines “lo=loc,7700,lsb,lcp", “ifc=2,agc”and “bbc001=3480.4,a,32,1” etc. for all BBCs.

FS examples: ACQUIR (3/3)

Sv/IAARAS

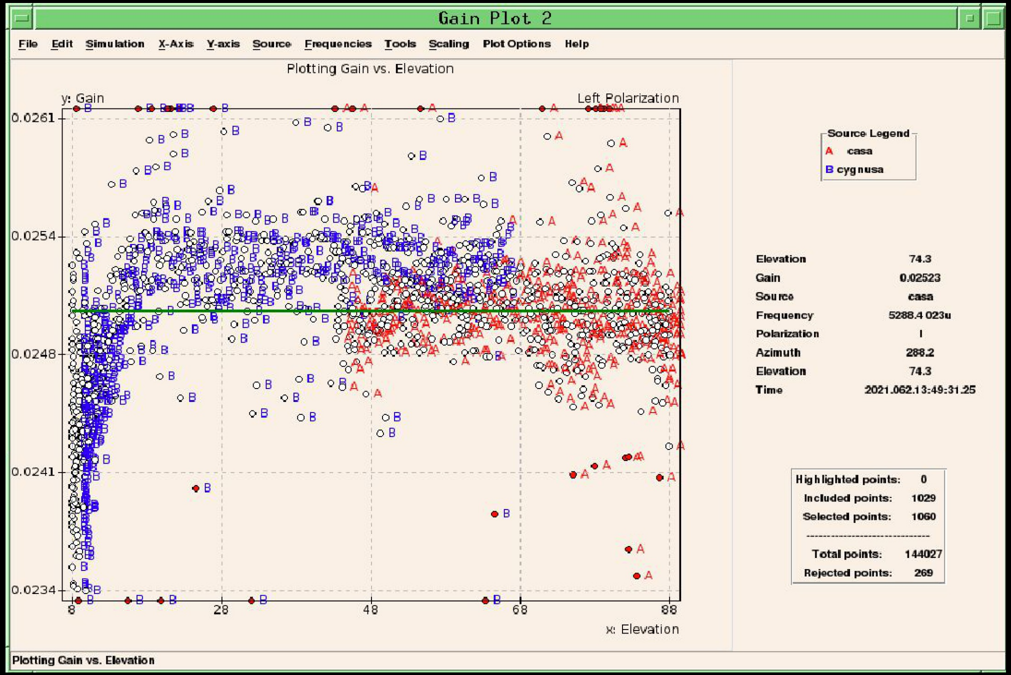
- Execution: In FS, run ”proc=point” and then ”acquire”.
- This should keep running ONOFF on the defined sources until...
- To stop, run ”kill” in FS.
- Logfile ”/usr2/log/acquir.log” can be analysed with e.g. GNPLT.
- Note: Can watch ONOFF ”VAL” lines during ACQUIR, e.g.

```
2021.074.15:59:17.85#onoff#    source       Az    El   De    I P   Center   Comp   Tsys  SEFD   Tcal(j) Tcal(r)
[...]
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 061u 8 r  10408.40 1.0015 54.82 2168.6  89.206  0.99
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 062u 8 r  10280.40 1.0028 50.18 1951.9  92.030  0.97
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 063u 8 r  10248.40 0.9888 48.72 1909.6  89.867  0.98
2021.074.15:59:17.96#onoff#VAL casa       304.5 53.0 064u 8 r  10216.40 0.9794 49.01 1951.0  78.622  1.00
```

FS examples: GNPLT "Gain Plot"

Bd/IAARAS

- Run "gnplt" on FS computer
- File-->New-->"open your logfile"
  Edit-->Delete points with bad GC (to filter obvious bad data)
  Edit-->Gain vs El-->Left-->All-->018u
- Can fit Gain/Tcal using "Tools" menu.
- Can update RXG file with new data.



Summary

Gs/NASA

- Ampcal is important for optimal geodetic results
- Requirements: a working noise diode and a backend capable of communicating TPI values (preferably with FS) every second
- Stations: Measure GAIN and TCAL (FS or Y-factor) !
- FS tools ONOFF, ACQUIR and GNPLT can help you
- Future possible topics for the IVS:
  - How to ship ampcal data in geo-community ?
  - What about ref source polarisation for VGOS obs (Tau A etc.) ?
  - What is the uncertainty of FS flux density models ?

References and reading tips

- Upcoming TOW 2021: https://www.haystack.mit.edu/conference-2/tow2021/
- Good review of both cm and mm ampcal, by Sarah Issaoun for the EHT: https://eventhorizontelescope.org/files/eht/files/EHT_memo_Issaoun_2017-CE-02.pdf
- Tailored for centimetre-VLBI by Uwe Bach, from TOW 2015: https://ivscc.gsfc.nasa.gov/meetings/tow2015/Bach.Sem1.pdf
- An Introduction to Calibration techniques for VLBI (including ampcal, but also other things): http://adsabs.harvard.edu/pdf/1995ASPC...82..161M
- General good talk by Scott Ransom about amplitudes, flux densities and surface/source brightness (often confused/mixed carelessly): https://events.asiaa.sinica.edu.tw/school/20160815/talk/sransom0818.pdf
- Field-System documentation and help files