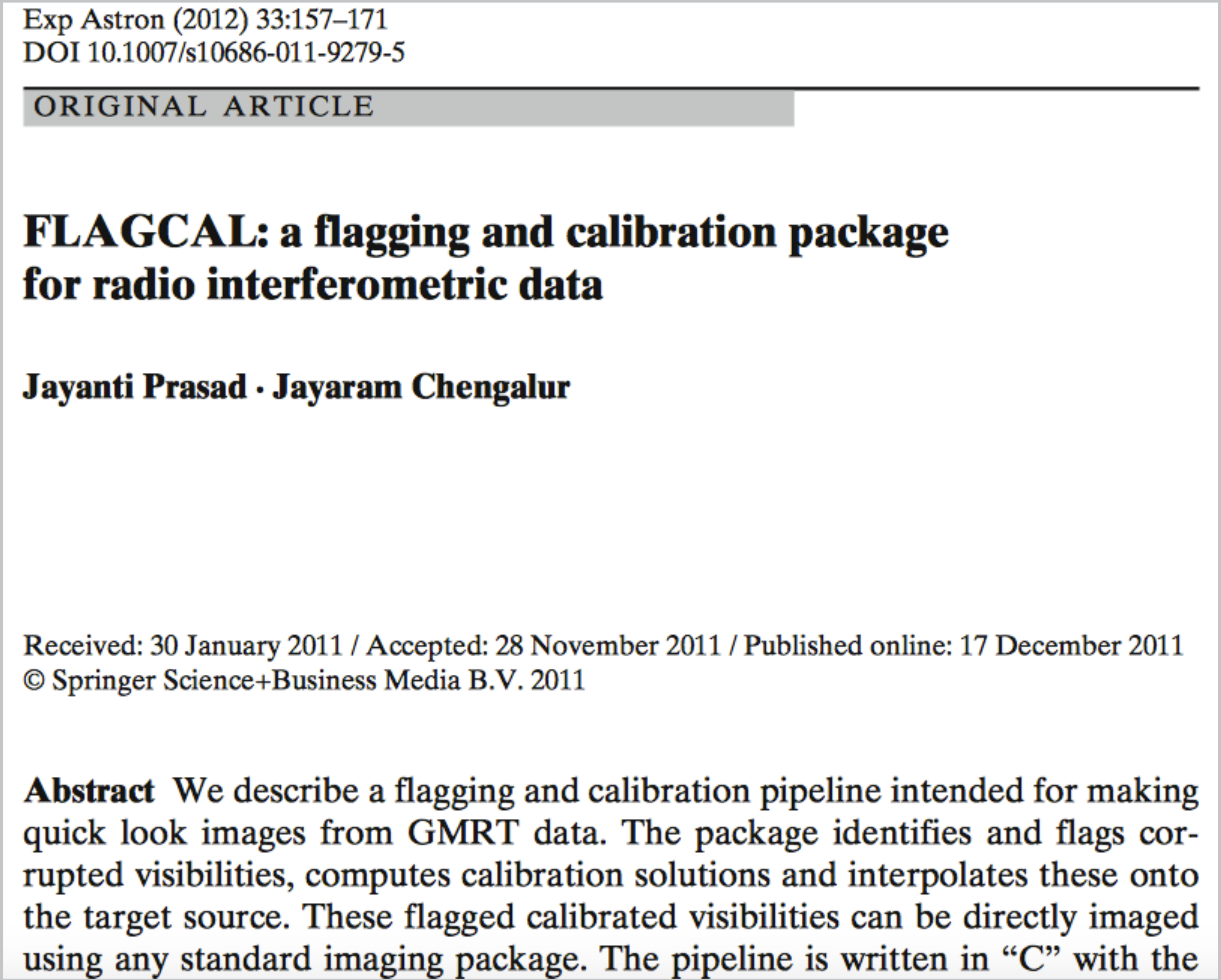
CALIBRATION I

DHARAM V. LAL

with inputs from

- NCRA-TIFR RA school
- NRAO Synthesis imaging school

CALIBRATION AND EDITING



Exp Astron (2012) 33:157–171
DOI 10.1007/s10686-011-9279-5

ORIGINAL ARTICLE

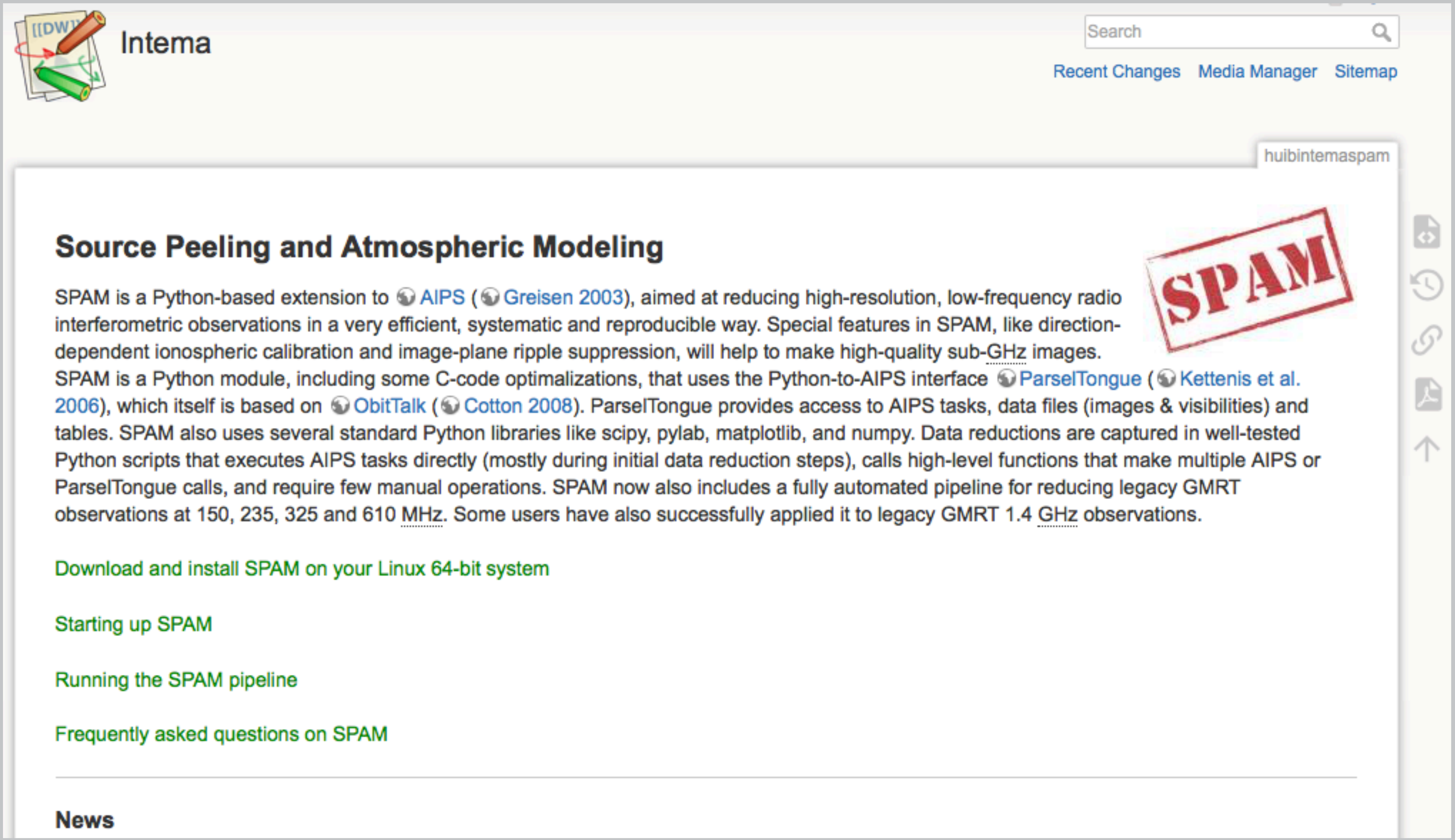
FLAGCAL: a flagging and calibration package for radio interferometric data

Jayanti Prasad · Jayaram Chengalur

Received: 30 January 2011 / Accepted: 28 November 2011 / Published online: 17 December 2011

Abstract We describe a flagging and calibration pipeline intended for making quick look images from GMRT data. The package identifies and flags corrupted visibilities, computes calibration solutions and interpolates these onto the target source. These flagged calibrated visibilities can be directly imaged using any standard imaging package. The pipeline is written in “C” with the

CALIBRATION AND EDITING AND IMAGING



Source Peeling and Atmospheric Modeling

SPAM is a Python-based extension to AIPS (Greisen 2003), aimed at reducing high-resolution, low-frequency radio interferometric observations in a very efficient, systematic and reproducible way. Special features in SPAM, like direction-dependent ionospheric calibration and image-plane ripple suppression, will help to make high-quality sub-GHz images. SPAM is a Python module, including some C-code optimalizations, that uses the Python-to-AIPS interface ParselTongue (Kettenis et al. 2006), which itself is based on ObitTalk (Cotton 2008). ParselTongue provides access to AIPS tasks, data files (images & visibilities) and tables. SPAM also uses several standard Python libraries like scipy, pylab, matplotlib, and numpy. Data reductions are captured in well-tested Python scripts that executes AIPS tasks directly (mostly during initial data reduction steps), calls high-level functions that make multiple AIPS or ParselTongue calls, and require few manual operations. SPAM now also includes a fully automated pipeline for reducing legacy GMRT observations at 150, 235, 325 and 610 MHz. Some users have also successfully applied it to legacy GMRT 1.4 GHz observations.

Download and install SPAM on your Linux 64-bit system

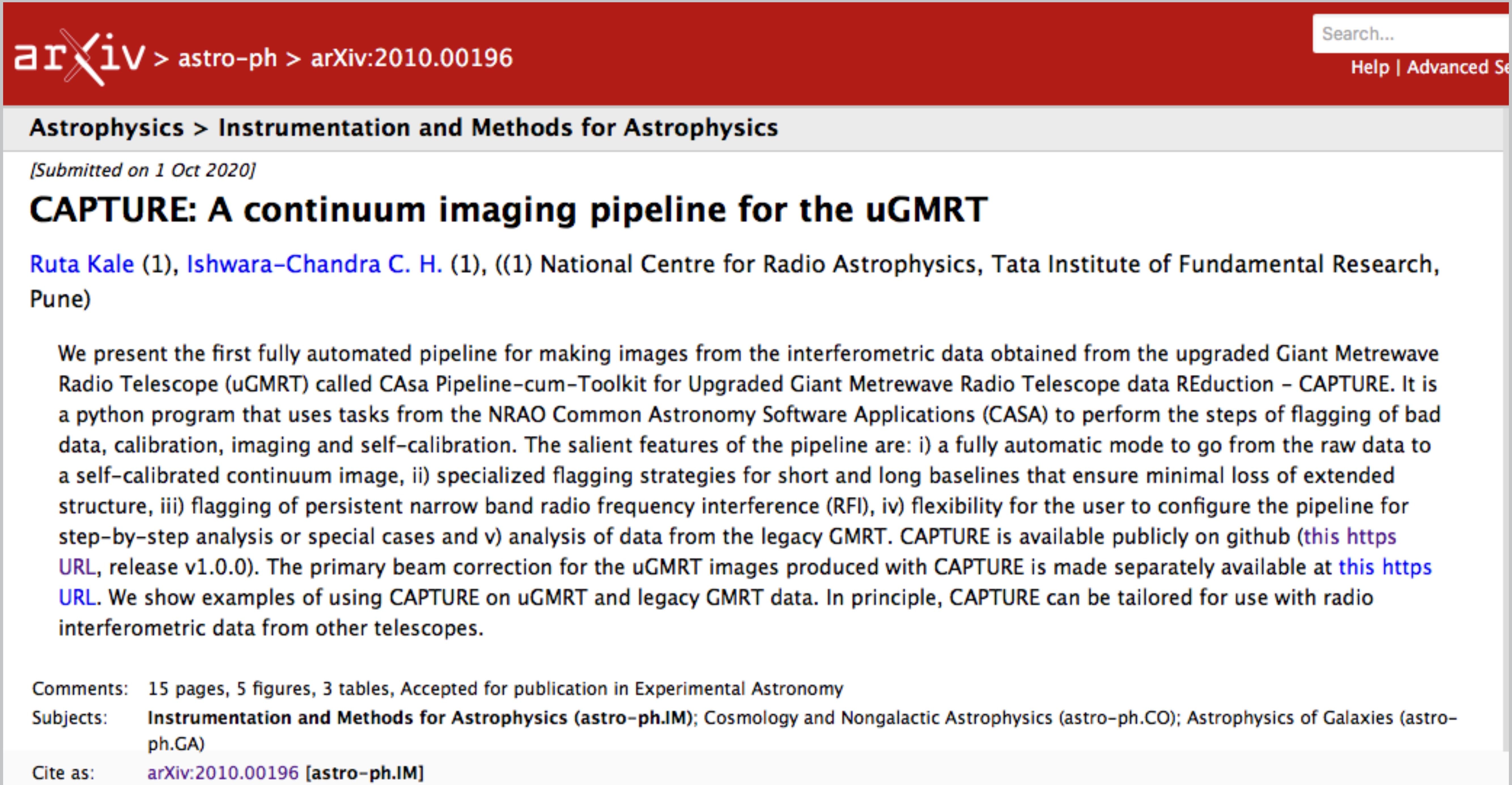
Starting up SPAM

Running the SPAM pipeline

Frequently asked questions on SPAM

News

CALIBRATION AND EDITING AND IMAGING



Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 1 Oct 2020]

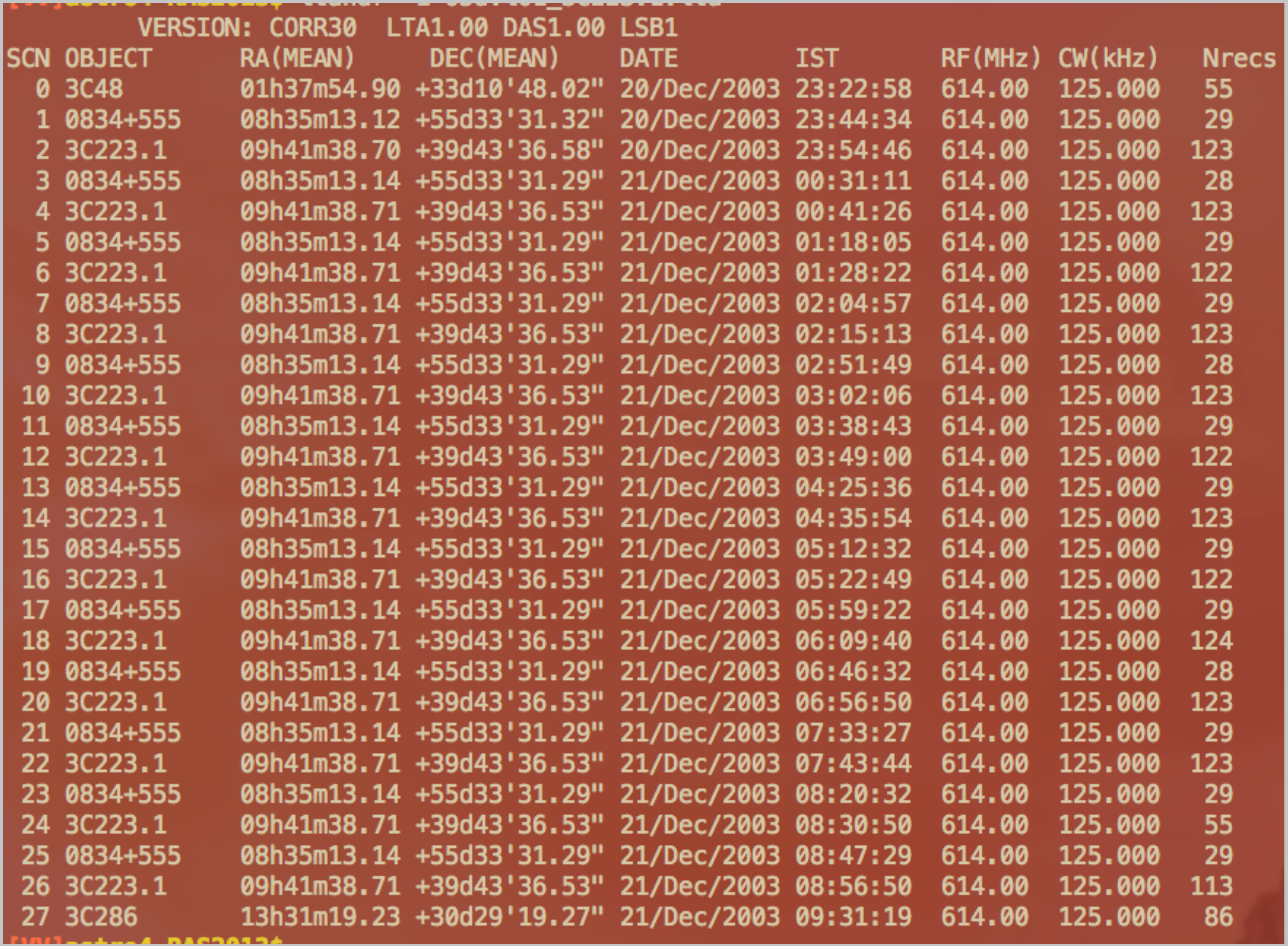
CAPTURE: A continuum imaging pipeline for the uGMRT

Ruta Kale (1), Ishwara-Chandra C. H. (1), ((1) National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune)

We present the first fully automated pipeline for making images from the interferometric data obtained from the upgraded Giant Metrewave Radio Telescope (uGMRT) called CAsa Pipeline-cum-Toolkit for Upgraded Giant Metrewave Radio Telescope data REduction - CAPTURE. It is a python program that uses tasks from the NRAO Common Astronomy Software Applications (CASA) to perform the steps of flagging of bad data, calibration, imaging and self-calibration. The salient features of the pipeline are: i) a fully automatic mode to go from the raw data to a self-calibrated continuum image, ii) specialized flagging strategies for short and long baselines that ensure minimal loss of extended structure, iii) flagging of persistent narrow band radio frequency interference (RFI), iv) flexibility for the user to configure the pipeline for step-by-step analysis or special cases and v) analysis of data from the legacy GMRT. CAPTURE is available publicly on github (this https URL, release v1.0.0). The primary beam correction for the uGMRT images produced with CAPTURE is made separately available at this https URL. We show examples of using CAPTURE on uGMRT and legacy GMRT data. In principle, CAPTURE can be tailored for use with radio interferometric data from other telescopes.

Comments: 15 pages, 5 figures, 3 tables, Accepted for publication in Experimental Astronomy
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); Astrophysics of Galaxies (astro-ph.GA)
Cite as: arXiv:2010.00196 **[astro-ph.IM]**

TYPICAL GMRT OBSERVATION



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  0 3C48            01h37m54.90 +33d10'48.02" 20/Dec/2003 23:22:58  614.00  125.000    55
  1 0834+555        08h35m13.12 +55d33'31.32" 20/Dec/2003 23:44:34  614.00  125.000    29
  2 3C223.1         09h41m38.70 +39d43'36.58" 20/Dec/2003 23:54:46  614.00  125.000   123
  3 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 00:31:11  614.00  125.000    28
  4 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 00:41:26  614.00  125.000   123
  5 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 01:18:05  614.00  125.000    29
  6 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 01:28:22  614.00  125.000   122
  7 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 02:04:57  614.00  125.000    29
  8 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 02:15:13  614.00  125.000   123
  9 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 02:51:49  614.00  125.000    28
 10 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 03:02:06  614.00  125.000   123
 11 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 03:38:43  614.00  125.000    29
 12 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 03:49:00  614.00  125.000   122
 13 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 04:25:36  614.00  125.000    29
 14 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 04:35:54  614.00  125.000   123
 15 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 05:12:32  614.00  125.000    29
 16 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 05:22:49  614.00  125.000   122
 17 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 05:59:22  614.00  125.000    29
 18 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 06:09:40  614.00  125.000   124
 19 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 06:46:32  614.00  125.000    28
 20 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 06:56:50  614.00  125.000   123
 21 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 07:33:27  614.00  125.000    29
 22 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 07:43:44  614.00  125.000   123
 23 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 08:20:32  614.00  125.000    29
 24 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 08:30:50  614.00  125.000    55
 25 0834+555        08h35m13.14 +55d33'31.29" 21/Dec/2003 08:47:29  614.00  125.000    29
 26 3C223.1         09h41m38.71 +39d43'36.53" 21/Dec/2003 08:56:50  614.00  125.000   113
 27 3C286           13h31m19.23 +30d29'19.27" 21/Dec/2003 09:31:19  614.00  125.000    86
[VV]astro4 RAS2013$
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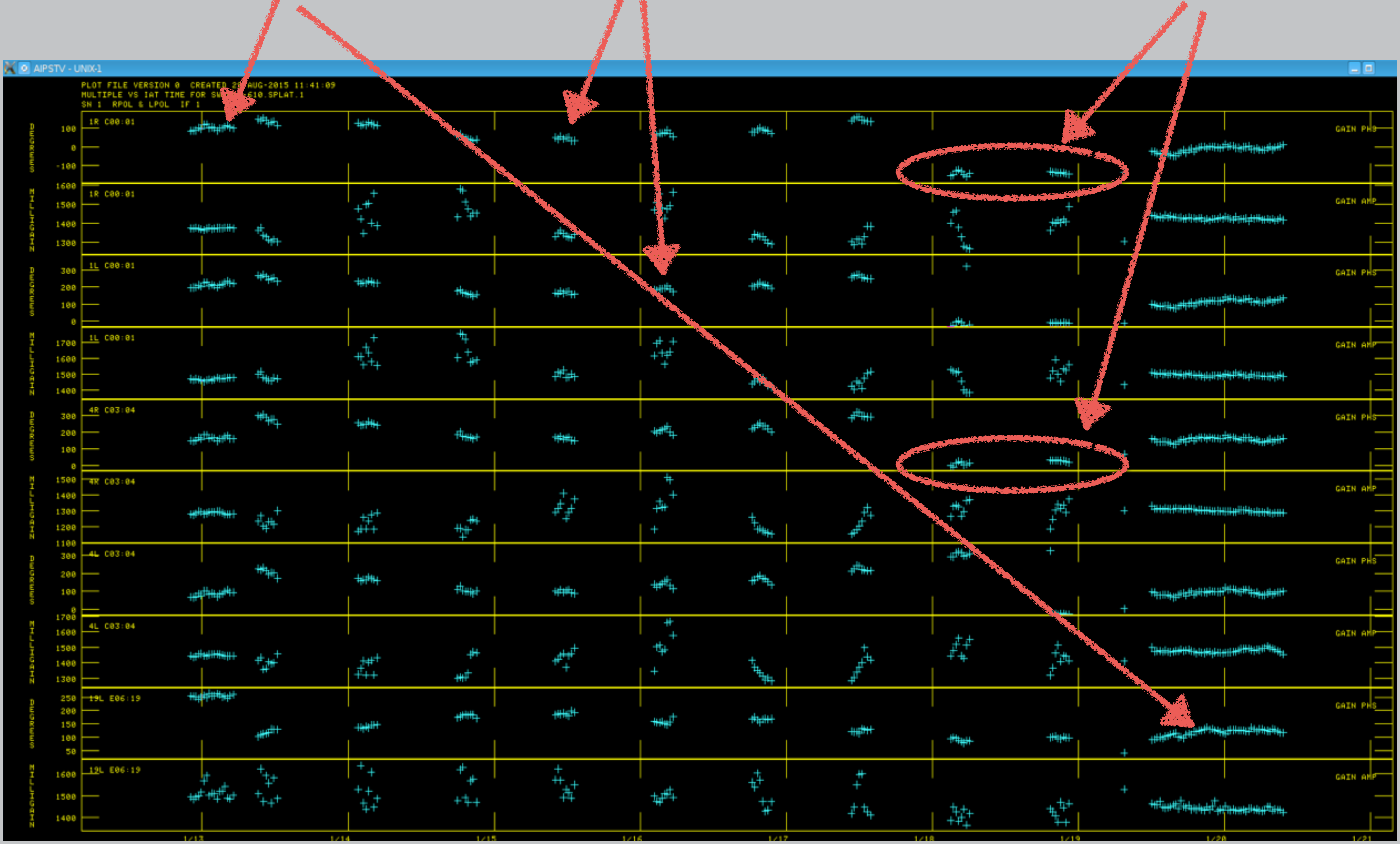
TYPICAL GMRT OBSERVATION



Flux density calibrator scans

Phase calibrator scans

??

WHAT IS DELIVERED BY, SAY, GMRT?

- An enormous list of complex visibilities!
  - at each time-stamp,
  - 435 baselines
    - for each baseline, upto 16k spectral channels
      - for each channel, 2 or 4 complex correlations (polarisations)
        - RR, RL, LR and LL
- Additional info:
  - antenna configuration, frequency label info

- $\mathrm{vis}_{\mathrm{total}} = N_{\mathrm{bl}} \times N_r \times N_f \times N_{\mathrm{corr}} \times ??$

VISIBILITY: TRUE VS. OBSERVED PLUS "??"

- A comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy.
- Calibration is the effort to measure and remove the time-dependent and frequency-dependent atmospheric and instrumental variations.
- recover "true" value

$$V'(u,v) = S(u,v)V(u,v)$$

sampled visibility

sampling function

true visibility

baseline based complex gain

baseline based complex offset

complex noise

$$\tilde{V}_{ij}(t) = G_{ij}(t)V'_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t)$$

where $G_{ij}(t) = g_i(t)g_j^\star(t)$

VISIBILITY: TRUE VS. OBSERVED

- A comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy.

$$V'(u,v) = S(u,v)V(u,v)$$

- Calibratio
measure a
time-depe
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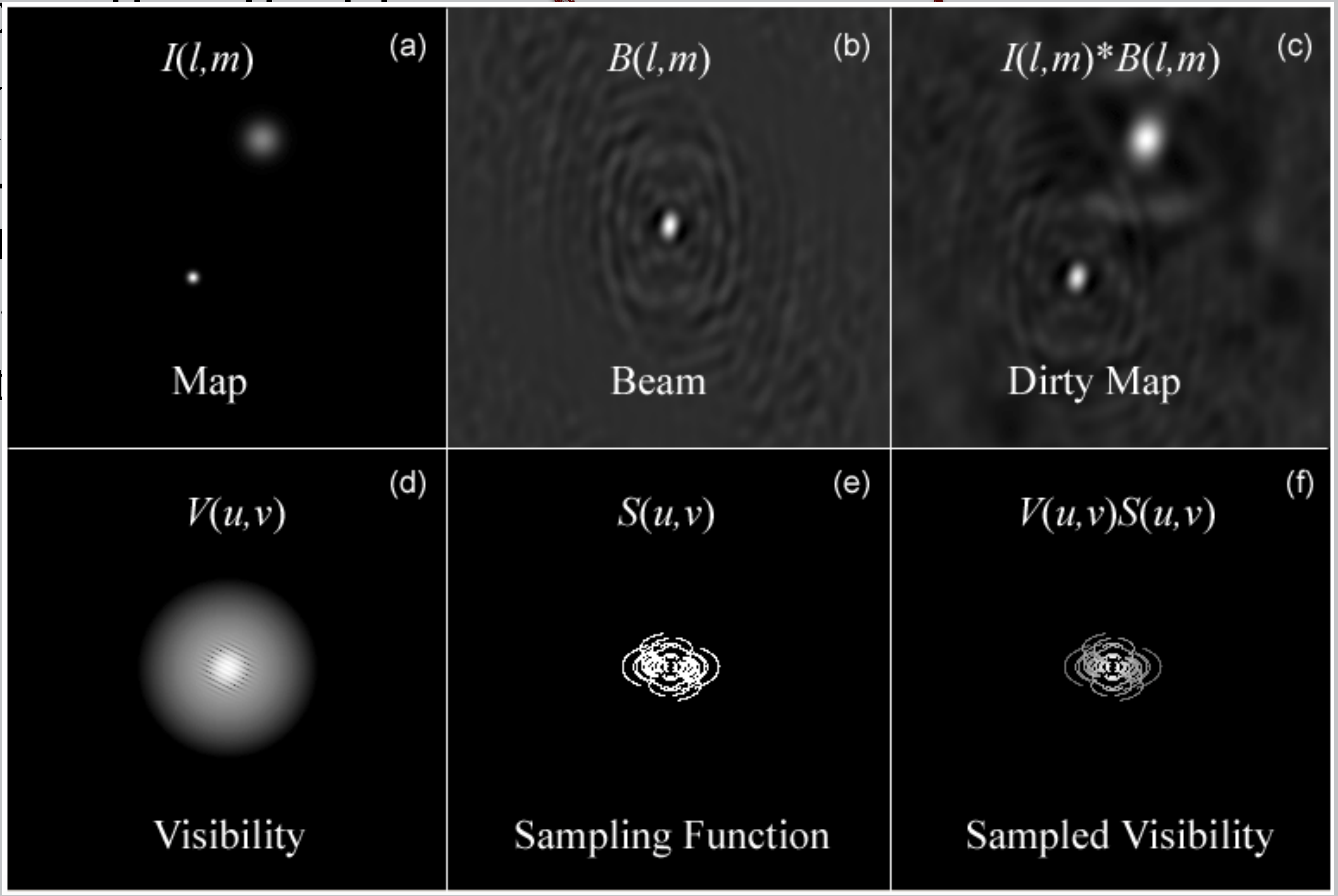
atmospher
variations.
- recover “tr



CALIBRATION METHODS

- Calibration sources in the sky: An interferometer measures phase differences, so there is no absolute phase reference. To determine antenna phase-offsets observations of a sky calibrator are required.
  - Further the array is not completely phase- or gain-stable, periodic observations of calibrators are used to monitor these changes. Next, the atmosphere will cause time-variable phase changes to occur in the data (mimicking the effect of unstable electronics), and observations of a calibrator sources are often made in an attempt to remove this effect.

- Self-calibration: The source being observed can be used as a test signal to calibrate the instrument.

GAIN: TIME AND FREQUENCY

- **sampled visibility** $V'(u,v) = S(u,v)V(u,v)$

sampling function

true visibility

- $\tilde{V}_{ij}(t) = G_{ij}(t)V'_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t)$

baseline based complex offset

complex noise

- $G_{ij}(t) = g_i(t)g_j^{\star}(t)$

baseline based complex gain

total gain on baseline i-j

- $G_{ij}(\nu,t) = G'_{ij}(t)B_{ij}(\nu,t)$

frequency dependent part of the gain

- $B_{ij}(\nu,t) \approx b_i(\nu,t)b_j^{\star}(\nu,t)$

(splitting the time and frequency dependence of the gain)

GAIN: TIME AND FREQUENCY

- Splitting the Time and Frequency dependence of the Gain
  - for large no. of antennas this improves the accuracy of the complex Gains considerably, as one uses
  - $\frac{1}{2} \times N_{\text{ant}}(N_{\text{ant}} - 1)$ baselines to derive N complex Gains.

time variable based continuum gain

- $G_{ij}(\nu \,.\, t) = G'_{ij}(t) B_{ij}(\nu, t)$

frequency dependent complex gain

- $B_{ij}(\nu, t) \approx b_i(\nu, t) b_j^{\star}(\nu, t)$

CALIBRATING GAIN: TIME

- sampled visibility $V'(u, v) = S(u, v)V(u, v)$

sampling function

true visibility

- $\tilde{V}_{ij}(t) = G_{ij}(t)V'_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t)$

baseline based complex offset

complex noise

- $G_{ij}(t) = g_i(t)g_j^{\star}(t)$

baseline based complex gain

- $G_{ij}(t) = g_i(t)g_j^{\star}(t) = a_i(t)a_j(t)e^{i(\phi_i(t)-\phi_j(t))}$

antenna based phase correction

antenna based amplitude correction

- $B_{ij}(\nu, t) \approx b_i(\nu, t)b_j^{\star}(\nu, t)$

frequency dependent complex gain

CALIBRATING GAIN: TIME

- The estimation of the Gain is the observed complex visibility of the calibrator, divided by its flux density.
  - assuming offset term / noise are negligible
- $G_{ij}(t) = g_i(t)g_j^\star(t) = a_i(t)a_j(t)e^{i(\phi_i(t)-\phi_j(t))}$
- $G_{ij}(t) = A_{ij}(t)e^{i\Phi_{ij}(t)}$
  - $A_{ij}(t) = a_i(t)a_j(t)$
  - $\Phi_{ij}(t) = \phi_i(t) - \phi_j(t)$
  - these terms can be easily solved for all N antennas!

GAIN: TIME AND FREQUENCY

- Splitting the Time and Frequency dependence of the Gain
  - for large no. of antennas this improves the accuracy of the complex Gains considerably, as one uses
  - $\frac{1}{2} \times N_{\text{ant}}(N_{\text{ant}} - 1)$ baselines to derive N complex Gains.

time variable based continuum gain

- $G_{ij}(\nu\, .\, t) = G'_{ij}(t) B_{ij}(\nu, t)$
- $B_{ij}(\nu, t) \approx b_i(\nu, t) b_j^{\star}(\nu, t)$

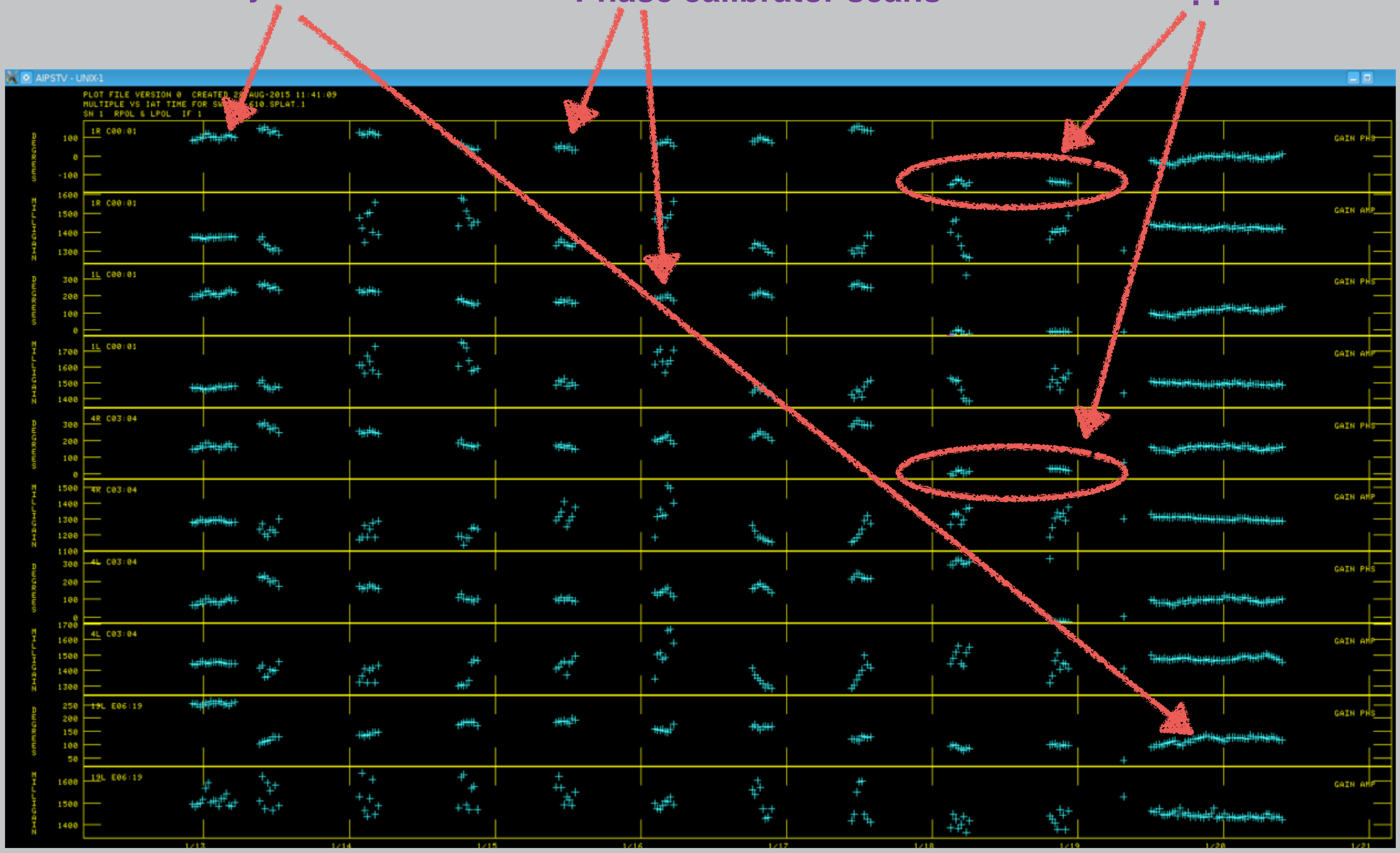
frequency dependent complex gain

TYPICAL GMRT OBSERVATION

Flux density calibrator scans

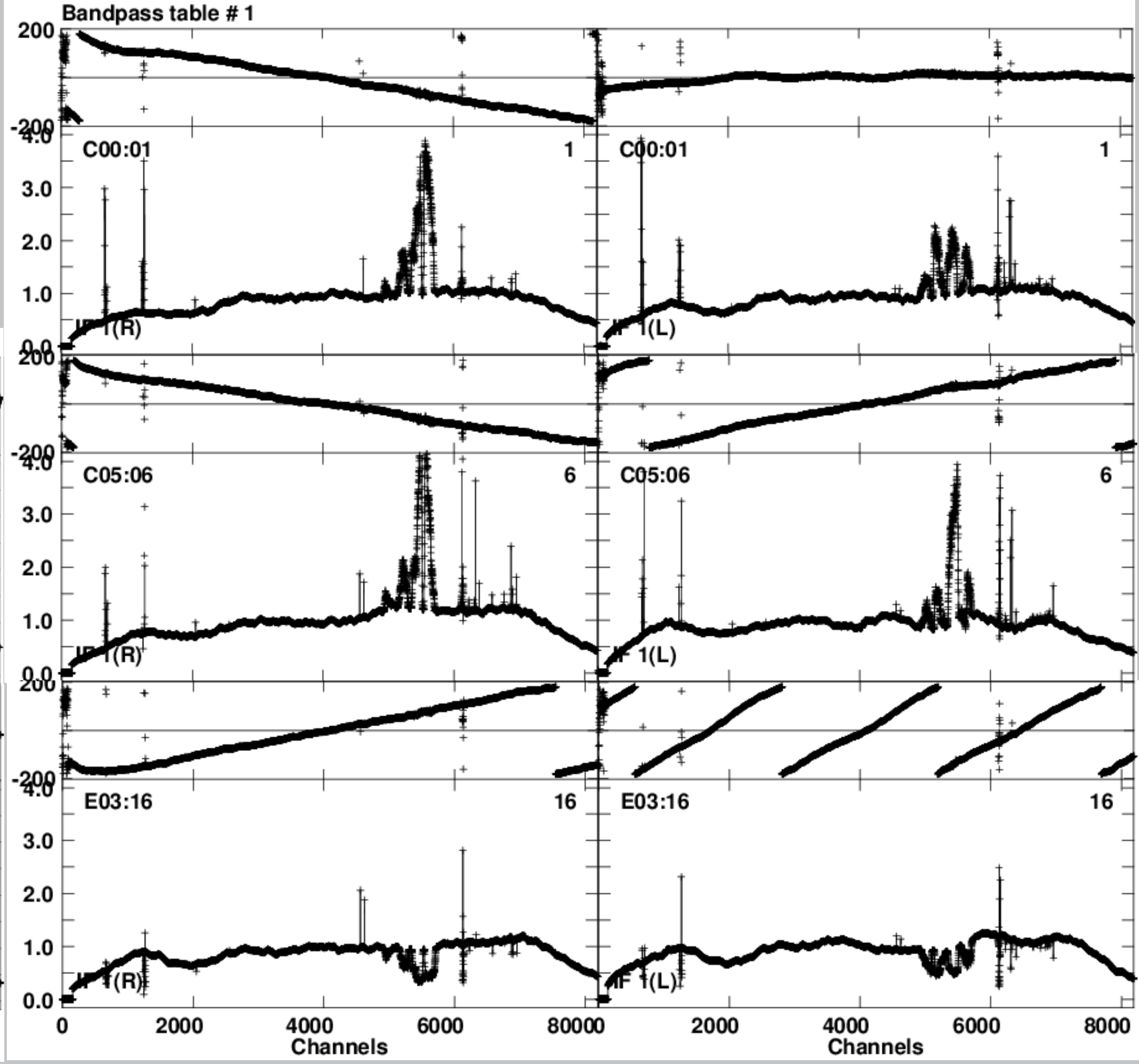
Phase calibrator scans

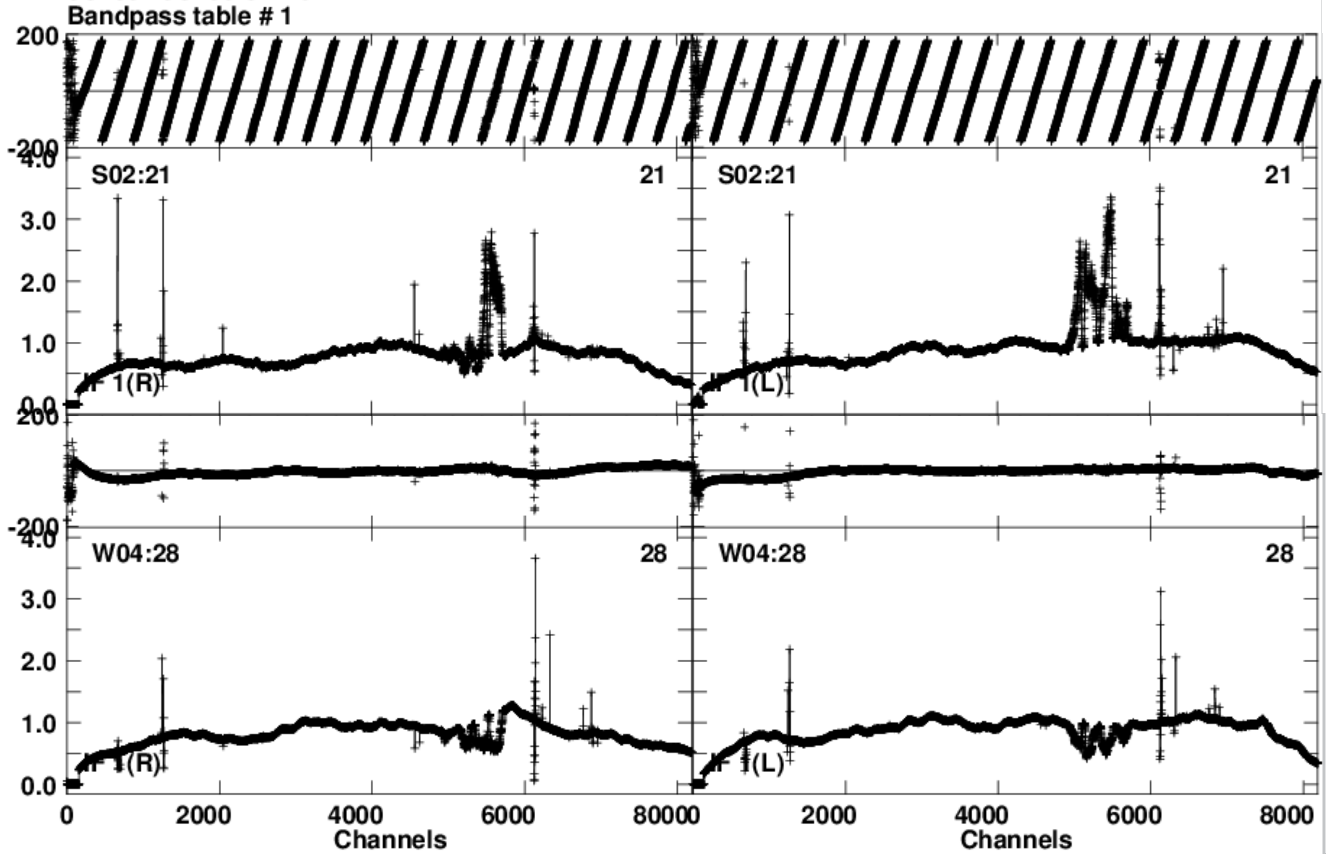
??



CALIBRATING GAIN: FREQUENCY

- Bandpass calibrator as a function of frequency/channel





CALIBRATION (RECAPITULATE)

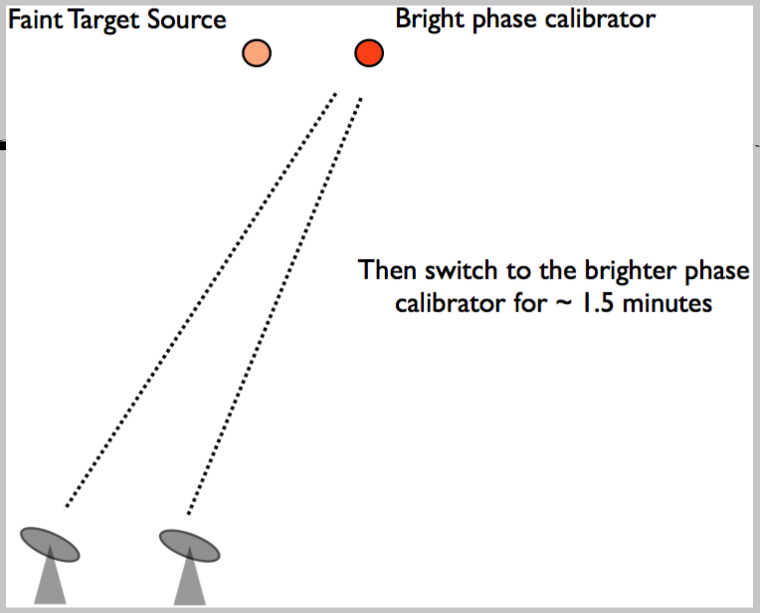
- $V'(u,v) = S(u,v)V(u,v)$
- $\tilde{V}_{ij}(t) = G_{ij}(t)V'_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t)$
- $G_{ij}(t) = g_i(t)g_j^{\star}(t)$
- $G_{ij}(\nu,t) = G'_{ij}(t)B_{ij}(\nu,t)$
- $B_{ij}(\nu,t) \approx b_i(\nu,t)b_j^{\star}(\nu,t)$

PHASE REFERENCING:

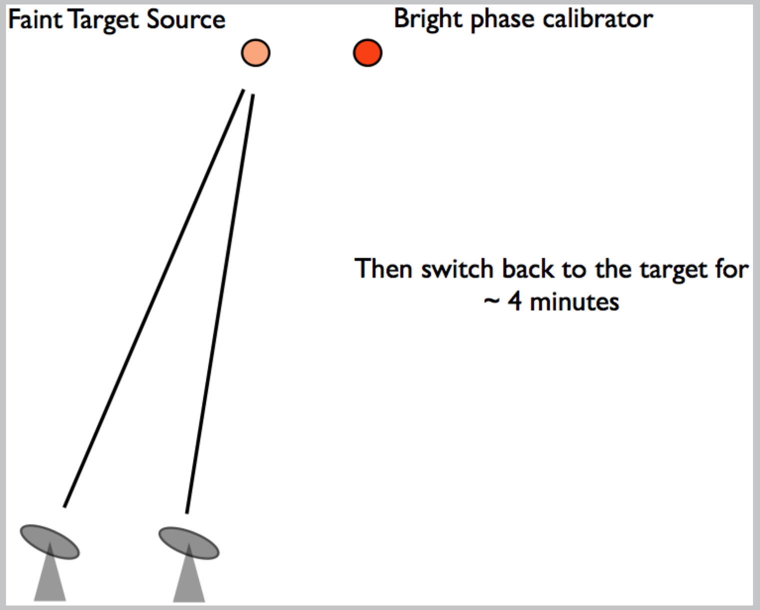
- So the idea is to take the telescope corrections (amplitude and phase) determined from calibrating the bright calibrator, and apply them to the faint target.
- The basic assumption is that for sources (both calibrator and target) located in roughly the same region of sky, corrections for one (calibrator)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

PHASE REFERENCING:

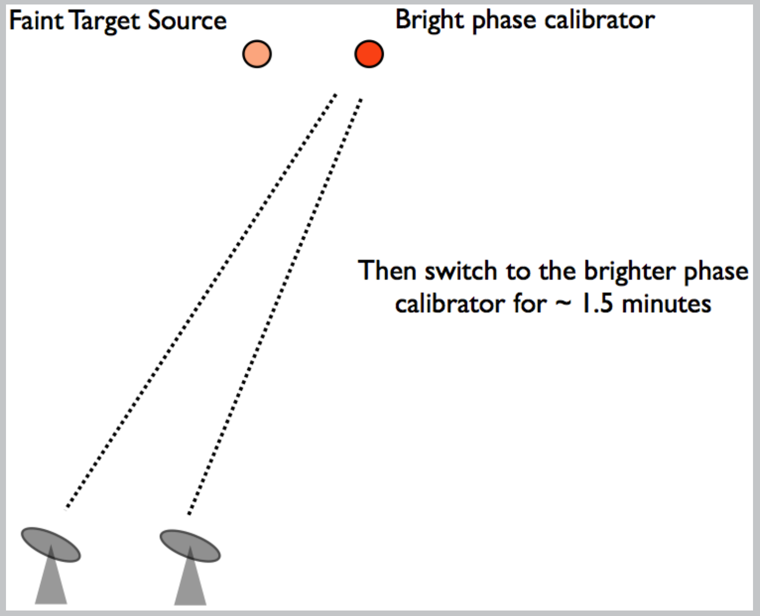
- The telescope corrections determined for the bright calibrator are applied to the target source data.
  - Phase reference observations specify a “cycle time” (= time on target + time on calibrator).
  - Cycle times ~30-8 mins to ~4-1.5 are common at m-cm wavelengths, but at much higher frequencies cycle times of 0.5 mins are sometime employed.
    - For short cycle times, the telescopes must be fast movers.



Then switch to the brighter phase calibrator for ~ 1.5 minutes



Then switch back to the target for ~ 4 minutes



Then switch to the brighter phase calibrator for ~ 1.5 minutes

PHASE REFEREN

- So the idea is to take t
(amplitude and phas
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- The basic assumptio
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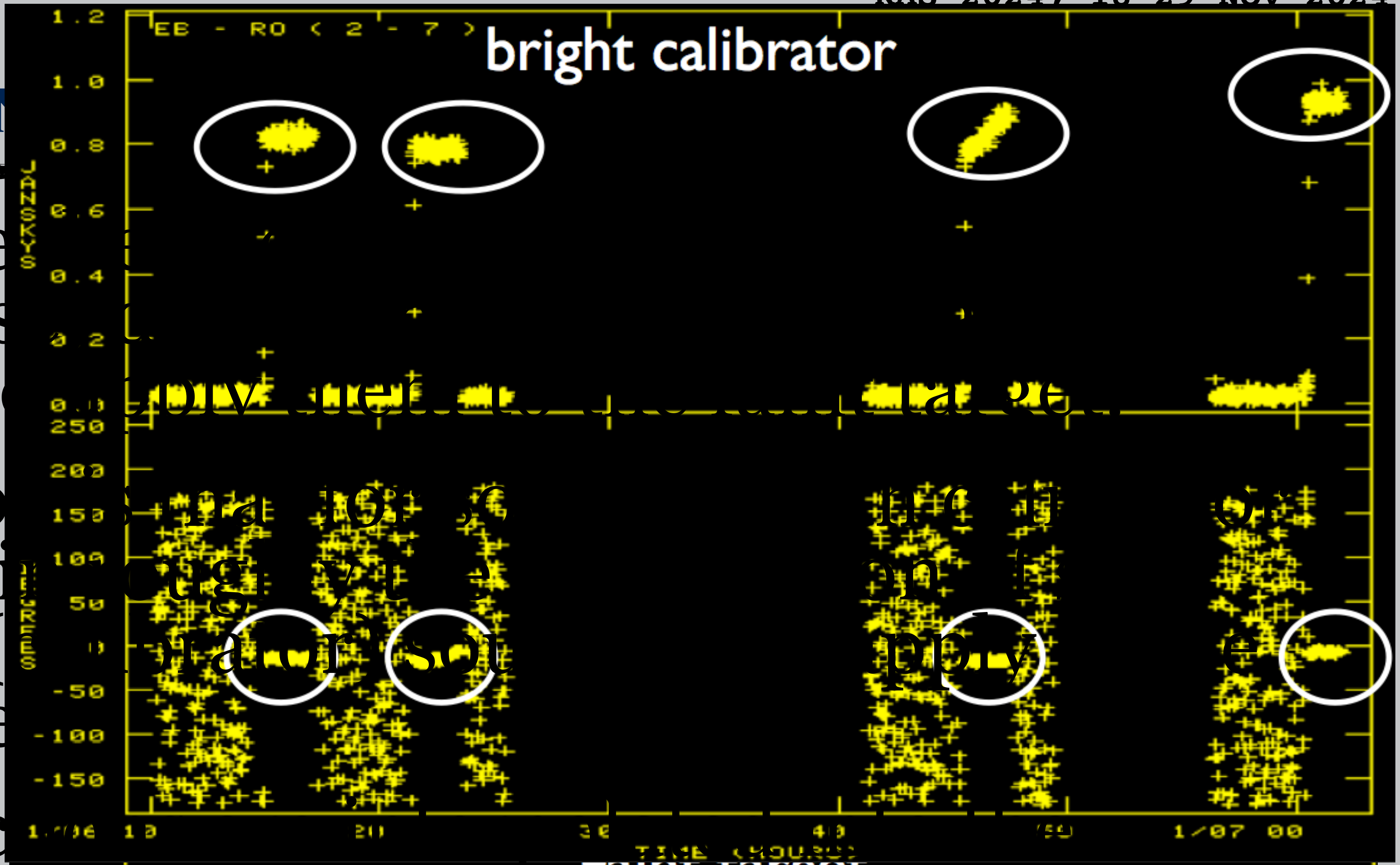
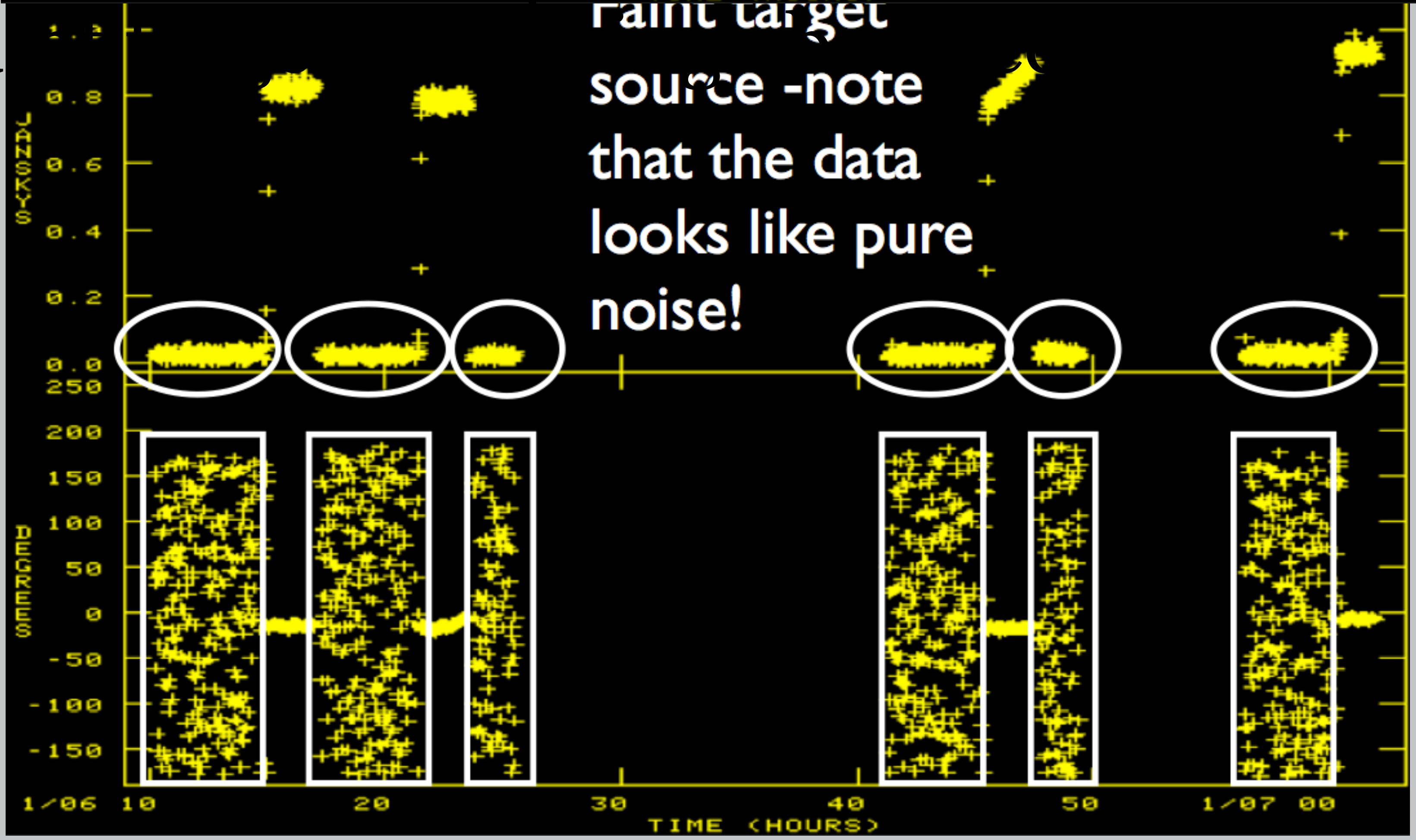
other (target) source
- The telescope correc
periods where the fa



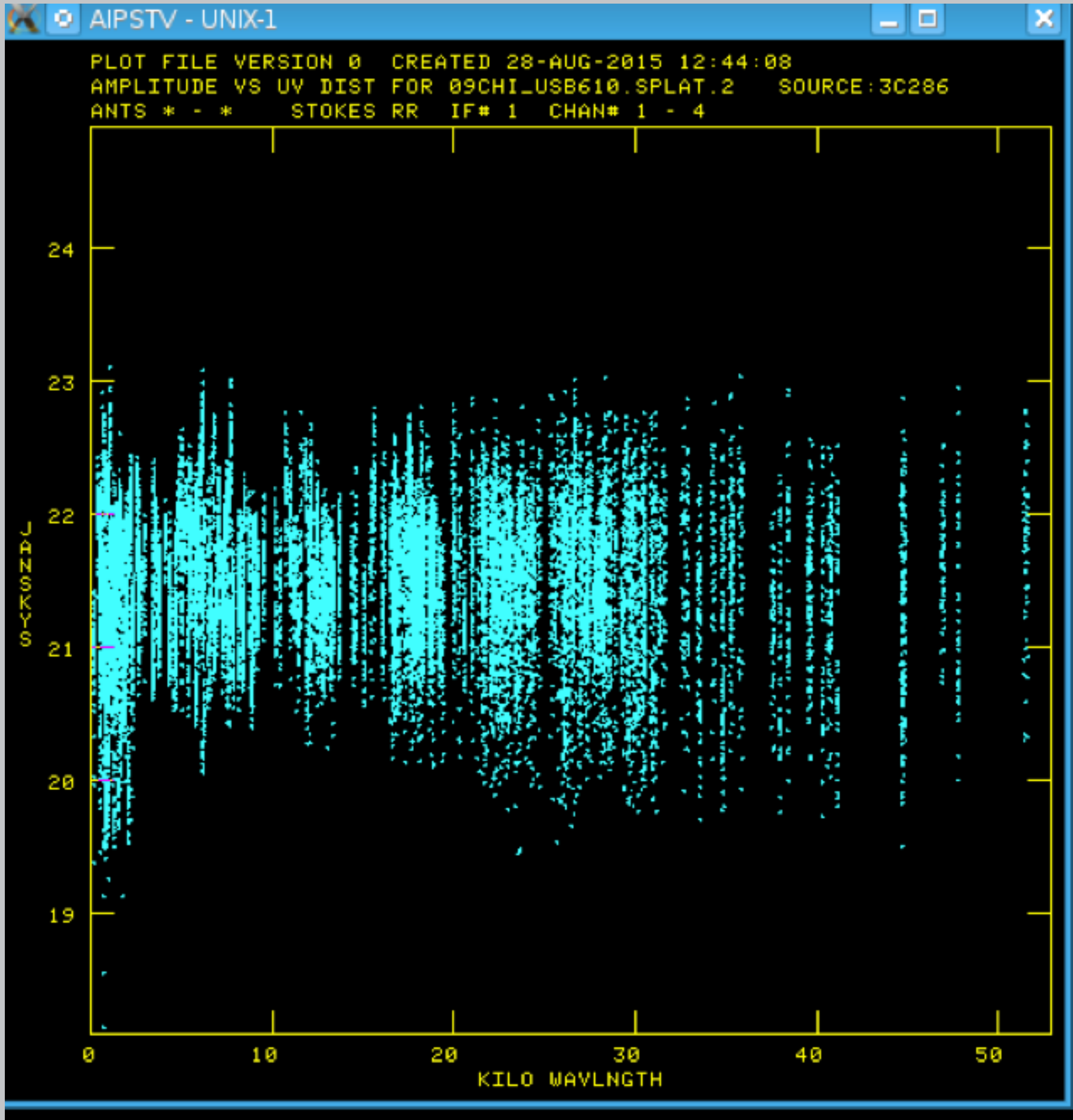
bright calibrator



Faint target source -note that the data looks like pure noise!

FLUX DENSITY AND PHASE CALIBRATION

- Calibrator source(s) as a function of UV-distance
  - flux density / phase calibrators



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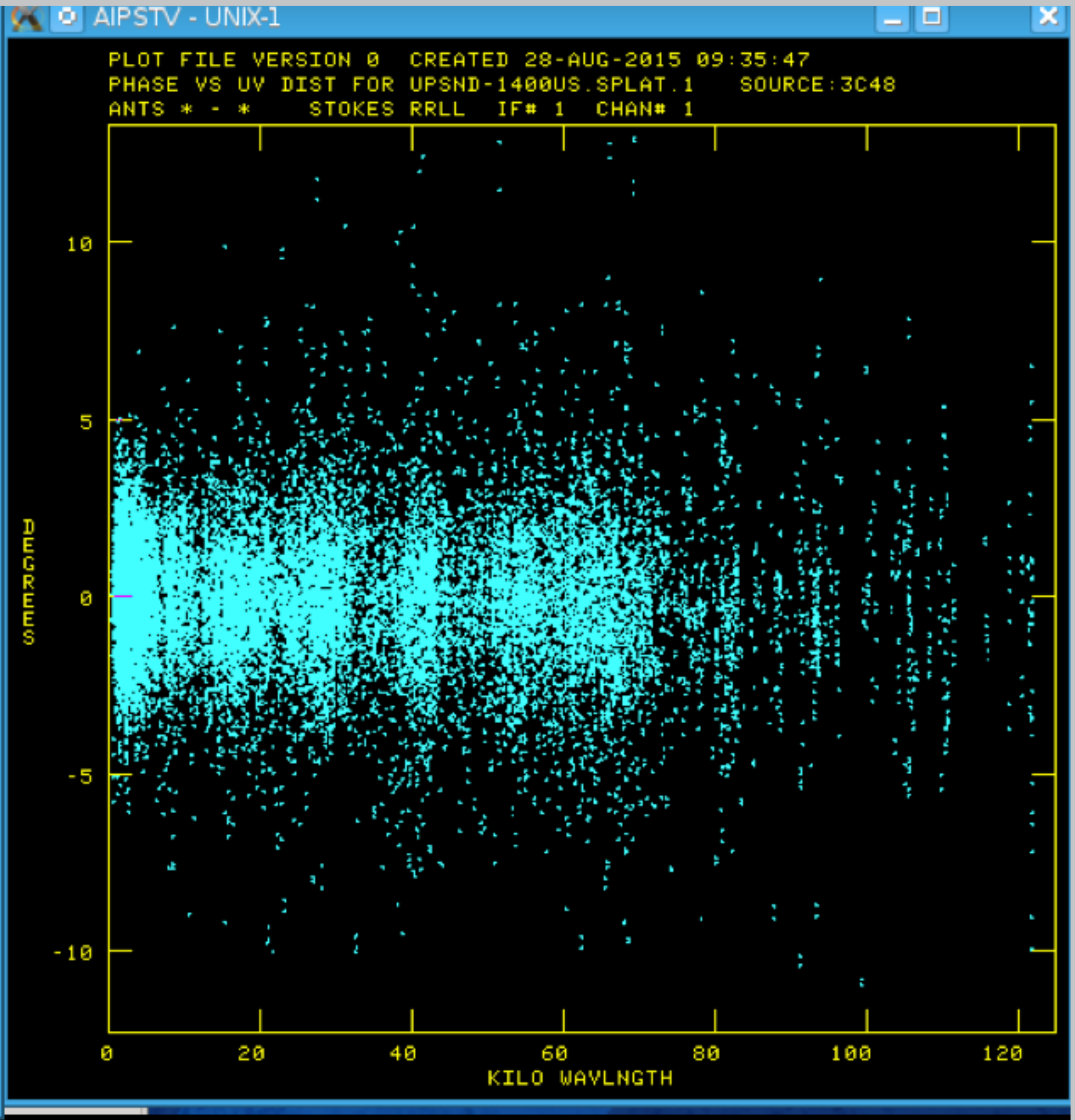
```



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PLOT FILE VERSION 0  CREATED 28-AUG-2015 09:35:47
PHASE VS UV DIST FOR UPSND-1400US.SPLAT.1   SOURCE:3C48
ANTS * - *     STOKES RRLL   IF# 1   CHAN# 1
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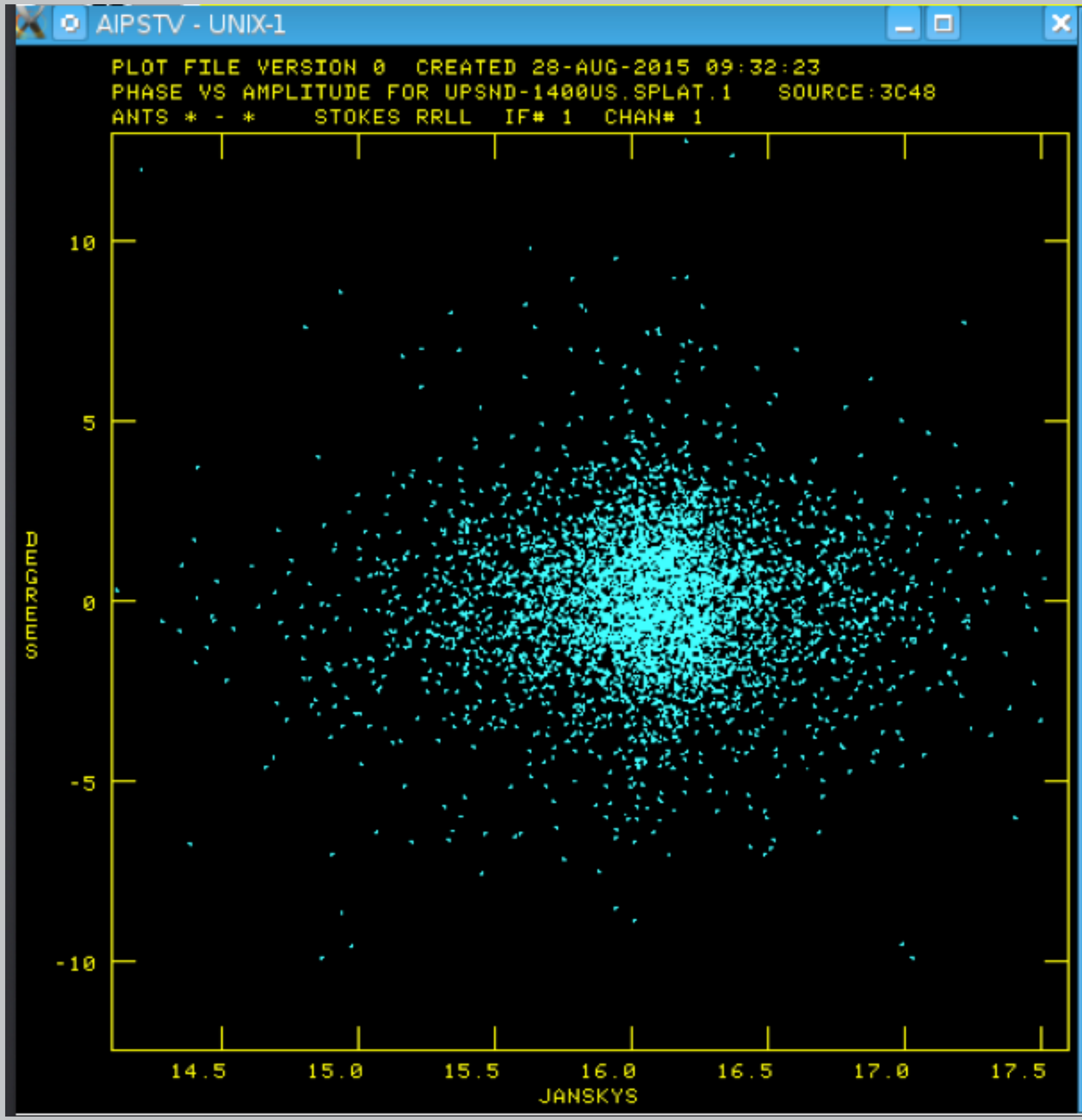
FLUX DENSITY AND PHASE CALIBRATION

- Calibrator source(s) as a function of UV-distance
  - flux density / phase calibrators



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PLOT FILE VERSION 0  CREATED 28-AUG-2015 09:32:23
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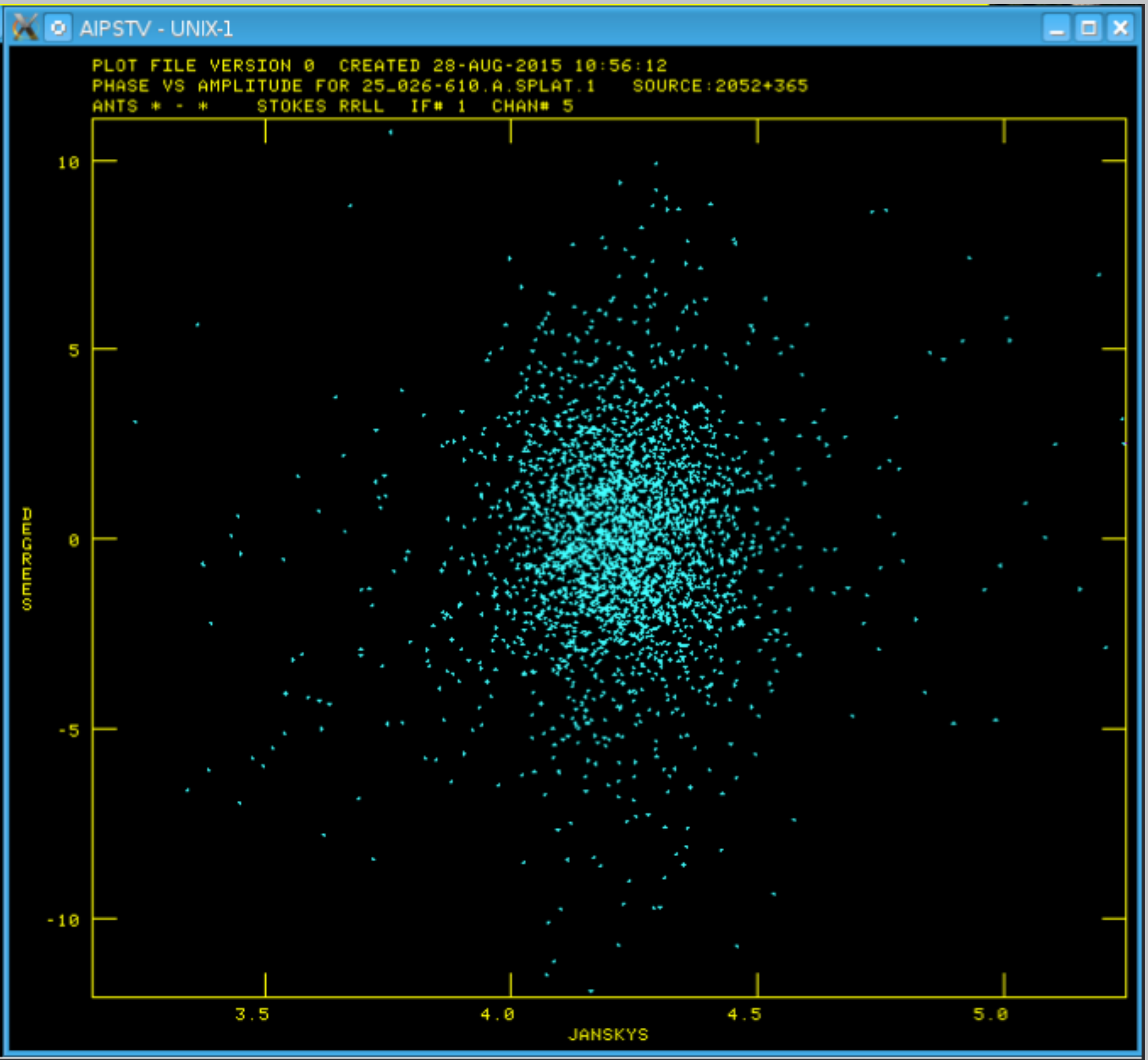

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PHASE VS AMPLITUDE FOR 25_026-610.A.SPLAT.1    SOURCE:2052+365
ANTS * - *     STOKES RRLL   IF# 1   CHAN# 5
```
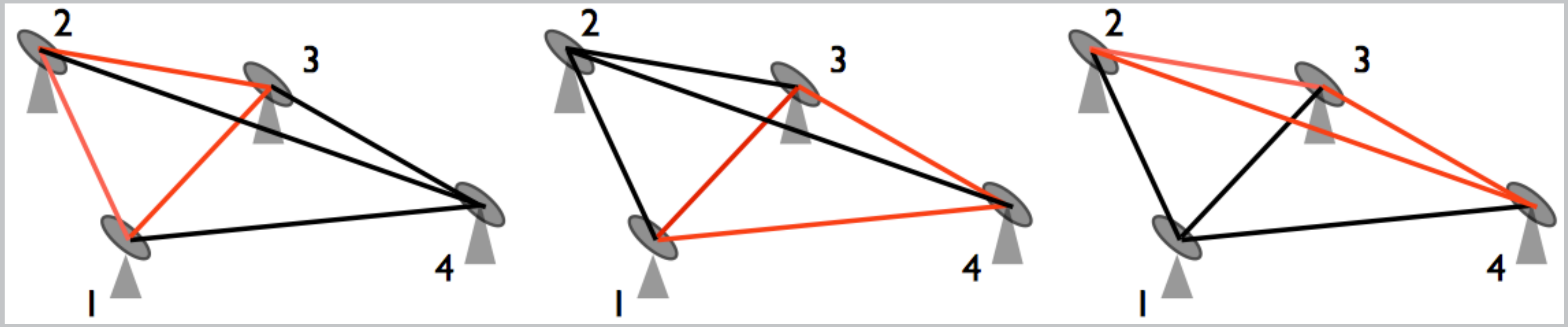
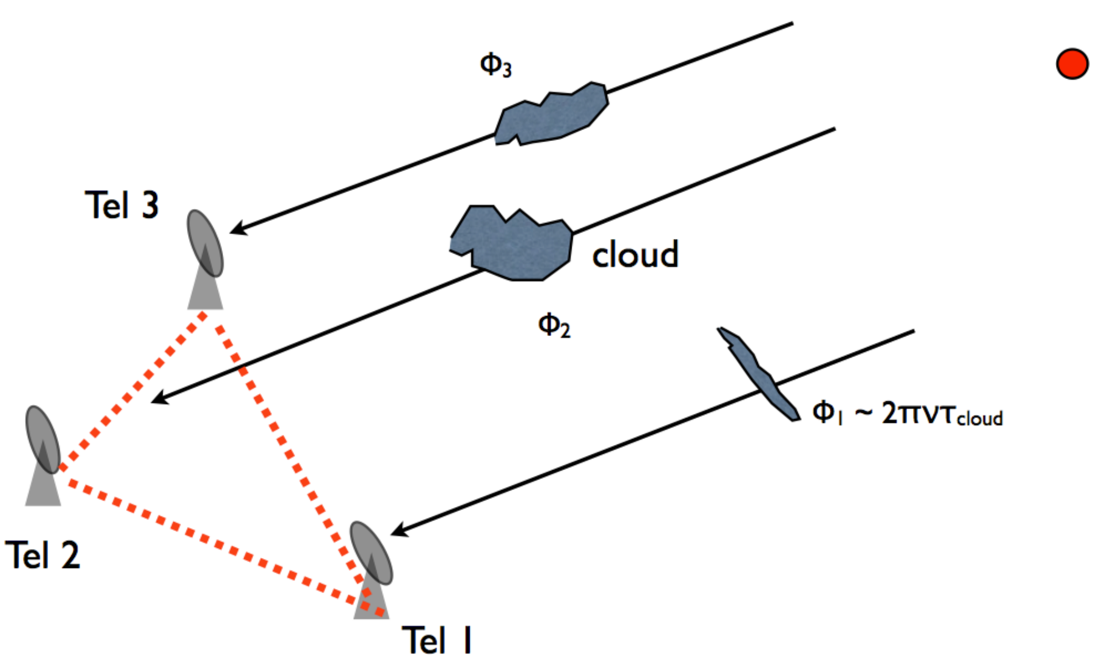

CLOSURE QUANTITIES: PHASES

- The formulation of adding 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,
  - $\frac{1}{2} \times (N_{\text{ant}} - 1)(N_{\text{ant}} - 2)$ independent closure phases
    - e.g. for $N = 4$, there are, 3 independent closure relations.



CLOSURE QUANTITIES: PHASES



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

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

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

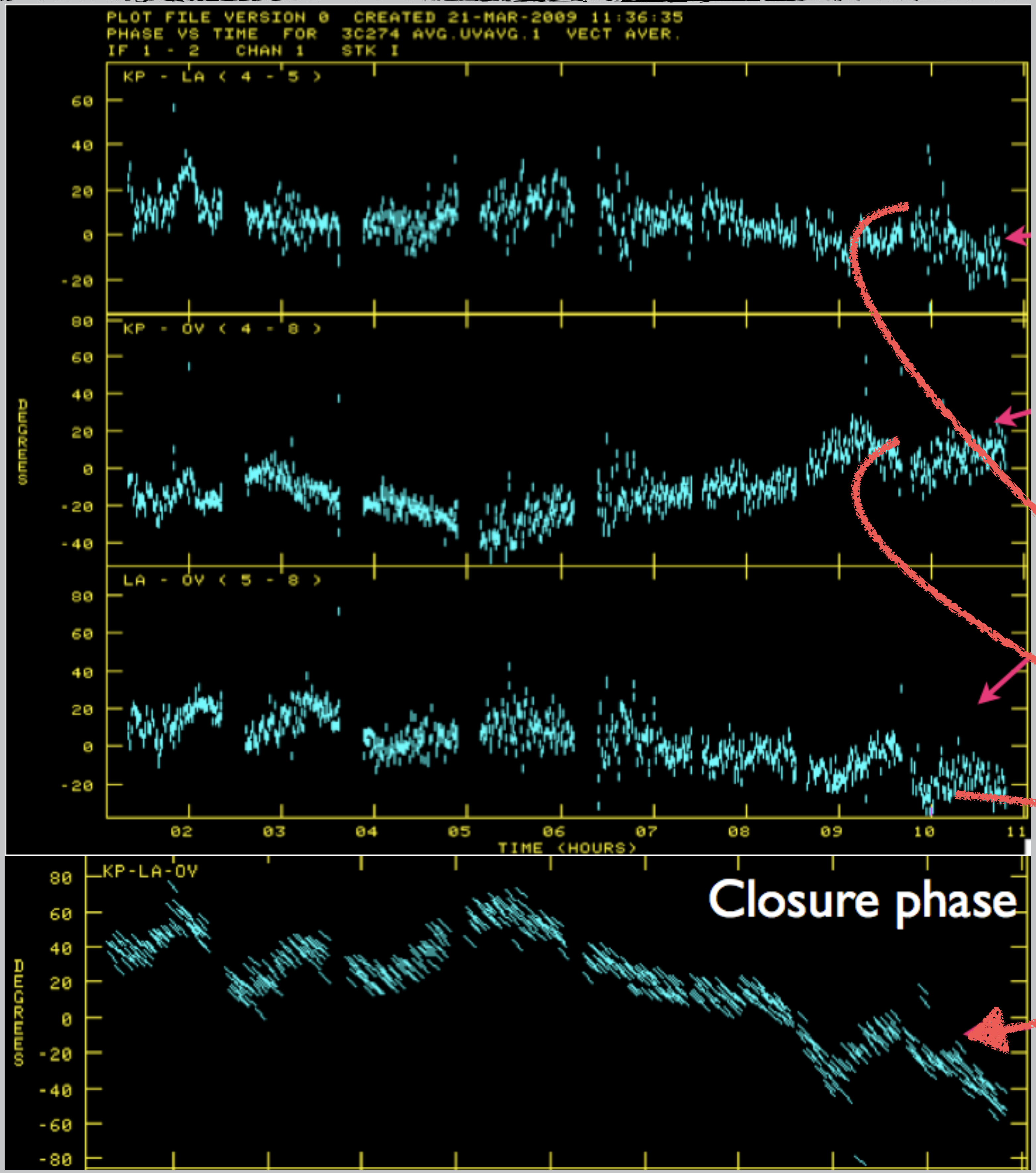
$$\phi_{12} + \phi_{23} + \phi_{31}$$

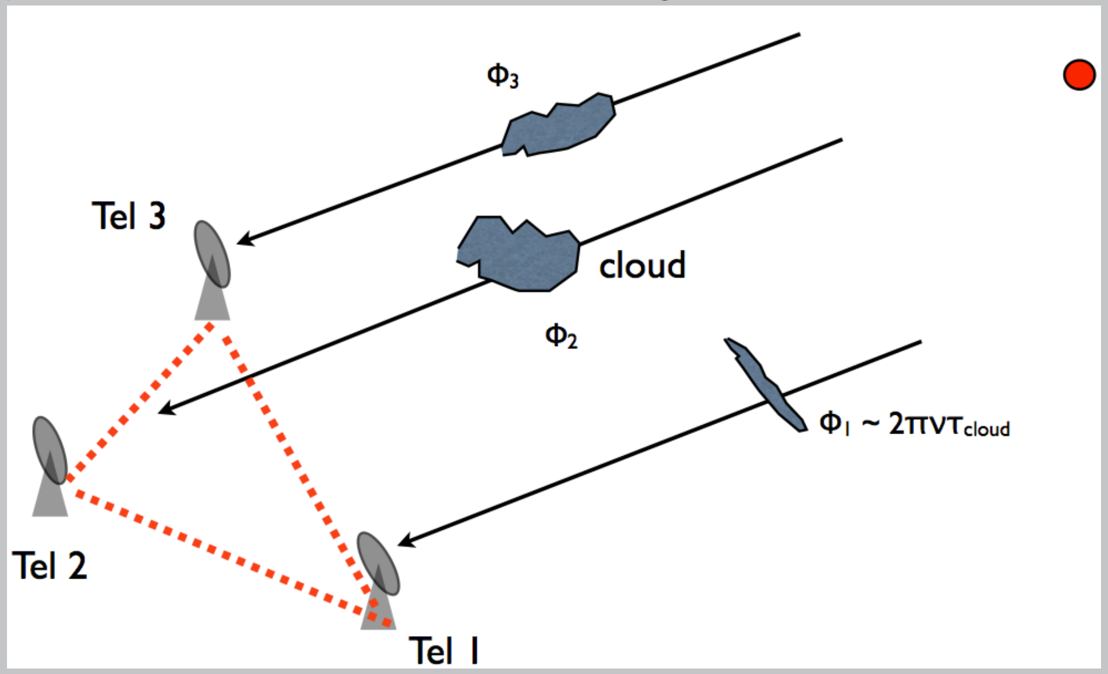
$$= \varphi_{12} + \varphi_{23} + \varphi_{31} + (\phi_1 - \phi_2) + (\phi_2 - \phi_3) + (\phi_3 - \phi_1)$$

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

closure phase!

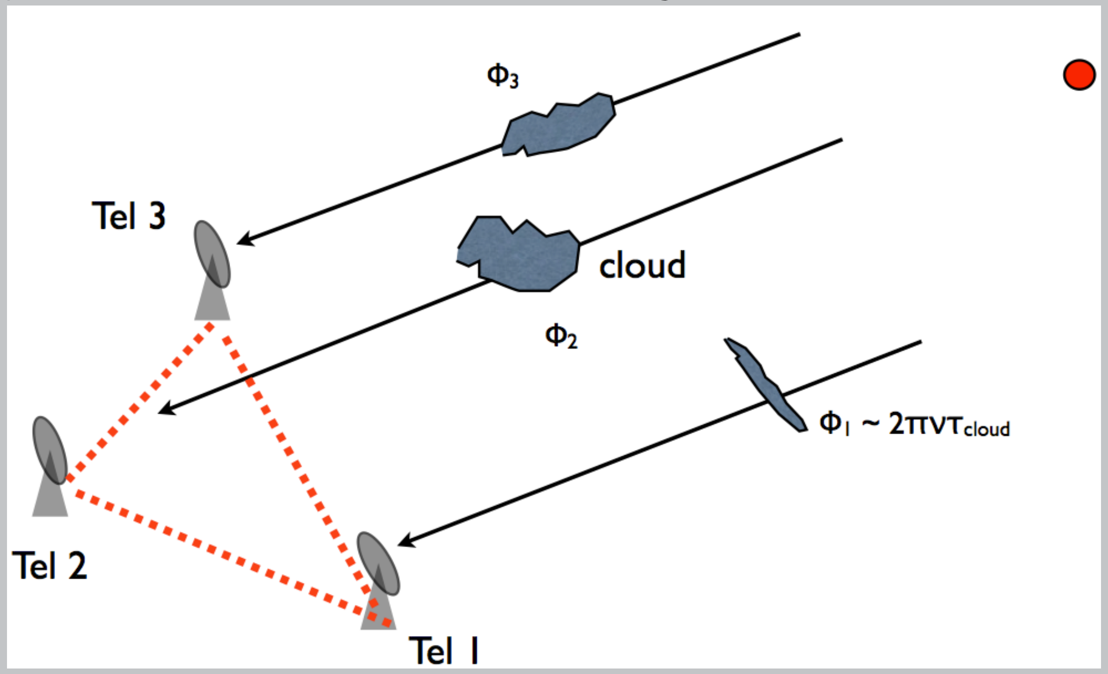
CLOSURE QUANTITIES: PHASES





- 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!

CLOSURE QUANTITIES: PHASES / AMPLITUDES



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

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

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

$$\phi_{12} + \phi_{23} + \phi_{31}$$

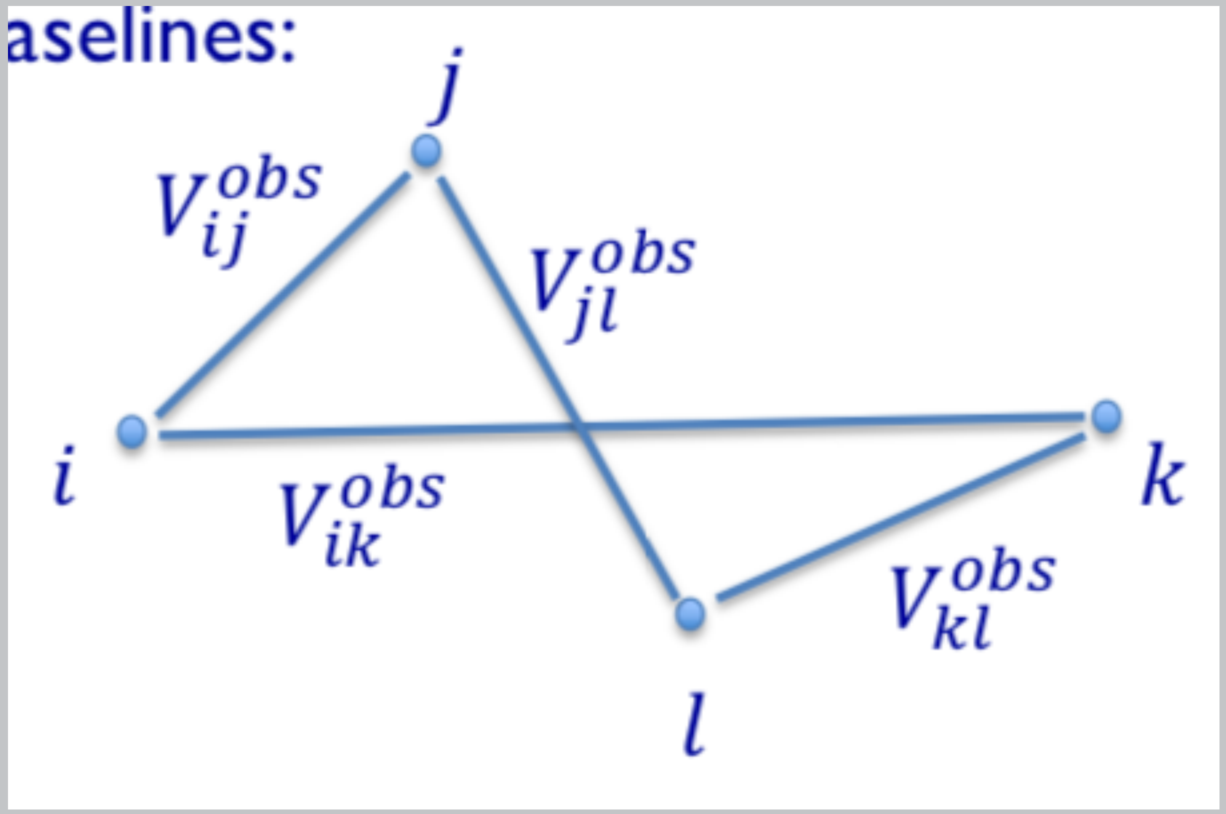
$$= \varphi_{12} + \varphi_{23} + \varphi_{31} + (\phi_1 - \phi_2) + (\phi_2 - \phi_3) + (\phi_3 - \phi_1)$$

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

closure phase!

$$\frac{A_{ij}^{\mathrm{obs}} . A_{kl}^{\mathrm{obs}}}{A_{ik}^{\mathrm{obs}} . A_{jl}^{\mathrm{obs}}} = \frac{A_{ij}^{\mathrm{true}} . A_{kl}^{\mathrm{true}}}{A_{ik}^{\mathrm{true}} . A_{jl}^{\mathrm{true}}}$$

closure amplitude!



CALIBRATION (RECAPITULATE)

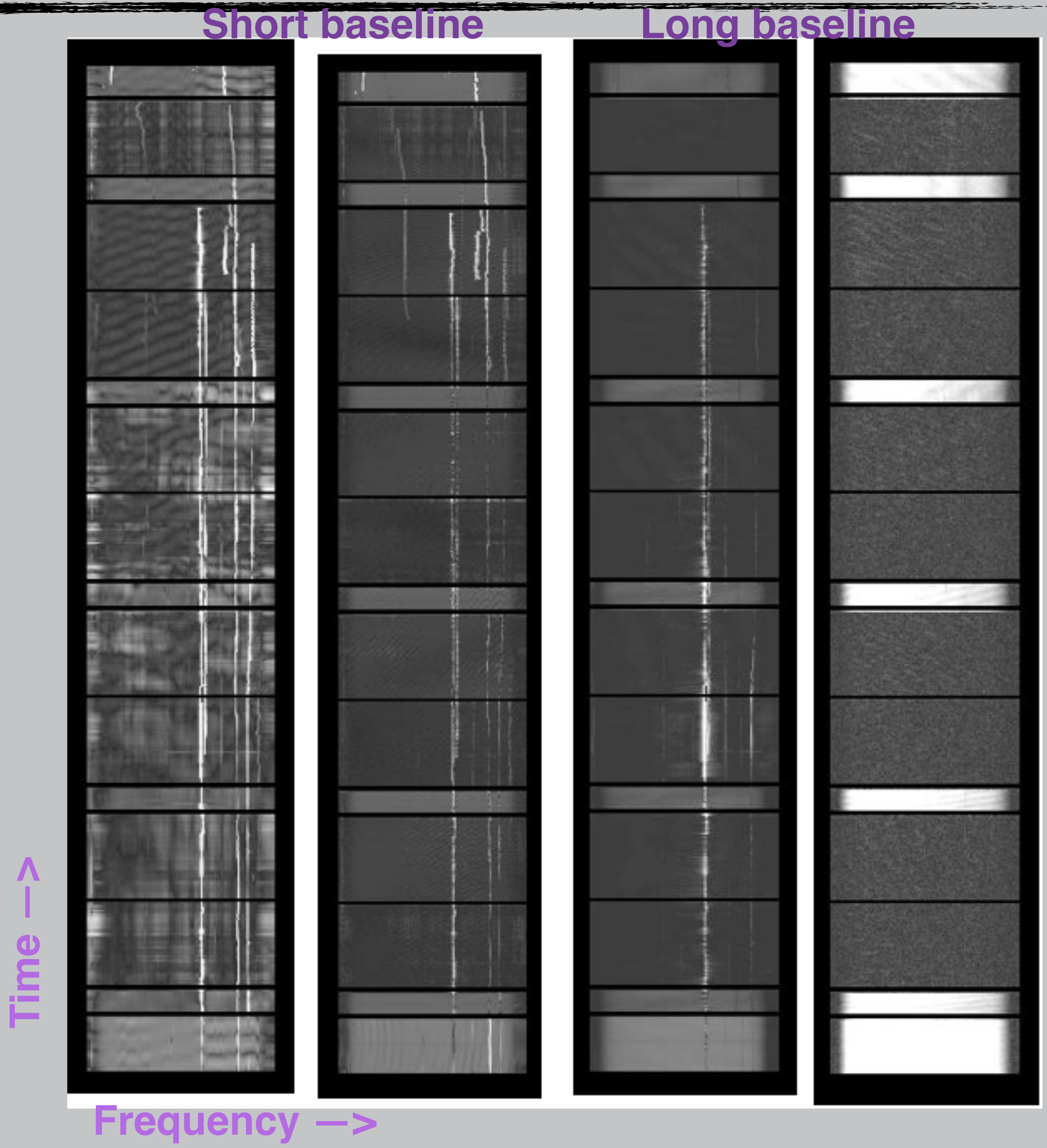
- $V'(u,v) = S(u,v)V(u,v)$
- $\tilde{V}_{ij}(t) = G_{ij}(t)V'_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t)$
  - $G_{ij}(\nu,t) = G'_{ij}(t)B_{ij}(\nu,t)$
    - $B_{ij}(\nu,t) \approx b_i(\nu,t)b_j^{\star}(\nu,t)$
- Phase referencing
- Closure phase / amplitude

HOW TO EDIT ... CALIBRATION?

- 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
- Editing obvious errors in the (u, v) plane

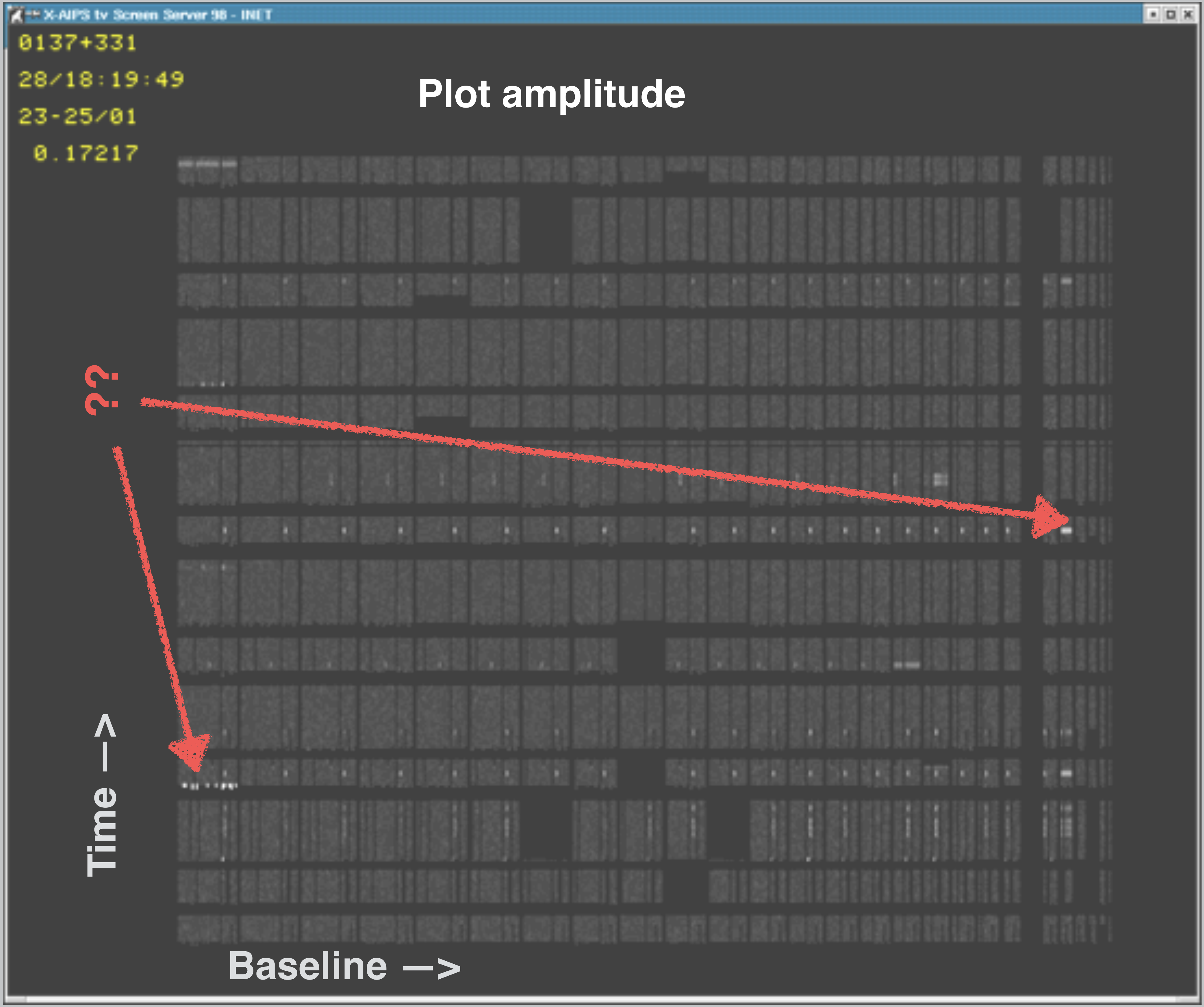
CULPRITS: 1 - RFI

- RFI environment worse on short baselines
  - several types
    - narrow-band,
    - wandering
    - wide-band



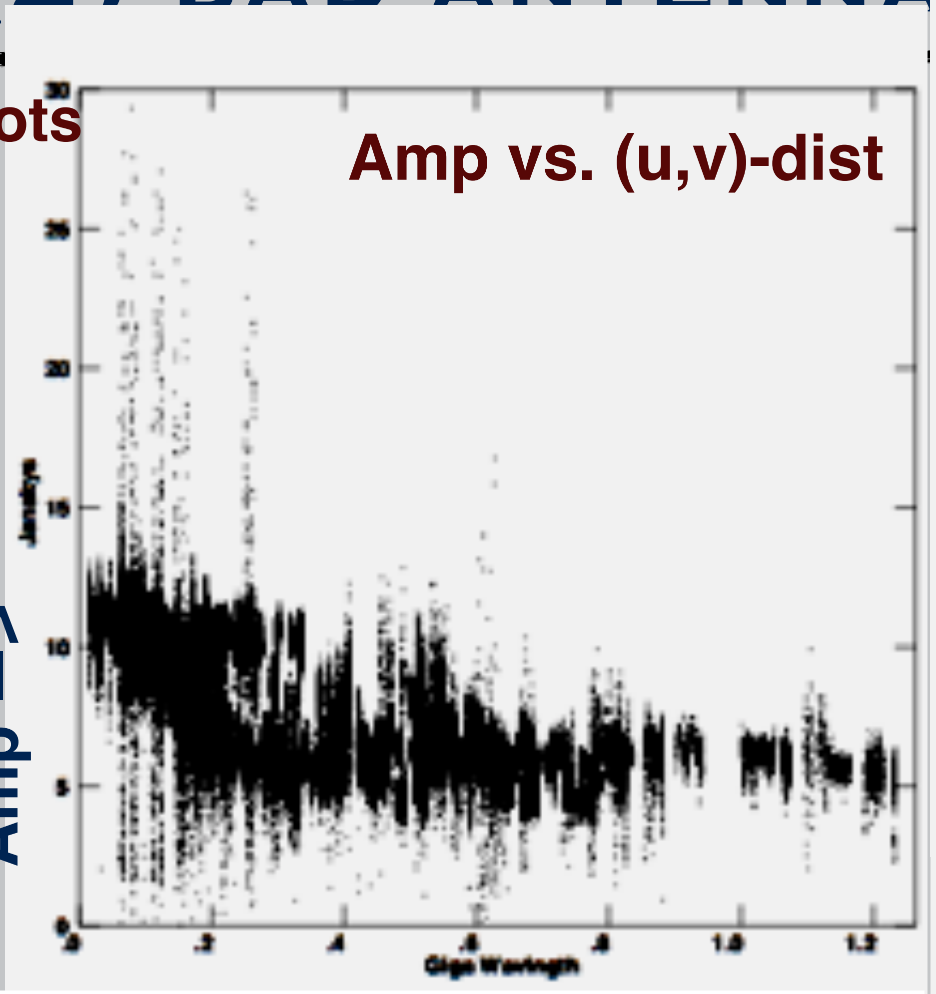
CULPRITS: (2) BAD ANTENNA

Antenna-X problem

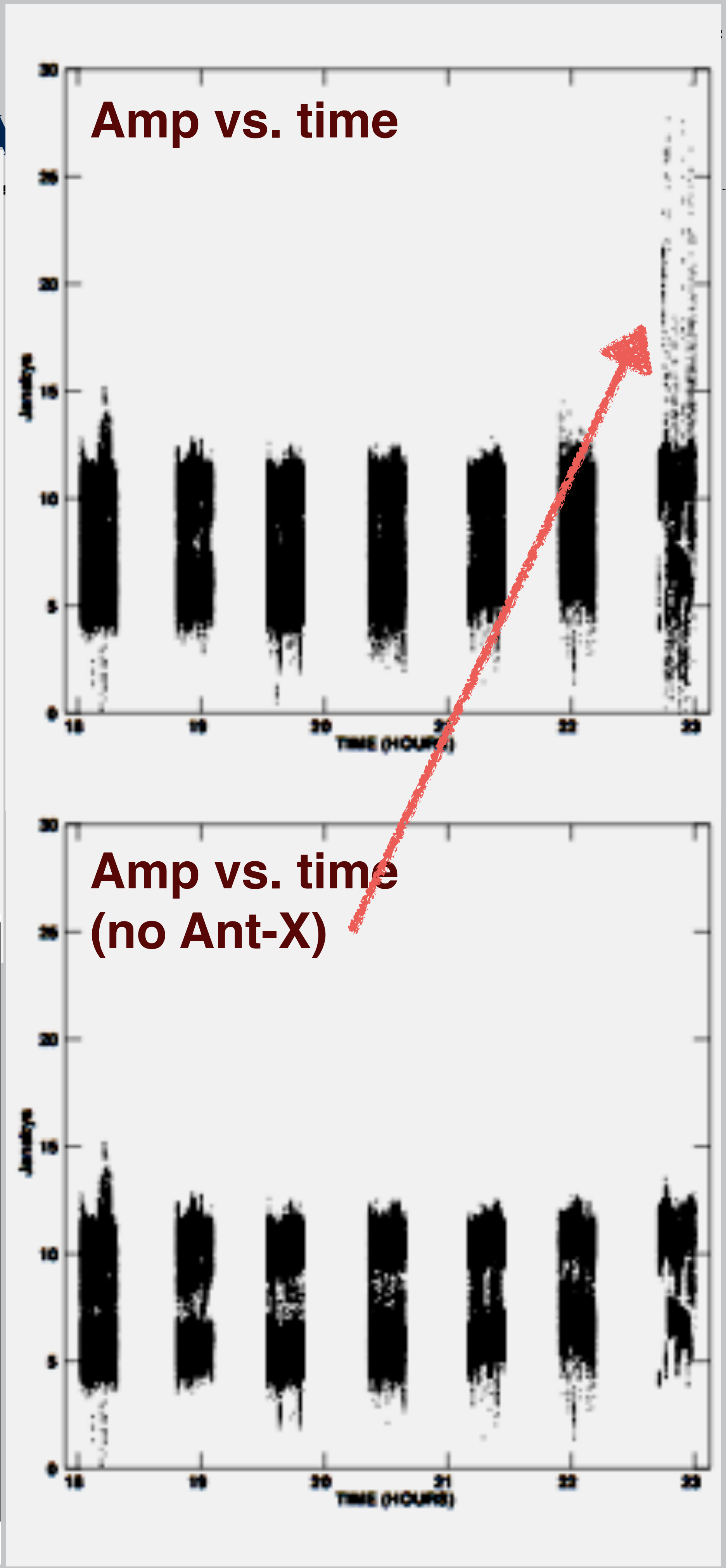


CULPRITS: (2) BAD ANTENNA

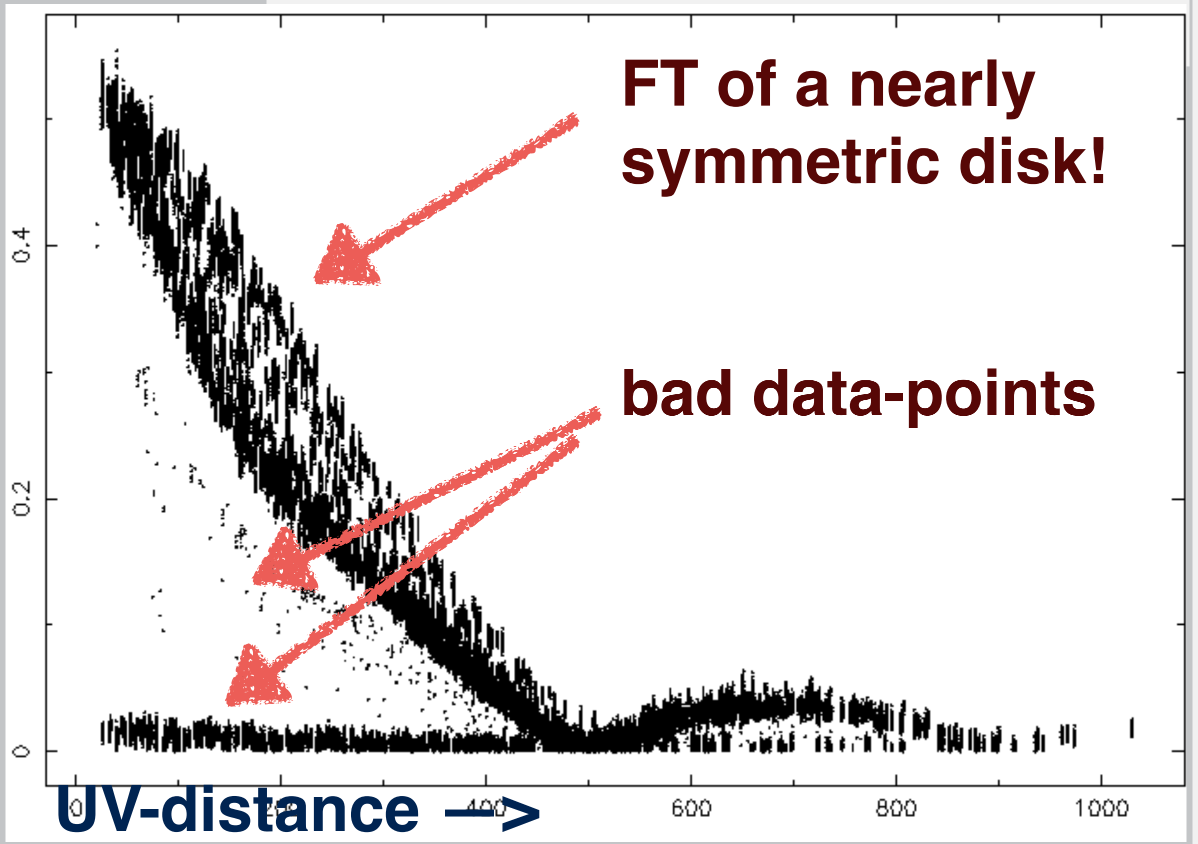
Visibility amplitude plots


Amp vs. (u,v)-dist

Amp -->


Amp vs. time

Amp vs. time
(no Ant-X)


FT of a nearly
symmetric disk!

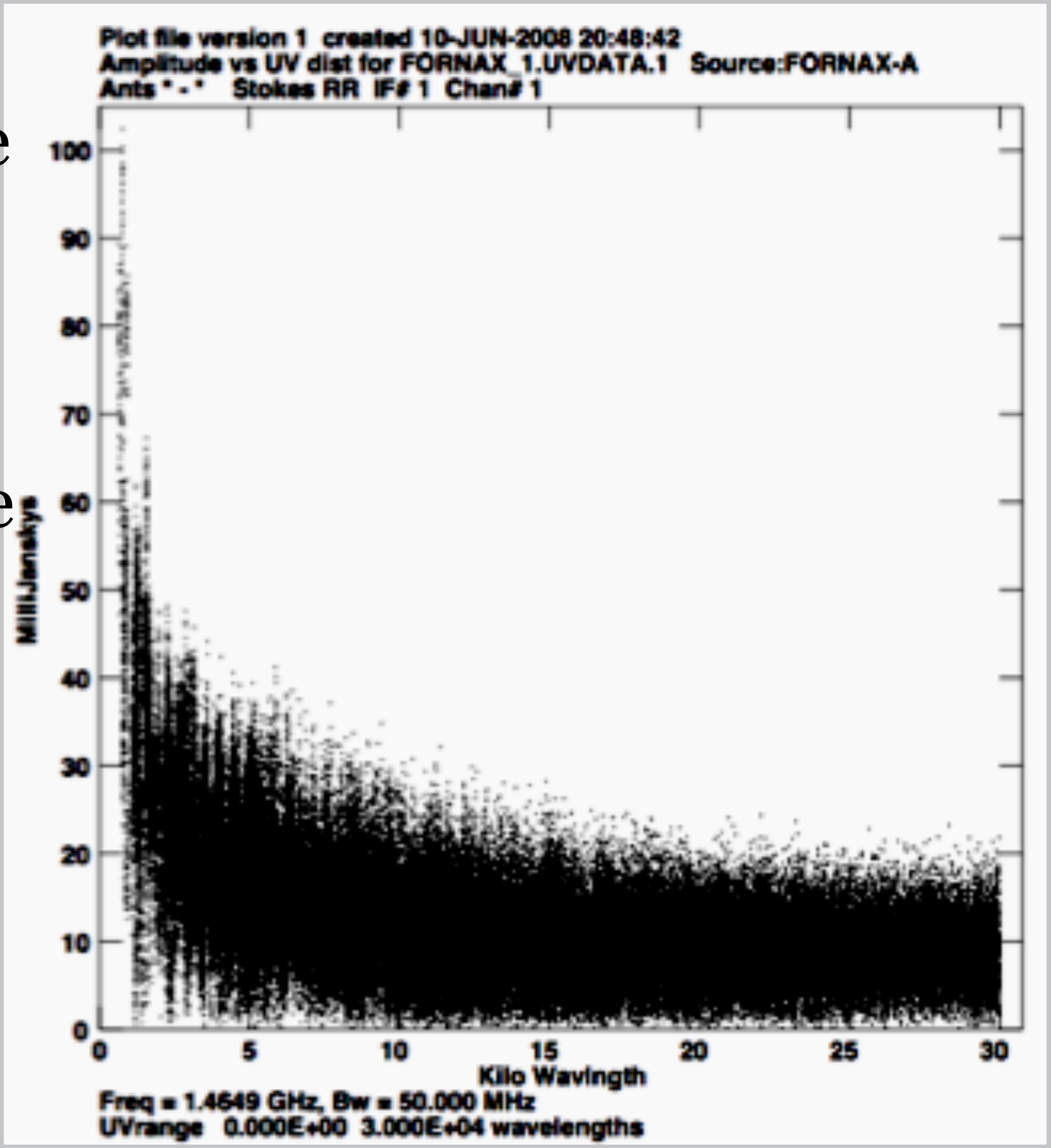
bad data-points

Amp -->

UV-distance -->

CULPRITS: (NONE), BUT...

- 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.

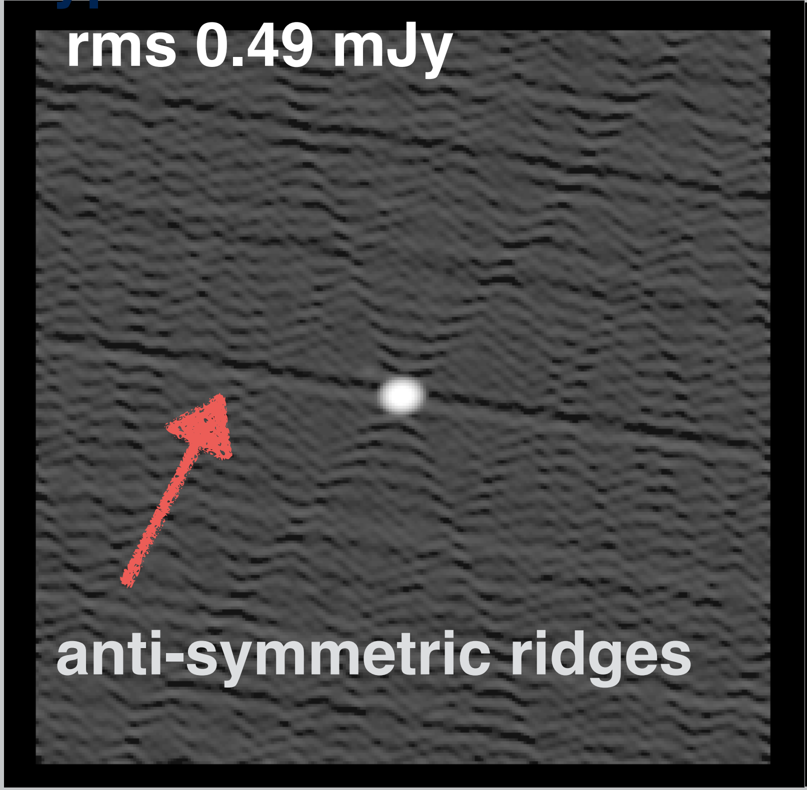


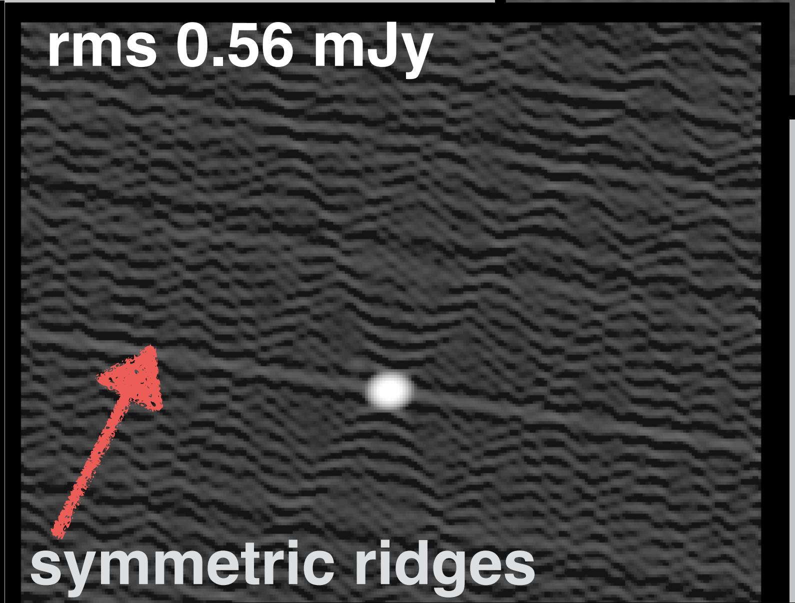
MORE CULPRITS:

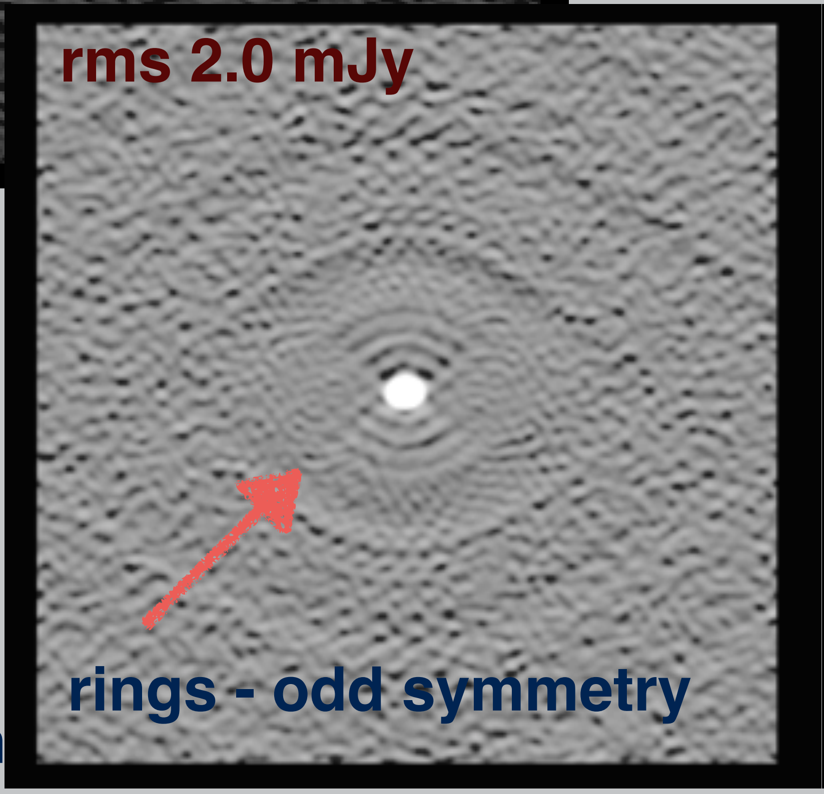
10 deg phase error for one antenna

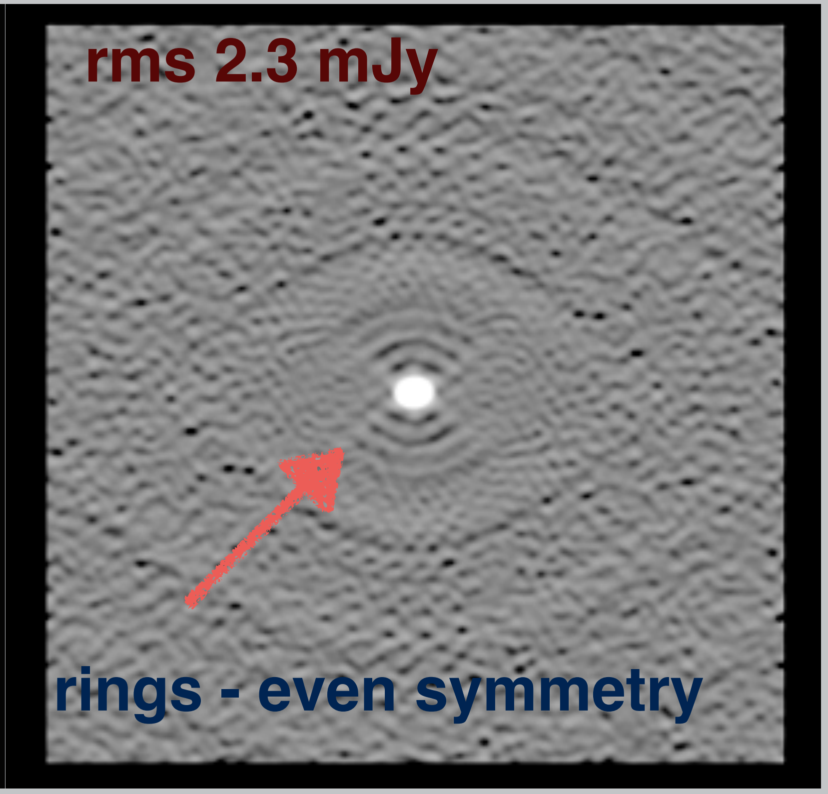
20% amplitude error for one antenna

Typical effect from one bad antenna





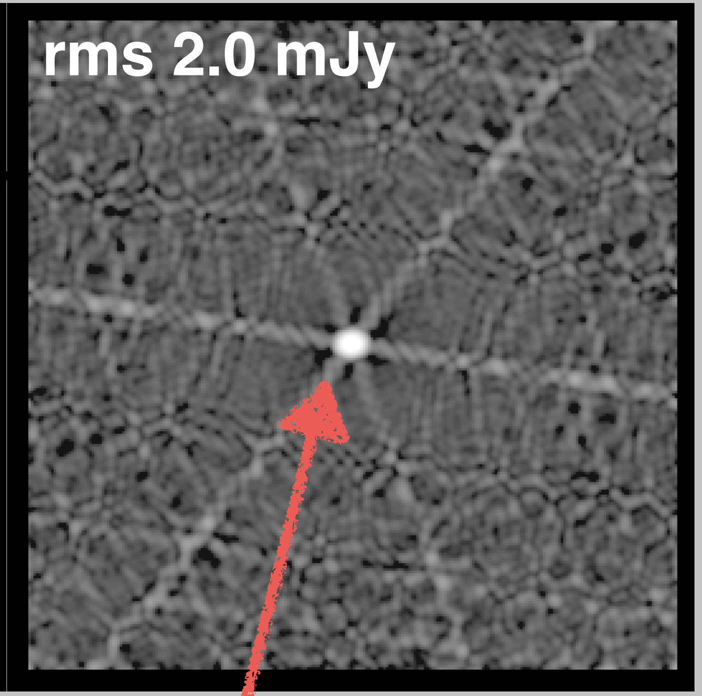




Note! 10 deg phase error to 20% amplitude errors cause similar sized artefacts

Persistent error over most of run

Bad data over short period of time



6-fold symmetric pattern due to GMRT “Y”.

Image has properties of dirty beam

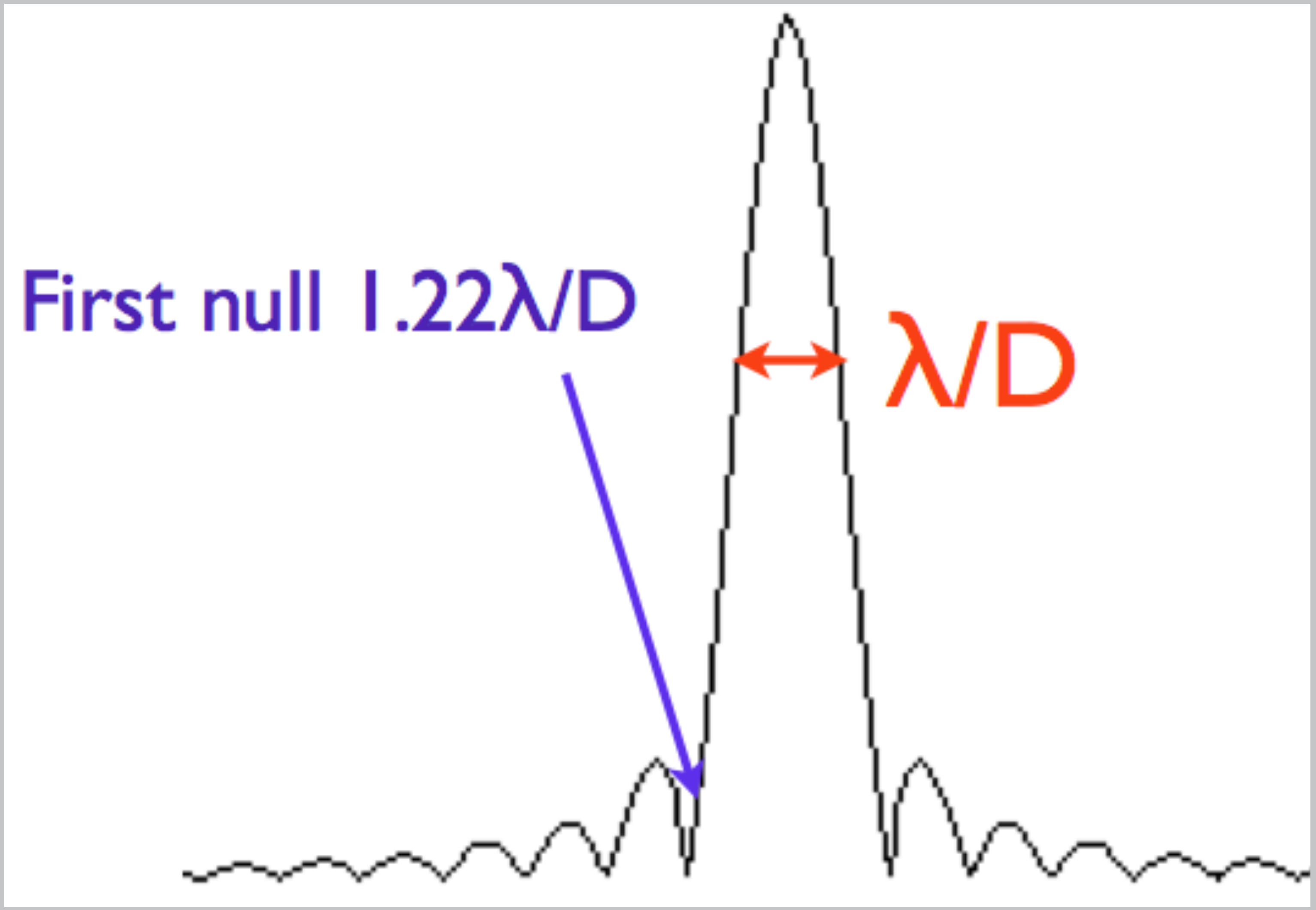
10% amp error for all antennas on one scan

CALIBRATED VISIBILITIES

- Analyse directly $V(u, v)$ samples by model fitting
    - – good for simple structures, e.g. point sources, ...
    - – sometimes for statistical descriptions of sky brightness
- recover an image from the observed incomplete and noisy samples of its Fourier transform for analysis
    - – Fourier transform $V(u, v)$ to get Dirty image
    - – beyond Dirty image – perform deconvolution

PRIMARY BEAM CALIBRATION

- 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.



CALIBRATION: ASSUMPTIONS

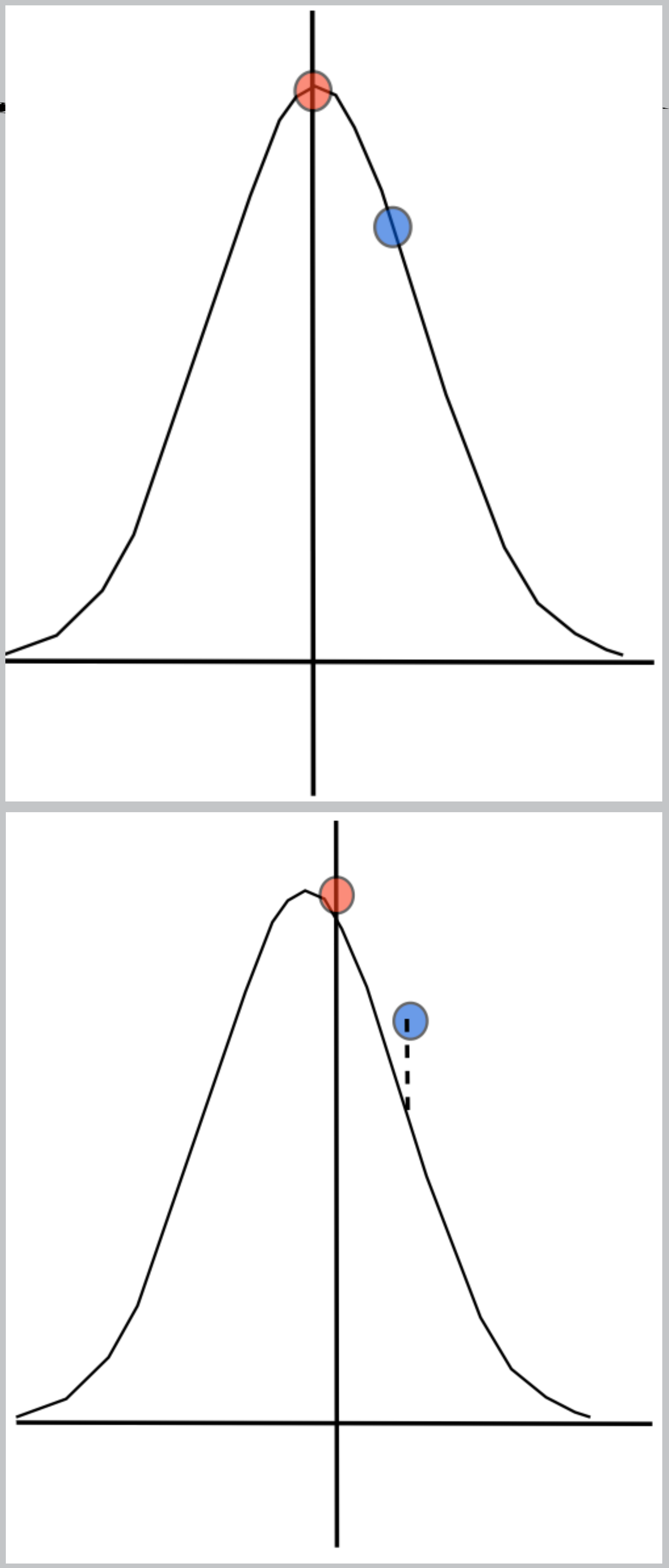
- The tracking of the centre of the PB for all antennas must follow the intended sky position
- The Gain of an antenna decreases when observations are made near the horizon - the dependence of Gain upon zenith angle.
- Delay calibration: small, residual delays!
- Antenna position(s) - baseline length!
- Path length changes in the ionosphere
- ....

HIGH DYNAMIC RANGE IMAGING

- At low frequencies (e.g. 1.4 GHz or below) 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 due to errors in correlator.
  - (ii) telescope pointing errors,
  - (iii) non-isoplanatic effects.

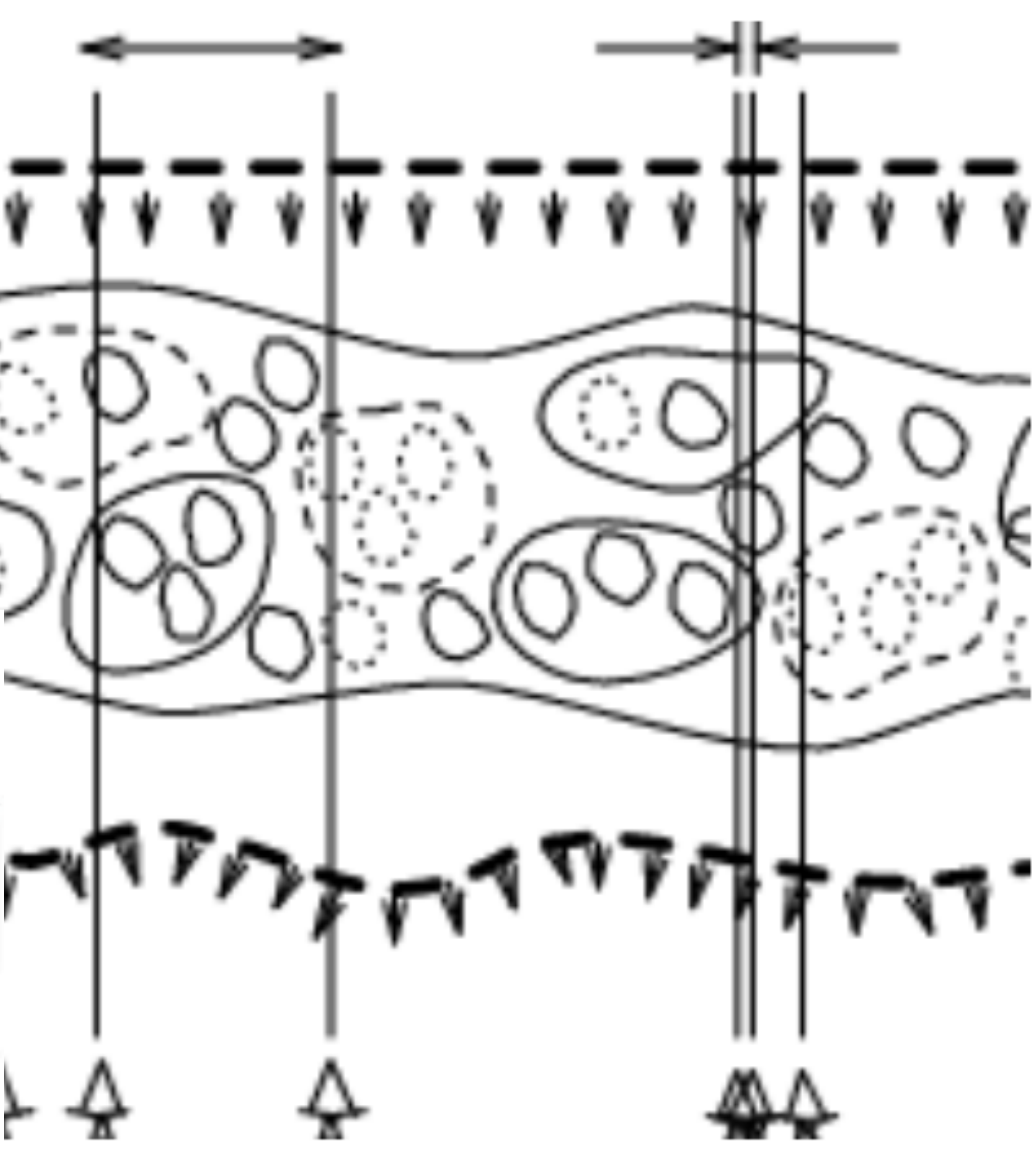
HIGH DYNAMIC RANGE IMAGING

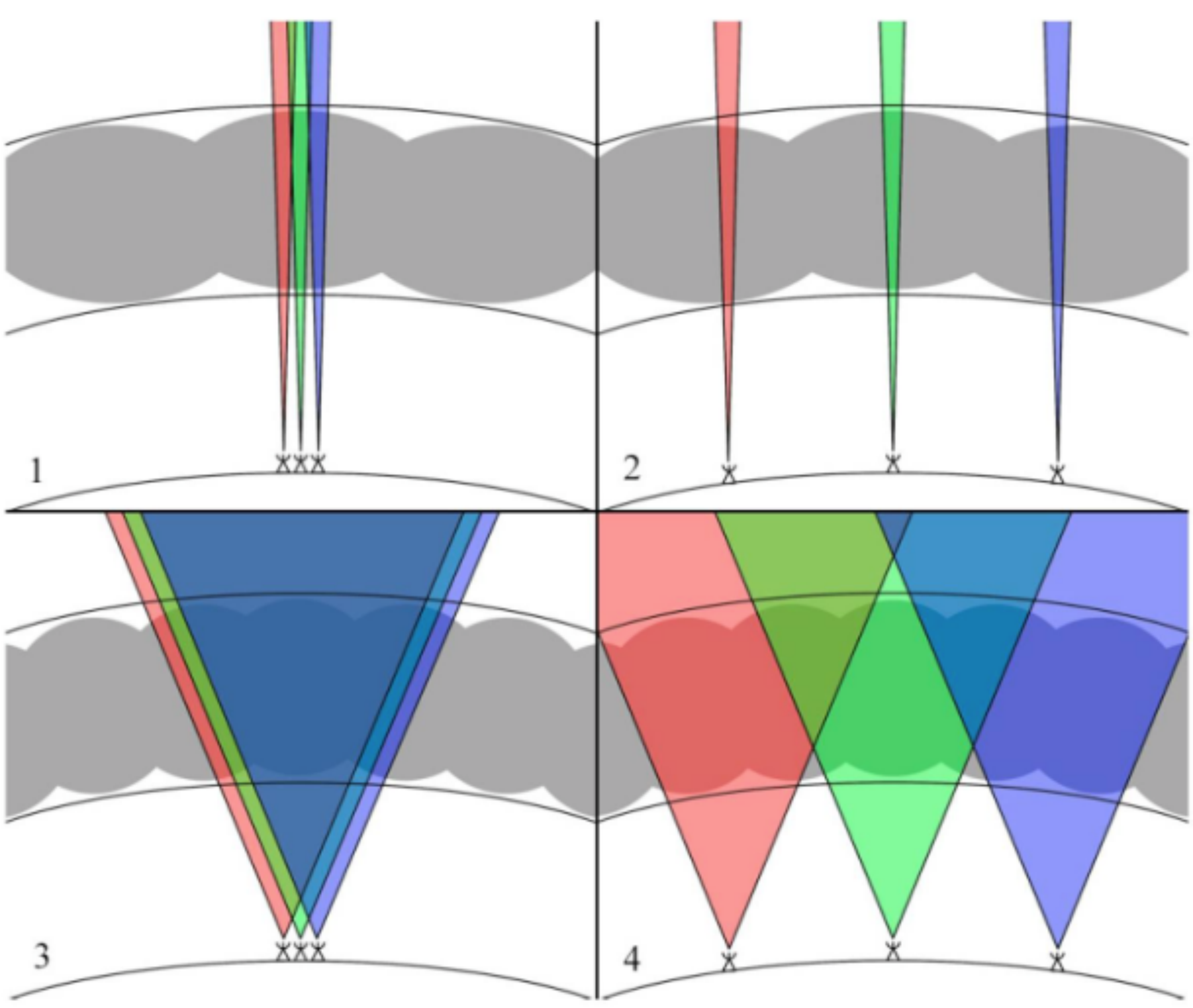
- <u>Telescope pointing errors</u>: Pointing errors are problematic; the effect is not uniform over FoV., e.g., sources at the edge of PB (where response of PB is changing quickly) or there is a large reduction of telescope response at their position, this is difficult for the calibration methods to cope with.



High dynamic range im

- non-isoplanatic effects:





CALIBRATION (RECAPITULATE)

- $$V'(u,v) = S(u,v)V(u,v)$$
- $\tilde{V}_{ij}(t) = G_{ij}(t)V'_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t)$
  - $G_{ij}(\nu,t) = G'_{ij}(t)B_{ij}(\nu,t)$
    - $B_{ij}(\nu,t) \approx b_i(\nu,t)b_j^{\star}(\nu,t)$
- Phase referencing
- Closure phase / amplitude
- Bad data editing
- (more) issues

VISIBILITY: TRUE VS. OBSERVED

- A comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy.
- Calibration is the effort to measure and remove the time-dependent and frequency-dependent atmospheric and instrumental variations.
- recover "true" value

$$V'(u,v) = S(u,v)V(u,v)$$

sampled visibility

true visibility

sampling function

VISIBILITY: TRUE VS. OBSERVED

- A comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy.

$$V'(u,v) = S(u,v)V(u,v)$$

- Calibratio
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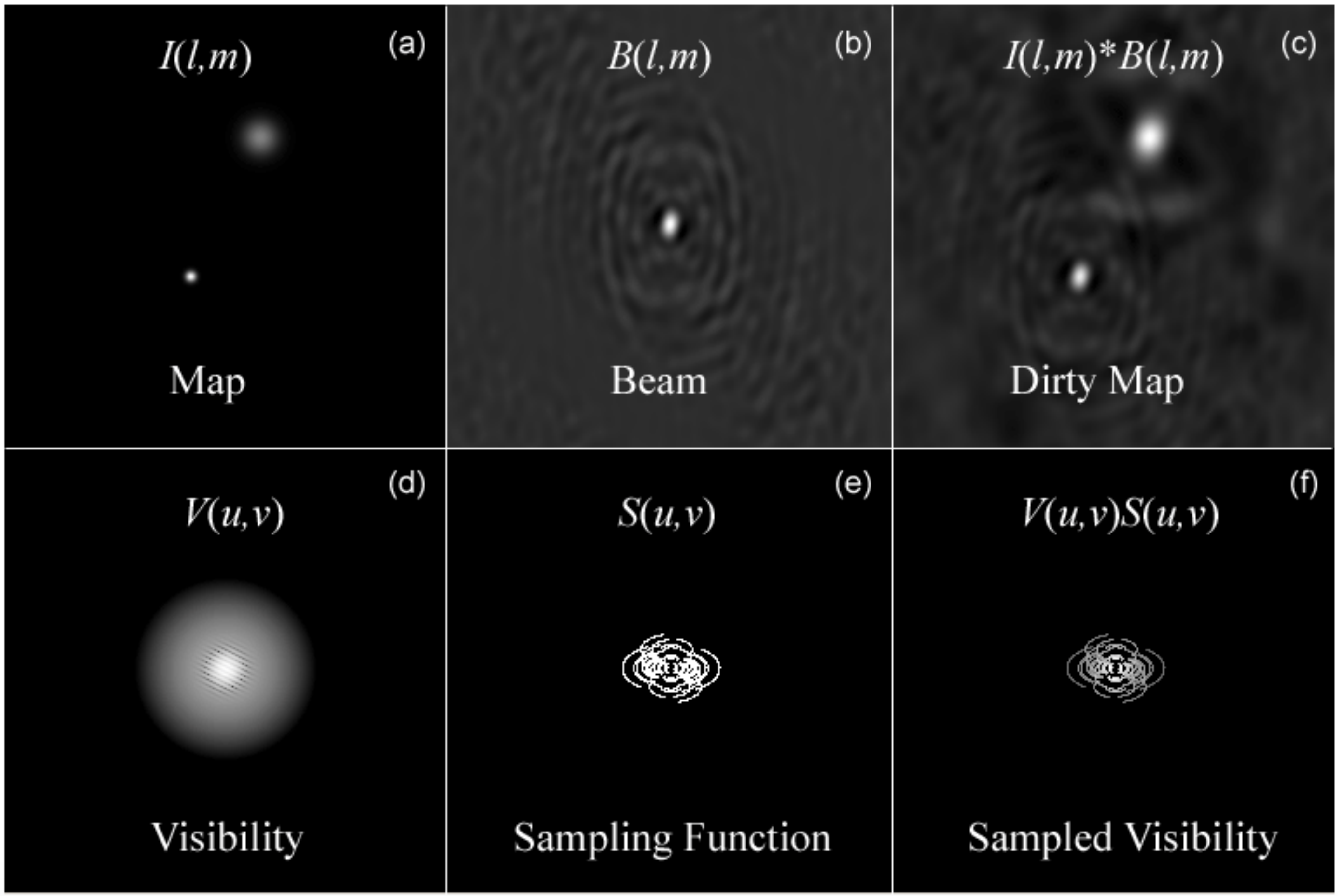

MORE (SUBSEQUENT LECTURES?)

- Self calibration
- Bandwidth averaging/smearing
- Time averaging
- High dynamic range imaging

MORE (SUBSEQUENT LECTURES?)

- Self calibration
- Bandwidth averaging/smearing
- Time averaging
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Thank you!