Station Amplitude Calibration:
Why we need it and how to do it

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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
What is station amplitude calibration?

• “Logging the total power every second”

• How do we set the scale? Inject known power = noise diode = fixed reference

• Electronics may vary, noise diode = fixed reference

Changes:
Source, receiver temp, atmosphere, LNA gain, backend attenuation,...
Ampcal/Fluxcal/Tsys monitoring?

• 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!

- Scan length?

  Source flux density varies...

- 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 * $V_{12} \sqrt{SEFD_1 \times SEFD_2}$* 

  Corr. amp.

  Ampcal ant 1 & 2

- Ampcal → source flux density → better scheduling → better results!
Why ampcal for geodesy? Source structure!

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

astrogeo.org
Why ampcal for geodesy? VGOS $\rightarrow$ circular

• VGOS observe dual linear (H,V) polarisations

• Geodetic analysis simpler in circular polarisation

• Can convert from linear $\rightarrow$ circular using e.g. “polconvert”

• Optimal conversion requires ampcal (relative sensitivity of H/V)
Why ampcal for geodesy astronomy?

• 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

• 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
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.
Example:
ONSA13NE
SEFD vs elevation
H-pol
5.3 GHz
Cyg A + Cas A
FS, SEFD, **TSYS**, GAIN, DPFU, TCAL, RXG, TPI

• 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 \( P = k \times T \).

• Note: TSYS may change with time and direction.
FS, SEFD, **TSYS**, GAIN, DPFU, TCAL, RXG, TPI

- Example:
  - ONSA13NE
  - TSYS vs elevation
  - H-pol
  - 5.7 GHz
  - Cyg A + Cas A
• 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 * \( \eta / 2k \) [K/Jy]**
• Example:
  ONSALA60
  X-band
  GAIN=DPFU* POLY(el)

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

- Example:
  - ONSA13NE
  - GAIN vs elevation
  - H-pol
  - 5.3 GHz
  - Cyg A + Cas A
FS, SEFD, T SYS, GAIN, DPFU, **TCAL**, RXG, TPI

• **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!).
• 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).
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
* 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

• **Total Power Indicator** = total power in arbitrary units.

• Usually seen as TPI\textsubscript{on} or TPI\textsubscript{off}, representing the total power with noise diode ON and OFF respectively.

• **Yj RDBE LOG TPI Example:** Detector 1, TPI\textsubscript{on}, TPI\textsubscript{off}, 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:
  \[ TSYS = TCAL \times 0.5 \times (TPI\textsubscript{on} + TPI\textsubscript{off})/(TPI\textsubscript{on} - TPI\textsubscript{off}) \]

• Note: Factor 0.5 since noise diode emits power 50 % of the time.
Going from TPI+GAIN+DPFU+TSYS to SEFD

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

• SEFD(t) = TSYS(t) / GAIN(el)

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

  = [(TPlon + TPloff)/(TPlon - TPloff)]*TCAL*0.5/ (DPFU [K/Jy]*POLY(el))
Going from TPI+GAIN+DPFU+TSYS to SEFD

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

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

TPI measured every second by backend (and written to log file)
Going from TPI+GAIN+DPFU+TSYS to SEFD

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

  = [(TPlon + TPloff)/(TPlon - TPloff)]*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

• 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

• 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 * $\eta / 2k$ [K/Jy] $\equiv \pi * r^2 * 0.5 / 2760$ [K/Jy]
How to measure TPI, GAIN and TCAL

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

• Example:
  ONSA13NE
  TCAL vs Frequency
  H-pol
  VGOS Band D
  Cyg A + Cas A
How to measure TPI, GAIN and TCAL

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}) \times (P_{cal-on} − P_{cal-off}) / (P_{hot} − P_{cold})

• **Pros:** Derived TSYS should be in (actual) Kelvin.

• **Cons:** Tricky without expertise and equipment.
Verify TPI, GAIN and TCAL

• 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

• Setup syntax “onoff=rep,rintp,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:

<table>
<thead>
<tr>
<th>Date</th>
<th>Az</th>
<th>El</th>
<th>De</th>
<th>IP</th>
<th>Center</th>
<th>Comp</th>
<th>Tsys</th>
<th>SEFD</th>
<th>Tcal(j)</th>
<th>Tcal(r)</th>
</tr>
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<tr>
<td>2021.074.15:59:17.85#onoff#</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2021.074.15:59:17.96#onoff#VAL casa</td>
<td>304.5</td>
<td>53.0</td>
<td>061u 8 r</td>
<td>10408.40</td>
<td>1.0015</td>
<td>54.82</td>
<td>2168.6</td>
<td>89.206</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>2021.074.15:59:17.96#onoff#VAL casa</td>
<td>304.5</td>
<td>53.0</td>
<td>062u 8 r</td>
<td>10280.40</td>
<td>1.0028</td>
<td>50.18</td>
<td>1951.9</td>
<td>92.030</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>2021.074.15:59:17.96#onoff#VAL casa</td>
<td>304.5</td>
<td>53.0</td>
<td>063u 8 r</td>
<td>10248.40</td>
<td>0.9888</td>
<td>48.72</td>
<td>1909.6</td>
<td>89.867</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>2021.074.15:59:17.96#onoff#VAL casa</td>
<td>304.5</td>
<td>53.0</td>
<td>064u 8 r</td>
<td>10216.40</td>
<td>0.9794</td>
<td>49.01</td>
<td>1951.0</td>
<td>78.622</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>
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)

• 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 acquire &
  enddef

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

  define kill 21063081106
  sy=brk acquire &
  sy=brk fivept &
  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)

• 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  Ip  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”

• 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

• 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


• 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