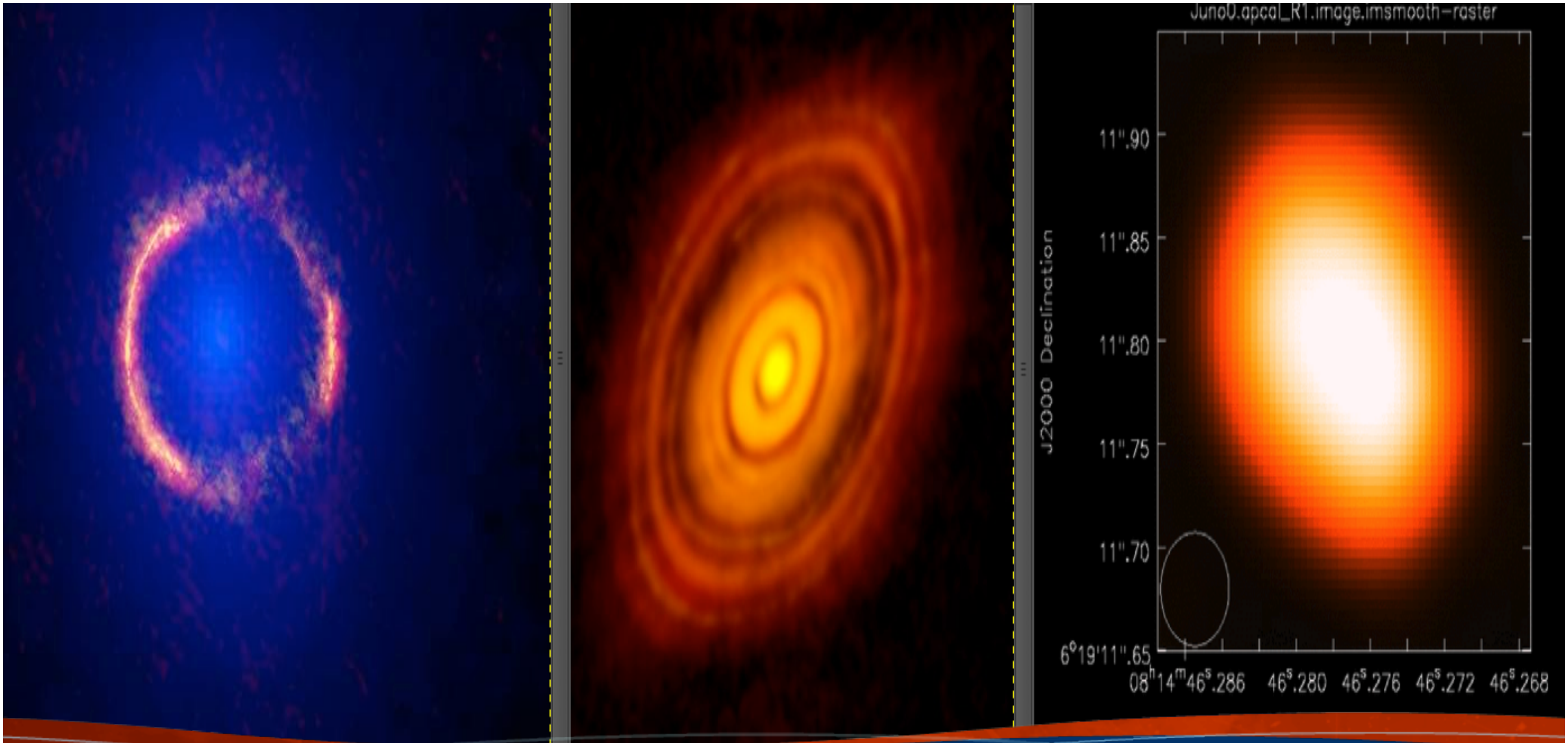


Basic Calibration

Al Wootten

Thanks to Moellenbrock, Marrone, Braatz

Outline

- Sketch of a ‘typical’ observation
- Short discussion of formalism
- Types of calibration
  - A priori
  - A posteriori
  - Examples
- Later more detail in lectures by Perez, Brogan

A 'Typical' Dataset and its Calibration

Investigate spectral line emission in a starburst galaxy

- Array: ALMA (Dec 2014), baselines 15 to 384m, 12m primary
- Sources (cals chosen by system based on science target; 2 executions):
  - Science Target: NGC253, 'Band 6' or $\lambda \approx 1.3$mm or $\nu \approx 230$GHz
  - Near-target calibrator: J0038-2459 (~2.1 deg from target)
  - Bandpass calibrator: J0334-4008 (J2258-2758)
  - Flux Density calibrator: Mars (Uranus)
- Signals: XX,YY correlations
- Three spectral windows centered at 227GHz
  - Two with 1.875 GHz bandwidth, 968 x 1.9 MHz channels (lines)
  - One with 2.0 GHz bandwidth, 128 x 31.25 MHz (continuum)

Measuring the Sky

- Formally, we wish to use our interferometer to obtain the visibility function:

$$V(u,v) = \int_{sky} I(l,m) e^{-i2\pi(ul+vm)} dl dm$$

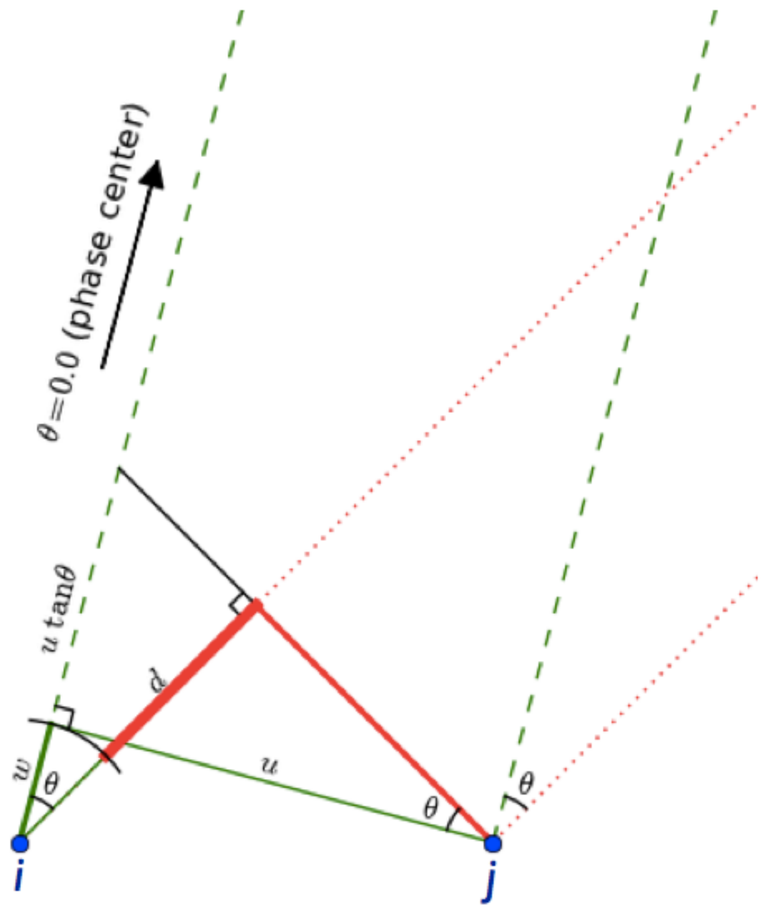
- ….a Fourier transform which we intend to invert to obtain an image of the sky:

$$I(l,m) = \int_{uv} V(u,v) e^{i2\pi(ul+vm)} du dv$$

- V(u,v) describes the amplitude and phase of two dimensional sinusoids which sum to an image of the sky
  - Amplitude describes how concentrated a signal
  - Phase describes its location
- The goal is to measure V(u,v)

Measuring V(u,v)

How do we measure *V(u,v)*?



- Consider direction-dependent arrival geometry for E-field disturbance reception at two points, i and j, relative to the phase center direction

$$d = (w_\lambda + u_\lambda \tan\theta)\cos\theta - w_\lambda$$
$$= u_\lambda \sin\theta + w_\lambda(\cos\theta - 1)$$
$$d(l) = u_\lambda l + w_\lambda\left(\sqrt{1-l^2} - 1\right) \quad \text{(1D)}$$
$$\left(\sin\theta = l;\ \cos\theta = \sqrt{1-l^2}\right)$$

$$d(l,m) = u_\lambda l + v_\lambda m + w_\lambda\left(\sqrt{1-l^2-m^2} - 1\right) \quad \text{(2D)}$$
$$\approx u_\lambda l + v_\lambda m \qquad (l,m << 1)$$

Direction-dependent signals: $s_j = s_i e^{i2\pi d(l,m)}$

Measuring V(u,v)

- Correlate the E-field disturbances, x_i & x_j arriving at spatially separate sensors
  - delay-aligned for the phase-center
  - s_i & s_j are the direction-dependent E-field disturbances
- Direction integral and product can be reversed, because the E-field disturbances from different directions don't correlate
- s_i and s_j (for a specific direction) differ only by a phase factor given by the arrival geometry
- $\langle|s_i|^2\rangle$ is proportional to the brightness distribution, *I(l,m)*

$$
\begin{aligned}
V_{ij}^{obs} &= \left\langle x_i \cdot x_j^* \right\rangle_{\Delta t} \\
&= \left\langle \int_{sky} s_i\, dl_i\, dm_i \cdot \int_{sky} s_j^*\, dl_j\, dm_j \right\rangle_{\Delta t} \\
&= \left\langle \int_{sky} s_i s_j^*\, dl\, dm \right\rangle_{\Delta t} \\
&= \int_{sky} \left\langle |s_i|^2 \right\rangle e^{-i2\pi d(l,m)}\, dl\, dm \\
&= \int_{sky} I(l,m)\, e^{-i2\pi d(l,m)}\, dl\, dm \\
&= \int_{sky} I(l,m)\, e^{-i2\pi (ul+vm)}\, dl\, dm
\end{aligned}
$$

In Reality

- So, in practice, we obtain an imperfect visibility measurement:

$$V_{ij}^{obs}(u,v) = \left\langle x_i(t) \cdot x_j^*(t) \right\rangle_{\Delta t}$$
$$= J_{ij} V_{ij}^{true}(u,v)$$

  - x_i & x_j are mutually delay-compensated for the phase center
  - Averaging duration is set by the expected timescales for variation of the correlation result (~seconds)
- J_{ij} is a generalized *operator* characterizing the *net* effect of the observing process for antennas *i* and *j* on baseline *ij*, which we must *calibrate*
  - Includes any required scaling to physical units
- Sometimes J_{ij} corrupts the measurement irrevocably, resulting in data that must be *edited* or *"flagged"*

Noise

- Normalized visibility: $$\sigma_{ij} = \frac{1}{\sqrt{2\Delta\nu\Delta t}}$$
  - Extra 2 (cf single-dish) comes from formation from separate telescopes
- Absolute visibility: $$\sigma_{ij} = \frac{\sqrt{T_i T_j}}{\sqrt{2\Delta\nu\Delta t}}$$
  - T_i, T_j are the system temperatures (total sampled powers), in whatever units the corresponding data are in
  - (The numerator, as measured by the correlator, is the factor by which visibilities are typically normalized, e.g. ALMA)
- Formal Visibility Weights: $$w_{ij} = \frac{1}{\sigma_{ij}^2}$$

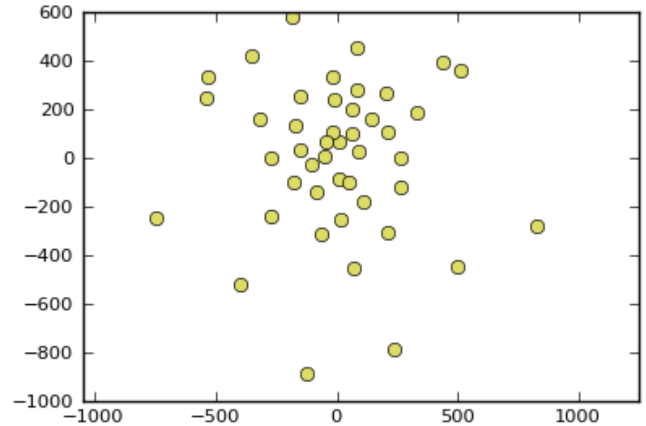
In Practice: Several Categories

- A priori "calibrations" (provided by the observatory)
  - Antenna positions, earth orientation and rate, clock(s), frequency reference
  - Antenna pointing/focus, voltage pattern, gain curve
  - Calibrator coordinates, flux densities, polarization properties
- Absolute *engineering* calibration (dBm, K, volts)?
  - Amplitude: episodic (ALMA) or continuous (EVLA/VLBA) *Tsys* or switched- power monitoring to enable calibration to nominal K (or Jy, with antenna efficiency information)
  - Phase: WVR (ALMA), otherwise practically impossible (relative antenna phase)
  - Traditionally, we concentrate instead on ensuring instrumental *stability* on adequate timescales
- ***Cross-calibration***
  - Observe strong astronomical sources near science target against which calibration (*Jij*) can be solved, and transfer solutions to target observations
  - Choose appropriate calibrators; usually ***point sources*** because we can easily predict their visibilities (Amp ~ constant, phase ~ 0)
  - Choose appropriate timescales for calibration

Calibration

- Calibration is not all post-processing!
  - Precalibration—measurements which vary slowly and are used to correct signals at the time of observation
    - Typically fundamental to the instrument
    - Often collected during special sessions well before observing
  - Postcalibrations--Quantities measured before, during or after observation and applied in data postprocessing
- Some calibrations may be applied irreversibly during observations

A priori Calibration



- A priori “calibrations” (provided by the observatory)
  - Antenna positions, earth orientation and rate, clock(s), frequency reference
  - Antenna pointing/focus models, voltage pattern, gain curve
  - Calibrator coordinates, flux densities, polarization properties
- BUT…they may not be completely correct!

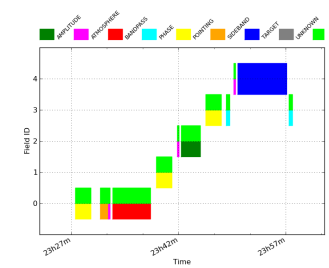
Some 'Absolute' *a priori* Calibrations

- Flux Density Calibration
  - Radio astronomy flux density scale set according to several "constant" radio sources, and planets/moons
  - Use resolved models where appropriate
- Astrometry
  - Most calibrators come from astrometric catalogs; sky coordinate accuracy of target images tied to that of the calibrators
  - Beware of resolved and evolving structures, and phase transfer biases due to troposphere (especially for VLBI)
- Polarization
  - Usual flux density calibrators also have significant stable linear polarization position angle for registration
  - Calibrator circular polarization usually assumed zero (?)
- Relative calibration solutions (and dynamic range) insensitive to errors in these "scaling" parameters

What is in the Data?

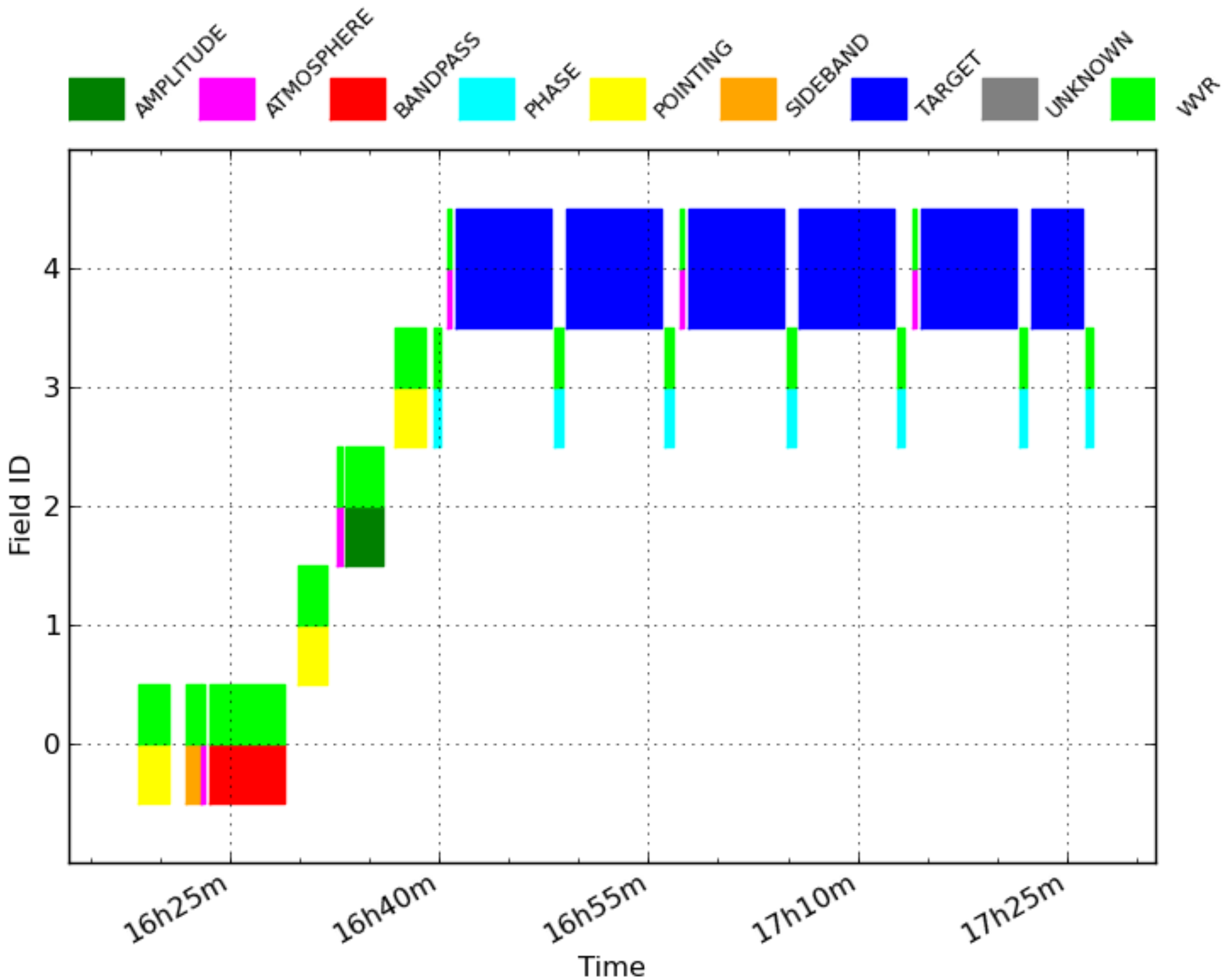
- An *enormous* list of complex visibilities! *(Enormous!)*
  - At each timestamp (~1-10s intervals): N(N-1)/2 baselines
    - EVLA: 351baselines
    - VLBA: 45 baselines
    - ALMA: 1225-2016 baselines (Our example: 34 Ants, 561 baselines)
  - For each baseline: up to 64 Spectral Windows ("spws", "subbands" or "IFs")
  - For each spectral window: tens to thousands of channels
  - For each channel: 1, 2, or 4 complex correlations (polarizations)
    - EVLA or VLBA: RR or LL or (RR,LL), or (RR,RL,LR,LL)
    - ALMA: XX or YY or (XX,YY) or (XX,XY,YX,YY)
  - With each correlation, a weight value and a flag (T/F)
  - Meta-info: Coordinates, antenna, field, weather, frequency label info
- Ntotal = Nt x Nbl x Nspw x Nchan x Ncorr visibilities
  - ~few 10^6 x Nspw x Nchan x Ncorr vis/hour →→10s to 100s of GB per observation

Calibration Process

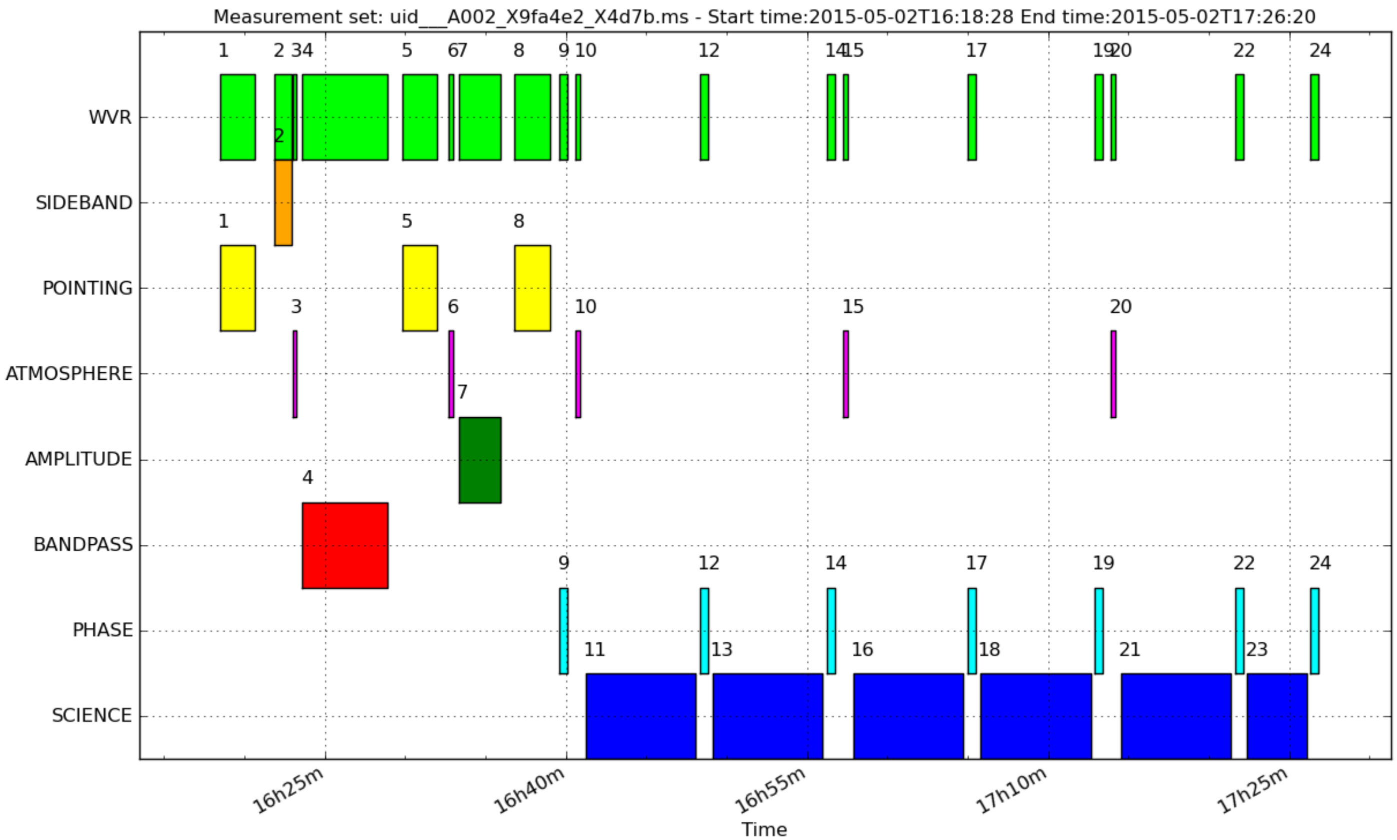


- Make sure that the antenna pointing is on-source.
  - More important the higher the frequency (smaller primary beam)
  - If not, you will flag the data!
- Receiver tuning to optimize sensitivity (Tsys)
- Tune and correct frequency-dependent telescope response (Bandpass cal)
- Remove effects of atmospheric water vapor, dry air (Phase cal)
- Correct time-varying instrument phases and amplitudes (Phase/gain cal)
- Set absolute flux scale (Flux cal)
- Remove problematic data (flagging) (then may cal again!)

Graphic Representation (1 SB)

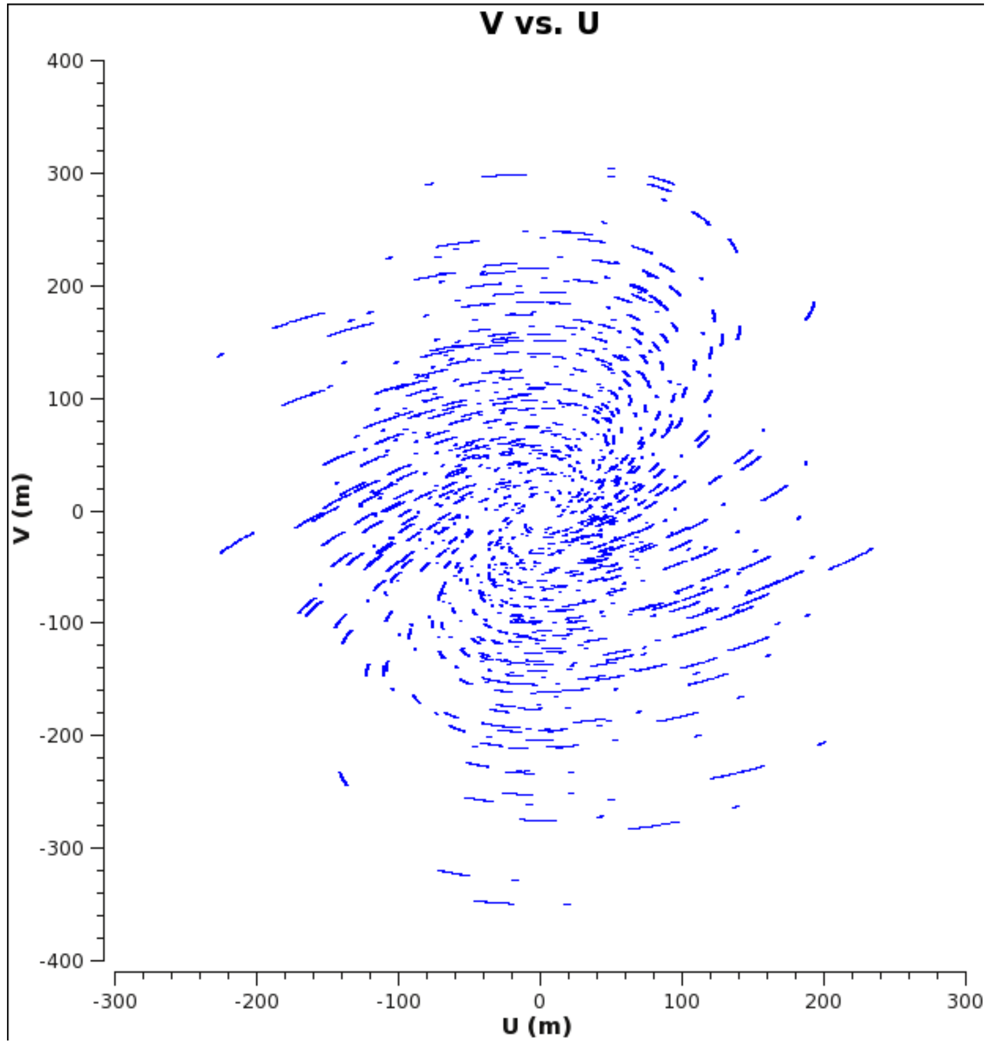


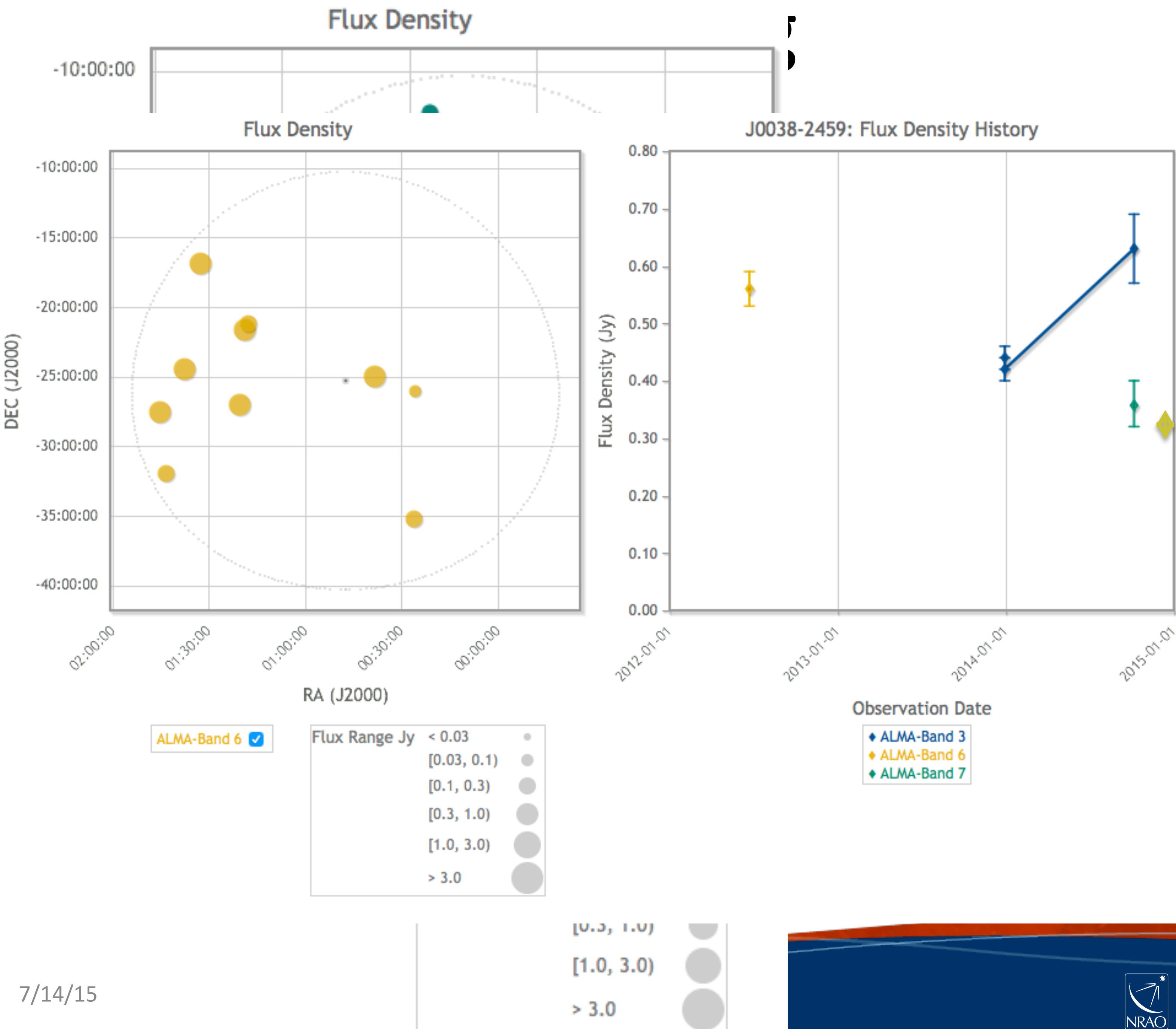
Intent vs time



U-v Source Coverage

Earth carries the antennas as it turns beneath the source
Sweeping out samples in the Fourier plane. Sampling is rather sparse on this short track but the source is probed on many spatial scales.
Note the missing samples near the center to be supplied by single ALMA elements, or by the Morita Array of 7m antennas.




Flux Density
-10:00:00
Flux Density
-10:00:00
-15:00:00
-20:00:00
-25:00:00
-30:00:00
-35:00:00
-40:00:00
DEC (J2000)
02:00:00
01:30:00
01:00:00
00:30:00
00:00:00
RA (J2000)
ALMA-Band 6
Flux Range Jy
< 0.03
[0.03, 0.1)
[0.1, 0.3)
[0.3, 1.0)
[1.0, 3.0)
> 3.0
J0038-2459: Flux Density History
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Flux Density (Jy)
2012-01-01
2013-01-01
2014-01-01
2015-01-01
Observation Date
ALMA-Band 3
ALMA-Band 6
ALMA-Band 7
[0.3, 1.0)
[1.0, 3.0)
> 3.0

Pointing and Mosaics

- In a mosaic, several observations toward adjacent points are combined in imaging to form an image of a region larger than the beam.
- The ‘trueness’ or fidelity of an image to reality depends critically on pointing
- ALMA antenna requirements: ‘blind’ pointing to 2”, local pointing to 0.6” (tradeoff in antenna cost)
  - Poor registration of fields in a mosaic degrades image quality rapidly. 0.6” is adequate for observations through ALMA Band 7
  - In general ALMA antennas meet the pointing specfication (but things happen)
- All 3 designs of ALMA 12m antennas move very fast

Primary Beam

- For performance to 950 GHz, for an affordable price we could get good performance with
  - Specification (12m antennas): 25µm, (7m): 20µm
  - Also critical for accurate mosaics, for which it should be measured to 6% on the power pattern. ALMA currently uses a model rather than a measured beam
- Subreflector and feed positioning
  - ALMA subreflectors may be tilted to align the beam with the receivers, which are offset from the geometric center of the antenna.

Postcalibration

- Delay
  - Includes source position, earth orbit and orientation, station location, atmosphere, antenna structure, and electronic delay.
    - The latter three may fluctuate, limiting resolution
    - ALMA has specifications for these, allocated to components of the system
    - After correction, corrected visibility phase fluctuations should be less than 57^{o} at 950 GHz for times <10s.
  - Precession, nutation and time must be accurate

Data Examination and Editing

- What to edit (much of this is automated):
  - Some real-time flagging occurred during observation (antennas off-source, LO out-of-lock, etc.). Any such bad data left over? (check operator's logs if available)
  - Any persistently 'dead' antennas (check operator's logs if available)
  - Periods of especially poor weather? (plots, check operator's log)
  - Any antennas shadowing others? Edit such data.
  - Amplitude and phase should be continuously varying—edit outliers
  - Radio Frequency Interference (RFI)? (little for ALMA now but just wait)
- Caution:
  - Be careful editing noise-dominated data.
  - Be conservative: those antennas/timeranges which are obviously bad on calibrators are probably (less obviously) bad on weak target sources—edit them
  - Distinguish between bad (hopeless) data and poorly-calibrated data. E.g., some antennas may have significantly different amplitude response which may not be fatal—it may only need to be calibrated
  - Choose (phase) reference antenna wisely (ever-present, stable response)
- Increasing data volumes increasingly demand automated editing algorithms…
- After calibration, go back, find problems, edit, calibrate again.

What is Bandpass Calibration?

In general, the goal of calibration is to find the relationship between the observed visibilities, V_{obs}, and the true visibilities, V:

$$V_{i\,j}(u,\nu)_{obs} = V_{i\,j}(u,\nu)_{true} J_{i\,j}\text{, or}$$

$$V_{i\,j}(t,\nu)_{obs} = V_{i\,j}(t,\nu) G_{i\,j}(t) B_{i\,j}(t,\nu)$$

where t is time, ν is frequency, *i* and *j* refer to a pair of antennas *(i,j)* (i.e., one baseline), *G* is the complex "continuum" gain, and *B* is the complex frequency-dependent gain (the "bandpass").

Bandpass calibration is the process of measuring and correcting the *frequency-dependent* part of the gains, $B_{i\,j}(t,\nu)$.

$B_{i\,j}$ may be constant over the length of an observation, or it may have a slow time dependence.

Why is BP Calibration important?

Good bandpass calibration is a key to detection and accurate measurement of spectral features, especially weak, broad features.

Bandpass calibration can also be the limiting factor in dynamic range of continuum observations.

- Bandpass amplitude errors may mimic changes in line structure with ν
- ν-dependent phase errors may lead to spurious positional offsets of spectral features as a function of frequency, mimicking doppler motions
- ν-dependent amplitude errors limit ability to detect/measure weak line emission superposed on a continuum source. Consider trying to measure a weak line on a strong continuum with ~ 10% gain variation across the band.

Bandpass Calibration

- Determine the variations of phase and amplitude with frequency
- Account for slow time-dependency of the bandpass response
- We will arrive at antenna-based solutions against a reference antenna
  - In principle, could use autocorrelation data to measure antenna-based amplitude variations, but not phase
  - Most bandpass corruption is antenna-based, yet we are measuring N(N-1)/2 baseline-based solutions
  - Amounts to channel-by-channel self-cal

Bandpass Calibration: What makes good calibrators?

- Best targets are bright, flat-spectrum sources with featureless spectra
  - Although point-source not absolutely required, beware frequency dependence of resolved sources
  - If necessary, can specify a spectral index using *setjy*

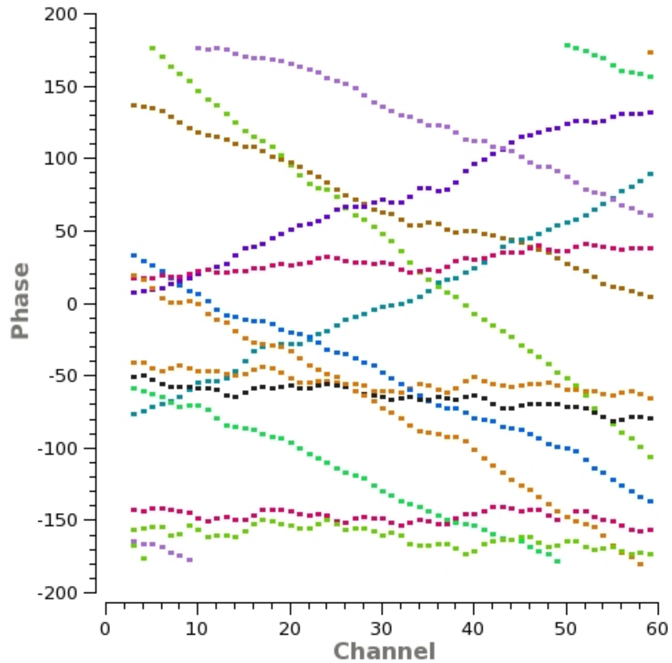
- Don't necessarily need to be near science target on the sky

Bandpass Calibration: Phase

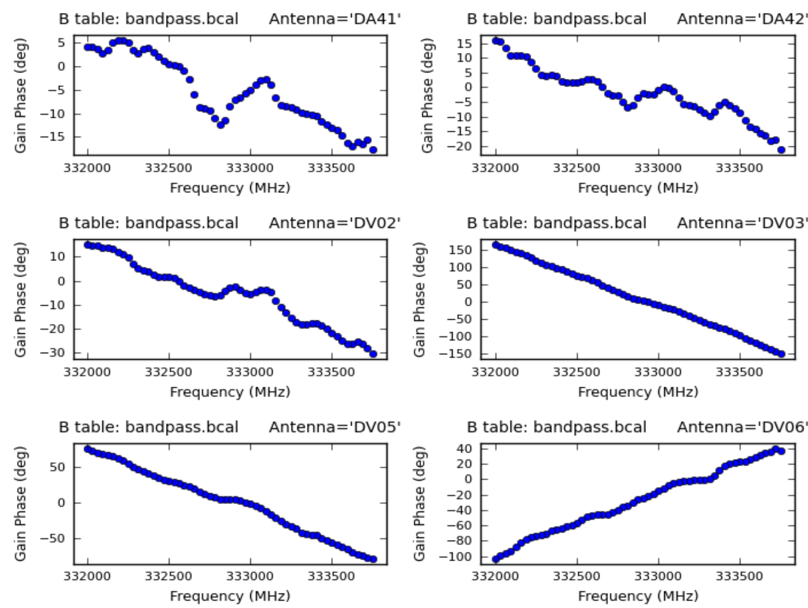
"Flat fielding" for the antennas

Typically, baseline responses are inverted to antenna-based correction

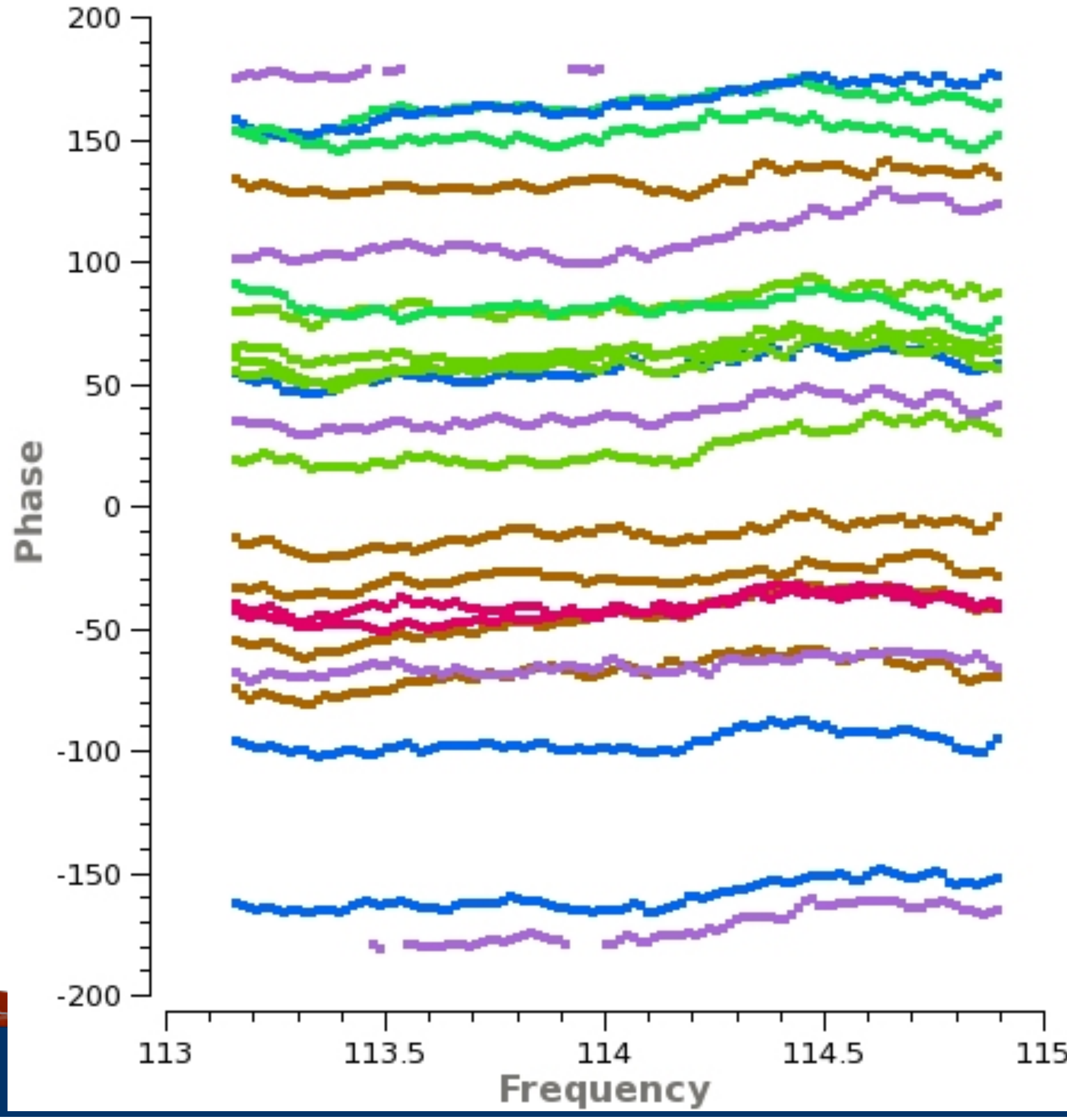
Baselines to one antenna



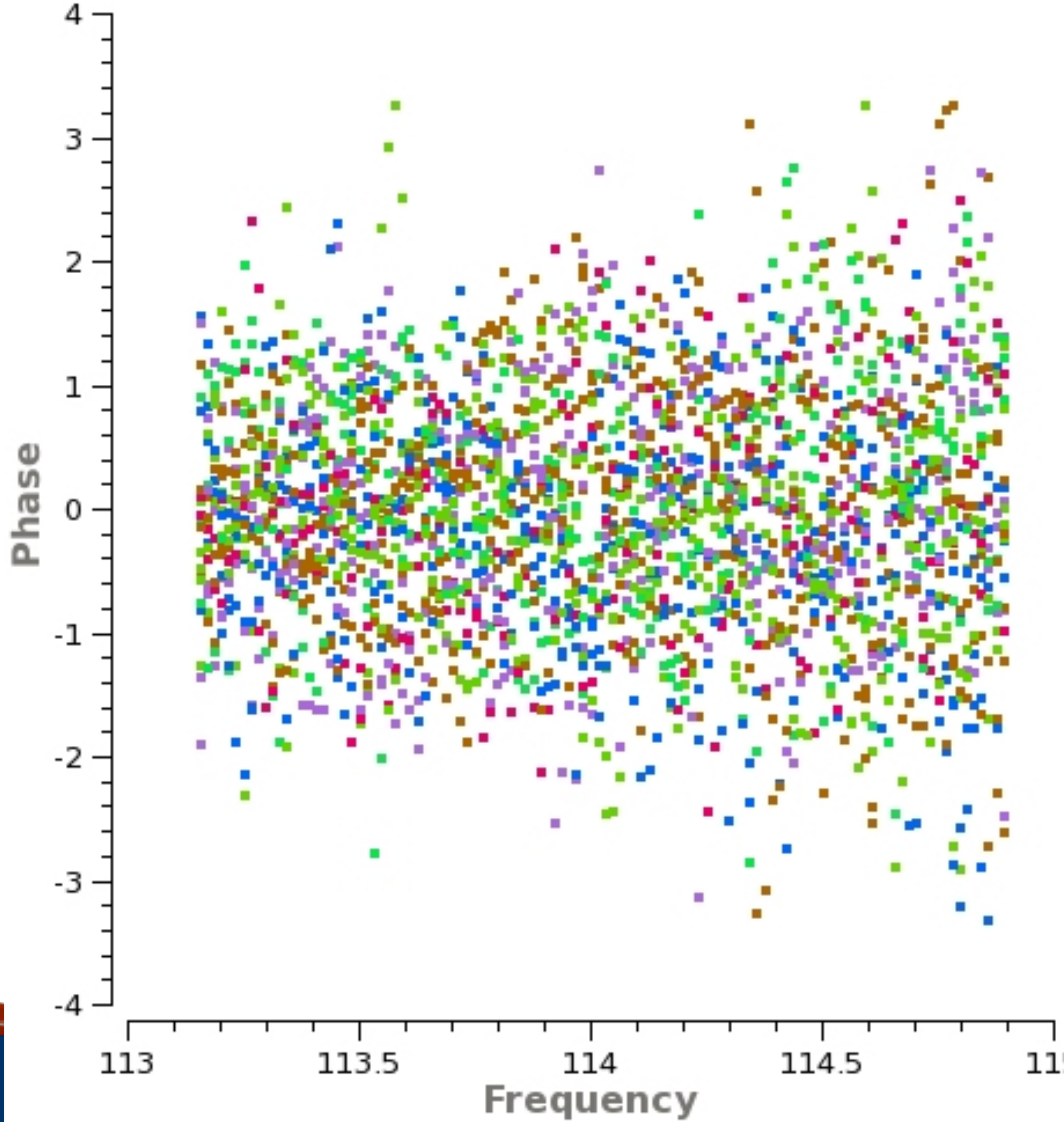
Antenna-based Bandpass Solutions



Bandpass Phase vs. Frequency (Before)

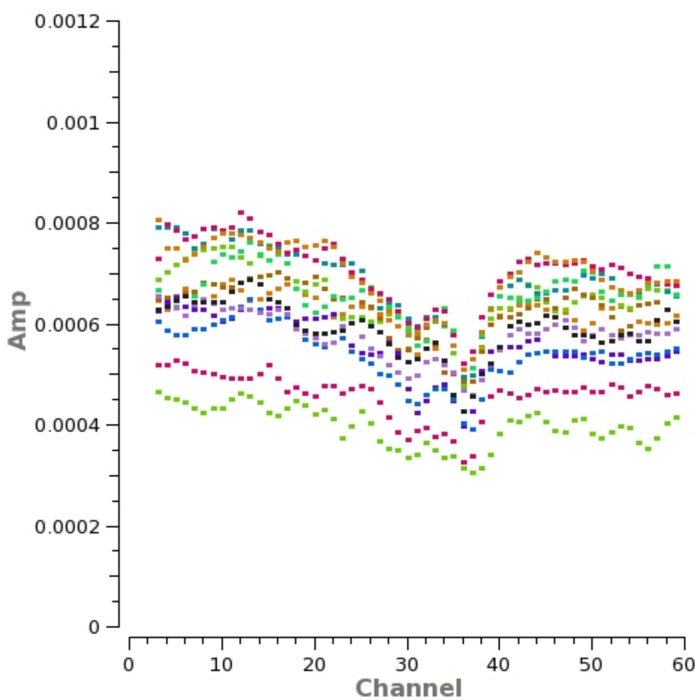


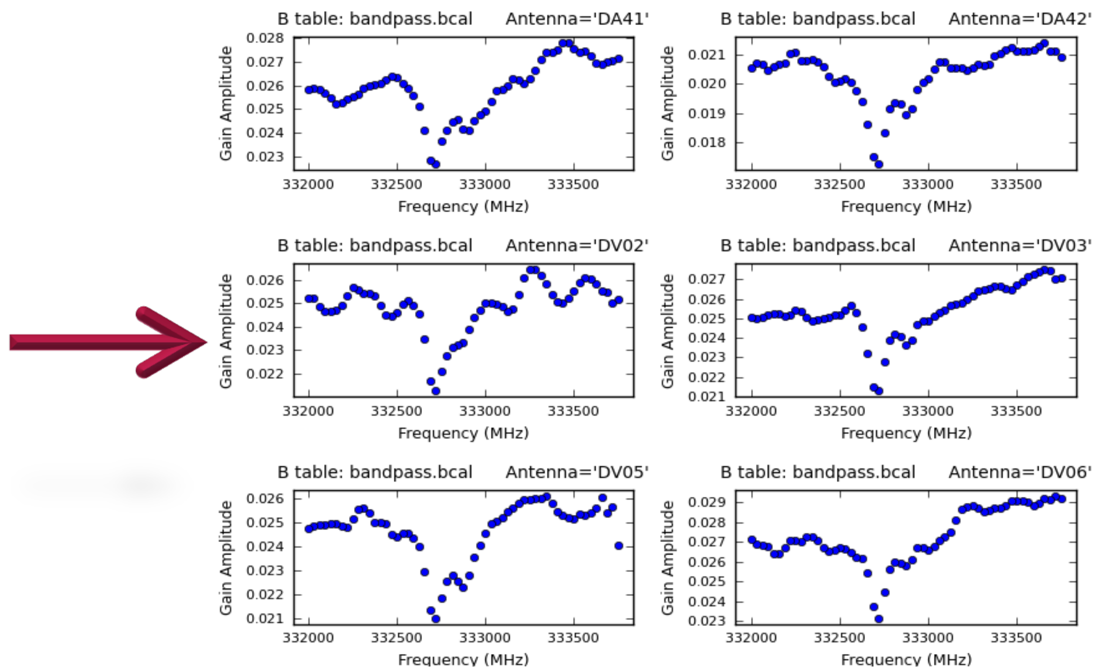
Bandpass Phase vs. Frequency (After)



Bandpass Calibration: Amplitude

Baselines to one antenna





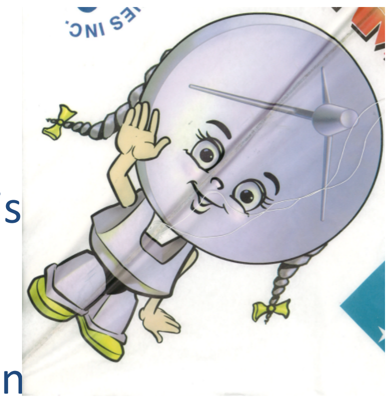
Amplitude Before Bandpass Calibration

Antenna-based Bandpass Solution

Gain (or Phase) Calibration

Determine the variations of phase and amplitude with time

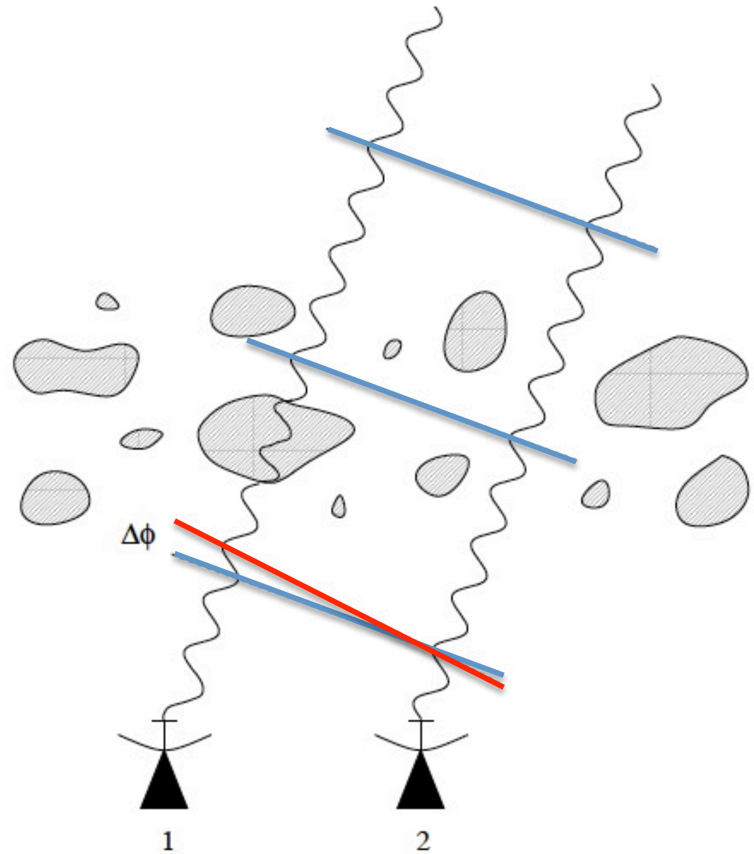
- First pass atmospheric correction from Water Vapor Radiometers
  - Can have time resolution of ~1 s (antenna crossing time with 12m/s wind)
- Final correction from gain calibrator (point source near to target)
  - Gives atmosphere and instrument correction near in time to observation (how often?)
- Since the "antenna-based" phase solution is derived from antenna phase *differences,* we do not measure phase absolutely
  - *relative* astrometry
- Phase solutions typically referred to a specific antenna, the refant, which is assumed to have constant phase (zero, in both polarizations)
  - refant typically near array center (like local conditions to other ants)
  - The refant's phase variation distributed to all other antennas' solution
  - For adequate time sampling, ensures reliable interpolation of phase, without ambiguity (c.f. arbitrary phase offsets between solutions)
- Problems:
  - A single good refant not always available over whole observation, due to flagging, etc.



Atmospheric Phase Correction

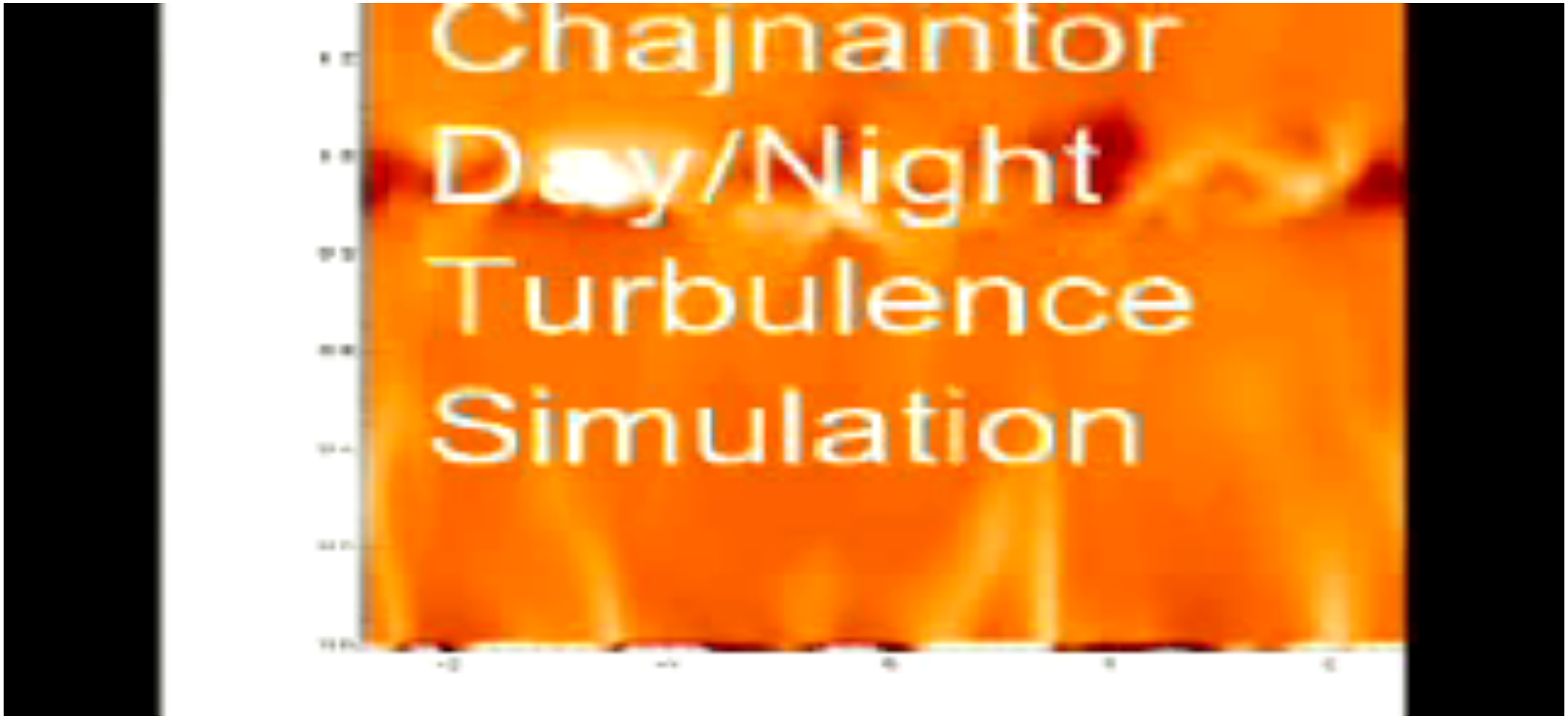
- Variations in the amount of precipitable water vapor (PWV) cause phase fluctuations and result in
  - Low coherence (loss of sensitivity)
  - Radio "seeing", typically 1″ at 1 mm
  - Anomalous pointing offsets
  - Anomalous delay offsets

Patches of air with different water vapor content (and hence index of refraction) affect the incoming wave front differently.

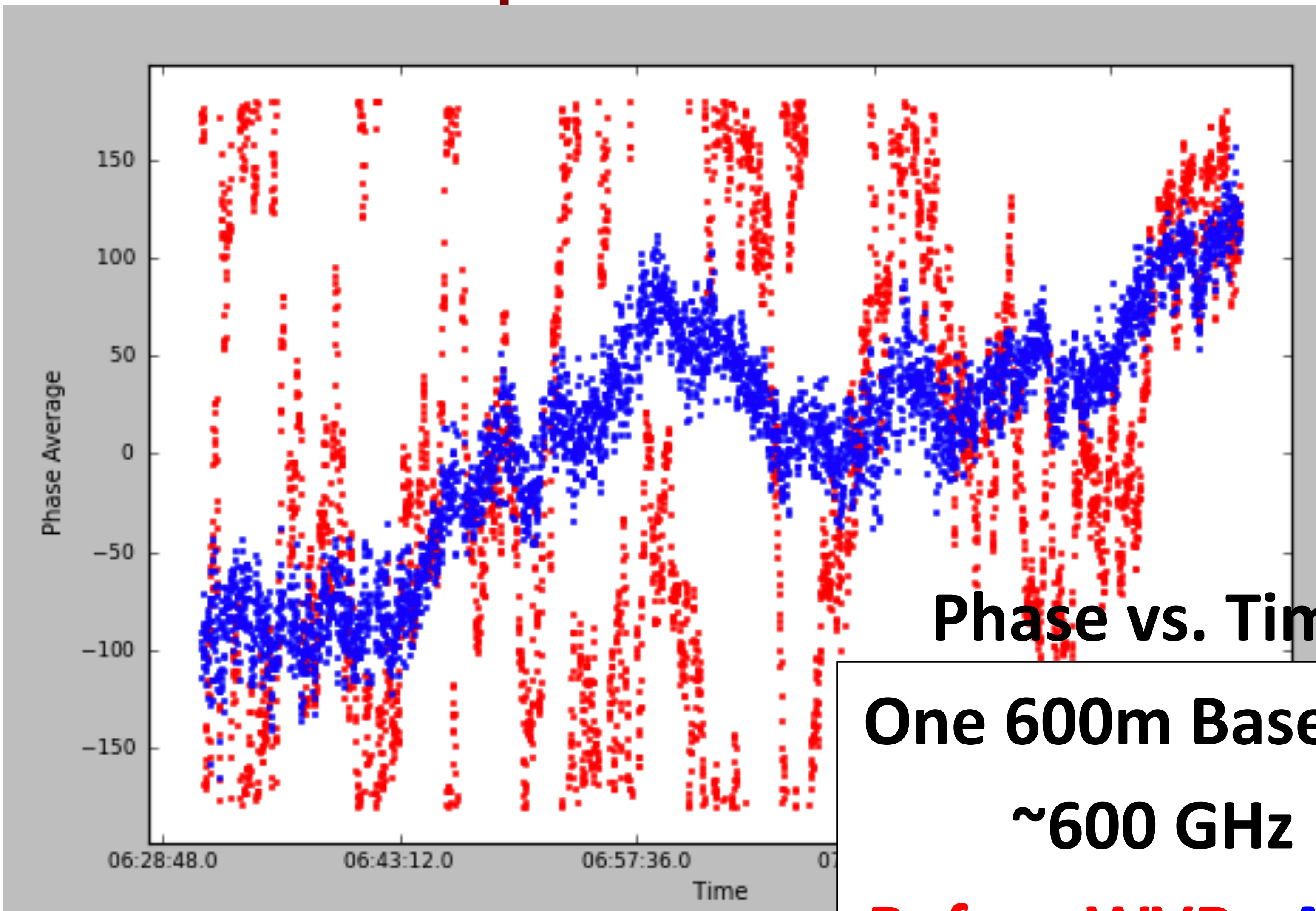


Day/night Atmosphere

See ALMA Memo No. 517



Water Vapor Correction on



Phase vs. Time

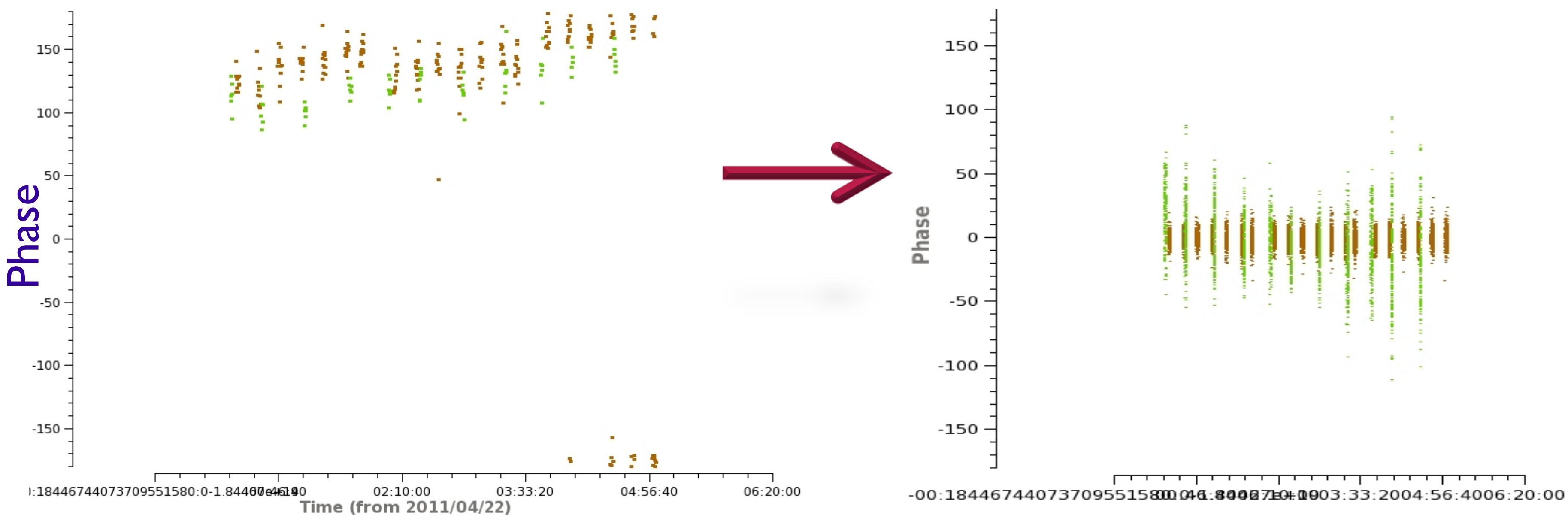
One 600m Baseline

~600 GHz

Before WVR, After WVR

Phase Calibration

The phase calibrator must be a point source close to the science target and must be observed frequently. This provides a model of atmospheric phase change along the line of sight to the science target that can be compensated for in the data.



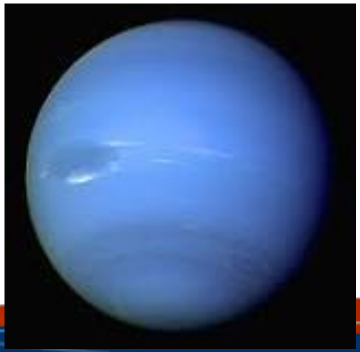
Time

Corrected using point source model

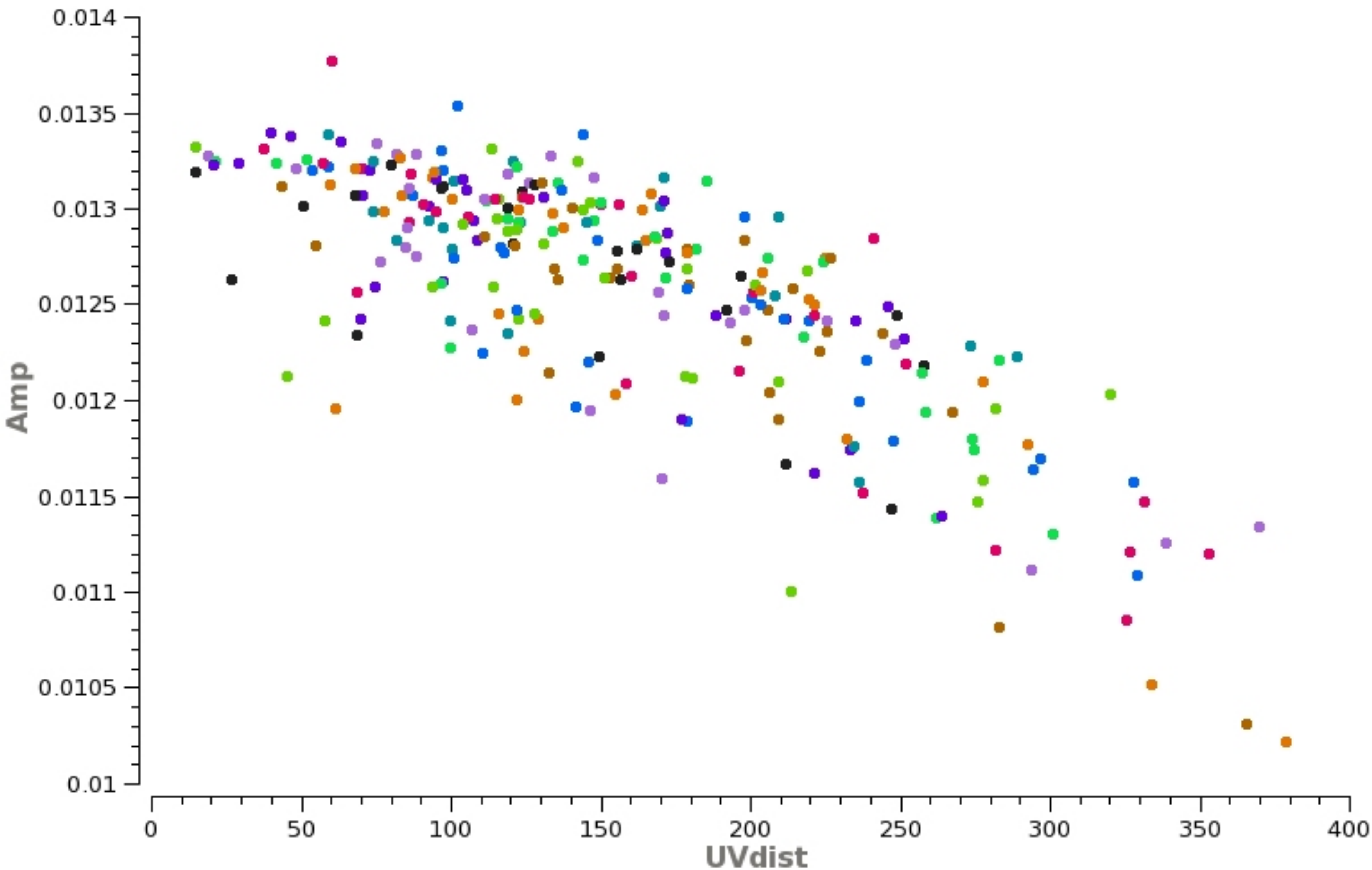
Flux (or Amplitude) Calibration

Two Steps:

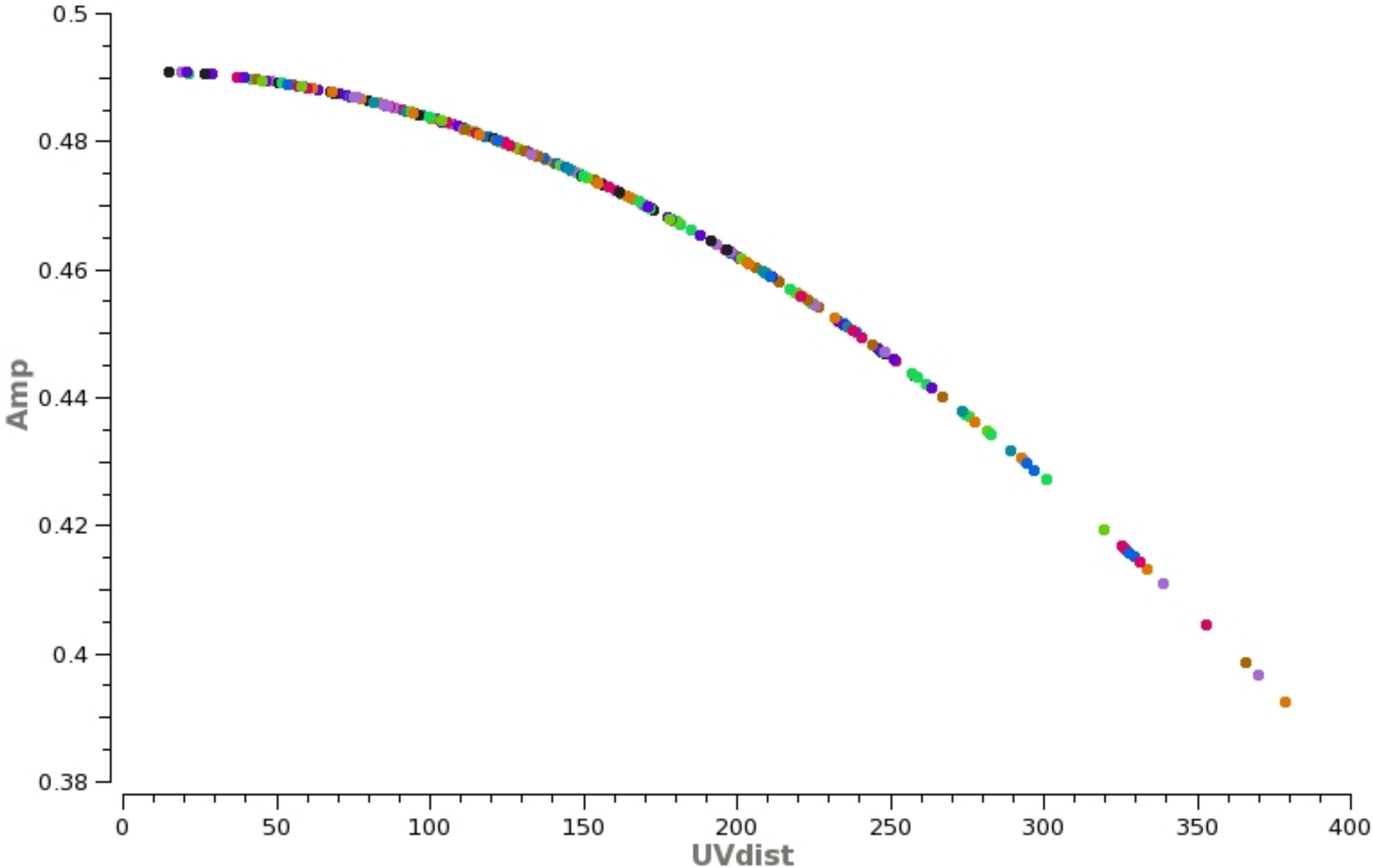
- Use calibration devices of known temperature (hotload and ambient load) to measure System Temperature frequently.
- Use a source of known flux to convert the signal measured at the antenna to common unit (Janskys). If the source is resolved, or has spectral lines, it must be very well modeled. See ALMA Memo 594 for discussion of Solar System absolute calibrators.
- The derived amplitude vs. time corrections for the flux calibrator are applied to the science target.



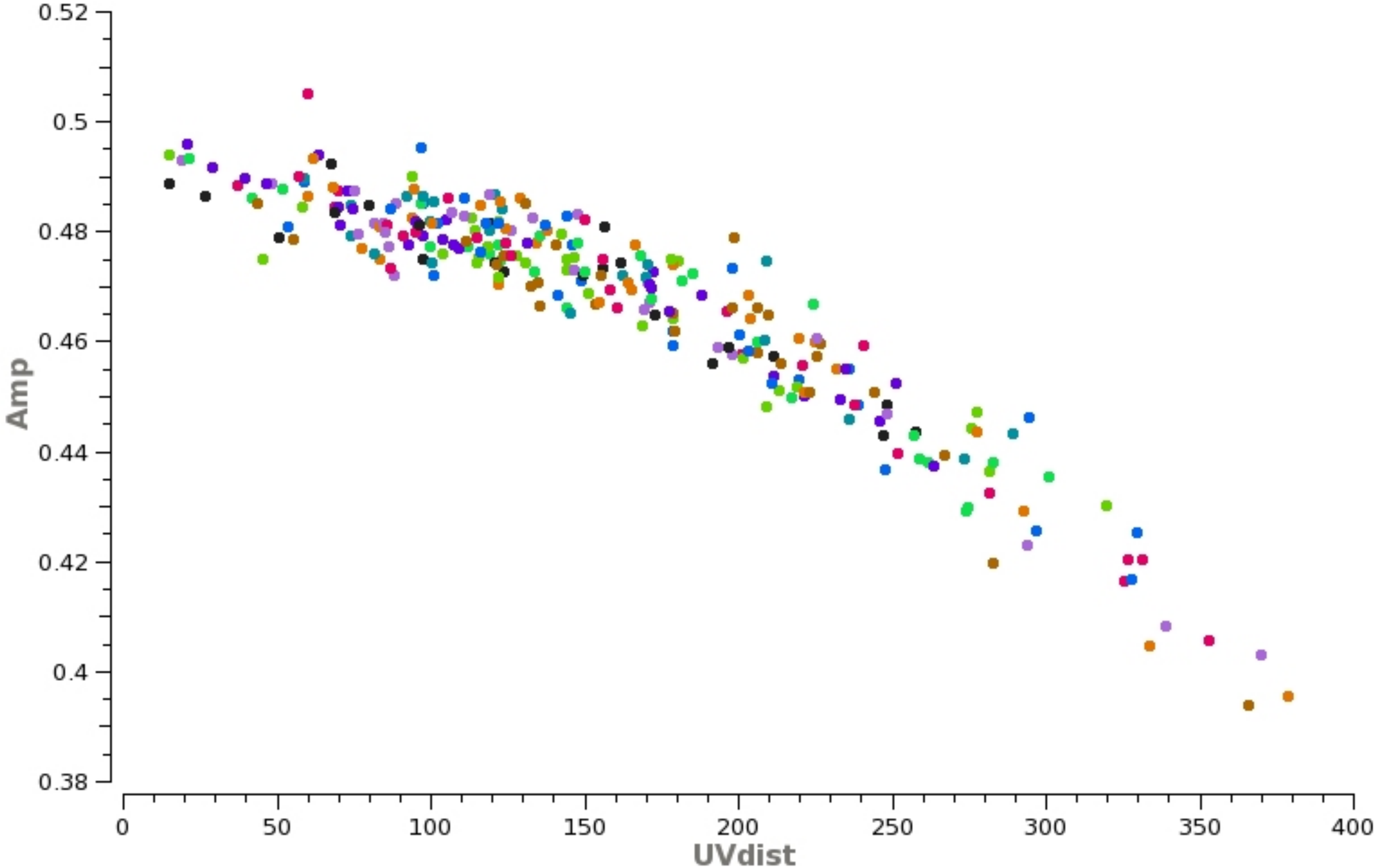
Ampcal Amplitude vs. uv-distance (Before)



Ampcal Amplitude vs. uv-distance (Model)

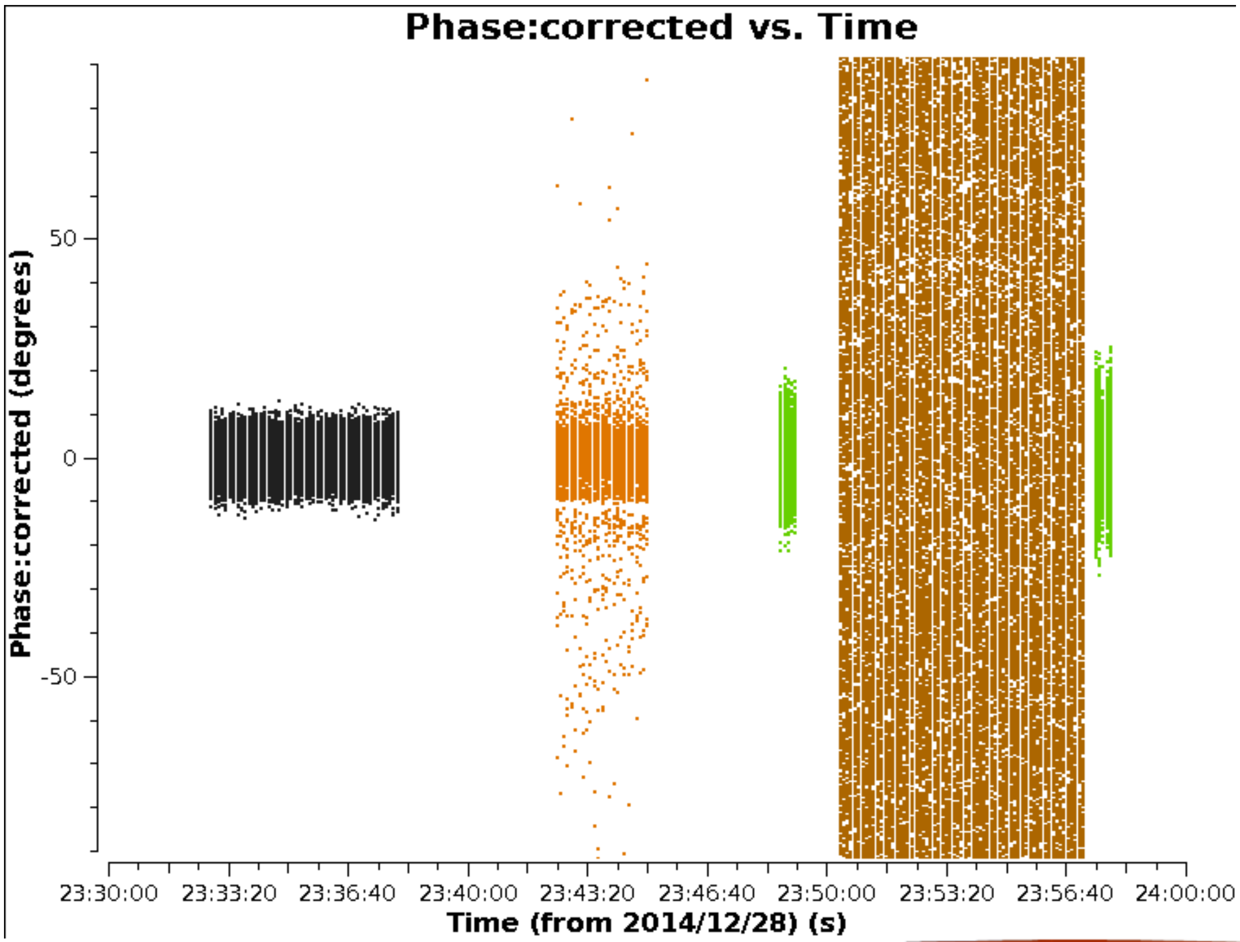


Ampcal Amplitude vs. uv-distance (After)



The 'calibrated' dataset: ϕ

Simplified—
Black: Passband cal
Orange: Flux cal
Green: Gain Cal
Brown: Source
here the source was observed only once. Owing to its complex structure, phases are scattered in such a plot.



Summary

- – Determining calibration is as important as determining source structure—can't have one without the other
- – Data examination and editing an important part of calibration
- – Calibration dominated by antenna-based effects
- – permits efficient, accurate and defensible separation of calibration from astronomical information (satisfies closure)
- – Full calibration formalism algebra-rich, but is *modular*
- – Calibration an iterative process, improving various components in turn, as needed
- – Point sources are the best calibrators
- – Observe calibrators according requirements of calibration components

Some good references

- Thompson, A.R., Moran, J.M., Swensen, G.W. 2004 "Interferometry and Synthesis in Radio Astronomy", 2nd edition (Wiley-VCH)

- Perley, R.A., Schwab, F.R., Bridle, A.H. eds. 1989 ASP Conf. Series 6 "Synthesis Imaging in Radio Astronomy" (San Francisco: ASP)
  – www.aoc.nrao.edu/events/synthesis

- Synthesis Imaging School Heavy Lecture: Moellenbrock
  -- https://science.nrao.edu/science/meetings/2014/14th-synthesis-imaging-workshop/program

- IRAM Interferometry School proceedings
  – www.iram.fr/IRAMFR/IS/IS2008/archive.html

- ALMA Calibration Plan
  -https://safe.nrao.edu/wiki/bin/view/ALMA/CalPlan