Data Calibration

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7th IRAM Millimeter Interferometry School
Grenoble, 4—8 October 2010
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
- No $(u,v)$ dependence
- Need various **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

New values can be entered off-line if necessary

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**
  $\rightarrow$ Amplitude decorrelation
  $\rightarrow$ Radio “seeing”

- 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

![Graph showing atmospheric transmission against frequency. Peaks at 22 GHz, 60 GHz, 118 GHz, 183 GHz, 325 GHz, and 380 GHz are labeled. Peaks correspond to water vapor (H₂O) and oxygen (O₂).]
The atmosphere
Absorption calibration

• Goals
  1. Correct for atmospheric absorption
  2. Backend counts → 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
  \[ \text{Counts} = \alpha (T_e^{-\tau} + T_{sys}) \]
- Observe sky, cold (4K), and warm (273 K) loads
- Compute:
  - System temperature \( T_{sys} \)
  - 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 (PdBI)** 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 second** at IRAM PdBI
- Keep both corrected and not corrected data
The atmosphere
WVR at 22 GHz

![Graph showing the atmospheric water vapor radiance (WVR) at 22 GHz with different water depth scenarios. The graph indicates the frequency range from 17 to 28 GHz with peaks around 22 GHz for different water depths.](image)
The atmosphere
Phase correction

- Limitations:
  - WVR stability and sensitivity
  - Uncertainties in the conversion factor

- **Cannot (yet) track the phase between sources**
- Only used for on-source phase fluctuations during \(~\text{minutes}\)
- Main effect = **remove the amplitude decorrelation**
Formalism

Visibilities

- Calibrate only temporal or frequency effects, no dependence on \((u,v)\)
- True visibility: \(V_{ij}(\nu,t)\) (baseline \(ij\))
- Observed visibility:
  \[
  V_{obs_{ij}}(\nu,t) = G_{ij}(\nu,t) V_{ij}(\nu,t) + \text{noise}
  \]
- \(G_{ij}\) = 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: \( V_{\text{obs}}_{ij} = G_{ij} V_{ij} = g_i g_j V_{ij} \)

• Baseline-based effect?
  – Correlator bandpass \( \rightarrow \) real-time calibration
  – Time and frequency averaging \( \rightarrow \) decorrelation
Formalism

Antenna-based gains

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

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

- Antenna-based gains:

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

- Can solve for antenna gains:

$$ (g_1)^2 = V_{\text{obs}_12} \, V_{\text{obs}_31} / S \, V_{\text{obs}_32} $$

- Do it for all triangles and average
Formalism

Antenna-based gains

- Observation of a **point source** of flux $S$:
  \[ V_{\text{obs}} = G_{ij} \, V \quad V = S \quad G_{ij} = \frac{V_{\text{obs}}}{S} \]

- Antenna-based gains: $g_i g_j = \frac{V_{\text{obs}}}{S}$

- $N$ 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**
Formalism

Gain decomposition

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: $\phi_{12} = \phi_1 - \phi_2$
  - Phase closure: $\phi_{12} + \phi_{23} + \phi_{31} = 0$

- 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
Data calibration
Steps

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 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 is 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 $\sim$1h
  - Antenna/electronics drifts

Phase calibration critical for final image quality
Phase calibration
Method

• Calibration
  – A point source (quasar) is observed every ~20min
  – 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.
Phase calibration strategies:

**Fits**
1. fit per baseline
2. compute antenna gains + fit per antenna

**Points**
1. use each point as calibration value + linear interpolation between the points
2. compute antenna gains + use each point as calibrator value + fit per antenna
Phase calibration
Strategies

\[ \text{phase} \]
\[ \text{time} \]
Phase calibration Strategies

Assumes
- excellent SNR for each point
- no atmospheric phase
Phase calibration
Strategies

Phase error from fast component

Fitted slow component

Actual slow component

Calibrator phases

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

(Lay, 1997)
Phase calibration
Strategies

Phase error from fast component

Fitted slow component

Actual slow component

Calibrator phases

Time

\( T_{\text{cyu}} \)

(Lay, 1997)

It is actually recommended to fit a curve that does not go through all points.
Phase calibration

Phase transfer

- 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. New receivers too sensitive – maybe for 0.8 mm band?
- Planned for ALMA high frequency receiver bands, but more problematic in submm domain (atmosphere)
Phase calibration

Radio seeing

- Phase fluctuations timescales:
  - < 1 minute: real-time atmospheric phase correction
  - 1 min – 1h: not corrected
  - > 1h: off-line phase calibration

- Can be estimated by rms of phase calibration fit
- Translate into a **radio seeing** \( \sim \) phase rms / baseline
- Typically \( 0.2''-1'' \)
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 $> \text{integration time (30 sec)}$

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

The problems

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

- Need \textbf{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 months) and 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
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