

Astronomical Techniques II

Lecture 9 - Calibration and Imaging

Divya Oberoi

IUCAA NCRA Graduate School

div@ncra.tifr.res.in

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Calibration Framework

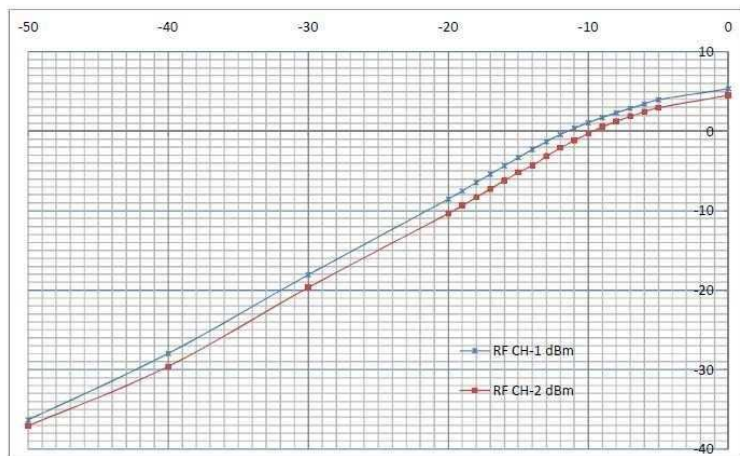
1 $\tilde{V}_{i,j}(t) = \mathcal{G}_{i,j}(t) V_{i,j}(t) + \epsilon_{i,j}(t) + \eta_{i,j}(t)$

- 1** $\mathcal{G}_{i,j}(t)$ - baseline based complex gain
- 2** $\epsilon_{i,j}(t)$ - baseline based complex offset
- 3** $\eta_{i,j}(t)$ - Gaussian random complex noise

Antenna based calibration

- 1 $\mathcal{G}_{i,j}(t) = g_i(t) g_j^*(t) = a_i(t)a_j(t)e^{i(\phi_i(t)-\phi_j(t))}$
- 2 No. of constraints $\sim 2 \times N(N - 1)/2$
- 3 No. of independent DoF $\sim 2N$
- 4 Vastly over determined problem
- 5 Assumptions
 - 1 All/most Data corruption happens before correlation
 - 2 *Linear* regime $\implies g_i(t)$ s are independent of $V_{i,j}(t)$
 - 3 One $g_i(t)$ specifies an antenna \implies *direction independent*
 - 4 Availability of a *perfect* calibrator

Linearity of GMRT 250–500 MHz front-end



Delay Calibration

$$\mathbf{1} \quad V_{ij}(t) = \int_0^\infty \left(\int_{-\infty}^\infty \int_{-\infty}^\infty A_\nu(l, m) B_\nu(l, m) e^{-2\pi i \nu \tau_g} dl dm \right) e^{2\pi i \nu (\tau_f - \tau_c)} \mathcal{G}_{ij}(t, \nu) d\nu$$

2 Residual delay gives rise to a phase ramp

$$\Delta\phi = 2\pi\nu(\tau_g + \tau_f - \tau_c)$$

3 $\Delta\phi$ has contributions from

- 1** the geometric delay (can be corrected precisely only one direction - the *phase center*)
- 2** the *fixed delay* - due to cables and electronics etc.

Time and Antenna locations

- 1** $\phi_g = 2\pi\nu\tau_g = 2\pi w = \frac{2\pi}{\lambda} (L_x \cos H \cos \delta - L_y \sin H \cos \delta + L_z \sin \delta)$
- 2** $\Delta\phi_g = \frac{2\pi}{\lambda} (\Delta L_x \cos H \cos \delta - \Delta L_y \sin H \cos \delta + \Delta L_z \sin \delta + \Delta H \cos \delta (L_x \sin H + L_y \cos H) + \Delta \delta (-L_x \cos H \sin \delta + L_y \sin H \sin \delta + L_z \cos \delta))$
- 3** Reduce $\Delta\phi_g(t)$ to (much) less than 1 radian over a characteristic time scale

Time scales

1 Time scale for calibration

1 < than the time scale over which ϕ_{sys} varies significantly

2 Time scale for integration over $V_{i,j}(t)$

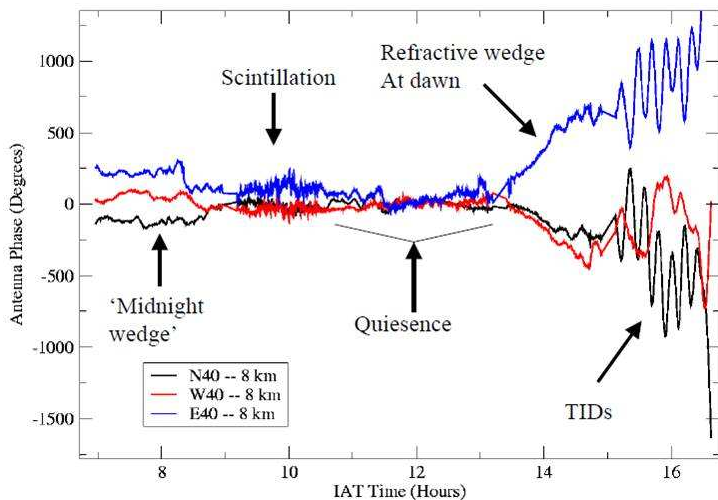
1 < than the time scale over which ϕ_{source} varies significantly

2 Includes contributions from propagation effects

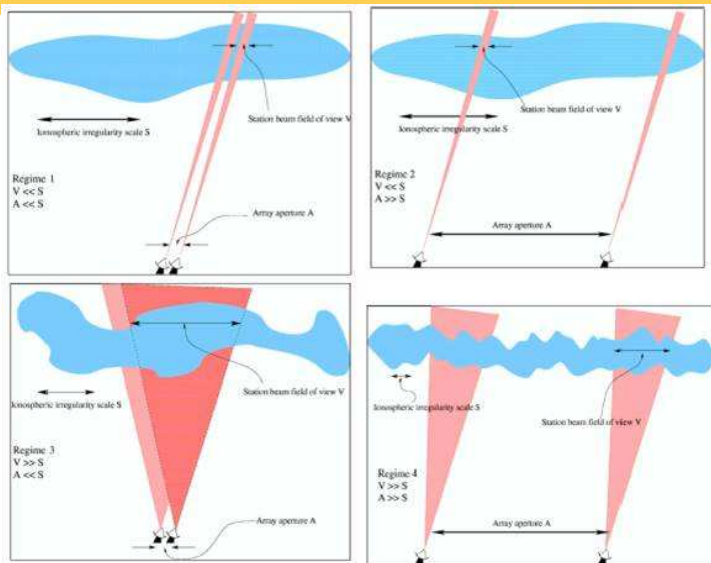
Propagation effects due to the atmosphere

- 1 Ionosphere at low frequencies, and Troposphere at high frequencies
- 2 Absorption (Emission) by the medium - attenuation (distortion) in amplitude
- 3 Distortion of the phase
- 4 Variability $\mathcal{P}(x, y, \theta, \phi, t)$
 - 1 Large scale changes (e.g. diurnal variation)
 - 2 Small scale changes (e.g. turbulence)

Ionospheric Propagation Effects



Ionospheric Calibration regimes



Direction Dependent Effects

- 1** Instrumental - Departures of individual primary beams from the reference model
 - 1** Mechanical deficiencies
 - 2** Residual pointing offsets
 - 3** usually stable or change in a predictable manner
- 2** Natural - Effects of propagation through the atmosphere - ionosphere, troposphere ($\mathcal{F}(x, y, \theta, \phi, t)$)
- 3** Image plane effects

Direction Dependent Effects...

1 Taking DDEs into account

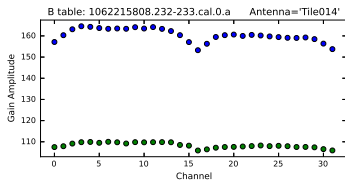
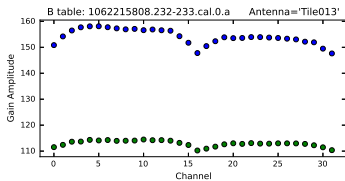
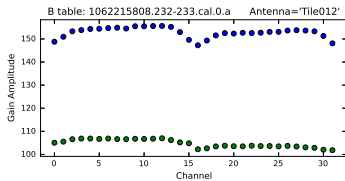
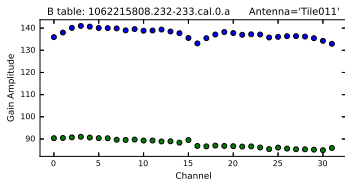
- 1 Account for differences between beams of different antennas
- 2 Need to be taken into account on a per visibility basis
- 3 Current approach - perturbation theory based
- 4 Enormous increase in computational complexity
- 5 Possible in research labs, but not in practise yet

Bandpass calibration

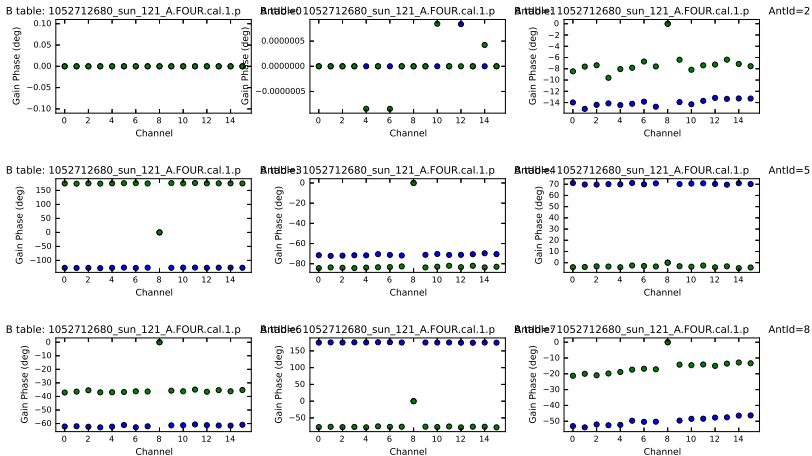
- 1 Delay calibration - removes any signal path (delay) differences across individual signal paths - pure phase ramps
- 2 Take into account changes in antenna gain with frequency

$$\mathcal{G}_{i,j}(\nu) = g_i(\nu) g_j^*(\nu)$$

Bandpass Amplitudes



Bandpass Phases



Calibration Model

- 1 $g_i(\nu, t) = g_i(\nu) g_i(t)$
- 2 $g_i(\nu)$ - **Bandpass** varies slowly - needs to be calibrated infrequently - typically at the start and end of an observing run
- 3 $g_i(t)$ - **Gain** varies faster - needs to be calibrated more frequently - typically every 30 min to an hour
 - 1 Flux calibration (amplitude) - stable and usually done at the start and end of an observation
 - 2 Phase calibration - variable,

Test signals in the sky

- 1 Accurately known positions in the sky
- 2 Not significantly variable
- 3 Known and simple spectra
- 4 Lie in comparatively 'empty' fields, no strong 'confusing' sources nearby
- 5 Firm prediction of $V_{i,j}(\nu, t)$

1 Flux calibration

- 1 Stable, regularly monitored fluxes with accurate radiometers
- 2 Unresolved, or a good model for the source
- 3 Usually quite a strong source
- 4 Primary flux calibrators - 3C48, 3C147, 3C286 and 3C295

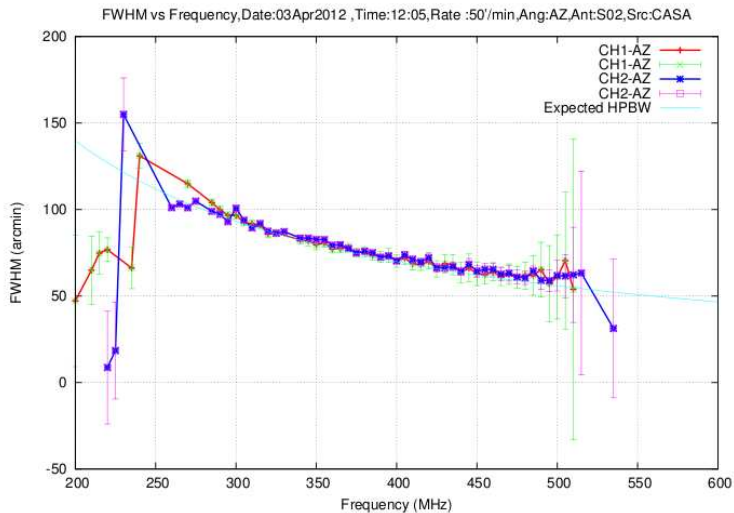
2 Bandpass calibration

- 1 Strong source
- 2 Source structure is less important

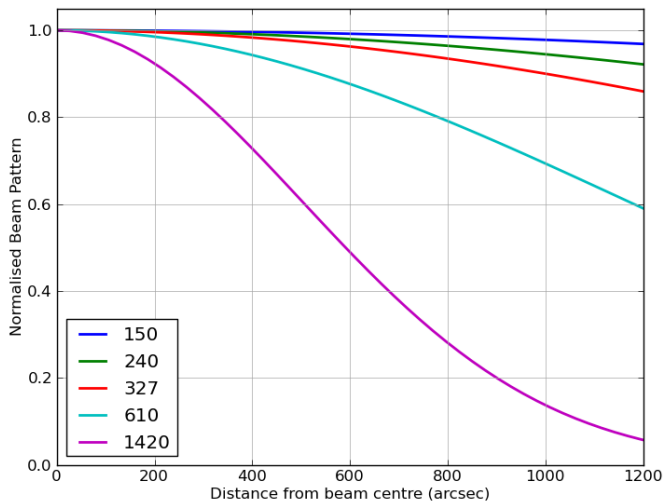
3 Phase calibration

- 1 Unresolved source close to the target source

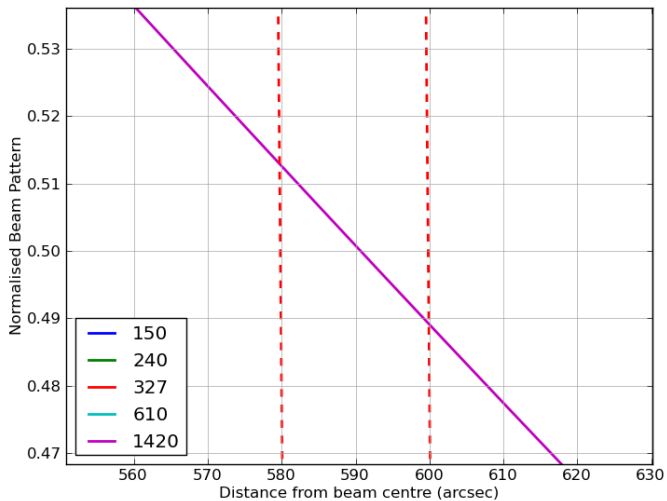
Beamwidth vs Freq.



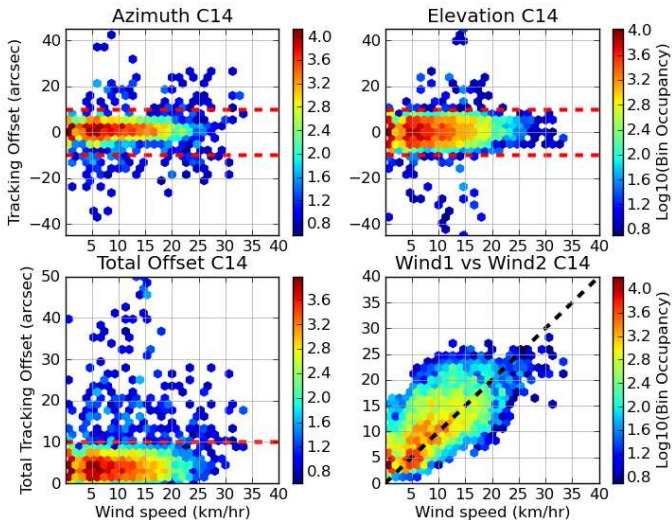
Impact of Tracking errors



Impact of Tracking errors



GMRT Tracking errors



Perytons at Parkes - 27 yr old Mircowaves!

Table 1. Properties of the perytons from January 2015

Date (dd-mm-yy)	Time (UTC)	DM (pc cm ⁻³)	DM error	S/N (beam 01)	Width (ms)	Telescope Azimuth (deg)	Telescope Elevation (deg)
2015-01-19	00:39:05	386.6	1.7	24.8	18.5	10.7	75.3
2015-01-22	00:28:33	413.8	1.1	42.5	18.5	73.9	36.2
2015-01-23	03:48:31	407.4	1.4	10.6	18.5	323.2	40.2

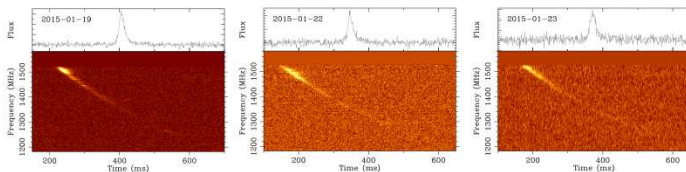


Figure 1. The time-frequency structure of the three January perytons. In the case of events on 2015-01-19 and 2015-01-23 the summed 13-beam data is shown. For 2015-01-22 only beam 01 is plotted as the outer beam data was not recorded to disk.

Petroff et al., 2015