VLBI Data Analysis

Calibration, Edition and Fringe Fitting

Eduardo Ros\textsuperscript{1,2} & Matthias Kadler\textsuperscript{3,4}


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Calibrating and editing

- **CALIBRATION**: Removal of instrumental factors in the measurements
- Every physicist has to calibrate the instrument of measure being used
- **EDITION**: *no data are better than bad data*
Calibration - why? (i)

- Synthesis radio telescopes are not perfect (surface accuracy, receiver noise, etc.)
- Technical devices with different processes involved (frequency conversion, digital sampling, etc.)
- Control during the observation occasionally fails: calibration or edition of the data
Calibration - why? (ii)

- Scheduling and observing errors do occur (wrong source positions, slewing times different than expected, etc.)
- Atmospheric and space weather (ionosphere) conditions are not ideal
- RFI
Calibration methods

- **Direct calibration:**
  - Some parameters of the observations are known (geometry of the interferometer)
  - VLA: amplitude stability over 1%
  - VLBI: impossible

- **Calibrator sources in the sky:**
  - Calibration observing well-known objects
  - Monitoring of phase: phase-referencing
  - Monitoring of gain: determination of amplitudes

- **Self-calibration**
Instrumental effects, stable with time

- Antenna position coordinates: *geodetic values (ITRF)*
- Antenna pointing corrections: *pointing model elaborated at the telescopes*
- Zero-point setting of instrumental delays: *known by GPS values or another methods*
Stable effects during the observation

- Dry component of the atmospheric delay: *meteorological values*
- Antenna gain as a function of elevation: *gain curves determined at the telescopes*
- Shadowing of antennas by close ones: *at close elements (VLA), known at the scheduling*
Variable effects during the observation

- Variations at the system temperatures: *direct measurements and recording of the data*
- Phase variations in the local oscillator: *to be tracked*
- Wet component of the atmospheric delay: *determined with meteorological measurements, WVR*
What do we want and what do we get

- We want to obtain the visibility function, which has to be inverted to obtain the brightness distribution:

\[
V(u, v) = \int I_v(x, y) e^{-i2\pi(ux+vy)} \, dx \, dy
\]

- We obtain the correlation of the electric field (voltage) sampled at pairs of telescopes (baselines \(ij\))

\[
V_{ij}(t) = \left\langle x_i(t)e^{i\phi_i^{\text{comp}}} \cdot x_j^{\ast}(t)e^{-i\phi_j^{\text{comp}}} \right\rangle_t
\]
The measured signal

- The net signal delivered by antenna $i$, $x_i(t)$, is a combination of the desired signal, $s_i(t,x,y)$, corrupted by a factor $J_i(t,x,y)$ and integrated over the sky, and noise, $n_i(t)$:

$$x_i(t) = \int J_i(t,x,y)s_i(t,x,y) \, dx \, dy + n_i(t)$$

$$= s_i'(t) + n_i(t)$$

- $J_i(t,x,y)$ is the factor to be calibrated, it is antenna-based

- Sometimes, the effects contained in this term are irreversible and the data have to be edited
Correlation of signals

- The noise doesn’t correlate:

\[ \langle x_i \cdot x_j^* \rangle = \langle (s_i' + n_i) \cdot (s_j' + n_j)^* \rangle \]

\[ = \langle s_i' \cdot s_j'^* \rangle + \langle s_i' \cdot n_j^* \rangle + \langle n_i \cdot s_j'^* \rangle + \langle n_i \cdot n_j^* \rangle \]

\[ = \langle s_i' \cdot s_j'^* \rangle \]

\[ = \langle \int J_i(t)s_i(t) \, dldm \cdot J_j^*(t)s_j^*(t) \, dldm \rangle \]

\[ = \langle \int J_i(t)J_j^*(t)s_i(t)s_j^*(t) \, dldm \rangle \]

- Even if \( n_j >> s_j \), the correlation isolates the desired signals
Calibration sequence
(signal path)

- Faraday rotation
- Tropospheric effects
- Parallactic angle
- Antenna voltage pattern
- Polarization leakage
- Electronic gain
- Bandpass response
Ionospheric Faraday Rotation

- The ionosphere is birefringent, and one hand of the circular polarization is delayed wrt the other, introducing a phase shift:

\[ \Delta \phi = 0.15 \lambda^2 \int B_n ds \text{ deg} \]

\[ \lambda \text{ in cm, } n_e ds \text{ in } 10^{14} \text{ cm}^{-2}, B_n \text{ in G} \]

- Rotates the linear polarization position angle

- Important at long wavelengths, at sunrise or sunset, and at a maximum of solar activity

- Example:

\[ TEC = \int n_e ds \sim 10^{14} \text{ cm}^{-2}; B_n \sim 1 \text{ G}; \lambda = 20 \text{ cm} \rightarrow \Delta \phi \sim 60^\circ \]
Troposphere

- Polarization-independent
- Amplitude effect: opacity
- Phase effect: refraction
- Effect: 2m (7ns) excess path length at zenith compared to vacuum
- Important at high frequencies, where water vapour absorbs and emits
- Correction: *water vapor radiometer, frequency switching?*
Parallactic angle

- Orientation of receiver with respect to the field of view
- Constant for equatorial telescopes
- Variable for alt-az

\[ \chi(t) = \arctan \left( \frac{\cos(l) \sin(h(t))}{\sin(l) \cos(\delta) - \cos(l) \sin(\delta) \cos(h(t))} \right) \]

where

- \( l \) = latitude,
- \( h(t) \) = hour angle,
- \( \delta \) = declination

- Rotates the position angle of linearly polarized radiation
Antenna voltage pattern

- Antennas have a direction-dependent gain
- Important for wide-field mapping (region of sky comparable or larger than $\lambda/D$
- Important at low frequencies
Polarization leakage

- Orthogonal polarizations are not completely isolated
- Feeds have a value of $d$ of a few percent or less
- Frequency-dependent
- For RCP/LCP systems, the total intensity image is affected as $\sim dQ, dU$ (important only for high dynamic range imaging), and the linear polarization imaging is affected as $\sim dI$ (very important)
Electronic gain (i)

- Includes most of the amplitude and phase effects introduced by the electronics: amplifiers, mixers, quantizers, digitizers
- Dominates all the other effects
- Causes the scaling from engineering to radio astronomical units (Jy)
- Excludes frequency-dependent effects
Electronic gain (ii)

- Flux density observed for a given baseline:

\[ S_{ij} = A_{ij}b \sqrt{\frac{T_{si}T_{sj}}{K_iK_j}} \]

- \( A_{ij} \) is the measured visibility amplitude (raw correlation coefficient)
- Digitization losses: \( b \)
- \( K_i \) are the antenna sensitivities (K/Jy)
- \( T_{si} \) are the system temperatures in K
Electronic gain (iii)

- It is instructive to express the system temperature in terms of the system equivalent flux density, \( SEFD \):

\[
SEFD_i = \frac{T_{s_i}}{K_i}
\]

- Examples at 5GHz:
  - Jodrell Bank, 26m, \( SEFD = 366 \) Jy
  - Effelsberg, 100m, \( SEFD = 39 \) Jy
  - Noto, 32m, \( SEFD = 220 \) Jy
  - VLBA antenna, 25m, \( SEFD = 300 \) Jy
Electronic gain (iv)

- Sensitivity of an interferometer:

\[
\Delta S_{ij} = \frac{1}{\eta_s} \sqrt{\frac{SEFD_i \cdot SEFD_j}{2\Delta \nu \tau_{acc}}}
\]

- Electronic losses \( \eta_s \)
- \( \Delta \nu \) is the observing bandwidth
- Accumulation time \( \tau_{acc} \)
Bandpass response

- Frequency-antenna electronics
- The filters used to select the frequency passbands are not square
- Typically normalized
More effects...

- Errors in the geometric and the clock models, affecting the phase: solved by FRINGE-FITTING
- Baseline-based errors not included into antenna-based factors
  - Correlators are designed to prevent that
  - Averaging in time and frequency
  - Correlated noise (RFI)
  - Indistinguishable from source structure effects
Planning for good calibration: values provided by the observatory

- Antenna positions, earth orientation
- Clocks
- Antenna pointing, gains, voltage pattern
- Calibrator coordinates, flux densities, polarization properties
Planning for good calibration: absolute calibration

- VLBI: FORGET IT!
Planning for good calibration: cross-calibration

- Observe nearby point sources (predictable visibilities) and transfer solutions to target observations
- Observe a calibrator of known flux density
- Polarization observations:
  - Observe strong and unpolarized calibrators
  - Observe a broad range of parallactic angle
Radio Frequency Interference

- Originated from human beings
- Obscures natural emission in spectral line observations
- Adds to total noise power, making the amplitude calibration more difficult
- Can correlate between antennas close to each other

Mitigation:
- Electronic design in antennas
- Choose interference-free frequencies
- Observe continuum channels in spectral-line modes to edit bad channels
Putting all that in practice.

The data reduction...
Raw correlator output

Raw Correlator Output Phases

Fringe rates

Delay

Before Calibration
System temperature calibration

Rain and low elevation effects

Graphics by C. Walker
The use of 2-bit sampling causes a bias in the data due to digitization - can be estimated from the data itself and corrected.

Amplitude corrections not larger than 5%
Gain curve correction

VLBA gain curves, dependence of the antenna gain as function of elevation.

Image by C. Walker
Atmospheric opacity

Absorption of the atmosphere
Pulse cal system (i)

Correction of the instrumental phase shifts: pulse injection once per microsecond

Pulse-cal tones

Monitoring of data

Graphics by C. Walker
Pulse cal system (ii)

Data aligned with pulse-cal

VLA: no phase-cal, phases are not aligned

Graphics by C. Walker
Ionosphere

Delay scales with $\frac{1}{\nu^2}$

Dominates at low frequencies

Can be corrected with dual band observations (8.4/2.3 GHz in geodesy)

Ionosphere models based in GPS measurements
Correction of parallactic angle

- Include the effect of the rotation of the receiver w.r.t. the sky in the phases
- Important in geodesy and in polarization observations
Editing bad data (i)

No data are better than bad data

- Automatic flagging of data: antenna off source, problems at synthesizers, low elevation
- Examining data: most of the causes of poor data are antenna-based
  - Weather
  - Bad playback
  - RFI
  - Bad automatic flagging
Editing bad data (ii)

Raw data, not edited

Edited data

Graphics by C. Walker
Editing bad data (iii)

- **Steps:**
  - Check the performance of the antennas in the logs, and edit consequently.
  - Removal of outliers and inconsistent data.
  - Editing during the calibration, if insuperable difficulties appear.
  - Editing during the imaging process, to improve the map quality.
Bandpass calibration

“Self-calibration” in each channel

Needed for spectral line analysis

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Eduardo Ros – Multiwavelength School

Graphics by C. Walker
Amplitude check

Visibility amplitude before mapping
Fringe fitting (i)

- Raw correlator data have phase slopes in time (fringe rate) and frequency (delay)
- Fringe fit is self calibration with first derivatives in time and frequency
- When is done:
  - Fit one scan to align channels: *manual phase cal*
  - Used to allow averaging in frequency and time, with corrections for smearing, getting a higher SNR for astronomical purposes (imaging)
  - Used to get slopes in frequency for geodetic purposes (the delay is the main observable)
Fringe fitting (ii)

- Steps in the process:
  - FFT in 2D to estimate rates and delays to the reference antenna – search windows can be restricted
  - Least squares fit to the phases starting at the FFT estimate
Fringe fitting (iii)

- **Baseline-based fringe fitting**
  - Not affected by poor source model
  - Used in geodesy

- **Global fringe fitting**
  - One phase, rate, and delay per antenna
  - All data used: high SNR
  - Source model allows improvement
  - Used for imaging
Fringe fitting (iv)

High SNR case

Input phase turns

Result of FFT

Graphics by C. Walker & G. Moellenbrock
Fringe fitting (v)

Low SNR case

Input phase turns

Result of FFT

Frequency

Delay

Images by C. Walker & G. Moellenbrock
Calibration step by step (i)

Phase slopes across each IF, offsets between IFs

Uncalibrated amplitudes (correlation coefficients)

Raw data from the correlator
Calibration step by step (ii)

Amplitude calibration

Calibrated amplitudes, in Jy
Phase calibration introduced

No offsets between different IFs
Calibration step by step (iv)

Solved for phase (equals zero) and delay (no slope).

The data can be averaged in time and frequency. READY TO MAP!

Fringe-fitting done
Polarization calibration

- Determination of the instrumental polarization: leakage factors at the antenna feeds, the so-called *D-terms*
- After fringe-fitting and self-calibration, use of a source model following the method described in Leppänen et al., AJ, 110, 2479 (1995) [multi-component similarity approximation]
- Absolute Electric Vector Position Angle (EVPA) calibration needed afterwards, comparing with a known, stable case (3C286, 3C138)
Astrometric/geodetic observations

- Use of the group delay using widely spread bandwidths
- Generally observing 2.3 and 8.4 GHz to remove ionosphere
- Solutions of data analysis:
  - Antenna and source positions
  - Earth orientation parameters (UT1-UTC, nutation, etc.)
  - Atmosphere and clock behavior
  - Accuracies better than 1 cm and 1 mas
- Geodesy: International VLBI Service
Credits

- Moellenbrock, 2002, Socorro Summer School, talk on *Calibration and Data Editing* (http://www.nrao.edu)
- Walker, 2002, Socorro Summer School, talk on *VLBI* (http://www.nrao.edu)