Introduction to offline calibration of ALMA science data

- Obstructions to the signal
- Instrumental calibration
- Using astrophysical standards
  - CASA implementation
- Calibration algorithms

- Focus on recent data
  - CASA guides & Tech handbook give more information

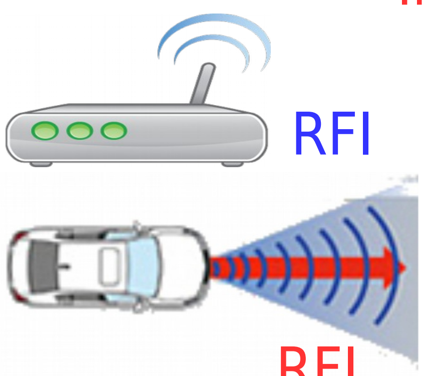
ALMA

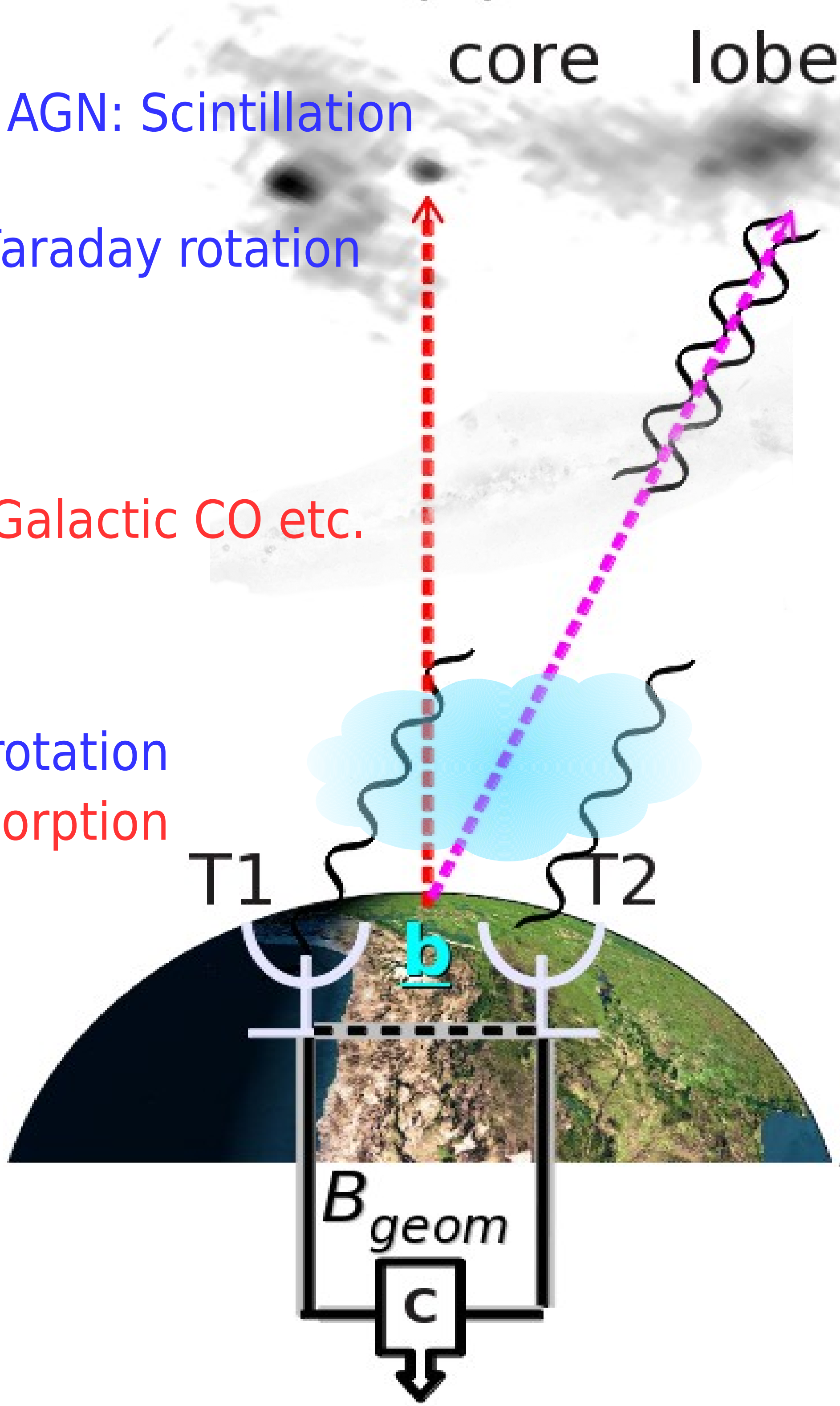
EUROPEAN ARC
ALMA Regional Centre || UK

eMERLIN
The University of Manchester
Jodrell Bank Observatory
MANCHESTER 1824
IVOA
EUROPEAN VLBI NETWORK
RadioNet

Hazards

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

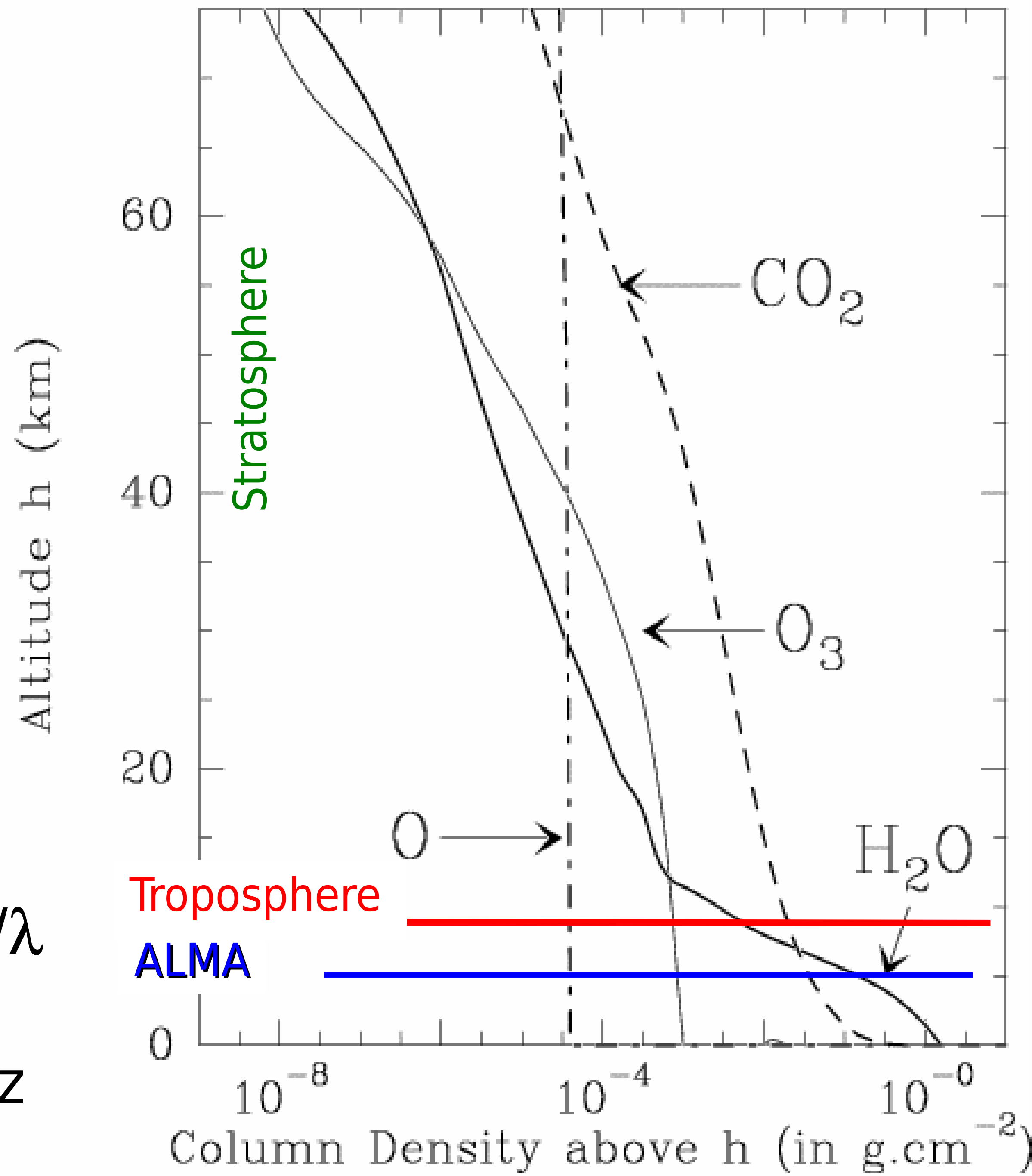




Troposphere

- 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

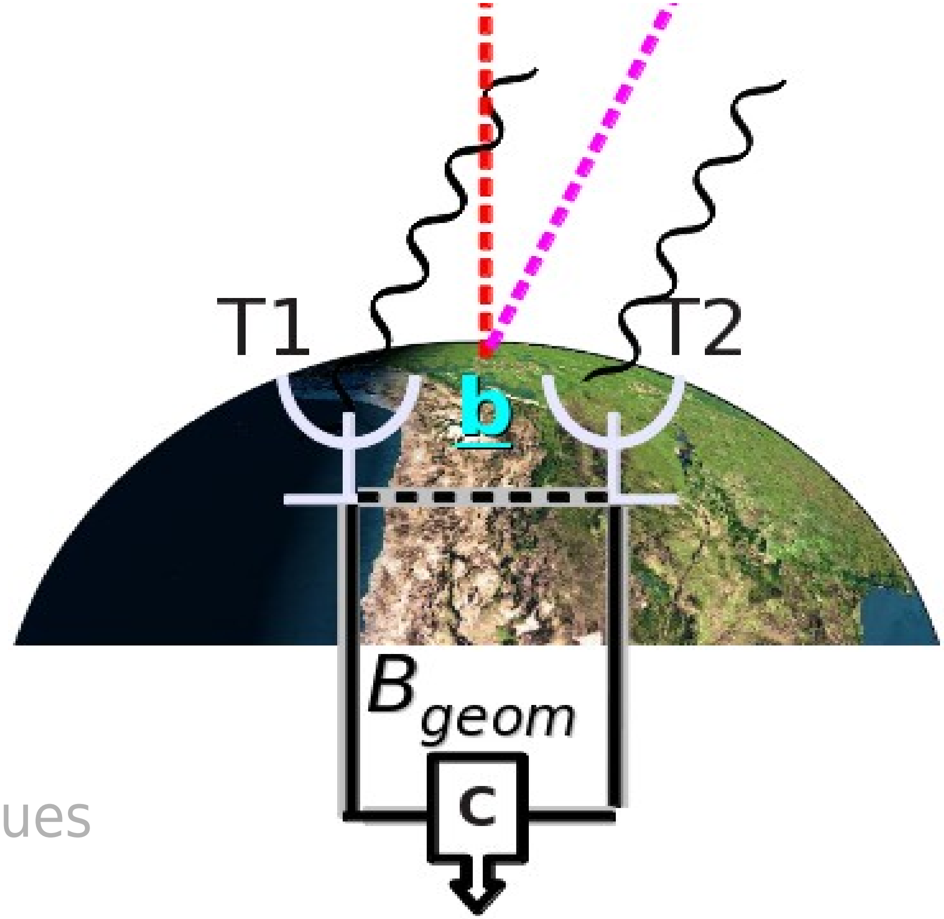


Hazards

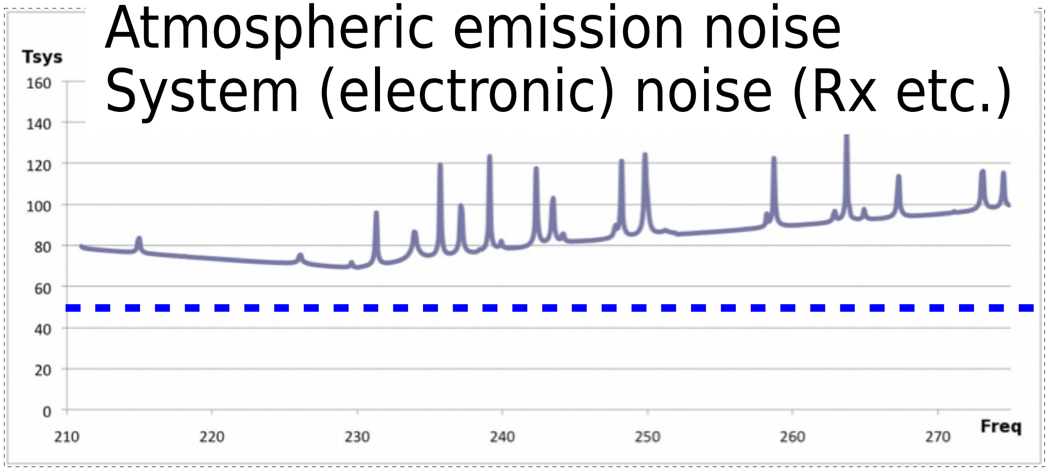
- At the telescope and later
  - Mostly high frequency
  - Less relevant now for ALMA

Antenna positions
Pointing, Focus
Efficiency (surface)

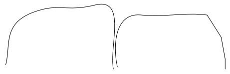
Timing and frequency information issues
(station clock, local oscillator...)



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

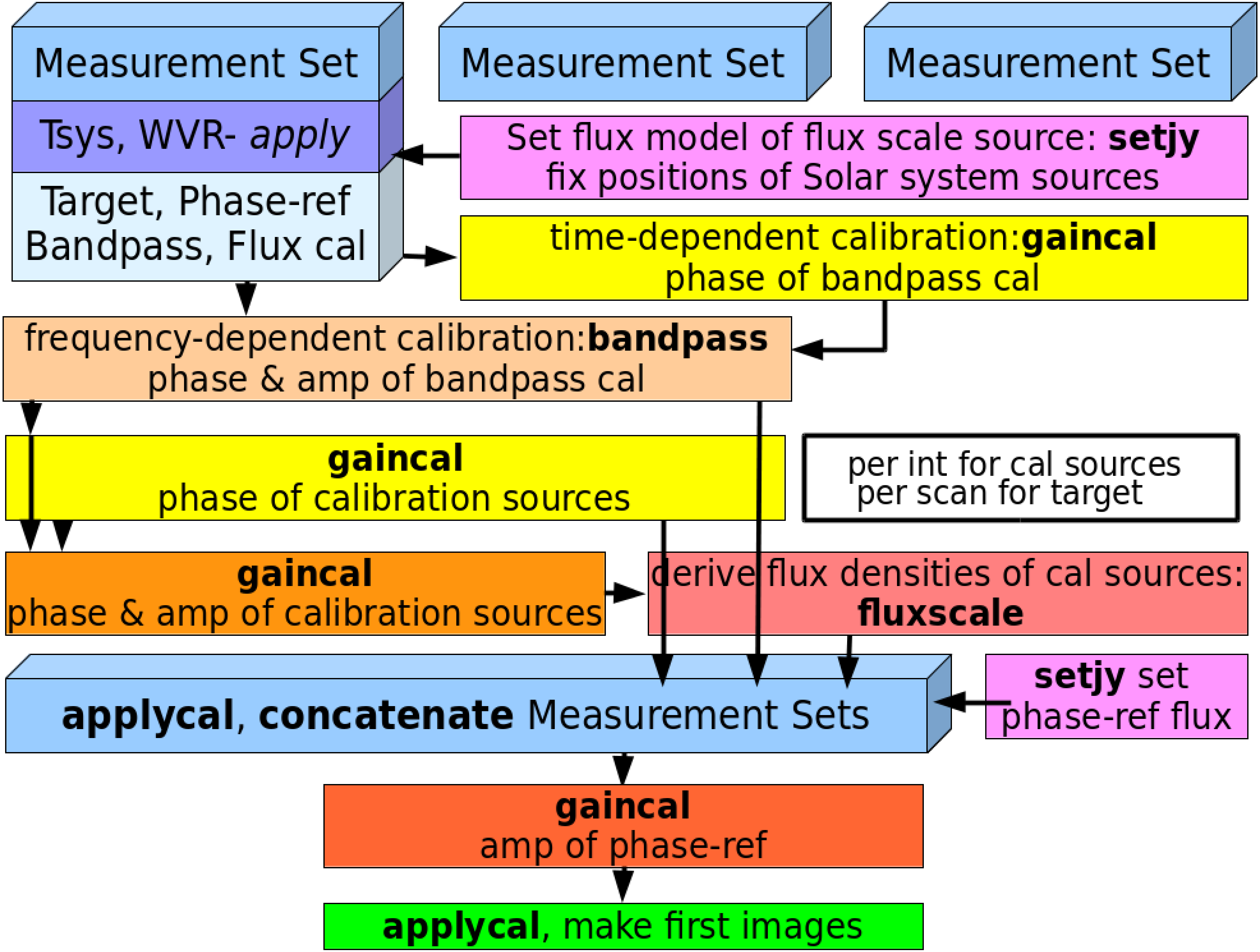


Insufficient corrections for delay tracking (ALMA Cycle 0, VLBI, e-MERLIN)

Bandpass response 

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.
- ALMA Science Data Model
  - XML structure to hold binary data + metadata
    - Very compact, good for transport
  - Convert to Measurement Set for easy access/ modification in processing
    - Huge data? Look up mms (multi-ms) for parallelisation



Measurement Set
Measurement Set
Measurement Set
Tsys, WVR- apply
Set flux model of flux scale source: setjy
fix positions of Solar system sources
Target, Phase-ref
Bandpass, Flux cal
time-dependent calibration:gaincal
phase of bandpass cal
frequency-dependent calibration: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

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!

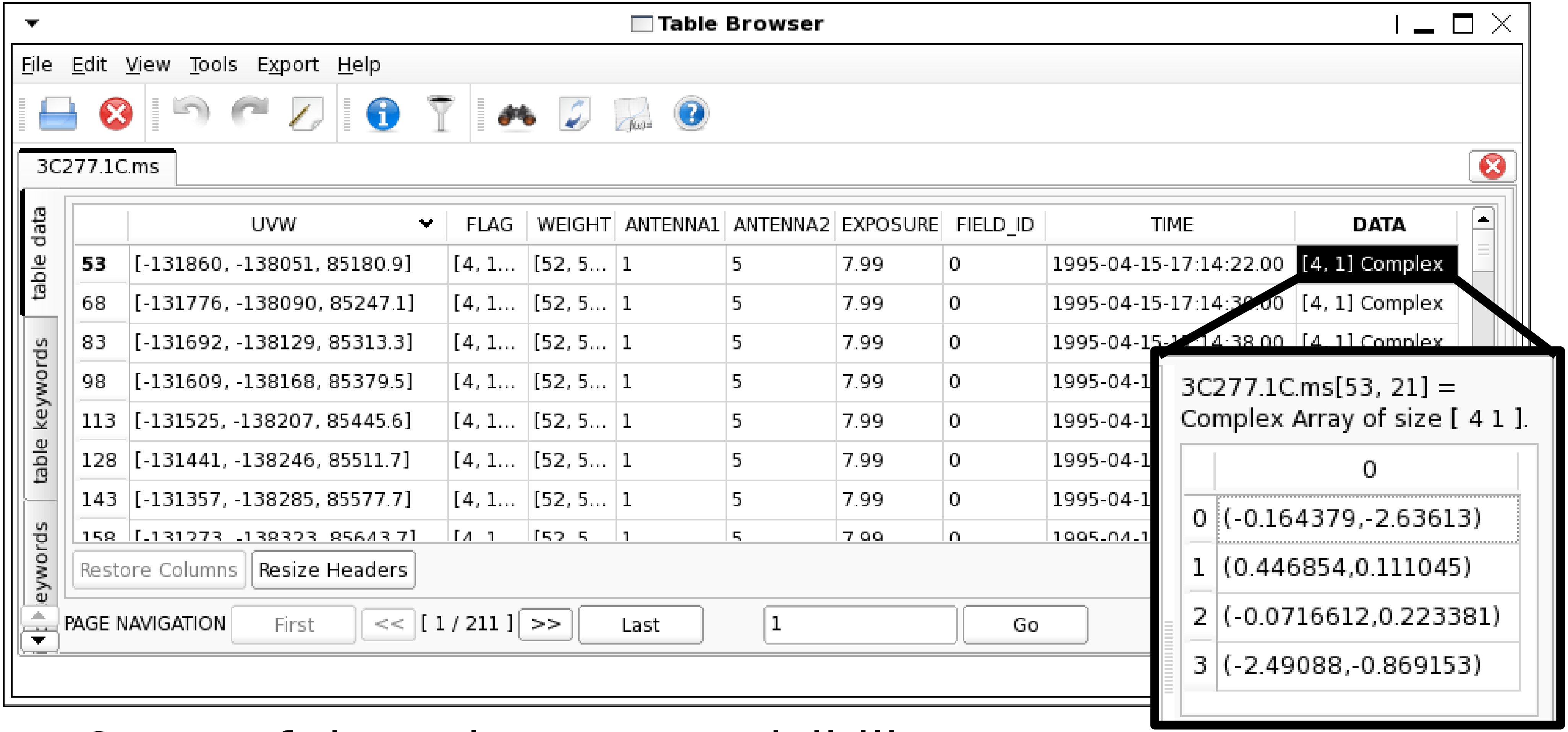
Measurement Set visibility data

- 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



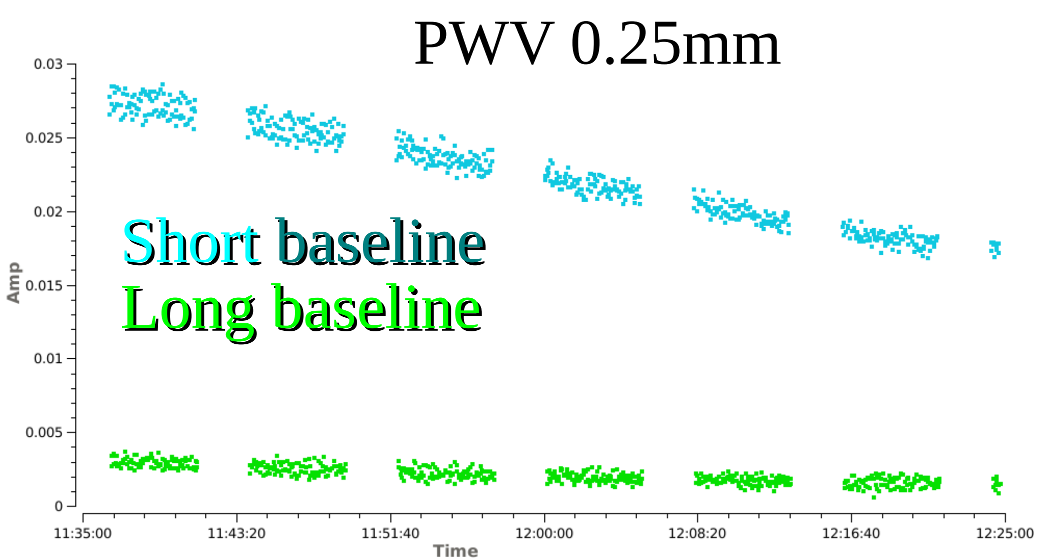
- Some of the columns per visibility
  - **Data**: Complex value for each of 4 correlations (RR RL LR LL) per spectral channel
    - Inspect in CASA `browsetable` or write to file

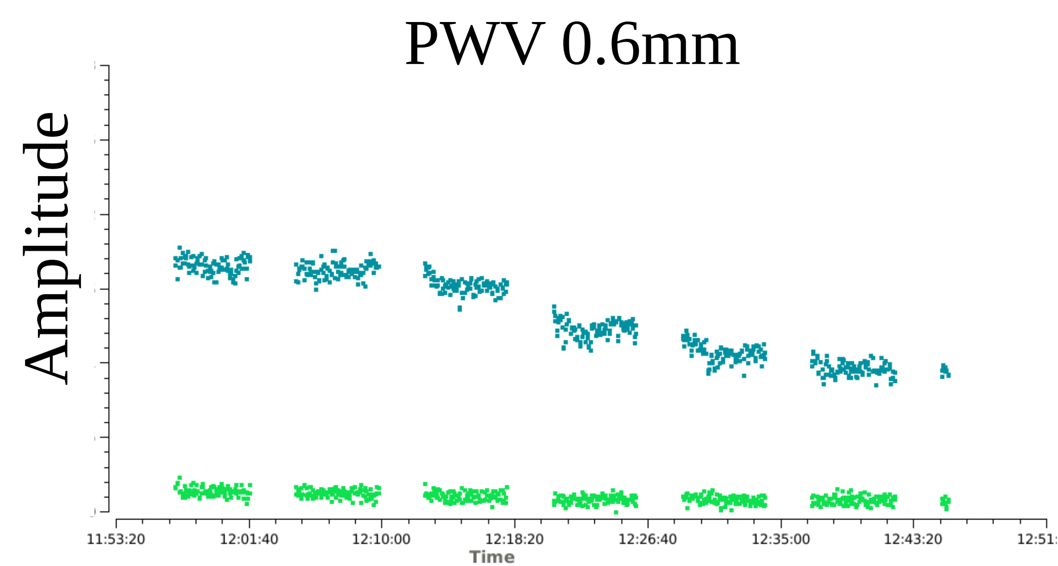
Atmospheric absorption, emission effect on amplitudes

- The atmosphere absorbs the astrophysical signal, and adds noise

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

  where the source would provide temperature *T* if measured above the atmosphere and *z* is the zenith distance
- Same source, same baselines
  - Raw amps lower at higher **P**reciptable **W**ater **V**apour





System temperature measurement

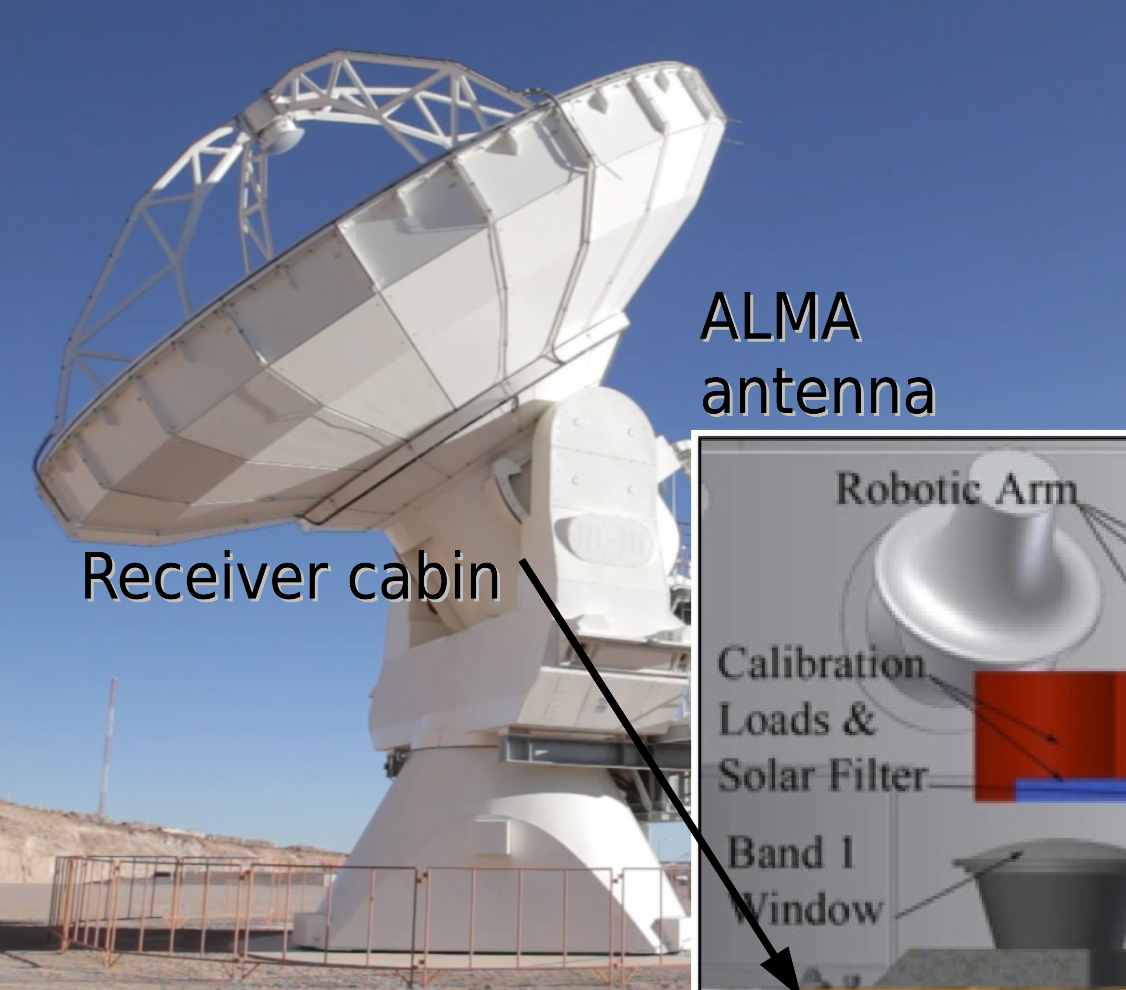
- Compare response to warm load and ambient cabin *T*

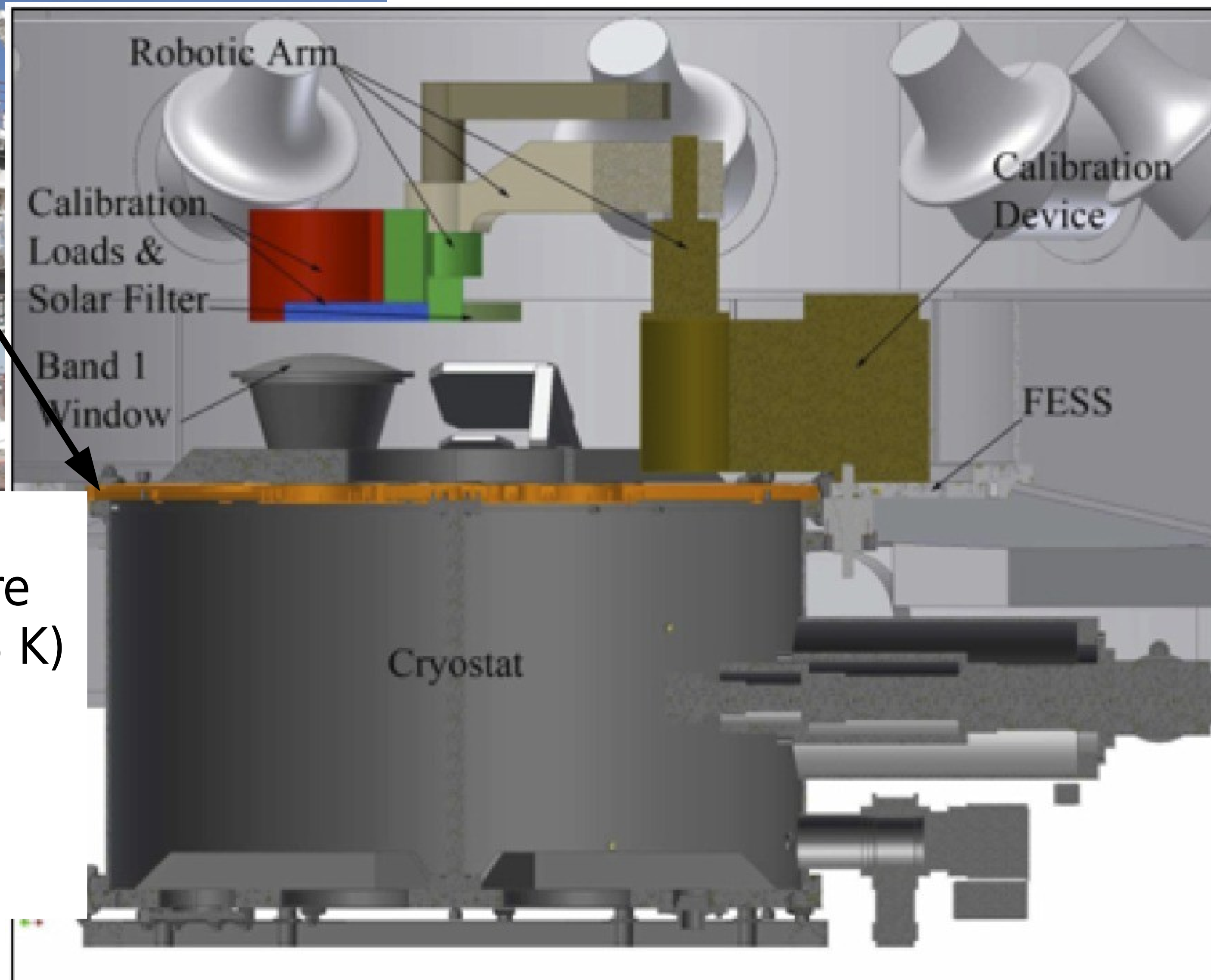
$$T_{sys}=\frac{1}{\eta_A e^{-\tau_{atm}}}\left[T_{Rx}+\eta_A T_{sky}+(1-\eta_A)T_{amb}\right]$$ (single or 2-sideband case)

  - Solve for T_{sys}

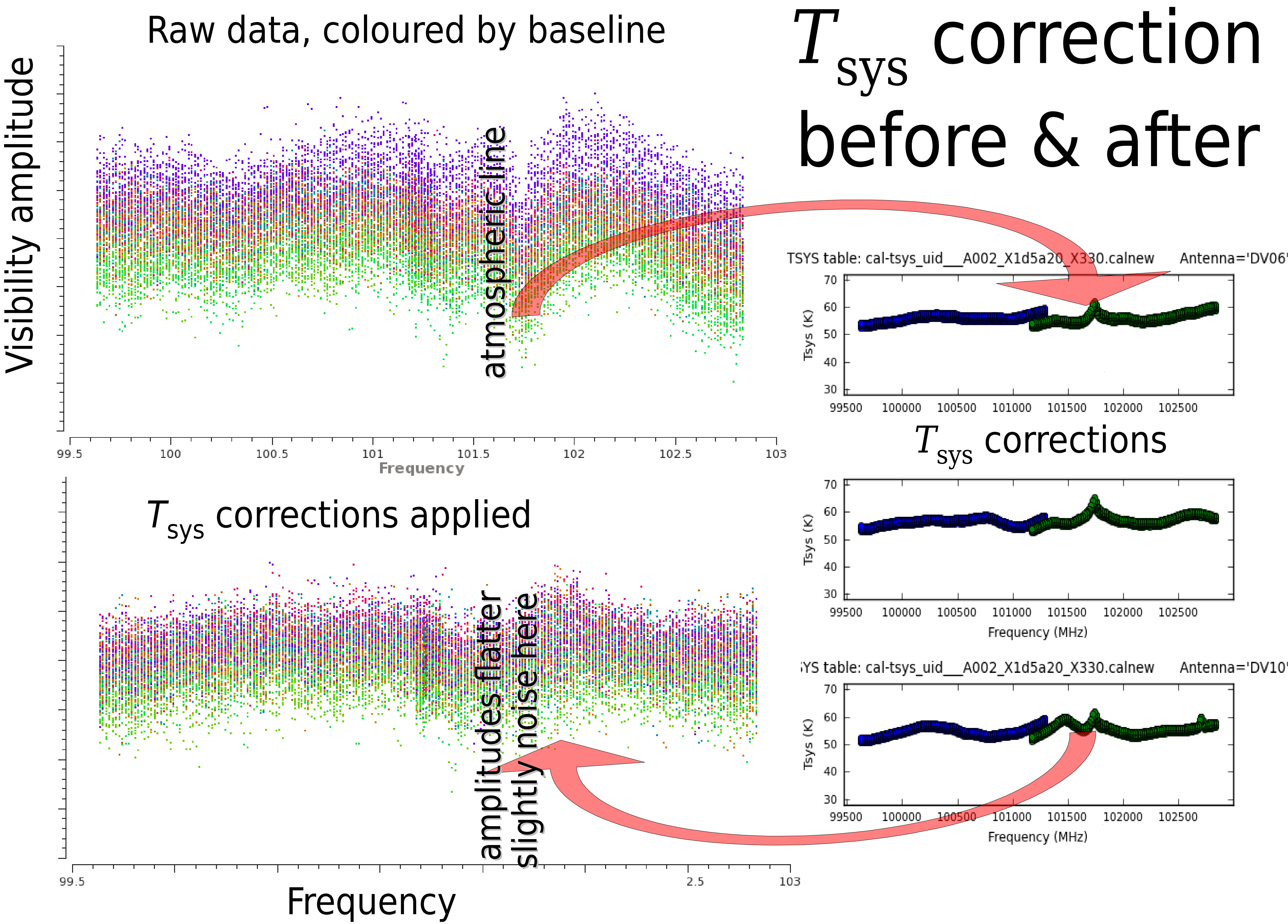
- Provides *relative* scaling of amplitudes (gain-elevation, bright sources, weather...)
- Can use to provide a scaling from correlator units
  - System Equivalent Flux Density SEFD (Jy) = T_{sys}/K
    - where $K = \eta_{\mathrm{A}}\, A_{\mathrm{eff}}\,/2\, k_{\mathrm{B}}$ (Kelvin per Jy)
      - Antenna area A_{eff}, efficiency η_A

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


T_{sys} correction before & after
Raw data, coloured by baseline
Visibility amplitude
atmospheric line
Frequency
T_{sys} corrections applied
amplitudes flatter
slightly noise here
Frequency
TSYS table: cal-tsys_uid___A002_X1d5a20_X330.calnew Antenna='DV06'
Tsys (K)
T_{sys} corrections
Frequency (MHz)
SYS table: cal-tsys_uid___A002_X1d5a20_X330.calnew Antenna='DV10'
Frequency (MHz)

Refractive phase error

- Electro-magnetic wave propagates distance d through medium with refractive index n

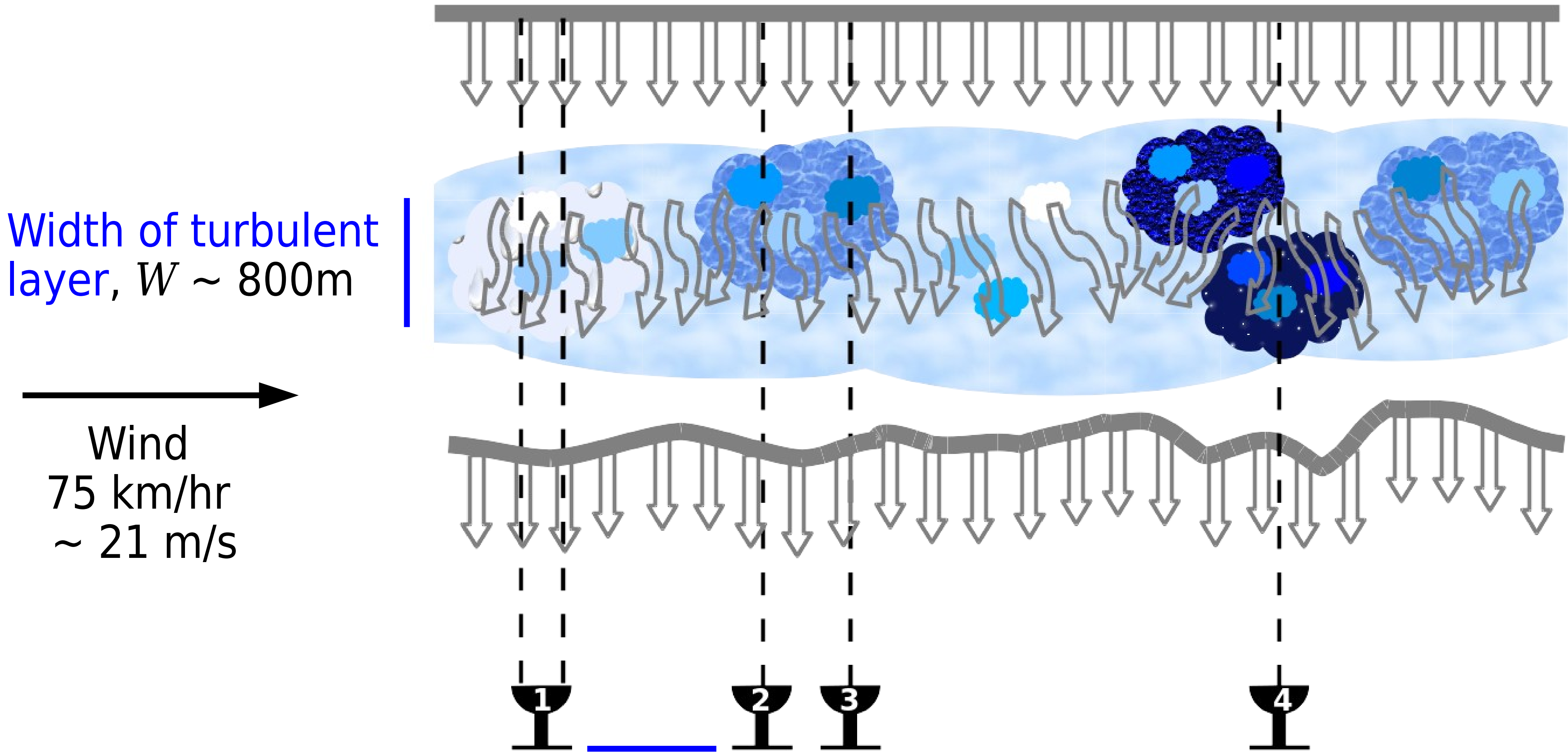
  $(n_{H2O}\text{-}1) \propto \mathrm{PWV} / d\, T_{atm}$

  - where PWV=precipitable water vapour column at atmospheric temperature T_{atm}
    - Refractive index mostly constant >100 GHz
- Total phase error $\Phi_e \propto (2\pi/\lambda)\,(n_{H2O}\text{-}1)d$

  $\propto (2\pi/\lambda)\,\mathrm{PWV}/\,T_{atm}$
- Average, *total* PWV and dry component effect on delay and pointing corrected on-line for ALMA
  - 1 mm PWV ~ 0.7 mm extra path ~ 0.0023 ns delay
  - Snell's Law: $\sin(i_{n\mathrm{H20}})/\sin(i_{n\mathrm{vacuum}}) = n_{\mathrm{H20}} / n_{\mathrm{vacuum}}$

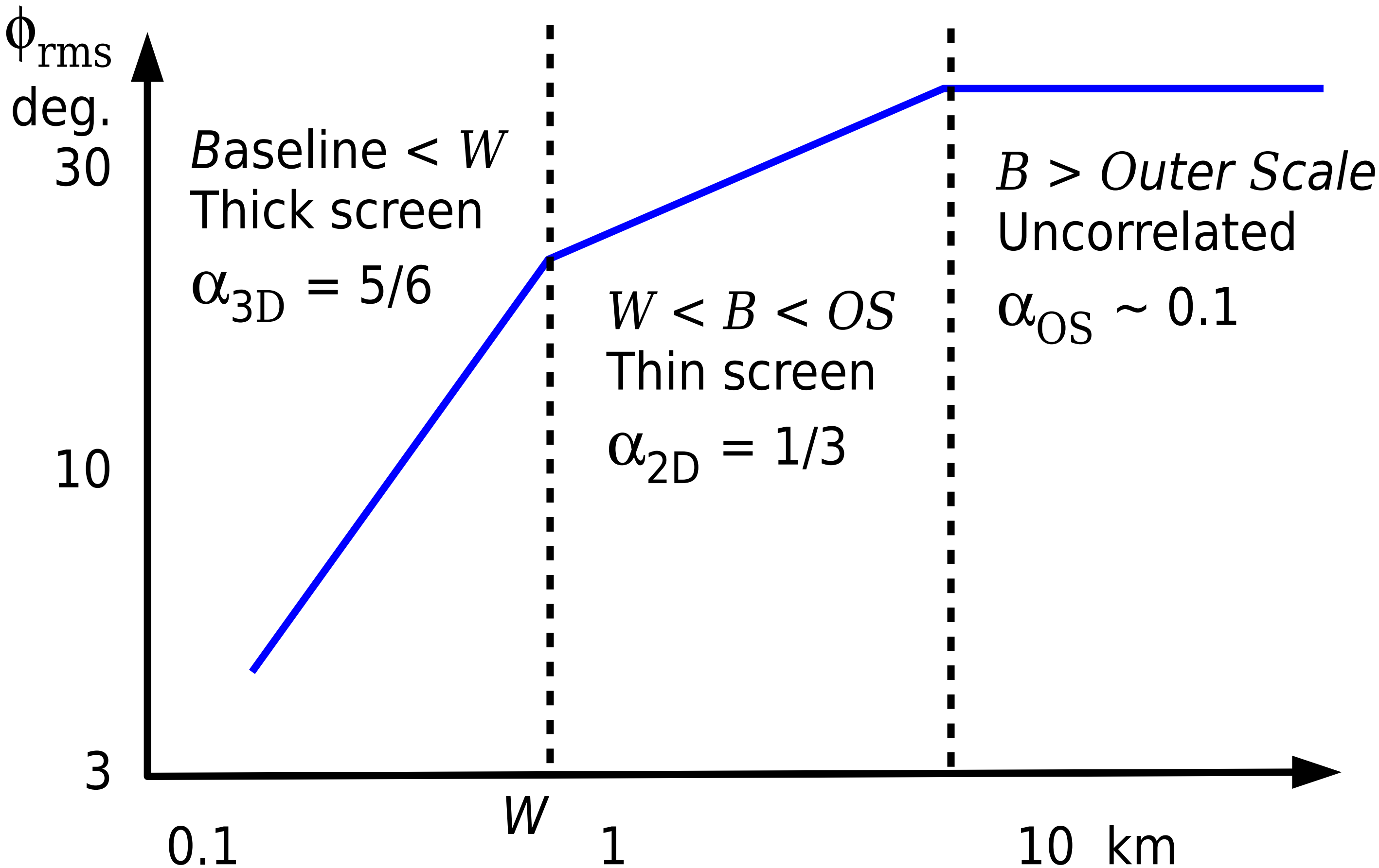
    Refraction angle $\delta\theta \sim \delta n \tan(i)$ < arcmin for ALMA
    - Bulk delay corrected on-line

Troposphere variability scales



- Isoplanatic patch > sky area above single mm antenna
- Antennas 1, 2, 3 see slightly different disturbances
- Sky above antenna 4 very different, varies independently
  - Residual phase fluctuations calibrated off-line

Kolmogorov turbulence



Kolmogorov prediction (*Coulman'90*)

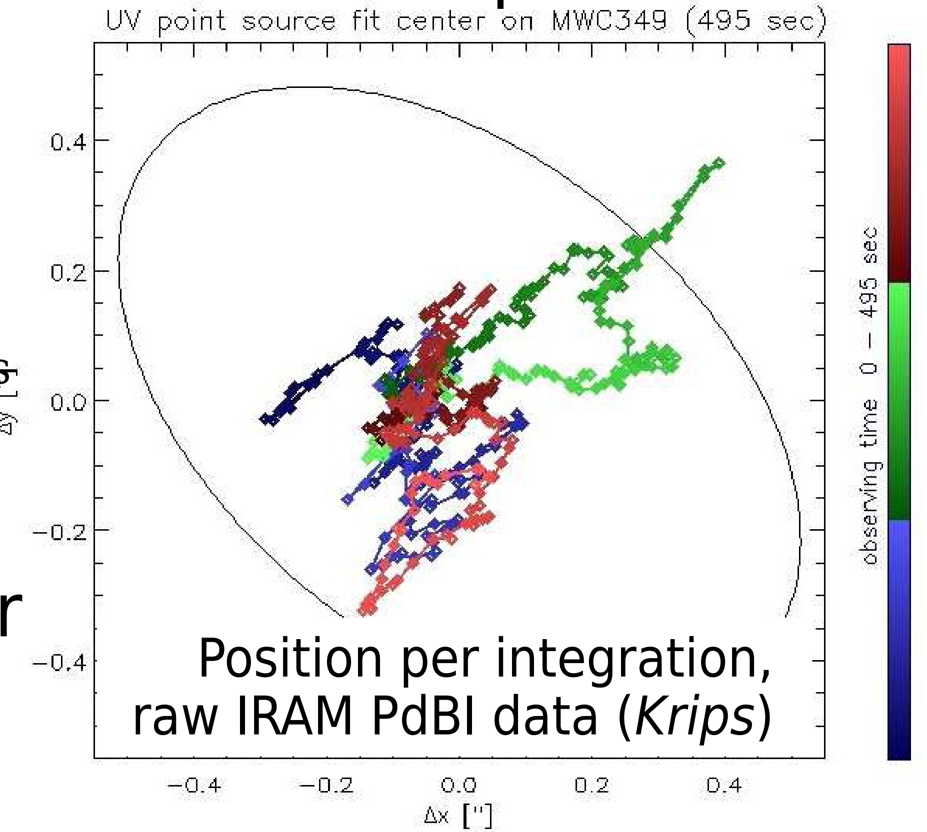
$$\phi_{rms} = \frac{K}{\lambda} B^{\alpha}$$

where K~100 at ALMA for λ in mm and α depends on the length of baseline B compared with W, the thickness of the turbulent layer

- Baseline 2-3 < W
  - Phase noise ϕ_{rms} increases as $B^{5/6}$
- Baselines 1-2, 1-3 > W but < OS: $\phi_{rms} \propto B^{1/3}$
- Baselines 4-* in outer scale regime: ϕ_{rms} levels off

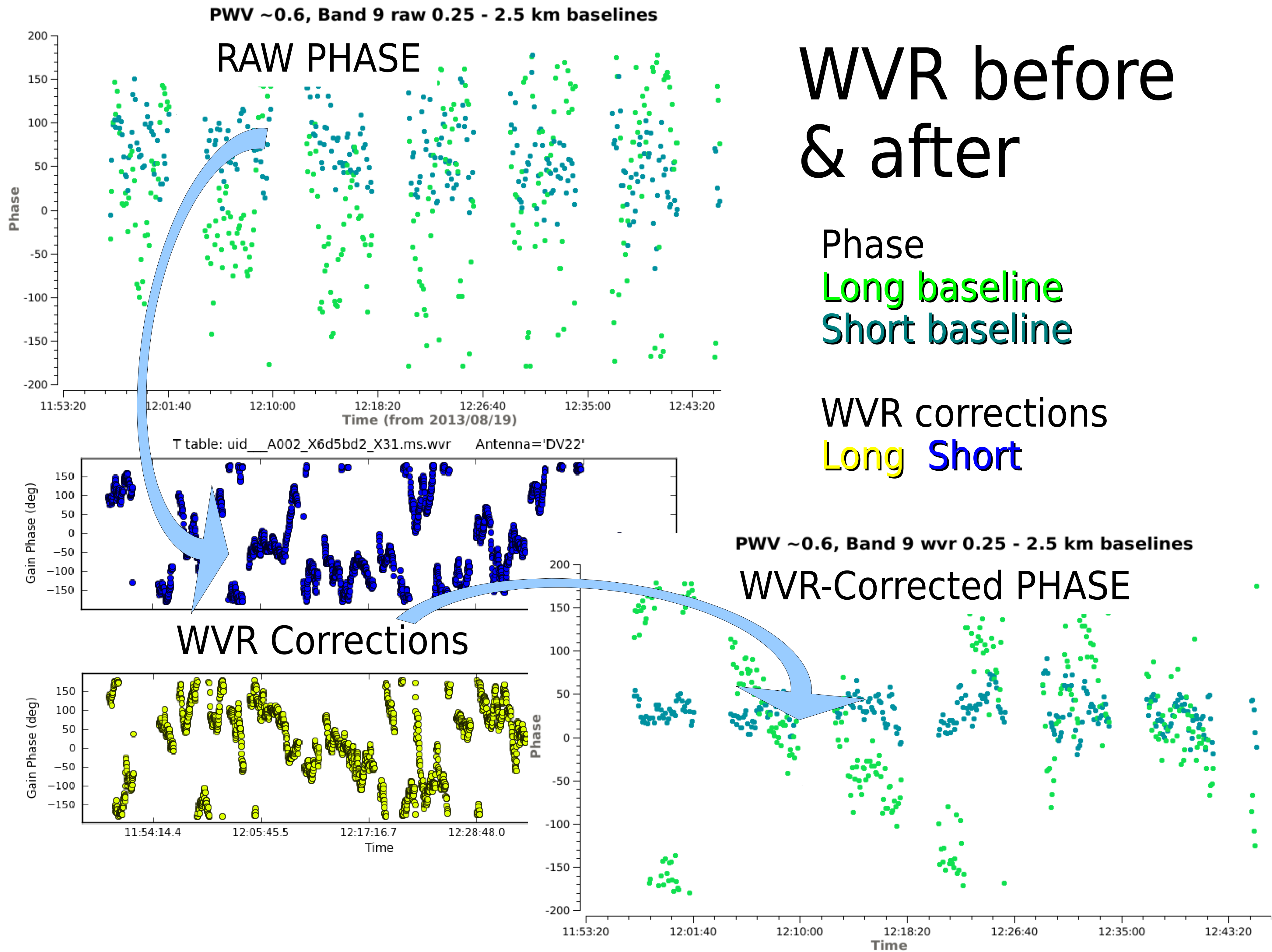
Refraction variations ⇒ phase errors ⇒ amplitude loss, position jitter

- Averaging fluctuating phase decorrelates amplitudes
  - Visibility $V = V_o e^{i\phi}$
    $\langle V \rangle = V_o \langle e^{i\phi} \rangle = V_o e^{-(\phi_{rms}^2)/2}$
    ϕ_{rms} in radians
    Lose ~2% amplitude for 10° ϕ_{rms}
    - In addition to absorption loss
- Fluctuations on time-scales
  ~1 sec: raw data position jitter



Position per integration, raw IRAM PdBI data (*Krips*)

- **W**ater **V**apour **R**adiometry
  - Measure sky emission around 183-GHz water line for each antenna, every ~second
    - Calculate PWV column and hence phase delay
      - Derive corrections $\Phi_e \propto (2\pi/\lambda)$ PWV

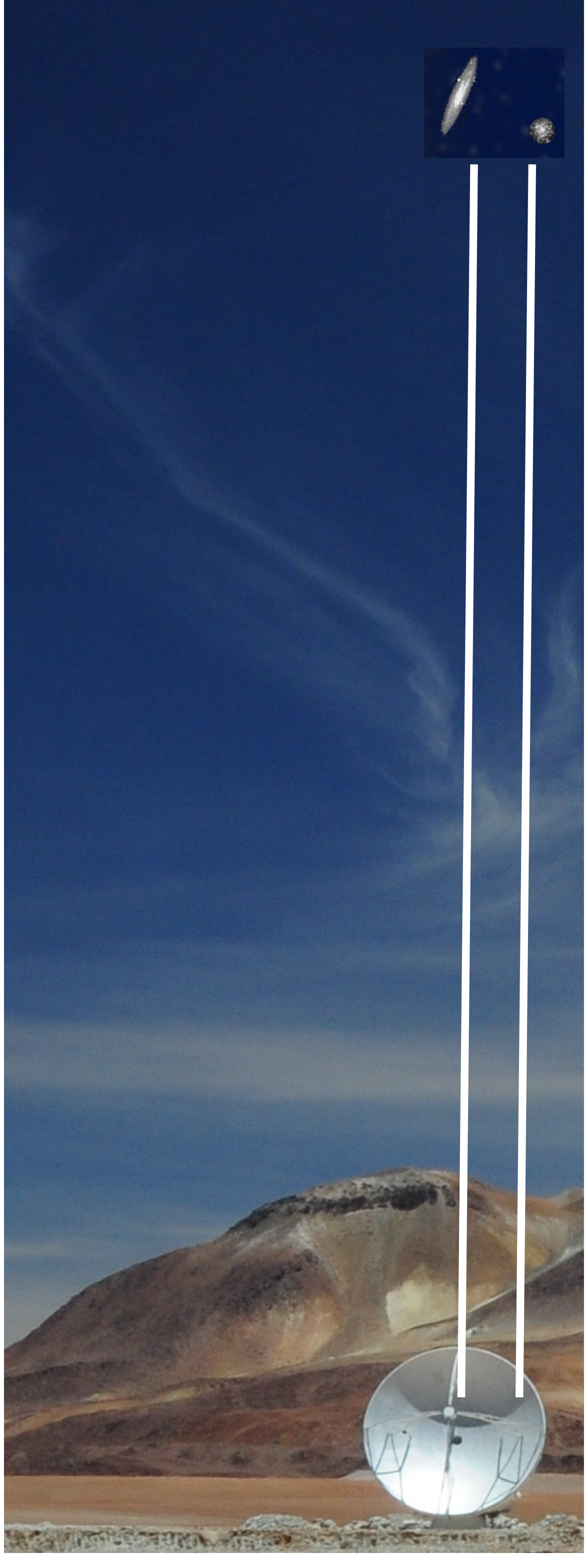

WVR before & after
Phase
Long baseline
Short baseline
WVR corrections
Long Short
PWV ~0.6, Band 9 raw 0.25 - 2.5 km baselines
RAW PHASE
Phase
Time (from 2013/08/19)
T table: uid___A002_X6d5bd2_X31.ms.wvr Antenna='DV22'
Gain Phase (deg)
WVR Corrections
Time
PWV ~0.6, Band 9 wvr 0.25 - 2.5 km baselines
WVR-Corrected PHASE
Time

Calibration using astrophysical sources

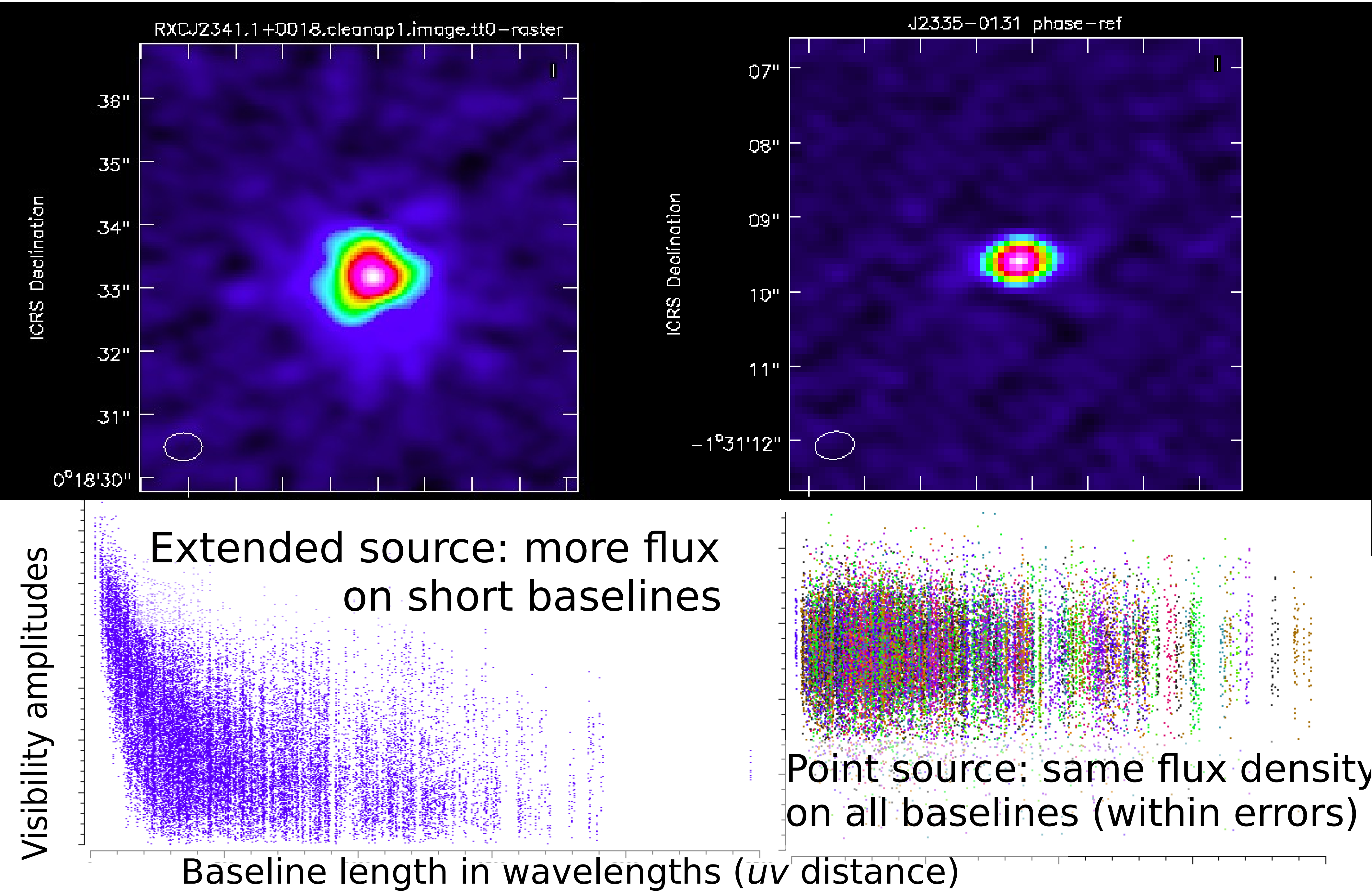
- A typical observation includes at least the following:
  - Science target source(s)
  - Phase reference calibrator close on sky to target
    - Bright enough to give good S/N in each scan
  - Bandpass calibration source
    - Strong enough to be seen in a single channel
  - Flux scale calibrator of 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**

Phase referencing

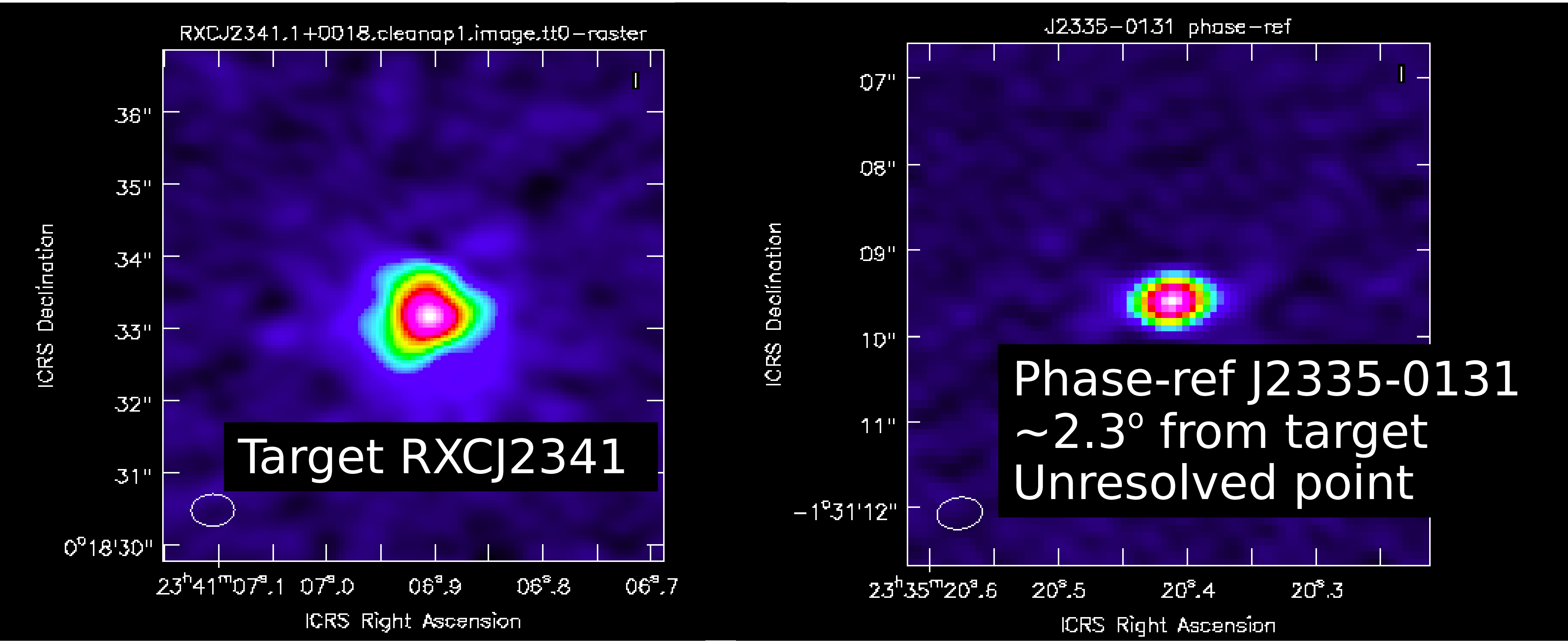
- Observe phase-ref source close to target
  - Point-like or with a good model
  - Close enough to see same atmosphere
    - ~2-15 degrees (isoplanatic patch)
  - Bright enough to get good SNR much quicker than atmospheric timescale τ
    - τ 10 min/30 s short/long B & low/high ν
  - Nod on suitable 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



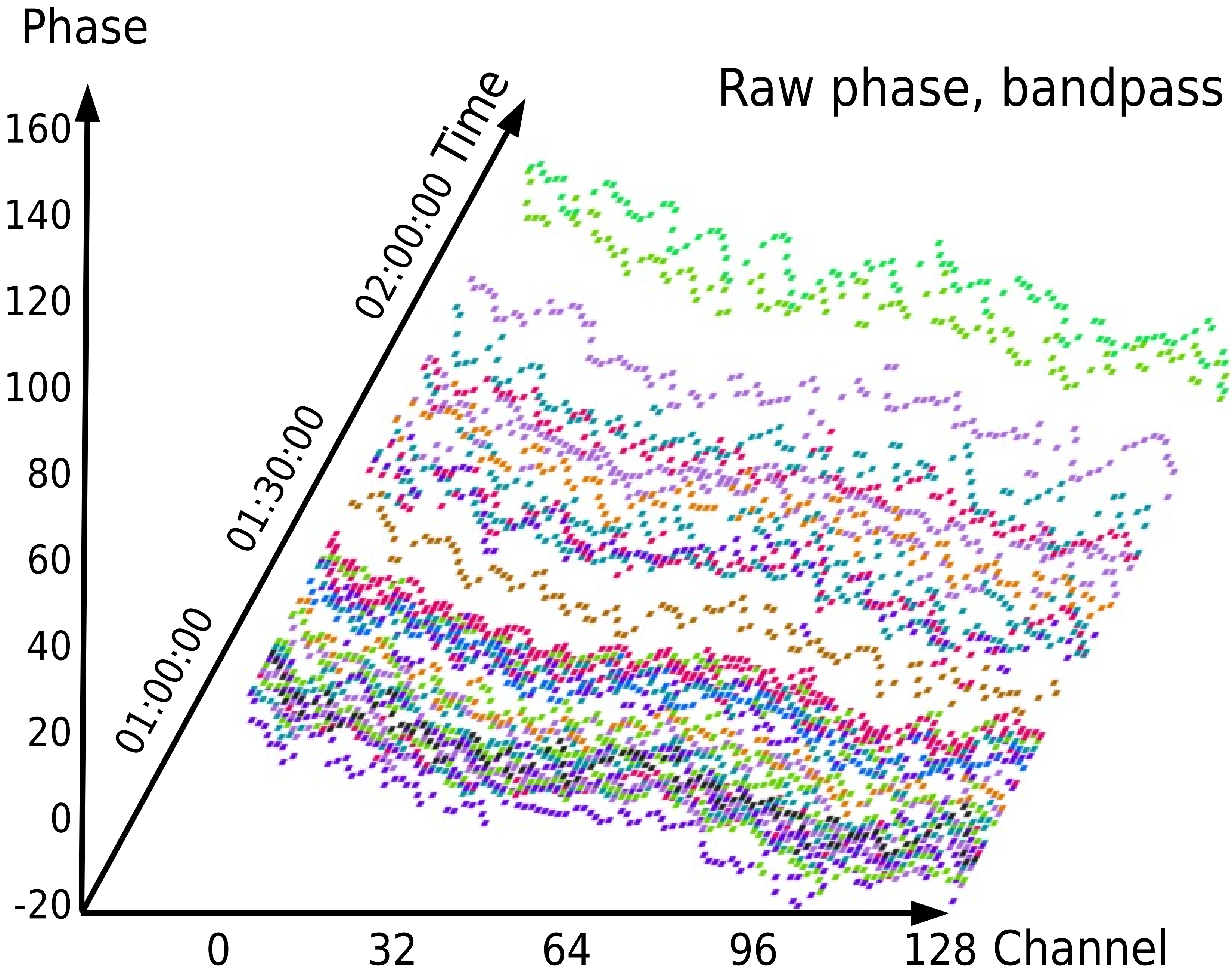
Phase referencing



- 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° phase slope across the band

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

Calibration strategy

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

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

    - $\sigma_{\rm array}$ 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 calibrator
    - First, time-dependent ϕ calibration
      - allow averaging up in time to get enough S/N per channel

Calibration with astrophysical sources

- Bandpass calibrator – bright as possible

1. Derive time-dependent phase (optional amp) calibration (G1) with solint int (if necessary select good channel range)

2. Apply calibration (G1), average all times for freq. dependent phase & amplitude calibration, i.e. bandpass calibration (B1).

  - Average narrow channels to ~5 – 20 MHz
    - G1 *is not used any more*

- Phase-reference – fairly bright source

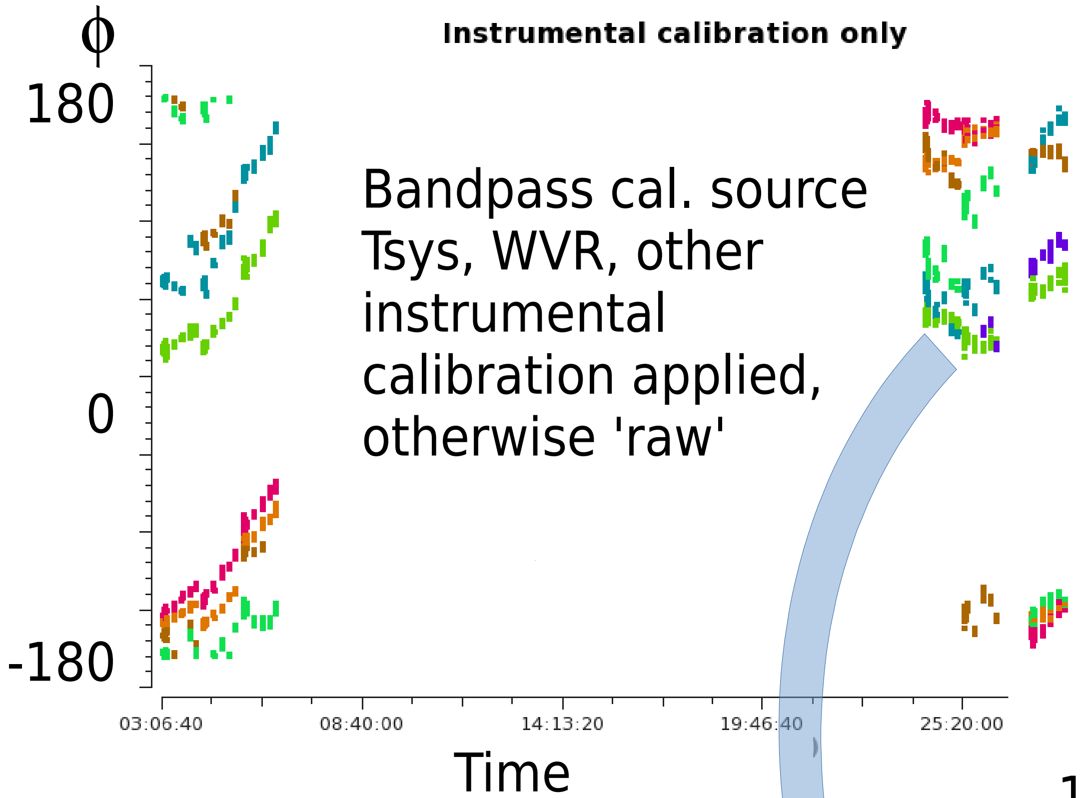
3. Apply B1 and derive time-dependent phase calibration (G2)

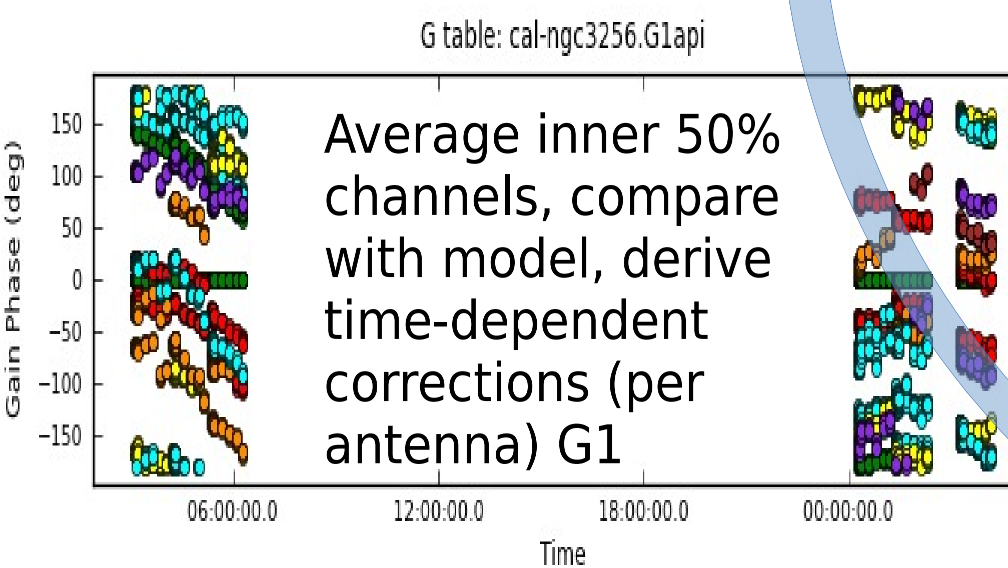
average all channels, shortest *dt* for enough SNR (default int)

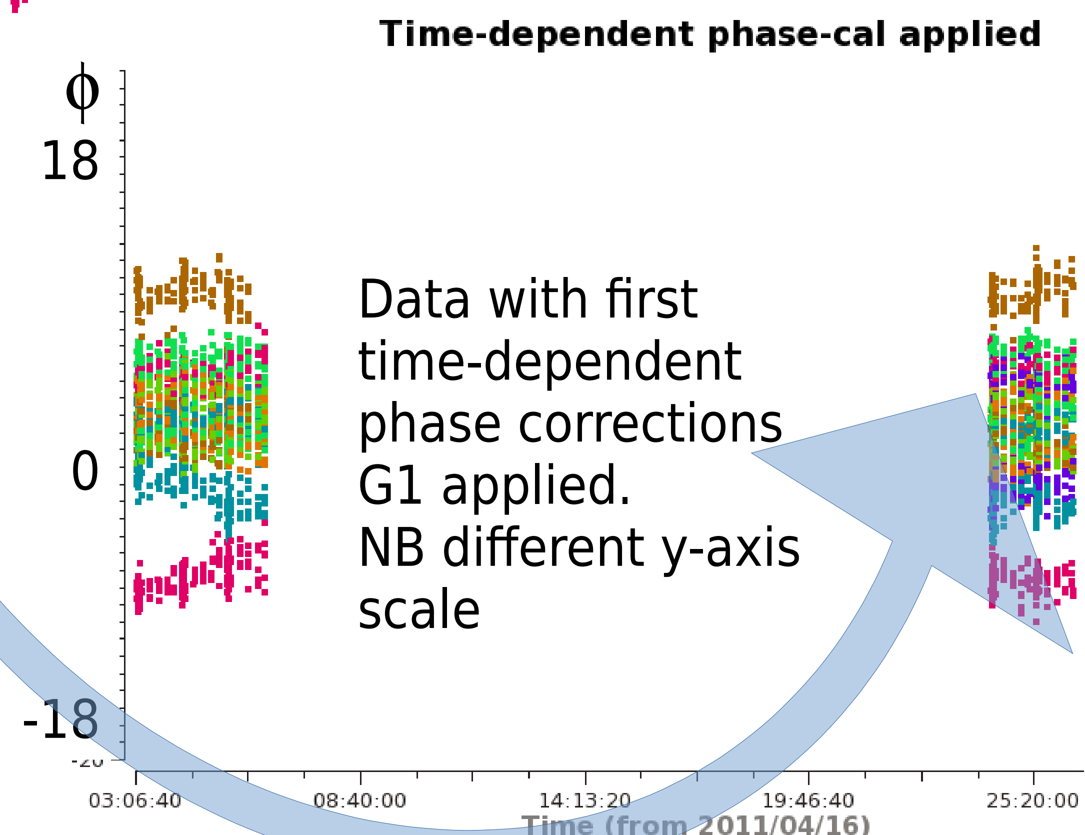
4. Apply B1, G2, derive time-dependent amp. cal. per scan (G3)

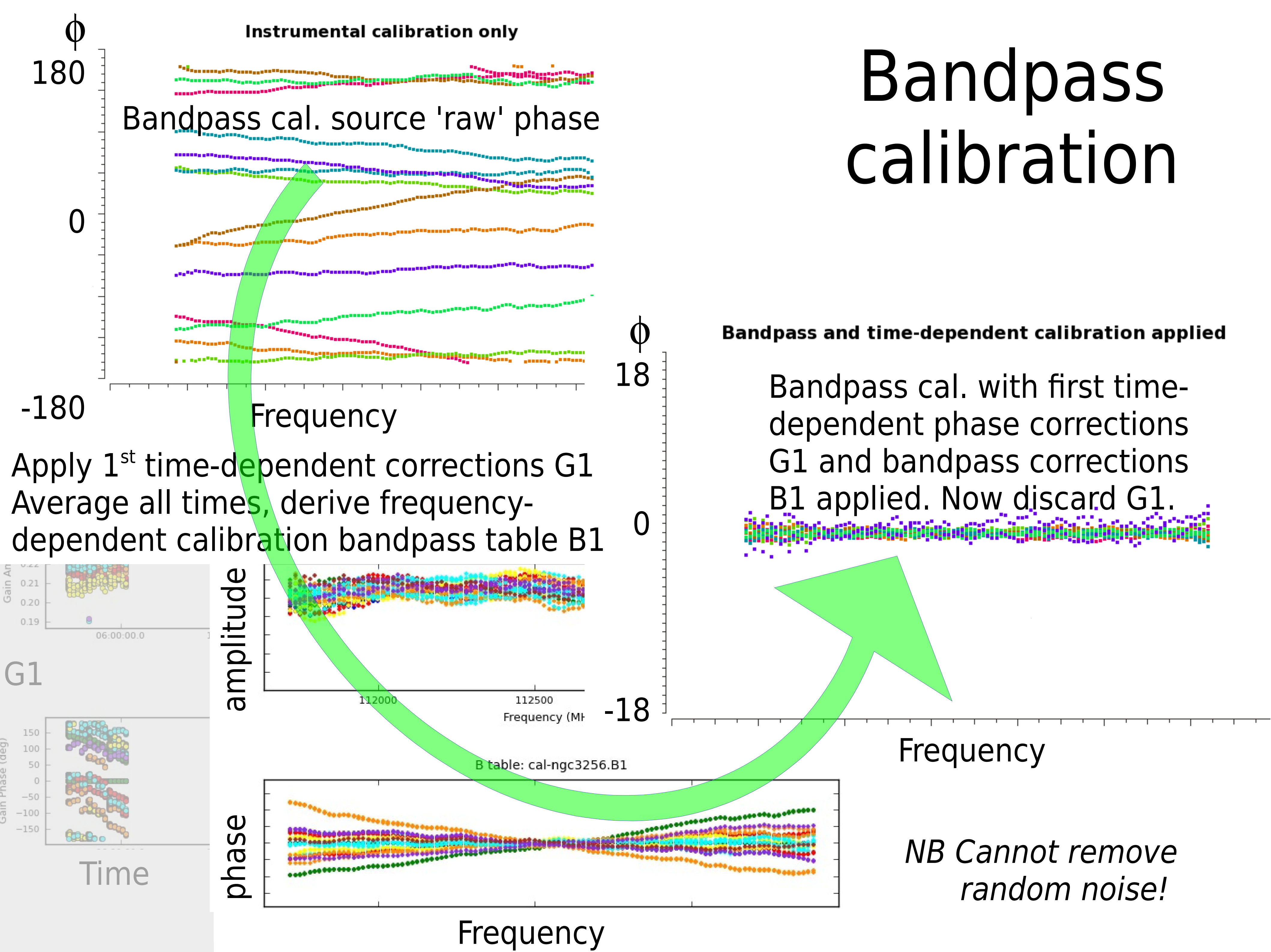
5. Apply B1 and derive time-dependent phase cal. *per scan* (G4) to maximise S/N and 'relevance' to target

First time-dependent phase correction





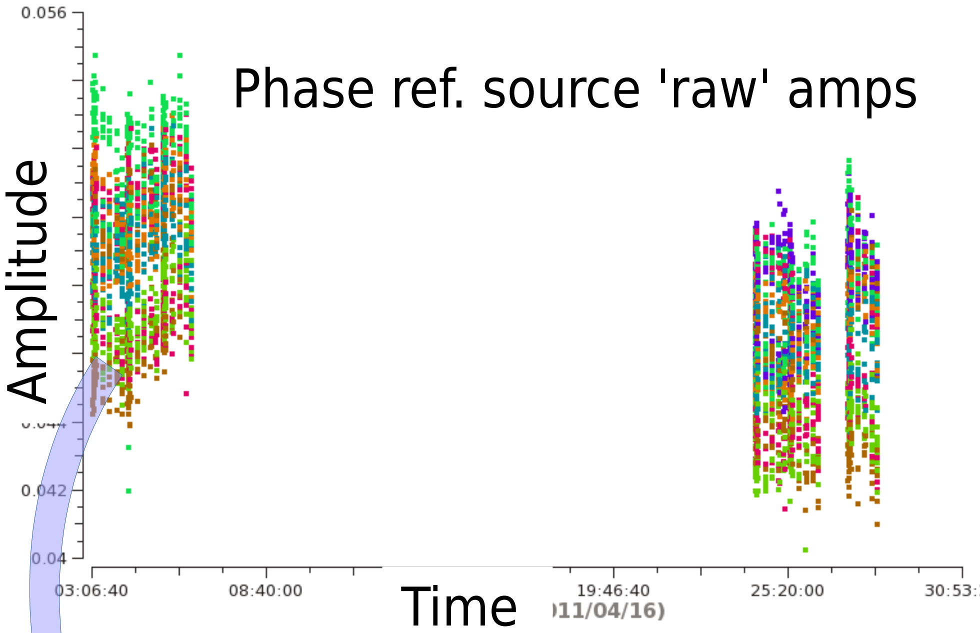


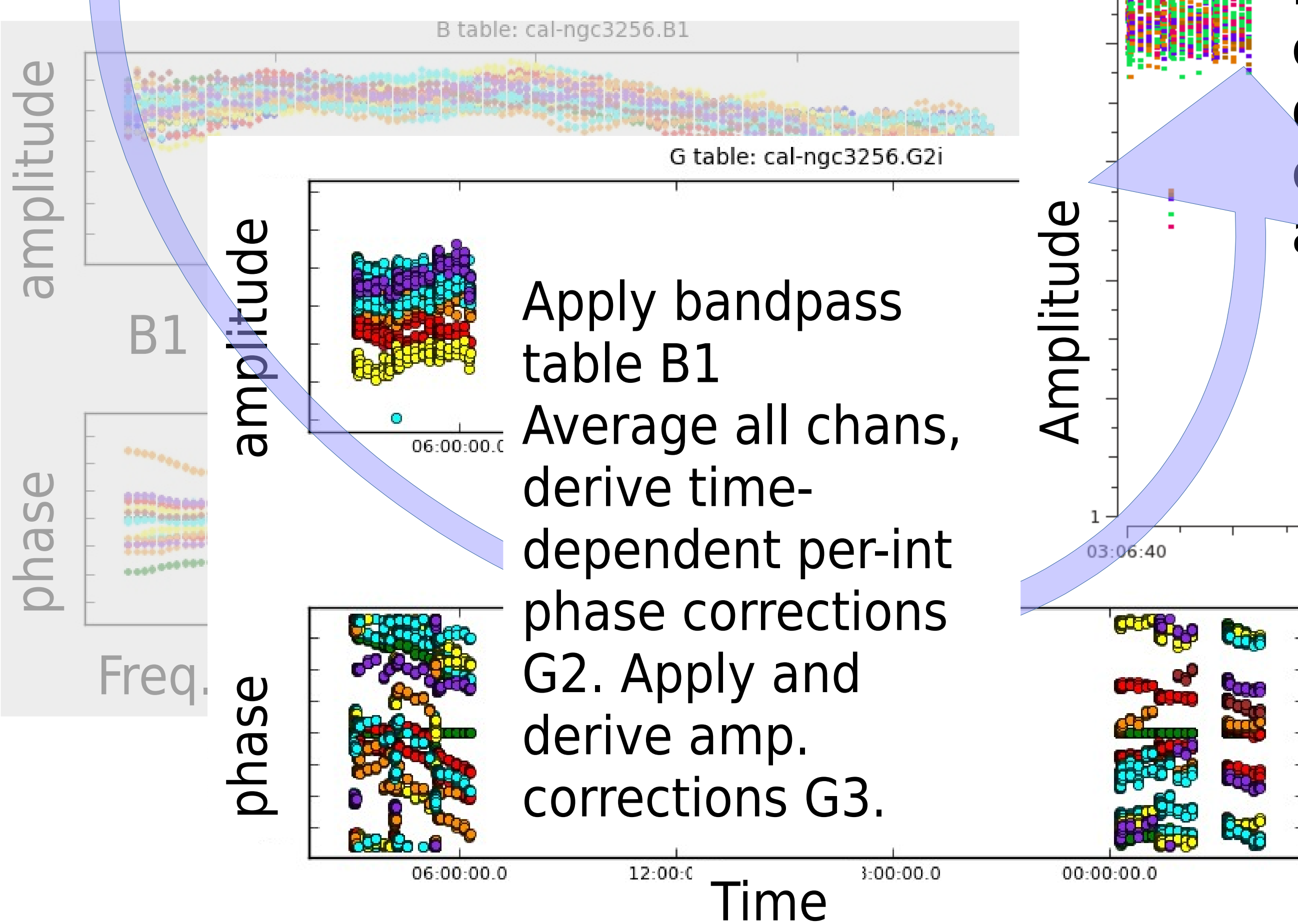


Bandpass calibration
Instrumental calibration only
ϕ
180
0
-180
Bandpass cal. source 'raw' phase
Frequency
Apply 1st time-dependent corrections G1
Average all times, derive frequency-dependent calibration bandpass table B1
G1
Time
amplitude
112000
112500
Frequency (MH
B table: cal-ngc3256.B1
phase
Frequency
Bandpass and time-dependent calibration applied
ϕ
18
0
-18
Bandpass cal. with first time-dependent phase corrections G1 and bandpass corrections B1 applied. Now discard G1.
Frequency
NB Cannot remove random noise!

Phase-ref amp & phase calibration

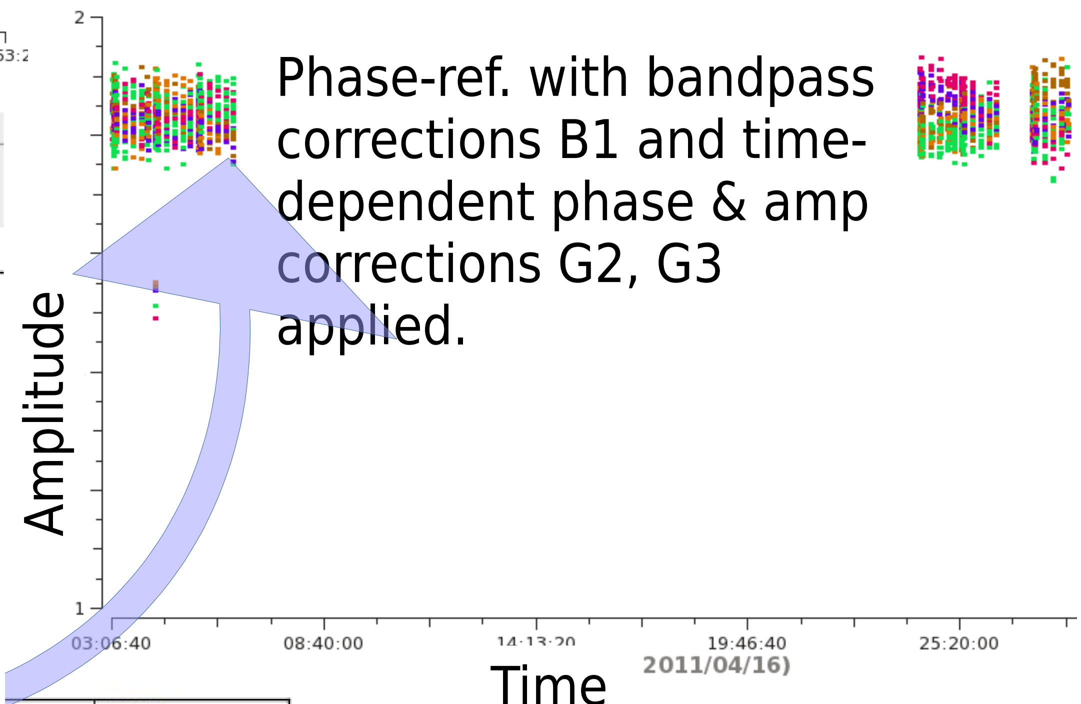
Phase ref. source 'raw' amps





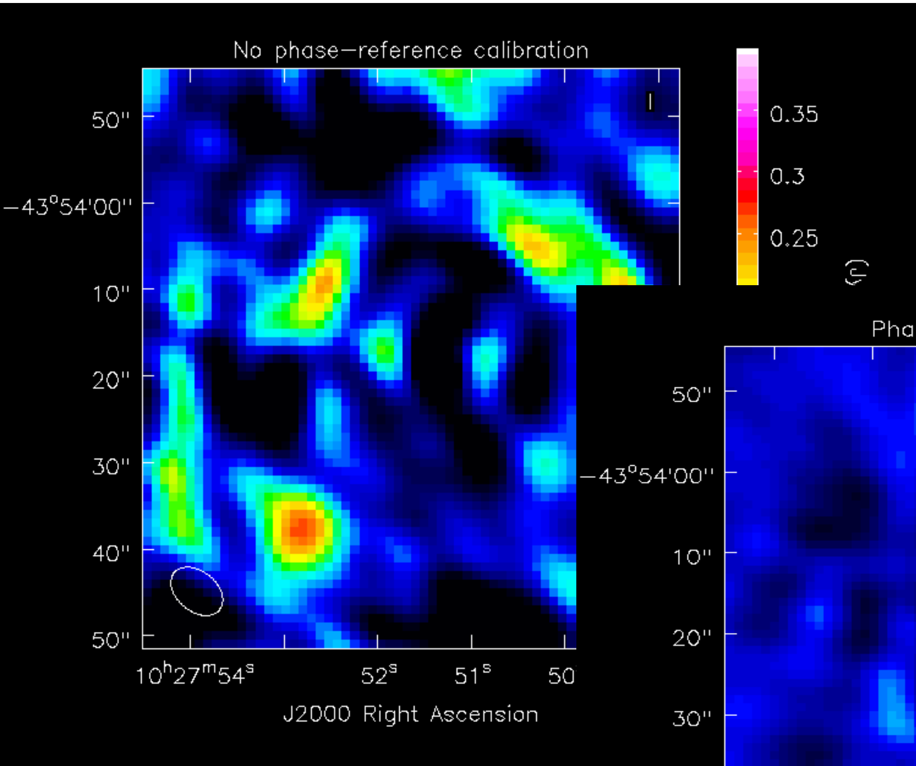
Apply bandpass table B1
Average all chans, derive time-dependent per-int phase corrections G2. Apply and derive amp. corrections G3.

Phase-ref. with bandpass corrections B1 and time-dependent phase & amp corrections G2, G3 applied.

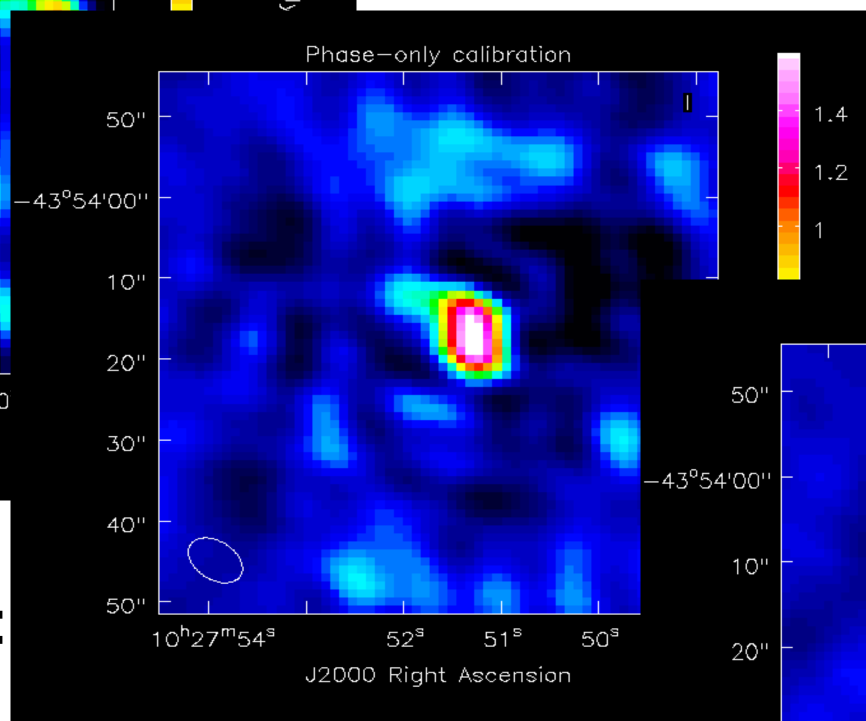


Derive per-scan phase-ref corrections G4
Apply B1, G2 and G4 to the phase-ref and the target

Phase & amp: effects on imaging

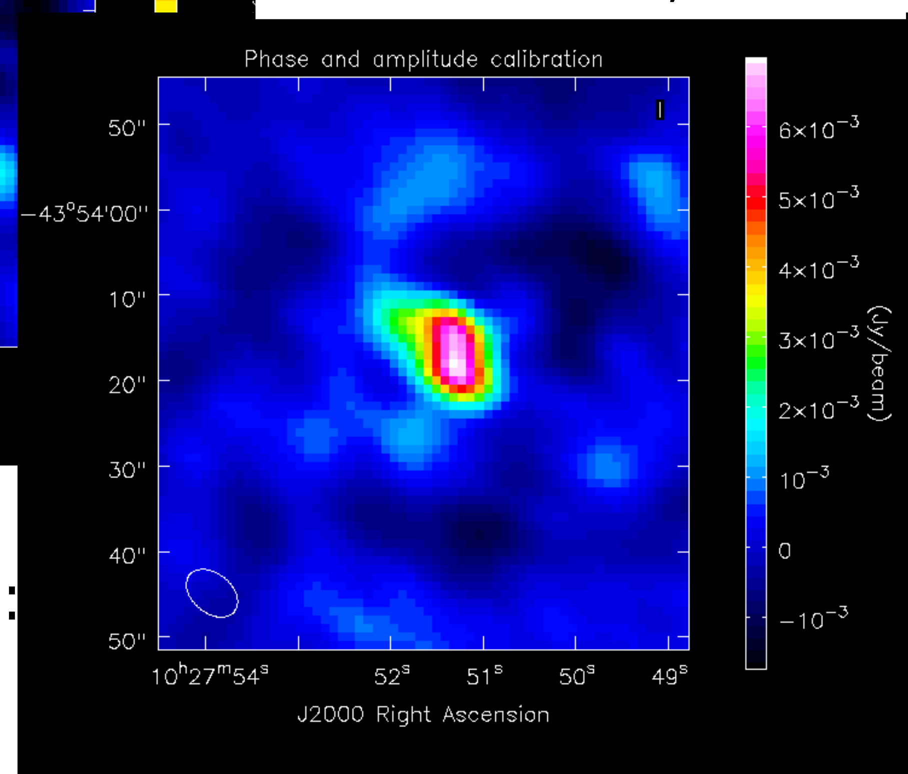


Tsys, WVR,
Bandpass cal only:
no source seen



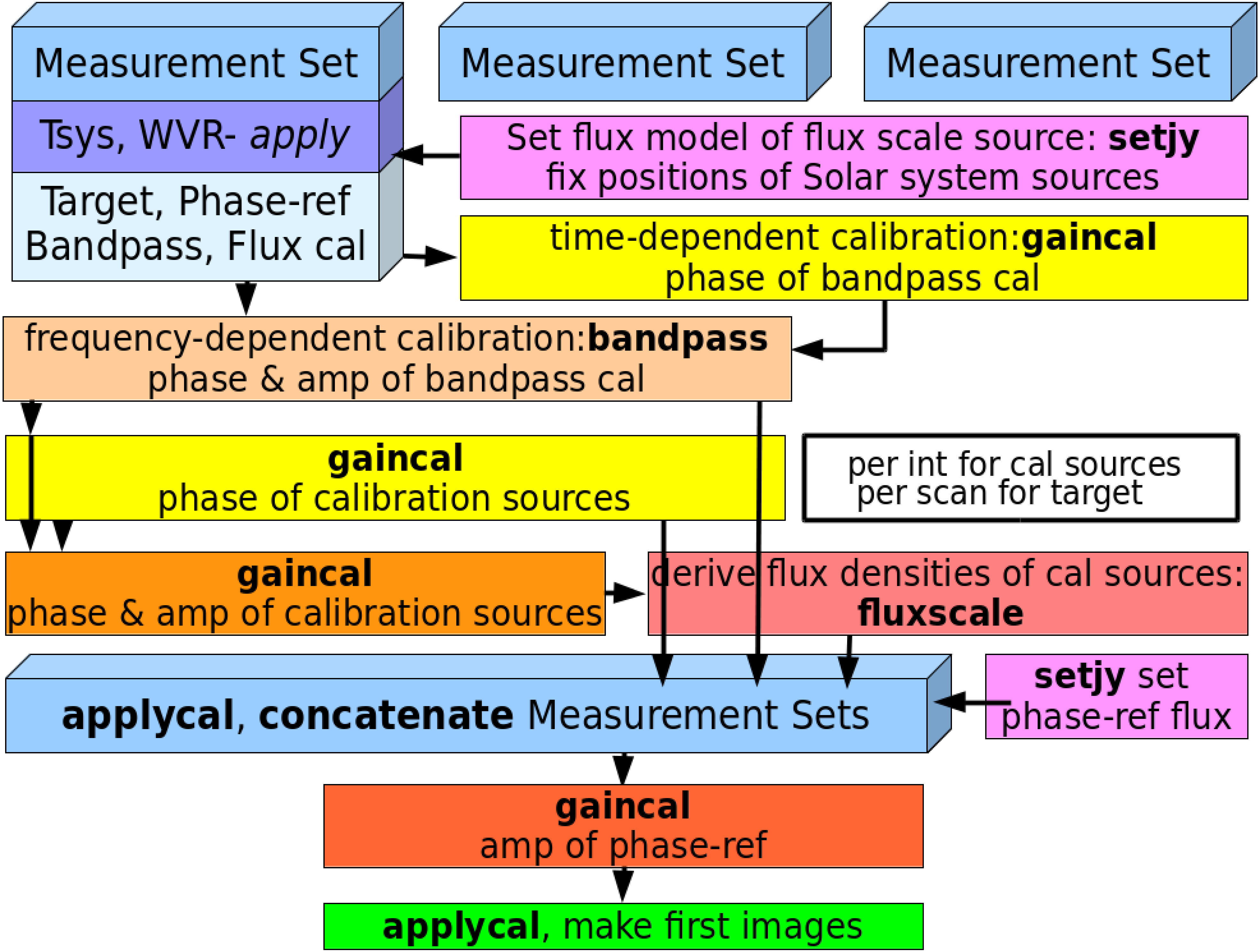
plus
phase-only solutions:
source seen, snr 15

plus
amplitude and phase
solutions:
source seen, snr 22

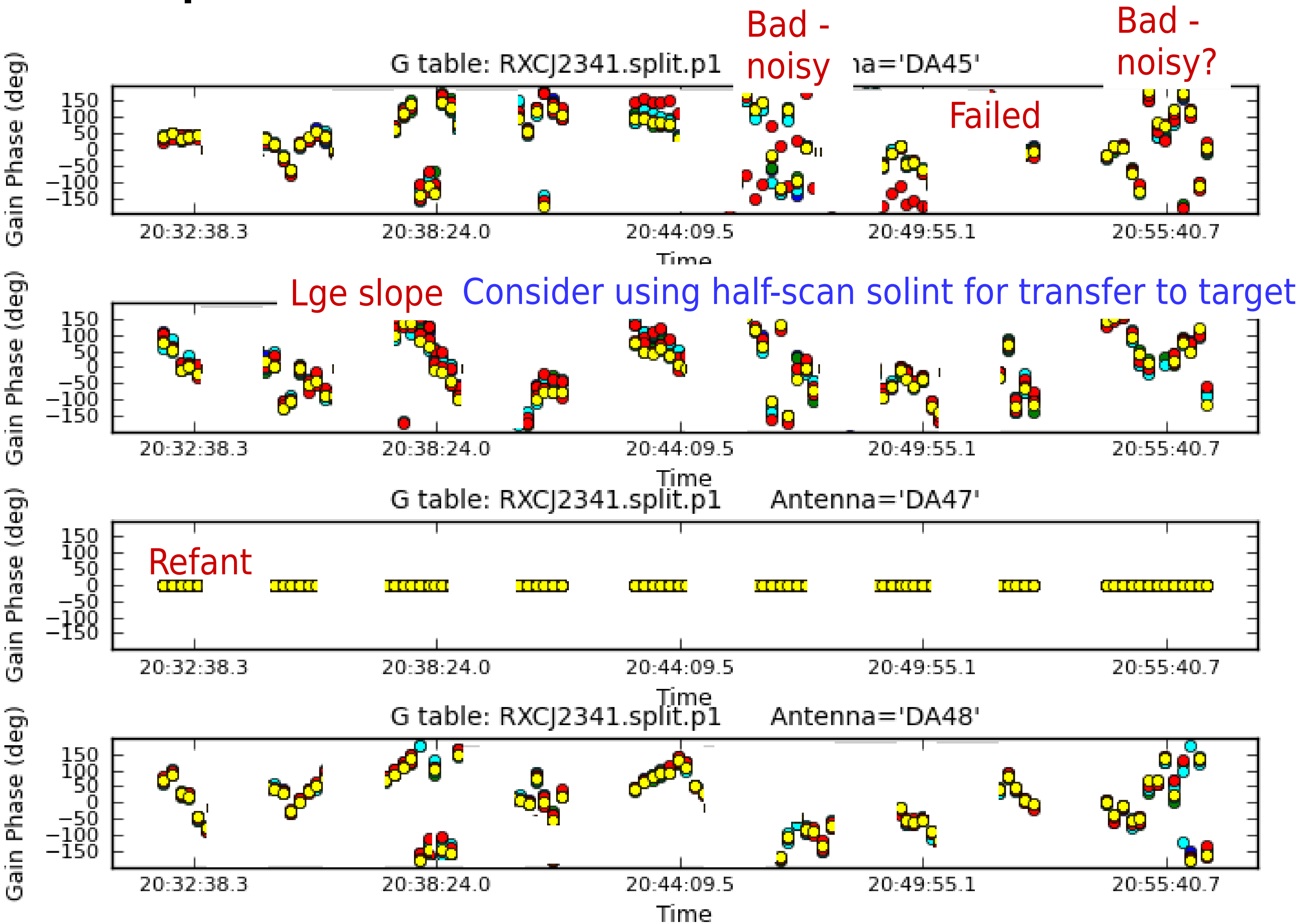


Flux scale calibration

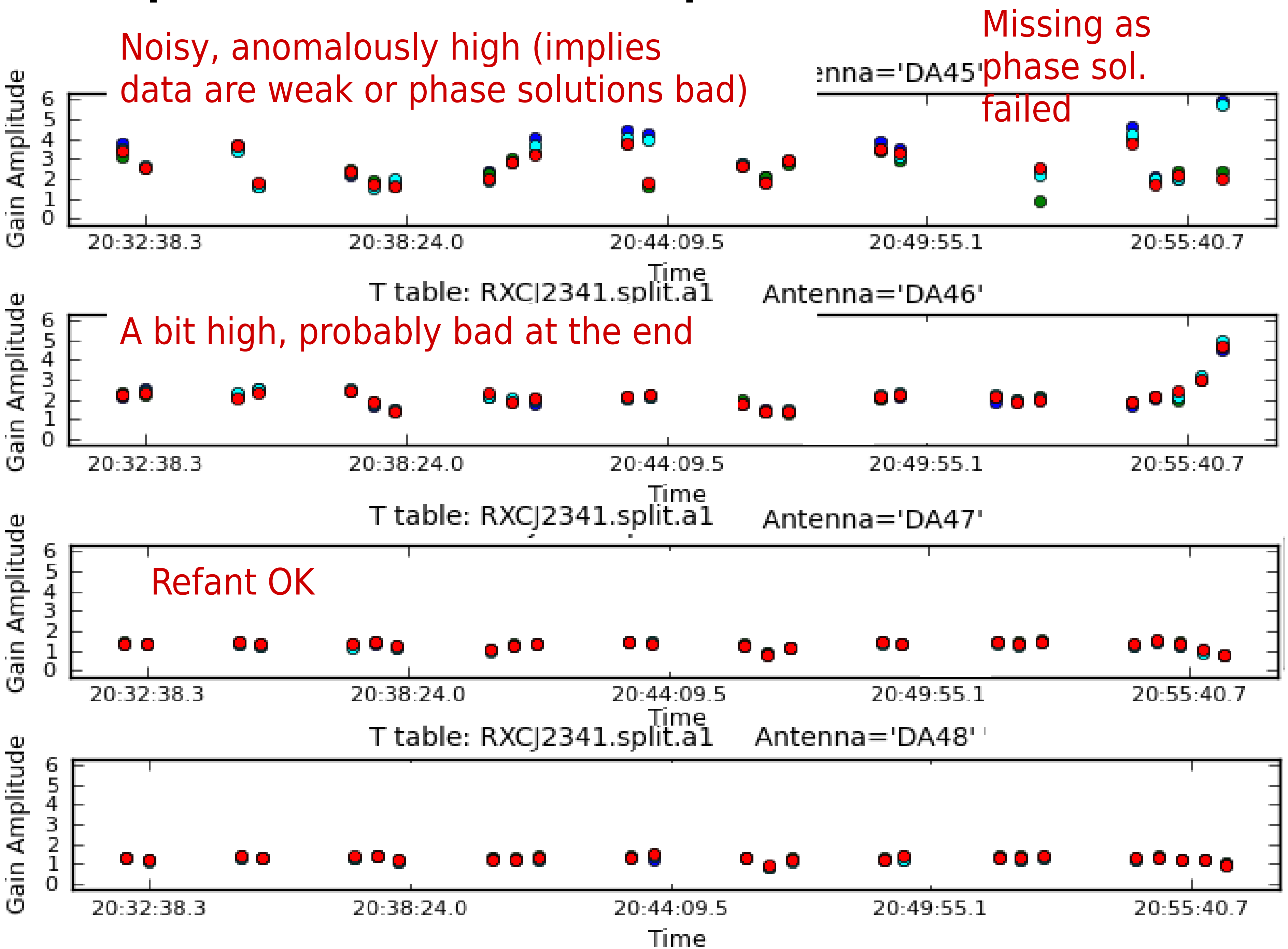
- QSO are mostly used for BP and time-dependent phase and amplitude calibration: sub-arcsec, bright sources
    - Small source, shorter light-travel diameter – Variable!
  - Monitor flux standards with respect to known source
- Flux–stable sources are mostly large, resolved
  - ALMA now mostly uses well-modelled smaller planets e.g. Neptune as primary reference for 'grid' QSOs.
- Calibrate time-varying gains, bandpass
  - Derive scaling factor from correlator units to Jy and apply to all sources (usually by scaling amp cal table G3)


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:**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

'Int' phase solutions point source



Amp solutions for point source



Simple calibration in practice

- Generally trust pipeline/observatory calibration
  - Check sample images/calibration plots/weblog (tomorrow)
  - If problems:
    - Good diagnostics: Flux scale, corrected BP cal bandpass
    - Check phase-ref solutions (next slides)
  - CASA divides complex solutions into data
    - High amp solution means actual data has low power
      - If applied to data, noise will be increased
- If you need to re-do calibration, or for self-cal:
  - Check actual data to estimate solints
  - Examine data for antennas with many failed/anomalous solutions
  - Check raw/earlier data in case previous calibration bad

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

Starting point

Goal

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

$\underline{I}$ mage

$\underline{A}$dditive baseline error

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.
- $\underline{V}_{ij}^{obs} = \mathbf{B}_{ij}\mathbf{G}_{ij}\mathbf{T}_{ij}\underline{V}_{ij}^{ideal}$
  - 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
  - I ignor online calibration (e.g. bulk delay), and polarization-related effects
    - XX and YY can have slightly different amplitudes which change with time, but total intensity is not affected

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 $\boldsymbol{V}(u,v)_{ij} = \begin{pmatrix} RR & RL \\ LR & LL \end{pmatrix}$
- 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 $\mathbf{E}_{ij}$ is written as

$$\mathbf{E}'_{ij} = \mathbf{e}'_i \mathbf{e}'^{\dagger}_j = \mathbf{J}_i \mathbf{E}_{ij} \mathbf{J}^{\dagger}_j$$

  - Jones matrices known so expression can be inverted:

$$\mathbf{E}_{ij} = \mathbf{J}_i^{-1} \mathbf{E}'_{ij} \mathbf{J}_j^{\dagger -1}$$

- 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 visibilities corrected for the errors represented by this Jones matrix, solved by to find corrections J_i, 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) $W_{ij} = s_{ij}^{-2}$ are derived from previous noise estimates e.g. sample size, scatter in previous solutions