Essentials of Radio and (Sub-)Millimeter Astronomy

Fabian Walter (MPIA)

Lecture 9

Basics of Interferometry: Calibration

slides: Essential Radio Astronomy by NRAO (Condon & Ransom)
Dr. Michael Wise (ASTRON)
Prof. David Wilner (Harvard)
see also SMA summer school 2021: https://lweb.cfa.harvard.edu/sma-school/program/
(Dr. Garrett Keating)

why calibrate?

- Radio telescopes are not perfect (e.g., surface accuracy, receiver noise, polarization purity, stability, etc.)
- Need to accommodate engineering (e.g., frequency conversion, digital electronics, etc.)
- Hardware or control software occasionally fails or behaves unpredictably
- Scheduling/observation errors sometimes occur (e.g., wrong source positions)
- Atmospheric conditions not ideal (not limited to "bad" weather, especially important at low and very high frequencies)
- Radio Frequency Interference (RFI)
- *Determining instrumental properties (calibration) ⇒ Prerequisite to determining source properties*

Types of Calibration

A priori "calibrations"

– Information provided by the observatory
– Antenna positions, earth orientation and rate, clocks
– Antenna pointing, voltage pattern, gain curve
– Calibrator coordinates, flux densities, polarization properties

Cross-calibration

– Observe strong nearby sources against which calibration can be solved, and transfer solutions to target observations

– Choose appropriate calibrators, usually point sources because we can easily predict their visibilities (Amplitude ~ constant, Phase ~ 0)

– Choose appropriate timescales for calibration

Self-calibration
– Correct for antenna based phase and amplitude errors together with imaging – Iterative, non-linear relaxation process
– Requires sufficient signal-to-noise at each solution interval
– Dangerous with small N arrays, complex sources, low signal-to-noise

Astronomical 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)

Linear Polarization Position Angle

– Usual flux density calibrators also have significant stable linear polarization position angle for registration

What Data is Delivered?

An enormous list of complex visibilities!

– At each timestamp (~1-10s intervals): N(N-1)/2 baselines

- EVLA: 351 baselines
- VLBA: 45 baselines
- ALMA: 1225-2016 baselines
- LOFAR: 1128 (LBA), 2016 (HBA), 41328 (AARTFAAC)

– For each baseline: 64-256 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 or LOFAR: 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, frequency label info

Ntotal = Nt x Nbl x Nspw x Nchan x Ncorr visibilities

⇒ 10s of GB to 10s of TBs of visibility data

Inspecting Visibility Data

Useful visualizations

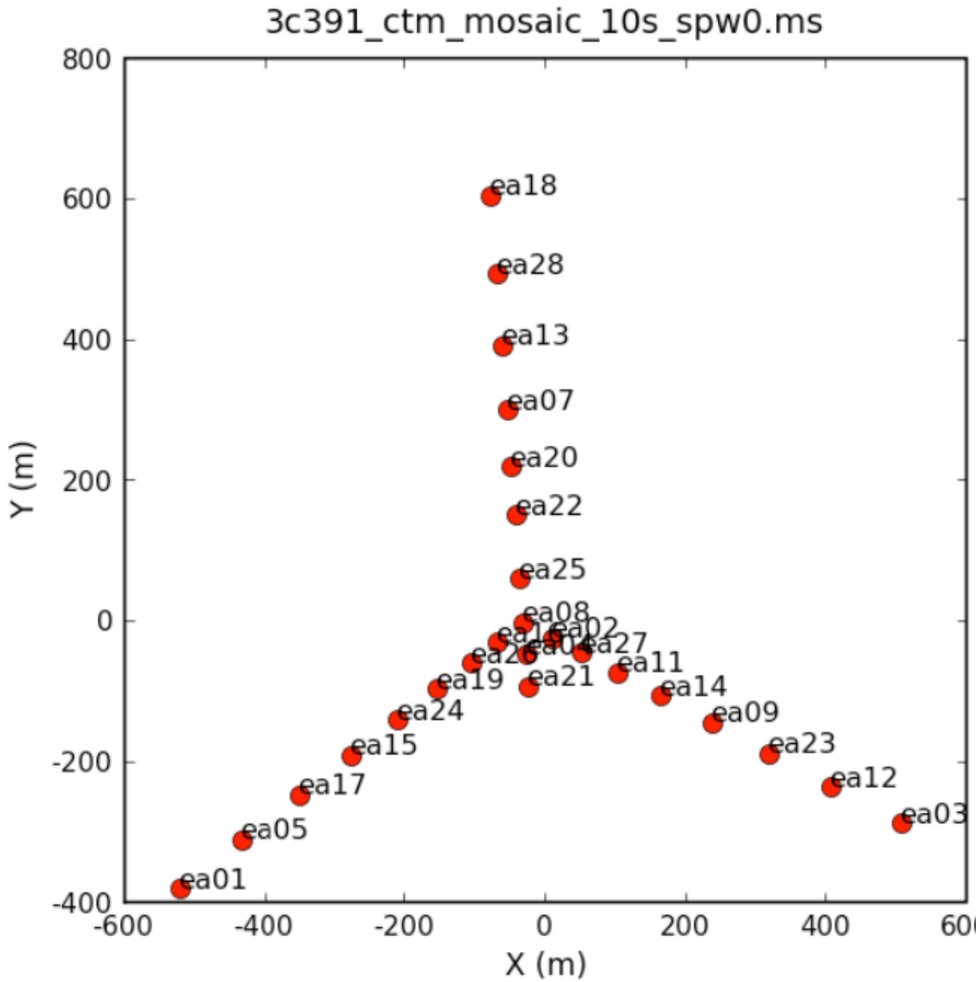
– Sampling of the (u,v) plane
– Amplitude and phase vs. radius in the (u,v) plane
– Amplitude and phase vs. time on each baseline
– Amplitude variation across the (u,v) plane
– Projection onto a particular orientation in the (u,v) plane

Advantages to inspecting *uv* data

– Insufficient (u,v)-plane coverage to make an image
– Inadequate calibration
– Quantitative analysis
– Direct comparison of two data sets
– Noise is uncorrelated in the (u,v) plane but correlated in the image
– Systematic errors are usually localized in the (u,v) plane

Typical Dataset (VLA)

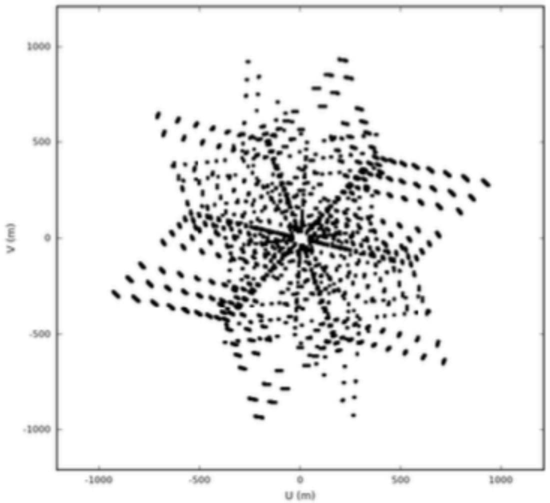
- Array:
  - EVLA D-configuration (Apr 2010)
- Sources:
  - Science Target: 3C391 (7 mosaic pointings)
  - Near-target calibrator: J1822-0938 (~11 deg from target)
  - Flux Density calibrator: 3C286
  - Instrumental Polarization Calibrator: 3c84
- Signals:
  - RR,RL,LR,LL correlations
  - One spectral window centered at 4600 MHz
  - 128 MHz bandwidth, 64 channels

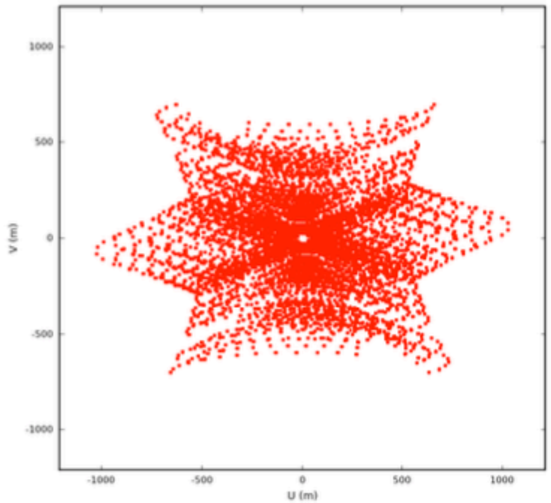


EVLA Antenna Designations

Observed uv Coverages

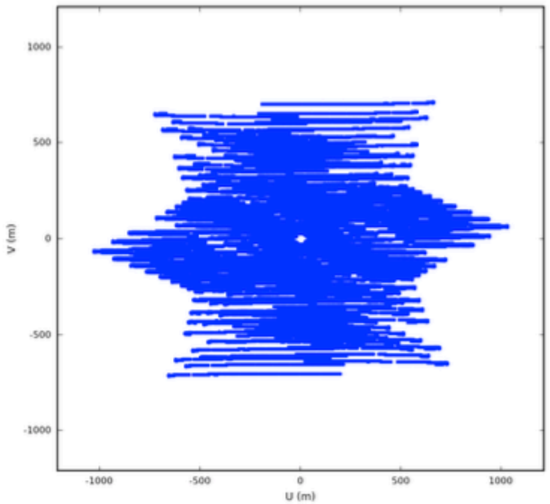
3C286
(Flux Density)

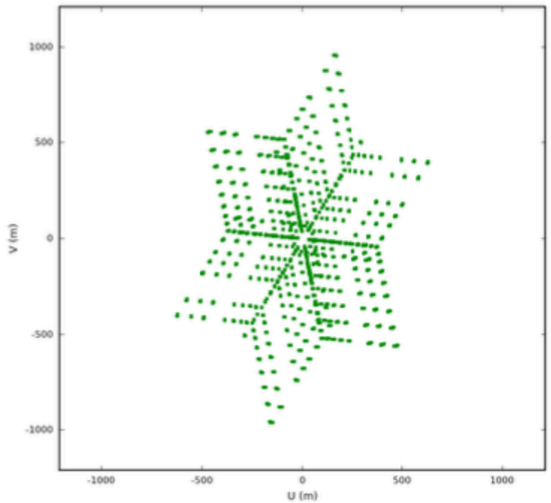




J1822-0938
(Gain Calibrator)

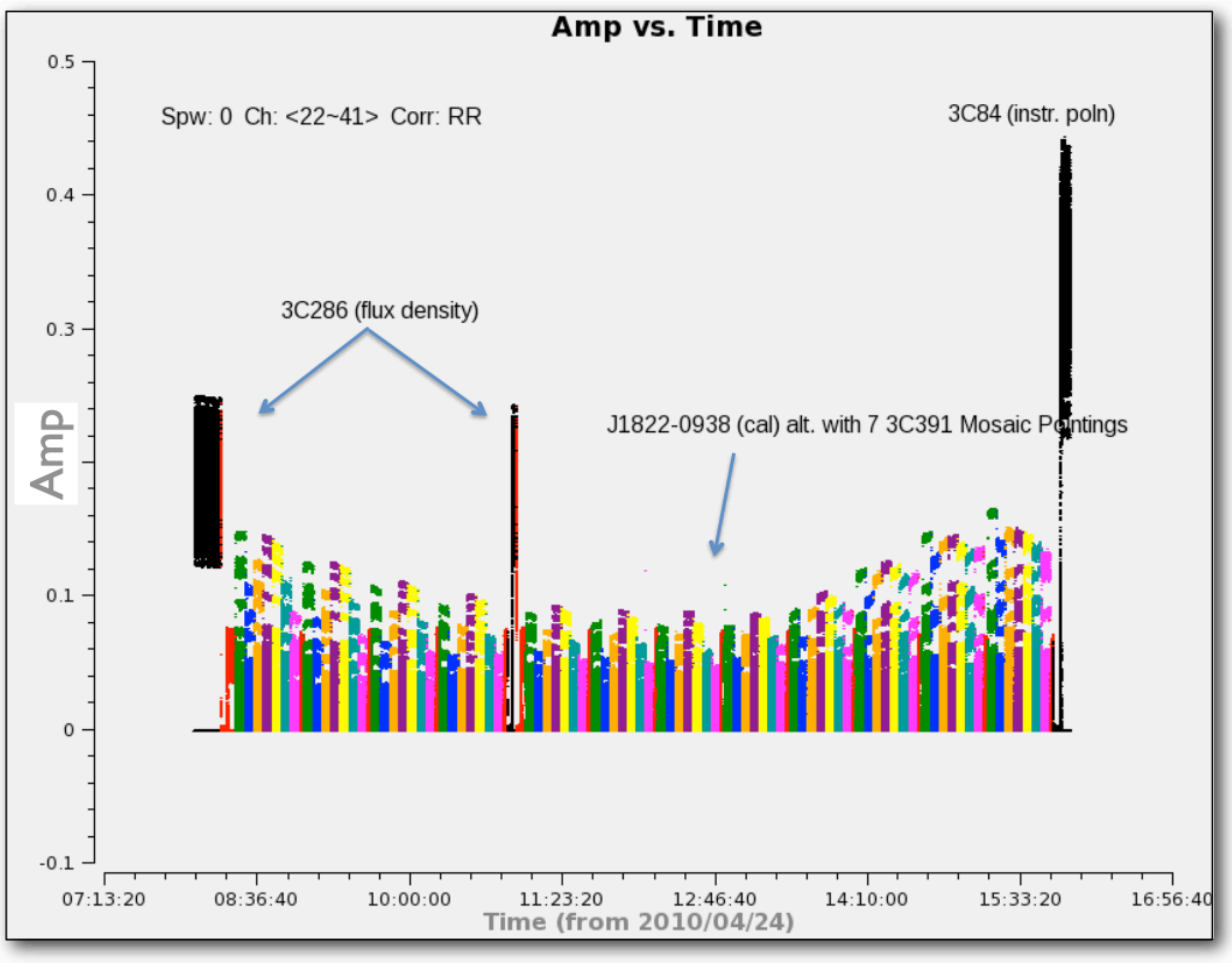
3C391
(Science Target)



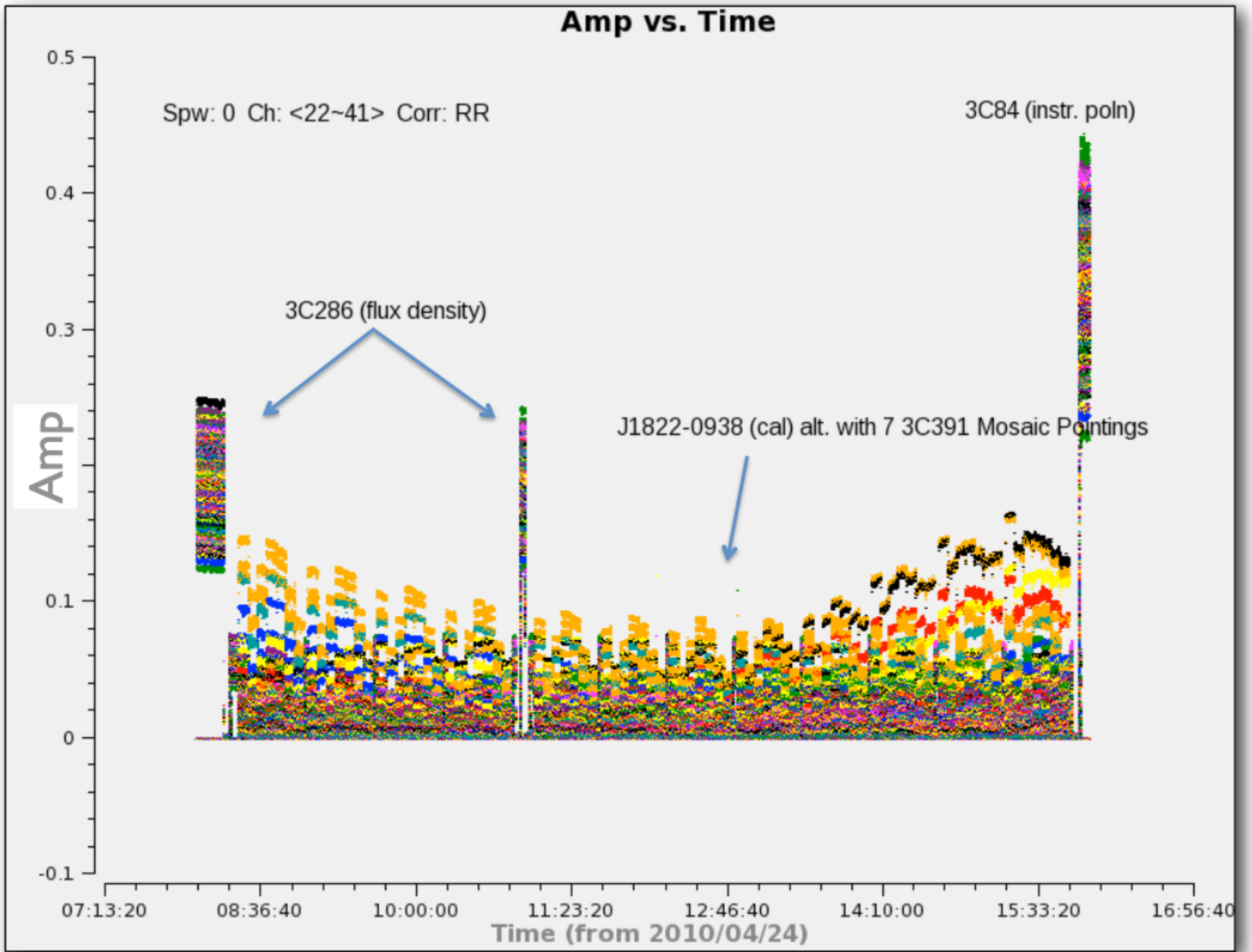


3C84
(Pol. Calibrator)

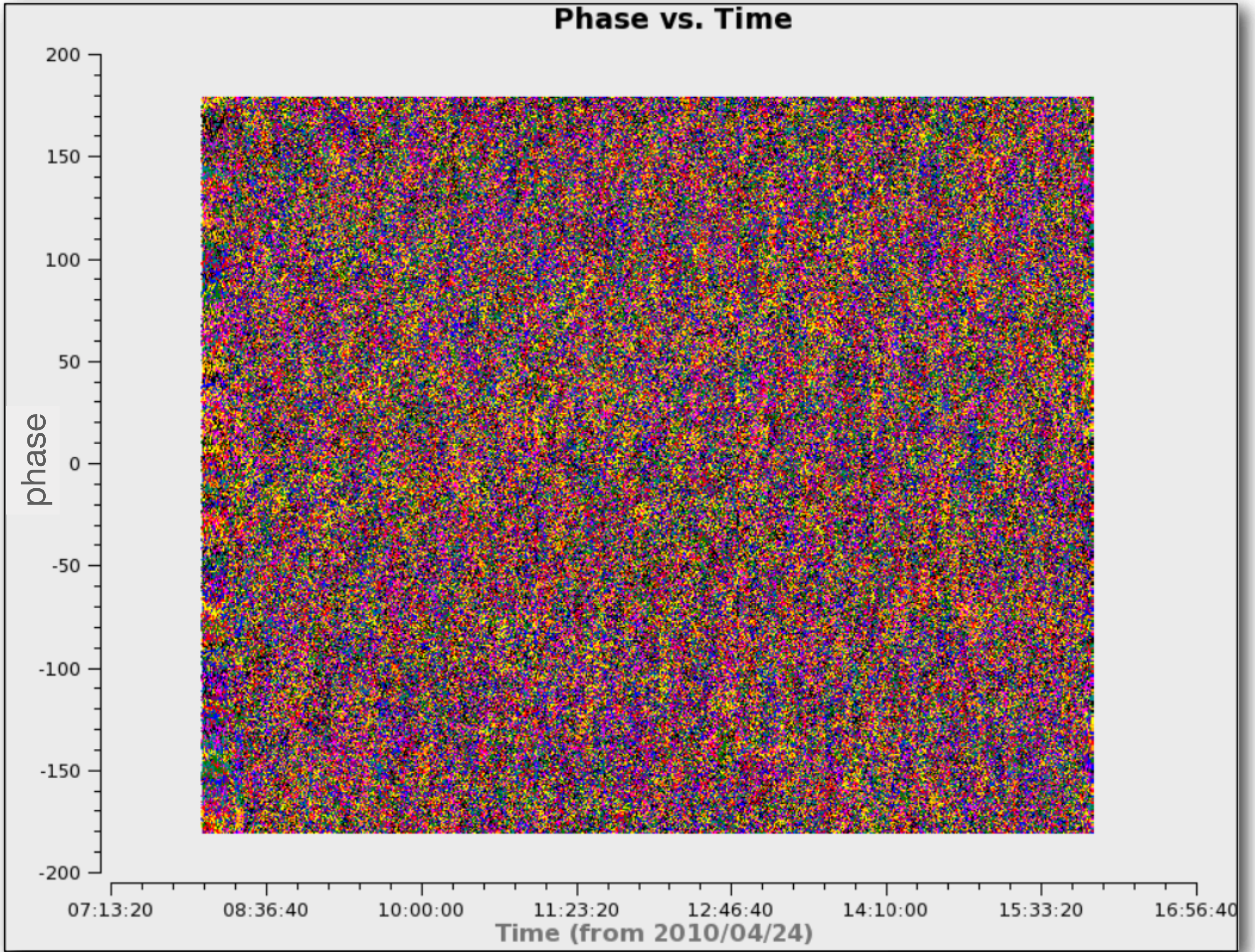
Visibilities (amplitude, color=different pointings)



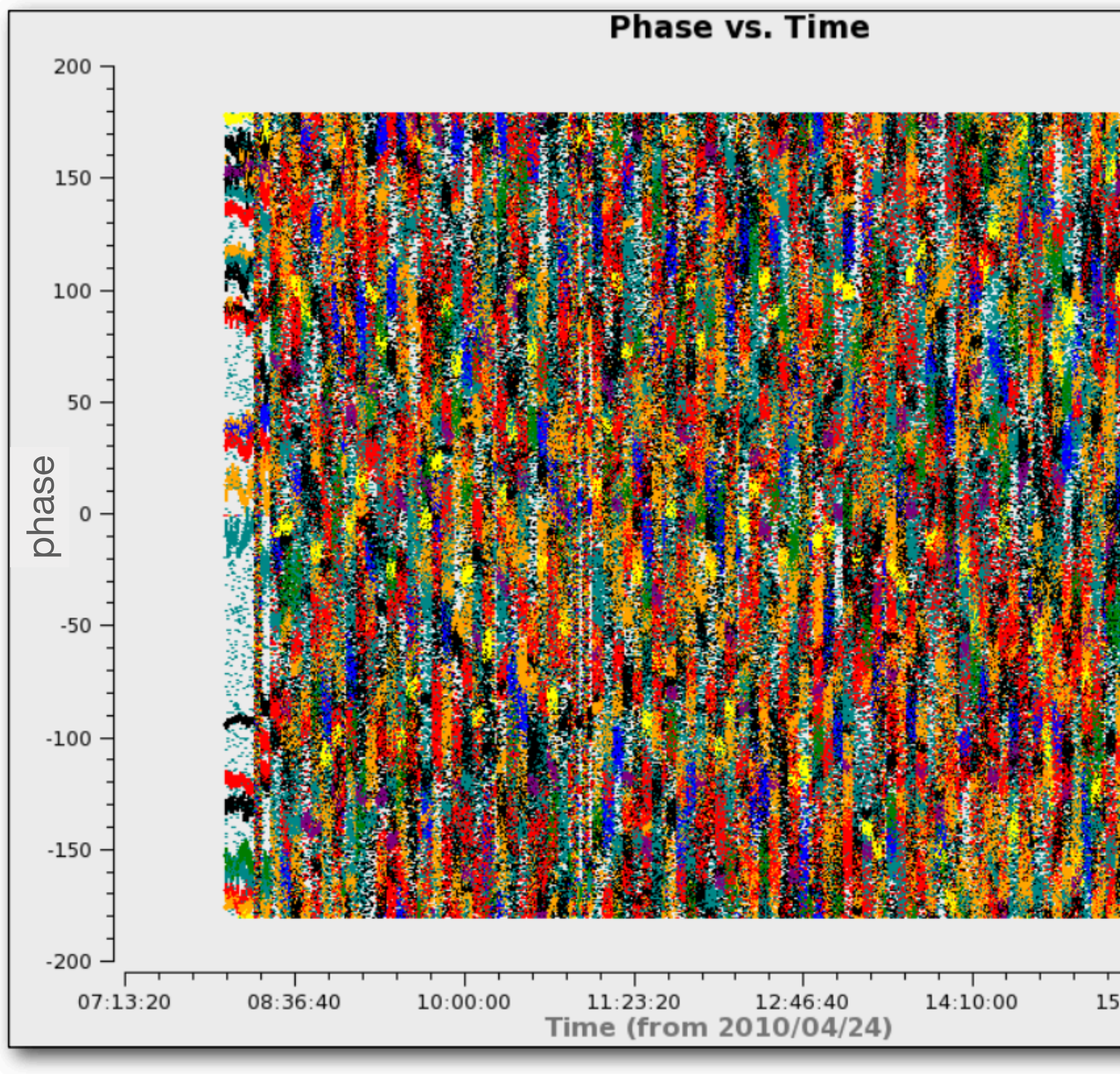
Visibilities (amplitude, color=different baselines)



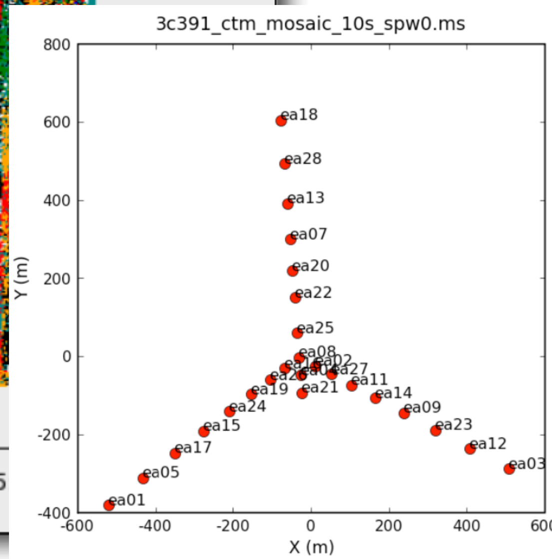
Visibilities (phases, color=different baselines)



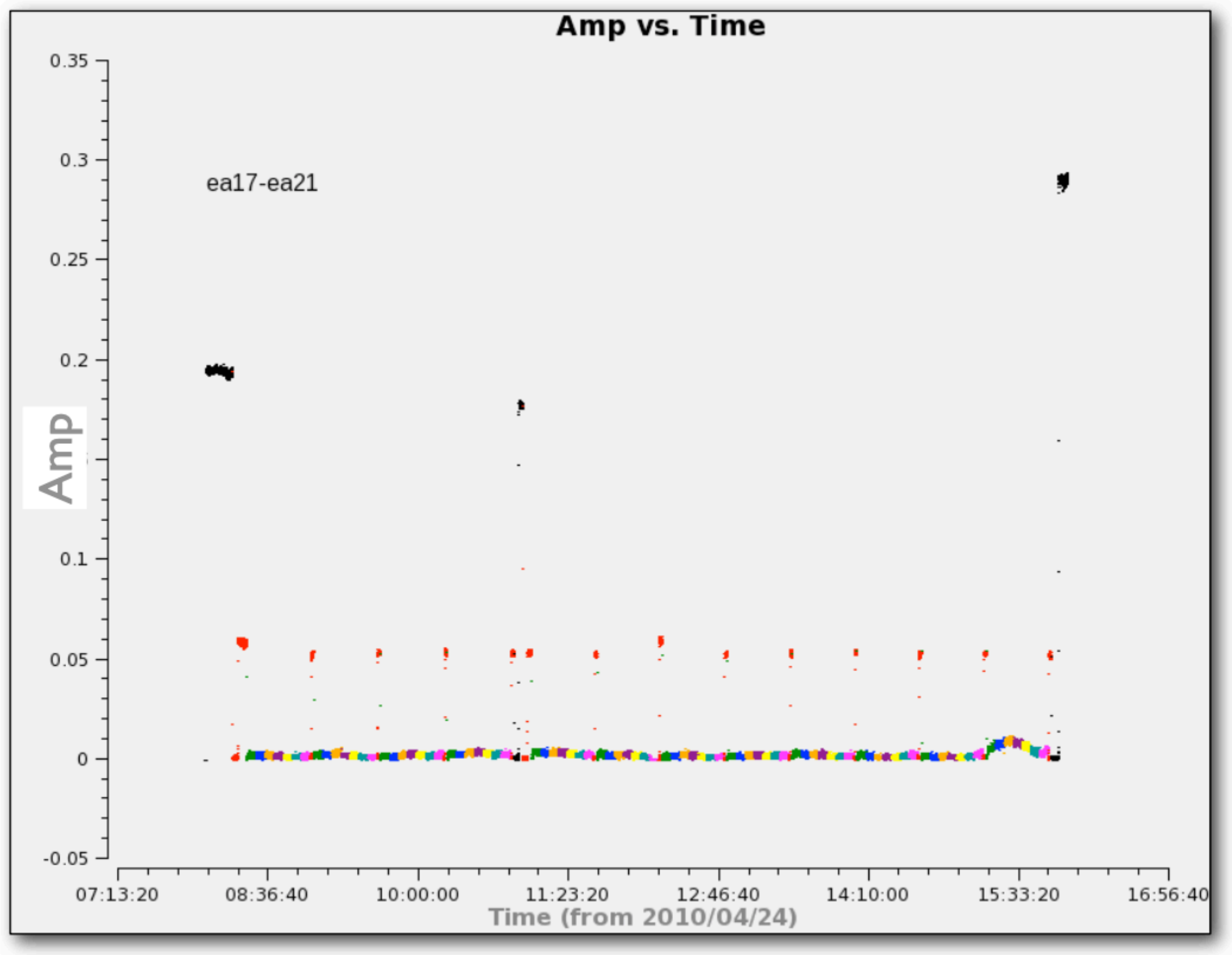
Visibilities (phases, baselines to just one antenna)

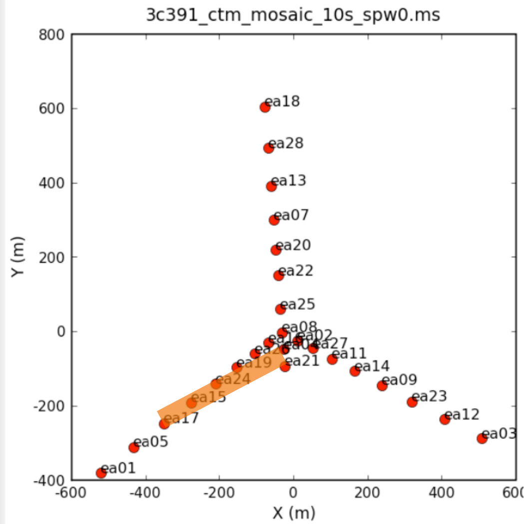


Baselines to antenna ea21

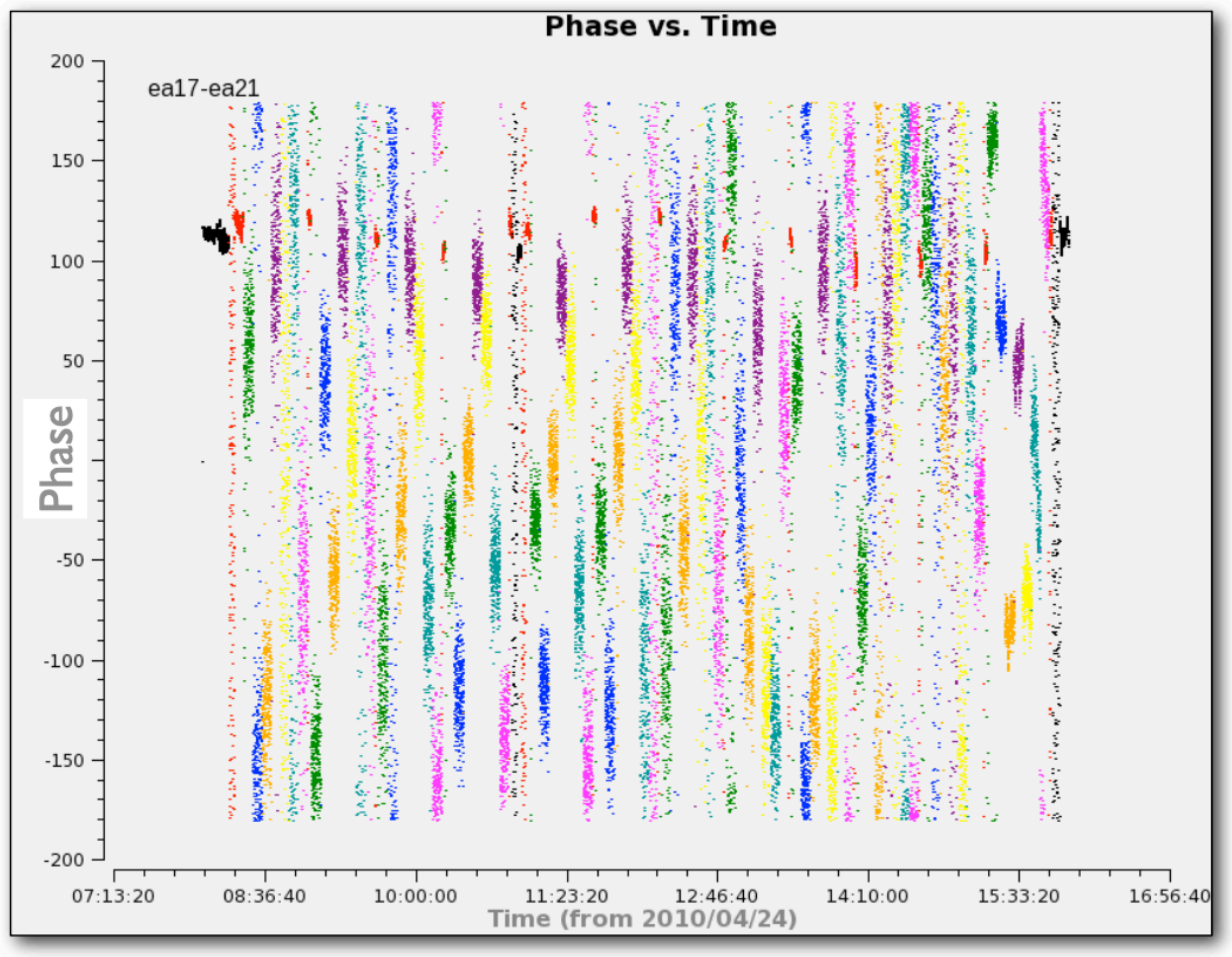


Visibilities (amplitude, singe baseline)



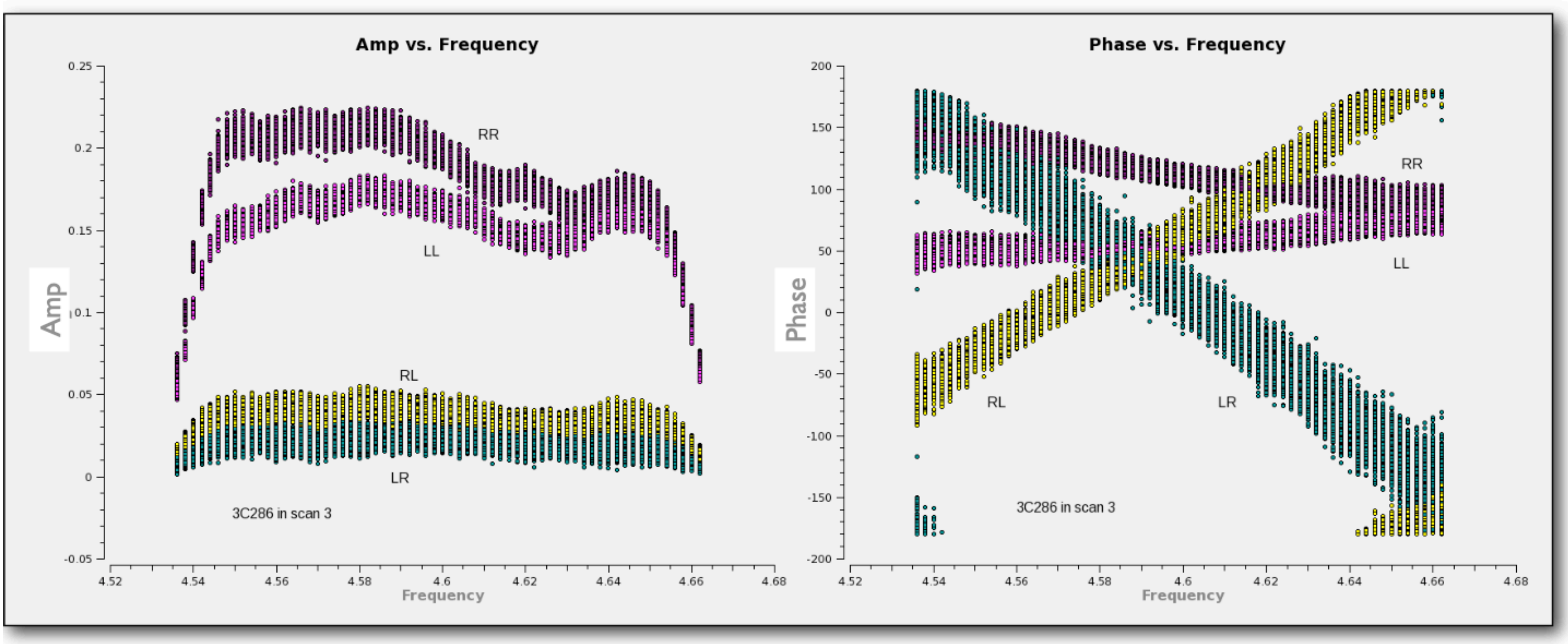


Visibilities (phase, singe baseline)



Visibilities (amplitude + phase, singe baseline)

vs. frequency



Baseline ea17-ea21 (all 4 polarizations)

Data Editing

- Initial data examination and editing very important
  - What to edit (much of this is automated):

  – Some real-time flagging occurred during observation

  – Any such bad data left over?

  – Any persistently “dead” antennas?

  – Periods of especially poor weather?

  – Amplitude and phase should be continuously varying $\Longrightarrow$ remove outliers – Any Radio Frequency Interference (RFI)?

- Caution:

  – Be careful editing noise-dominated data.

  – Be conservative $\Longrightarrow$ antennas or time-ranges which are bad on calibrators are probably bad on weak target sources $\Longrightarrow$ remove them

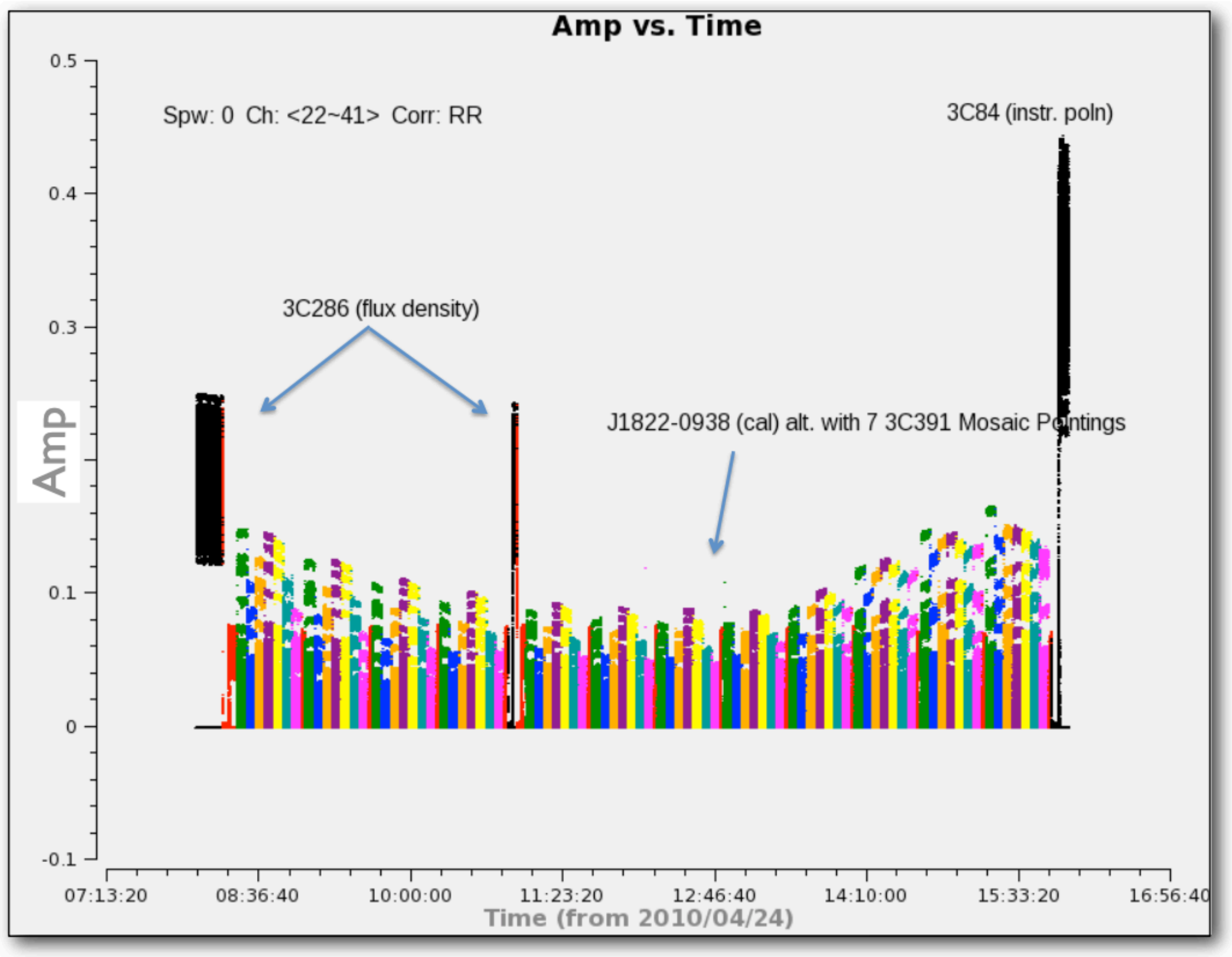
  – Distinguish between bad (hopeless) data and poorly-calibrated data. E.g., some antennas may have significantly different amplitude response which may not be fatal—it may only need to be calibrated

  – Choose (phase) reference antenna wisely (ever-present, stable response)

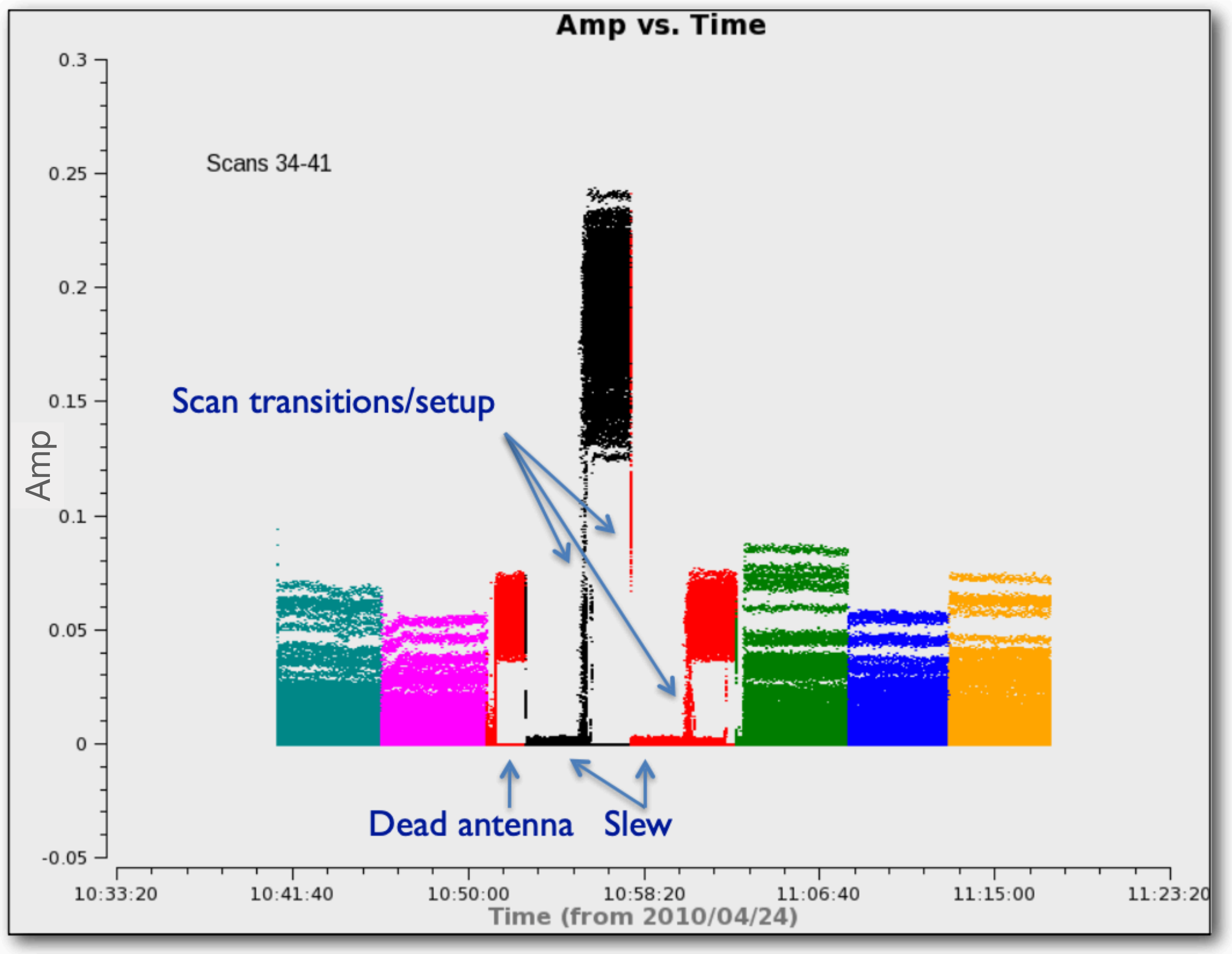
Increasing data volumes increasingly demand automated editing algorithms...

Bad data is worse than no data

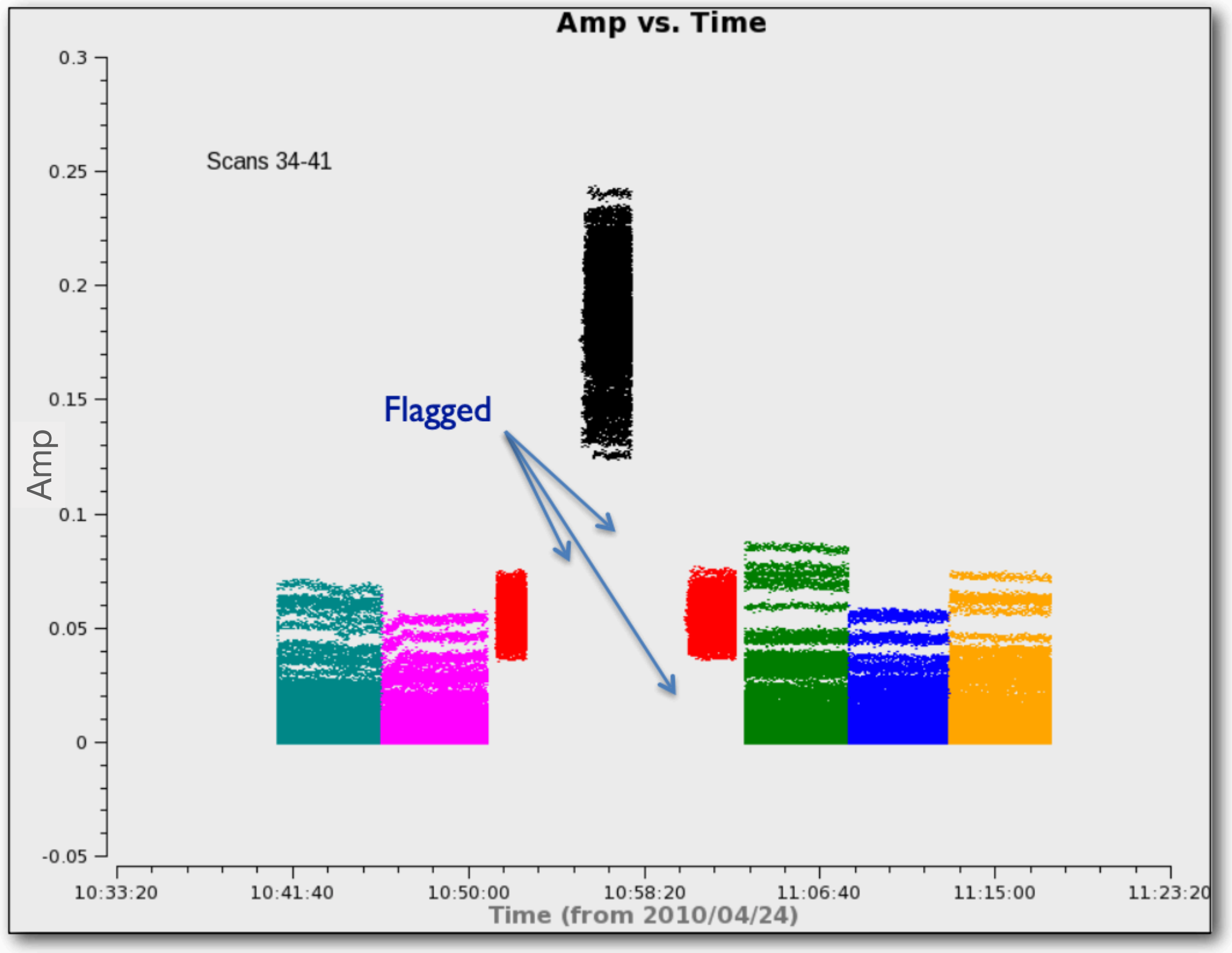
Data Editing: Example



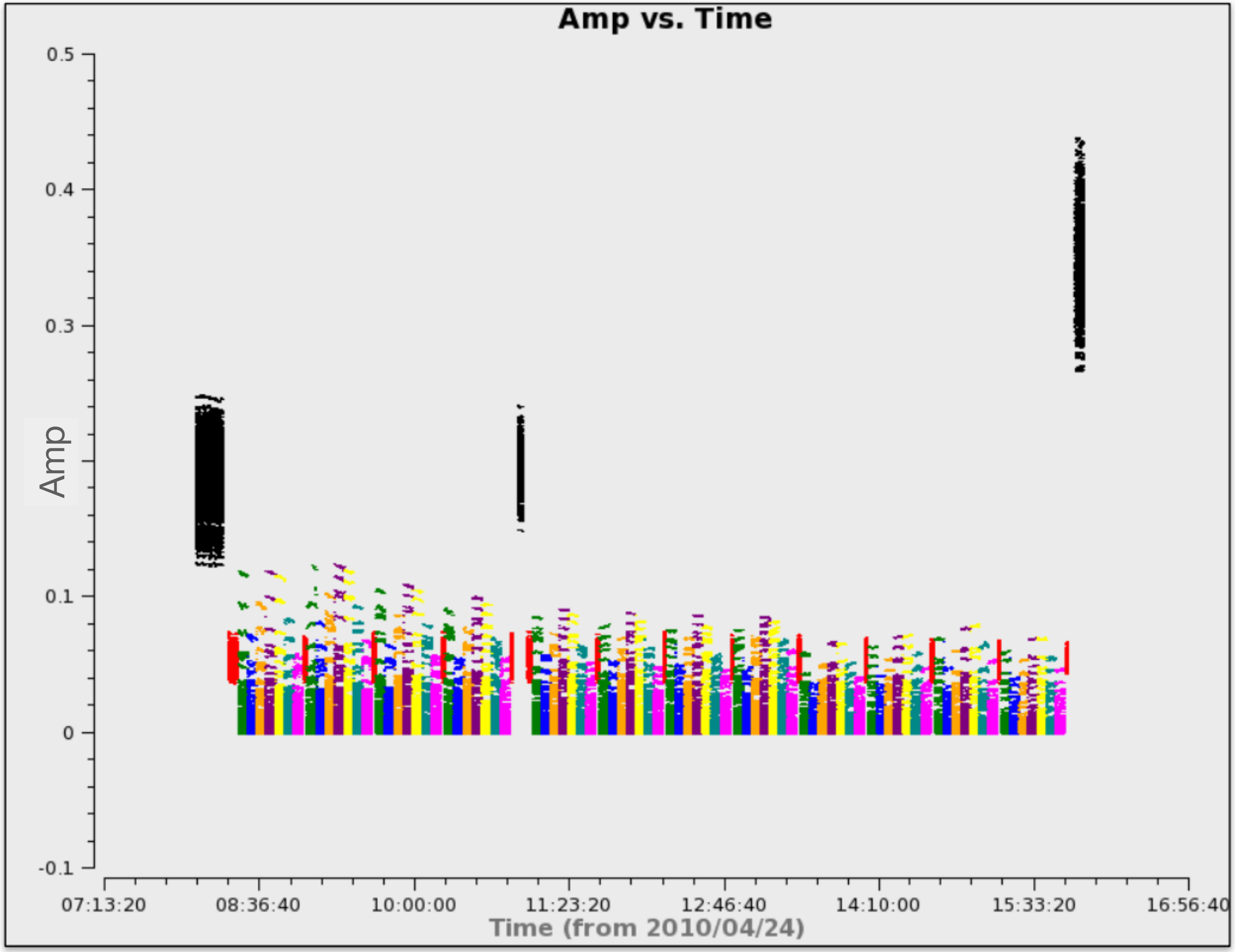
Data Editing: Example



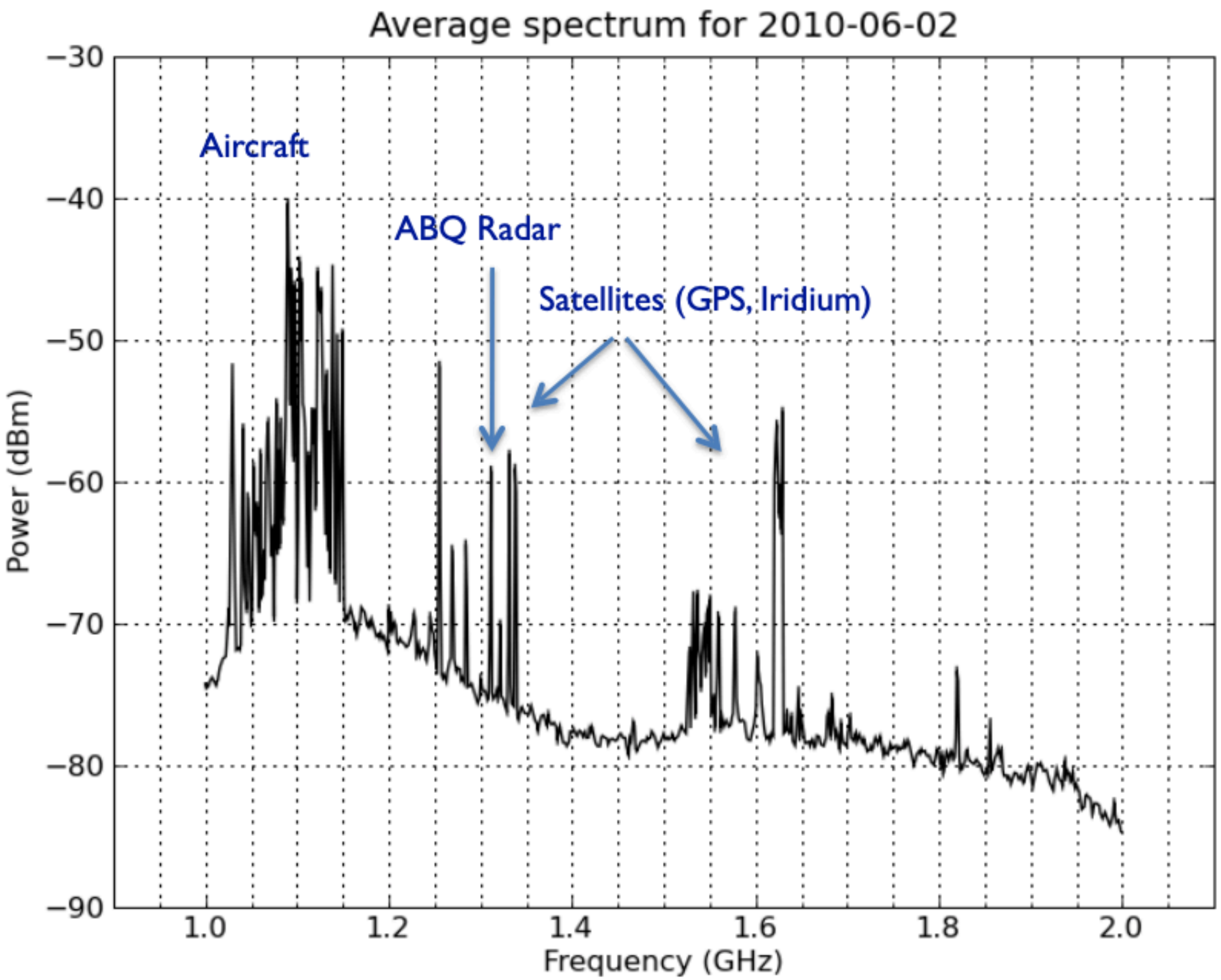
Data Editing: Example



Data Editing: Example

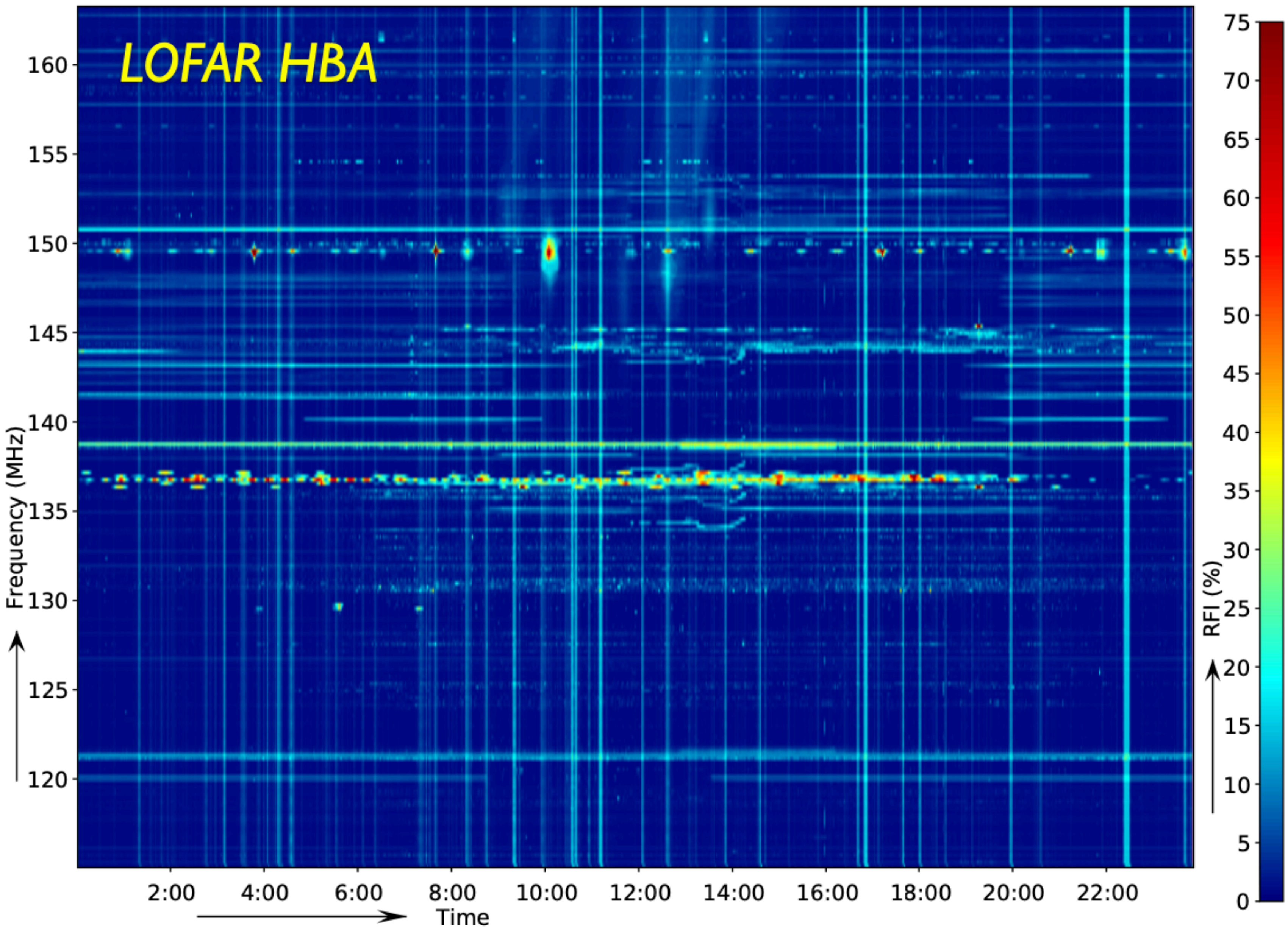


Radio Frequency Interference



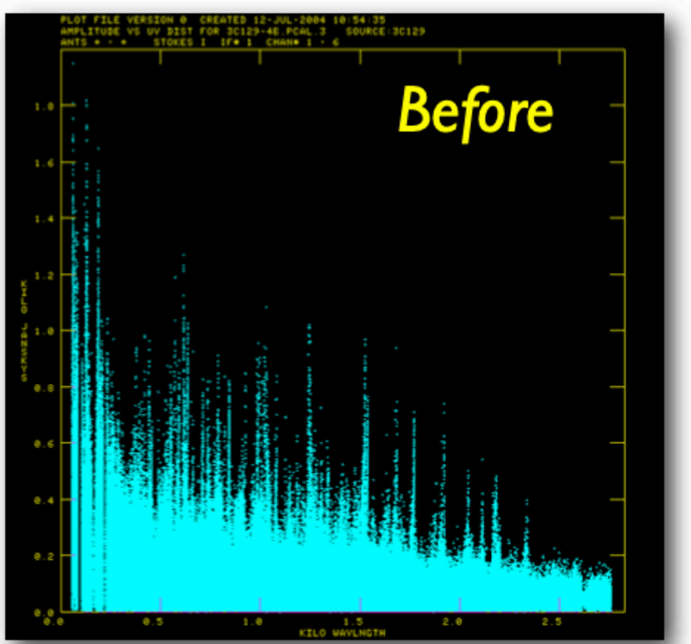
- RFI originates from man-made signals
- Generated in the antenna electronics or by external sources (e.g., satellites, air traffic, cell-phones, radio and TV stations, automobile ignitions, microwave ovens, computers and other electronic devices, etc.)
- Adds to total noise power in all observations, thus decreasing the fraction of desired natural signal passed to the correlator —> reduced sensitivity.
- Can correlate between antennas if of common origin and baseline short enough, thereby obscuring natural emission in spectral line observations
- Least predictable, least controllable threat to a radio astronomy observation

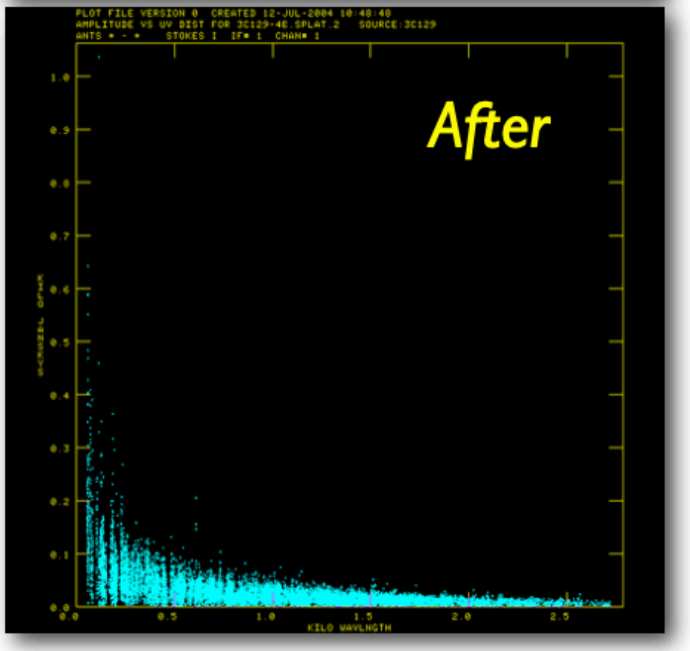
Radio Frequency Interference



Offringa et al. (2013)

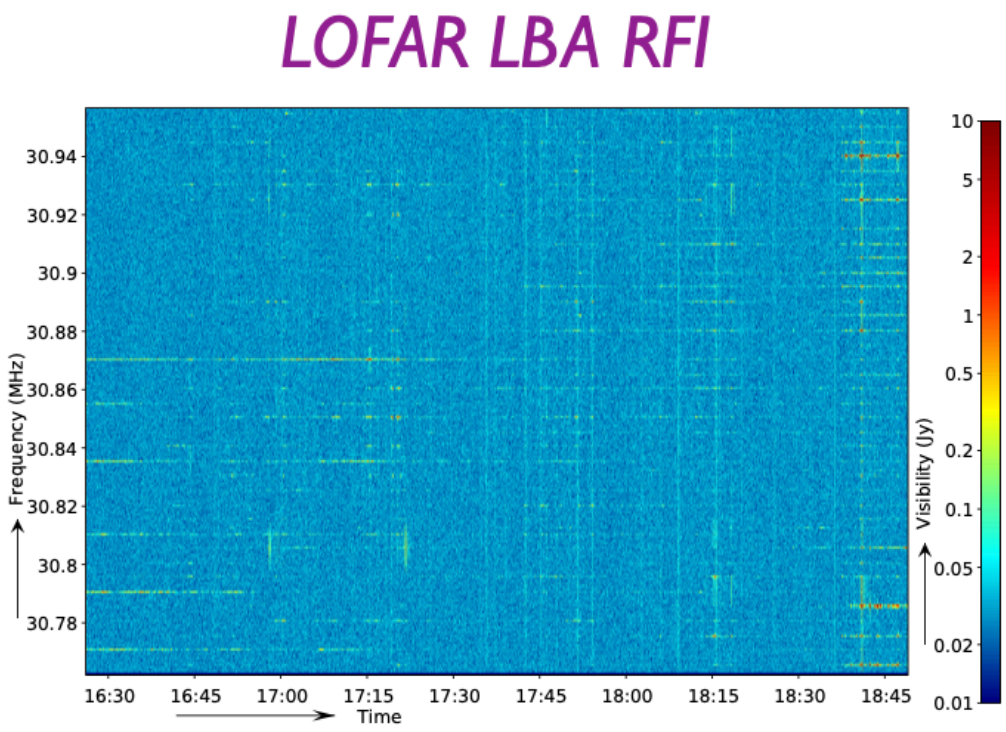
Radio Frequency Interference Removal

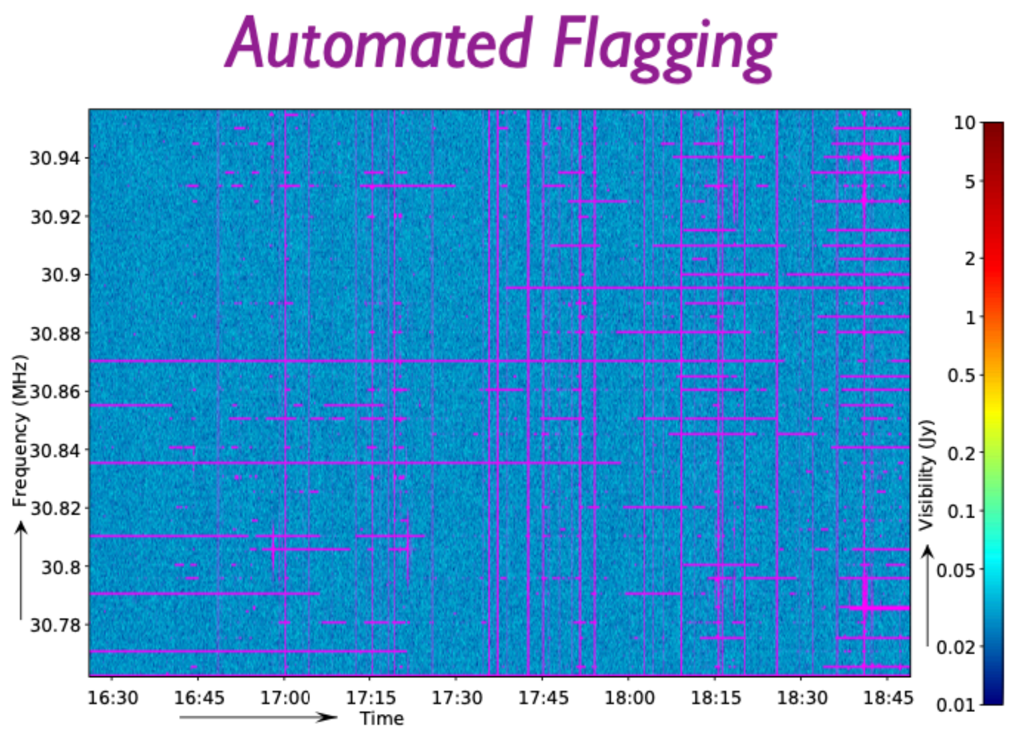




- RFI environment worse on short baselines
- Several 'types': narrow band, wandering, wideband, ...
- Wideband interference hard for automated routines
- Approach: averaging data in time and/or frequency makes it easier to isolate RFI, which averages coherently, from Gaussian noise, which does not
- Once identified, the affected times/baselines can be flagged in the un-averaged dataset
- Many tools available for manual editing: QUACK, SPFLG, TVFLG, UVPLT, UVFND, UVFLG, UVSUB, CLIP, FLGIT, FLAGR, ...

Radio Frequency Interference Automated Removal





Offringa et al. (2013)

Fundamental calibration equation

$$V_{ij}(t) = g_i(t)g_j^*(t)V^{true}(t) + \varepsilon_{ij}(t)$$

$V_{ij}(t)$	Visibility measured between antennas i and j
$g_i(t)$	Complex gain of antenna i
$V^{true}(t)$	True visibility
$\varepsilon_{ij}(t)$	Additive noise

Solving this set of coupled, linear equations is the calibration process.

Calibration with a point source

$$V_{ij}(t) = g_i(t)g_j^*(t)S + \varepsilon_{ij}(t)$$

S Strength of point source

- Solve for antenna gains via least squares algorithm
- Works well - lots of redundancy
- (N-1) baselines contribute to gain estimate for any antenna
- Gains are antenna based and direction independent
- Also know as "cross calibration"

finding point sources

The VLA Calibrator Manual

Hop to RA [01] [02] [03] [04] [05] [06] [07] [08] [09] [10] [11] [12] [13] [14] [15] [16]

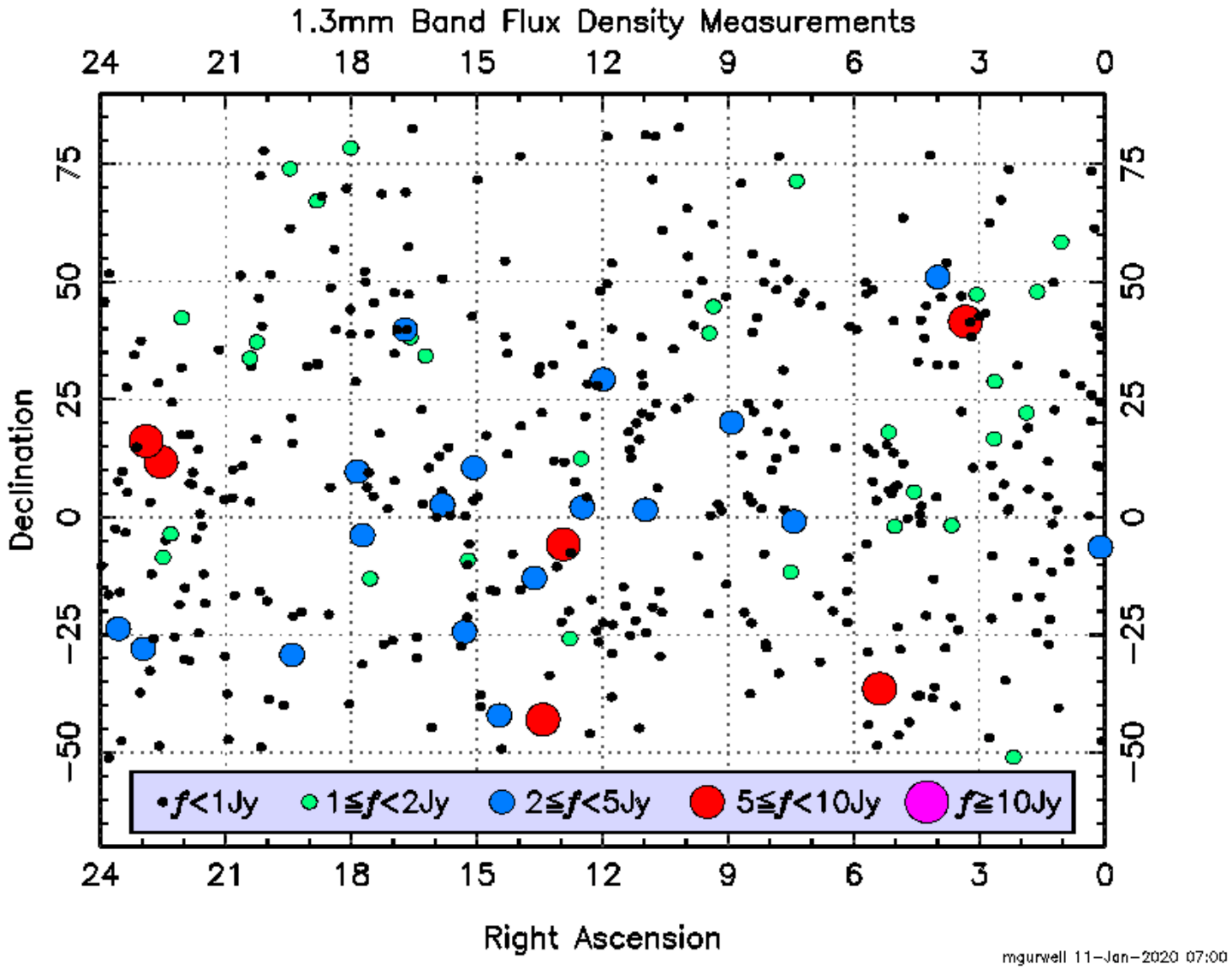
```
IAU NAME EQUINOX  PC RA(hh,mm,ss)     DEC(ddd,mm,ss)   POS.REF ALT.NAME
=======================================================================

0001+192    J2000  A 00h01m08.621563s  19d14'33.801860"  Aug01  JVAS
2358+189    B1950  A 23h58m34.865400s  18d57'51.753000"
-----------------------------------------------------
BAND        A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
0.7cm    Q  W W W W       0.18

0003-174    J2000  T 00h03m21.9969s   -17d27'11.781"
0000-177    B1950  T 00h00m48.4200s   -17d43'54.000"
-----------------------------------------------------
BAND        A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
 90cm    P  X S S S          7                     7
 20cm    L  X X X S        2.2                     7

0004+462    J2000  A 00h04m16.127651s  46d15'17.970010"  Aug01
0001+459    B1950  A 00h01m41.453100s  45d58'36.145000"
-----------------------------------------------------
BAND        A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
0.7cm    Q  W W W W       0.12

0004+203    J2000  B 00h04m35.7576s    20d19'42.249"     May01  JVAS
0002+200    B1950  B 00h02m01.6329s    20d03'00.311"
-----------------------------------------------------
BAND        A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
0.7cm    Q  W W W W       0.21

0005+544    J2000  A 00h05m04.363531s  54d28'24.926230"  Aug01
0002+541    B1950  A 00h02m29.056400s  54d11'43.187000"
-----------------------------------------------------
BAND        A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
  2cm    U  S S S S       0.48
0.7cm    Q  W W W W       0.46

0005+383    J2000  A 00h05m57.175409s  38d20'15.148570"  Aug01  CJ2
0003+380    B1950  A 00h03m22.335500s  38d03'33.410000"
-----------------------------------------------------
BAND        A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
 20cm    L  X X X X       0.52                      visplot
  6cm    C  P P P P       0.80                      visplot
3.7cm    X  P P P P       1.1
  2cm    U  S S S S       0.67                      visplot
0.7cm    Q  S S S S       0.8

0006-063    J2000  A 00h06m13.892894s -06d23'35.335300"  Aug01
0003-066    B1950  A 00h03m40.288800s -06d40'17.300000"
-----------------------------------------------------
BAND        A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
 20cm    L  S X X X       1.60          45
  6cm    C  P P P P       1.30
3.7cm    X  P P P P       1.60
  2cm    U  P P P P       1.10
0.7cm    Q  S S S S       1.5
```

```
Col 1 & 2:     Band and Band code.  For 1.3cm use 2cm entry.
Col 3-6:       Calibrator quality in the A, B, C and D configuration
               determined using a 50 MHz observing bandwidth:

               P = <3% amplitude closure errors expected
               S = 3-10% closure errors expected
               W = 10-?% closure errors expected.  Suitable for
                   calibration of phases only.
               C = Confused
               X = Do not use.  Too much resolution or too weak
               ? = Structure unknown

Col 7:         Flux = The approximate flux density of the source.
               Use only as an indicator of the source strength.

Col 8 & 9:     CALIB restrictions.  These are suggested UVLIMITS in
               thousands of wavelengths to use in CALIB to avoid
               data which are contaminated by structure.  A UVMIN
               (Col. 8) generally means the source is confused at
               short spacings.  A UVMAX (Col. 9) generally means the
               source is resolved at long spacings.  Setting WTUV=0.1
               in CALIB will help to ensure stability.
```

note: point sources are not necessarily point sources at all frequencies!

Available calibrators

note: for SMA



Calibration using a complex model

$$V_{ij}(t) = g_i(t) g_j^*(t) V_{ij}^{\text{model}} + \varepsilon_{ij}(t)$$

V_{ij}^{model} Model visibility

- Redundancy means that errors in the model average down
- Have N(N-1) equations with N unknowns

Why is a priori calibration insufficient?

Initial calibration based on calibrator observed before and/or after target

Gains were derived at a different time

– Troposphere and ionosphere are variable

– Electronics may be variable

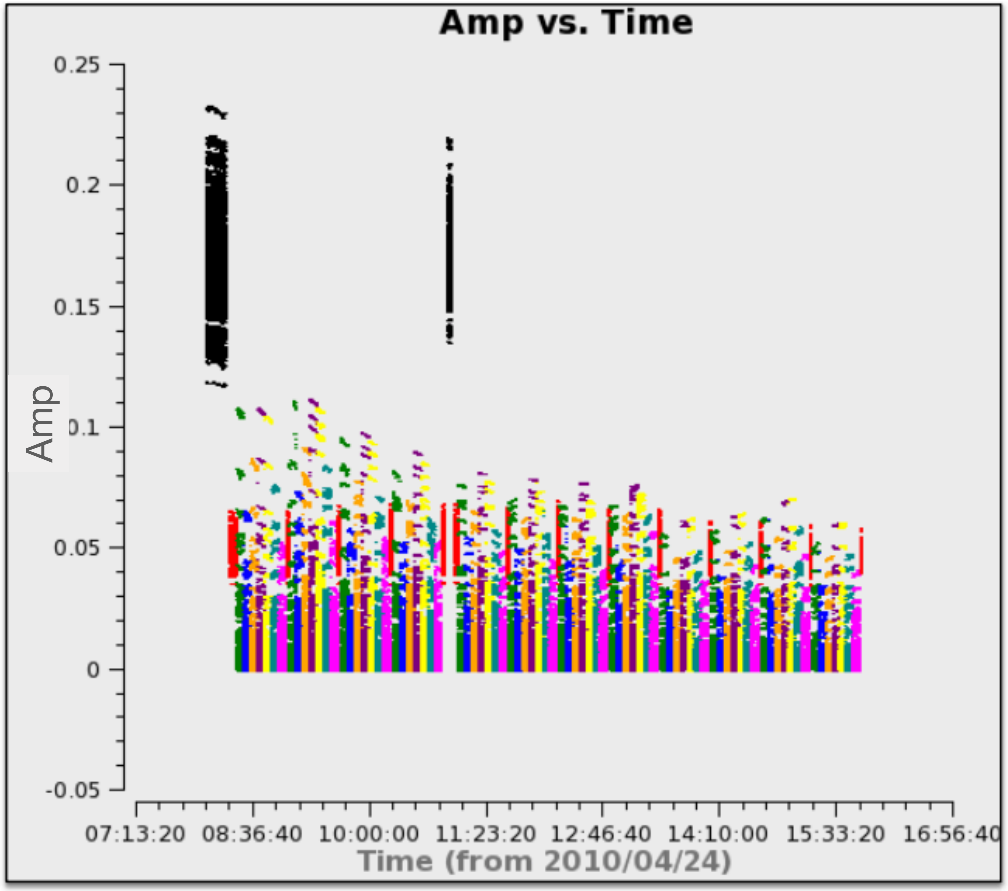
Gains were derived for a different direction

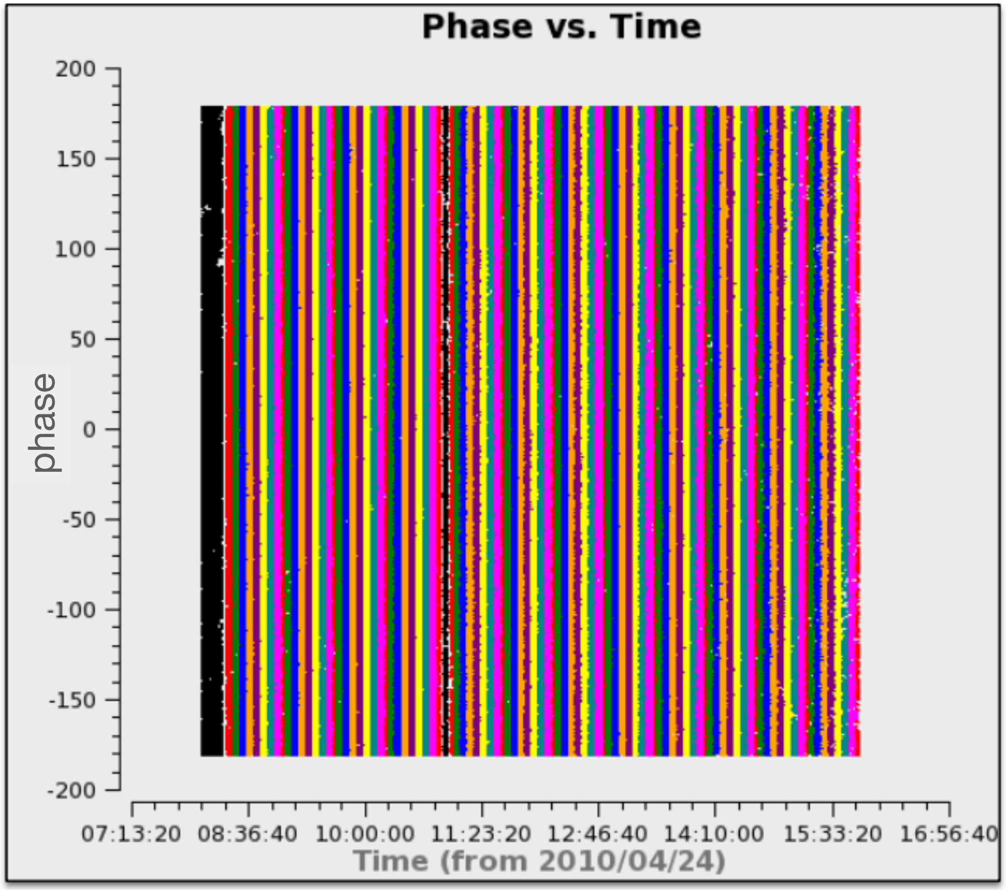
– Troposphere and ionosphere are not uniform

– > 1 GHz $\Longrightarrow$ troposphere, < 1 GHz $\Longrightarrow$ ionosphere

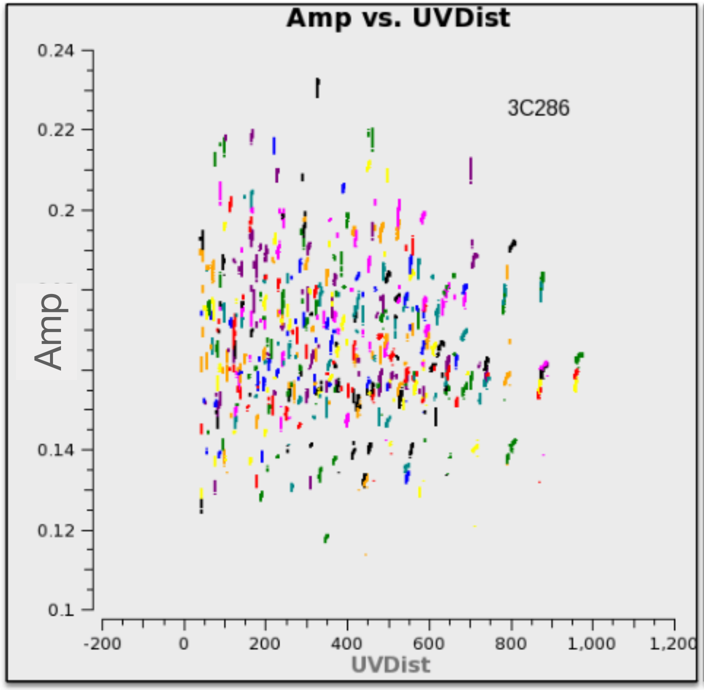
Observation might have been scheduled poorly for the existing conditions

Uncalibrated Data

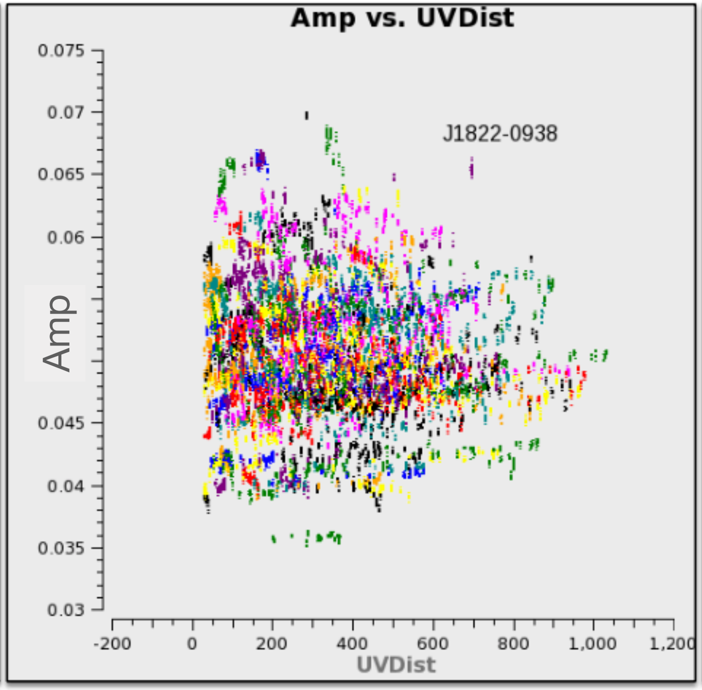




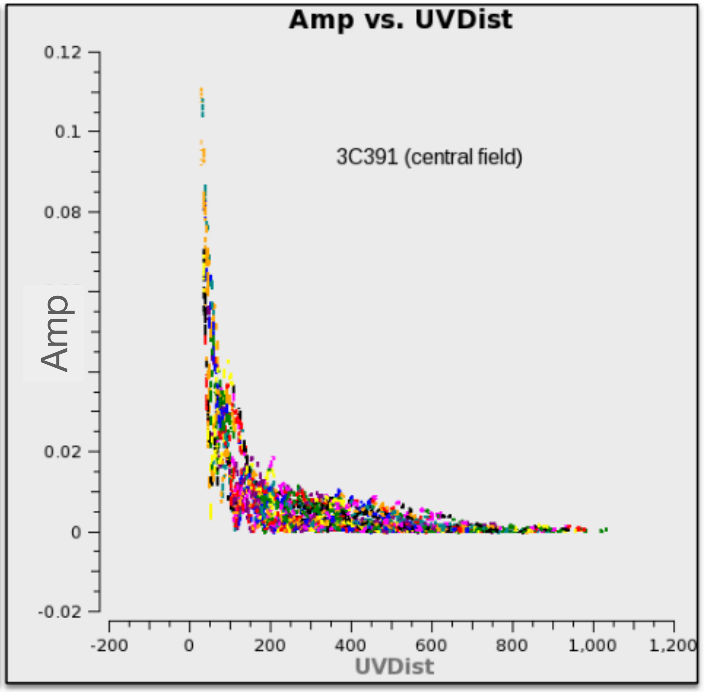
Uncalibrated Data - Amplitudes



flux density calibrator

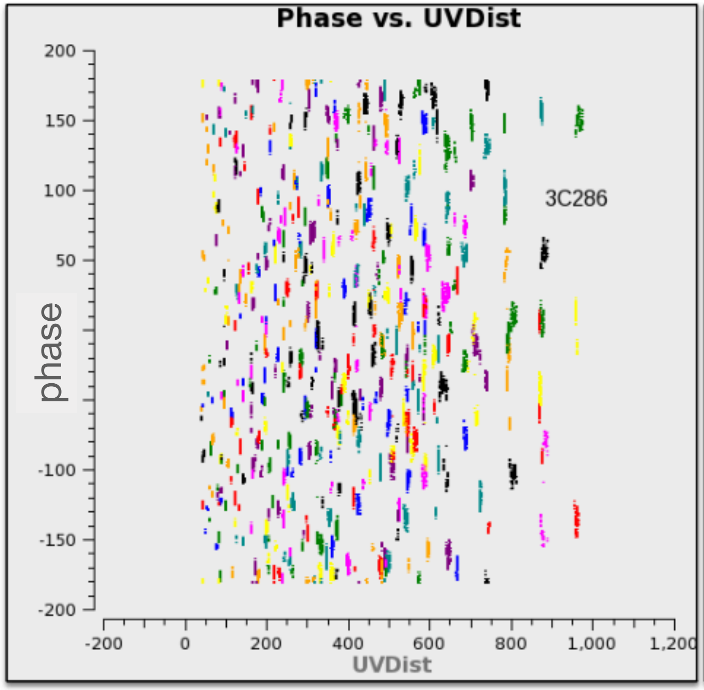


gain calibrator

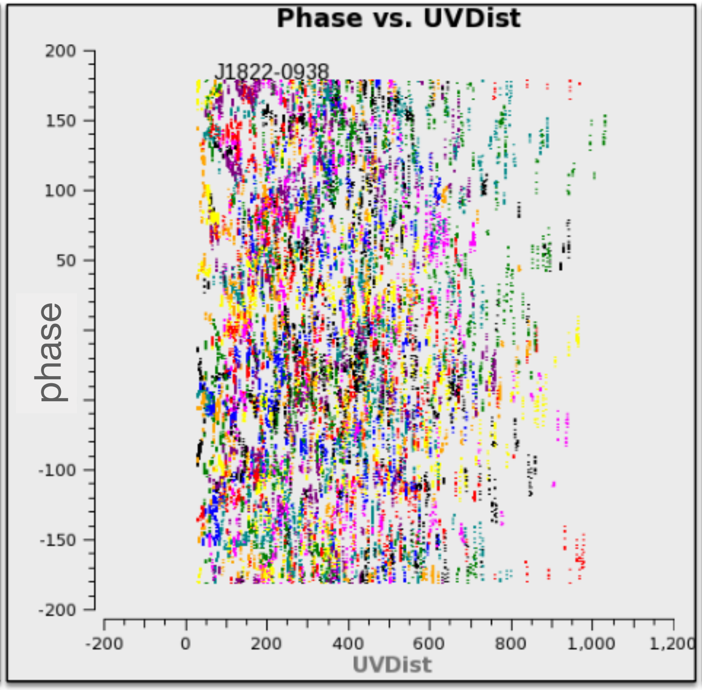


target

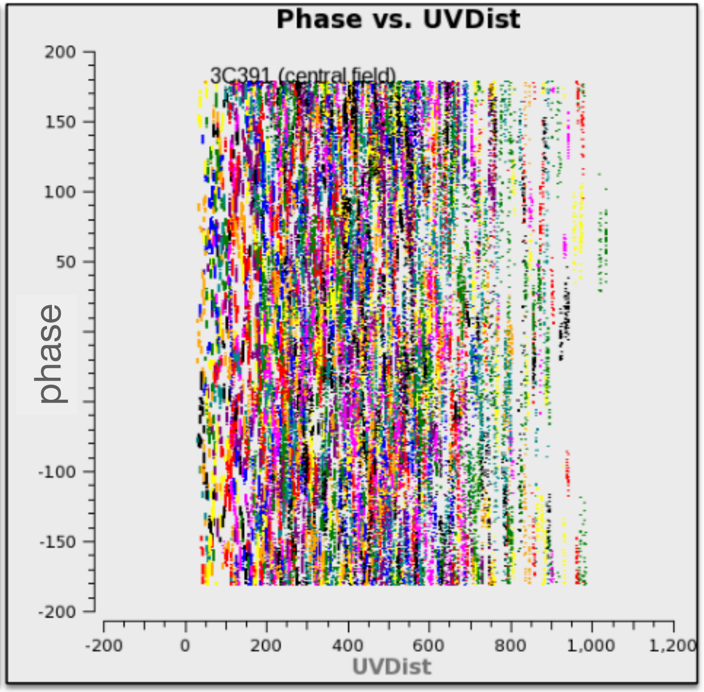
Uncalibrated Data - Phases



flux density calibrator

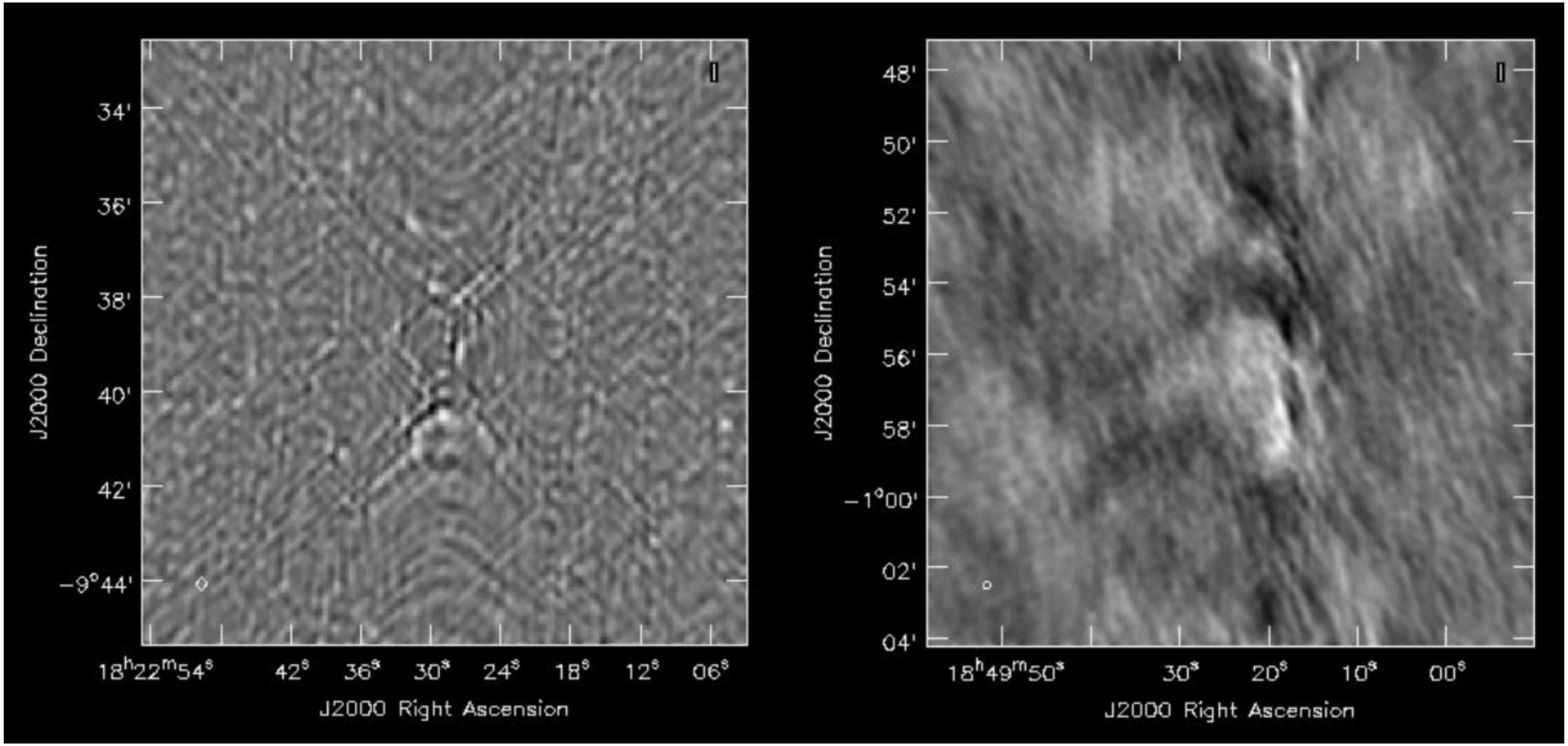


gain calibrator



target

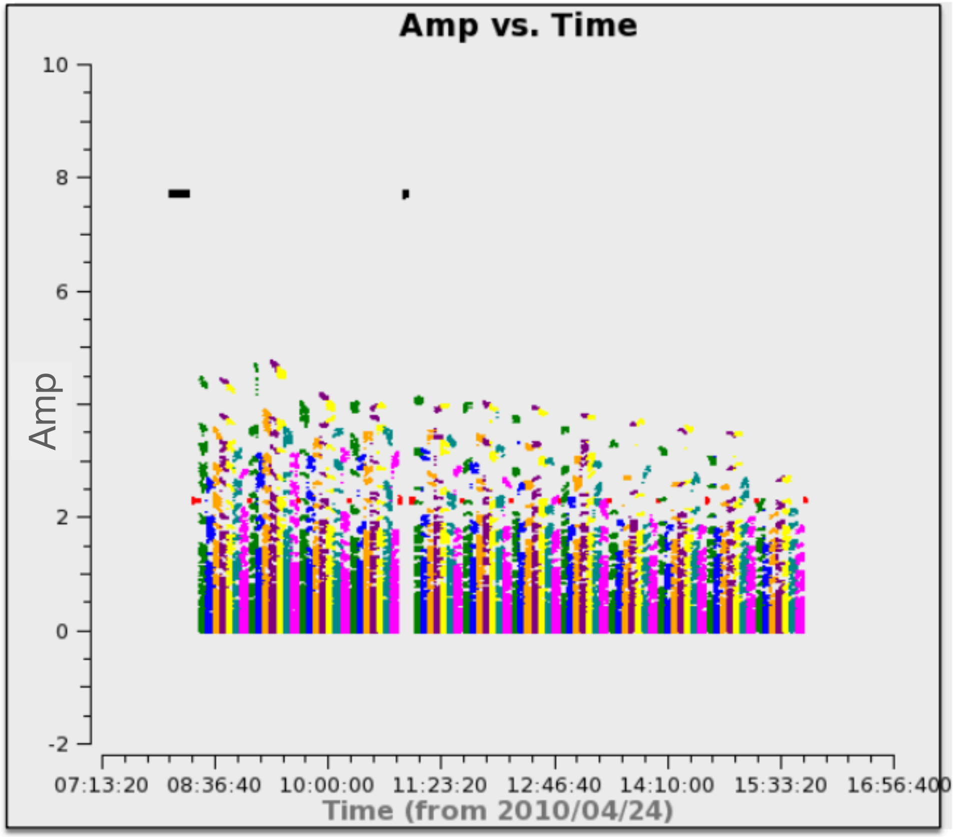
Uncalibrated Images

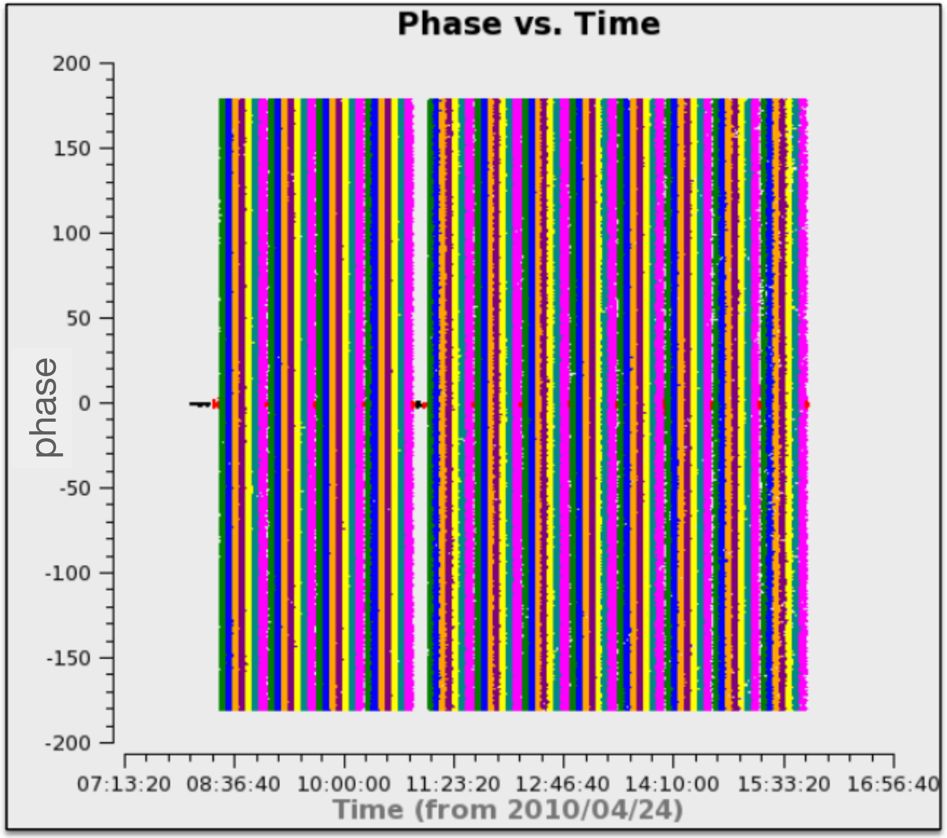


J1822-0938
(calibrator)

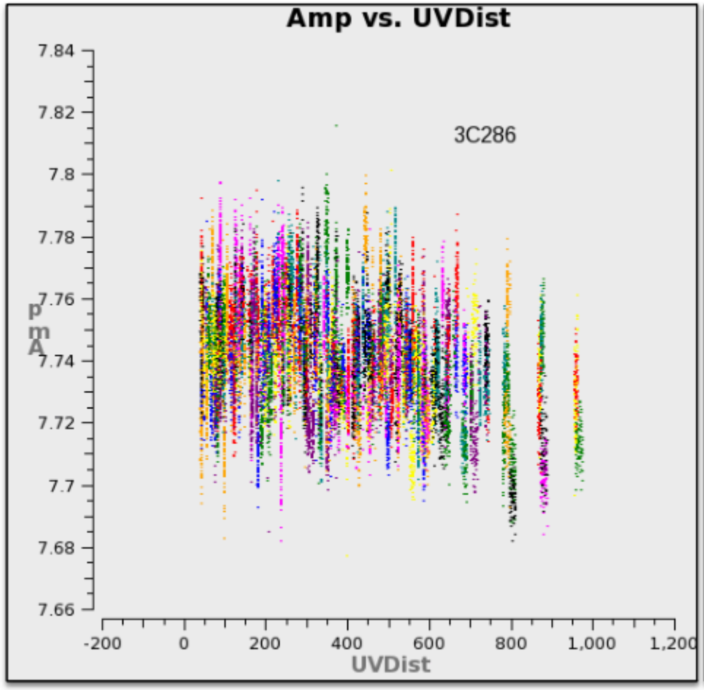
3C391
(science target)

Calibrated Data

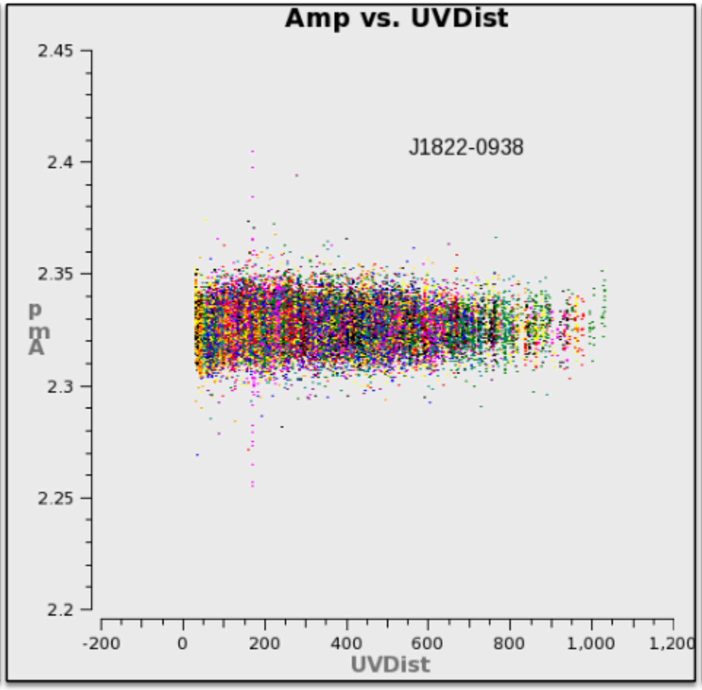




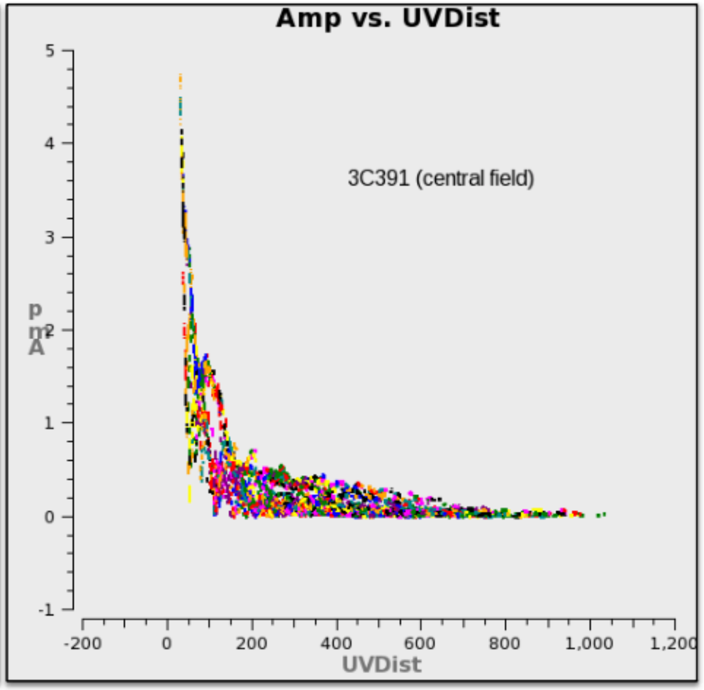
Calibrated Data - Amplitudes



flux density calibrator

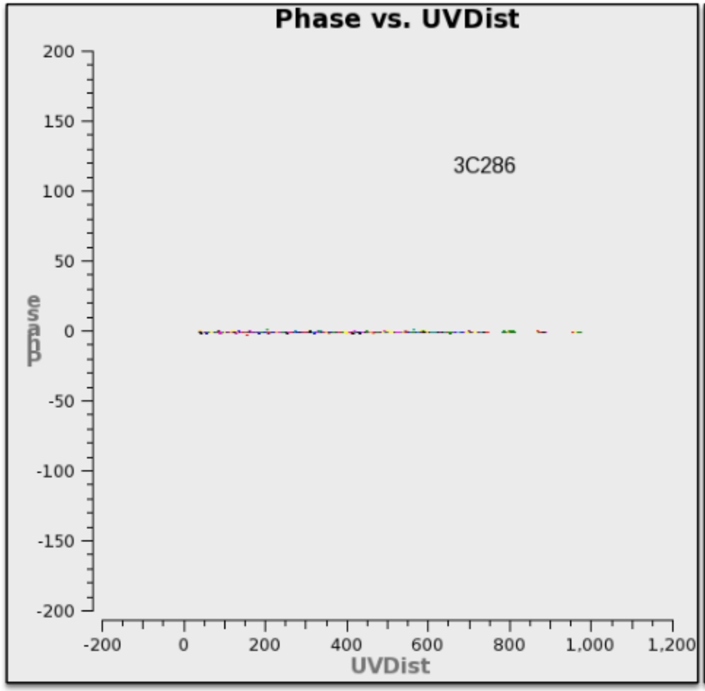


gain calibrator

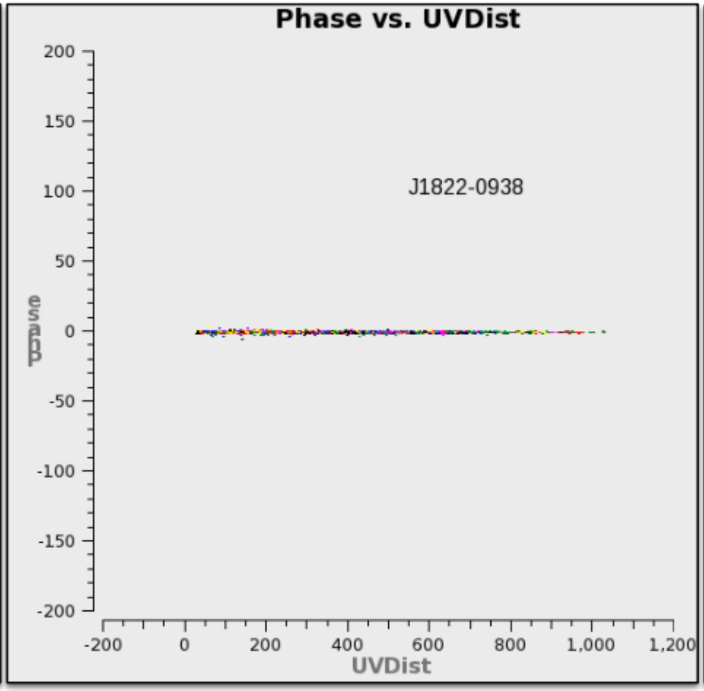


target

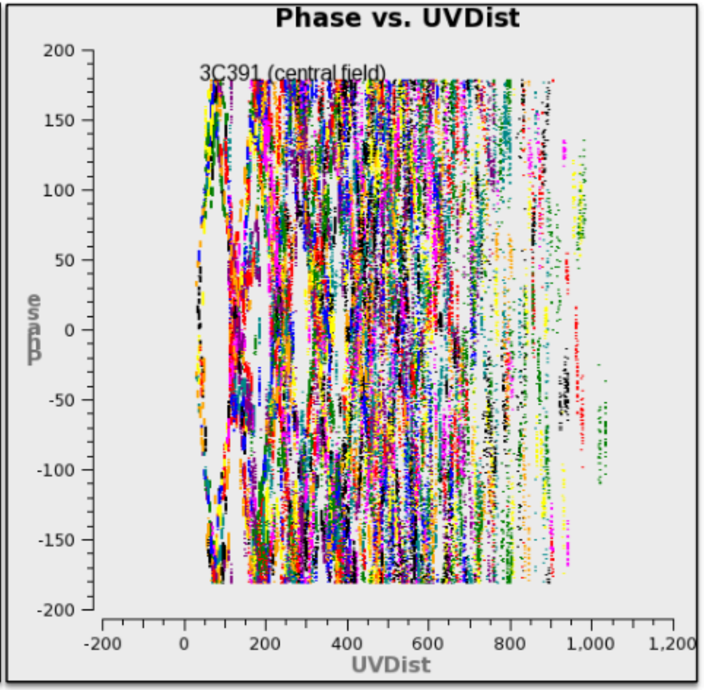
Calibrated Data - phases



flux density calibrator

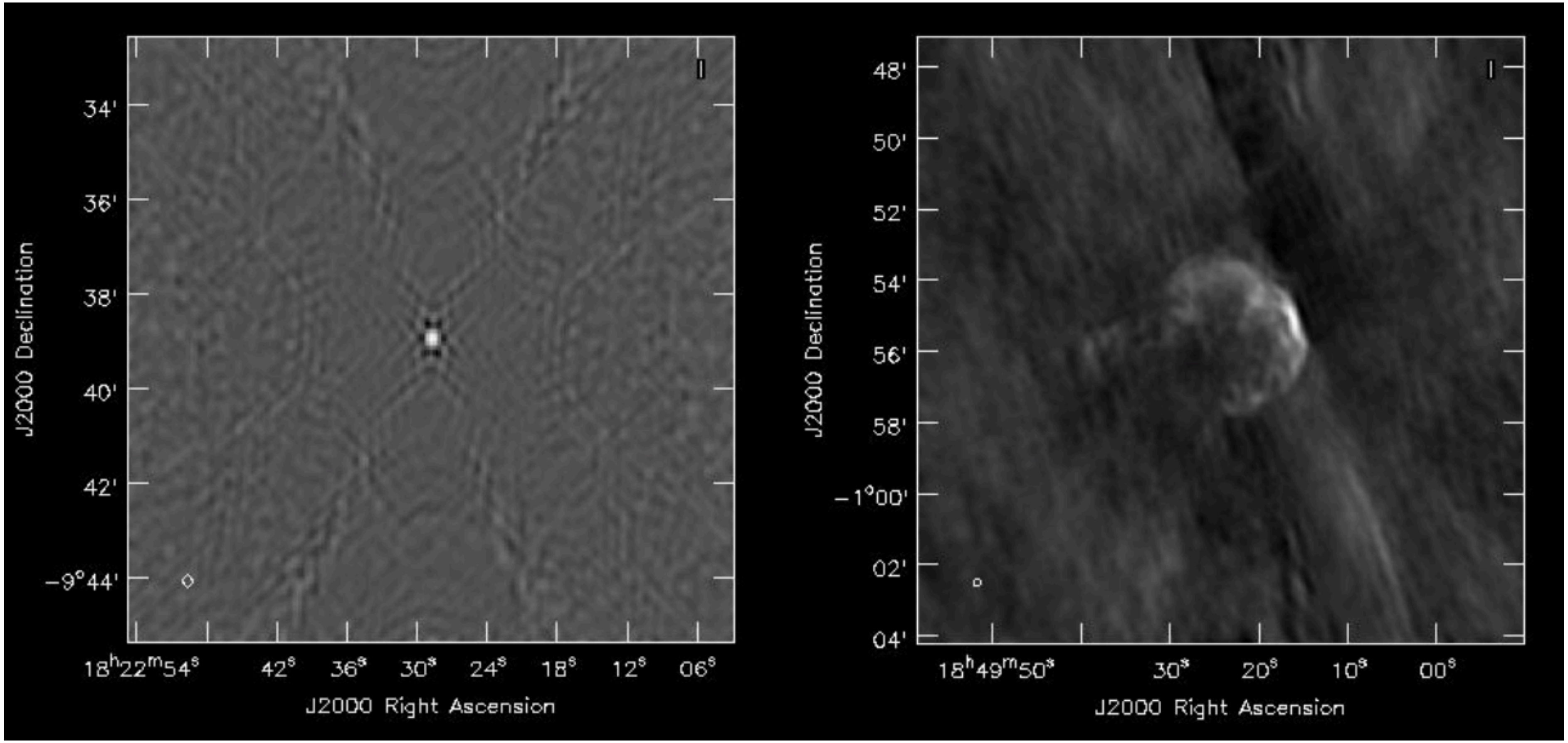


gain calibrator



target

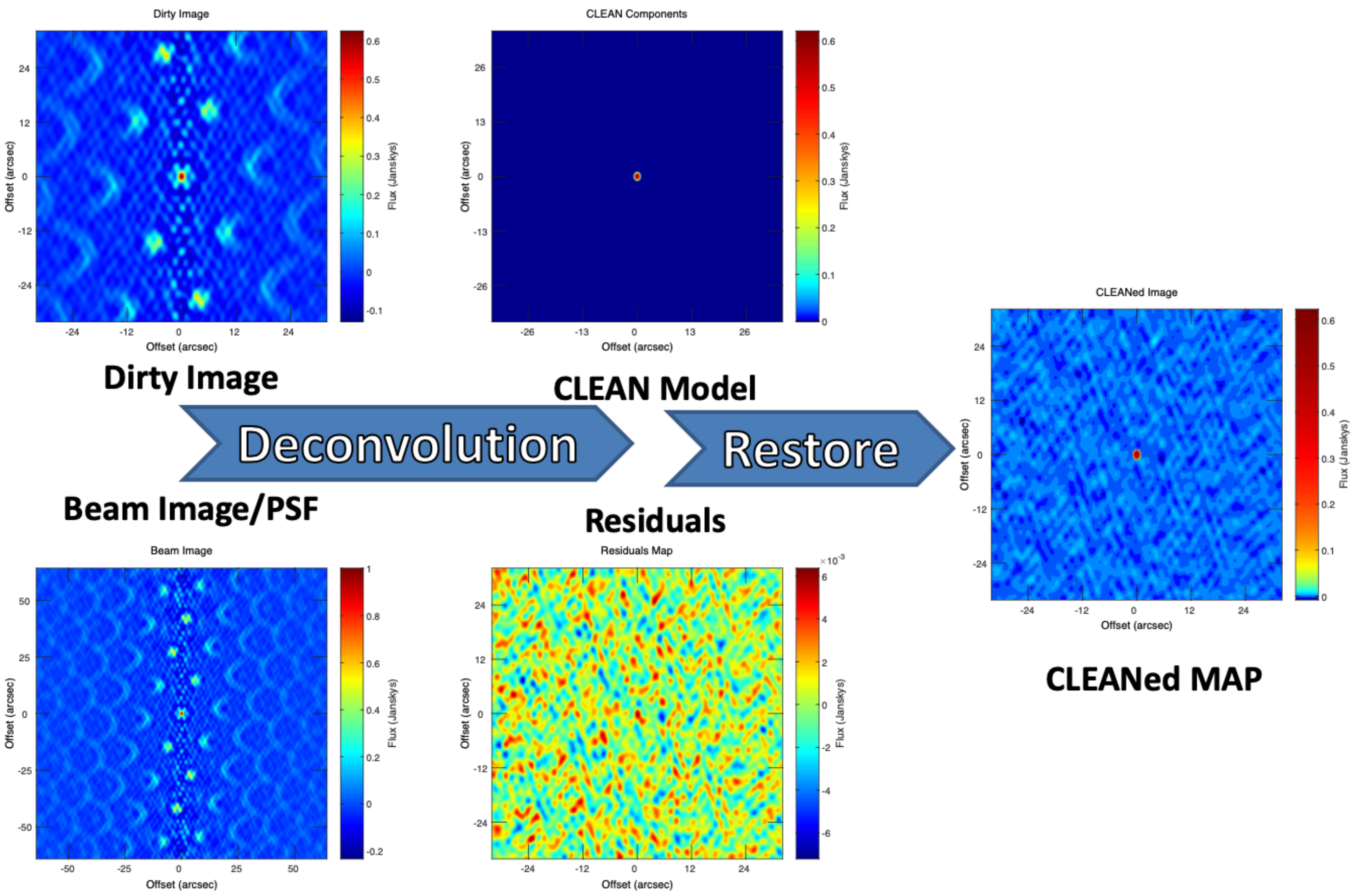
Calibrated Images



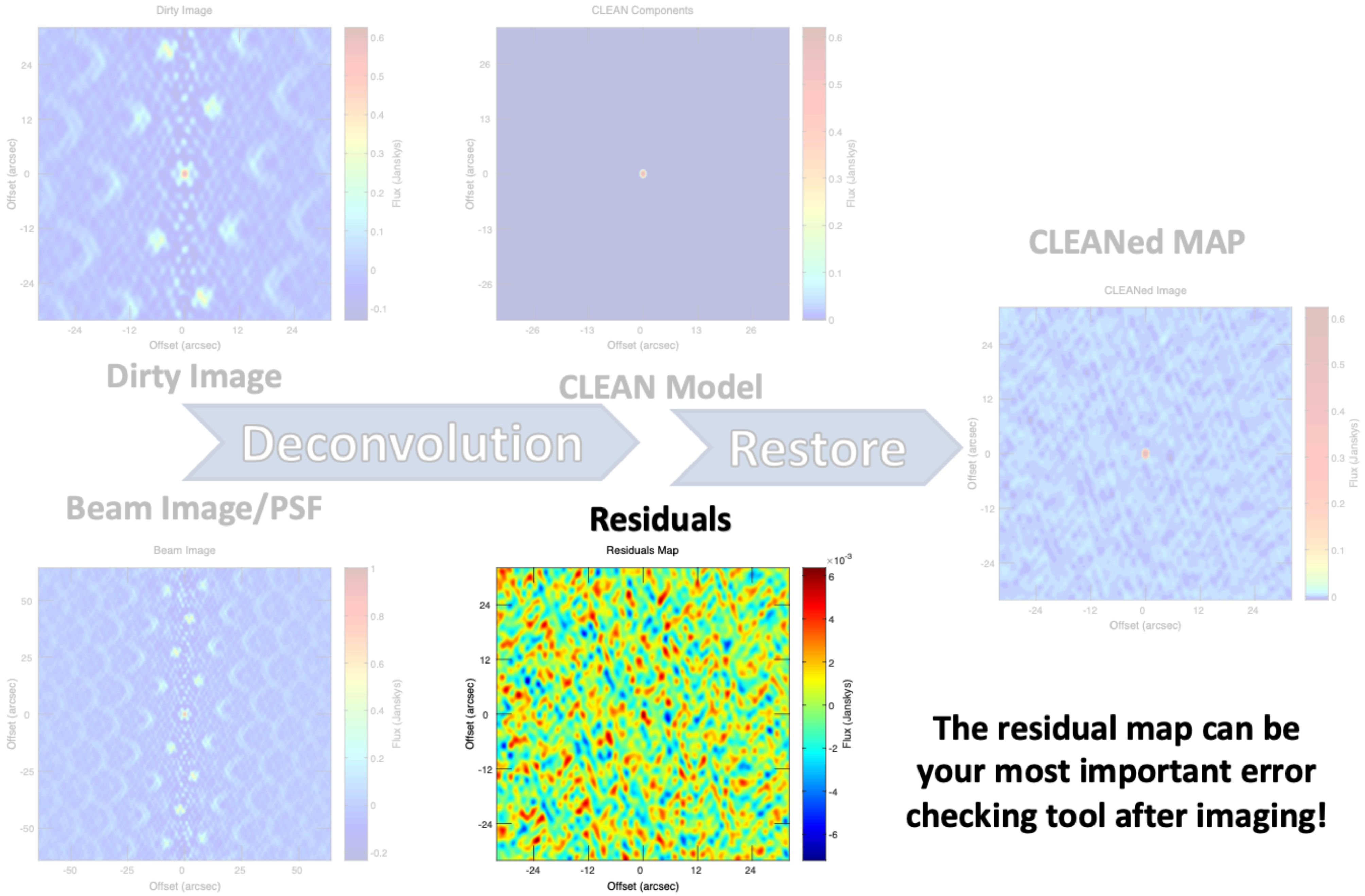
J1822-0938
(calibrator)

3C391
(science target)

Imaging Products

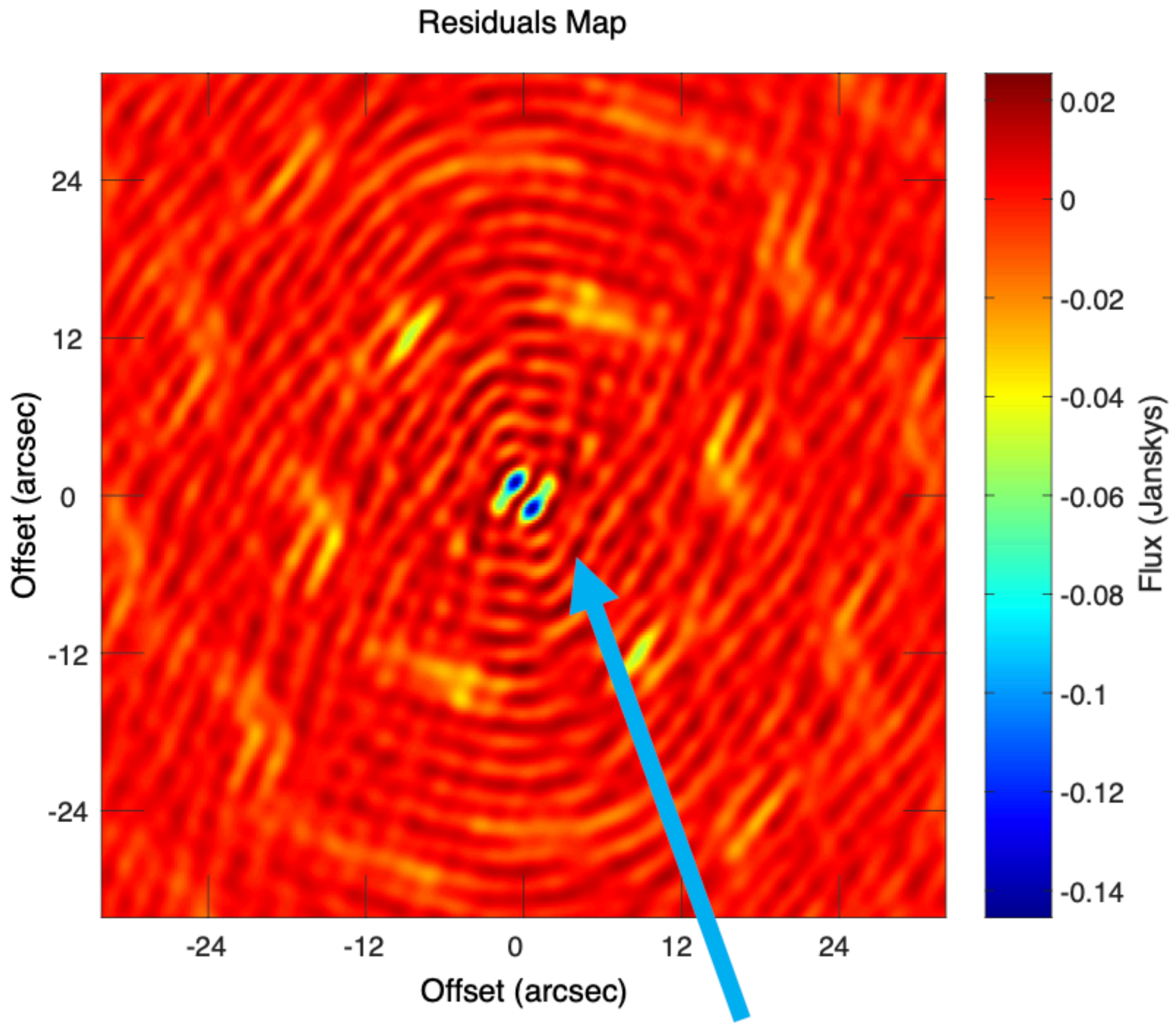


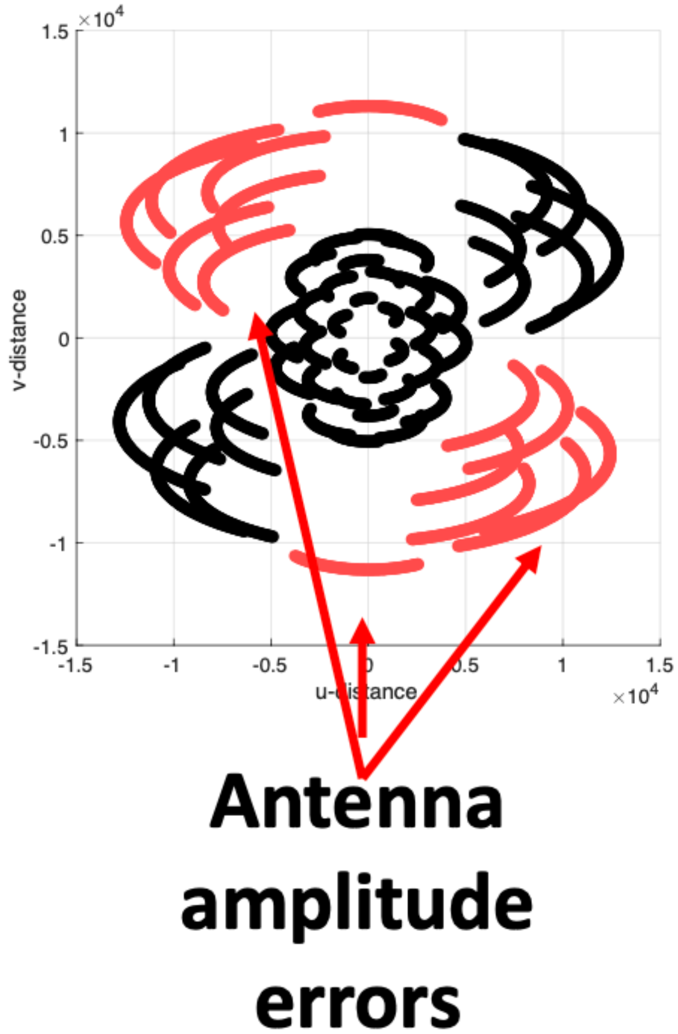
Imaging Products: the Residual Map



The residual map can be your most important error checking tool after imaging!

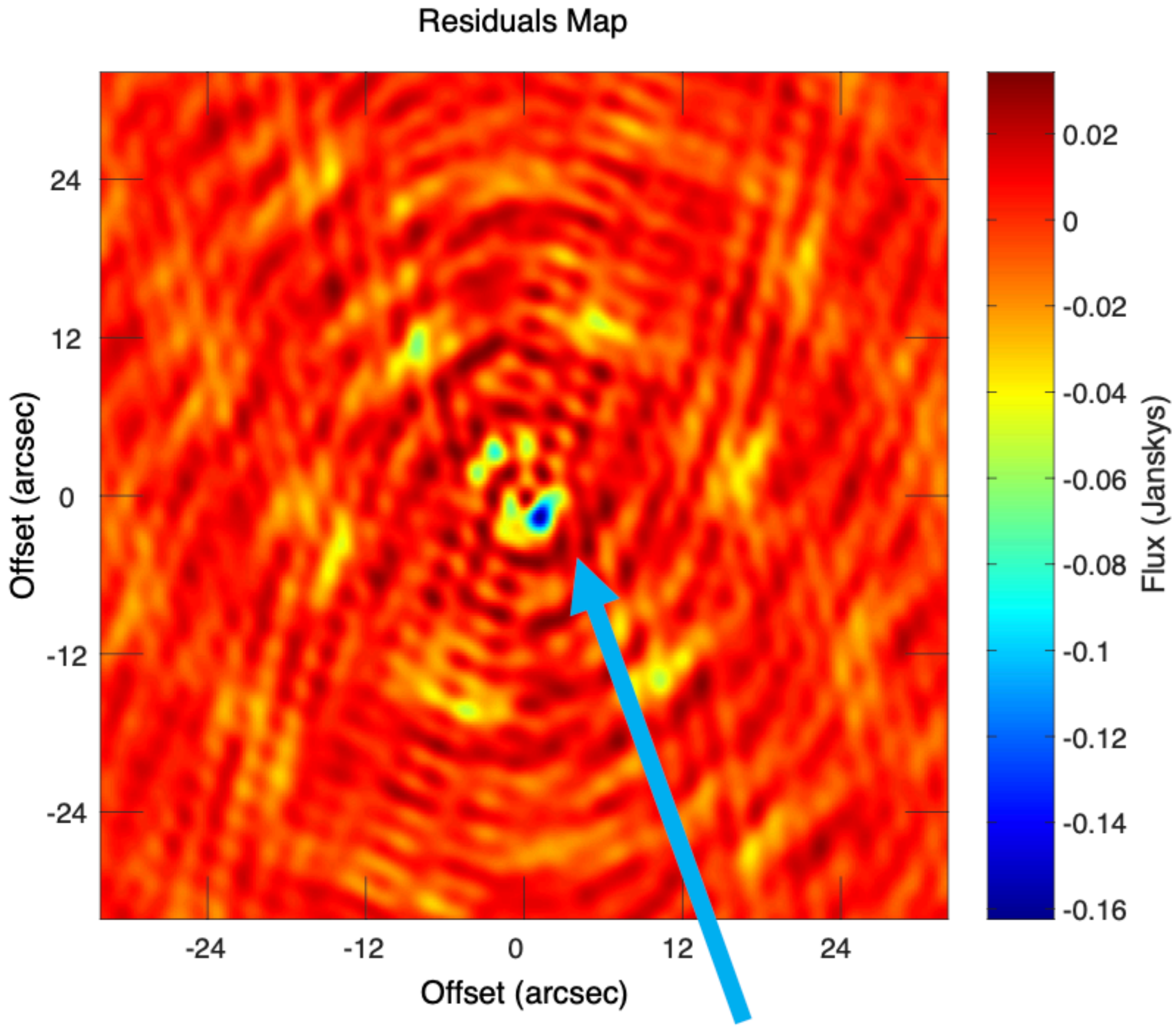
Symmetric Imaging Errors

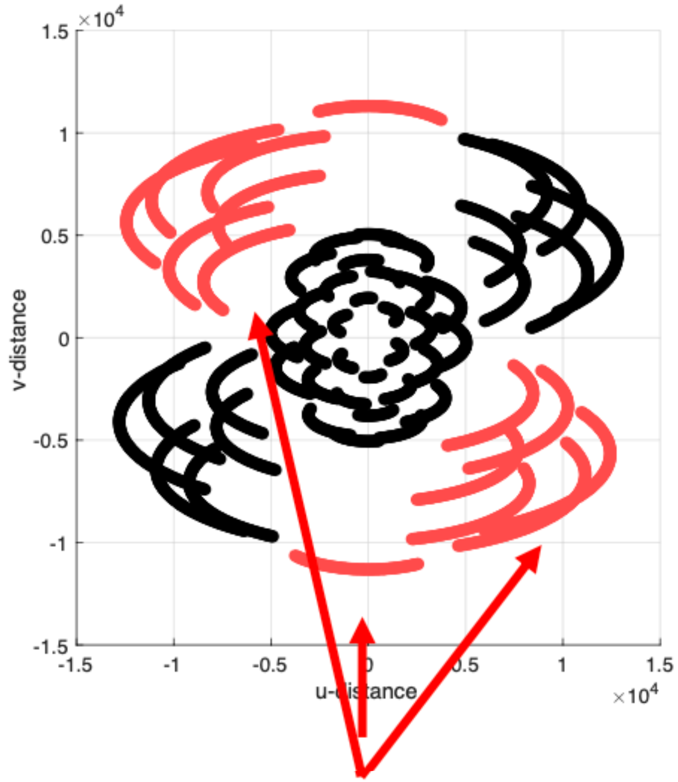




Symmetric errors in image/residuals

Anti-Symmetric Imaging Errors

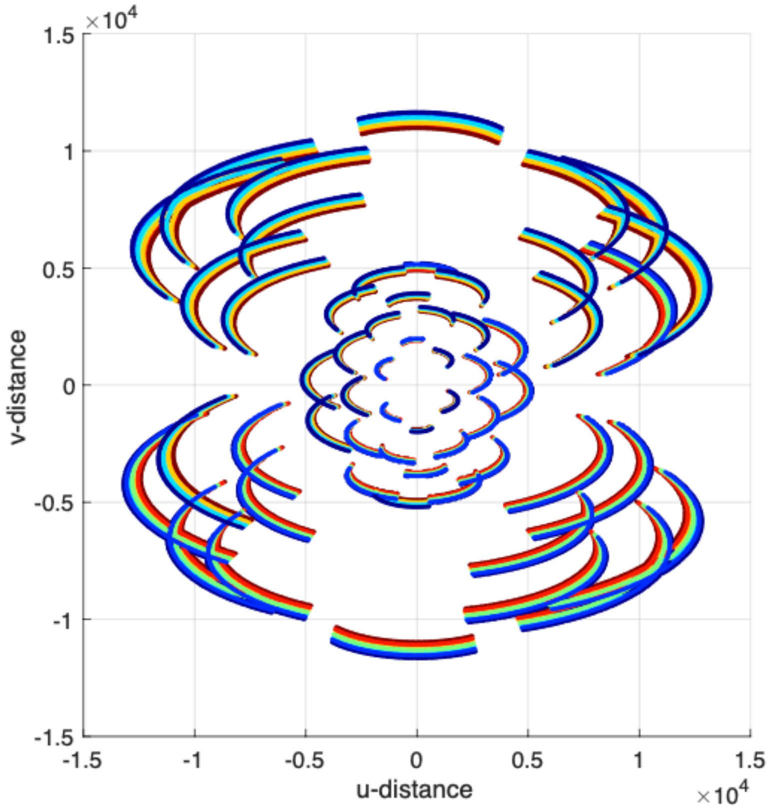


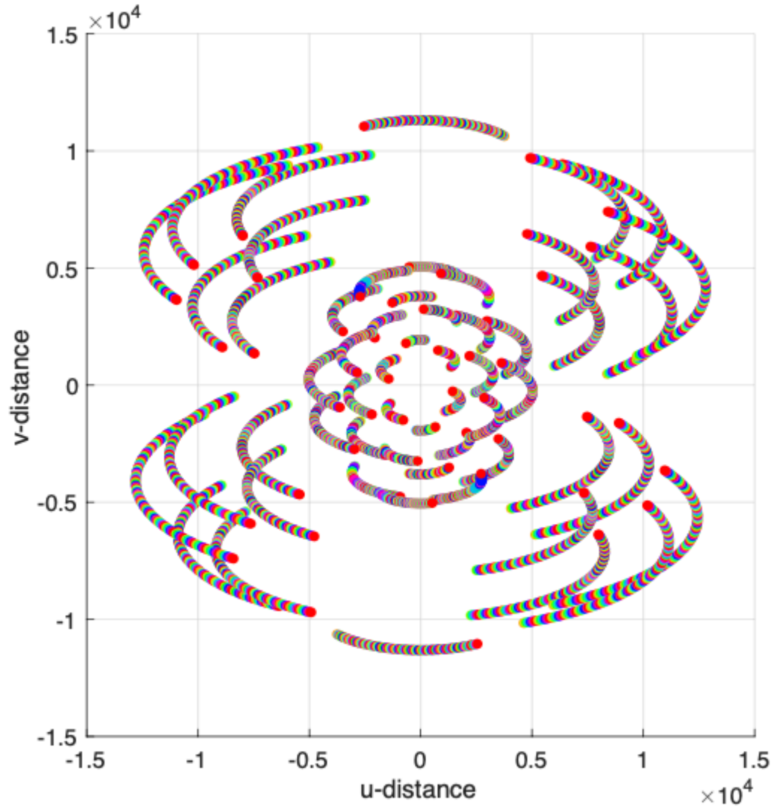


Antenna phase errors

Anti-symmetric errors in image/residuals

Artefacts from Interferometer



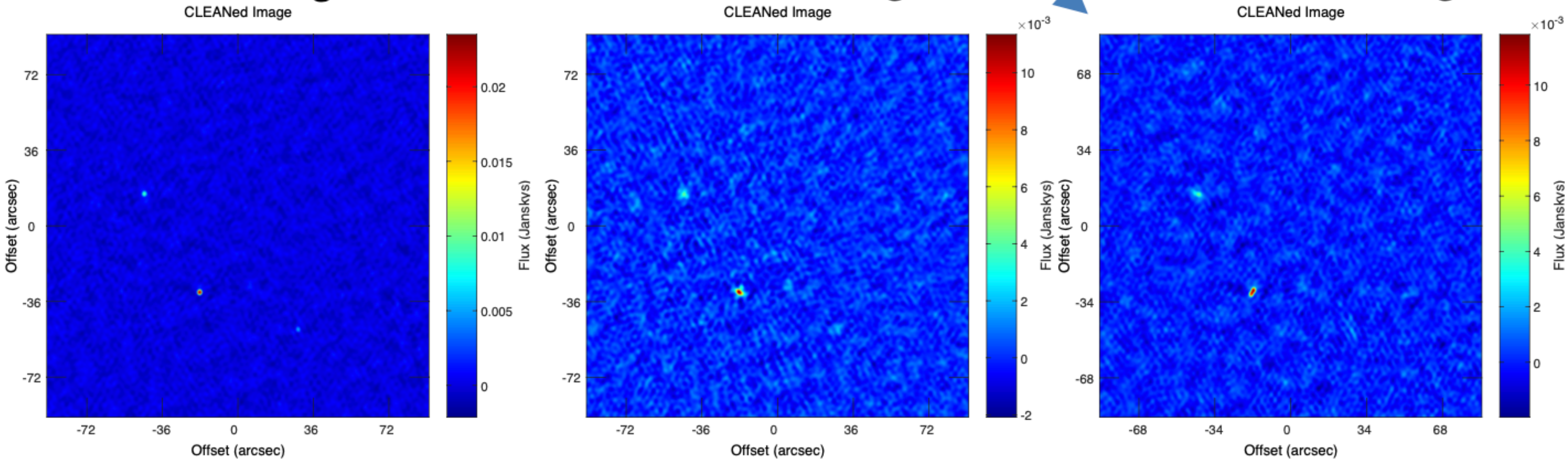


Each visibility contains information for multiple frequencies, as well as multiple times (i.e., multiple *uv*-positions), averaged together to at least *some* degree.

Artefacts from Interferometer

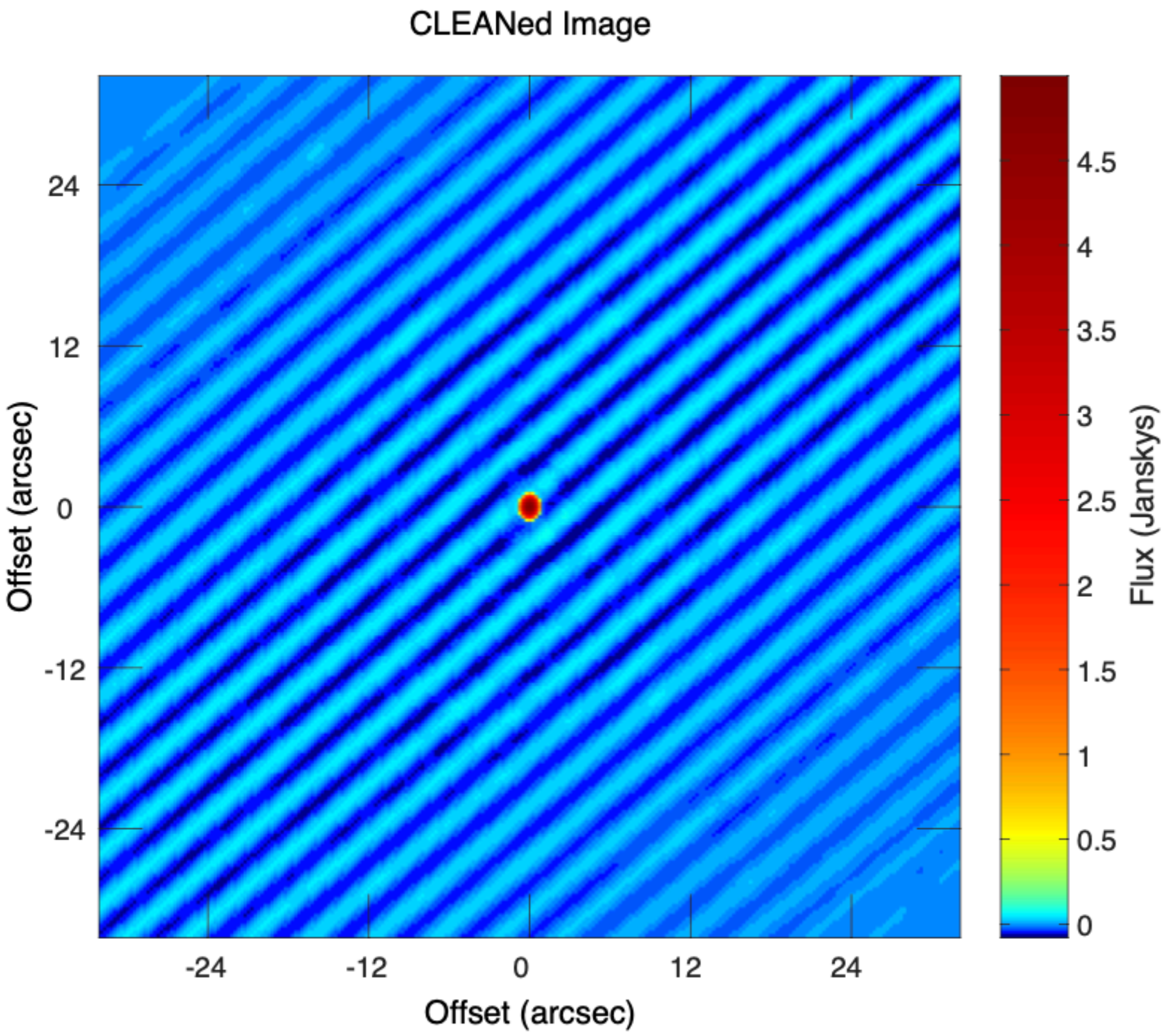
Multi-frequency synthesis can help here!

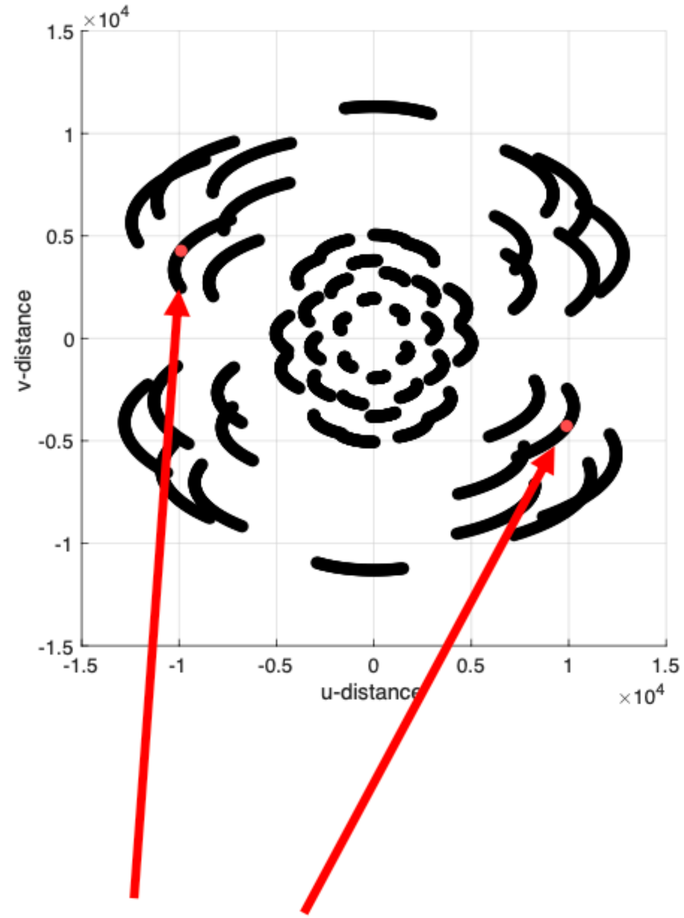
"Good" Image | **Time Smearing** | **Bandwidth Smearing**



Each visibility contains information for multiple frequencies, as well as multiple times (i.e., multiple *uv*-positions), averaged together to at least *some* degree.

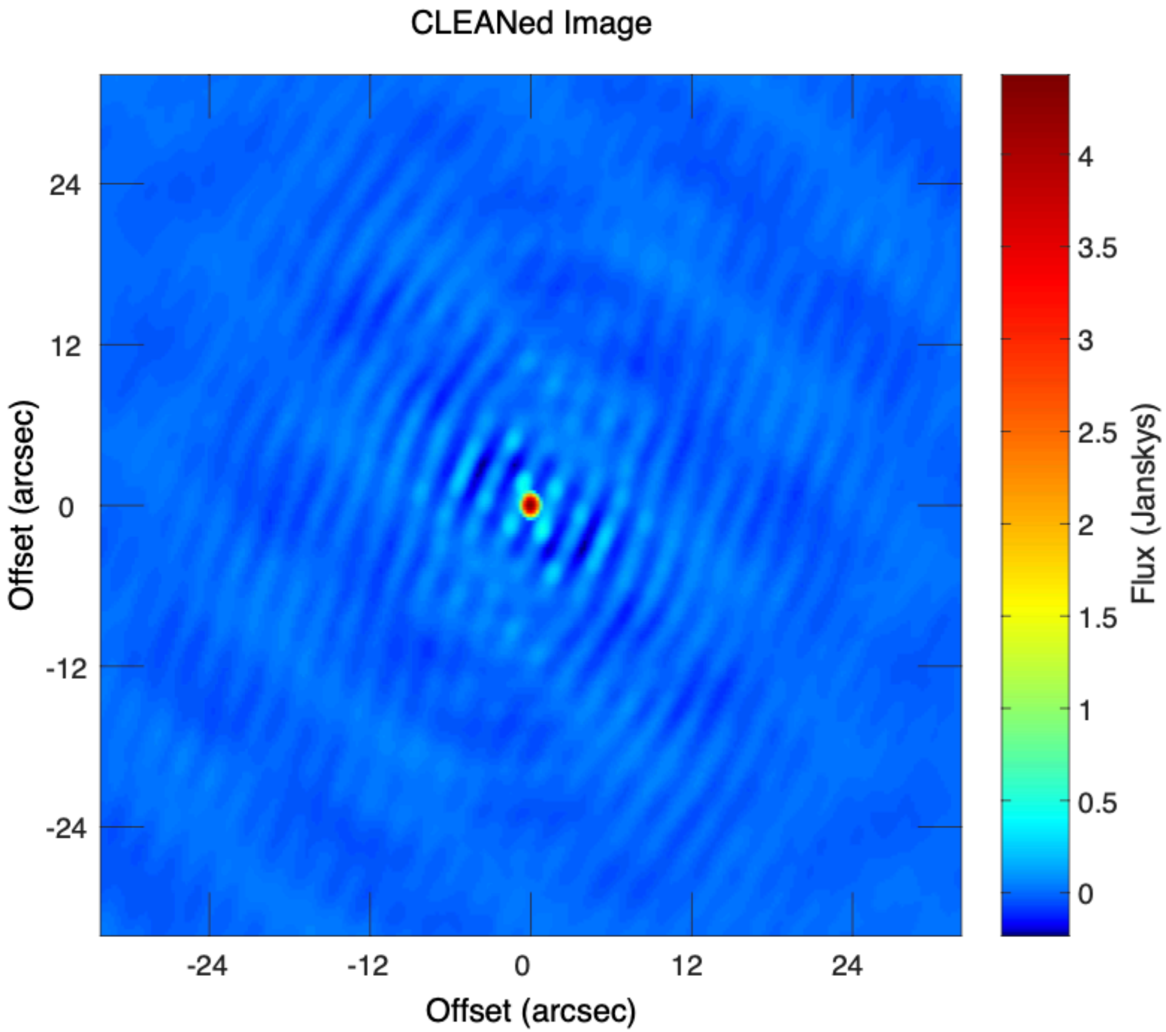
The Impact of Bad Data

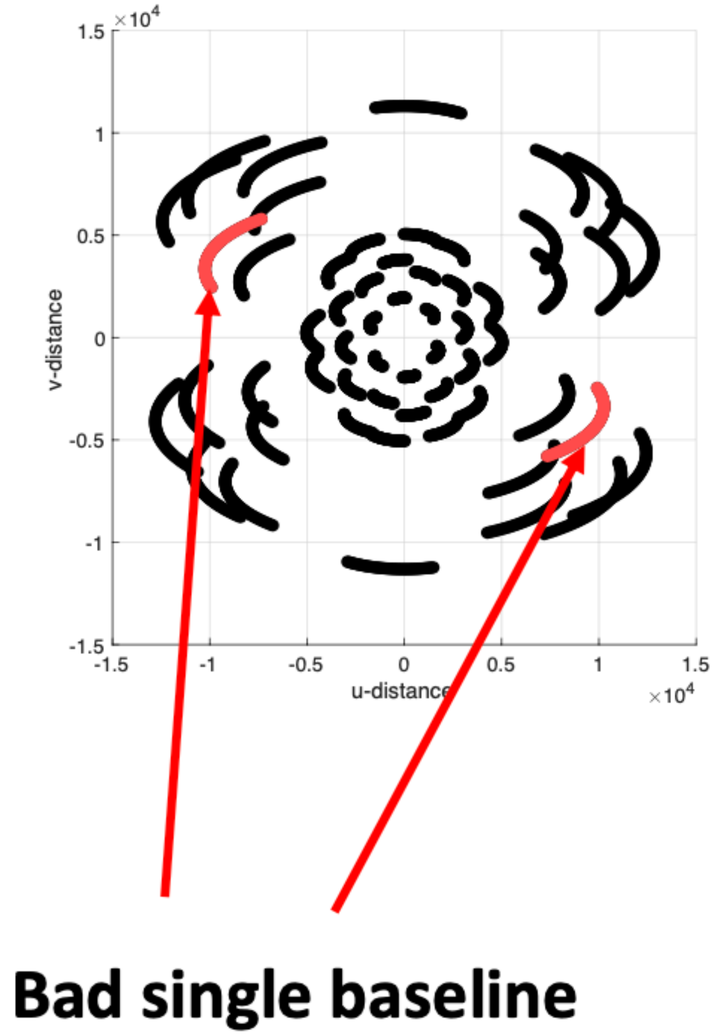




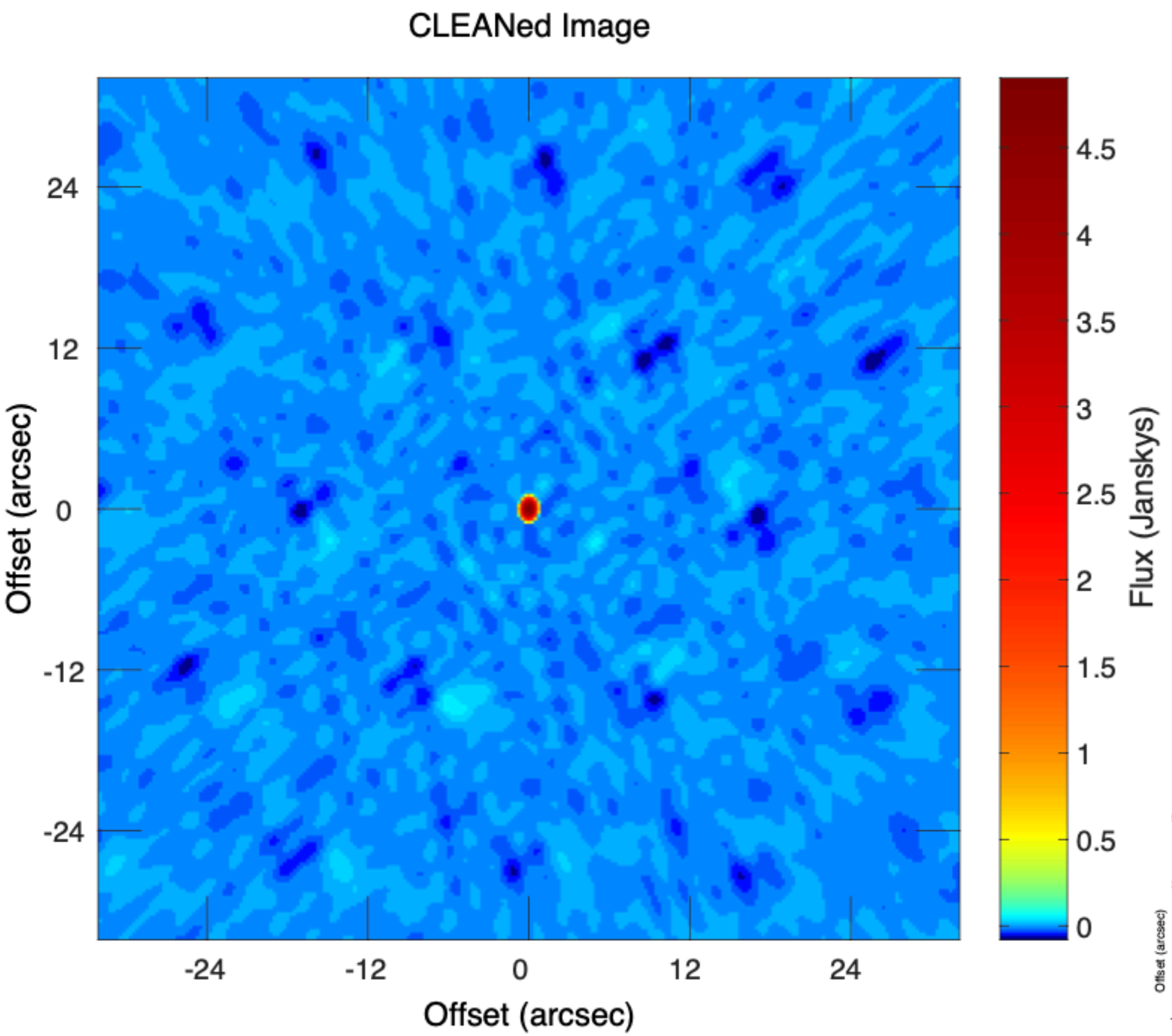
Bad single data point

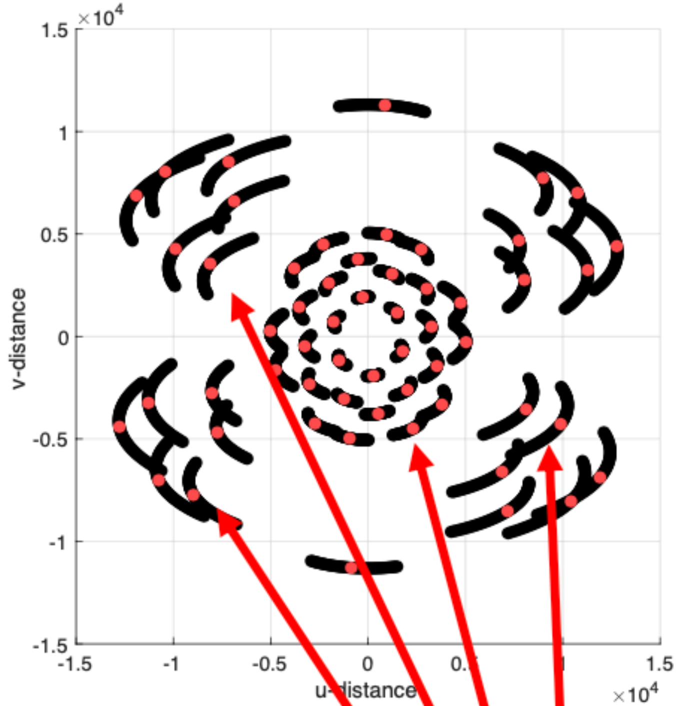
The Impact of Bad Data

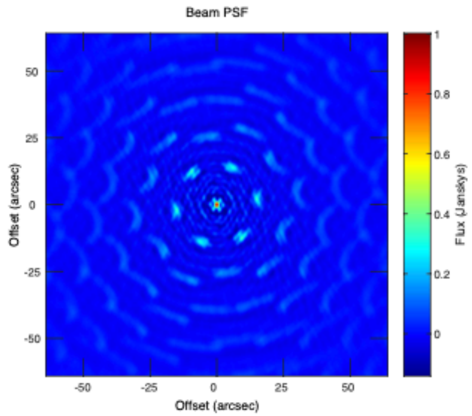




The Impact of Bad Data



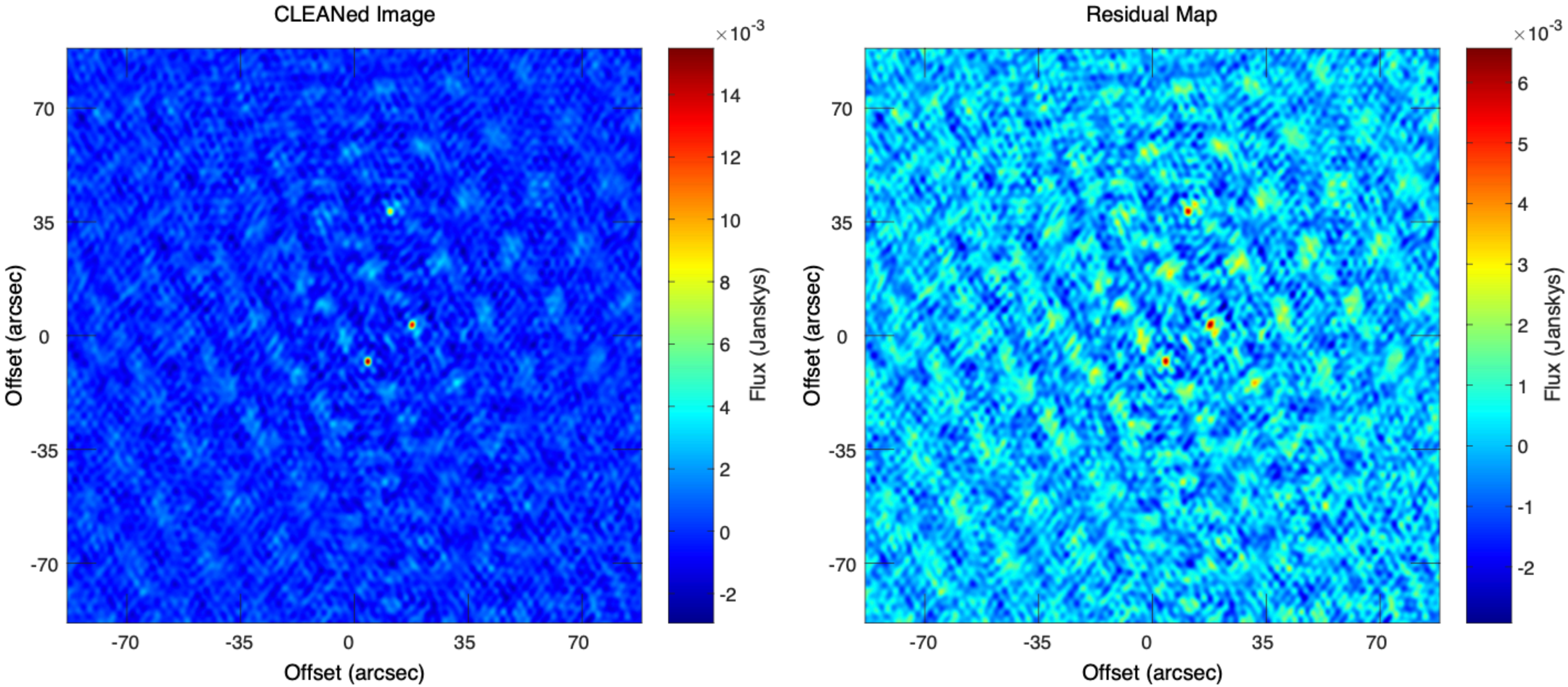




Bad single integration

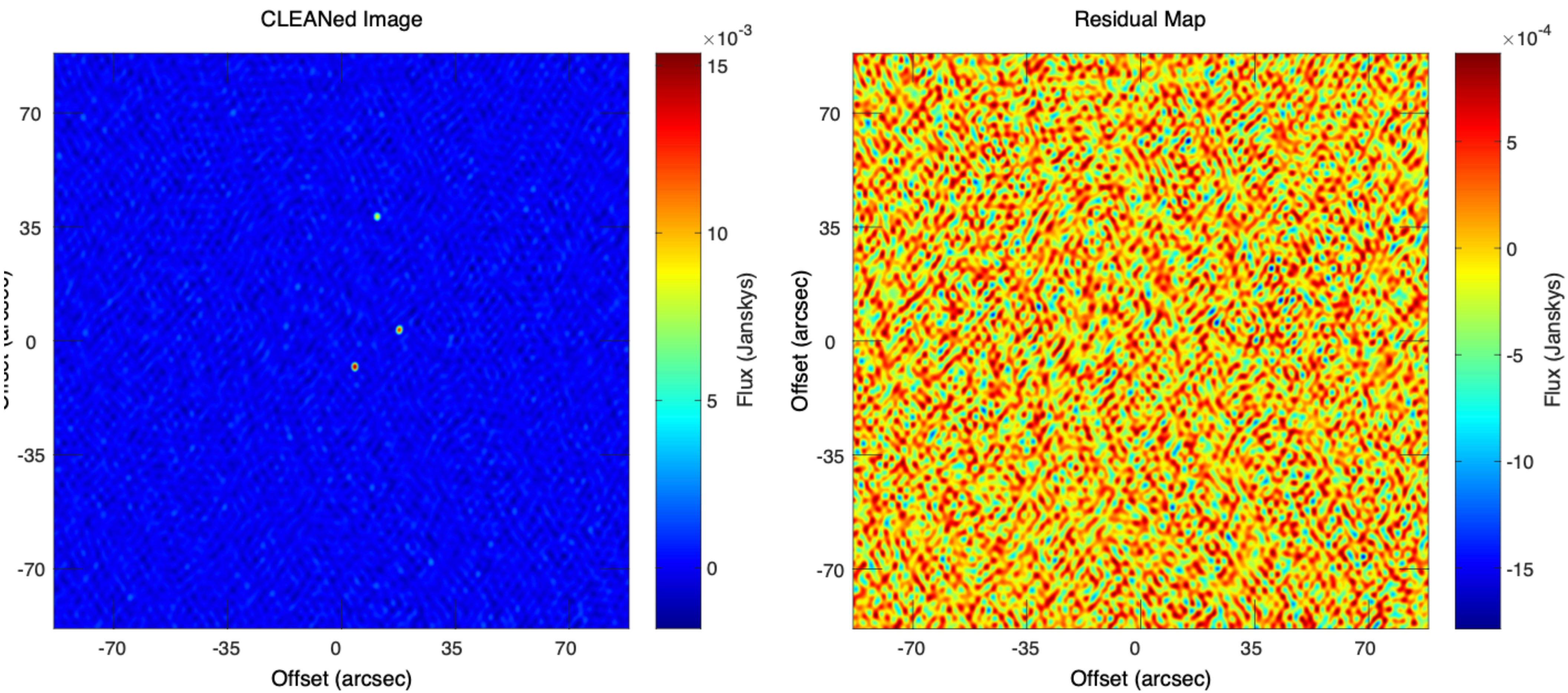
Hint: Artifacts look similar to PSF

Not cleaning deep enough



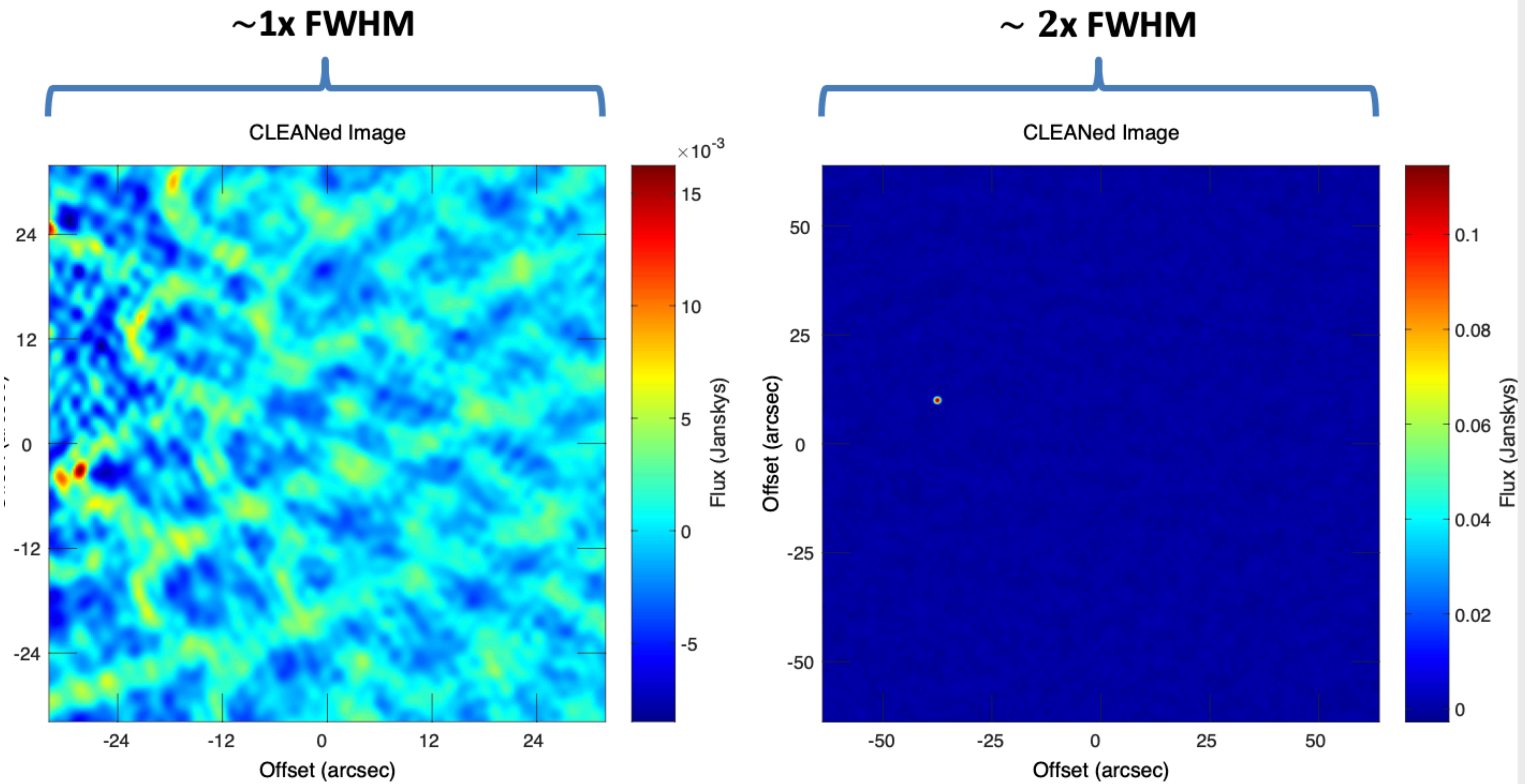
Under-CLEANing leaves source emission spread out by the PSF in your maps

Cleaning too deep



Over-CLEANing (e.g., CLEANing noise) will produce artifacts that can look like corrugated cardboard

Bright Sources outside Field



Emission outside of your imaging area will also leave artifacts

Just because you don't image it doesn't mean you won't see it – image more than the FWHM!

Recognizing Errors

Some Questions to ask:

Noise properties of image:

Is the rms noise about that expected from integration time?

Is the rms noise much larger near bright sources?

Are there non-random noise components (faint waves and ripples)?

Funny looking Structure:

Non-physical features; stripes, rings, symmetric or anti-symmetric
Negative features well-below a few times the rms noise
Does the image have characteristics that look like the dirty beam?

Image-making parameters:

Is the image big enough to cover all significant emission?
Is cell size too large or too small? ~4 points per beam okay

Is the resolution too high to detect most of the emission?

Recognizing Errors

Source structure should be "reasonable", the rms image noise as expected, and the background featureless. If not:

Examine (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)

Examine image plane

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

Are defects related to possible deconvolution problems?

Are other corrections/calibrations needed?

Does the field-of-view encompass all emission?

Issues to keep in mind

- No unique solution. In fact, there are infinite solutions.
- There will always be un-resolved structure $\Rightarrow$ Unphysical to believe structure < FWHM of beam
- Total integrated power is never measured $\Rightarrow$ Reconstruction of largest spatial scales is always an extrapolation
- Requires iterative, non-linear fitting process $\Rightarrow$ Compute intensive
- No unique prescription for extracting optimal solution
- $\Rightarrow$ Constrain the solution using astrophysical plausibility

Concluding remarks

- interferometry samples Fourier components of sky brightness
- make an image by Fourier transforming sampled visibilities
- deconvolution attempts to correct for incomplete sampling
- remember
  - there are an infinite number of images compatible with the visibilities
  - missing (or corrupted) visibilities affect the entire image
  - astronomers must make decisions in imaging and deconvolution

The next generation of Radio Interferometers - part I

The Hydrogen Array

Radio Interferometry: Theory, Techniques and Applications,
IAU Coll. 131, ASP Conference Series, Vol. 19, 1991,
T.J. Cornwell and R.A. Perley (eds.)

THE HYDROGEN ARRAY

P.N. WILKINSON
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL, United Kingdom

ABSTRACT The time is ripe for planning an array with a collecting area of 1 km^2 (14 times larger than Arecibo and 75 times larger than the VLA). In view of its major astronomical target I have dubbed this concept 'The Hydrogen Array', although 1μJy continuum sources will also be reliably detected. I present some initial thoughts about the issues involved.

INTRODUCTION

Since the late 1960s radioastronomers have increased the capability of their instruments many fold. The maximum resolution achieved with interferometry has increased from $\sim$ 50 milliarcsec to $\sim$ 50 microarcsec; the highest frequency in use has gone from $\sim$ 10 GHz to $>$ 350 GHz and the aperture plane coverage has improved from that of the One–Mile Telescope to that of the multi–configuration VLA. However, in terms of raw sensitivity the improvement has been less dramatic. The Arecibo telescope remains the world's largest and the improvements to system noise temperatures at decimetric and centimetric wavelengths have been relatively small ($\leq$ 5). Despite its limitations in sky and frequency coverage, the scientific output of the Arecibo telescope amply demonstrates the advantage of a collecting area 5–10 times larger than that of the largest steerable paraboloids.

Originally motivated by high redshift HI studies

Detect 21cm hydrogen emission line (HI) from normal galaxies anywhere in Universe (*z*~2)

Current science case is much broader

SKA nomenclature

SKA1: what money can build now

SKA2: square kilometer collecting area

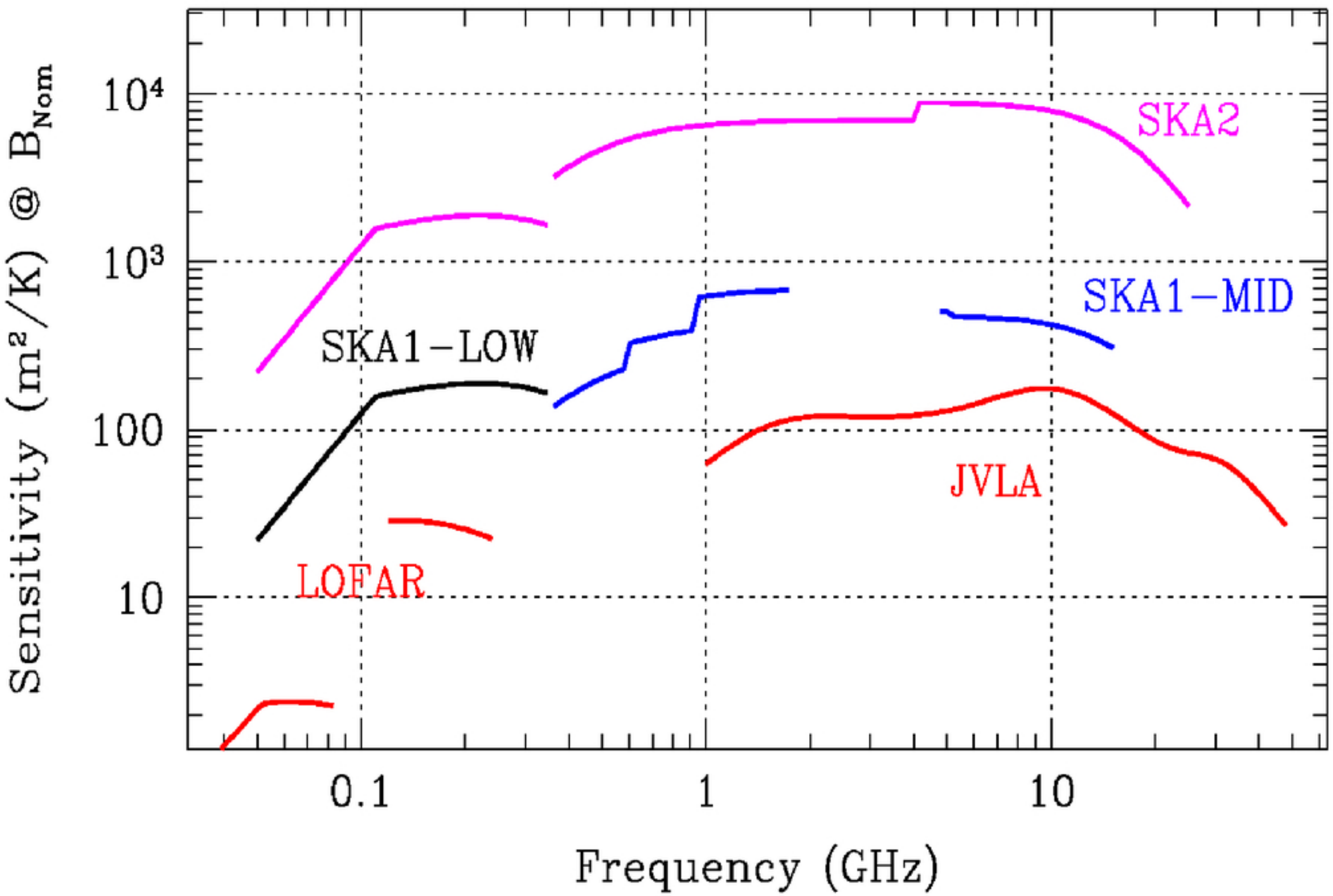
SKA-low: 50 MHz - 350 MHz

SKA-mid: 0.35 GHz - 15(?) GHz

SKA-high: 10 GHz - 50 GHz

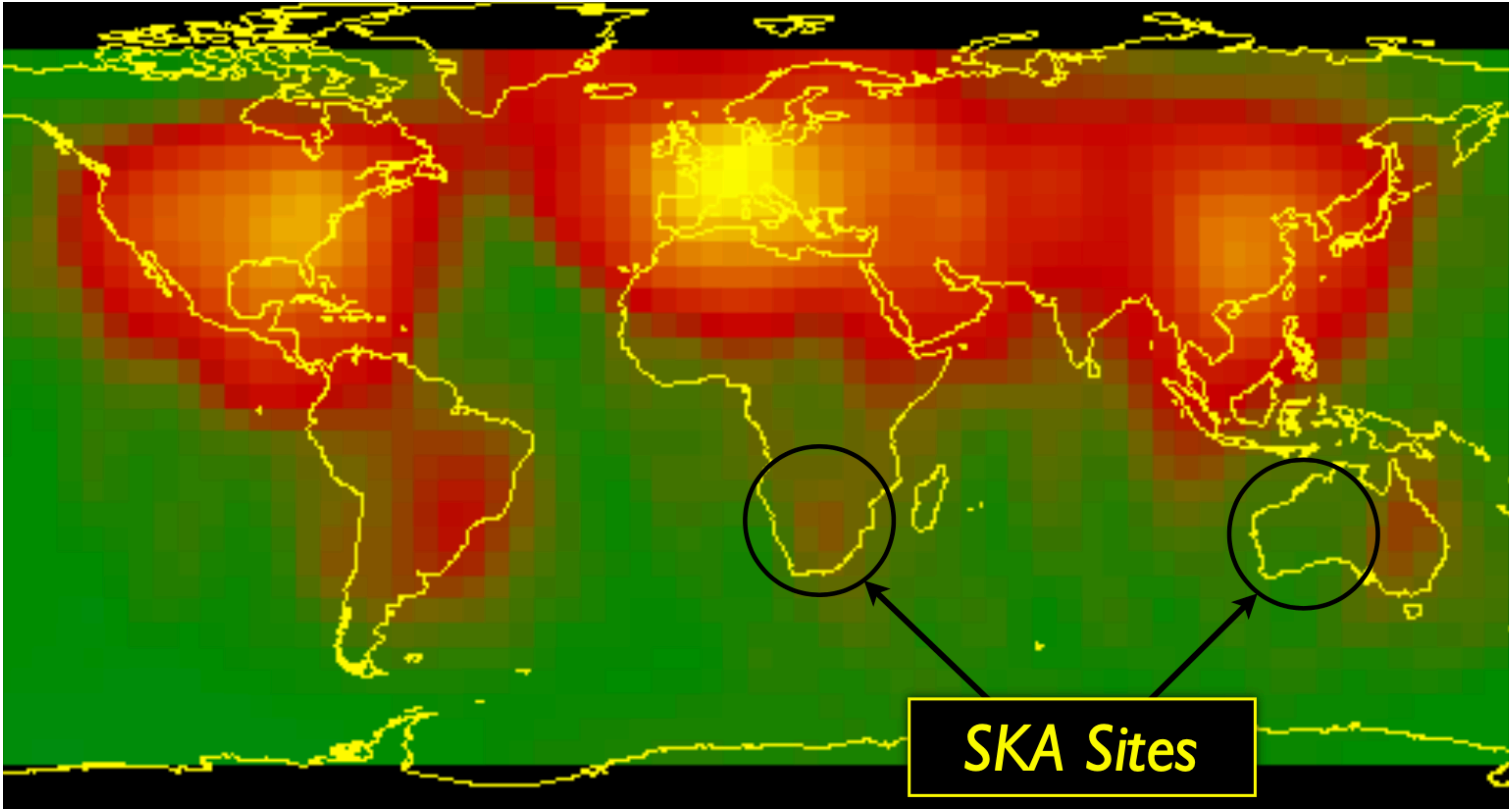
warning: many numbers that are in the literature assume SKA2 sensitivities!

True SKA (SKA2) vs. SKA1

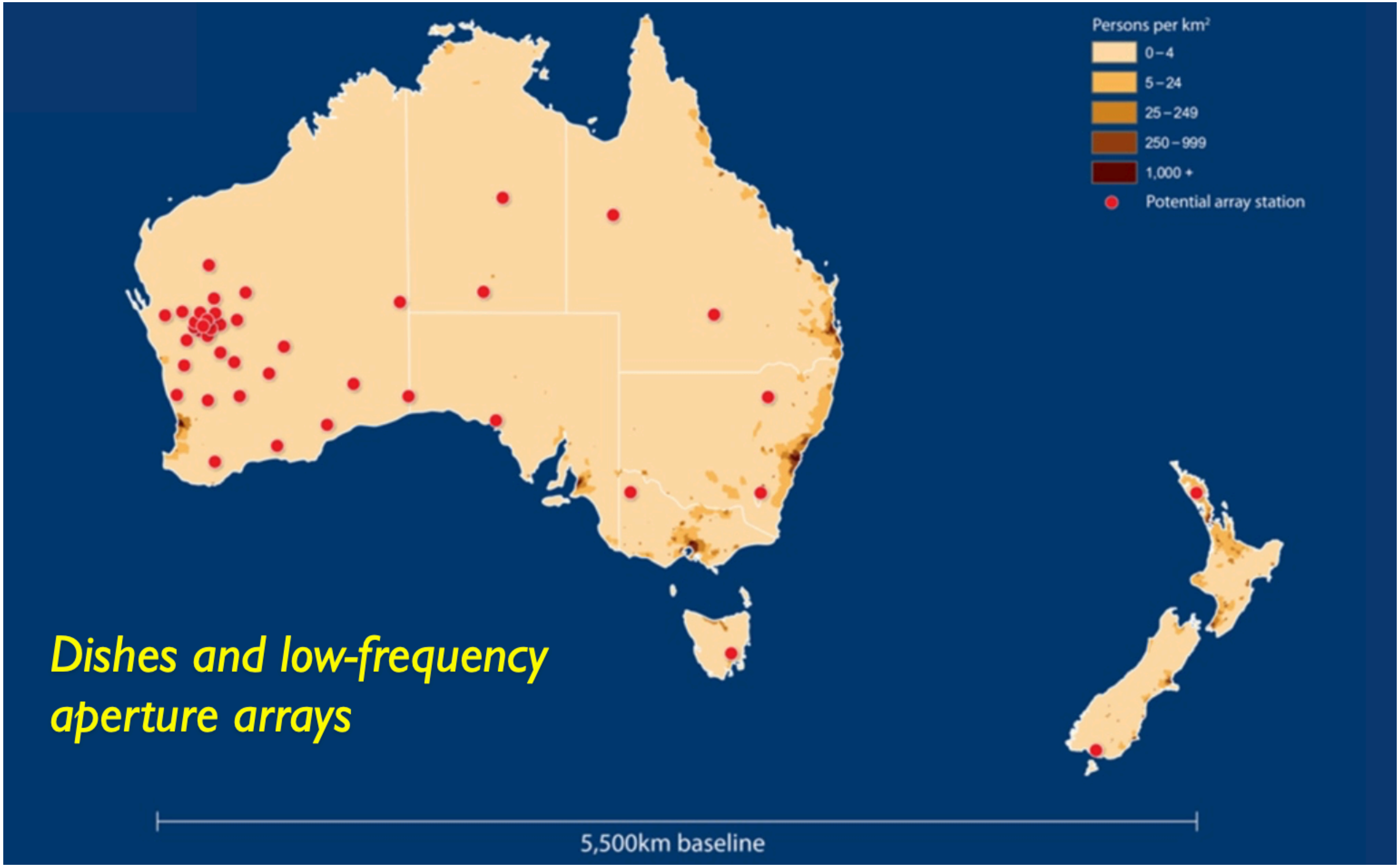


note: sensitivity of current SKA1 much below the line plotted here

World-wide radio quiet zones



Australian Site

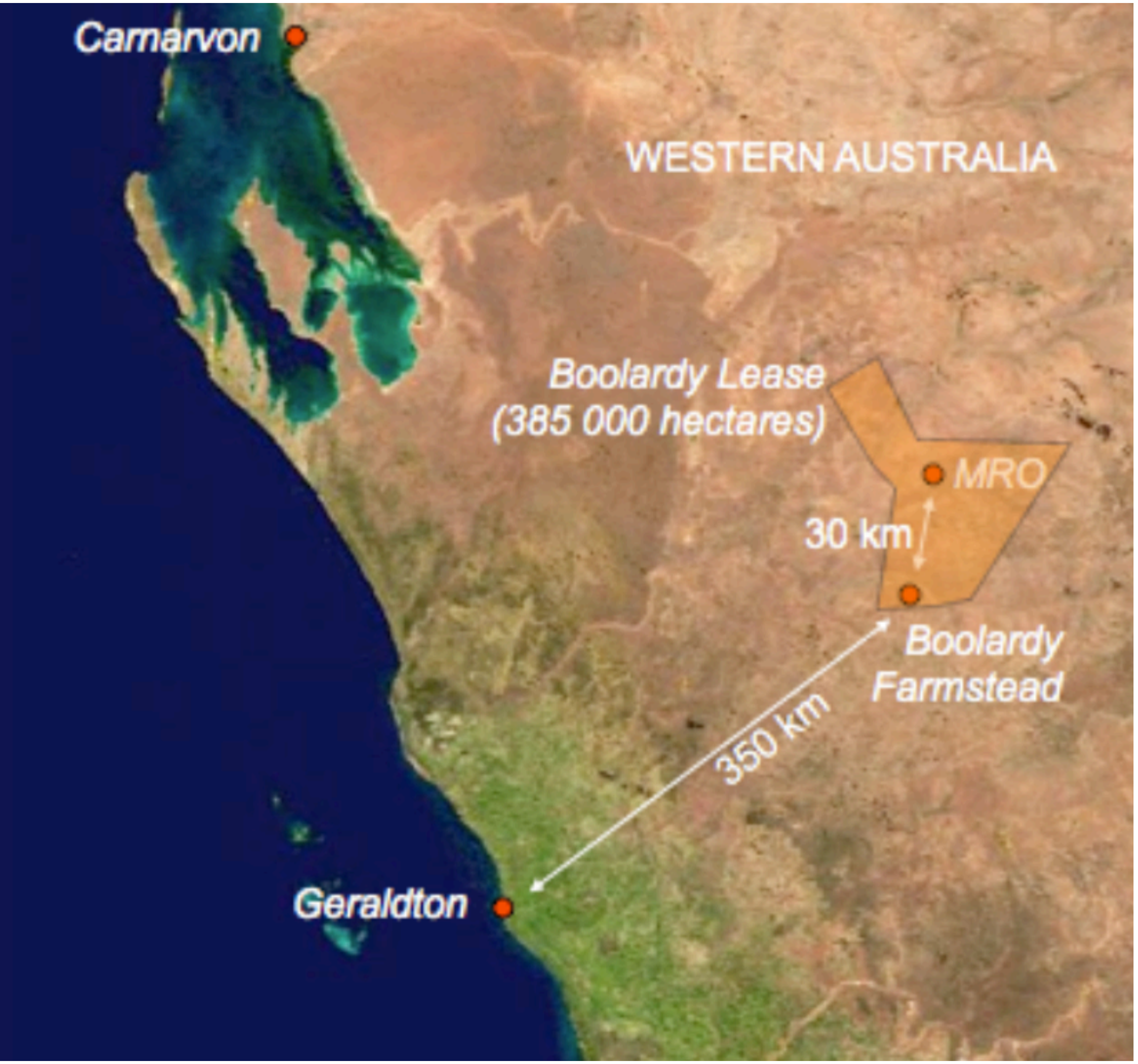


built prototype 'mid' array… but didn't get the bid

low-frequency only

ASKAP: Australian SKA Pathfinder

- Shire of Murchison
- 50,000 km^2
- 0 incorporated towns
- 29 sheep/cattle stations
- Population: 110



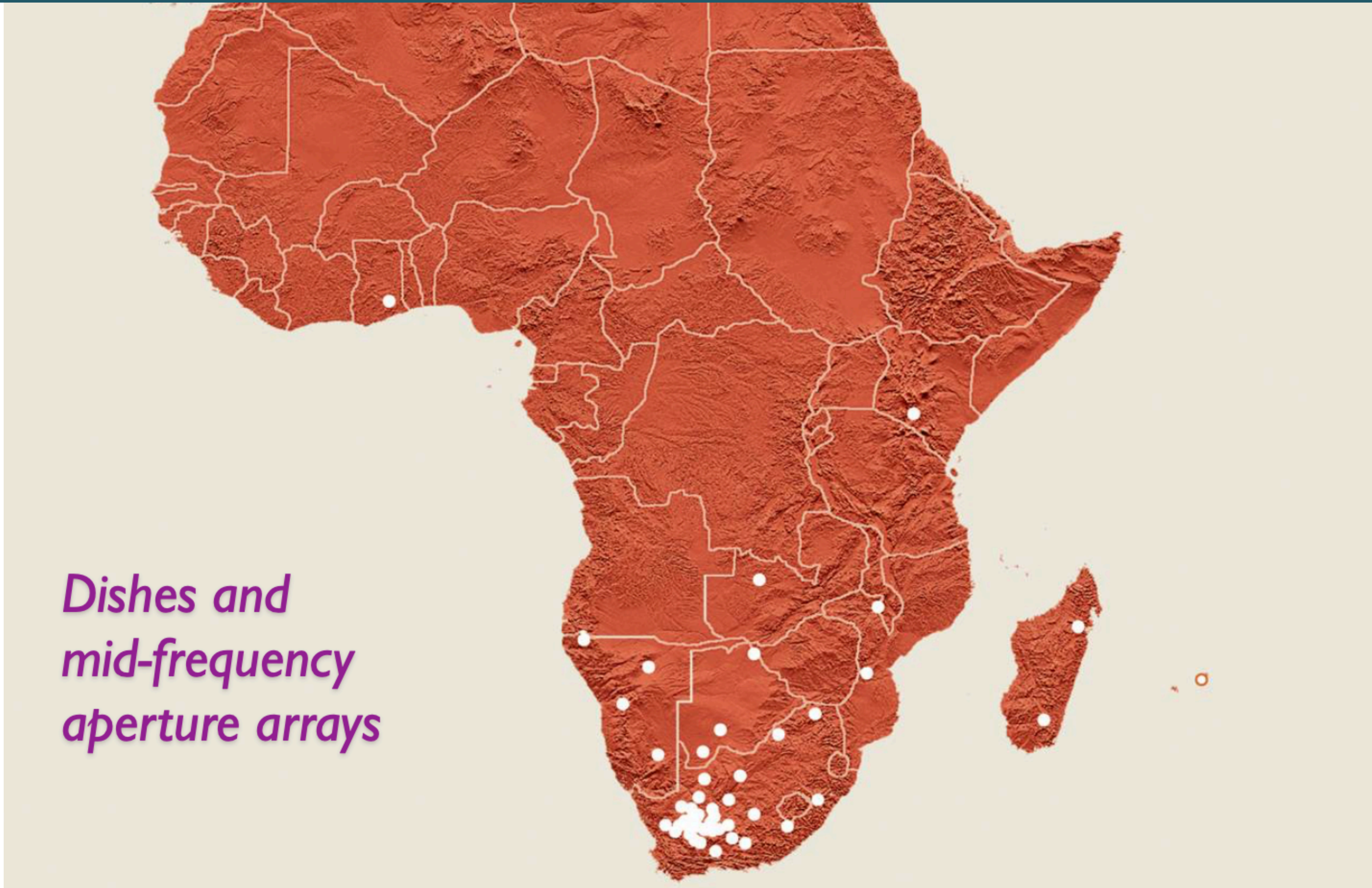
ASKAP: Australian SKA Pathfinder

built prototype ‘mid’ array… but didn’t get the bid

MWA: Australian Murchison Widefield Array

ultimately 2x 128 stations, 70-300 MHz

South African Site

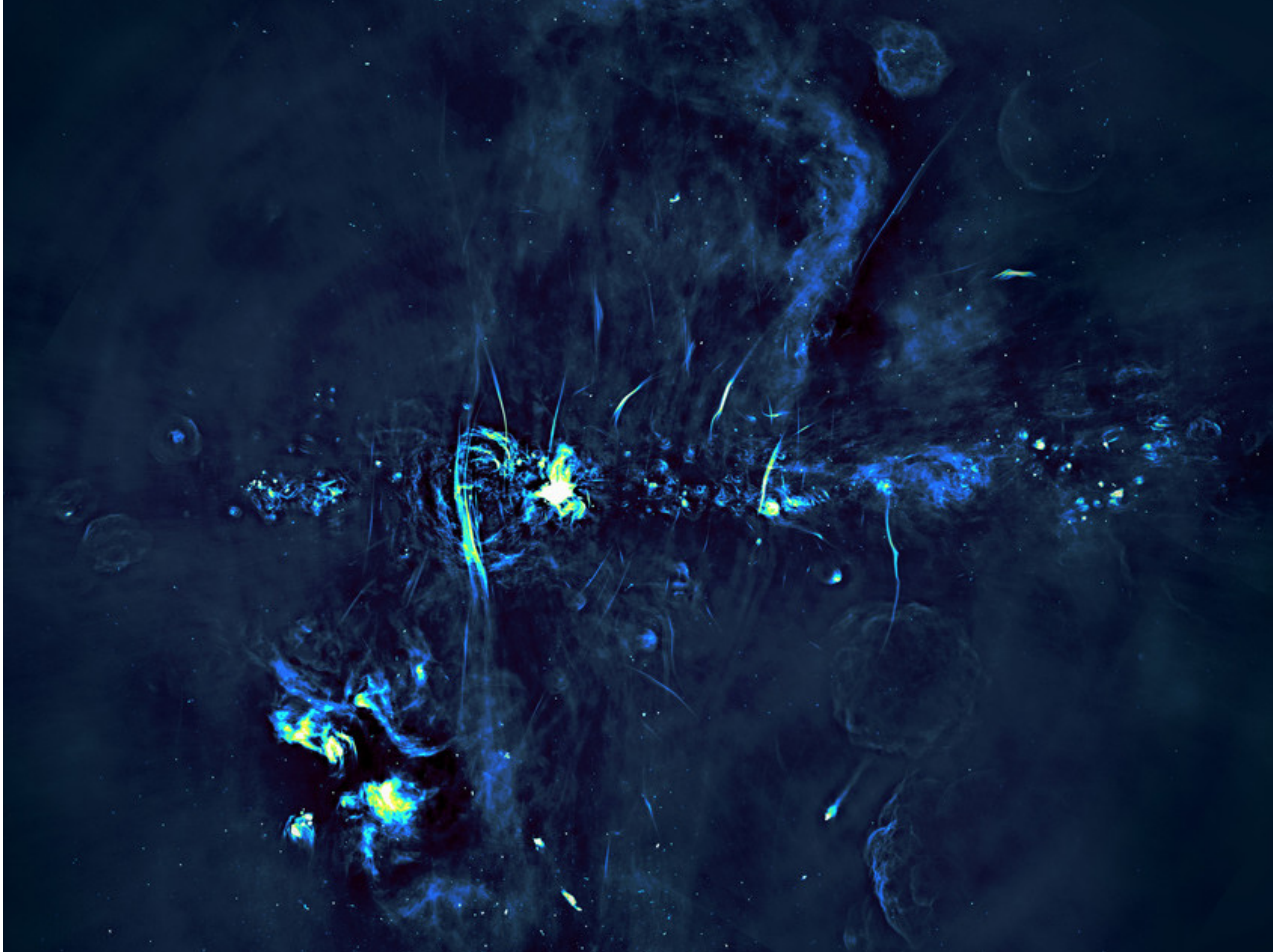


built prototype 'low' array… but didn't get the bid

mid-frequency only

South African Site: MeerKat

64 antennas, + 12 more under construction (MPG) —
ultimately will lead to SKA-1 with 180 (?) antennas — full funding not yet settled.



SKA1-low – the SKA's low-frequency instrument

The Square Kilometre Array (SKA) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe. It will have a uniquely distributed character: **one** observatory operating **two** telescopes on **three** continents. Construction of the SKA will be phased and work is currently focused on the first phase named SKA1, corresponding to a fraction of the full SKA. SKA1 will include two instruments – SKA1-mid and SKA1-low – observing the Universe at different frequencies.

SQUARE KILOMETRE ARRAY

Location: Australia

Frequency range:
50 MHz to **350 MHz**

~131,000
antennas spread between **500 stations**

Total collecting area: **0.4km²**

Maximum distance between stations: **>65km**

SKA1-low

Data transfer rate:
7.2 Terabits per second

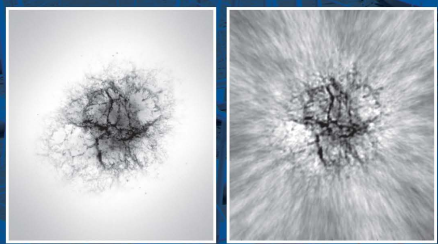


Image quality of SKA1-low (left) versus the best current facility operating in the same frequency range, the LOw Frequency ARray (LOFAR), in the Netherlands (right). SKA-low's resolution will be similar to LOFAR.

Compared to LOFAR Netherlands, the current best similar instrument in the world

25% better resolution

8x more sensitive

135x the survey speed

SKA1-mid – the SKA's mid-frequency instrument

The Square Kilometre Array (SKA) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe. It will have a uniquely distributed character: **one** observatory operating **two** telescopes on **three** continents. Construction of the SKA will be phased and work is currently focused on the first phase named SKA1, corresponding to a fraction of the full SKA. SKA1 will include two instruments – SKA1-mid and SKA1-low – observing the Universe at different frequencies.

SKA SQUARE KILOMETRE ARRAY

Location: South Africa

Frequency range:
350 MHz to **15.3 GHz**
with a goal of 24 GHz

197 dishes
(including 64 MeerKAT dishes)

Total collecting area:
33,000m²

or **126 tennis courts**

Maximum distance between dishes:
150km

SKA1-mid

Data transfer rate:
8.8 Terabits per second

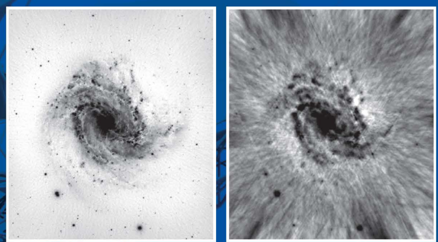


Image quality of SKA1-mid (left) versus the best current facility operating in the same frequency range, the Jansky Very Large Array (JVLA) in the United States (right). SKA-mid's resolution will be 4x better than JVLA.

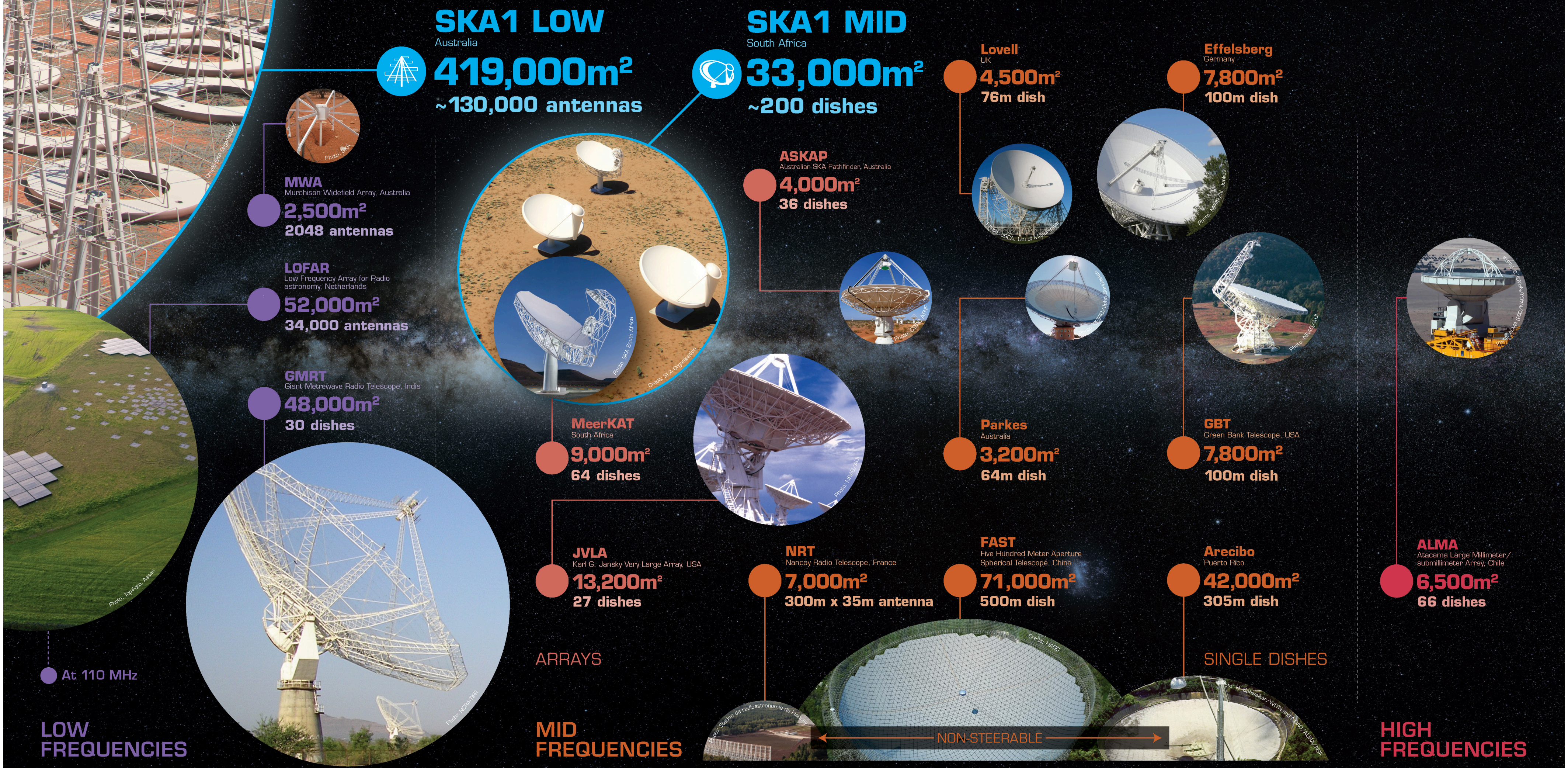
Compared to the JVLA, the current best similar instrument in the world:

4x the resolution

5x more sensitive

60x the survey speed

How does SKA1 compare with the world's biggest radio telescopes?



The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

A telescope's capacity to receive faint signals - called sensitivity - depends on its collecting area, the bigger the better. But just like you can't compare radio telescopes and optical telescopes, comparison only works between telescopes working in similar frequencies, hence the different categories above.

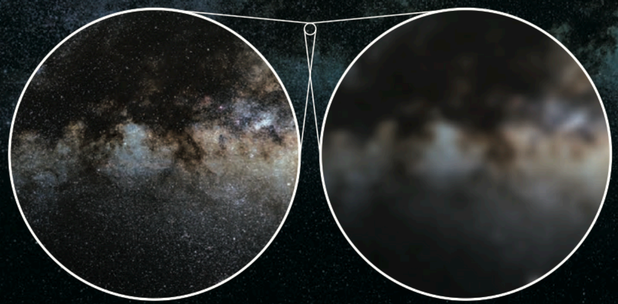
The collecting area is just one aspect of a telescope's capability though. Arrays like the SKA have an advantage over single dish telescopes: by being spread over long distances, they simulate a virtual dish the size of that distance and so can see smaller details in the sky, this is called resolution.

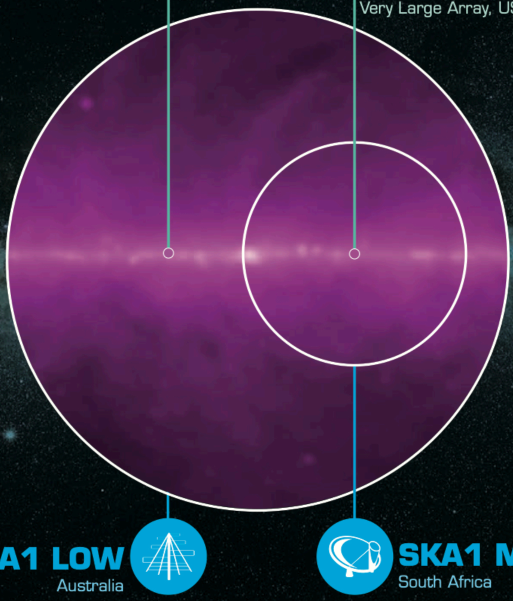
www.skatelescope.org Square Kilometre Array @SKA_telescope The Square Kilometre Array

How will SKA1 be better than today's best radio telescopes?

Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

The **Square Kilometre Array** (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.





SKA1 LOW x1.2 LOFAR NL

SKA1 MID x4 JVLA

RESOLUTION

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

SKA1 LOW x135 LOFAR NL

SKA1 MID x60 JVLA

SURVEY SPEED

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

SKA1 LOW x8 LOFAR NL

SKA1 MID x5 JVLA

SENSITIVITY

Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

www.skatelescope.org Square Kilometre Array @SKA_telescope YouTube The Square Kilometre Array

As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.