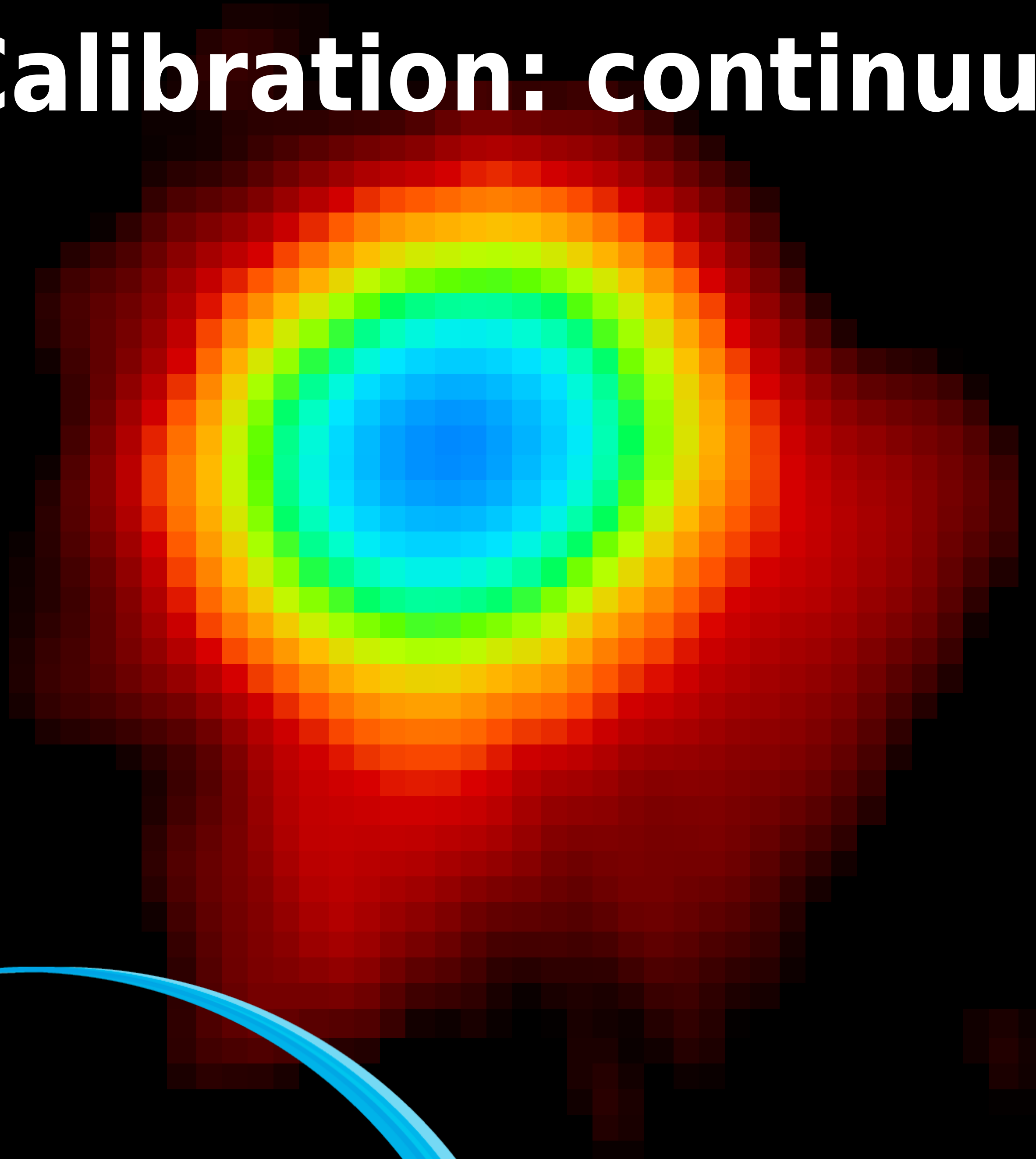
Calibration: continuum



EUROPEAN ARC

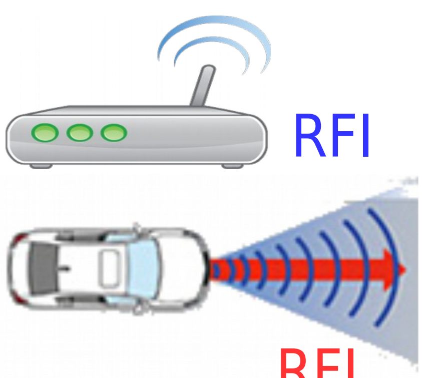
ALMA Regional Centre || UK

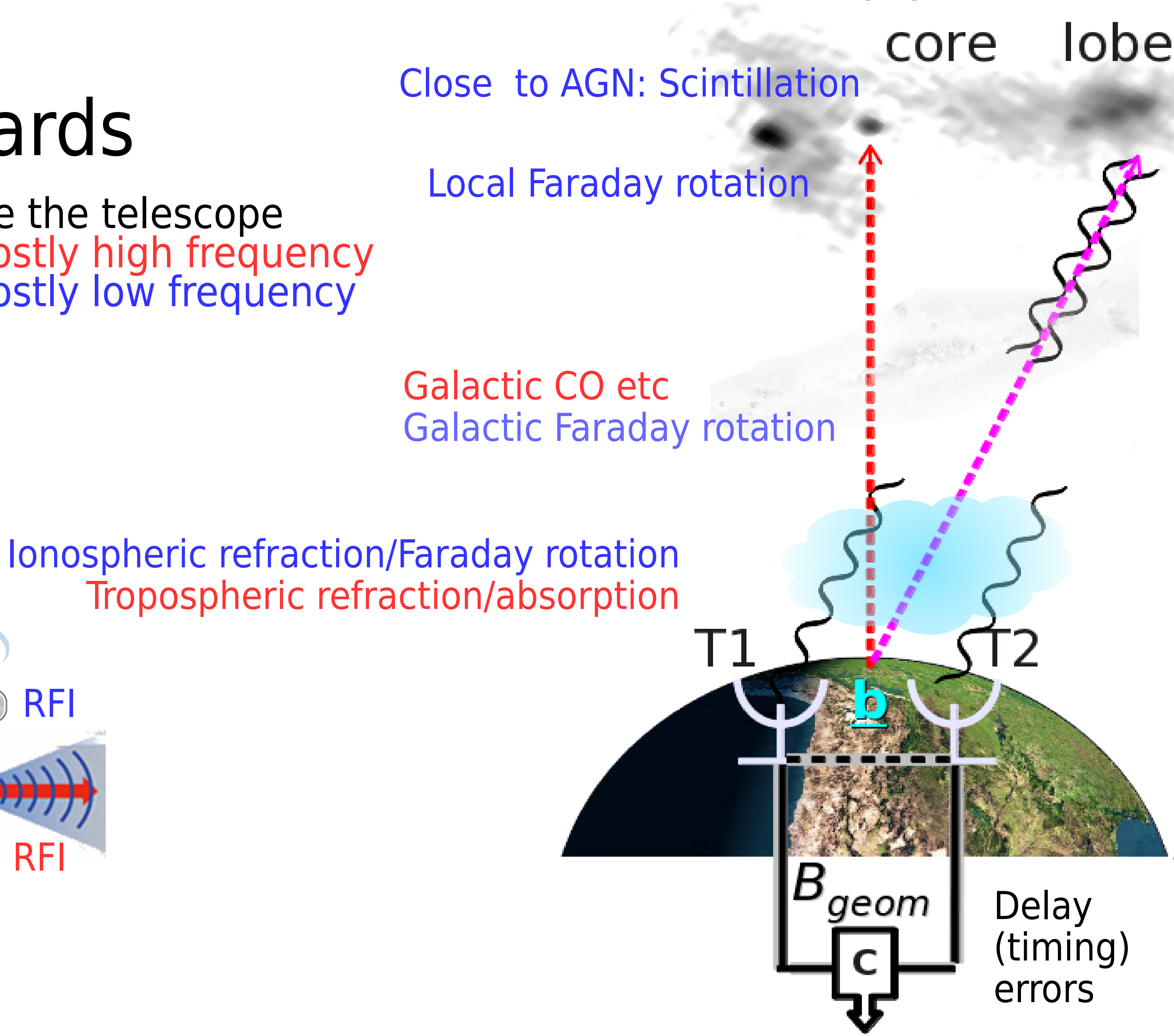
Summary

- What attacks the data
- Calibration before/during observations ('on-line')
- General post-observation calibration
  - Specific to observing modes, less so for targets
    - Bandpass, T_{sys} etc.
  - Often pipelined/performed by observatory staff
- Direction-dependent, astrophysical calibration
  - Phase-referencing
  - Target self-calibration
  - Some or all usually performed by proposers

Hazards

- Above the telescope
  - Mostly high frequency
  - Mostly low frequency

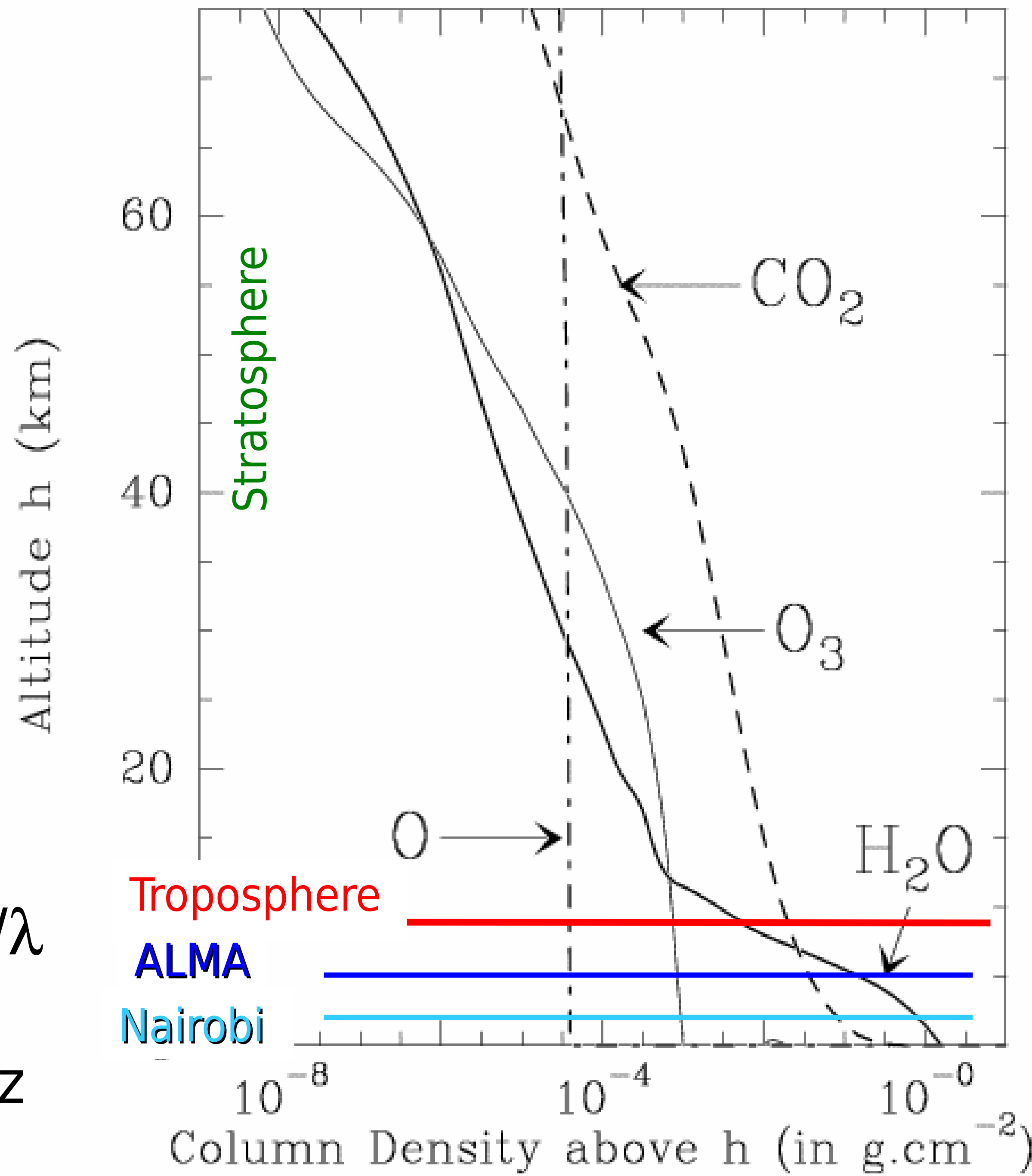




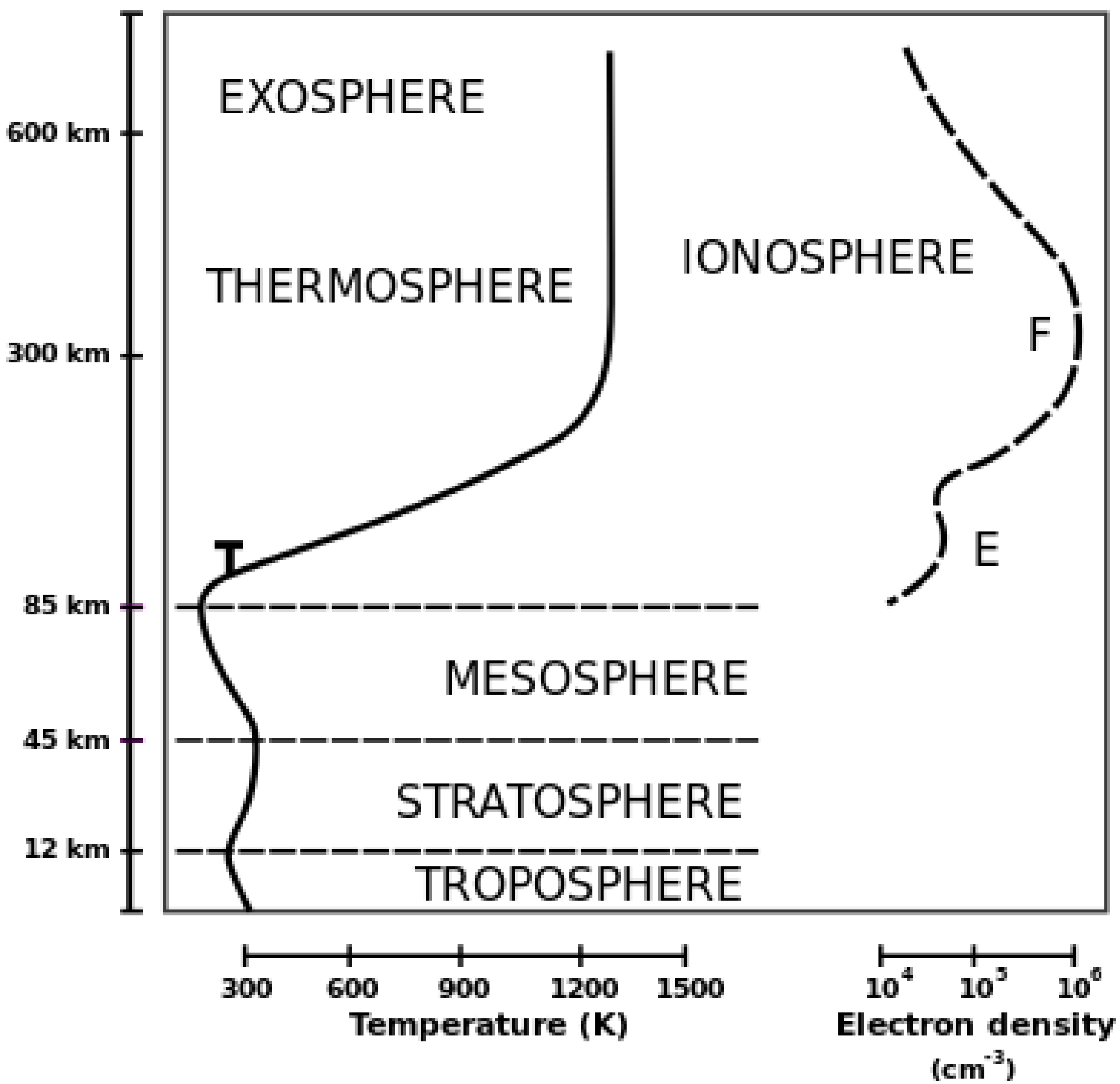
Troposphere

- Molecular refraction
  - 'Wet' H_2O vapour
    - Clouds worse!
  - 'Dry' e.g. O_2, O_3
- Refracts radio waves
- Phase distorted
  - $\Phi_c = n_{H2O}\, 2\pi/\lambda$
    - n_{H2O} water vapour refractive index
- Tropospheric errors $\propto 1/\lambda$
  - Significant at high frequencies $\nu \gtrsim 15$ GHz
  - Sub-mm observing at cold, high, dry sites

Column density as function of altitude



Ionosphere



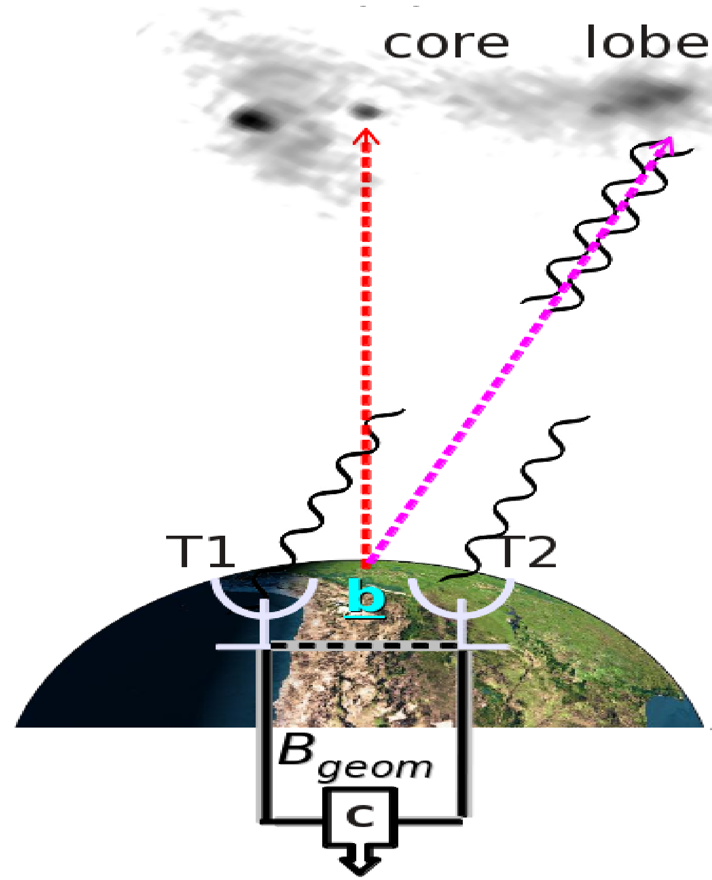
- Refraction by electrons
- Delay $\propto N_e \lambda^2$
  - N_e atmospheric electron column density
- Electrons spiral round Earth's magnetic field
  - Polarization angle of radiation Faraday rotated
- Ionospheric errors worst at ν<1 GHz
  - Exacerbated by Solar activity
  - λ>20m only from space – ionosphere not transparent
  - See LOFAR movie!

Hazards

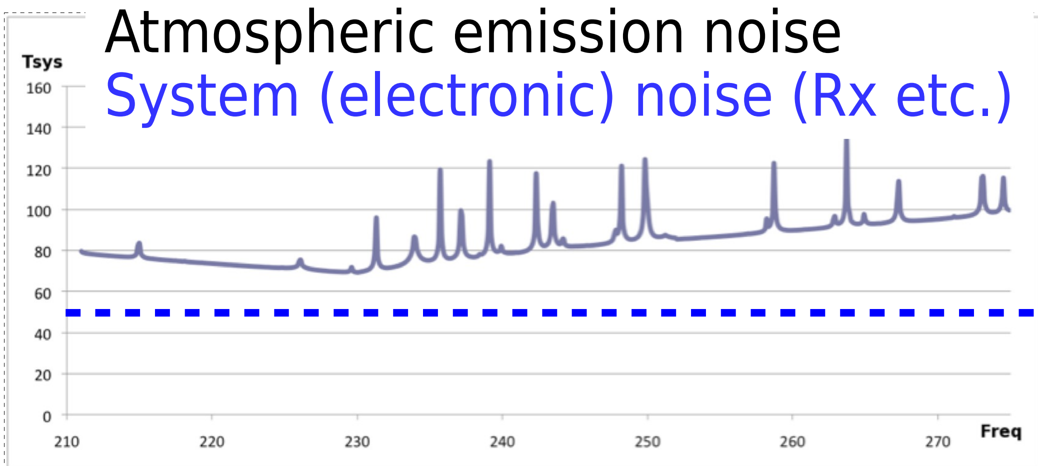
- At the telescope and later

Antenna positions
Pointing, Focus
Efficiency (surface)

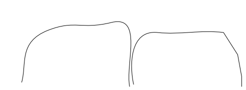
Timing and frequency information issues
(station clock, local oscillator...)



Atmospheric emission noise
System (electronic) noise (Rx etc.)

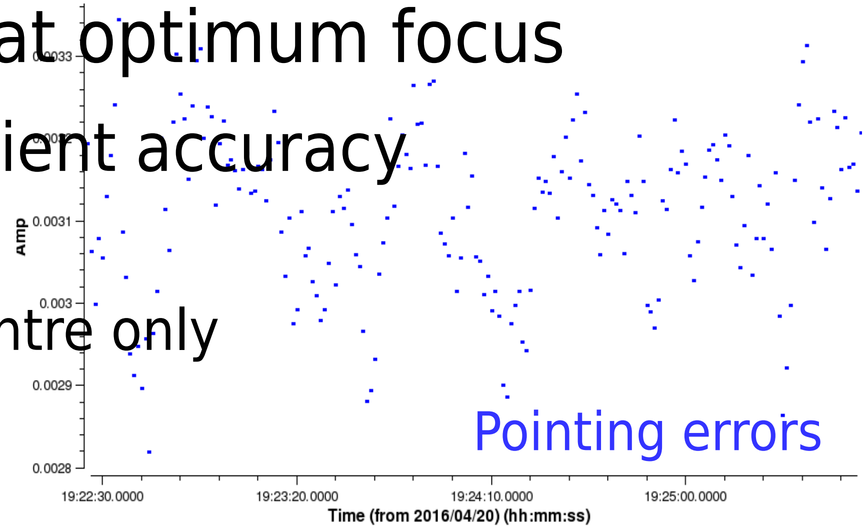


Insufficient corrections for
delay tracking

Bandpass response 

Calibration before/during observations

- Science observers don't usually need to worry about these (but you might when commissioning)
  - Applied before correlation
- Delay tracking
  - Correctable off-line if within Nyquist or sensitivity limit
  - Phase tones can be used to align antenna signals
- Antennas: receiver/subreflector at optimum focus
  - Pointing and tracking with sufficient accuracy
    - Error: 'scalloped' amps
      - Mitigated by self-cal at field centre only
  - Positions
    - Errors cause bad delays
    - Cannot transfer phase-ref corrections accurately to target



Off-line calibration

- Correlated data: series of complex visibilities
  - Metadata:
    - Descriptive: antenna table, source names etc.
    - Flagging: antenna not on source etc.
    - Calibration: Tsys measurements etc.
- Formats:
  - FITS (idi or uvfits) – stream of binary data + tables
  - Science Data Model – XML structure to hold binary data + metadata (very compact, good for transport)
    - Convert to Measurement Set or FITS for processing
  - Old proprietary formats: also must be converted

Visibility data: Measurement Set format

MAIN	**Model, e.g.:**	**Corrected data**	**Flags**
DATA *Original visibilities*	*FT of image made from MS* *FT of supplied model image* *FT of point flux density*	*Copy of visibilities with calibration tables applied* (Used in imaging not calibration)	(Edits are stored here first; backup tables can be made and used to modify)

- Instrumental calibration in tables inside MS
- Calibration derived during data reduction stored in external tables (similar format)
- Apply calibration to Data table to write Corrected
  - Corrected and Model can be re-initialised if you mess up!

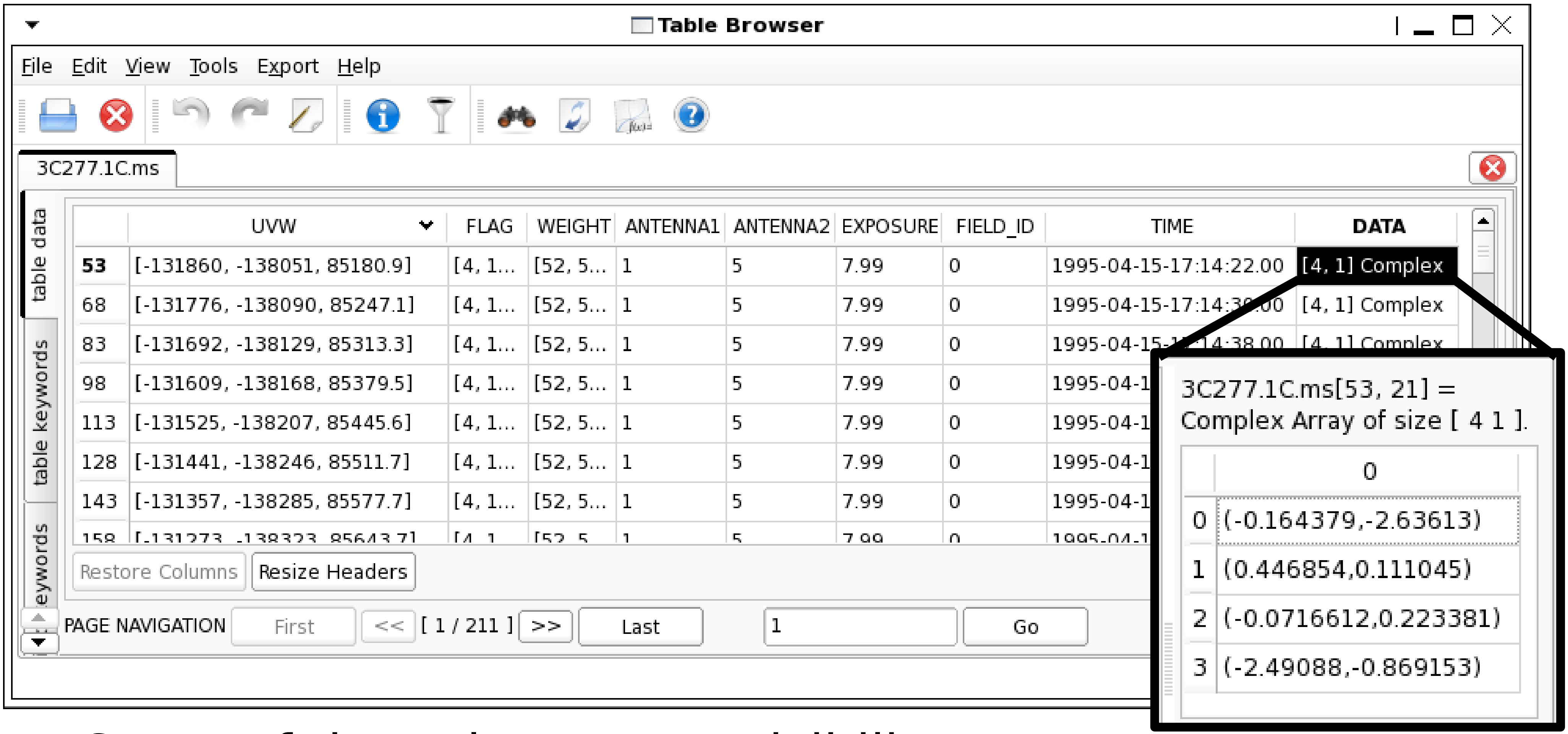
Measurement Set visibility data

- Directory of Tables
  - MAIN Data
    - Binary visibilities
  - Observational properties
  - Metadata
- Similar format for images
- Easy to access
- http://casa.nrao.edu/Memos/229.html

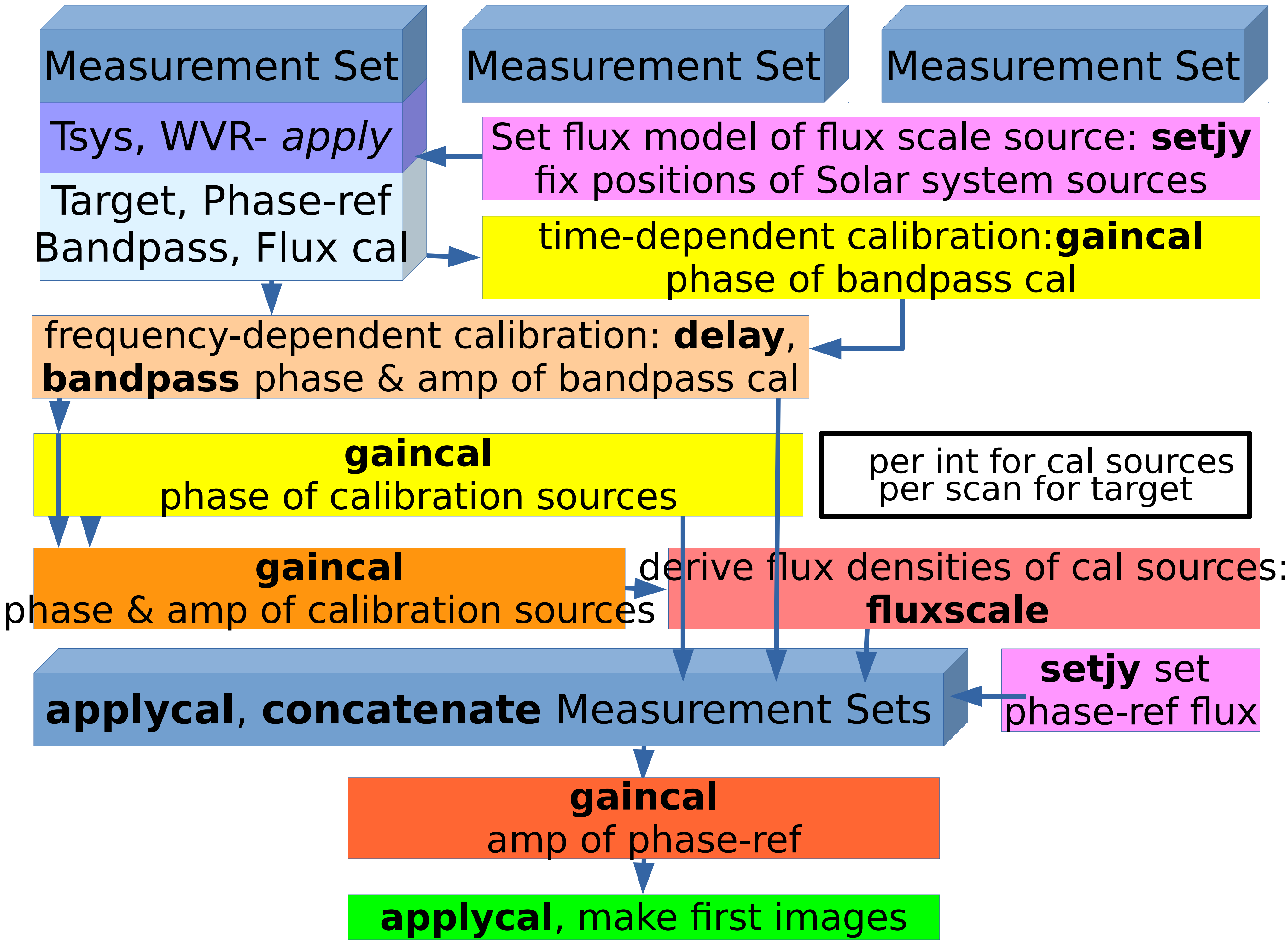
```
> tree jupiterallcal.split.ms
```

```
jupiterallcal.split.ms
|-- ANTENNA
|   |-- table.dat
|   |-- table.f0
|   |-- table.info
|   `-- table.lock
|-- DATA_DESCRIPTIO
|   |-- table.dat
|   |-- table.f0
|   |-- table.info
|   `-- table.lock
|-- FEED
|   |-- table.dat
|   |-- table.f0
|   |-- table.f0i
|   |-- table.info
|   `-- table.lock
|-- FIELD
|   |-- table.dat
|   |-- table.f0
|   |-- table.f0i
|   |-- table.info
|   `-- table.lock
|-- FLAG_CMD
|   |-- table.dat
|   |-- table.f0
|   |-- table.info
|   `-- table.lock
|-- HISTORY
|   |-- table.dat
|   |-- table.f0
|   |-- table.info
|   `-- table.lock
|-- OBSERVATION
|   |-- table.dat
|   |-- table.f0
|   |-- table.info
|   `-- table.lock
|-- POINTING
|   |-- table.dat
|   |-- table.f0
|   |-- table.f0i
|   |-- table.f1
|   |-- table.info
|   `-- table.lock
|-- POLARIZATION
|   |-- table.dat
|   |-- table.f0
|   |-- table.f0i
|   |-- table.info
|   `-- table.lock
|-- PROCESSOR
|   |-- table.dat
|   |-- table.f0
|   |-- table.info
|   `-- table.lock
|-- SOURCE
|   |-- table.dat
|   |-- table.f0
|   |-- table.f0i
|   |-- table.info
|   `-- table.lock
|-- SPECTRAL_WINDOW
|   |-- table.dat
|   |-- table.f0
|   |-- table.f0i
|   |-- table.info
|   `-- table.lock
|-- STATE
|   |-- table.dat
|   |-- table.f0
|   |-- table.info
|   `-- table.lock
|-- table.dat
|-- table.f0
|-- table.f1
|-- table.f2
|-- table.f2_TSM1
|-- table.f3
|-- table.f3_TSM1
|-- table.f4
|-- table.f5
|-- table.f6
|-- table.f6_TSM0
|-- table.f7
|-- table.f7_TSM1
|-- table.f8
|-- table.f8_TSM1
|-- table.info
`-- table.lock
```

Measurement Set MAIN table



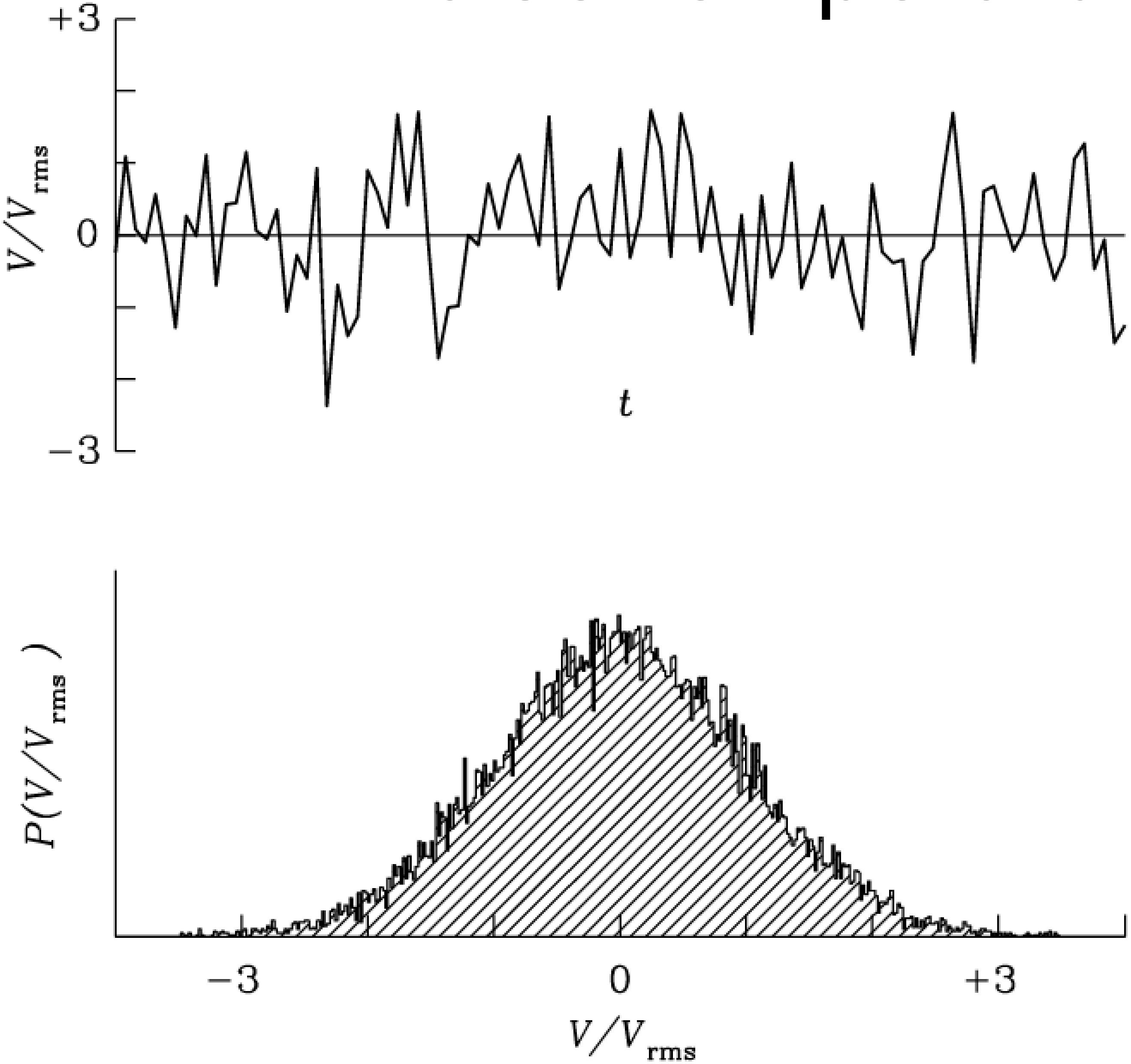
- Some of the columns per visibility
  - **Data**: Complex value for each of 4 correlations (RR RL LR LL) per spectral channel
    - Inspect in CASA browsetable or write to file


Measurement Set
Measurement Set
Measurement Set
Tsys, WVR- apply
Target, Phase-ref
Bandpass, Flux cal
Set flux model of flux scale source: setjy
fix positions of Solar system sources
time-dependent calibration:gaincal
phase of bandpass cal
frequency-dependent calibration: delay,
bandpass phase & amp of bandpass cal
gaincal
phase of calibration sources
per int for cal sources
per scan for target
gaincal
phase & amp of calibration sources
derive flux densities of cal sources:
fluxscale
applycal, concatenate Measurement Sets
setjy set
phase-ref flux
gaincal
amp of phase-ref
applycal, make first images

Noise temperatures

- Output of a single antenna is a rapidly fluctuating random voltage signal
- If we have a bandwidth $\Delta\nu$ then the sampling theorem tells us that we need to sample at a rate $2\Delta\nu$ to adequately represent the signal (even if the ‘signal’ is noise!)
- So we are taking samples from a random distribution centred around zero.

Noise temperatures



100 samples in time series

20,000 samples as a histogram

Figure from https://www.cv.nrao.edu/course/astr534/Radiometers.html

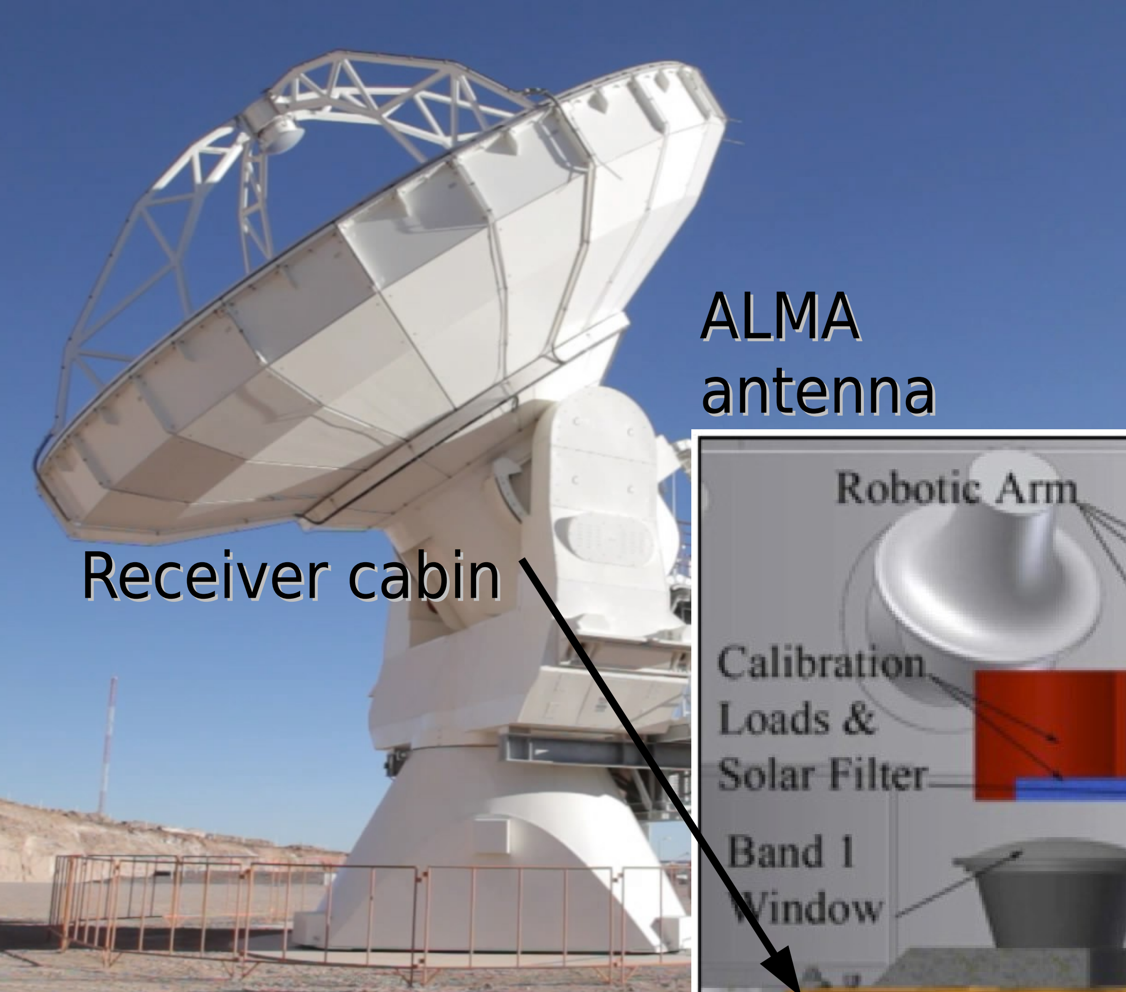
Noise temperatures

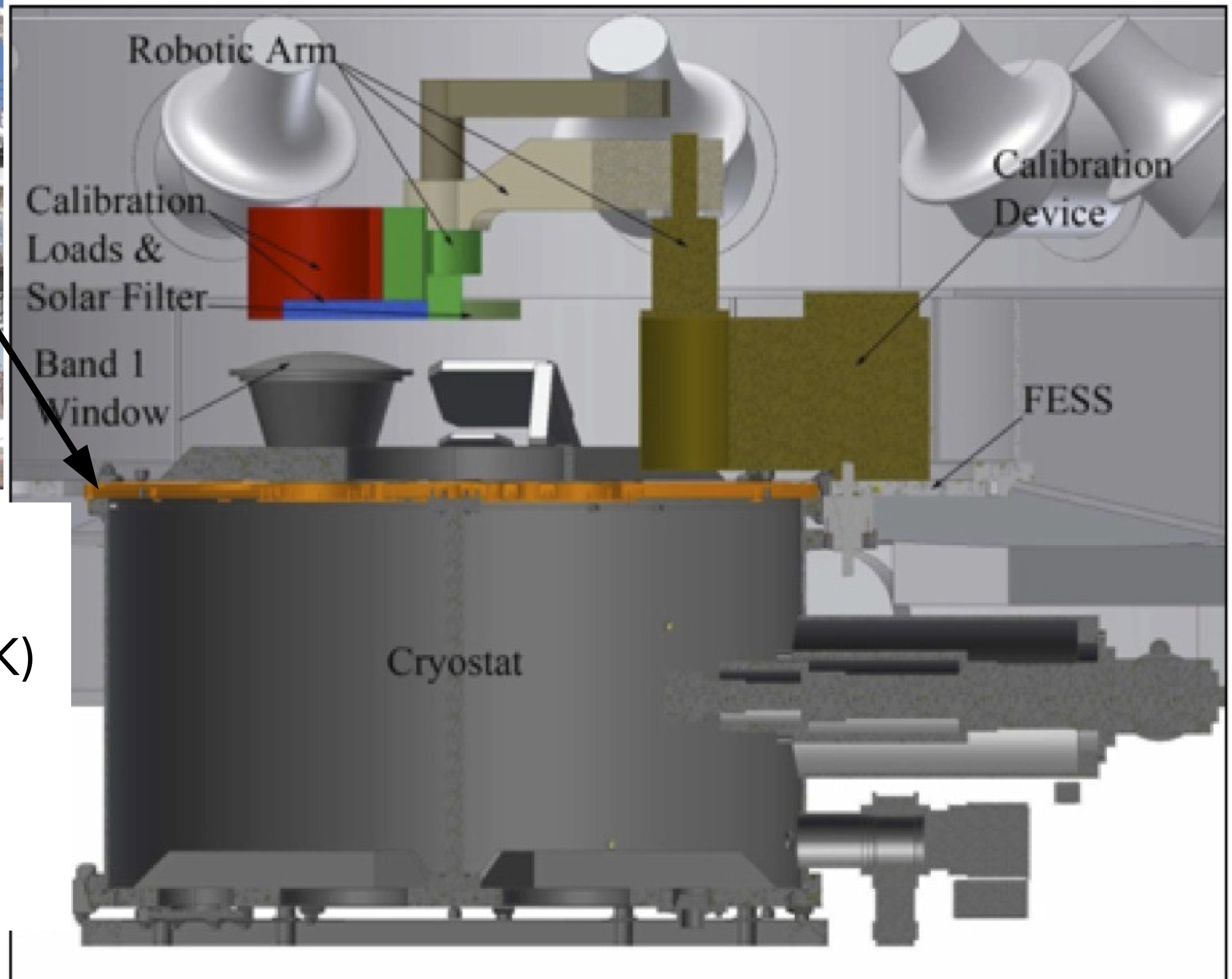
- If we put this noise voltage across a resistor it would generate some heat – $P = V^2/R$
- In electronics theory we find that the noise power of a resistor is given by $P = kT\,\Delta\nu$ where k is Boltzmann's constant.
- So we can define the *noise temperature* of any system as the power per unit bandwidth divided by k, i.e. $T = P/k\Delta\nu$
- For a radio telescope this temperature when no source is being observed is the *system temperature* T_{sys}
- Note that it is nothing to do with the actual temperature!

System temperature measurement

- Point at a standard signal
  - Long wavelengths: fire a noise diode
  - (sub-)mm: use a warm (thermal) 'load' (e.g. ALMA ACD)
  - Measure noise temperature with & without the load
  - Solve for T_{sys}
- Normally provides *relative* scaling of amplitudes (gain-elevation, bright sources, weather...)
- Use to provide a scaling from correlator units
  - System Equivalent Flux Density SEFD (Jy) = T_{sys}/K
    - where $K = \eta_{\mathrm{A}}\, A_{\mathrm{eff}}\,/2\, k_{\mathrm{B}}$ (Kelvin per Jy)
      - Antenna area A_{eff}, efficiency η_A
      - This is the flux density that would cause the noise temperature to be 2x the system temperature.

ALMA Amplitude Calibration Device (ACD)





One load at temperature of receiver cabin (~293 K)
Other load at 353 K
Swing into beam every few minutes

Tsys and gain-elevation

- Typical T_{sys} values are 10 – 100 K at frequencies from 1 to ~200 GHz; few 100 K at lower/higher frequencies
- The most sensitive antennas have low SEFD and T_{sys}
  - Few-Jy sources raise T_{sys} significantly
    - Must allow for this for accurate amplitude calibration
- Atmosphere adds noise and absorbs signal

$$T_{received(sky)} = T_{source} e^{\tau_{atm}/\cos z} + T_{atm}\left(1 - e^{\tau_{atm}/\cos z}\right)$$

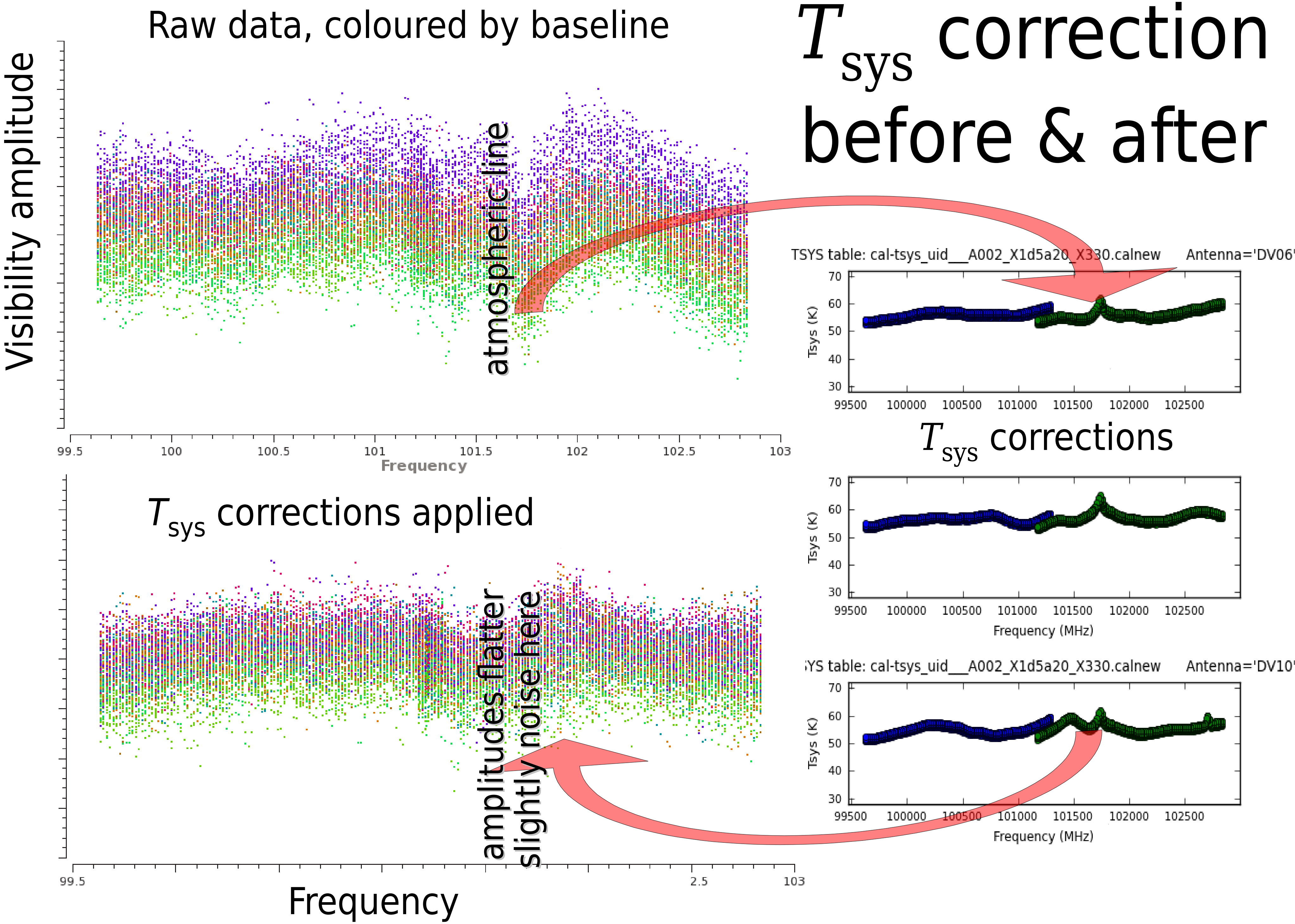
source would provide temperature T if measured above the atmosphere optical depth τ_{atm} and z is the zenith distance

  - i.e. noise is increased for observing at low elevation (large z)
    - T_{sys} measurements include this
    - &/or apply analytic gain-el curve (assume τ_{atm} stable)

Using instrumental calibration

- Calibration measurements supplied with data can include T_{sys}, gain-elevation and WVR
  - Water Vapour Radiometry (at mm/sub-mm wavelengths): measure atmosperic water line every few seconds, calculate refractive delay of phase and/or absorption
- Antenna position corrections may also be available
- Others include weather tables to refine gain-el; GPS measurements for position and Faraday rotation
- May need reformatting or removal of bad values
  - Usually employing standard scripts, often by observatory staff

T_{sys} correction before & after

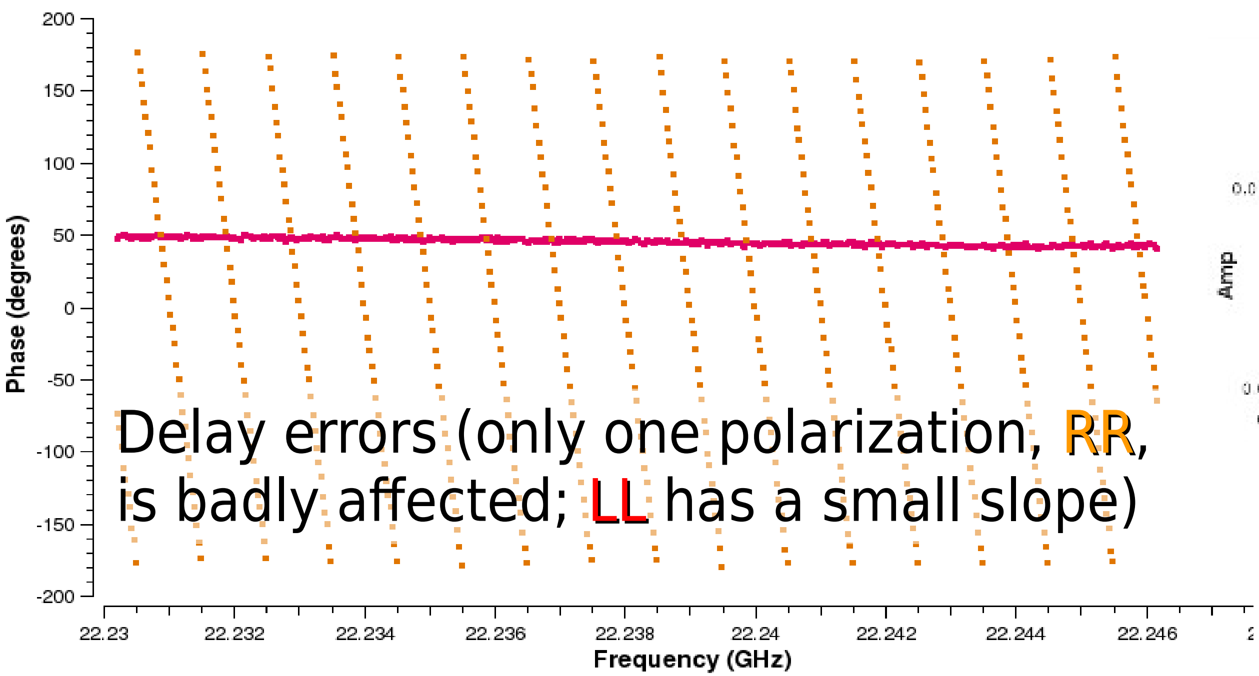


Calibration using astrophysical sources

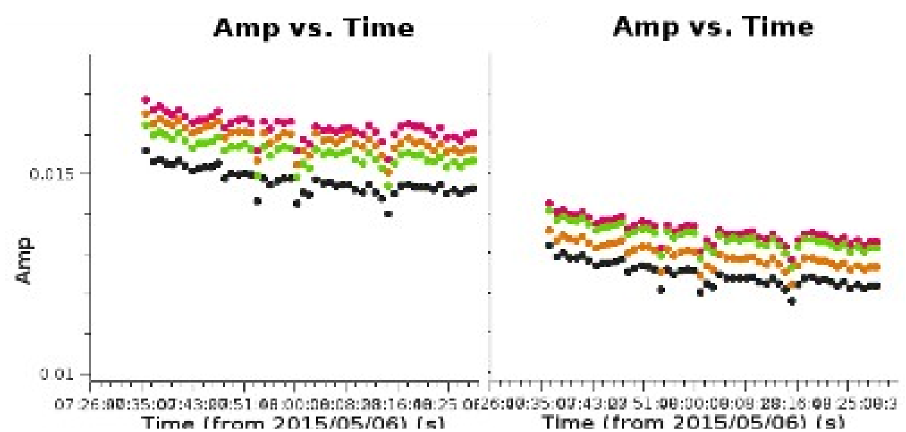
- A typical observation includes at least the following:
  - Science target source(s)
  - Phase reference calibrator close on sky to target
    - Bright enough to give good S/N in each scan
  - Bandpass calibration source
    - Strong enough to be seen in a single channel
  - Flux scale calibrator of known flux density
- A calibrator: may be used in more than one role
  - Needs accurate position, compact structure (or good model).
- **Calibration software compares the visibilities for a source with a model and calculates corrections to bring the observed visibilities closer to the model**

Delay calibration

- Biggest errors due to instrumental timing errors
  - Usually stable for hours or more
  - ~16 turns of phase in 16 MHz = 2π per MHz
    - 1/1MHz = 1μs delay correction needed
      - Averaging across phase errors makes amps decorrelate



Delay errors (only one polarization, RR, is badly affected; LL has a small slope)



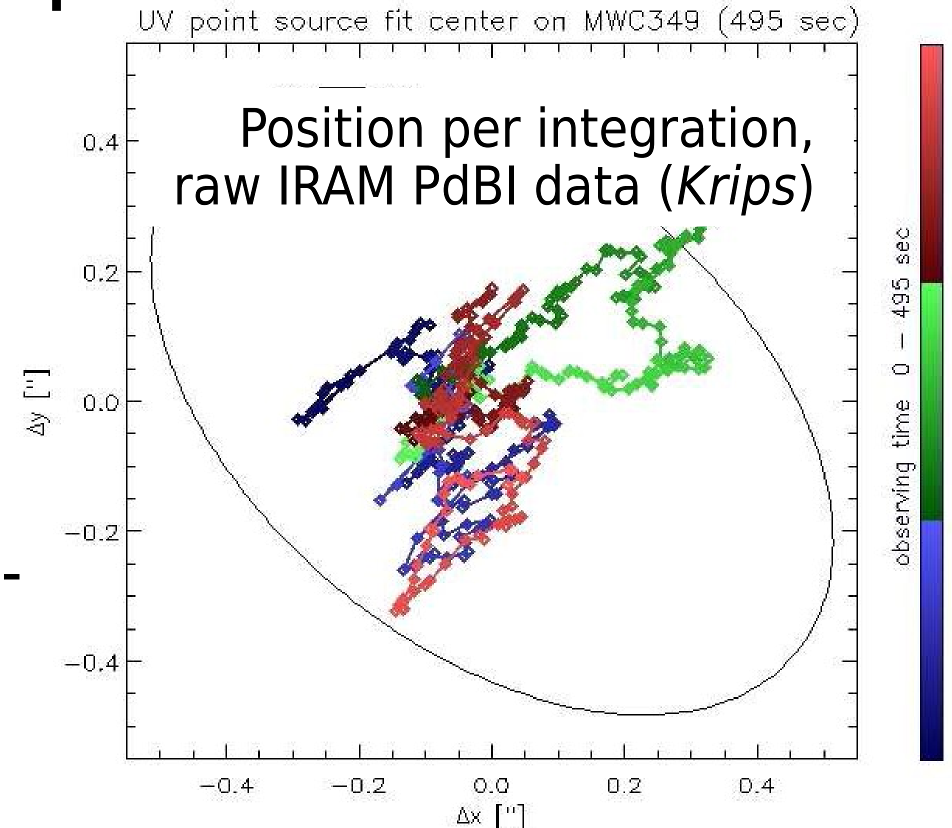
One channel (noisier but stronger)

All channels averaged (weaker)

- Averaging over phase fluctuations causes decorrelation of amplitudes
  - Visibility $V = V_o e^{i\phi}$ so $\langle V \rangle = V_o \langle e^{i\phi} \rangle = V_o e^{-(\phi_{rms}^2)/2}$
    - ϕ_{rms} in radians
  - e.g. Lose 2% amplitude for 10° ϕ_{rms}
    - Independent from direct amplitude errors

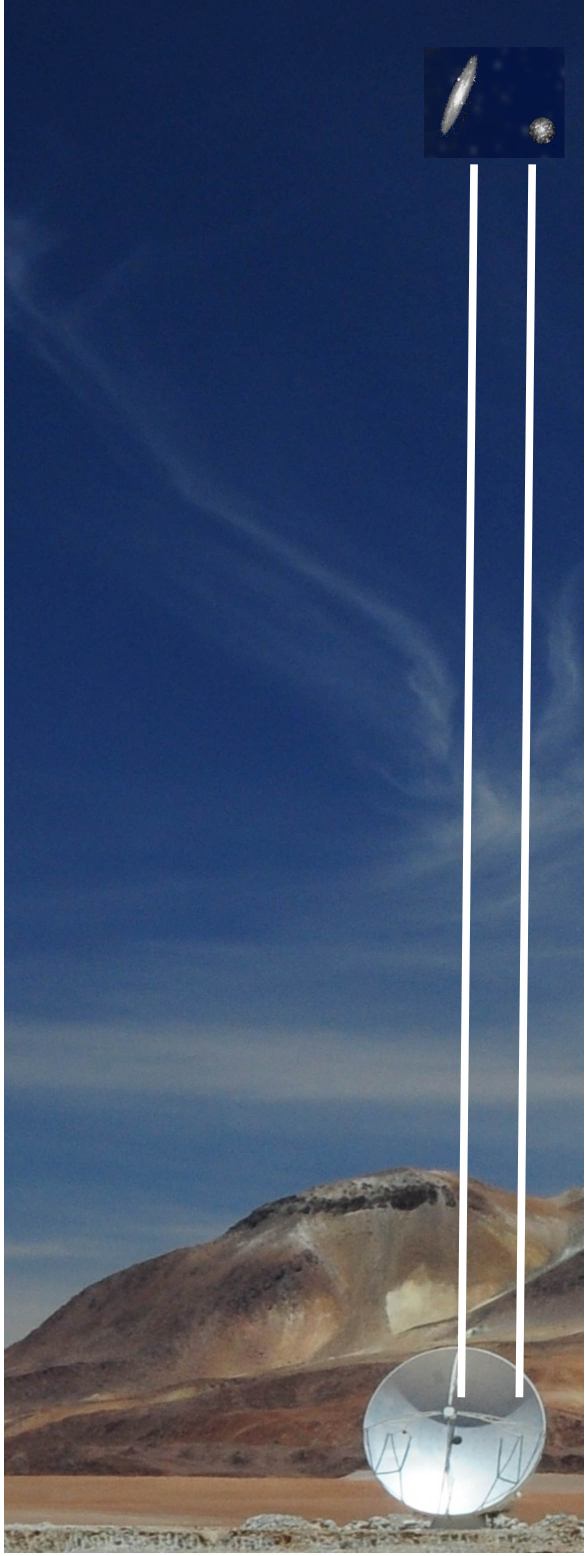
Phase errors cause position errors

- Phase error worse at very long or short λ
  - Precision limit to resolution
    - Like optical 'seeing'
- At <1 GHz or >30 GHz atmospheric fluctuations on time-scales of few sec
  - Raw data position jitter

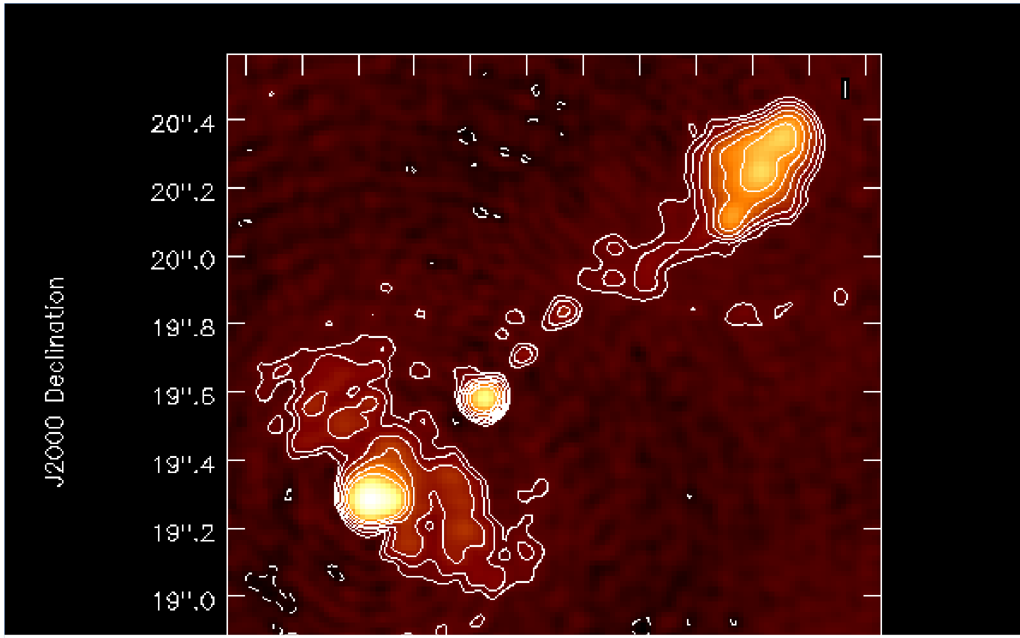


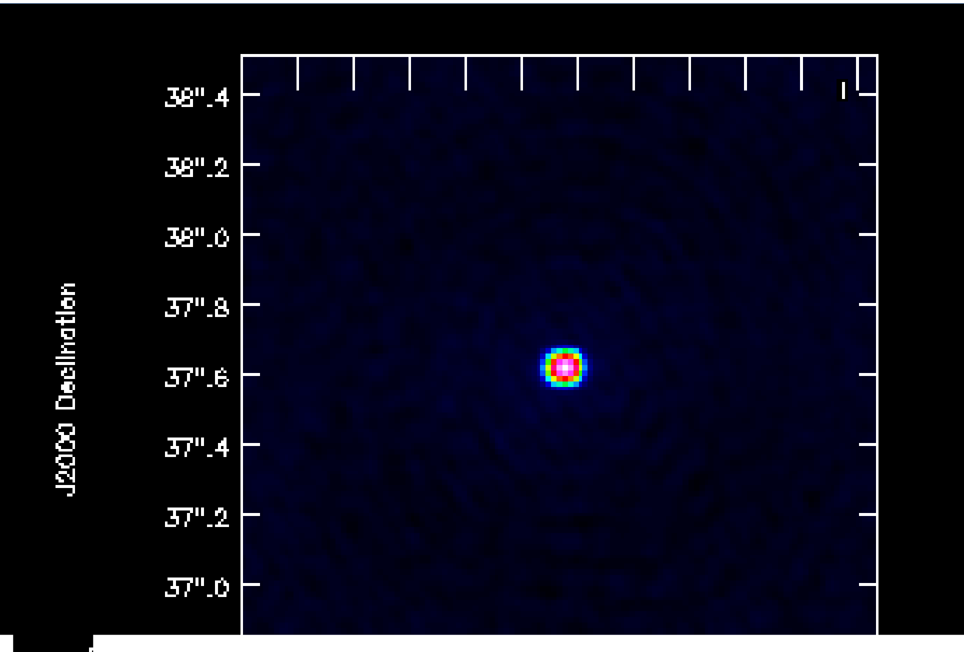
Phase referencing

- Observe phase-ref source close to target
  - Point-like or with a good model
  - Close enough to see same atmosphere
    - ~2-15 degrees (isoplanatic patch)
  - Bright enough to get good SNR much quicker than atmospheric timescale τ
    - τ 10 min/30 s short/long B & low/high ν
  - Nod on suitable timescale e.g. 5:0.5 min
    - Derive time-dependent corrections to make phase-ref data match model
    - Apply same corrections to target
  - Correct amplitudes similarly
- Self-calibration works on similar principle

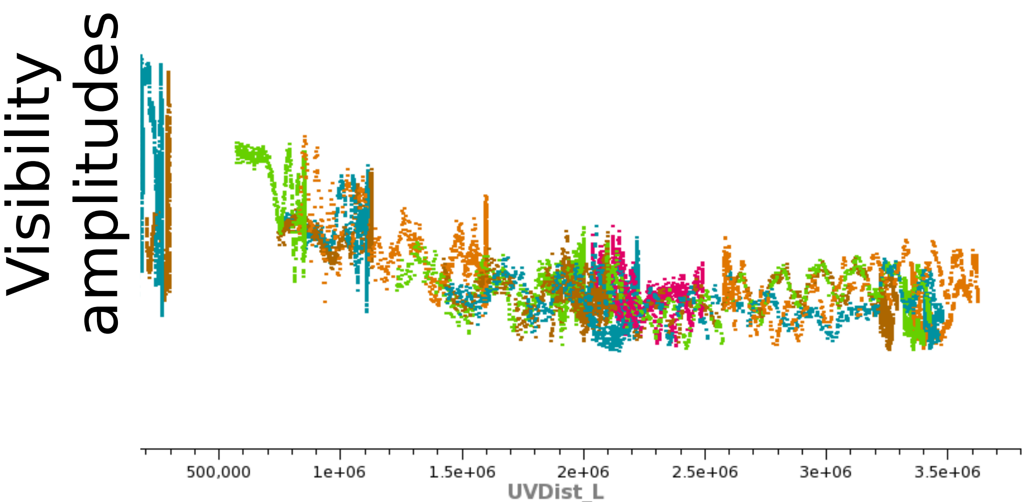


Source structure in *uv* plane

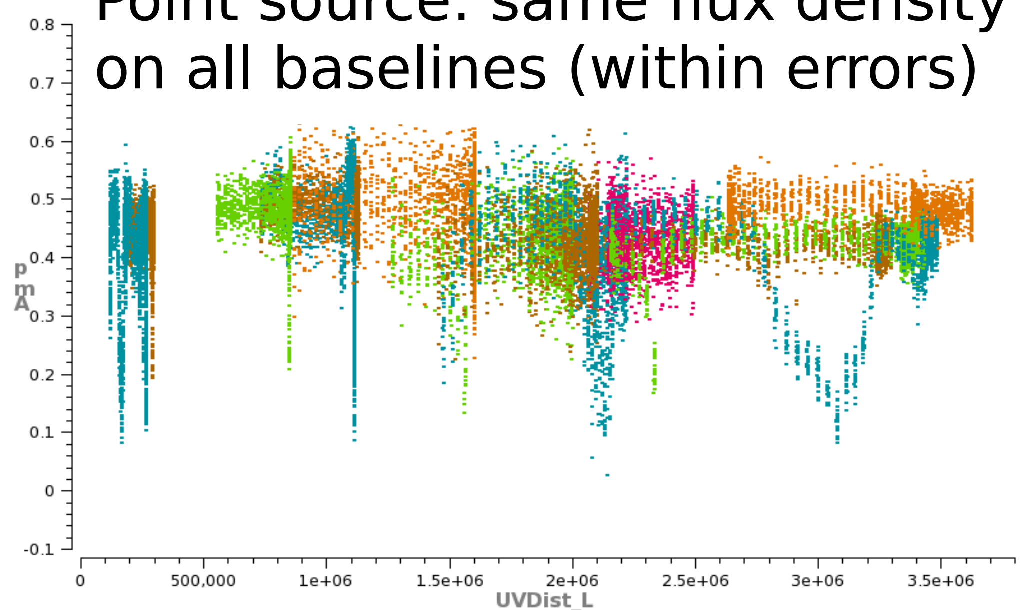




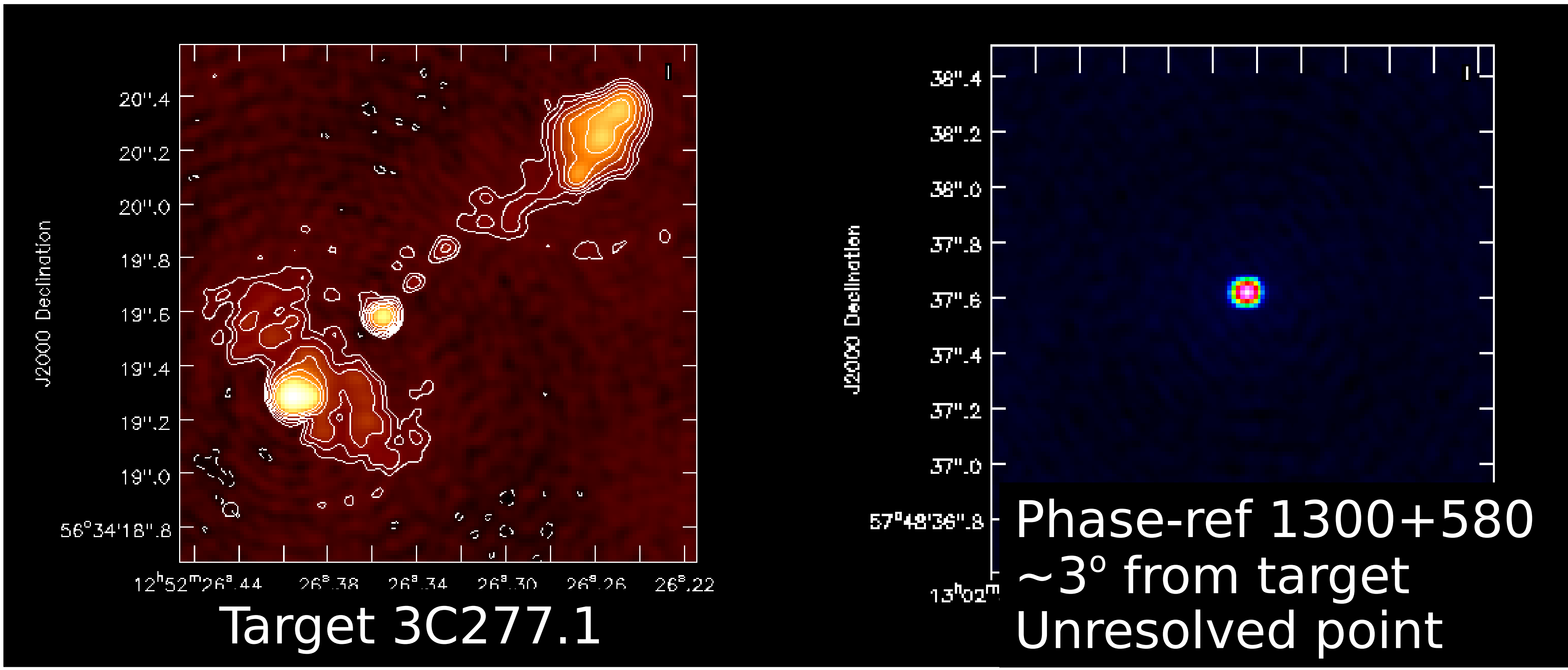
Extended source: more flux on short baselines



Point source: same flux density on all baselines (within errors)

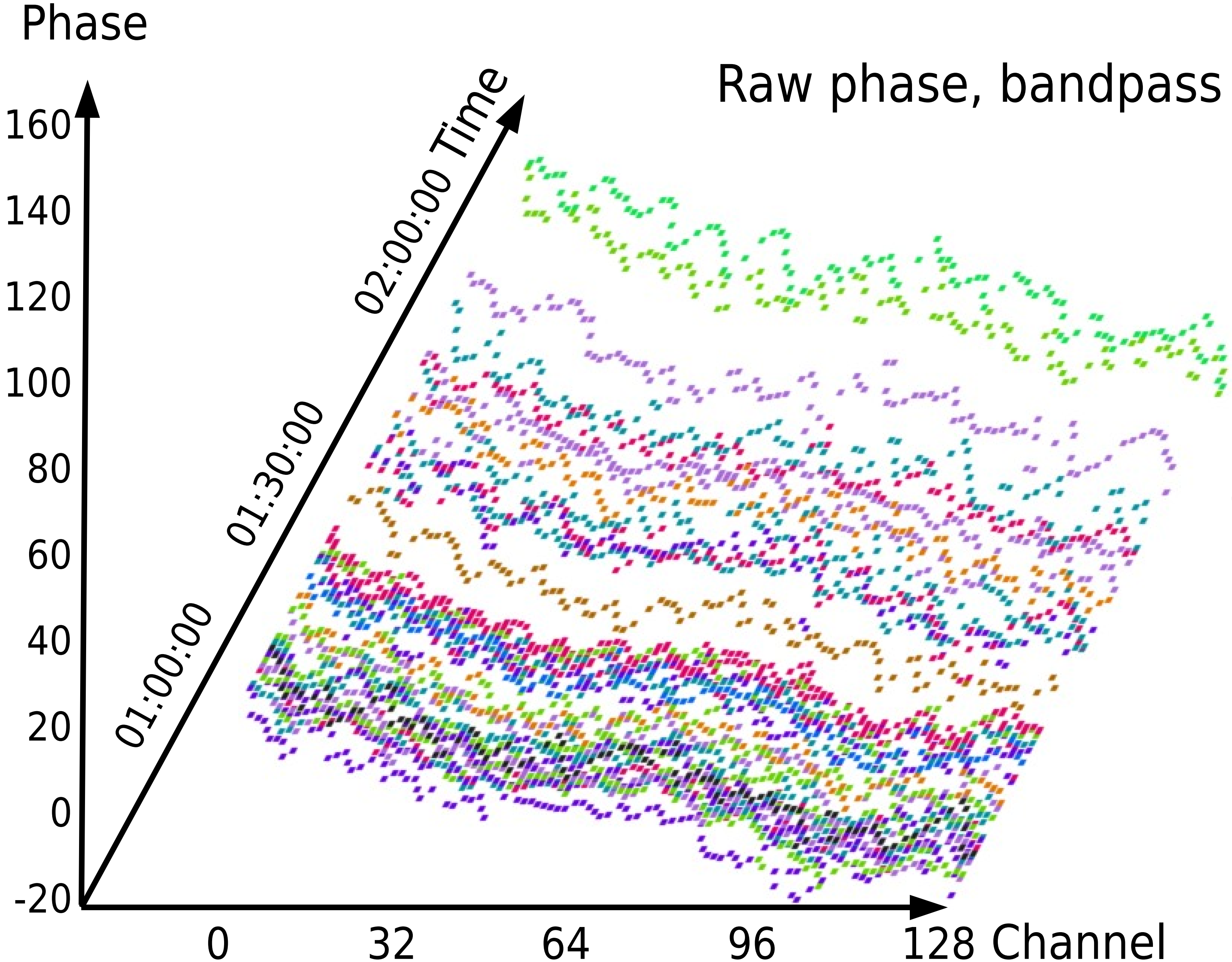


Phase referencing



- Phase reference has accurate position; should have flat amplitudes and 0 phases; use this as model
- Calculate corrections to make actual phase-ref phases match model
- Apply these to phase-ref and target

Phase errors in 3D



Raw phase, bandpass calibrator

Each scan in a different colour

~30^o phase slope across the band

Phase as a whole drifts ~140^o in 2 hr <2^o per min

Calibration strategy

- Need Signal to Noise Ratio $\sigma_{\mathrm{ant}}/S_{\mathrm{calsource}} > 3$
  - per calibration interval per antenna

$$\sigma_{ant}(\delta t, \delta \nu) \approx \sigma_{array} \sqrt{\frac{N(N-1)/2}{N-3}}$$

    - σ_{array} is noise in all-baseline data per time-averaging interval per frequency interval used for calibration
  - Have to average in time and/or frequency
    - Bandpass first or time-dependent cal. first?
      - *Do not average over interval where phase change d$\phi > \pi/4$*
    - *Keep polarizations separate if possible in early calibration*
- Usually start with bandpass calibration
    - May need to perform time-dependent ϕ calibration first
      - allow averaging up in time to get enough S/N per channel

Calibration with astrophysical sources

- Bandpass calibrator – bright as possible
  - This example: $d\phi<\pi/4$ over inner 50% band

1. Average inner 50% band, perform time-dependent phase & amp calibration (G1) with solint required for SNR
- If atmospheric lines, chose channel intervals to avoid

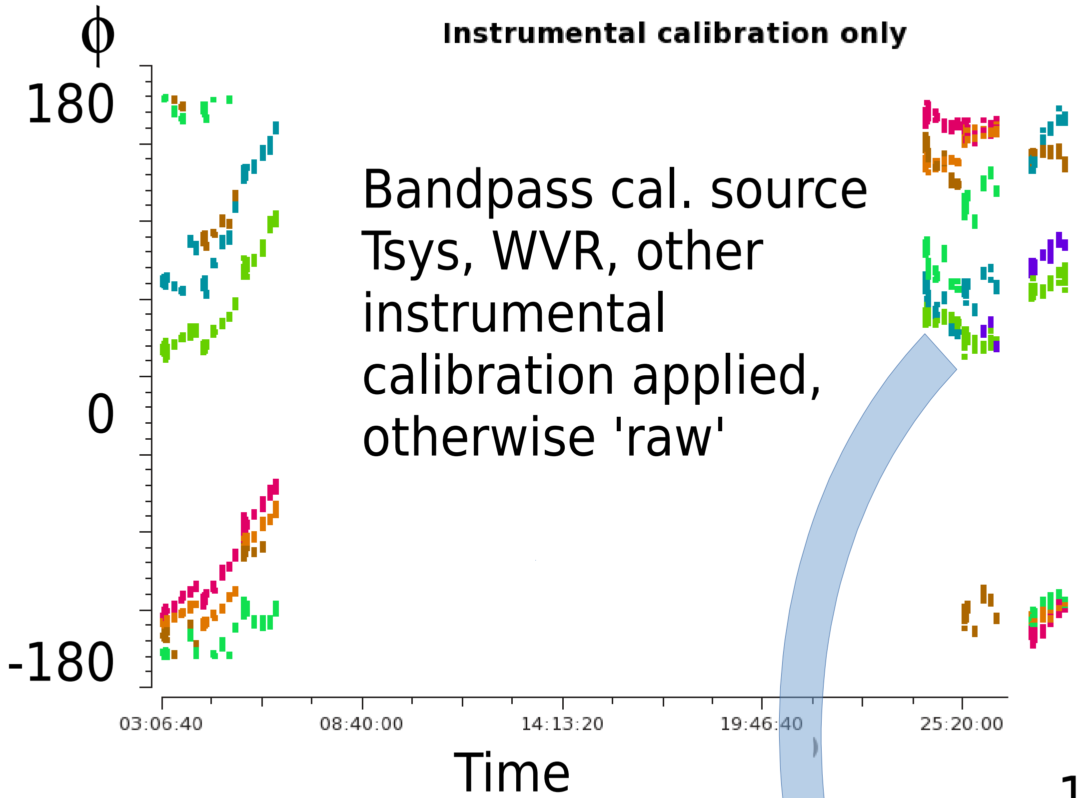
2. Apply calibration (G1), average all times for freq. dependent phase and amplitude calibration, i.e. bandpass calibration (B1).
- Smooth every e.g. 20 channels if necessary for SNR
  - G1 *is not used any more*

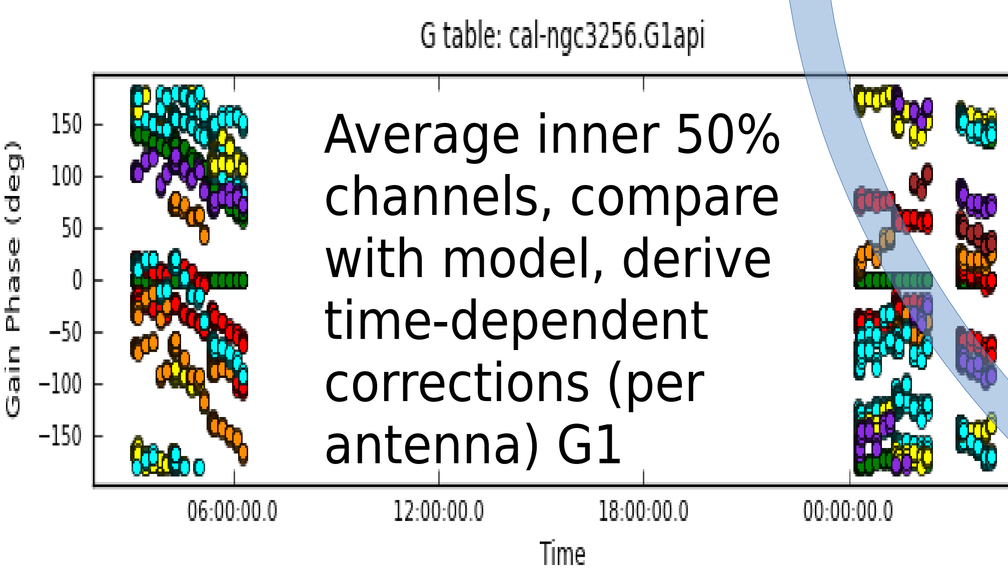
- Phase-reference – fairly bright source

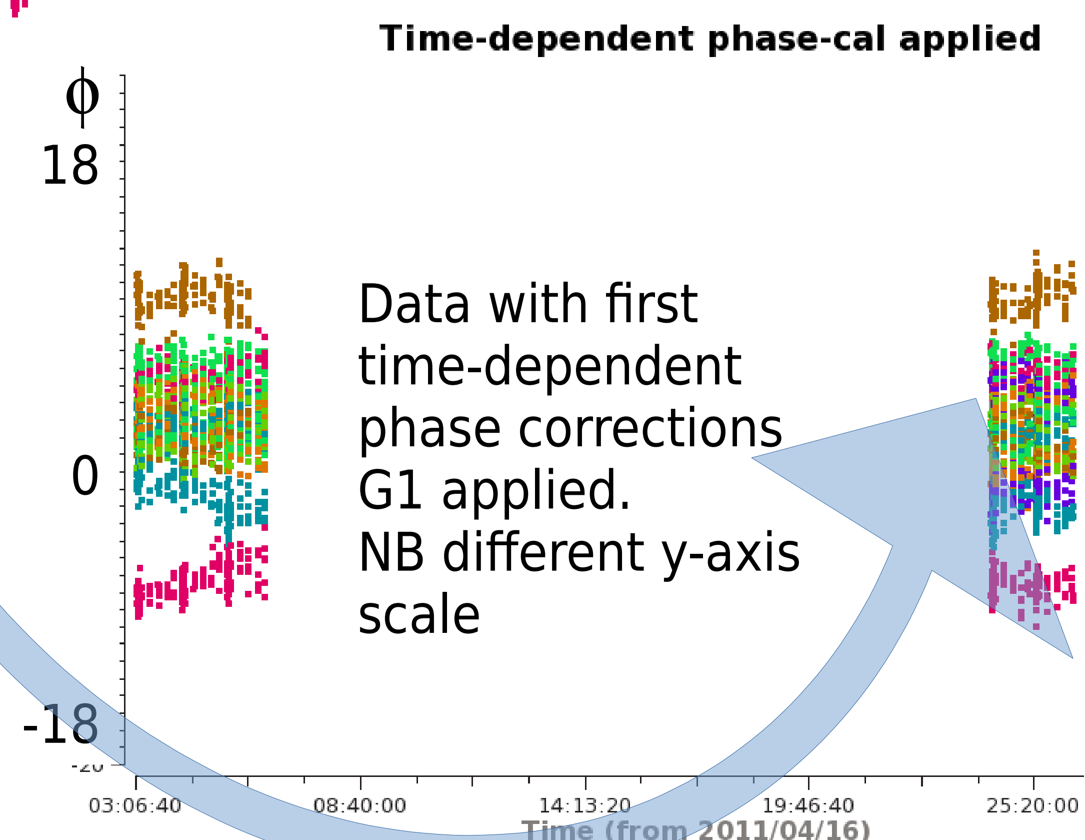
3. Apply B1 and perform time-dependent phase calibration (G2) averaging all channels, shortest *dt* for enough SNR
- Apply B1 for all calibration hereafter, to all sources

4. Apply B1 and G2 and perform time-dependent amp. cal. (G3)

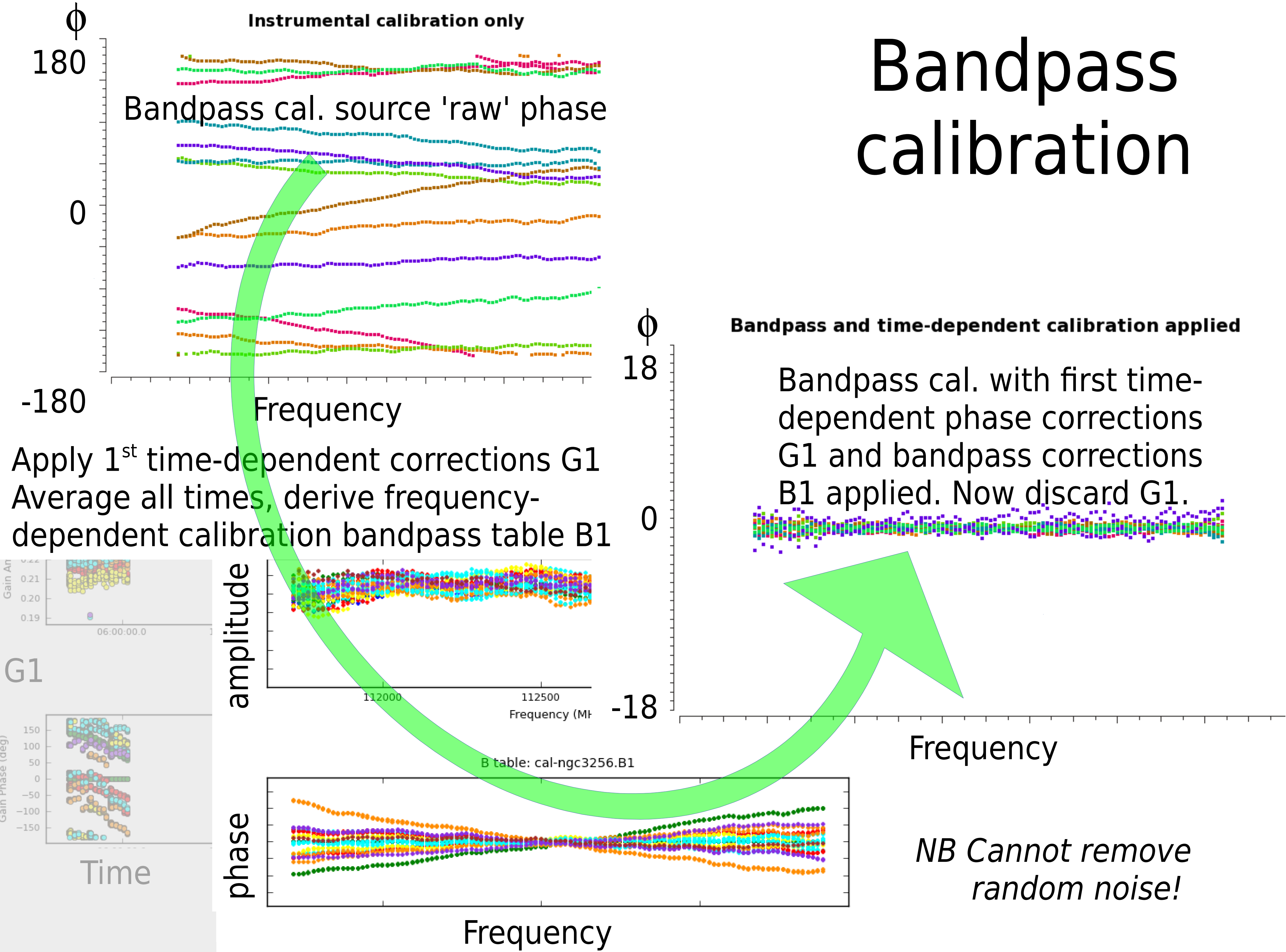
First time-dependent phase correction

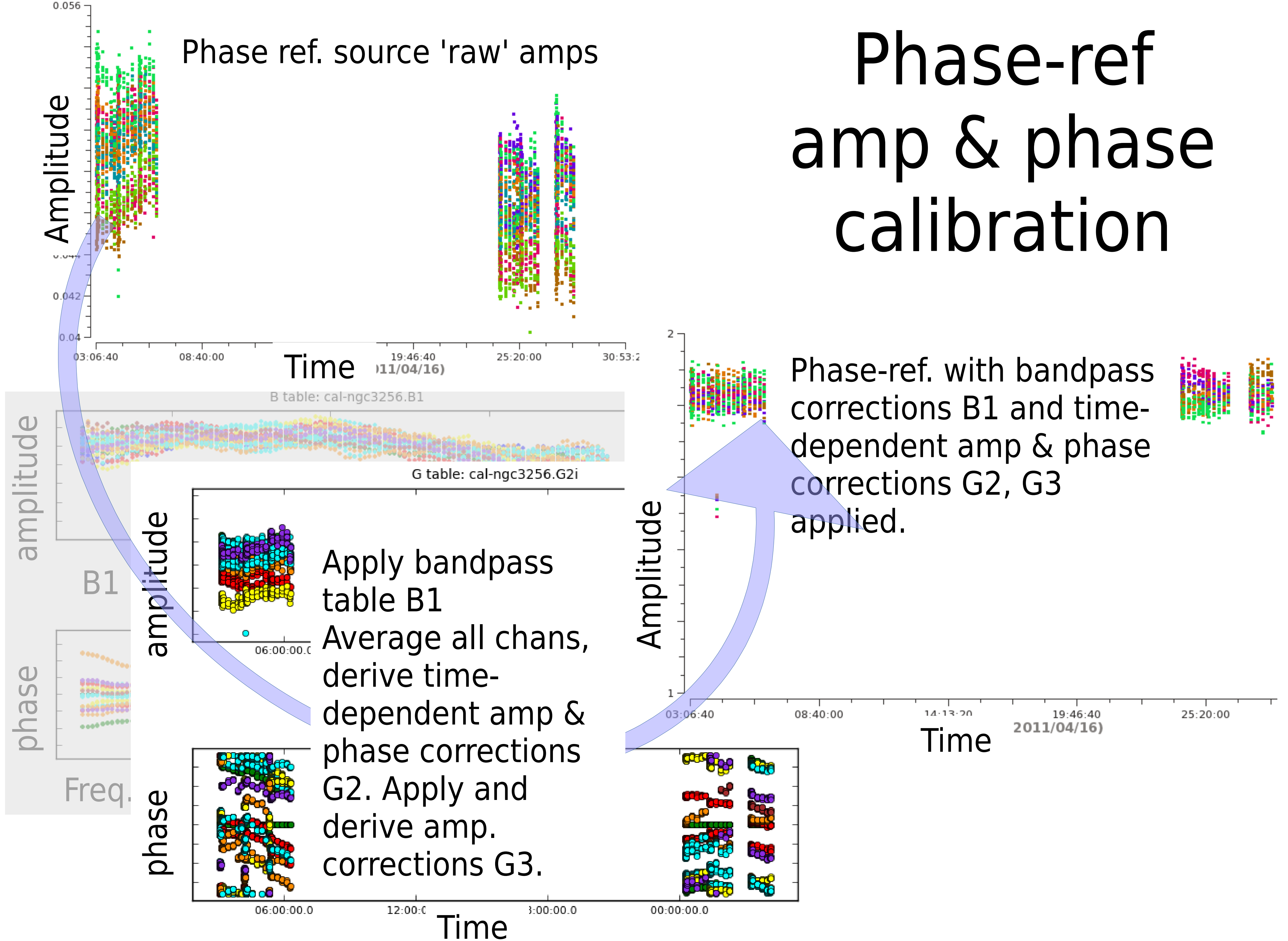




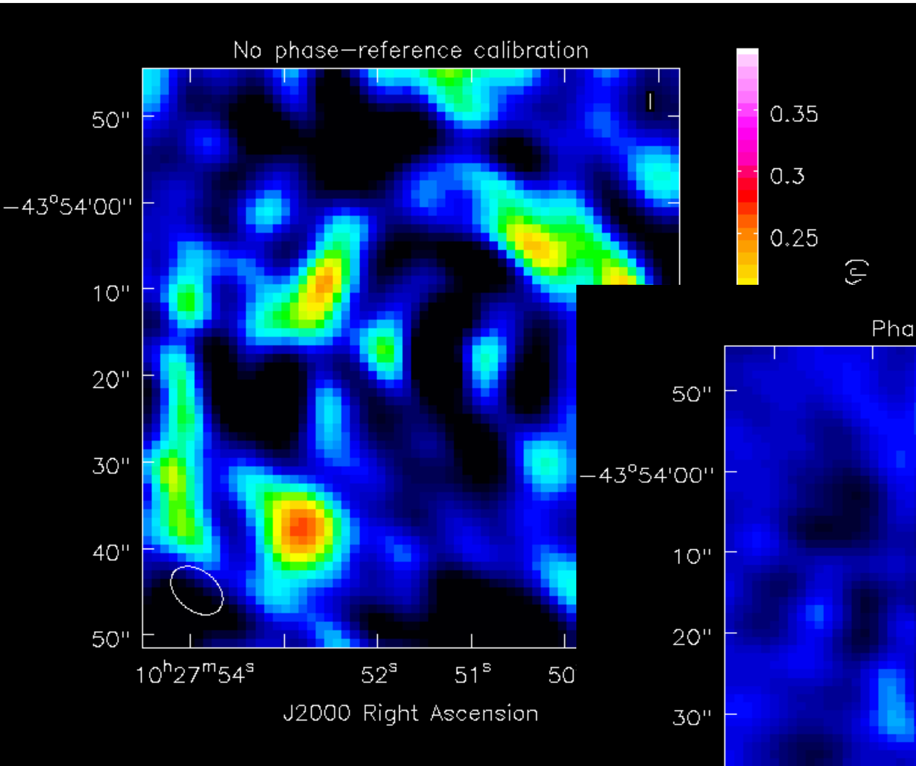


Bandpass calibration

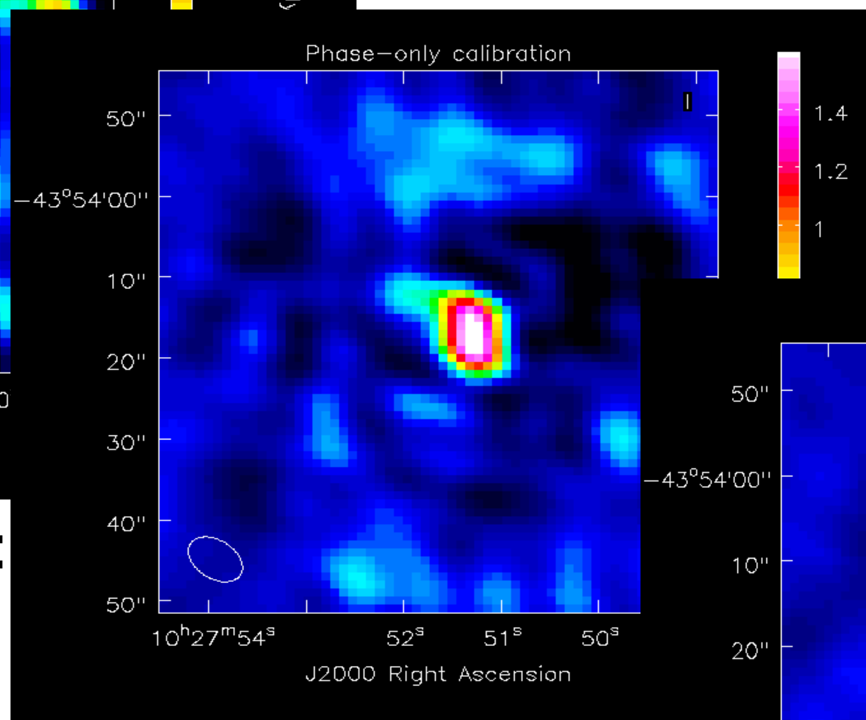



Phase-ref
amp & phase
calibration
Phase ref. source 'raw' amps
Amplitude
Time
0.056
0.042
0.04
03:06:40
08:40:00
19:46:40
25:20:00
B table: cal-ngc3256.B1
amplitude
B1
phase
Freq.
G table: cal-ngc3256.G2i
amplitude
phase
06:00:00.0
Time
Apply bandpass
table B1
Average all chans,
derive time-
dependent amp &
phase corrections
G2. Apply and
derive amp.
corrections G3.
Phase-ref. with bandpass
corrections B1 and time-
dependent amp & phase
corrections G2, G3
applied.
Amplitude
2
1
03:06:40
08:40:00
19:46:40
25:20:00
2011/04/16)
Time

Effects on imaging

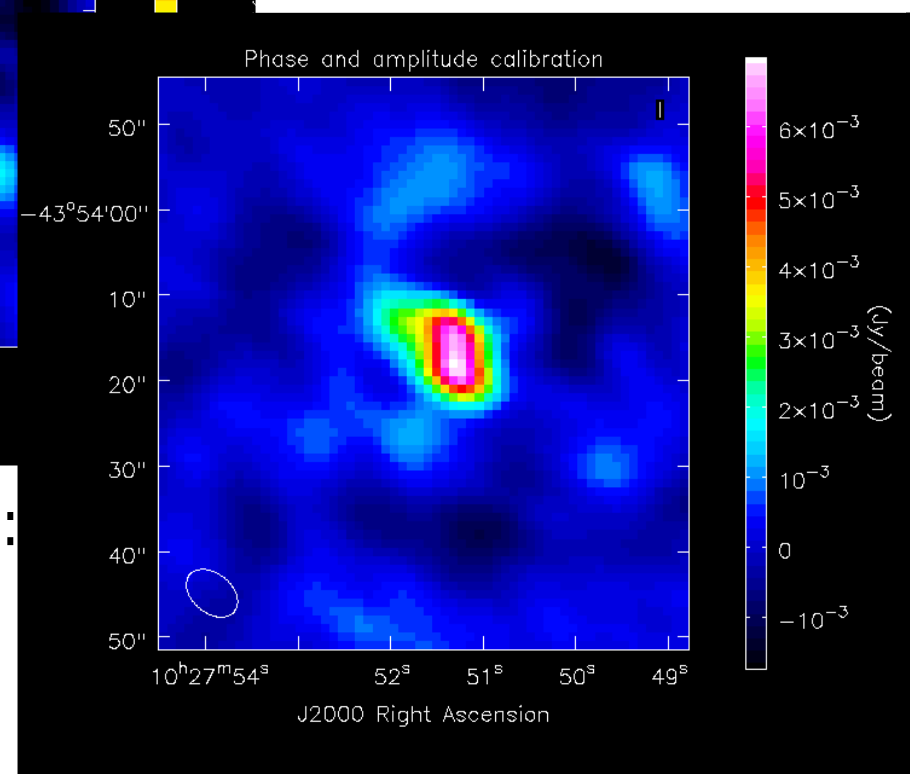


Bandpass cal only:
no source seen



Phase-only solutions:
source seen, snr 15

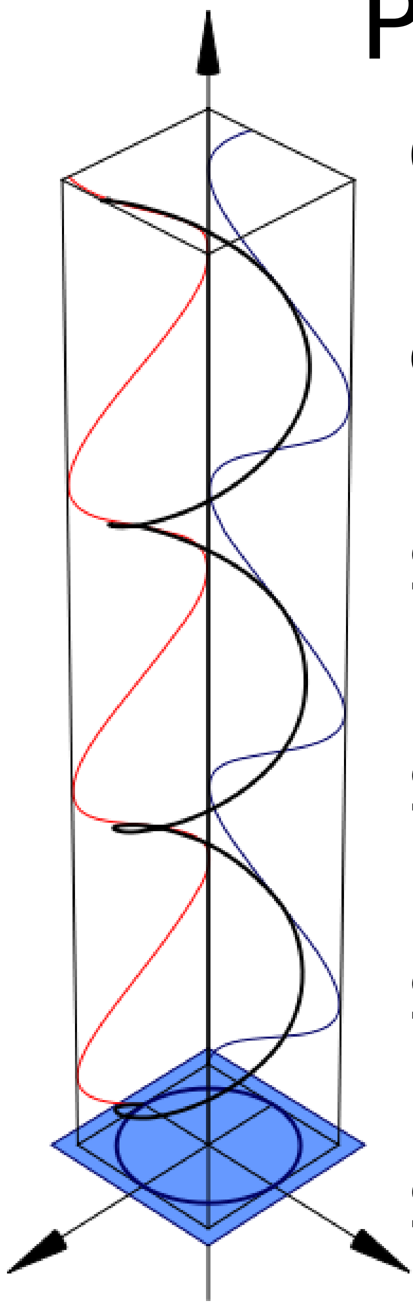
Amplitude and
phase solutions:
source seen, snr 22



Flux scale calibration

- QSO are often used for BP and time-dependent phase and amplitude calibration: sub-arcsec, bright sources
    - Small source, shorter light-travel diameter – Variable!
  - To use as flux standard, monitor wrt. stable source
- Flux–stable sources are mostly large, resolved
  - Use a stable source with an image model
    - or bootstrap using short baselines only
- Calibrate time-varying gains, bandpass
  - Derive scaling factor from correlator units to Jy and apply to all sources
- Or just use T_{sys}

Polarization jargon: Rx feeds



CIRCULAR feeds

Left/Right/cross correlations LL RR LR RL

Stokes I = (RR+LL)/2

Stokes V = (RR-LL)/2

Stokes Q = (RL + LR)/2

Stokes U = (RL – LR)/2*i*

LINEAR feeds

Correlations XX, YY, XY, YX

Stokes I = (XX+YY)/2

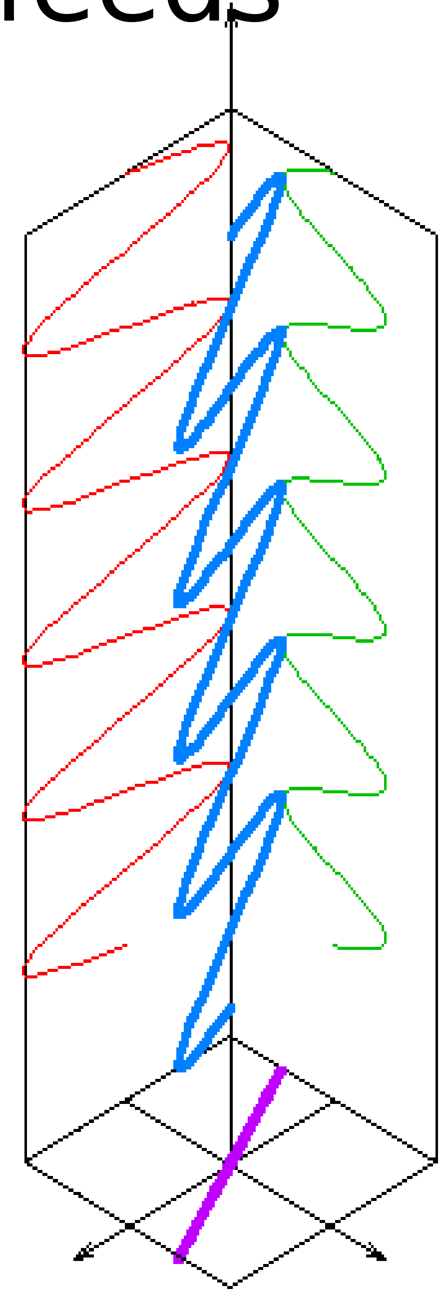
Stokes Q = (XX – YY)/2

Stokes U = (XY – YX)/2

Stokes V = (XY – YX)/2*i*

Polarized intensity P = √(Q^2+U^2+V^2)

Polarization angle χ = ½ atan(U/Q)



Diagrams thanks to Wikipedia

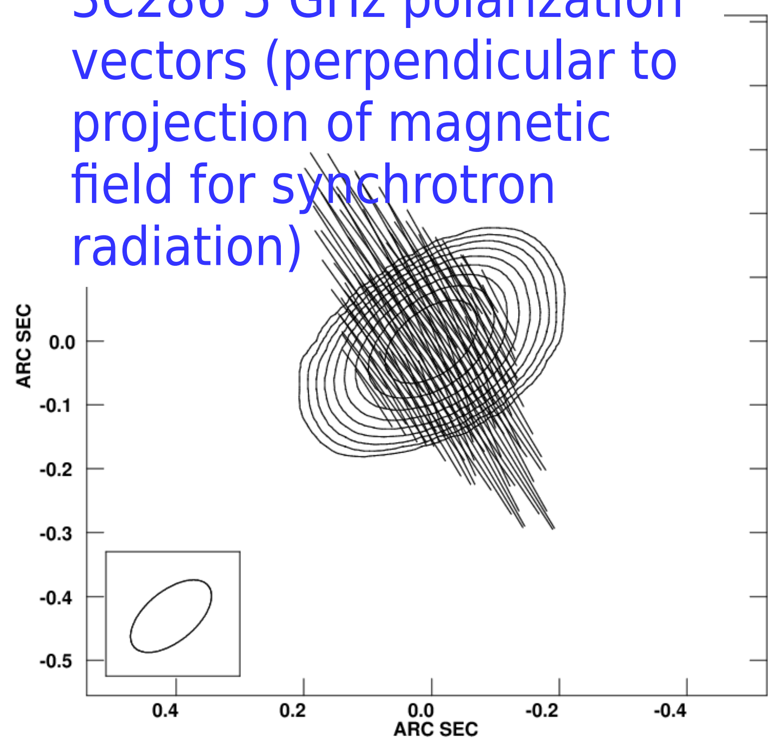
Polarization leakage calibration

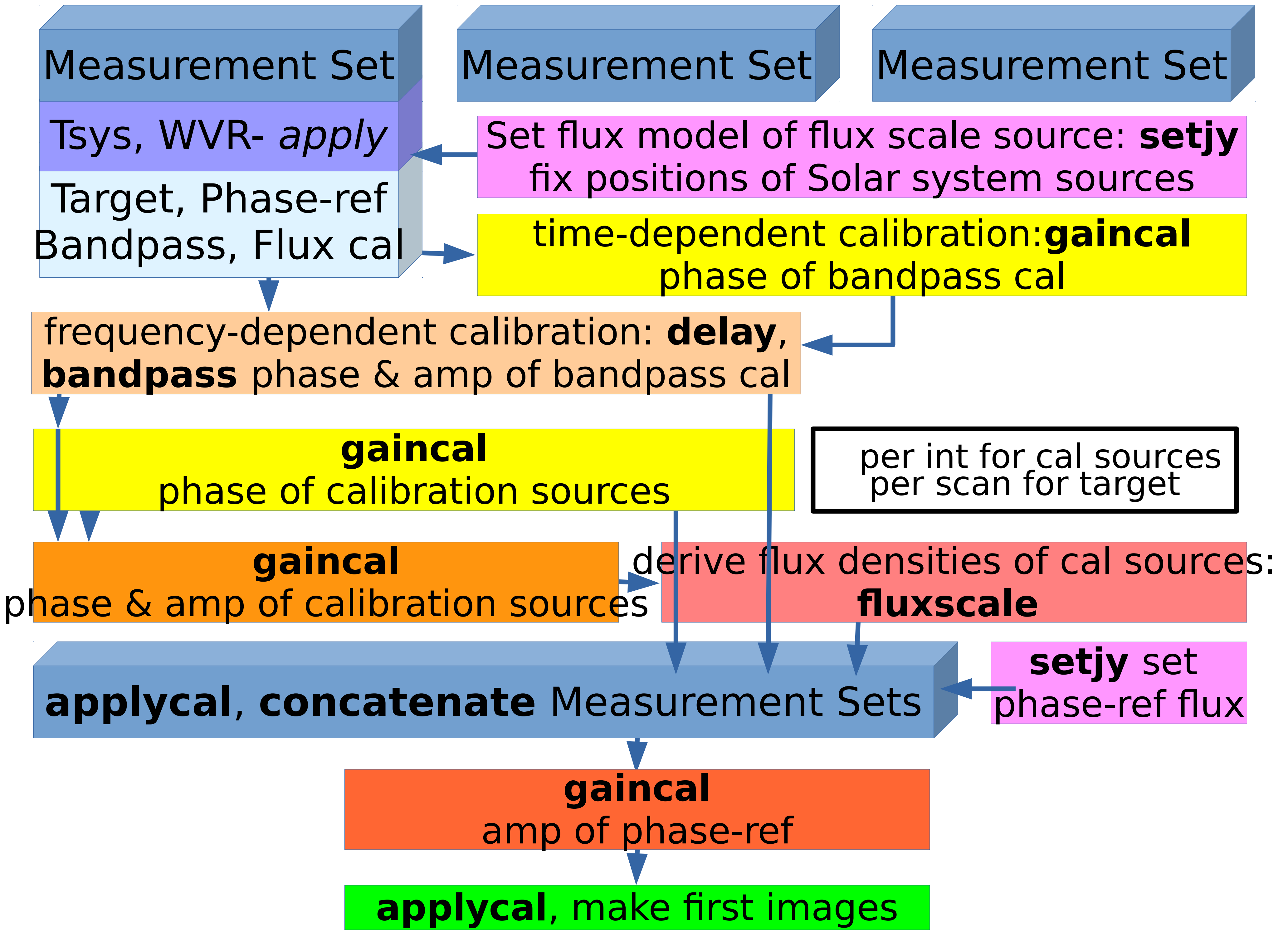
- Receiver feeds sensitive either to (L, R) or (X, Y)
  - Gains can differ so start calibrating separately
    - For small fields, fainter sources, can treat independently
      - Combine to make total intensity images
- Actually few% signal leaks between polarizations
  - Most QSO linearly polarised so need to solve for:
      - Source polarization,
      - Receiver leakage,
      - Rotation of Rx feeds on the sky as alt-az mount tracks
        - (may have starting model for linear feeds)
      - Need at least 3 scans over >60^{o} rotation for solutions
- Must calibrate polarization for high dynamic range or wide field imaging as dishes have slightly asymmetric responses
  - Even if you don't care about target polarization

Polarization angle calibration

- Polarization angle unknown for circular feeds
  - Origin of phase is arbitrary
  - Use a standard source to set conventional angle
    - 3C286 dominated by core, ~10% polarised
      - Consistent 33^o position angle
- Faraday rotation by ionosphere serious and variable at long λ
- Observe standard often &/or use GPS or other estimate of ionospheric electron content

3C286 5 GHz polarization vectors (perpendicular to projection of magnetic field for synchrotron radiation)





Measurement Set
Measurement Set
Measurement Set
Tsys, WVR- apply
Target, Phase-ref
Bandpass, Flux cal
Set flux model of flux scale source: setjy
fix positions of Solar system sources
time-dependent calibration:gaincal
phase of bandpass cal
frequency-dependent calibration: delay,
bandpass phase & amp of bandpass cal
gaincal
phase of calibration sources
per int for cal sources
per scan for target
gaincal
phase & amp of calibration sources
derive flux densities of cal sources:
fluxscale
applycal, concatenate Measurement Sets
setjy set
phase-ref flux
gaincal
amp of phase-ref
applycal, make first images

Libraries use Measurement Equation

$$\underline{V}_{ij} = \mathbf{M}_{ij}\mathbf{B}_{ij}\mathbf{G}_{ij}\mathbf{D}_{ij}\int \mathbf{E}_{ij}\mathbf{P}_{ij}\mathbf{T}_{ij}\mathbf{F}_{ij} S \underline{I}_n\,(x,y)\ \exp[i2\pi(u_{ij}x+v_{ij}y)]\ dxdy + \underline{A}_{ij}$$

Vectors

$\underline{V}$ isibility = *f(u,v)*

$\underline{I}$ mage

$\underline{A}$dditive baseline error

Starting point

Goal

Scalars

Methods

S (mapping $\underline{I}$ to observer polarization)

x,y image plane coords

u,v Fourier plane coords

i,j telescope pair

Jones Matrices

Hazards

Multiplicative baseline error

Bandpass response

Generalised electronic gain

Dterm (pol. leakage)

E (antenna voltage pattern)

Parallactic angle

Tropospheric effects

Faraday rotation

Using the Measurement Equation

- *Hamaker, Bregman & Sault 1996*
  - Decompose into relevant calibration components e.g.
- $\underline{V}_{ij}^{obs} = \mathbf{B}_{ij}\mathbf{G}_{ij}\mathbf{D}_{ij}\mathbf{P}_{ij}\mathbf{T}_{ij}\mathbf{F}_{ij}\underline{V}_{ij}^{ideal}$
  - Chose one (or a few) at a time
    - Usually solve fastest-varying first
      - (so averaging over slower-varying)
  - Compare data with model or idealisation
    - Linearise and solve by χ^2 (or other) minimization

The method behind solving the ME

- Express the correlator output as the coherency matrix of the signals from each pair of antennas *ij*.
  - Using a circular polarization basis, form outer product:

$$\mathbf{E}_{\mathrm{ij}} = \mathbf{e}_{\mathrm{i}} \mathbf{e}_{\mathrm{j}}^{\dagger} = \begin{pmatrix} R_i \\ L_i \end{pmatrix} \begin{pmatrix} R_j^* & L_j^* \end{pmatrix} = \begin{pmatrix} R_i R_j^* & R_i L_j^* \\ L_i R_j^* & L_i L_j^* \end{pmatrix}$$

    - Equivalent to $\boldsymbol{V}(u,v)_{\mathrm{ij}} = \begin{pmatrix} RR & RL \\ LR & LL \end{pmatrix}$
- Replace signal $\mathbf{e}$ from each antenna with corrupted signal $\mathbf{e}'_{\mathrm{i}} = \mathbf{J}_{\mathrm{i}}\, \mathbf{e}_{\mathrm{i}}$
  - $\mathbf{J}_{\mathrm{i}}$ is a (2 x 2) Jones matrix for antenna-based terms e.g., for the complex 'gain' errors affecting amplitude and phase: $\mathbf{J}_{\mathrm{G}} = \begin{pmatrix} g_R & 0 \\ 0 & g_L \end{pmatrix}$

The method behind solving the ME

- The corruption of the 'true' visibilities $\mathbf{E}_{\mathrm{ij}}$ is written as

$$\mathbf{E}'_{\mathrm{ij}} = \mathbf{e}'_{\mathrm{i}} \mathbf{e}'^{\dagger}_{j} = \mathbf{J}_{\mathrm{i}} \mathbf{E}_{\mathrm{ij}} \mathbf{J}^{\dagger}_{\mathrm{j}}$$

  - Jones matrices known so expression can be inverted:

$$\mathbf{E}_{\mathrm{ij}} = \mathbf{J}_{\mathrm{i}}^{-1} \mathbf{E}'_{ij} \mathbf{J}_{\mathrm{j}}^{\dagger -1}$$

- If polarization is ignored and errors are constant across the (small) field of view, this can be linearised

$$V_{ij}^{obs} - J_i J_j^* V_{ij}^{mod}$$

  - V^{mod} are model visibilities corrected for the errors represented by this Jones matrix: solve to find corrections $\mathrm{J_i}$, $\mathrm{J_j}$ to apply per antenna by minimising

$$\chi^2 = \sum \left| V_{ij}^{obs} - J_i J_j^* V_{ij}^{mod} \right|^2 W_{ij}$$

  - Weights (if any) $W_{\mathrm{ij}} = \mathrm{s}_{\mathrm{ij}}^{-2}$ are derived from previous noise estimates e.g. sample size, scatter in previous solutions

Simple calibration in practice

- Pointing etc. should be corrected pre-observations
  - Check if you see suspicious errors for a new telescope!
- Apply instrumental measurements e.g. T_{sys}
- Inspect brightest compact source (usually BP cal)
  - May need to apply delay corrections next
    - Flag bad data (but try calibrating it first if unsure)
- Iteratively derive solutions for phase as a function of time and frequency till you can average optimally
  - Also amplitude solutions vs bandpass and time
  - Use flux standard to set flux scale if available
- Apply bandpass/delay solutions to phase ref & target; apply phase-ref time-dependent solutions to target

Calibration notes

- Always inspect the calibration solutions
  - If they look like random noise they won't do any good!
    - Look at the data – try a different averaging interval?
    - Have you applied necessary prior calibration?
    - Are there bad data?
      - You can always delete or clear calibration and try again
- Check for source resolution
  - Look at visibilities vs uv distance &/or image calibrators if you are not sure they are point-like
    - Build up model by cycles of imaging and calibration if a calibrator is resolved
- See later tutorials for advanced calibration