Pointing & Single-Dish Amplitude Calibration

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- 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 \( (\eta_A) \)
  - 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: $\theta = \frac{\lambda}{D}$

- **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% $\text{HPBW}$ causes 3% loss of sensitivity
  - 20% $\text{HPBW}$ 10%
  - 30% $\text{HPBW}$ 22%

- Detailed analysis of pointing errors required to achieve a pointing model good to 10% $\text{HPBW}$ 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 offset $<\lambda$ mostly biases pointing, with less loss of gain
Antenna Efficiency

- Power received from an unpolarized source by a perfect antenna:
  \[ P = \frac{1}{2} S A_{\text{geom}} \Delta v \]
  - Units of \( S \) = Jansky (10^{-26} \text{ Watts per m}^2 \text{ per Hz})

- Effective aperture: fraction of total power actually picked up by real antenna:
  \[ A_{\text{eff}} = \eta_A A_{\text{geom}} \]

- \( \eta_A \) is the aperture efficiency. It depends on:
  - Reflector surface accuracy
  - Feed illumination / spill-over
  - Subreflector/leg blockage

- \( \eta_A \) 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:
  \[ T_A = \frac{1}{(2k) \ \eta_A \ A_{geom} \ S} \]
  \[ = \pi \ D^2/(8k) \ \eta_A \ S \]

- 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:

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

- $T_{rcvr}$: LNAs, mixers, etc.
- $T_{struct}$: antenna structure, ground spill-over, sidelobes, etc.
- $T_{sky}$: 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 $\gg T_A$
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:

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

- Gain (or sensitivity) $\Gamma$ 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:

  $$\Gamma = \eta_A \pi D^2 / (8k)$$
  $$\sim 3 \times 10^{-4} \eta_A D^2$$
Importance of SEFD

- Invariably in radio astronomy, system noise dominates over power from the source in the beam.
  - 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 \( SEFD = \frac{T_{sys}}{\Gamma} \), 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 “$g$”):

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

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

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

- Assumptions: receiver remains in linear regime; $g$, $T_{sys}$ constant
$T_{sys}$ via a cal-diode at $T_{cal}$

- **Noise-cal signal at $T_{cal}$:**
  \[
  P_{on} = g (T_{cal} + T_{sys}) \\
  P_{off} = g (T_{sys})
  \]

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

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

- $T_{sys}$ needs an accurate measurement of $T_{cal}$

- **Sources for $T_{sys}$ calib.:** strong, non-variable, point-like
A measure of $T_{cal}$ can also come from hot & cold loads:

\[ P_{\text{cal.on}} - P_{\text{cal.off}} = g(T_{cal} + T_{\text{sys}}) - g(T_{\text{sys}}) = g(T_{cal}) \]
\[ P_{\text{hot}} - P_{\text{cold}} = g(T_{\text{hot}} - T_{\text{cold}}) \]

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

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

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

- Onsala85 at 18cm, Nov 2009 — Feb 2010

On 18cm LCP $T_{\text{cal}}$ from calonl.rxg

- 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:

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

- 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 ($\rightarrow$ 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:
  
  \[ P_{\text{cal.on}} - P_{\text{cal.off}} = g \left( T_{\text{cal}} + T_{\text{sys}} \right) - gT_{\text{sys}} = gT_{\text{cal}} \]
  
  \[ P_{\text{on.src}} - P_{\text{off.src}} = g \left( T_A + T_{\text{sys}} \right) - gT_{\text{sys}} = gT_A \]

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

\[ \text{GAIN} = \frac{P_{\text{on.src}} - P_{\text{off.src}}}{P_{\text{cal.on}} - P_{\text{cal.off}}} \frac{T_{\text{cal}}}{S} \]

- FS program acquit to collect gain-calibration data
Plots leading to SEFD: $T_{\text{sys}}$

- $T_{\text{sys}}$ vs. elevation:

\[ T_{\text{atm}} = T_{\text{zenith}} \left( 1 - e^{-\tau / \sin(El)} \right) \]
Plots leading to SEFD: Gain

- Gain vs. elevation:

![Gain vs. Elevation - Lovell 76m Telescope - Feb 2004 5002 MHz LCP](image1)

![Antenna Gain Curves at different wavelengths.](image2)
Plots leading to SEFD: SEFD itself

- SEFD vs. elevation: \( \text{SEFD} = \frac{T_{\text{sys}}}{\text{GAIN}} \)
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 $\rightarrow$ GAIN
  - $SEFD = \frac{T_{sys}}{GAIN}$

- 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)
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:

\[ T_{sys} = T_{cal} \frac{\text{tpi} - \text{tpzero}}{\text{tpical} - \text{tpi}'} \]

Representative \( \text{tpical-tpi}' \) (\( \text{tpdiff} \)) value \( \sim 1000 \)
- Too low \( \rightarrow \) larger scatter
- \( \sim 0 \) \( \rightarrow \) dead cal-diode (?)
- Jumps \( \rightarrow \) change in attenuation; usable cal-diode
What the Astronomer Wants

- $T_{sys}$ within an experiment
  - typical - 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 $\rightarrow$ 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

2: tpicd monitors both tpi and tpi’ continuously

- 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. / $T_{\text{cal}}$ 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 beamwidth format:
  * model value
  * if type is frequency, 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 COEFFICIENTS ... [max coeff = 10]
  * FORM - POLY only for now
  * TYPE - ELV only for now
  * COEFFICIENTS - variable number of number values
  ELEV POLY 6.69503E-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 16.3489
  lcp 1611.0 17.5230
  lcp 1613.0 18.6960
  lcp 1615.0 20.0320
  rcp 1607.0 22.6755
  rcp 1609.0 22.6380
  rcp 1611.0 23.0990
  rcp 1613.0 23.3920
  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 typical – 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)
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: $t$, $v$-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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