Calibration principles

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Data calibration

Outline

- **Introduction**
- **The atmosphere** our best enemy
- **Formalism** deriving antenna gains
- **Bandpass** phase and amplitude vs freq
- **Phase** phase vs time
- **Amplitude** amplitude vs time
- **Flux** absolute flux scale
Introduction

Measurements

• At any time \( t \), the interferometer provides:
  – \( V(\nu,t) \) = spectrum
  – \( V(t) \) = continuum data = spectrum average

• We do not consider \((u,v)\) dependence, only \( t \)

• Need various \textit{calibrations} because
  – electronics have variable gains (both amp. and phase, both frequency and time)
  – atmosphere absorption and path length fluctuations
Introduction

Telescope calibration

- Pointing
- Focus
- IF filters band pass
- Atmospheric calibration
- Antenna positions
- Delay
- Atmospheric phase correction

Real-time calibrations

Done real-time but new values can be entered off-line if necessary

Done real-time but uncorrected data are also stored
The atmosphere
Our best enemy

- Thermal emission $\rightarrow$ noise
- **Absorption of incoming signal** $\rightarrow$ attenuation
- Time- and position- dependent **phase error**
  $\rightarrow$ Radio “seeing”
  $\rightarrow$ Amplitude decorrelation

- Amount of **water vapor is highly variable** in time
  - Need real-time calibration of signal attenuation
  - Need real-time calibration of phase fluctuations
The atmosphere

Absorption
The atmosphere Absorption calibration

- Goals
  1. Correct for atmospheric absorption
  2. Backend counts $\rightarrow$ Temperature (Kelvin)

- At mm wavelengths, this must be done very often (20 min) because
  - Receiver gain drift
  - Atmosphere fluctuations
The atmosphere

Absorption calibration

• Assume linear answer of receiving system
  \[ \text{Counts} = \alpha (T_e^{-\tau} + T_{\text{sys}}) \]
• Observe sky, cold (4K), and warm (273 K) loads
• Compute:
  – System temperature \( T_{\text{sys}} \)
  – Receiver gain \( \alpha \)
  – Atmosphere opacity \( \tau \) (using atm. model)
The atmosphere
Phase correction

• Timescale of phase fluctuations: seconds to hours

• Need **real-time correction** of fluctuations during basic integration time (< 1 min) to avoid
  – loss of amplitude = **decorrelation** by \( \exp(-\sigma^2/2) \)
  – “**seeing**” (phase ↔ position)

• This is conceptually similar to **piston correction** in adaptative optics in optical/IR domain
The atmosphere
Phase correction

- Predict amount of water from **water line at 22 GHz (NOEMA)** or **183 GHz (ALMA)** using dedicated receivers (Water Vapor Radiometers = WVR)

- Measurement → Atmospheric **model** → Water vapor content → Path delay → Atmospheric phase → Real-time correction

- Done **every few second** at NOEMA
- Keep both corrected and not corrected data
The atmosphere
22 GHz WVR (PdBI)

New generation under development
The atmosphere

183 GHz WVR (ALMA)
Dedicated talk by M. Bremer
Amplitude vs time for calibrator (point source)
Baseline-based calibration vs. antenna-based calibration
Formalism
Visibilities

• Calibrate only temporal or frequency effects, do not consider dependence on \((u,v)\)
• True visibility: \(V_{ij}(\nu,t)\) (baseline ij)
• Observed visibility:
\[
V_{\text{obs}ij}(\nu,t) = G_{ij}(\nu,t) V_{ij}(\nu,t) + \text{noise}
\]
• \(G_{ij}\) = complex gain (amplitude & phase)
• Scalar description – no polarization
Formalism

Gain decomposition

• **Most of the effects are antenna-based**
  – Pointing, Focus, Antenna position, Atmosphere, Receivers noise, Receivers bandpass...

• **Gain decomposition**: \( V_{obs_{ij}} = G_{ij} V_{ij} = g_i g_j V_{ij} \)

• Baseline-based effect?
  – Correlator bandpass → real-time calibration
  – Time and frequency averaging → decorrelation
Formalism

Antenna-based gains

- Observation of a **point source** of flux $S$:

$$V_{\text{obs}} = G_{ij} V \quad V = S \quad V_{\text{obs}} = G_{ij} S$$

- Antenna-based gains:

$$V_{\text{obs}} = g_i g_j S$$

- Can solve for antenna gains with 3 antennas

$$ (g_1)^2 = \frac{V_{\text{obs}_{12}} V_{\text{obs}_{31}}}{S \ V_{\text{obs}_{23}}} $$
Formalism

Antenna-based gains

- Observation of a **point source** of flux $S$:

  $$V_{\text{obs}} = G_{ij} V \quad V = S \quad V_{\text{obs}} = G_{ij} S$$

- Antenna-based gains:

  $$V_{\text{obs}} = g_i g_j S$$

- $N$ complex unknowns (one $g_i$ per antenna)
- $N(N-1)/2$ equations (one per baseline)
- **System is over-determined** and may be solved by a method of **least squares**
Antenna “observation” = $g_i \sqrt{S}$
Ref. antenna: phase = 0
Advantages of using the antenna-based gains:

1. most of the effects are truly antenna-based
   example: pointing, focus, ...

2. precision to which antenna gains are determined is improved by a factor $\sqrt{N}$ over the precision of the measurement of baseline gains
Formalism

Closure relations

- Phase closure relation (point source):
  - Antenna-based decomposition: $\varphi_{12} = \varphi_1 - \varphi_2$
  - Phase closure: $\varphi_{12} + \varphi_{23} + \varphi_{31} = 0$

- Very useful relation when phases are too unstable to be directly measured (VLBI, optics)
- Similar relations exists for amplitude ratios

- The decomposition in antenna-based gains implicitly takes into account the closure relations
Data calibration

Time/Frequency

- **Basic assumption: time- and frequency-variations are decoupled**

- Quite robust:
  - Frequency response mostly due to receivers; stable until retuning
  - Time variations (atmosphere, antennas, ...) mostly achromatic
Millimeter interferometers

- **Bandpass** (amplitude and phase vs. frequency)
- **Phase** vs. time
- **Flux** scale
- **Amplitude** vs. time
Bandpass calibration

The problems

- Frequency dependence of the interferometer response arises from:
  - **Receivers intrinsic response**
  - Delay offsets (slope on phase)
  - Coaxial cables attenuation
  - Antenna chromatism
  - Atmosphere (O2, O3 lines)
  - ...
Bandpass calibration

Method

- A strong quasar is observed at the beginning of each project

- **Phase should be zero** (point source)
  **Amplitude vs. frequency should be constant** (continuum source)

- Potential problem: spectral index of quasars over large bandwidth
Bandpass calibration

Method

- Time calibration + average (improve the SNR)
- **Solve for antenna-based gains**
- **Fit as a function of frequency** (polynom)
- NB: gains defined such that integral = 1
- Apply the bandpass to all data

- Assume bandpass is constant with time
- Must be recalibrated if receivers are retuned
Bandpass calibration

Accuracy

- RF bandpass phase accuracy → uncertainty on relative positions of spectral features

- Rule of thumb:

\[
\text{Position error / Beam} = \frac{\Delta \Phi}{360}
\]

- 1” resolution observations, \(\Delta \Phi = 5 \text{ deg, error} = 0.015”\)
Bandpass calibration

Accuracy

- RF bandpass amplitude accuracy → may be important to detect weak line on a strong continuum

- Bandpass curve is a multiplicative factor
Phase calibration

The problems

- **Short-term time variation** of the phase is caused by the atmosphere

- **Long-term** time variation:
  - Antenna position errors (period 24 h)
  - Atmosphere up to ~1h
  - Antenna/electronics drifts

Phase calibration critical for final image quality
Phase calibration

Method

- Calibration
  - A point source (quasar) is observed every few min
  - Its phase must be zero
  - Solve for antenna-based gains
  - Fit as a function of time (spline)
  - Better: use two calibrators
  - Apply to all data
  - Plot per baseline: measurements + combination of antenna-based fits
Phase fluctuations are dominated by the instrument at those timescales.
• Atmosphere and most of the instrumental fluctuations scale with frequency

• **Phase transfer:**
  1. use low-frequency data (highest SNR) to derive phase curve
  2. scale according to frequency ratio
  3. correct the high frequency data
230 GHz data, no phase transfer
230 GHz, with phase transfer

- **Still residual phase** – most certainly due to the LO phase drifts, different between the two receivers – need final calibration

- Routinely used with old PdBI receivers. Planned for NOEMA (dual-band observations)

- Planned for ALMA high frequency receiver bands, but more problematic in submm domain (atmosphere)
Phase calibration strategies:
- effect of the noise on calibrators measurements?
- interpolation from calibrators to source?

**Fits**
1. Derive antenna phase
2. Fit continuous curve (e.g. spline)
3. Use that curve to correct source data in between calibrators

**Points**
1. Derive antenna phase
2. Trust it: use that value as calibration
3. Interpolate between the calibrators
Phase calibration

Strategies
Phase calibration

Strategies

Calibration at series of points + linear interpolation
Phase calibration

Strategies

Continuous fitting
Measurements have error bars
Phase calibration

Strategies

Measurements have error bars

Real phase: slow component
Phase calibration

Strategies

Measurements have error bars
Real phase: slow + fast component
Phase calibration
Strategies
Phase calibration
Strategies

phase

time
Phase is sampled at intervals $T_c \rightarrow$ fit is sensitive to errors due to the presence of the fast component ($<2T_c$), which can be large
Equivalent to **aliasing** of fast component into slow component
It is actually recommended to fit a curve that does not go through all points.
Phase calibration strategies:
- effect of the noise on calibrators measurements?
- interpolation from calibrators to source?

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Limited SNR & phase noise
OK if excellent SNR & no atmospheric phase noise
Phase calibration strategies:

- effect of the noise on calibrators measurements?
- interpolation from calibrators to source?

**Fits**
1. Derive antenna phase
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**Points**
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- **Limited SNR & phase noise**
  - NOEMA, ALMA high freq

- **OK if excellent SNR & no atmospheric phase noise**
  - VLA, ALMA low freq
Phase calibration

Radio seeing

- Phase fluctuations timescales:
  - $< 1$ min: real-time (WVR) phase correction
  - $1$ min – $20$ min: not corrected
  - $>20$ min: off-line phase calibration

- Can be estimated by rms of phase calibration fit
- Translate into a **radio seeing** $\sim$ phase rms / baseline
- Can be a fraction of the beam $\Rightarrow$ larger effective beam...
Seeing

Simulations: increasing the phase noise 3:10:50:100 (Nikolic et al. 2008)
Phase calibration

Fast switching

- **Reduce the switching time** calibrator-source down to 10 seconds

- **Advantages**: Remove a larger part of the atmospheric fluctuations spectrum. Perfect complement to the WVR corrections (second timescale)

- **Drawbacks**: Observing efficiency is decreased. Puts very strong constrains on the antennas and acquisition system.

- Planned for ALMA?
Phase calibration
Auto-calibration

• Simple case where the field contains a strong point source

• Can be used to calibrate out almost all phase fluctuations at periods > integration time (30 sec)

• Excellent results but for very specific projects
  – Absorption lines in quasars
  – Stars with strong maser lines
Phase calibration
Self-calibration

- **Extended (but simple) bright source?**
  1. Classical calibration with calibrators
  2. Source imaging & deconvolution
  3. Predicted visibilities ("model")
  4. Divide observed source visibilities by model
  5. Calibrate remaining variations
  6. Go to 2

- Can work because $N_{ant} < N_{baseline}$
- Requires enough SNR on source in each individual integration
Amplitude calibration

The problems

- Temperature (K) $\rightarrow$ Flux (Jansky)
  - Scaling by **antenna efficiency** (Jy/K)
  - **Not enough for mm-interferometers** because
    - Amplitude loss due to decorrelation
    - Variation of the antenna gain (pointing, focus)

- Need **amplitude referencing to a point source** (quasar) to calibrate out the temporal variation of the antenna efficiency – just like phase calibration
Flux calibration

The problems

• Problem: **all quasars have varying fluxes** (several 10% in a few weeks) and varying spectral indexes

• **Cannot rely on a priori antenna efficiency** to measure their fluxes (decorrelation...)

• Need to measure the quasar fluxes against
  – Planets
  – Strong quasars (RF)
  – MWC349, CRL618, ...

• Can be **difficult** if a good accuracy is required
Flux calibration

The problems

- Problem: all quasars have varying fluxes (several 10% in a few weeks) and varying spectral indexes
- Cannot rely on a priori antenna efficiency to measure their fluxes (decorrelation...)
- Need to measure the quasar fluxes against
  - Planets
  - Strong quasars (RF)
  - MWC349, CRL618, ...
- Can be difficult if a good accuracy is required

Caution: terminology

“(Absolute) Flux calibration” vs “Amplitude calibration”

Dedicated talk by
A.Castro-Carrizo
Flux calibration

Not a simple x factor
Flux calibration
Not a simple x factor
Flux calibration
Not a simple x factor

Wrong flux calibration can mimic source structure
Data calibration

Conclusions

• All calibrations rely on astronomical observations of quasars = point source, continuum
• **Phase** calibration is the most critical for image quality
• **Flux** calibration is the most difficult in practice