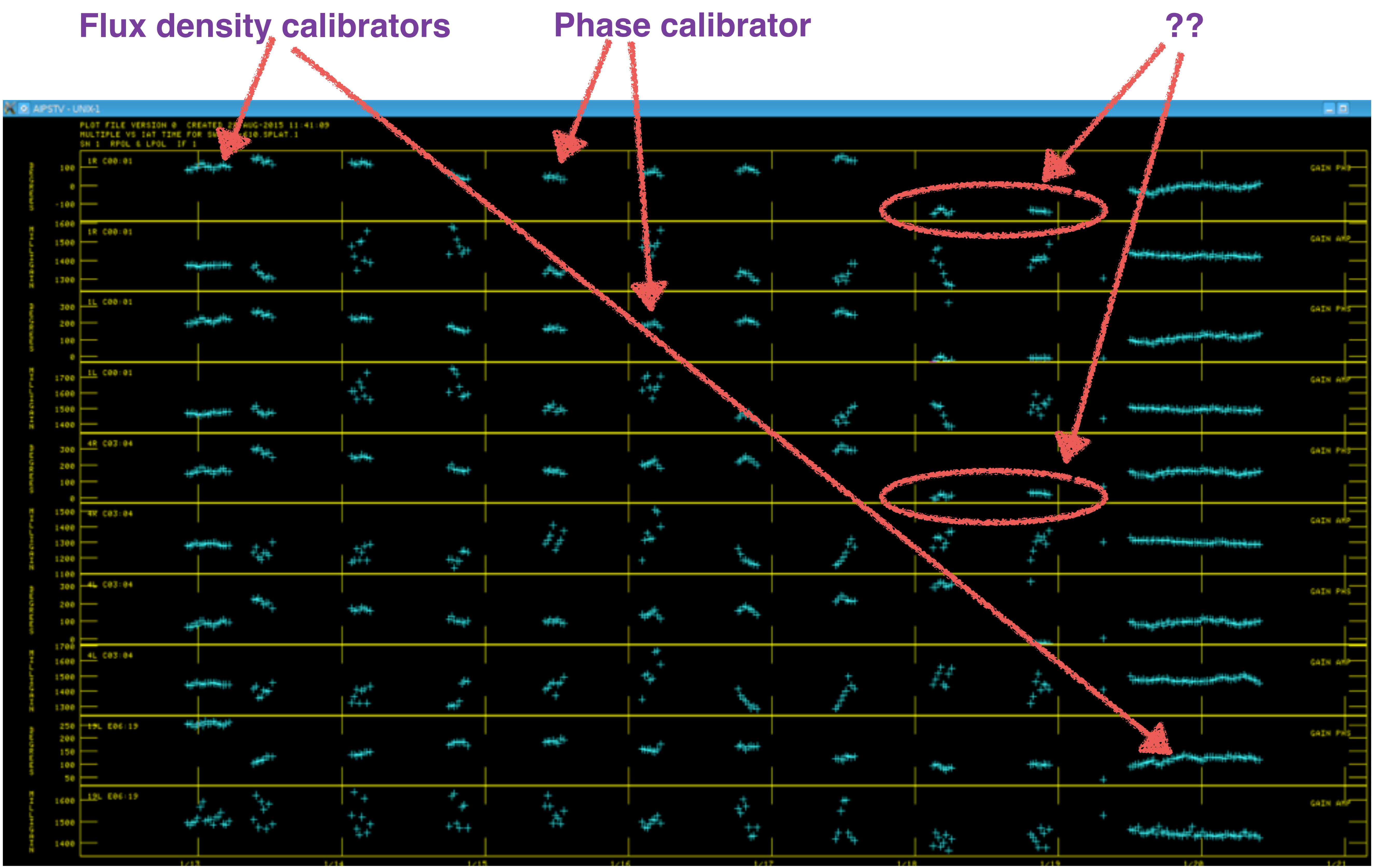
Calibration and advanced radio interferometry

- Introduction to interferometry
  - concept behind interferometry
  - 2-element interferometer
  - its comparison (fringes) with Young’s double slit experiment
  - beam-size, resolution
- Why radio interferometry?
- Correlators
  - concept of visibility and synthesis imaging (aperture synthesis)
- Imaging and deconvolution
  - Fourier and image planes (Visibilities and image plane)
  - Imaging via CLEAN algorithm
- Sensitivity

- Low frequency interferometry
  - Advanced calibration techniques
  - Error recognition and image analysis

GMRT observation



Calibration and advanced radio interferometry

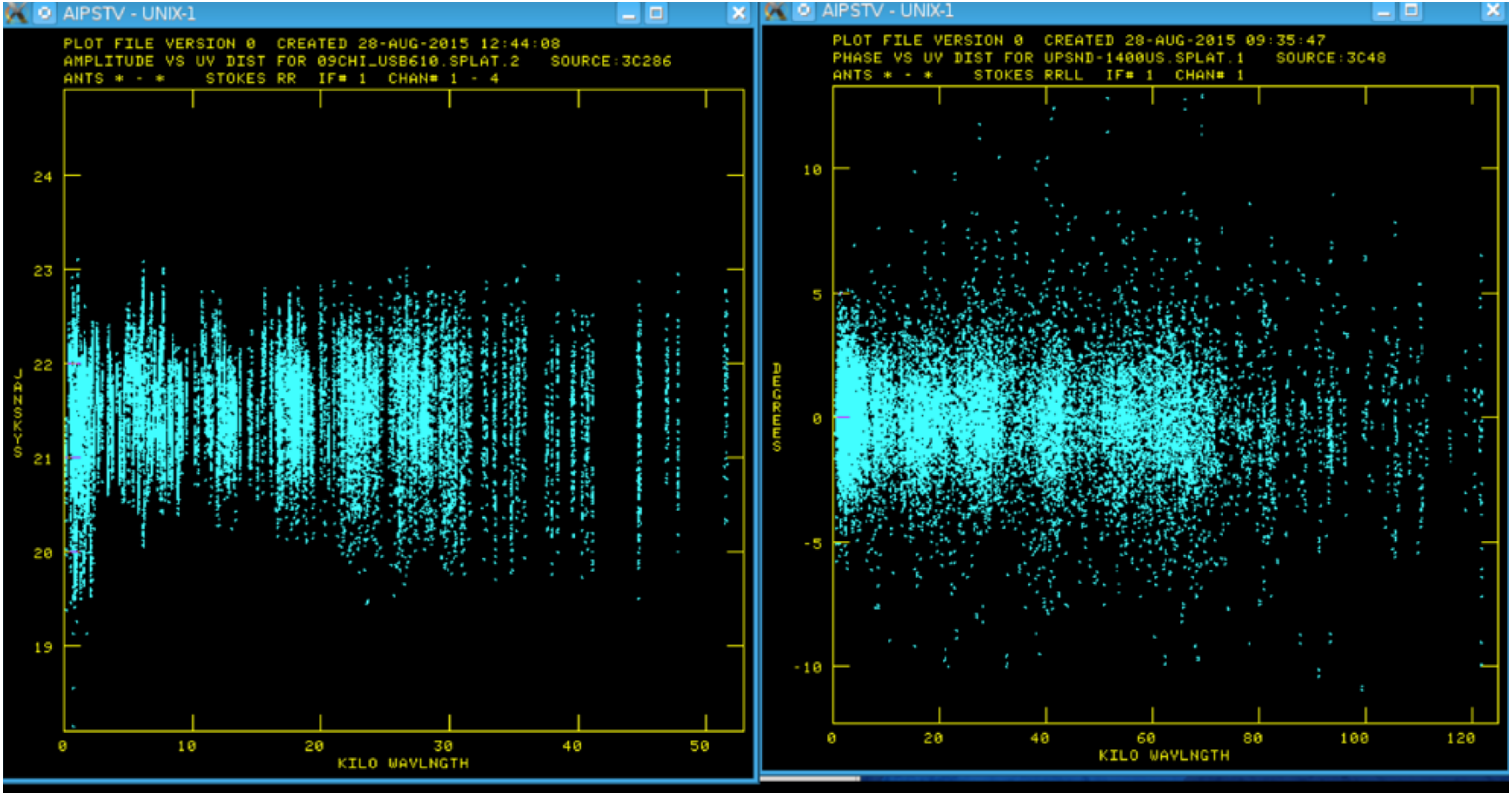
- Issues pertaining to low-frequency interferometry
  - Advanced calibration techniques
    - typical observation
    - calibration
    - bandwidth smearing
    - time averaging smearing
    - primary beam attenuation
  - deconvolution - more algorithms
  - high dynamic range imaging

- Large field-of-view imaging

- Error recognition and image analysis
  - RFI
  - Bad / Dead antenna
  - Amplitude and phase-errors
  - Deconvolution errors

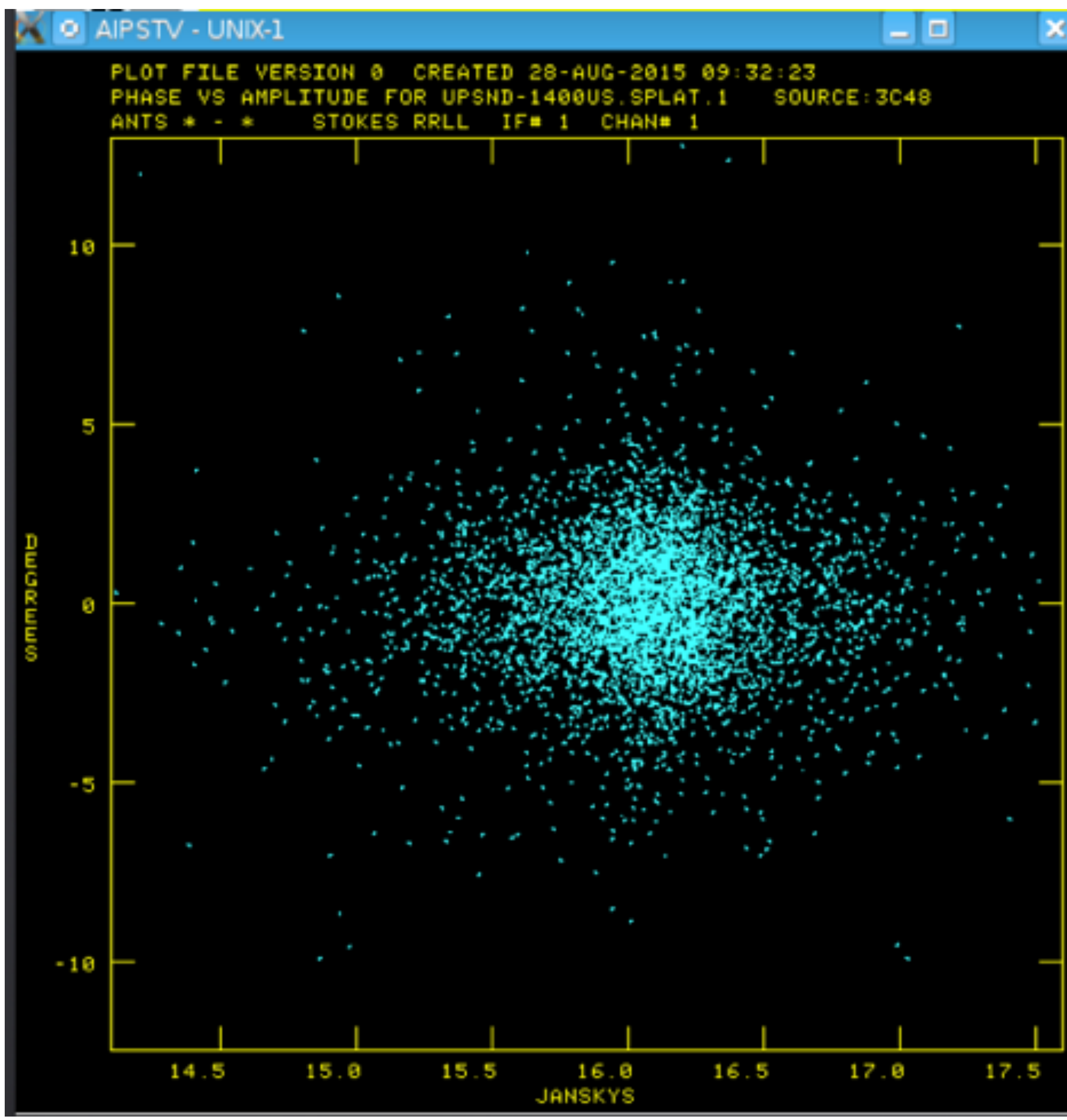
Flux density and phase calibration

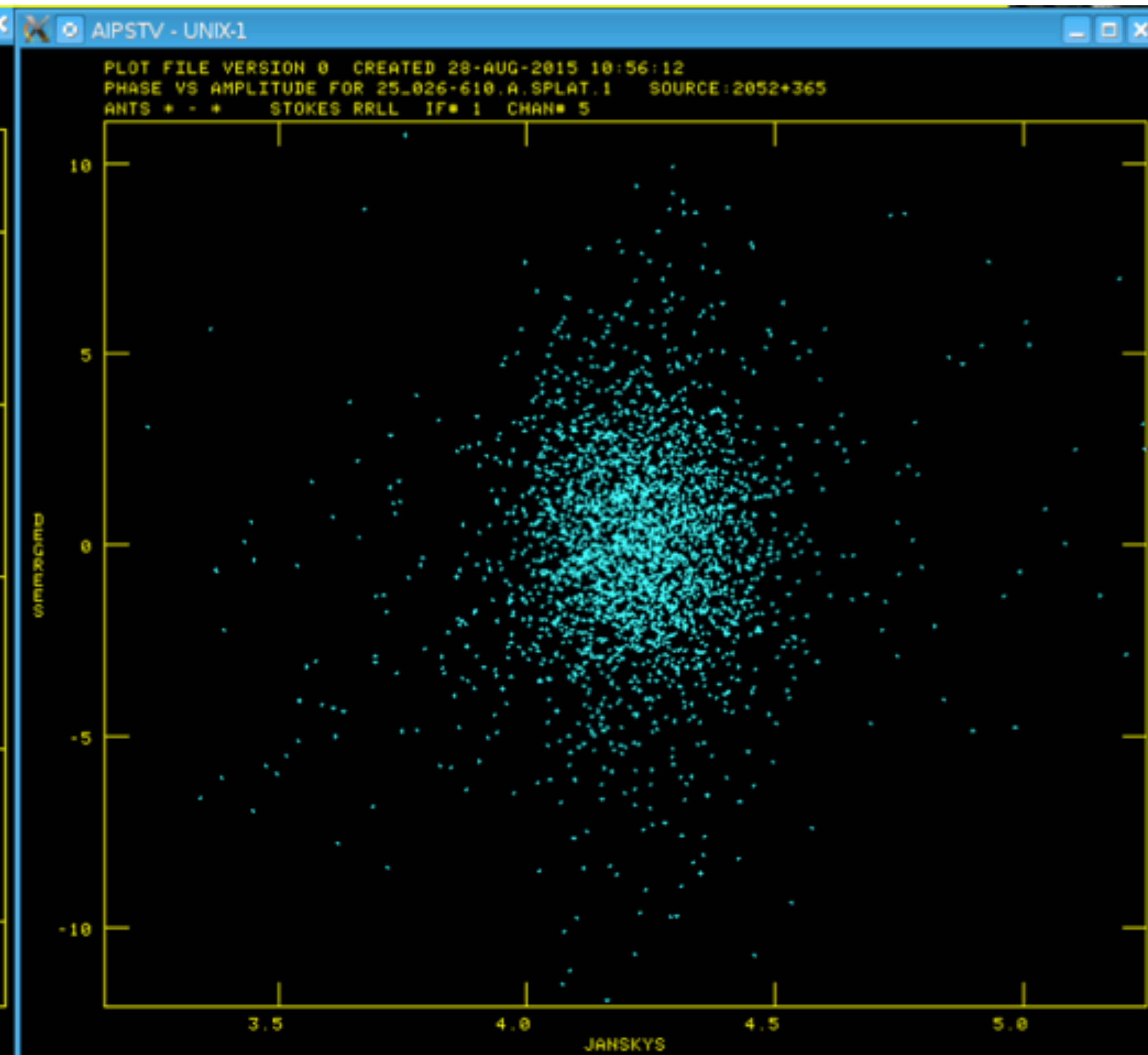
- Flux density as a f'n of UV-distance
  - flux density and phase calibrators



Flux density and phase calibration

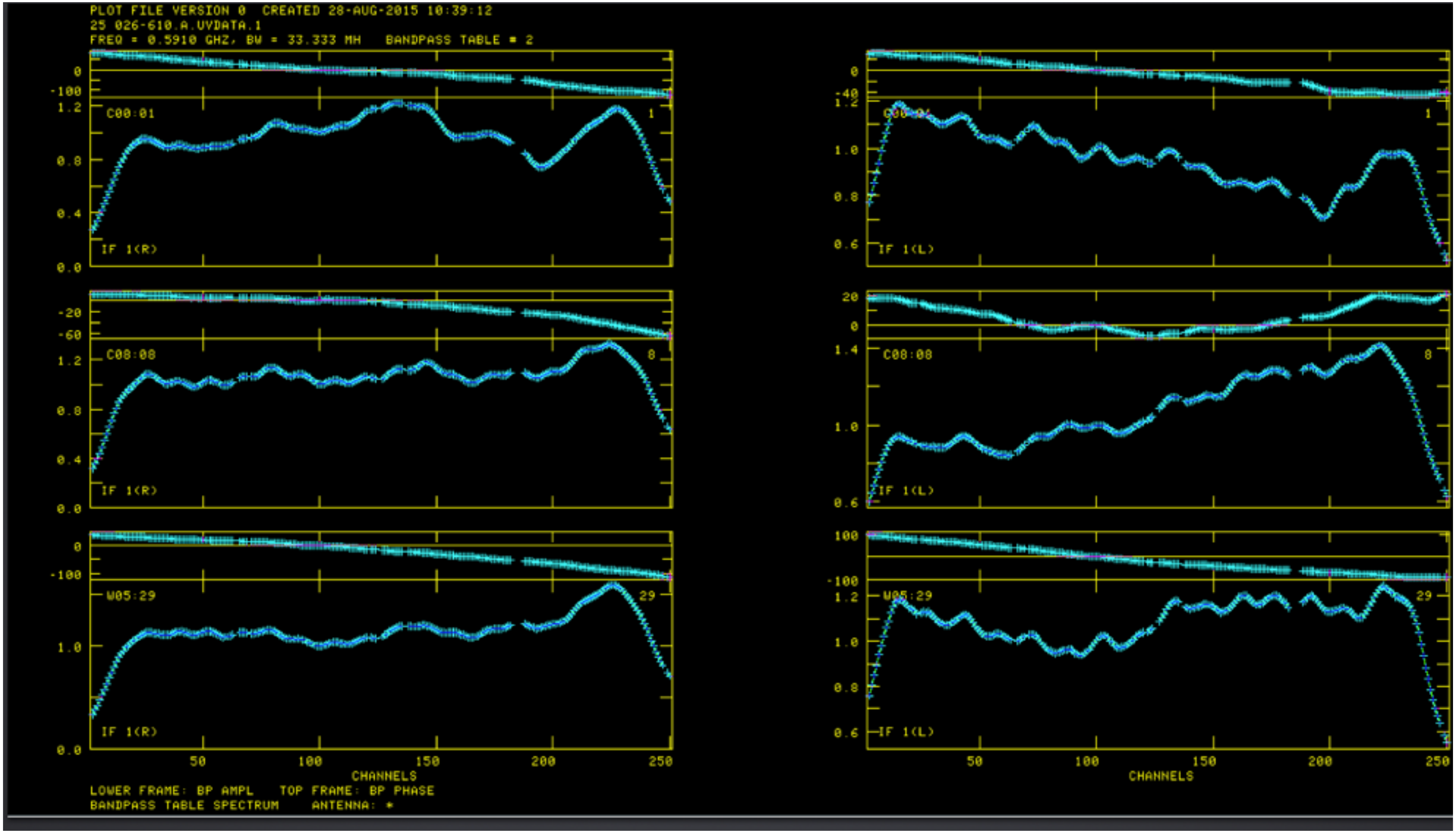
- Phase as a f'n of flux density
  - flux density and phase calibrators





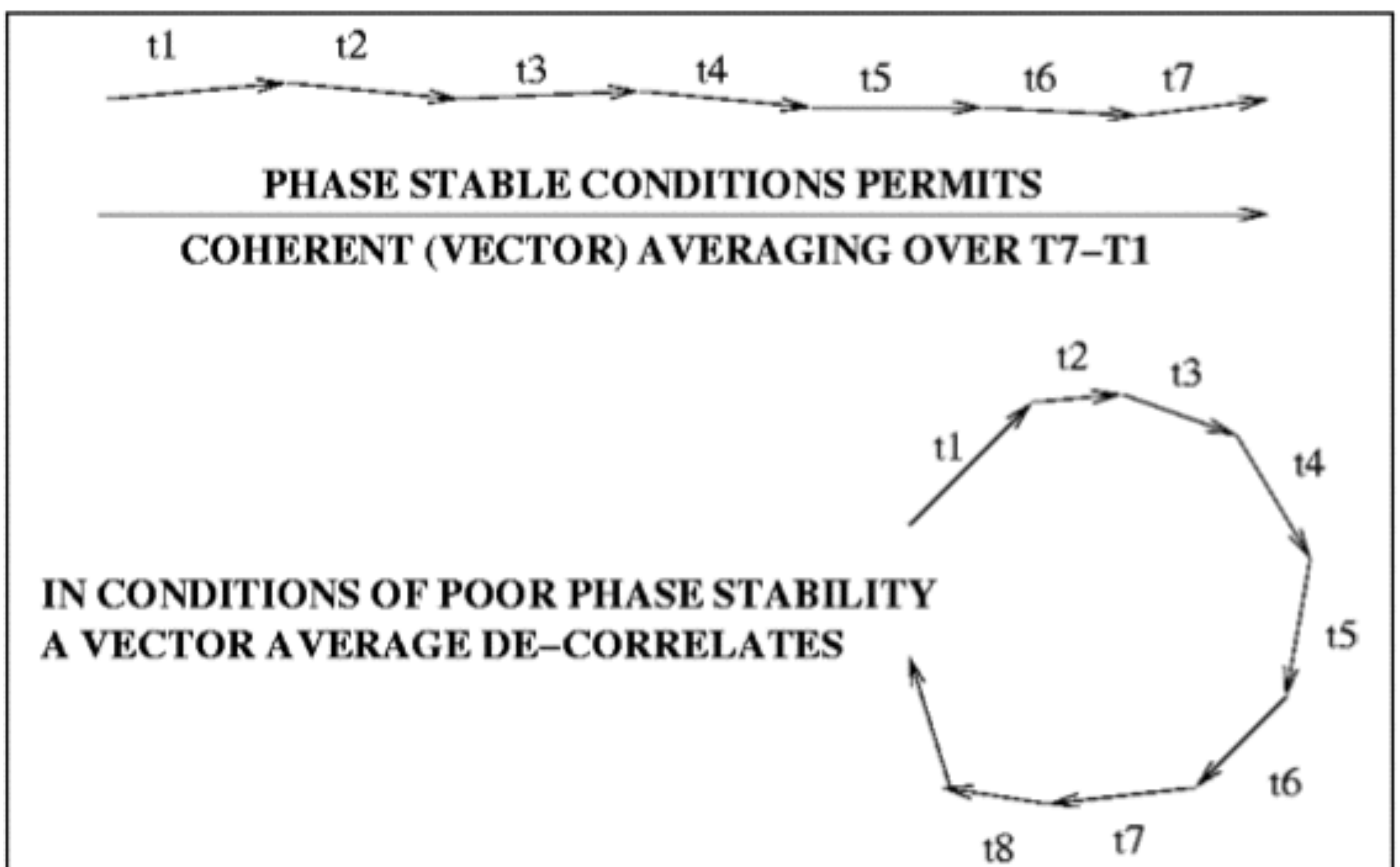
Band-shapes

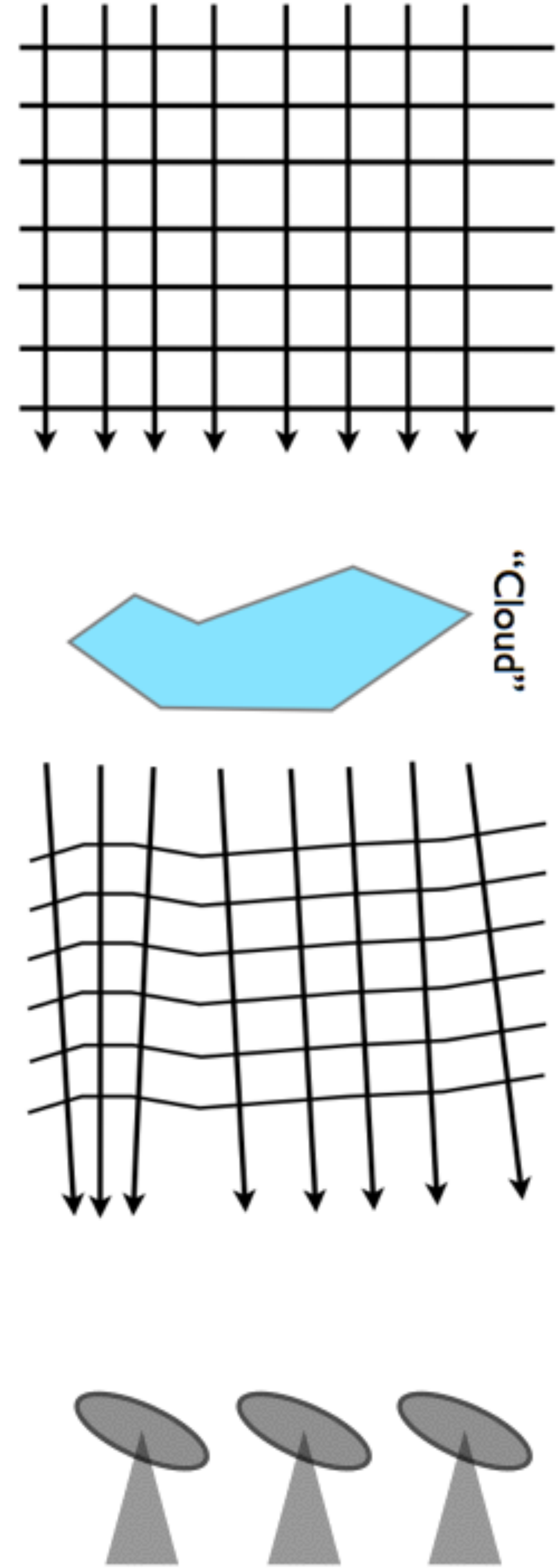
- Band-shapes
  - flux density and phase as a f'n of channel / frequency
    - (band-pass calibrators)



Phase stability

- The problems introduced by the distortions of the incoming wavefront as it passes through the Earth's atmosphere
  - (Troposphere / Ionosphere).
- These introduce phase errors across the wave front that rapidly vary with time and across the radio telescope array.

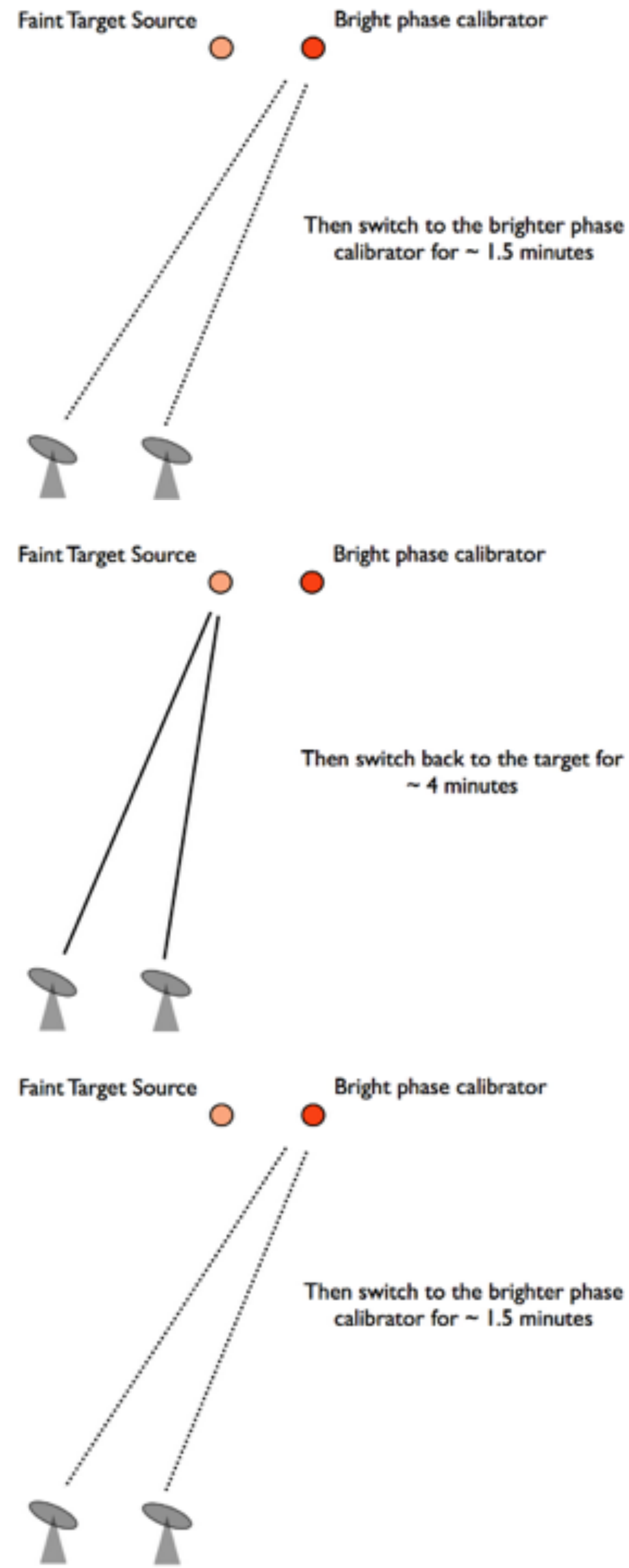




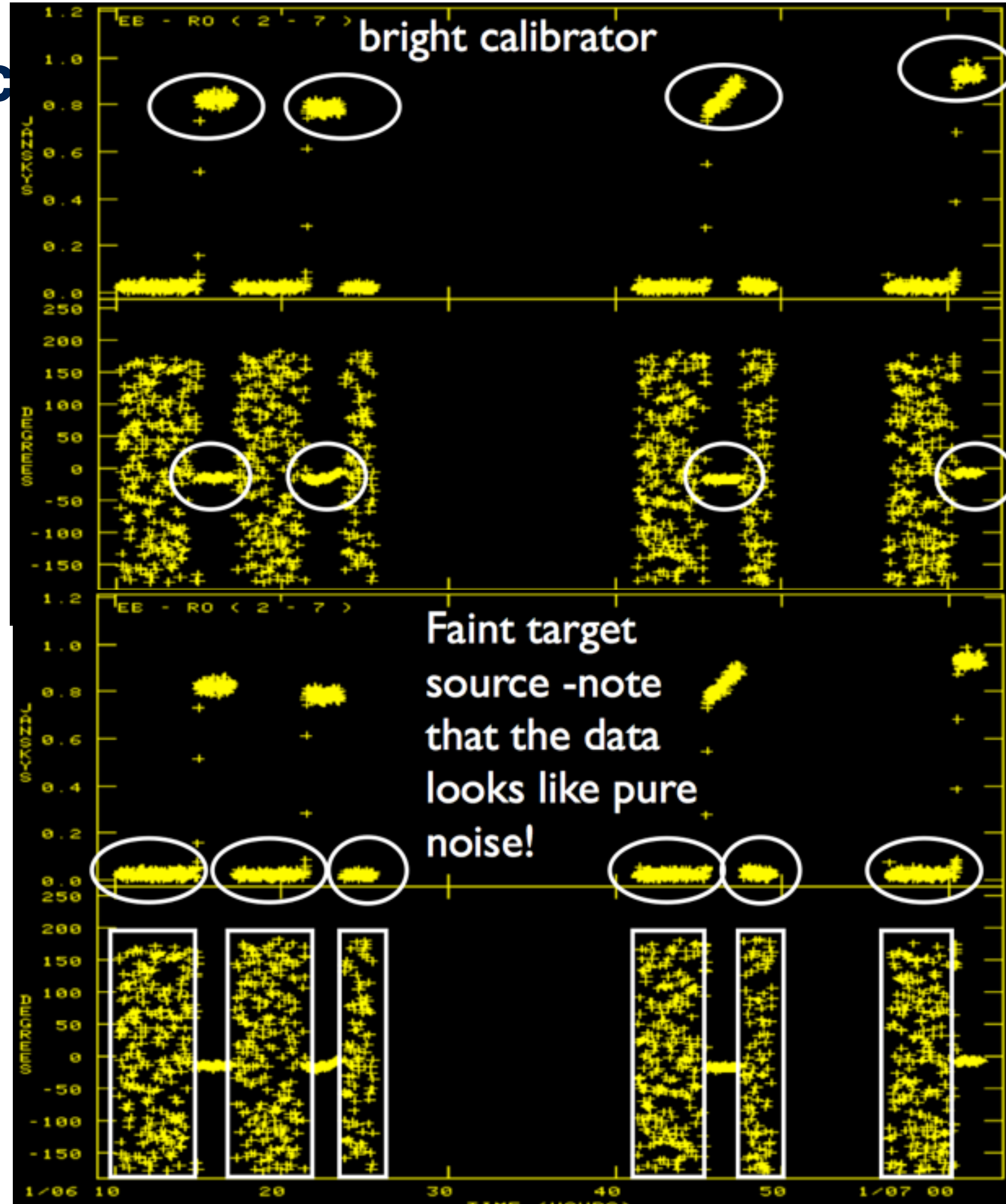
Phase referencing

- Self-calibration requires the target source to be detected (SNR > 1) within the coherence time, on the majority of baselines for reliable telescope corrections and target image to be generated.
- for a single interferometer baseline
  - the sensitivity is high and most of the radio sources are fainter!

- The technique of Phase Referencing is used to detect these sources
- The telescope corrections determined for the bright calibrator are applied to the target source data.
  - Phase reference observations specify a "cycle time" (= time on target + time on calibrator). Cycle times ~ 30-8 mins are common at m-cm wavelengths, but at much higher frequencies cycle times of 0.5 mins are sometime successfully employed.
  - For short cycle times, the telescopes must be fast movers.



Phase referenc

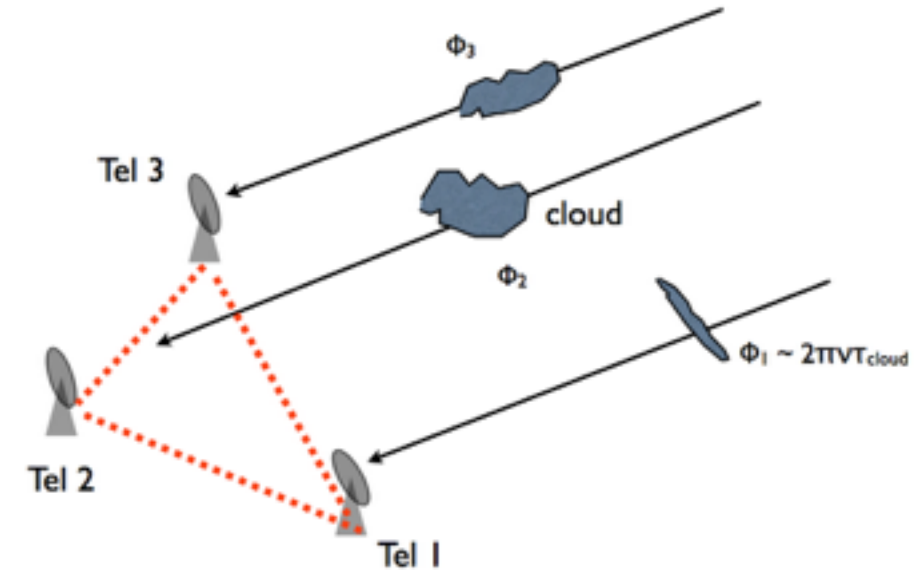


- So the idea is to take the telescope corrections (amplitude and phase) determined from self-calibrating the bright calibrator, and apply them to the faint target.
- The basic assumption is that for sources located in roughly the same region of sky, corrections for one source, also apply to the other.
- The telescope corrections are interpolated into the periods where the faint target was being observed

Making an image - self-calibration

- Even in the case of large-N, some extra a-priori information must be used to make progress, in the calibration of interferometry data. In particular, we make a few assumptions
  - (i) the sky is positive
  - (ii) the brightness distribution the interferometer is sensitive to is of limited extent.
- With these assumptions in place, we can begin to make progress.
- Telescope errors do not only
  - effect the phase of the visibility,
  - the amplitude can also be degraded.
    - However, phase errors usually dominate!
- In order to consider methodology, e.g., self-calibration to correct for amplitude errors, we must use a complex formalism
  - $V_{ij}^{obs}(t) = g_i(t)\, g^*_j(t)\, V_{ij}^{true}(t)$
    - where V_{ij} are the measured and true visibilities, and
    - $g_i(t)$ and $g^*_j(t)$ are known as the complex gains of
    - telescopes i and j
  - The gains contain corrections to both the amplitude and phase of the visibility
    - $g_i(t)=a_i(t)e^{i\phi_i(t)}$

Closure phase



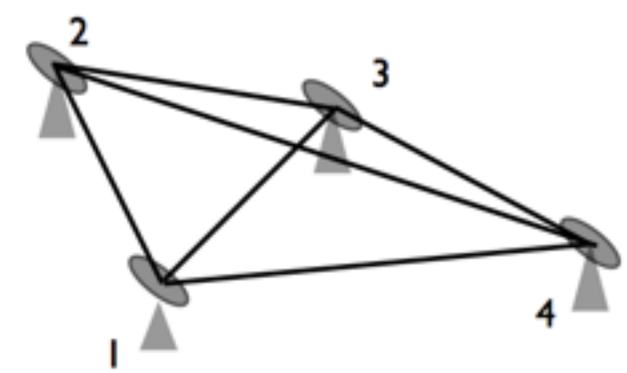
$$\Phi_{12} = \varphi_{12} + \phi_1 - \phi_2$$

$$\Phi_{23} = \varphi_{23} + \phi_2 - \phi_3$$

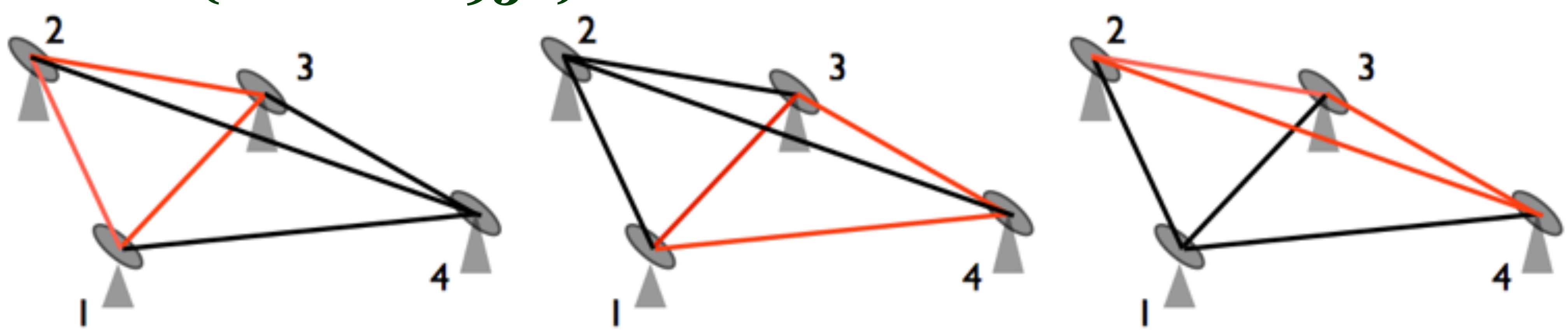
$$\Phi_{31} = \varphi_{31} + \phi_3 - \phi_1$$

$$\Phi_{12} + \Phi_{23} + \Phi_{31} = \varphi_{12} + \varphi_{23} + \varphi_{31} + (\phi_1 - \phi_1) + (\phi_2 - \phi_2) + (\phi_3 -$$

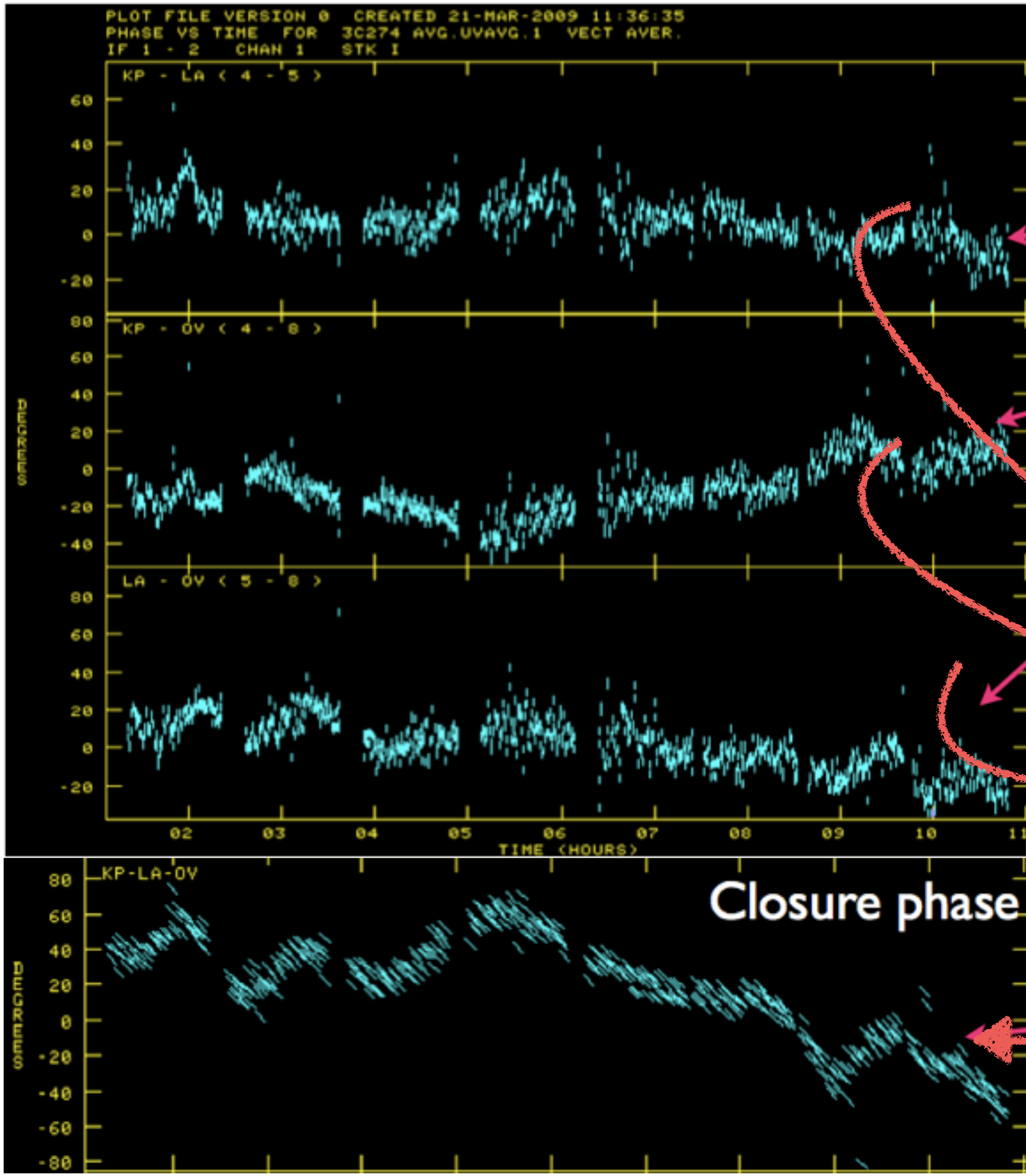
closure phase $$= \varphi_{12} + \varphi_{23} + \varphi_{31}$$



- This formulation of adding together the observed visibility phases together of any 3 telescopes is
- known as forming a "closure triangle".
- For a given array of N telescopes, there are,
  - (N-1)(N-2)/2 independent closure phases
- e.g. for N=4, there are,
  - 3 independent closure relations.
- This concept of closure phase was first discovered by Roger Jennison (MNRAS 1958)



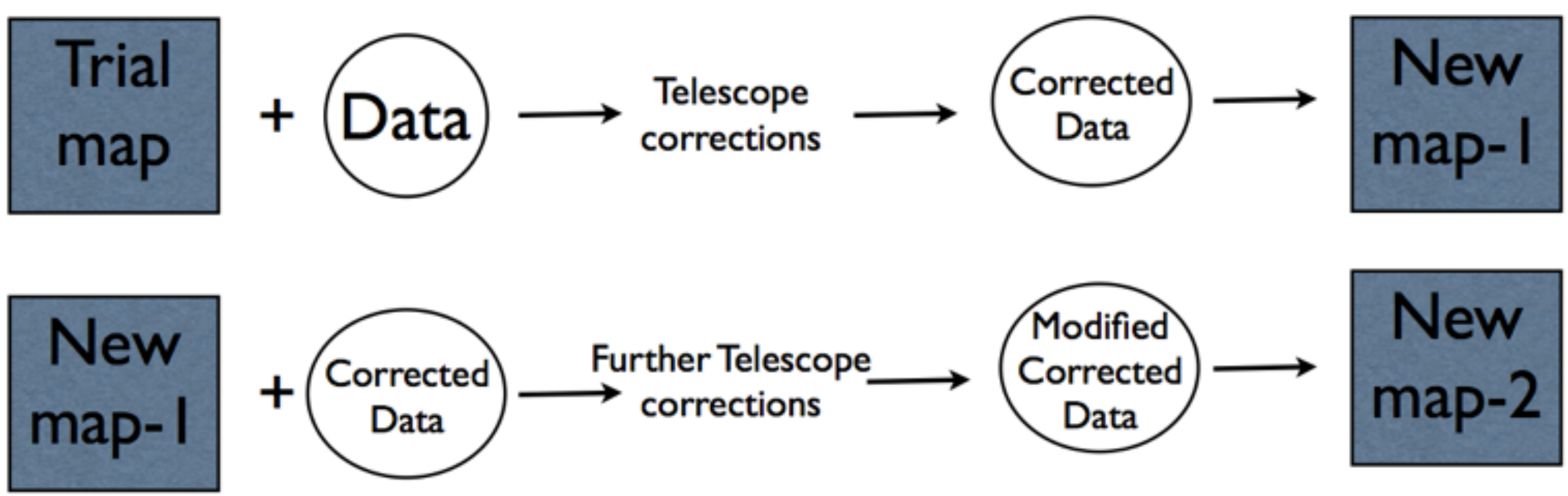
Closure phase



- Closure phase: tells us something about the source visibility alone!
- So from the closure relations we have (N-1)(N-2)/N good observables (measurements).
- However, there are N telescope unknowns. We can reduce this to (N-1) unknowns if we make one of the telescopes the “reference antenna”
- Note that the ratio of
  - good observables/unknowns is (N-2)/N
- Tells us something about the source visibility phase, the atmospheric induced distortions to the phase, telescope, electronic etc.
- Closure phase: tells us something about the source visibility alone!

Making an image - self-calibration

- Even in the case of large-N, some extra a-priori information must be used to make progress, in the calibration of interferometry data. In particular, we make a few assumptions
  - (i) the sky is positive
  - (ii) the brightness distribution the interferometer is sensitive to is of limited extent.
- With these assumptions in place, we can begin to make progress.



Bandwidth averaging/smearing

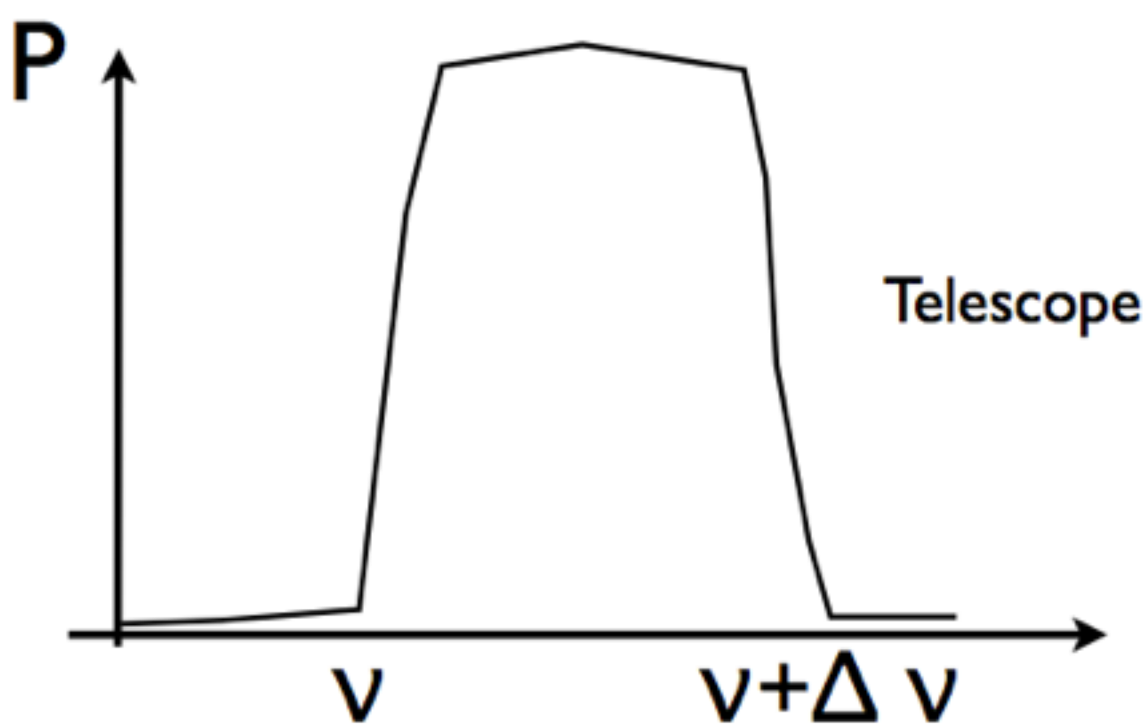
- During correlation, the delay is correct for only one particular point on the sky - usually the phase centre (where the target is located).
- For all other source positions there will be an error introduced by applying a delay that is strictly only true for the phase centre & a particular frequency
- Another complicating factor is that interferometers observe a range of frequncies simultaneously, Δv.

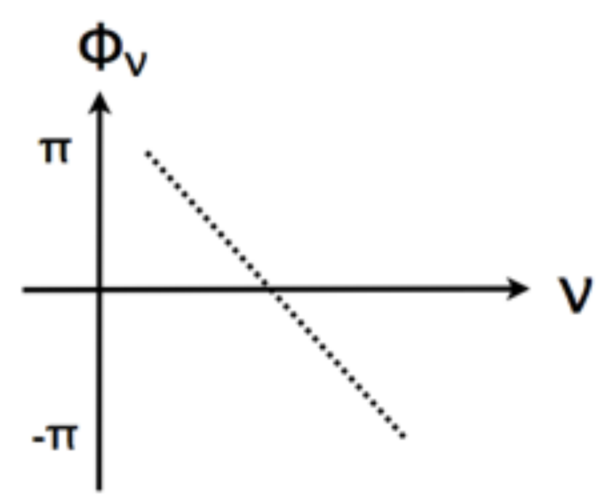
Averaging visibilities over finite BW results in chromatic aberration worsens with distance from the phase centre!

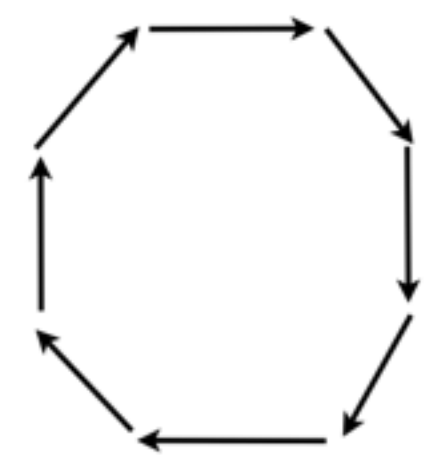
=> radial smearing $(\Delta v/v_o) x (\theta_o/\theta_{synth}) \sim 2$

=> $I_o/I = 0.5$

=> worse at higher resolutions





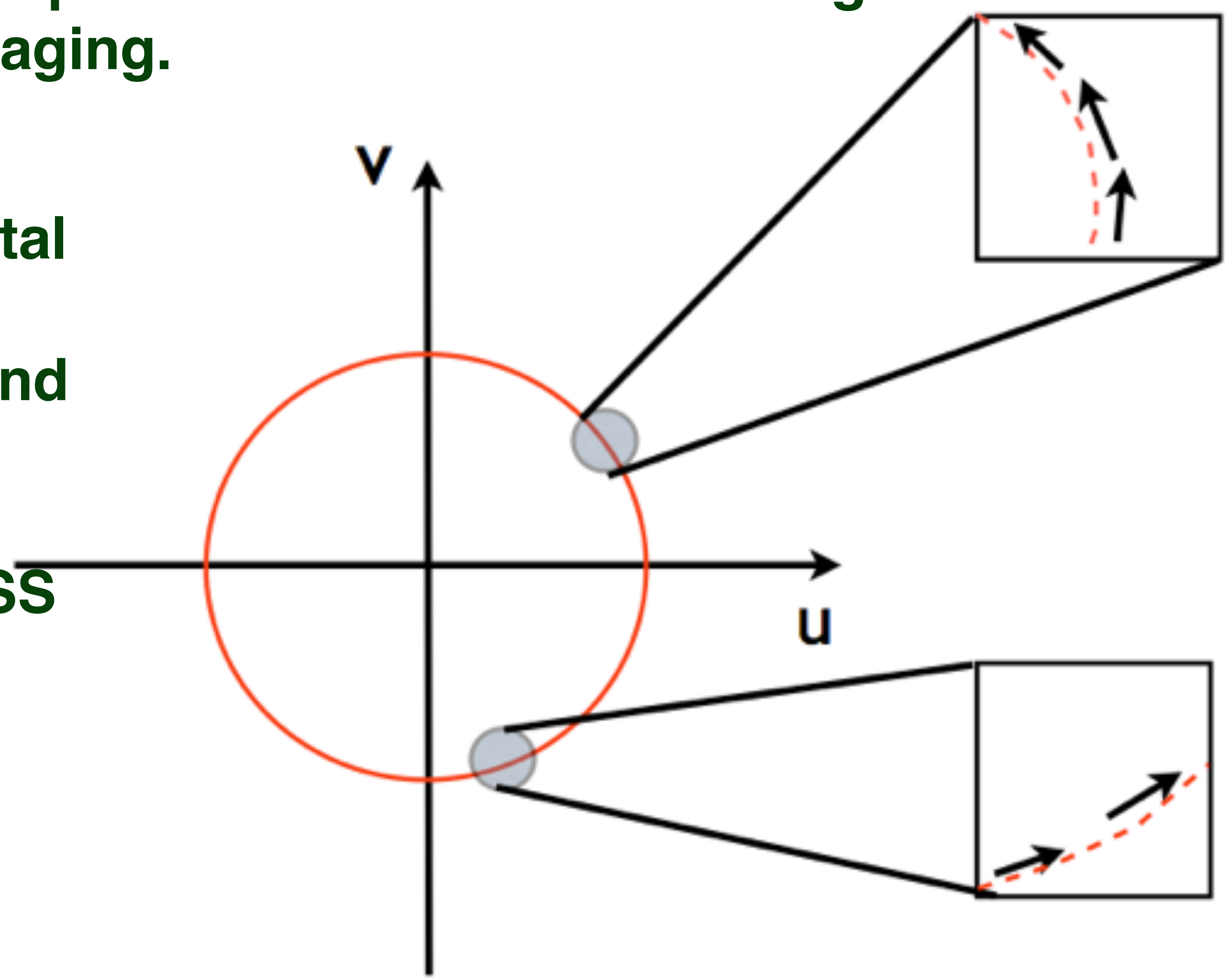


Time averaging

- Time averaging leads to more complex smearing of the source in the image plane than the radial smearing associated with bandwidth smearing. The smearing depends on the (u,v)-coverage.
  - When the (u,v)-coverage is very fore-shortened, i.e. 1-D (e.g. in the case of the arm antennas of the GMRT observing a low declination source), then you can expect time smearing to produce azimuthal smearing, in the image plane.
- For a given array, time averaging is usually the main limitation to the field of view at HIGH frequencies. At low frequencies bandwidth smearing tends to be a bigger problem than time averaging.

- Unlike bandwidth smearing, time averaging does not preserve the total flux density.
- The effects of bandwidth smearing and time averaging are additive

=> DON'T AVERAGE THE DATA UNLESS YOU HAVE TO!

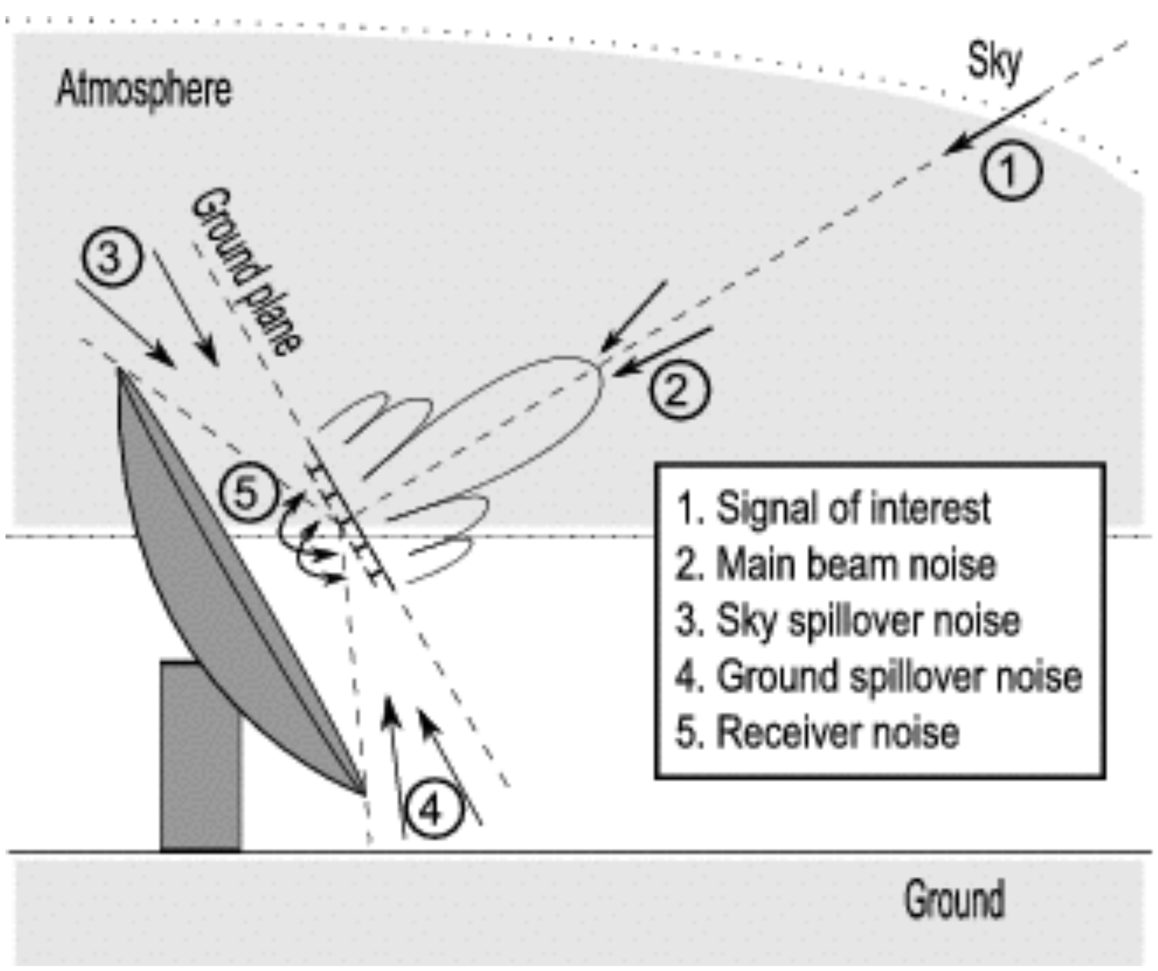


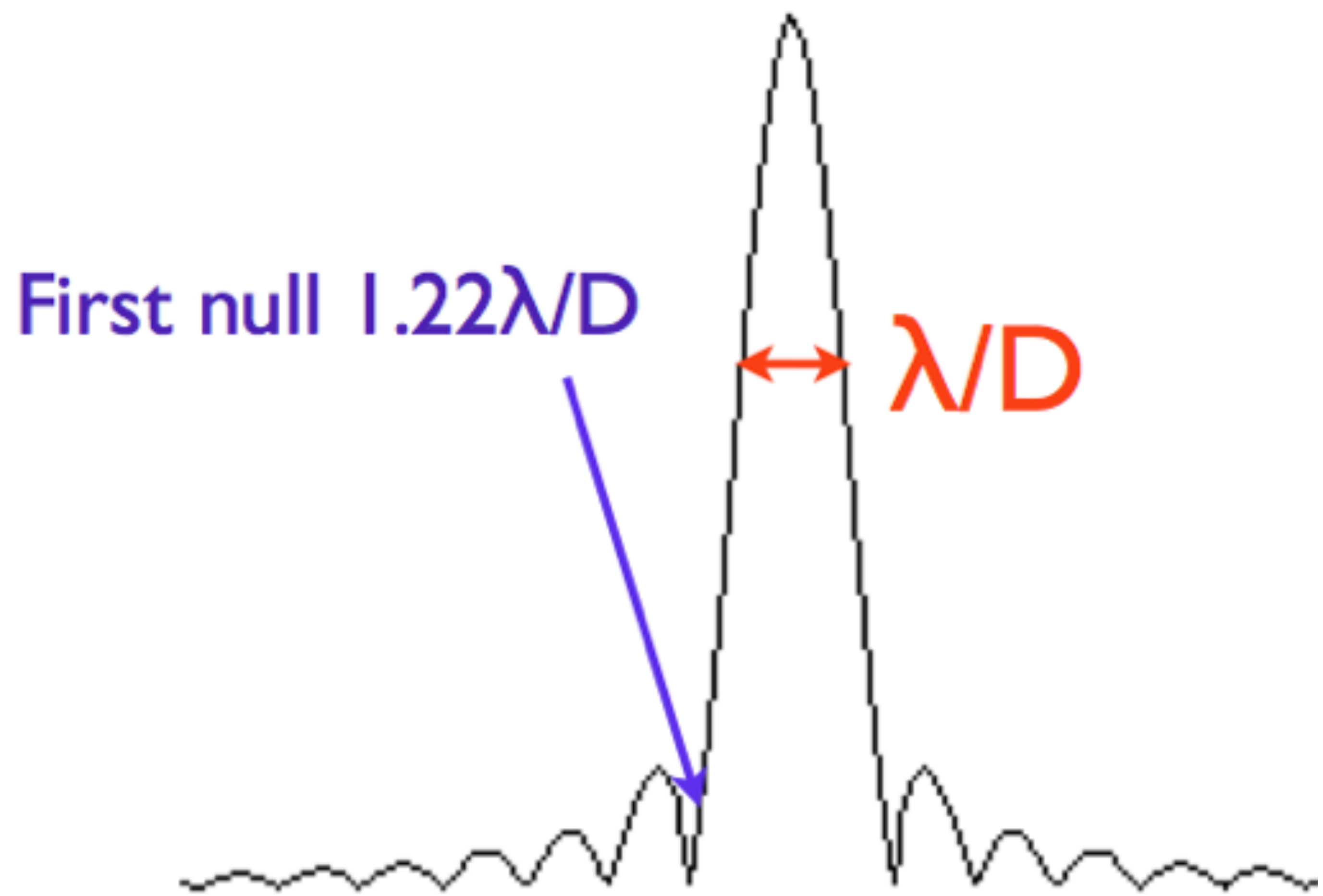
Bandwidth and Time averaging

- The effect of bandwidth smearing scales as θ_{beam}, i.e. it scales as baseline length. Bandwidth smearing is a big problem forVLBI arrays when the observer desires to image a large field of view;
- for bandwidth smearing the integrated flux density measured in the map is preserved but the surface brightness is reduced
- Note! for a given array/observations, the bandwidth smearing is independent of the observing frequency
- Just like bandwidth smearing the effect of time averaging scales with the desired field of view $d\theta$.
- Unlike bandwidth smearing, time averaging does not preserve the total flux density.
- The effects of bandwidth smearing and time averaging are additive
- averaging the data always leads to information loss.
- DON'T AVERAGE THE DATA UNLESS YOU HAVE TO
  - (or at least understand that the FoV is heavily reduced after averaging).

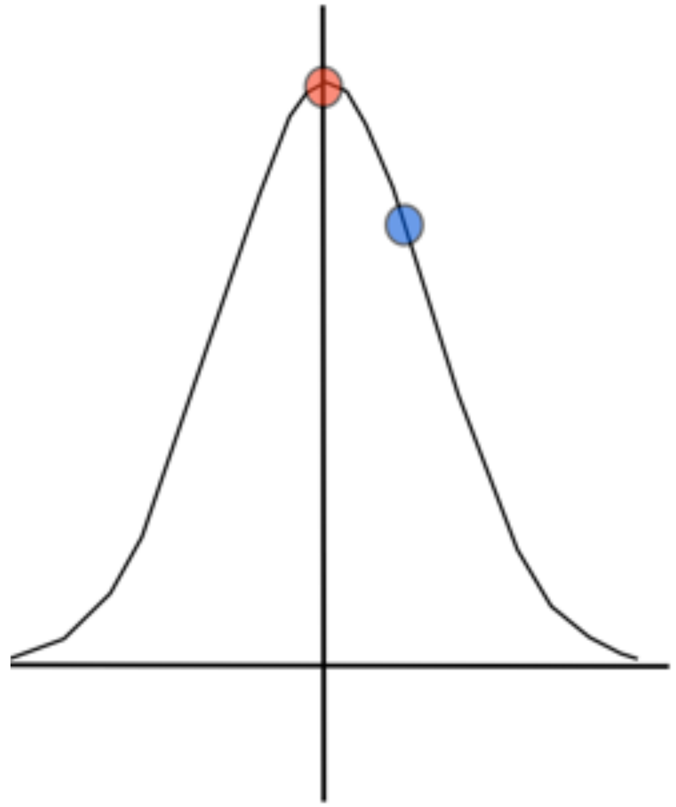
Primary beam attenuation

- The shape of the antenna power pattern represents the ultimate restriction on the observers field of view.
- The change in the response of the primary beam of antennas in an array can be corrected for, if the shape of the primary beam is well measured and if the array is made up of antennas of the same type/size.
  - This is called making a primary beam correction.
  - If this is not applied, the flux densities you measure at the edge of the fields will be less than the true flux density.

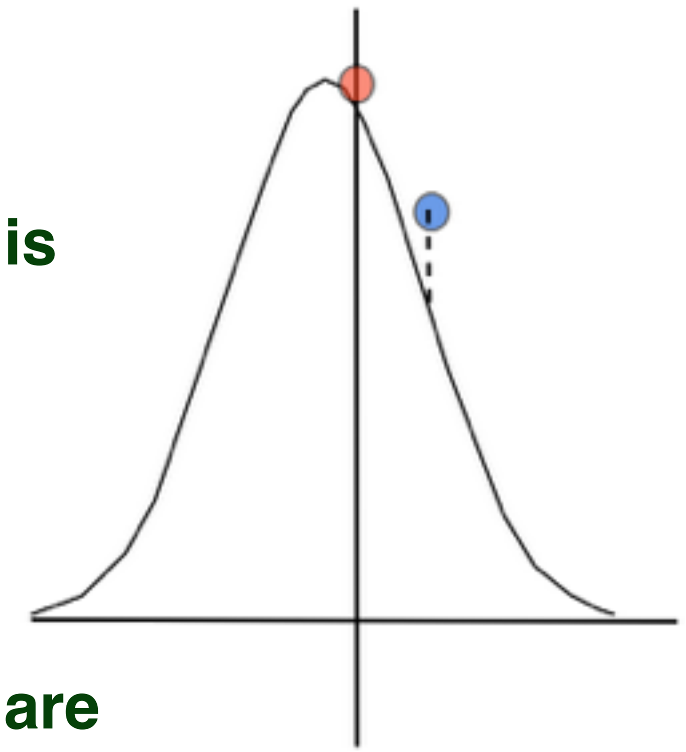




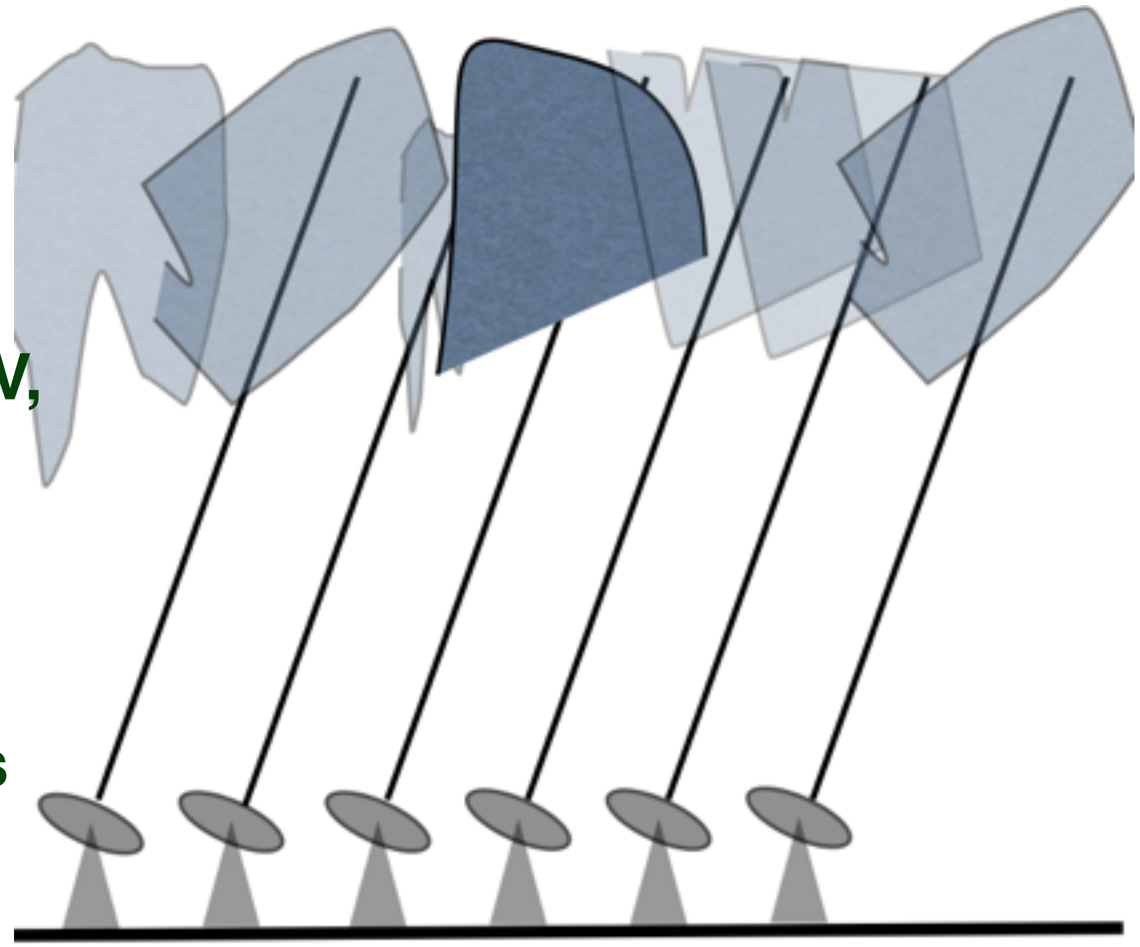
High dynamic range



- At low frequencies (e.g. 1.4 GHz) there are always bright sources in the field of view of GMRT, and it is difficult to achieve the noise levels one expects from thermal noise calculations. Or, the image is “Dynamic range limited”.
- Errors that limit the dynamic range of an image include
  - (i) non-closing errors due to baseline based errors, e.g.,
    - changes in passbands on short times or errors in correlator,
  - (ii) telescope pointing errors,
  - (iii) non-isoplanatic effects.
- Pointing errors are problematic; the effect is not uniform over FoV.
  - e.g., sources at the edge of PB (where response of PB is changing quickly) or there is a large reduction of telescope response at their position,
    - this is difficult for self-cal to cope with;
      - since it determines a single telescope-based amplitude correction.
  - Instead, in practice the self-cal corrections (solutions) are usually biased towards the position of the brightest source in the field.



High dynamic range



- Non-isoplanicity, cases when the amplitude and phase corrections vary across the FoV,
  - they are function of time position.
    - gi(t1, θ1) = gi(t1,θ2)
    - FoV (θ1-θ2) << Isoplantatic patch
    - self-cal algorithms can cope with the FoV, which we wish to image, that is smaller than isoplanatic patch.
    - The case we wish to avoid:
      - gi(t1,θ1) ≠ gi(t1,θ2)
      - FoV (θ1-θ2) >> Isoplantatic patch

- Reality is different: non-isoplanicity is a problem at low frequency (< a few hundred MHz)
  - FoV / PB is larger;
  - Ionosphere is far away (100’s of km c.f. the troposphere);
  - Isoplanatic patch size is < ~10 km;
  - PB covers more than one patch typically;
  - Different patch over each antenna - even for relatively short baseline arrays.
- Errors (due to non-isoplanicity) or pointing errors limit the dynamic range of images.

- Isoplanatic patch size is < ~10 km;
- beam covers more than one patch typically;
- Different patch over each antenna - even for relatively short baseline arrays.

Calibration and advanced radio interferometry

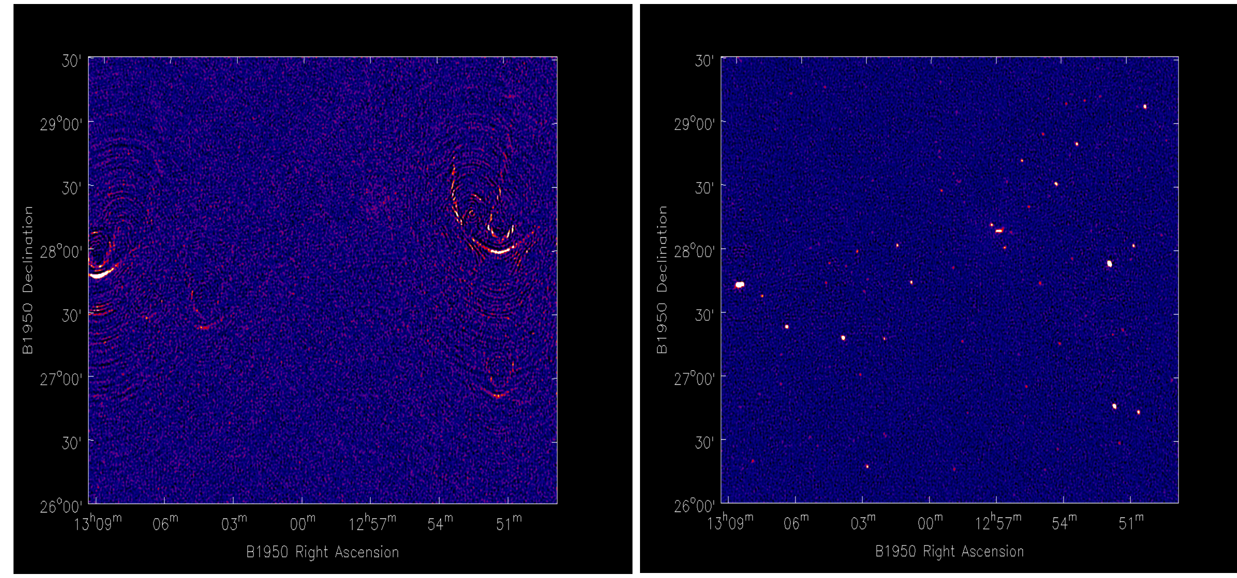
- Issues pertaining to low-frequency interferometry
  - Advanced calibration techniques
    - typical observation
    - calibration
    - bandwidth smearing
    - time averaging smearing
    - primary beam attenuation
  - deconvolution - more algorithms
  - high dynamic range imaging

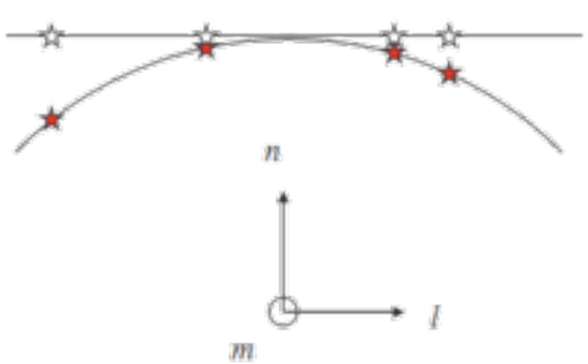
- Large field-of-view imaging

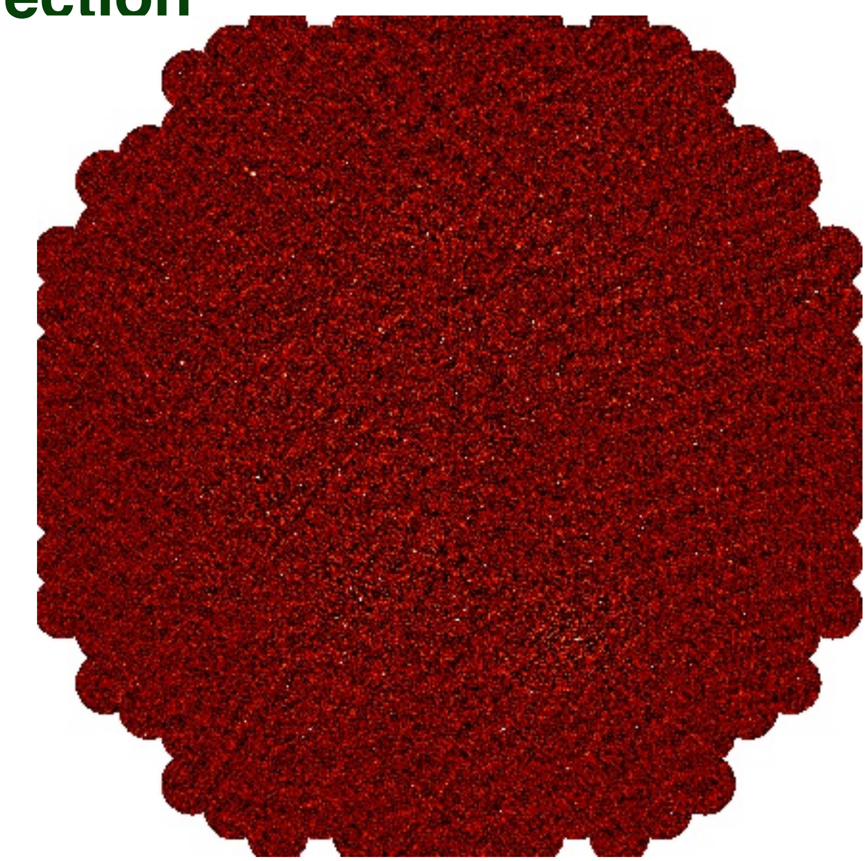
- Error recognition and image analysis
  - RFI
  - Bad / Dead antenna
  - Amplitude and phase-errors
  - Deconvolution errors

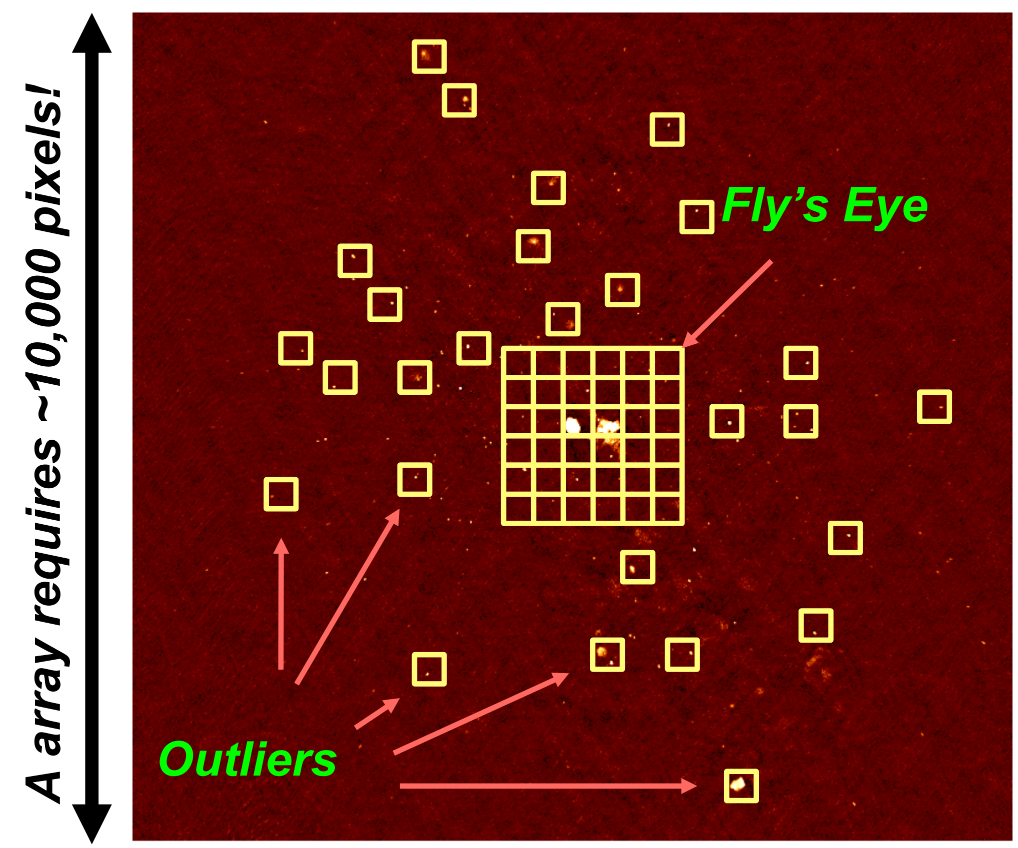
Large FoV - full field vs. targeted imaging

- Noncoplanar baselines: (u,v, and w)
  - Important if $$\frac{B\lambda}{D^2} > 1$$
  - shape of array varies over FoV
    - => in AIPS multi-facet imaging,
    - => in CASA w-projection or facets
- Imp. for all observations below 1 GHz and
  - for high resolution,
  - high dynamic range (at 1.4 GHz!), reduces side-lobes of confusing sources
- Requires a lot of computing power and disk space
  - AIPS: IMAGR (DO3DIMAG=1, NFIELD=N, OVERLAP=2)
  - CASA: w-projection



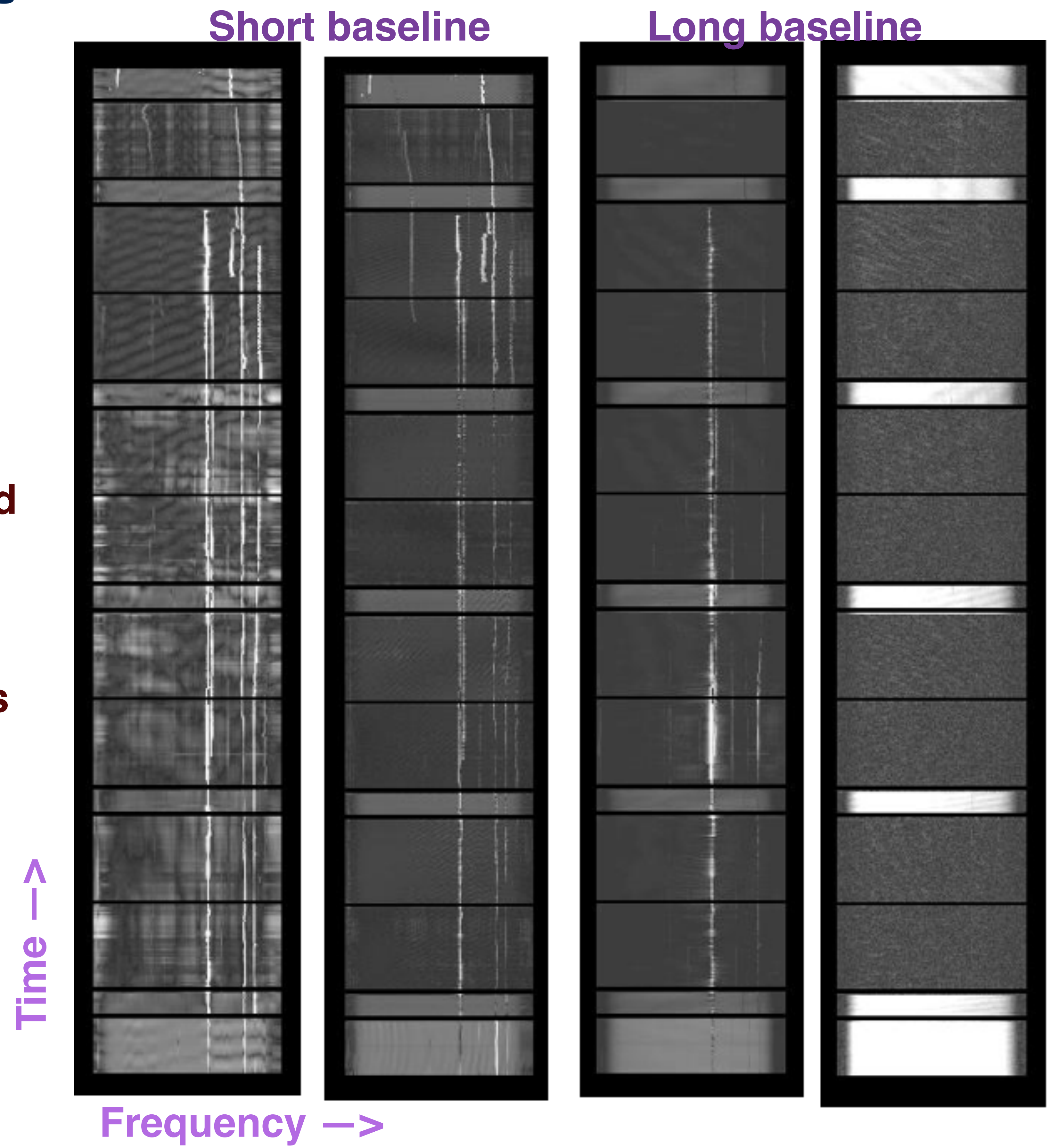






Radio frequency Interference

- RFI environment worse on short baselines
- Several ‘types'
  - narrow band,
  - wandering,
  - wideband,
  - ...
- Wideband interference hard for some automated routines
- Examples using AIPS tasks
  - FLGIT,
  - FLAGR,
  - RFI,
    - NEW: UVRFI



Obvious Image problems

Top image cannot be right!

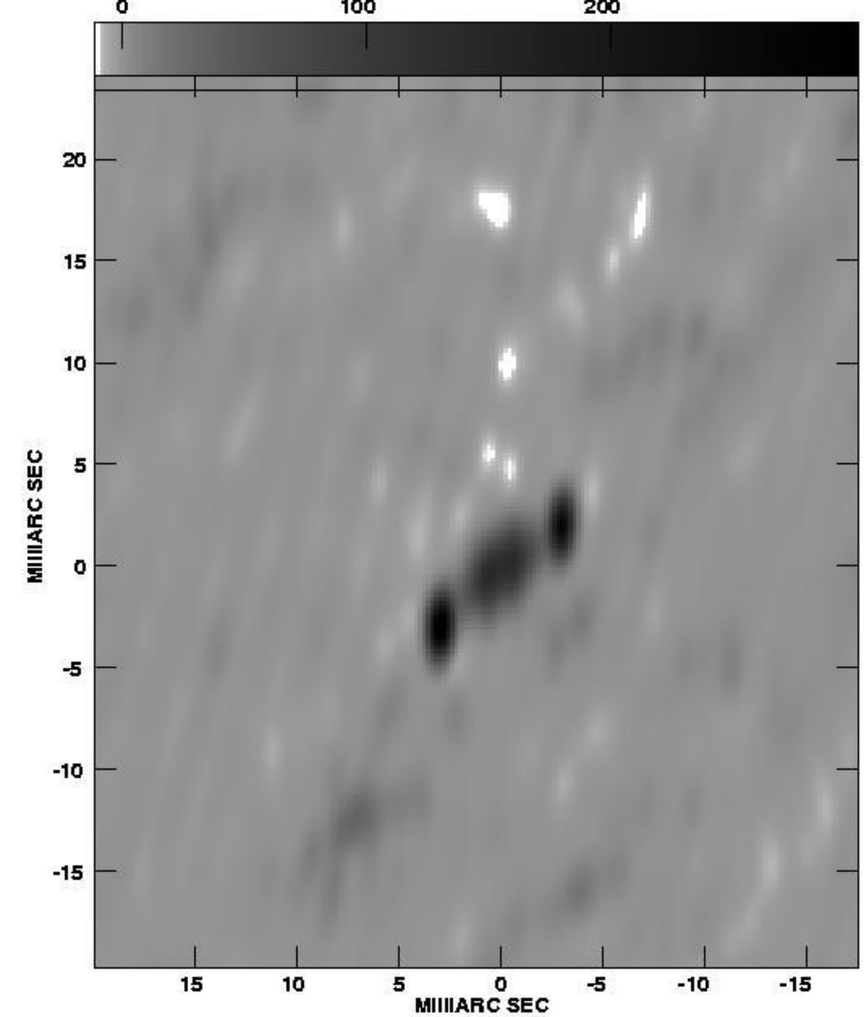
- This is either most remarkable radio source ever, or I have made an error in making the image.
- Clear signs of problems
  - Image rms > expected rms
  - Unnatural features in the image

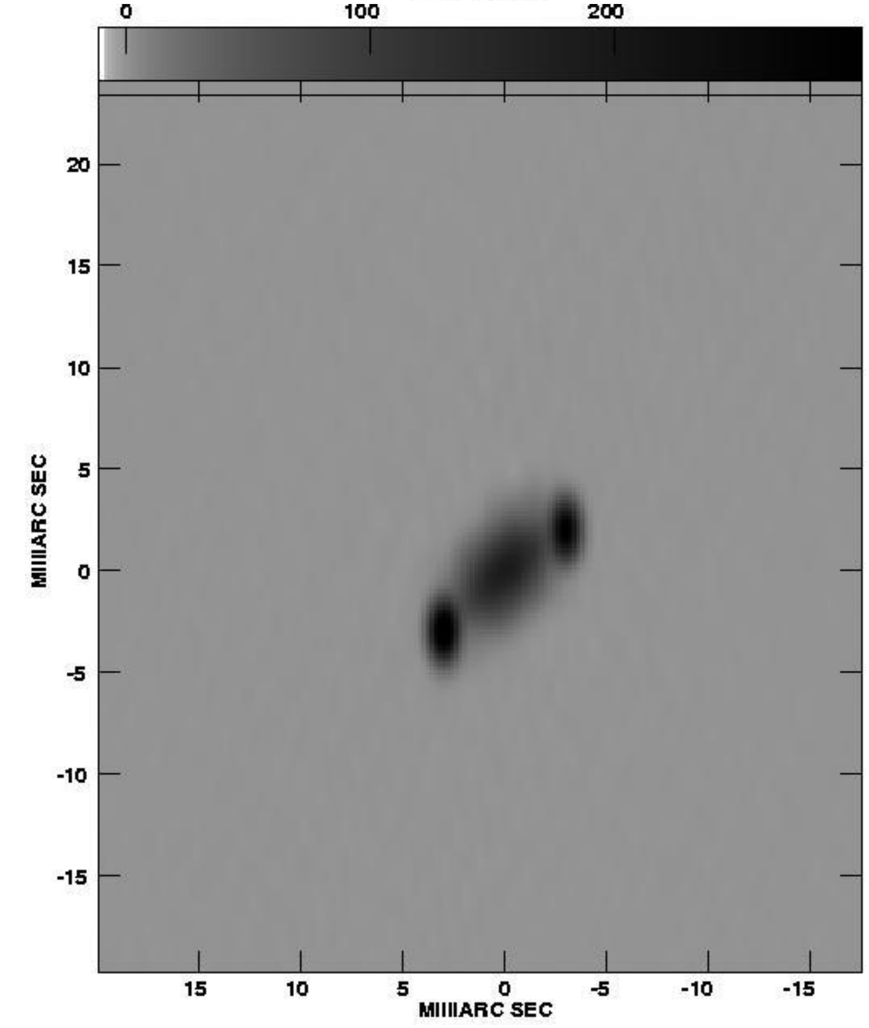
- How can the problems be found and corrected?

After lots of work, I can finally analyse this image and get some interesting scientific results.

- What were defects?
  - Two antennas had 10% calibration errors, and one with a 5 deg error, plus a few outlier points.

How to find the errors and remove them.





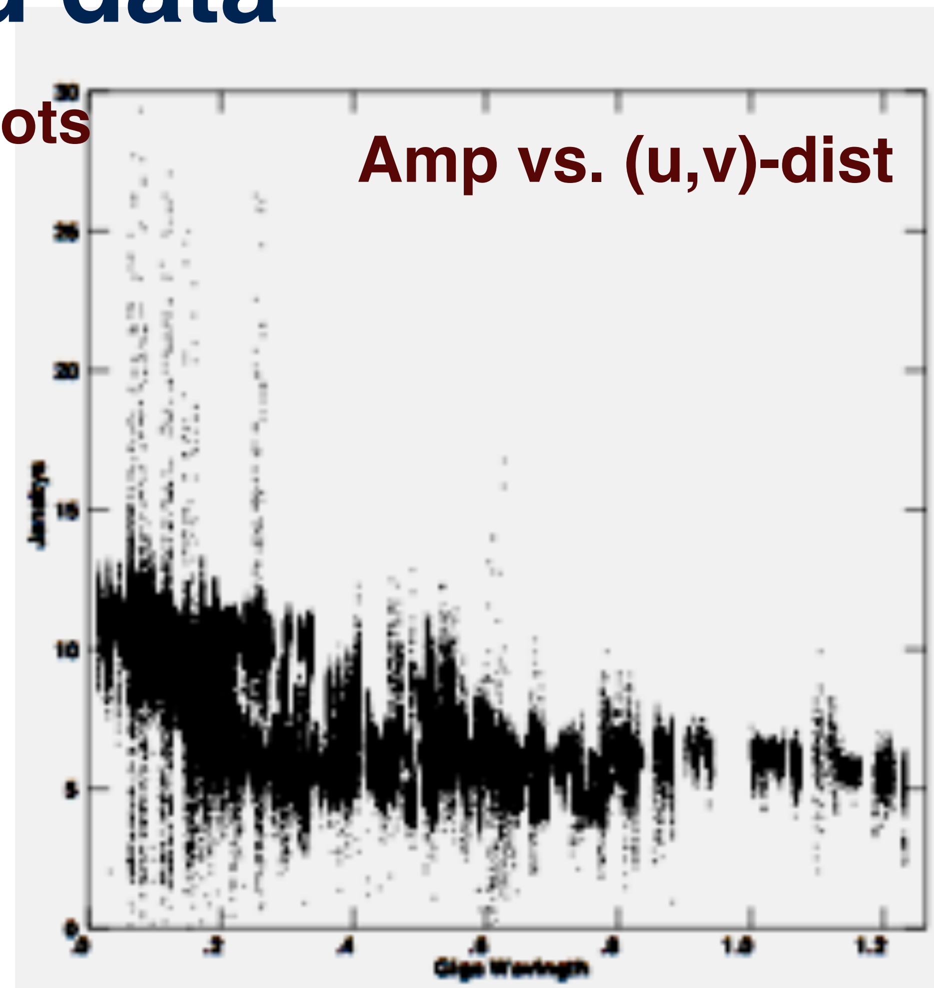
Errors: Image-plane / (u,v)-plane inspection

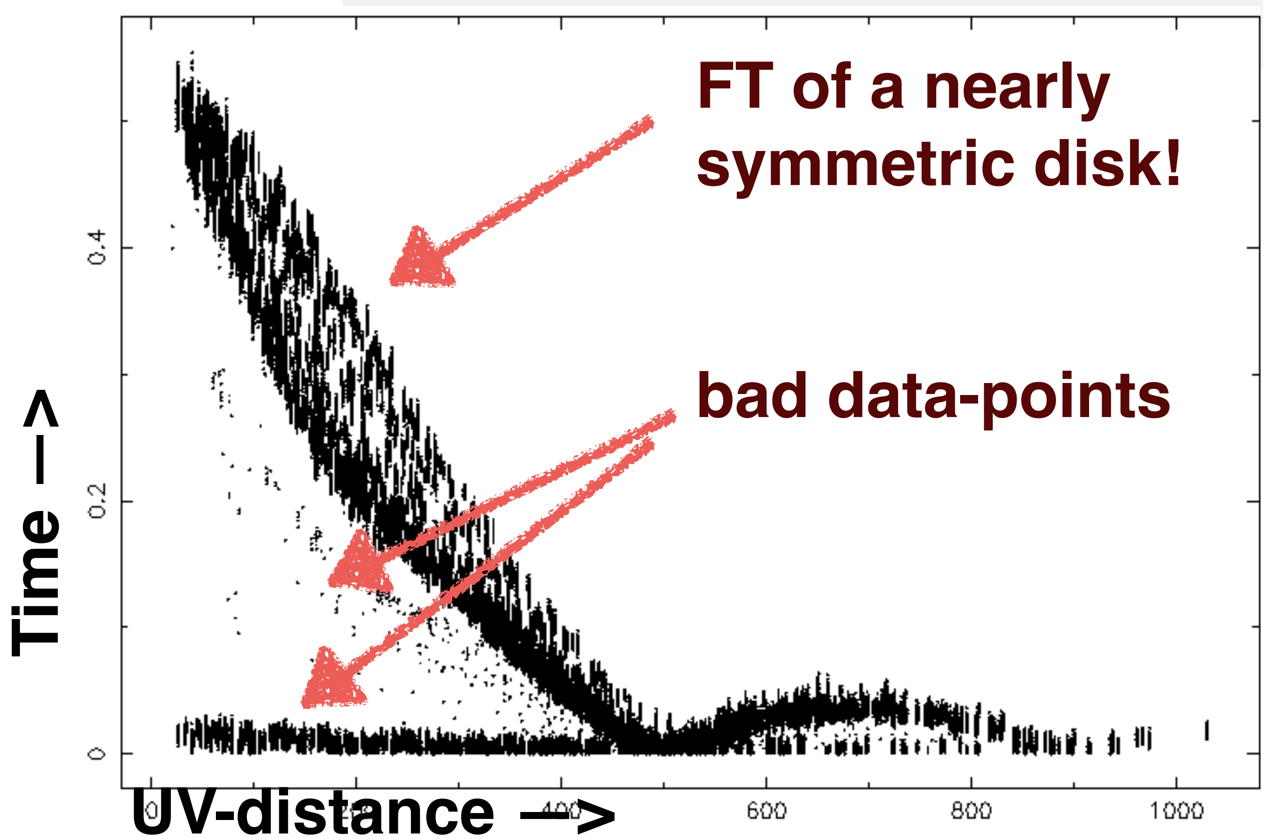
- Assuming that data have been edited and calibrated reasonably successfully.
  Self-calibration is often necessary at low frequencies!

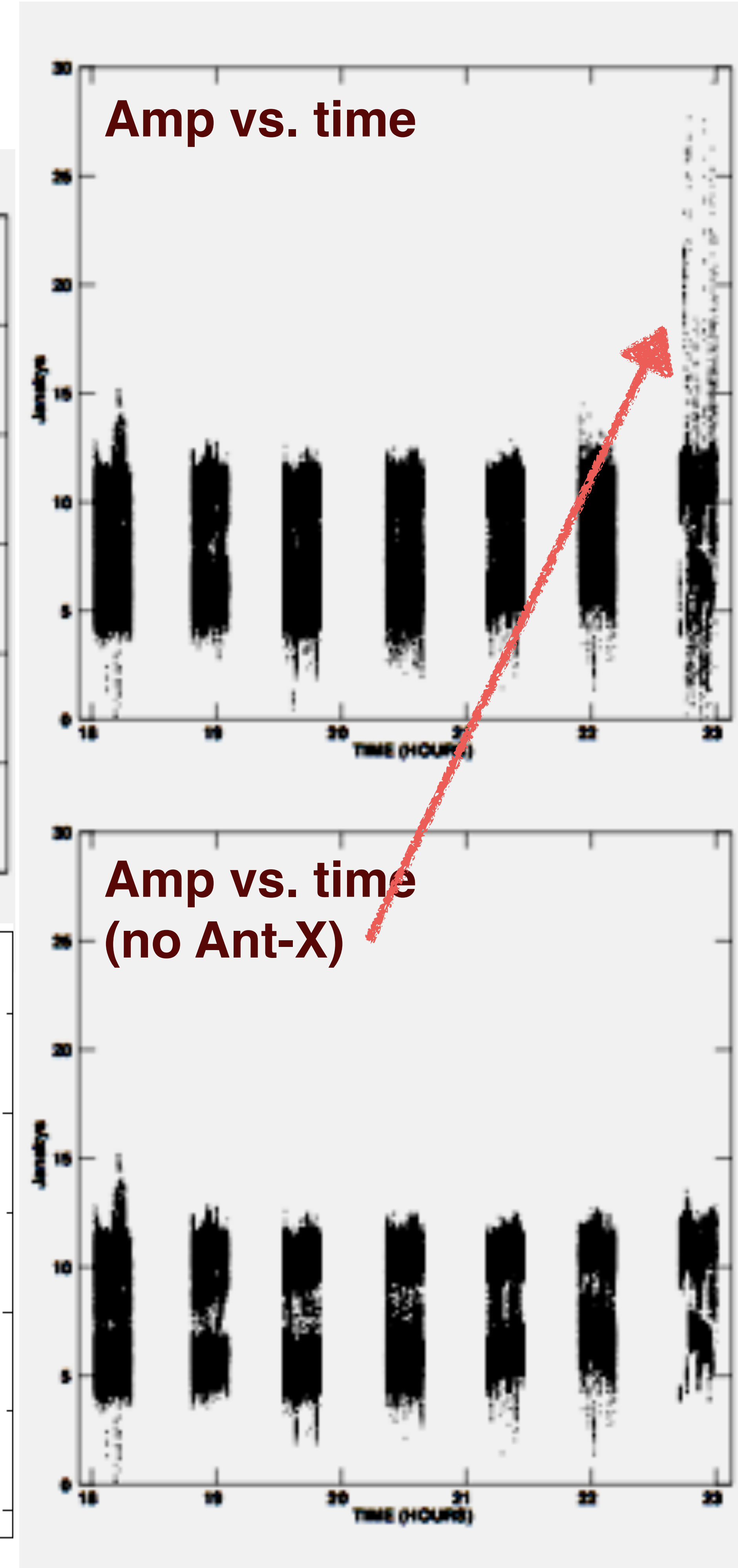
- So, the first serious display of an image leads one—
- to inspect again and clean-up the data repeating some or all reduction steps.
  - removal of one type of problem can reveal next problem!
- once all is well, proceed to image-analysis and obtain scientific results from the image.
- Errors obey Fourier transform relationship
  - Narrow feature in (u,v) plane <-> wide feature in image plane
  - Wide feature in (u,v) plane <-> narrow feature in image plane
    Note: easier to spot narrow features
  - Data (u,v) amplitude errors <-> symmetric image features
  - Data (u,v) phase errors <-> asymmetric image features
  - An obvious defect may be hardly visible in the transformed plane
  - A small, almost invisible defect may become very obvious in Fourier plane
- Editing obvious errors in the u-v plane
  - Mostly consistency checks assume that the visibility cannot change much over a small change in (u,v) spacing
  - Also, double-check gains and phases from calibration processes. These values should be relatively stable.

Editing bad data

Visibility amplitude plots



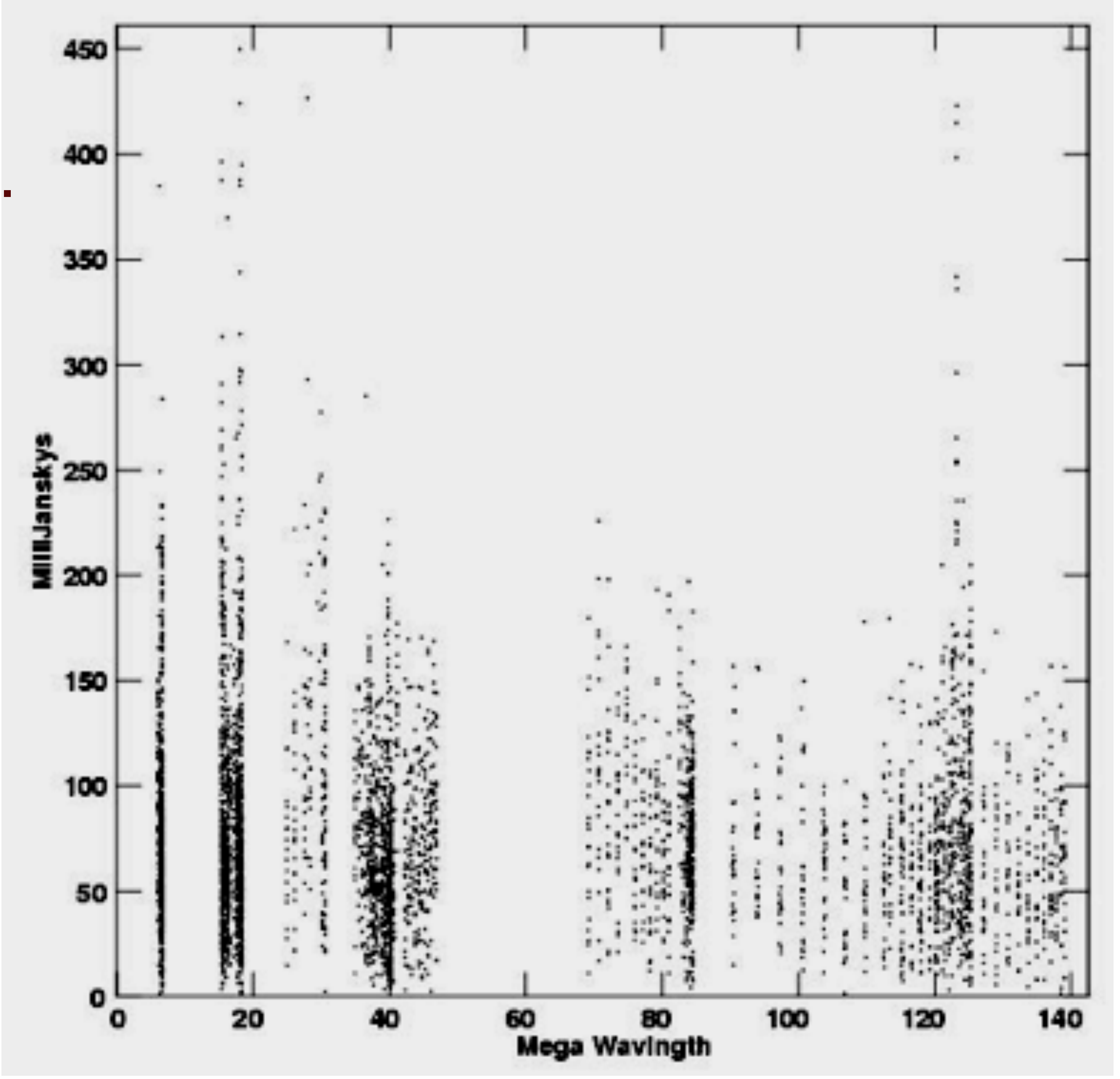




Editing bad / dead antenna

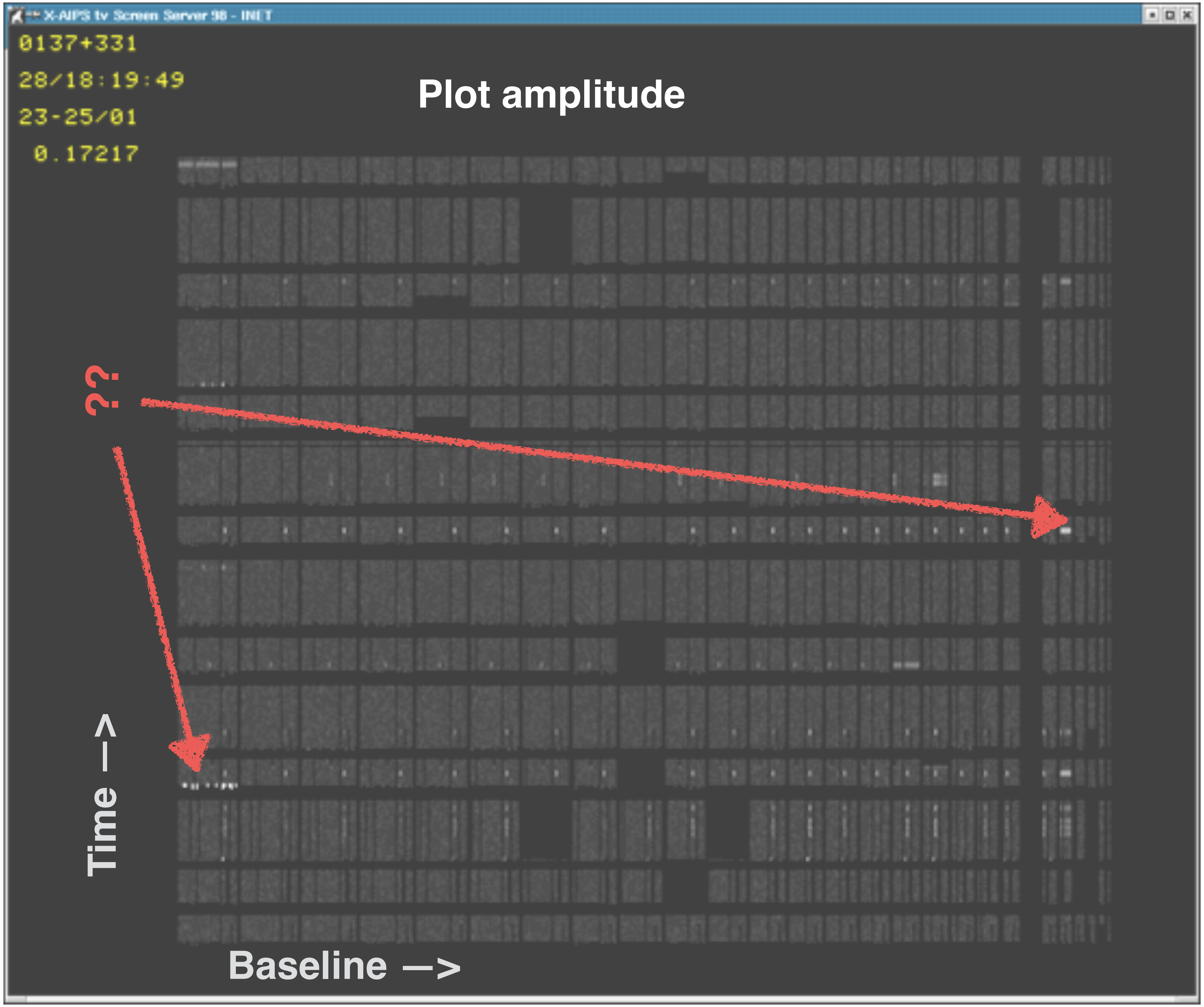
No source structure information is detected. Noise dominated!

All one can do is remove outlier points above a flux density threshold. Precise level not important as long as large outliers removed.



Editing bad / dead antenna

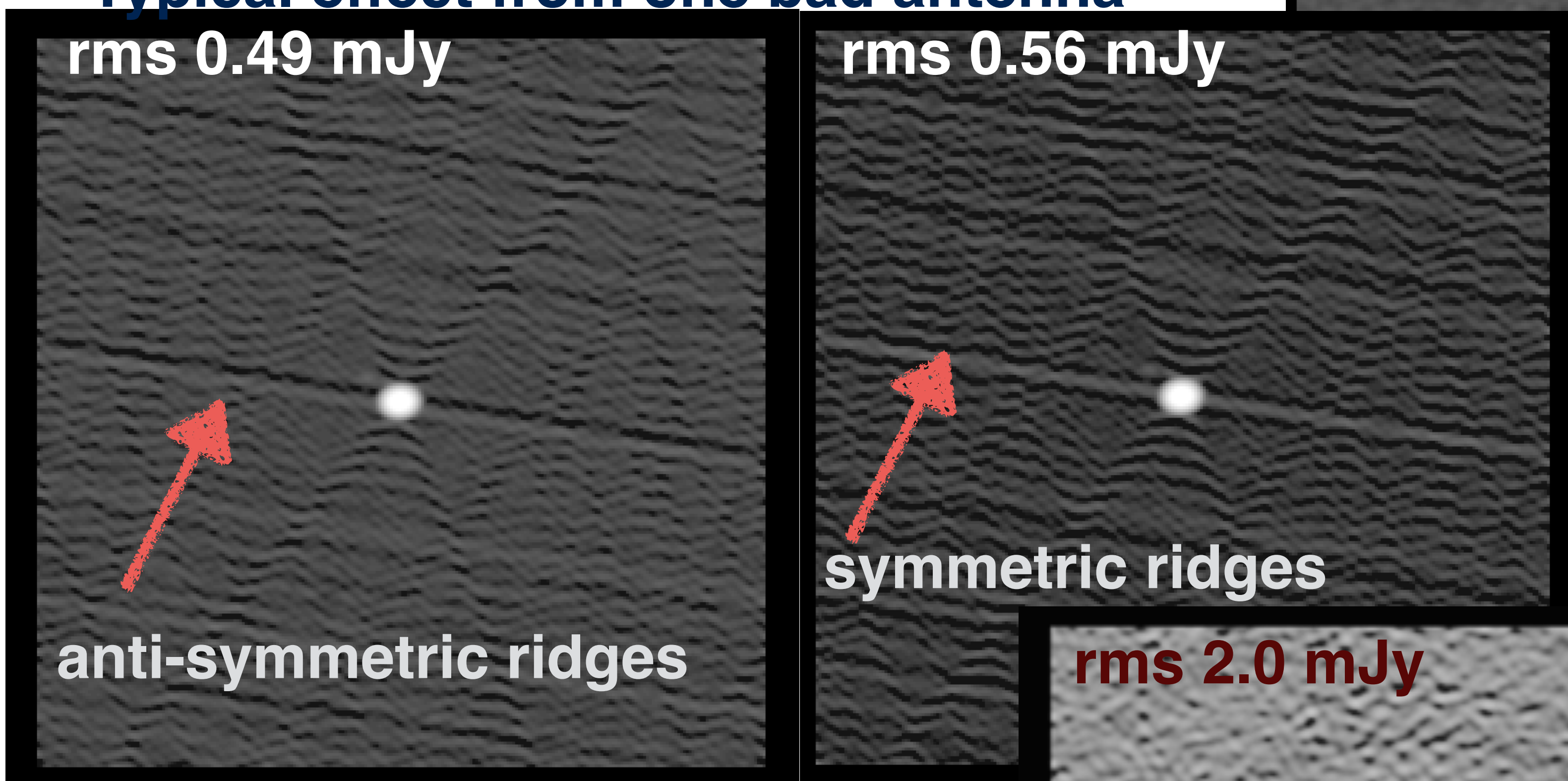
Antenna-X problem



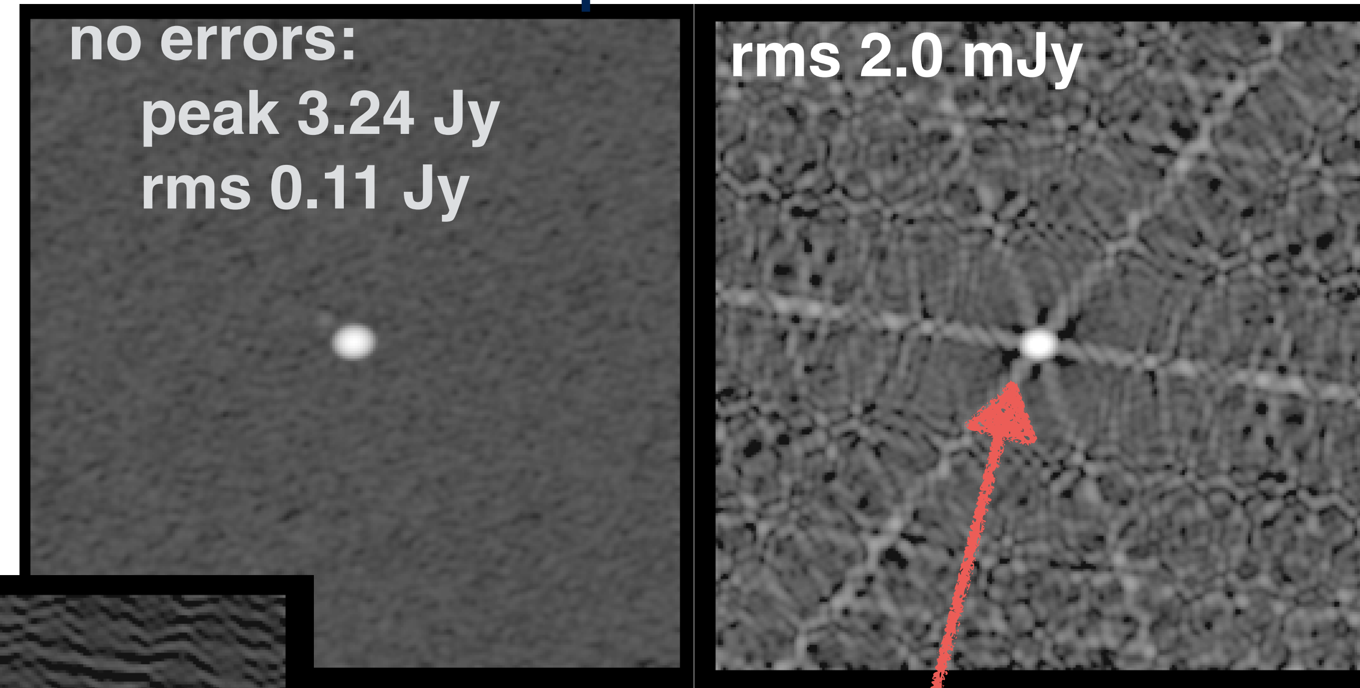
Editing bad data

10 deg phase error for
one antenna
20% amplitude error for
one antenna

Typical effect from one bad antenna



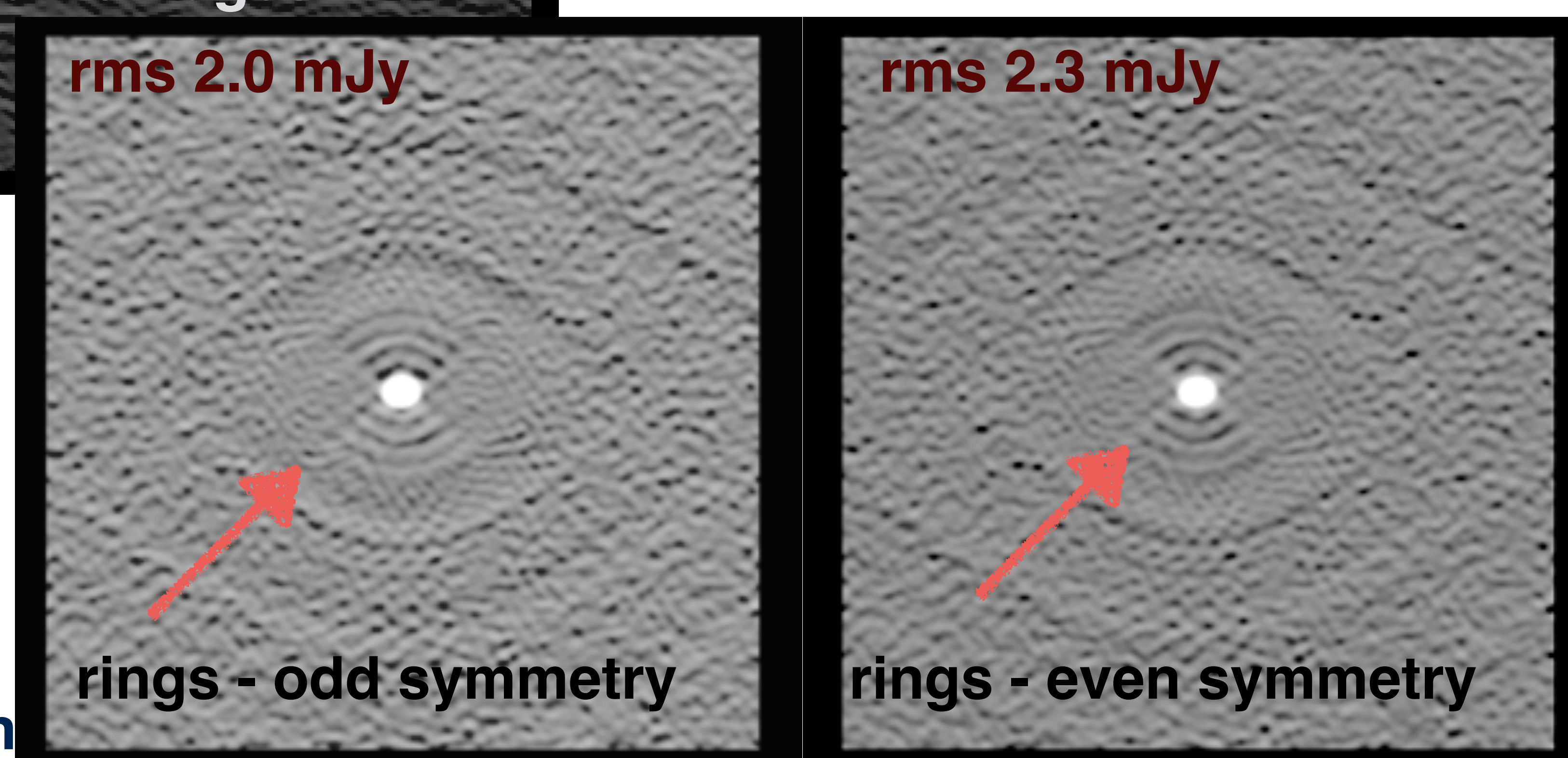
Bad data over short period of time



6-fold symmetric pattern due to
GMRT “Y”.
Image has properties of dirty beam
10% amp error for all antennas on
one scan

Note! 10 deg phase error
to 20% amplitude
errors cause similar
sized artefacts

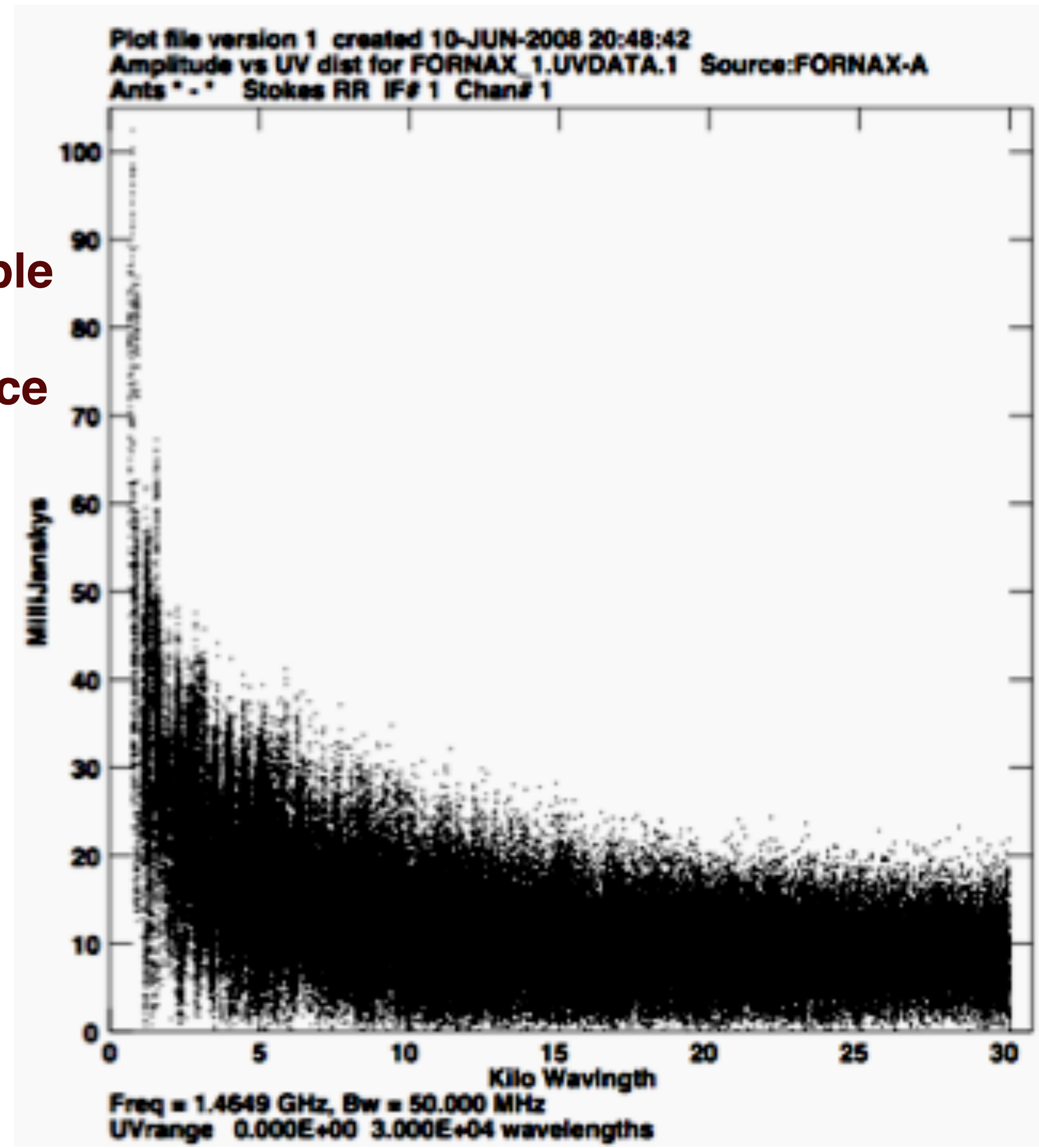
Persistent error over most of run



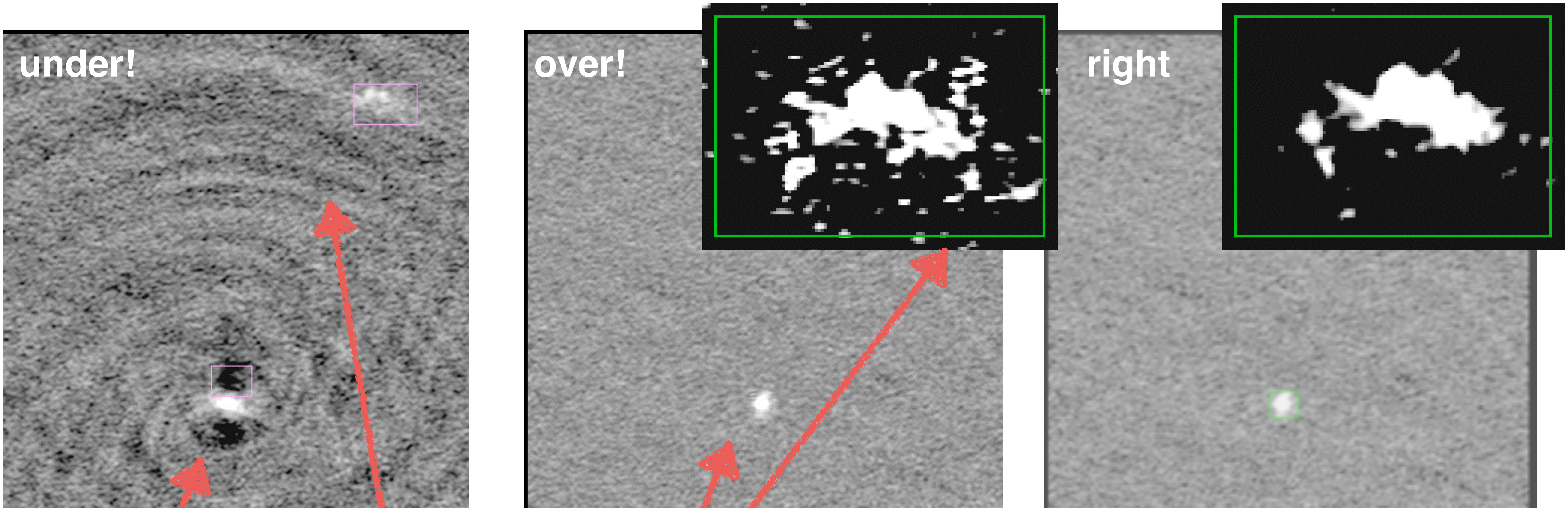
Deconvolution errors

Even if the data are perfect, image errors and uncertainties will occur because the (u-v) coverage is not adequate to map the source structure.

The extreme rise of visibility at the short spacings makes it impossible to image the extended structure. One is better of imaging the source with a cutoff below about 2 kilo-wavelengths.



Deconvolution errors - how deep to CLEAN?



Emission from a source sitting on top of a -ve bowl!

Regions within CLEAN boxes appear “mottled”

Background is thermal, noise-dominated; no “bowls” around source

Residual side-lobes dominate the noise

Finding hidden bad data …

Summary - Error recognition

- Obvious outlier data (u-v) points:
    - e.g. a 5% antenna gain calibration error is difficult to see in (u,v) data, but will produce a 1% effect in image with specific characteristics.
  - 100 bad points in 100,000 data points gives an 0.1% image error (unless the bad data points are 1 million Jy)
  - Look at the data to find gross problem in image plane -> hard!, other than a slight increase in noise
  - Non-Data Problems:
    - Perfect data but unstable algorithms. Common but difficult to discern!
- Editing obvious errors in the (u,v) plane
  - Mostly consistency checks assume that visibility cannot change much over a small change in (u,v) spacing,
- (U,V) data

  Look for outliers in (u,v) data using several plotting methods.
  Check calibration gains and phases for instabilities.
  Look at residual data - (u,v)-data - clean components.

IMAGE plane

  Do defects resemble the dirty beam?
  Are defect properties related to possible data errors?
  Are defects related to possible deconvolution problems?

Calibration and advanced radio interferometry

Thank you

- Issues pertaining to low-frequency interferometry
  - Advanced calibration techniques
    - typical observation
    - calibration
    - bandwidth smearing
    - time averaging smearing
    - primary beam attenuation
  - deconvolution - more algorithms
  - high dynamic range imaging

- Large field-of-view imaging

- Error recognition and image analysis
  - RFI
  - Bad / Dead antenna
  - Amplitude and phase-errors
  - Deconvolution errors

Acknowledgements

- NRAO Synthesis imaging school
- NCRA-TIFR RA school
- D. Oberoi / C.H. Ishwara-Chandra
- Mike Garrett
- ...