Astronomical Techniques II
Lecture 8 - Calibration and Imaging

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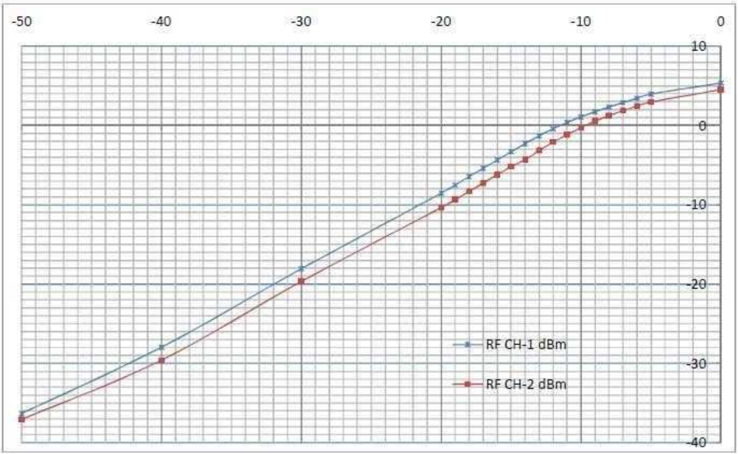
Calibration Framework

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. *Linear* regime $\implies$ $g_i(t)$s are independent of $V_{i,j}(t)$
   2. $g_i(t)$s are *direction independent*
   3. Availability of a *perfect* calibrator

Linearity of GMRT 327 MHz front-end



Direction Dependent Effects

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. Enromous increase in computational complexity
    5. Possible in research labs, but not in practise yet

Delay Calibration

1. $V_{i,j}(t) =$
$$\int_0^\infty \left(\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A_\nu(l, m)\, B_\nu(l, m) e^{-2\pi i \nu \tau_g)}\, dl\, dm \right)$$
$$e^{2\pi i \nu \Delta \tau_r} \mathcal{G}_{i,j}(t, \nu)\, d\nu$$
2. Residual delay gives rise to a phase ramp $\Delta\phi = 2\pi\Delta\nu(\tau_g - \tau_r)$
3. τ_g 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. $\phi_g = 2\pi\nu\tau_g = 2\pi w = \frac{2\pi}{\lambda}(L_x\ cosH\ cos\delta - L_y\ sinH\ cos\delta + L_z\ sin\delta)$
2. $\Delta\phi_g = \frac{2\pi}{\lambda}(\Delta L_x\ cosH\ cos\delta - \Delta L_y sinH\ cos\delta + \Delta L_z\ sin\delta$
$+\Delta\alpha\ cos\delta(L_x\ sinH + L_y\ cosH)$
$+\Delta\delta(-L_x\ cosH\ sin\delta + L_y\ sinH\ sin\delta + L_z\ cos\delta))$
3. Reduce $\Delta\phi_g(t)$ to less than 1 radian

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

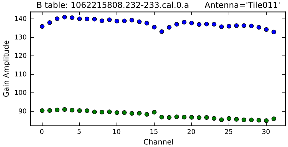
Propagation effects due to the atmosphere

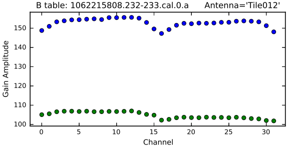
1. Ionosphere at low frequencies, and Troposphere at high frequencies
2. Absorption by the medium - reduction in amplitude
3. Distortion of the phase

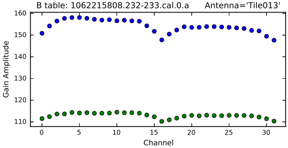
Bandpass calibration

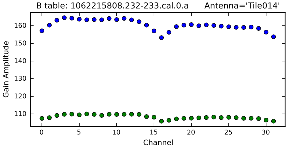
1. Delay calibration - removes any propagation differences across individual signal paths - pure phase ramps
2. Take into account changes in antenna gain with frequency $\mathcal{G}_{i,j}(\nu) = g_i(\nu)\, g_j^*(\nu)$

Bandpass Amplitudes

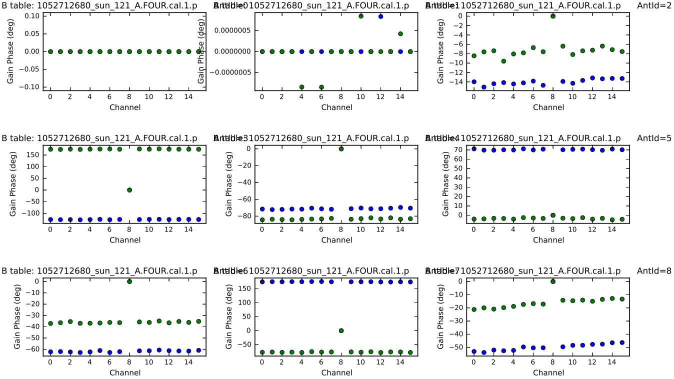








Bandpass Phases



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 much 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

Closure Quantities

1. $\mathcal{G}_{i,j}(t) = g_i(t)\ g_j(t)\ g_{i,j}(t)$
    1. $\mathcal{A}_{i,j}(t) = a_i(t)\ a_j(t)\ a_{i,j}(t)$
    2. $\phi_{i,j}(t) = \phi_i(t) - \phi_j(t)\ + \phi_{i,j}(t)$
2. Closure Amplitude (for a point source of flux S)
    1. $\tilde{A}_{i,j} = a_i\ a_j\ a_{i,j}\ S$
    2. $a_{i,j} = \dfrac{\tilde{A}_{i,j}}{a_i\ a_j\ S}$
3. Closure Phase
    1. $\tilde{\phi}_{i,j} = \phi_i - \phi_j + \phi_{i,j}$
    2. $\phi_{i,j}(t) = \tilde{\phi}_{i,j}(t) - \phi_i(t) + \phi_j(t)$