Calibration (I)

20th NRAO Synthesis Imaging Summer School

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UNIVERSITY OF OXFORD
BREAKTHROUGH LISTEN
RATT https://ratt.center
NRF National Research Foundation
SARAO South African Radio Astronomy Observatory
UK Research and Innovation
erc European Research Council

“Bad calibration in radio interferometry has the potential to produce garbage more than in just about any other kind of experiment.”

Neal Jackson
(Jodrell Bank CfA)

“Calibration is a dark art!”

Too many people
(Too often)

“No, it isn’t.”

The appropriate response to that
(Every time)

Recall the **van Cittert-Zernike theorem…**

Each antenna pair in an array samples a Fourier component of the radio sky brightness distribution

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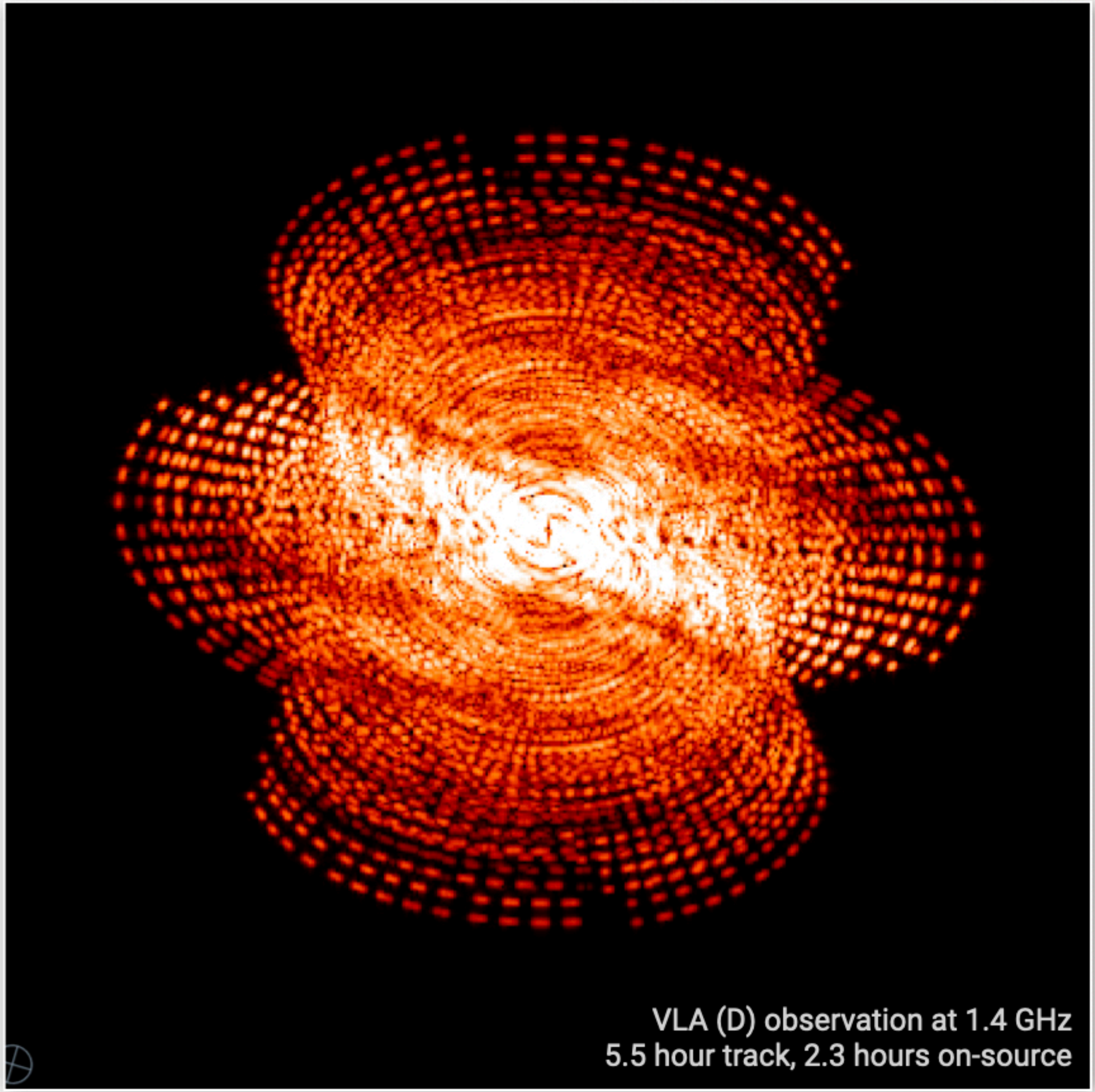
Lots of antennas + earth rotation -> lots of information about the brightness distribution in the Fourier domain



Gridded visibility amplitudes (uncalibrated)

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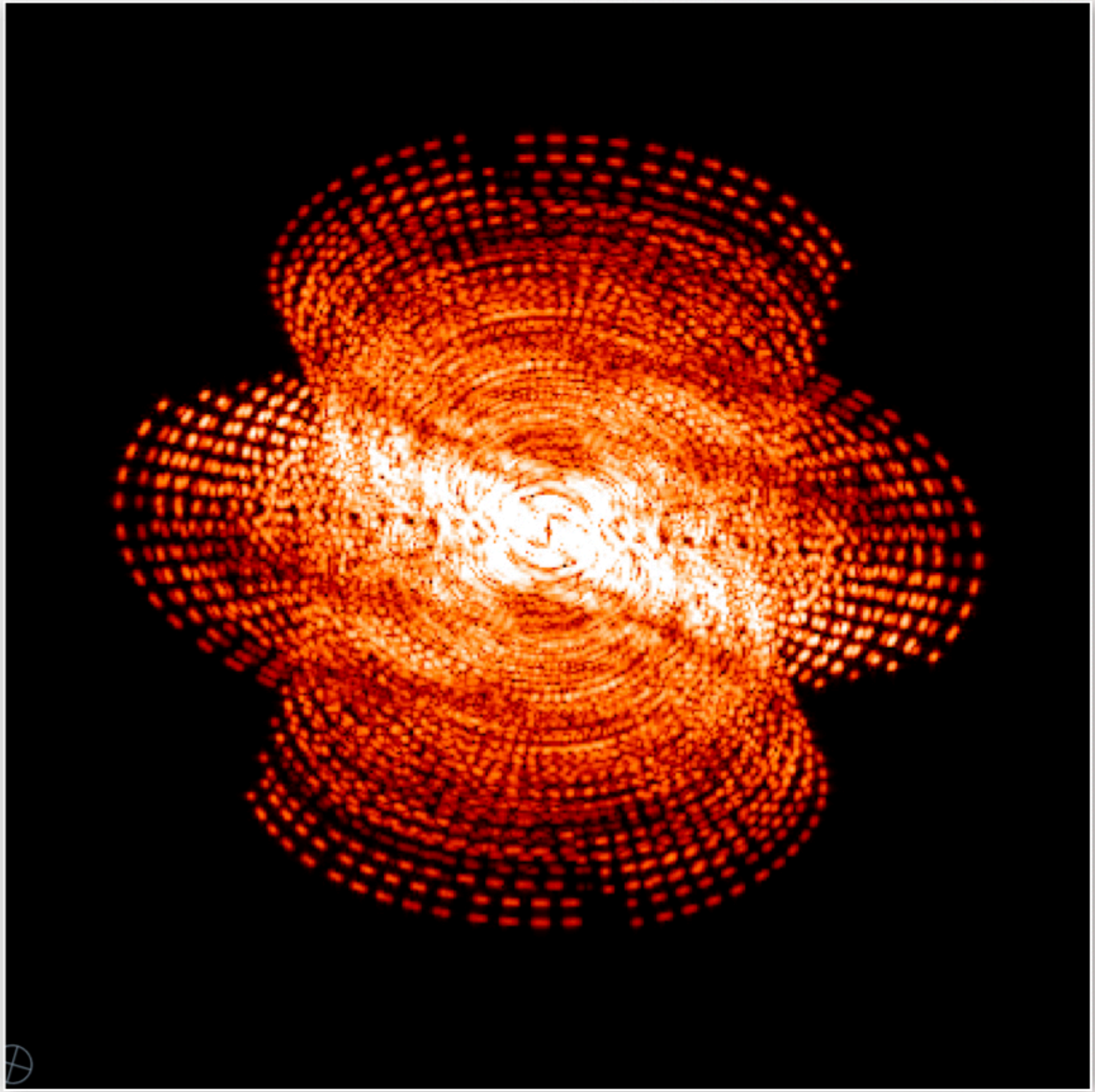
A long track with a modern radio telescope can produce a database containing many billions of visibilities



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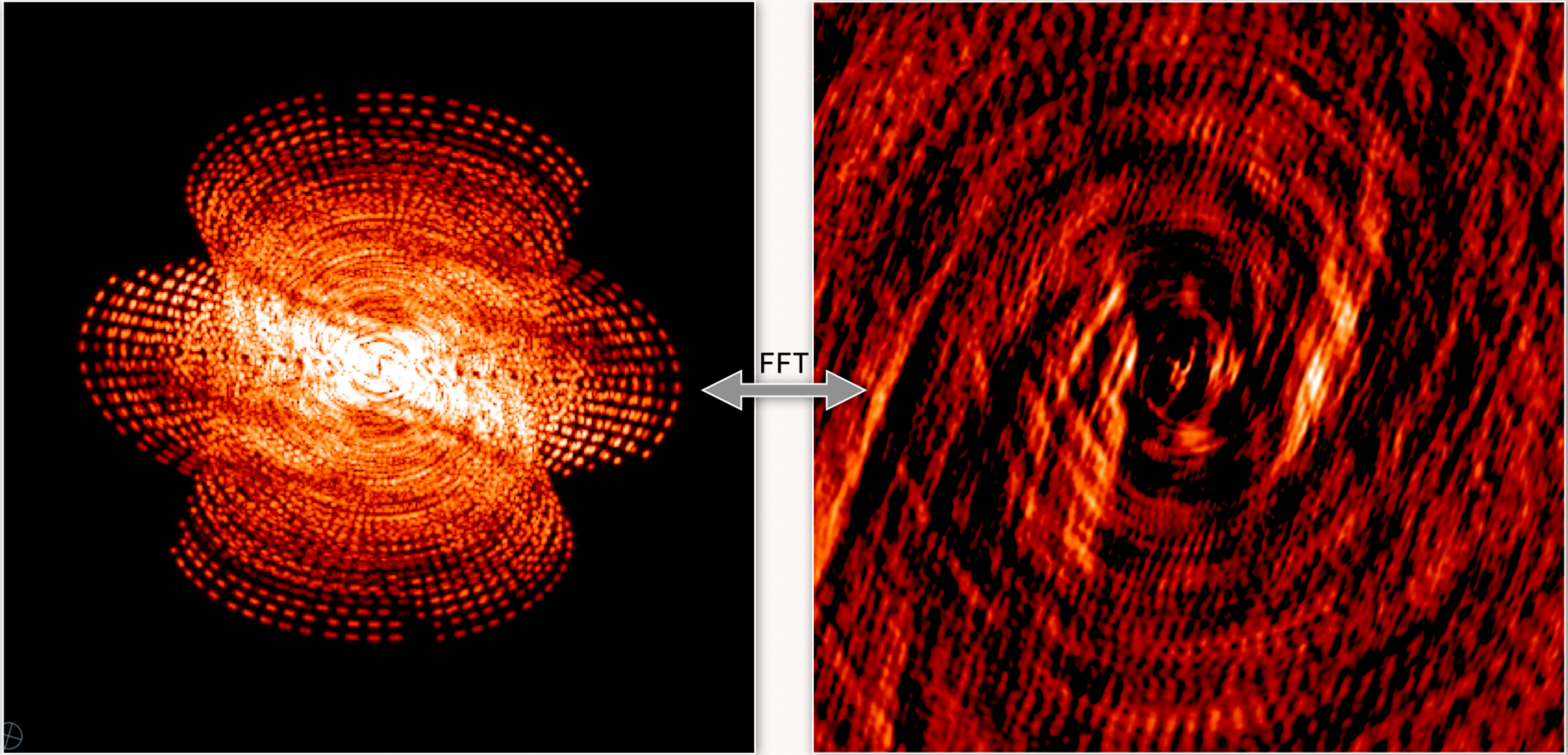

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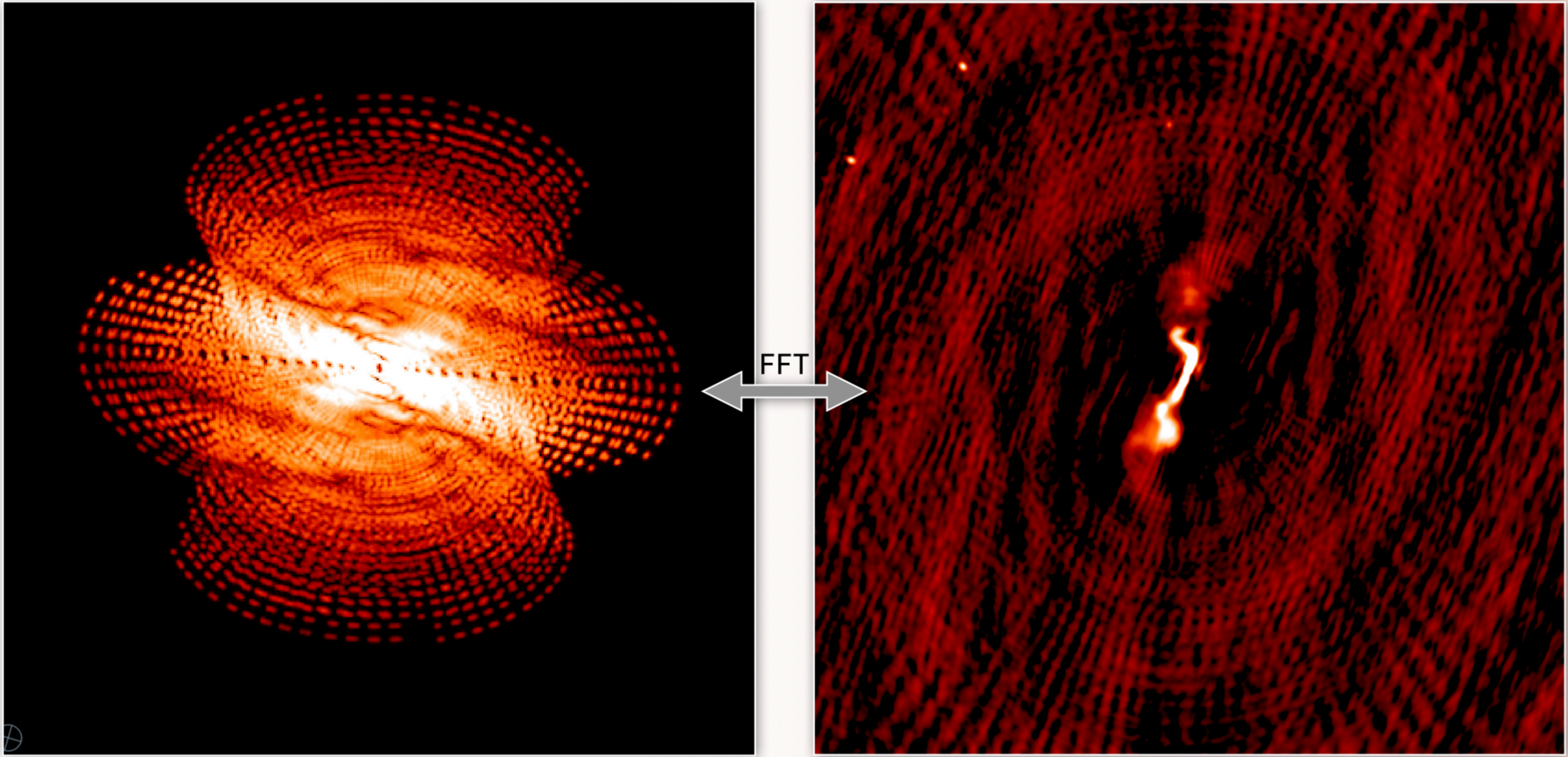
Dirty image (Uncalibrated)



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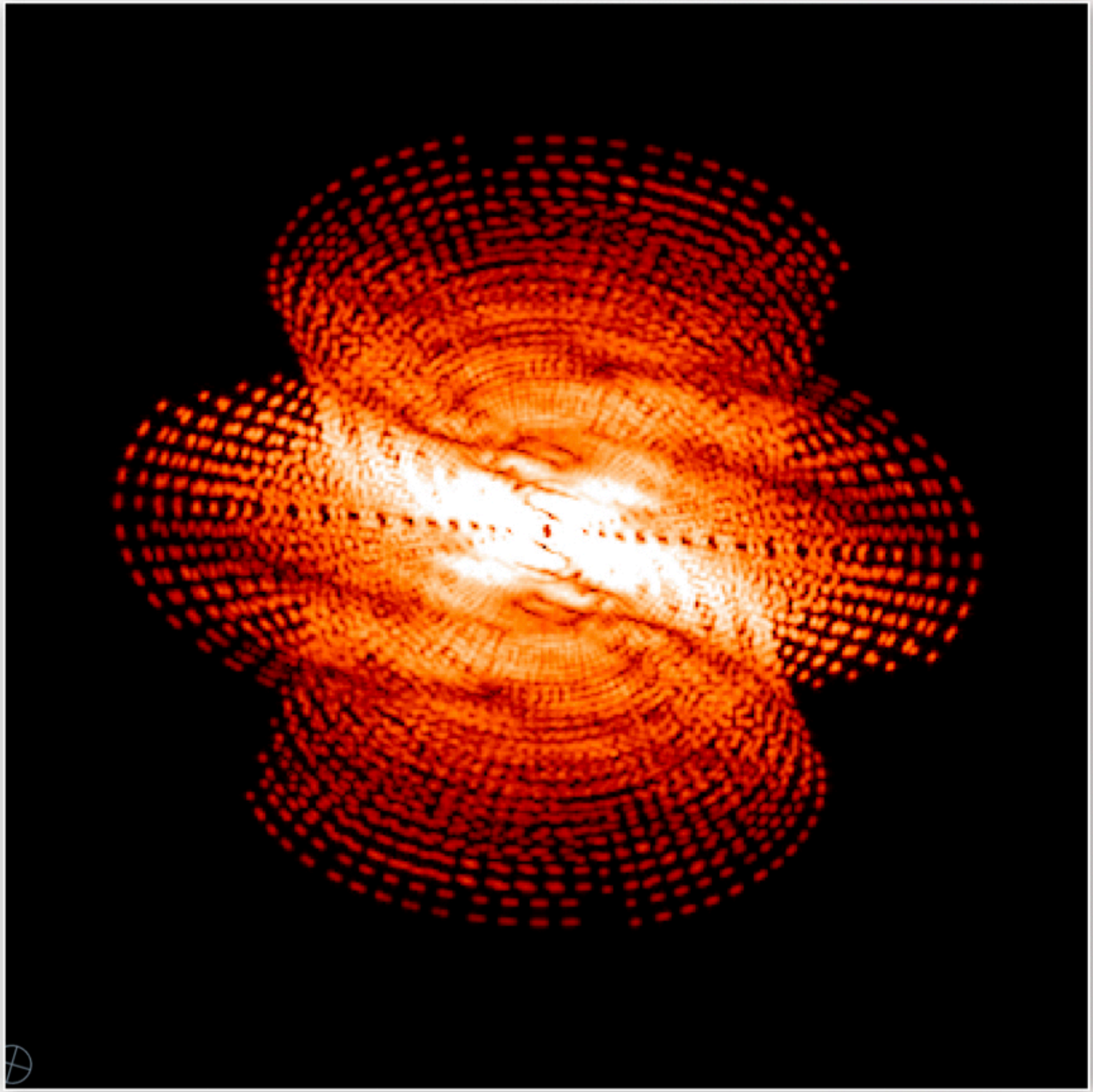

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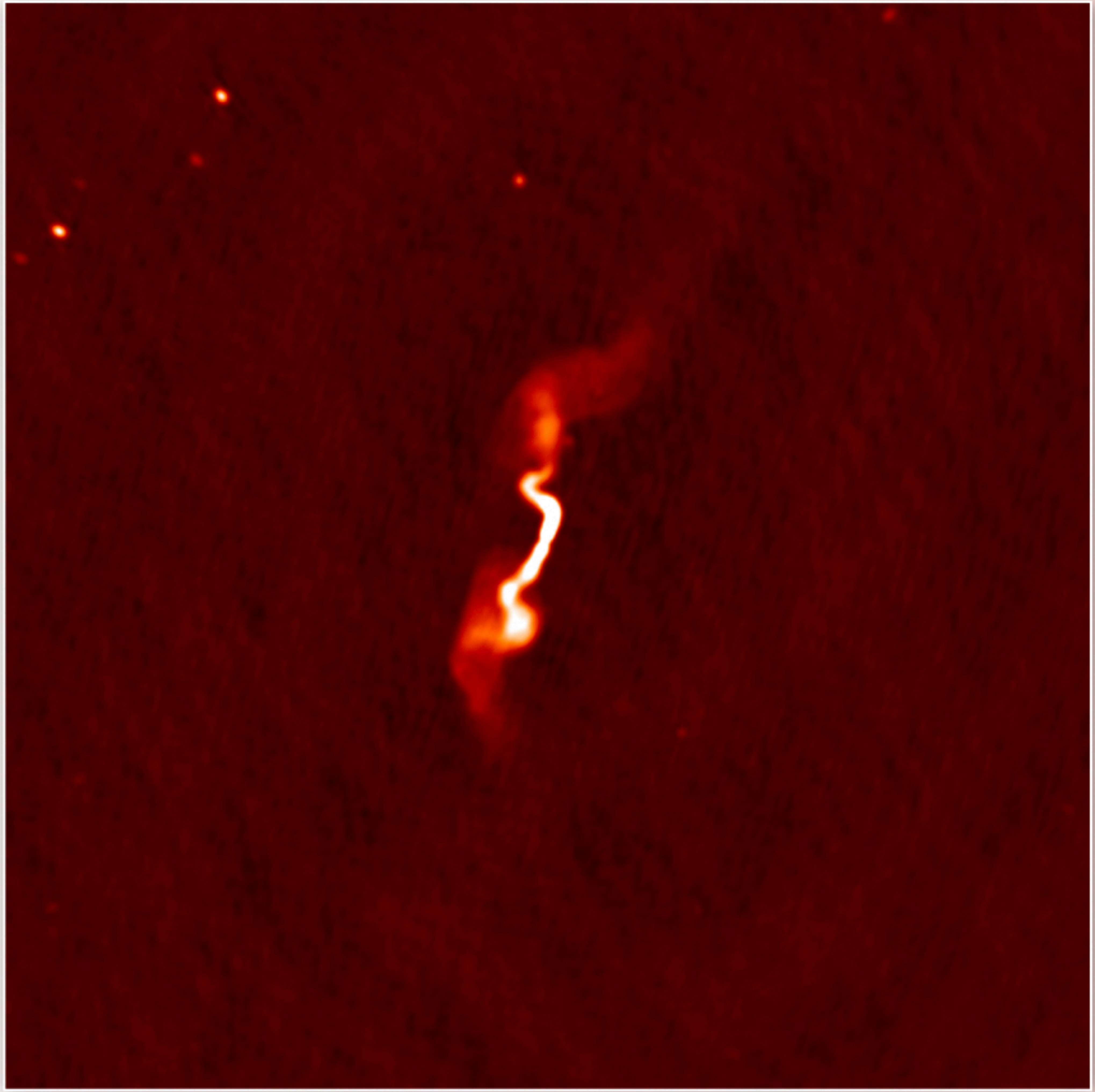

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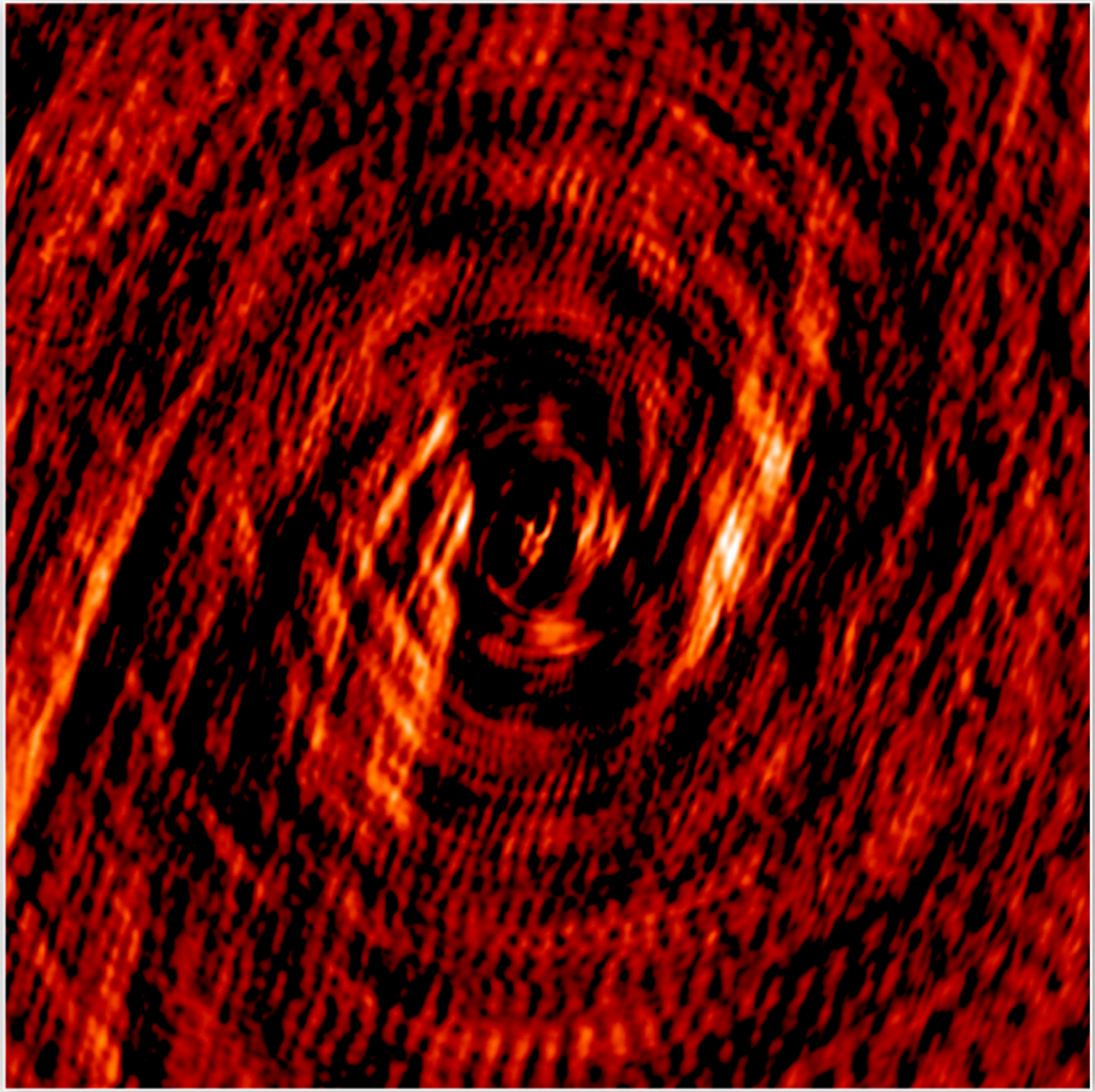
(Calibrated & Deconvolved)



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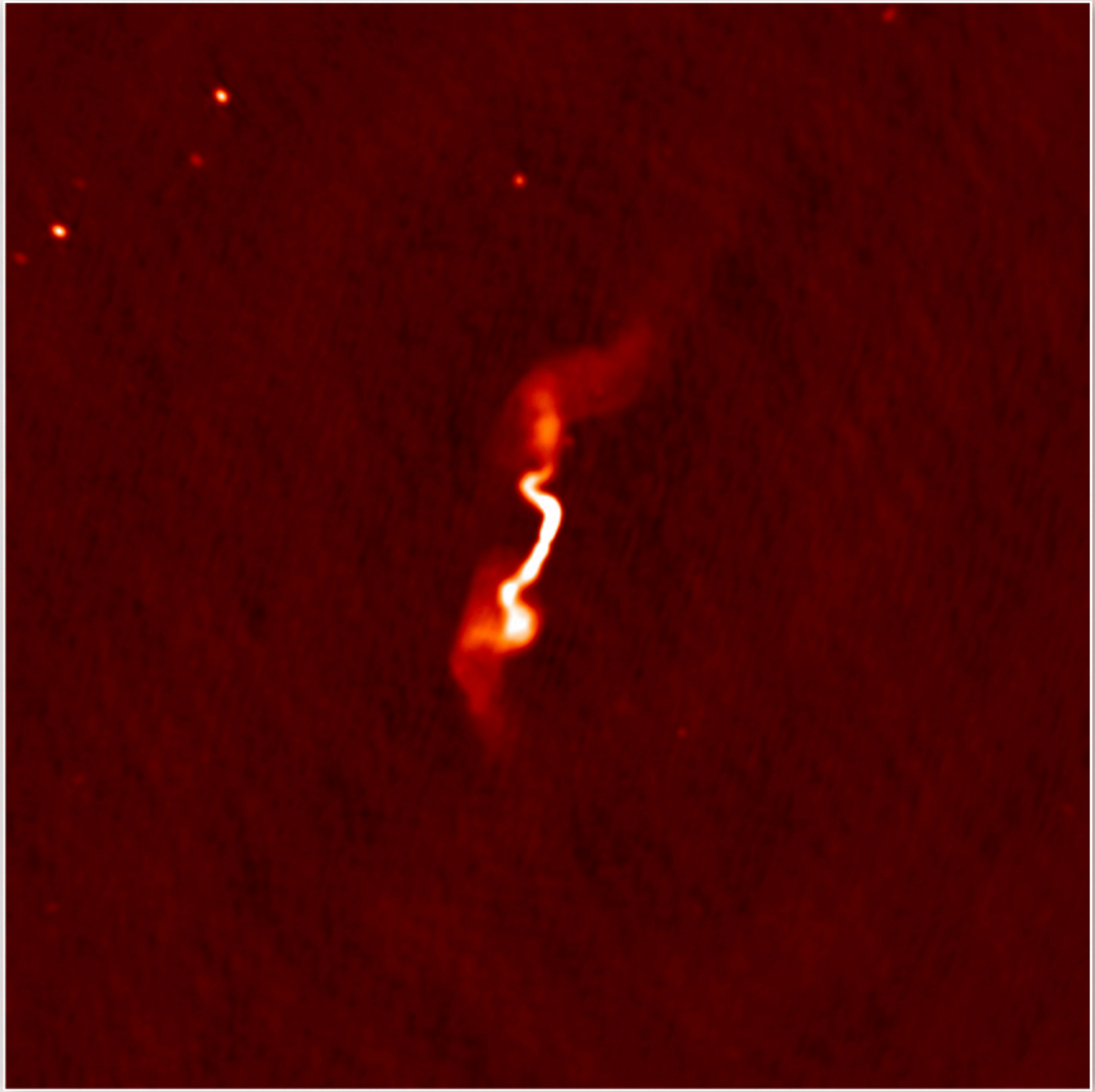

Dirty image
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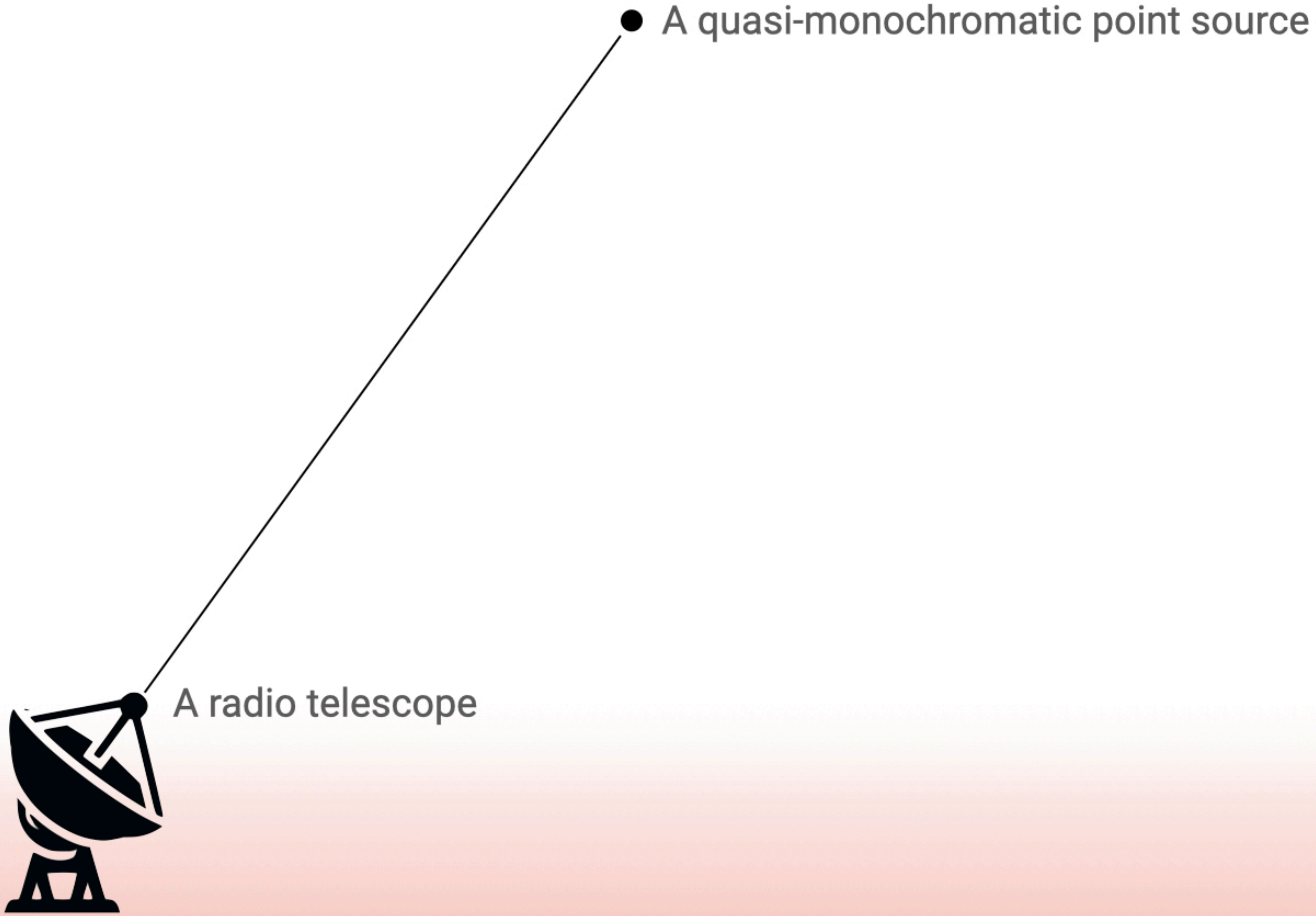
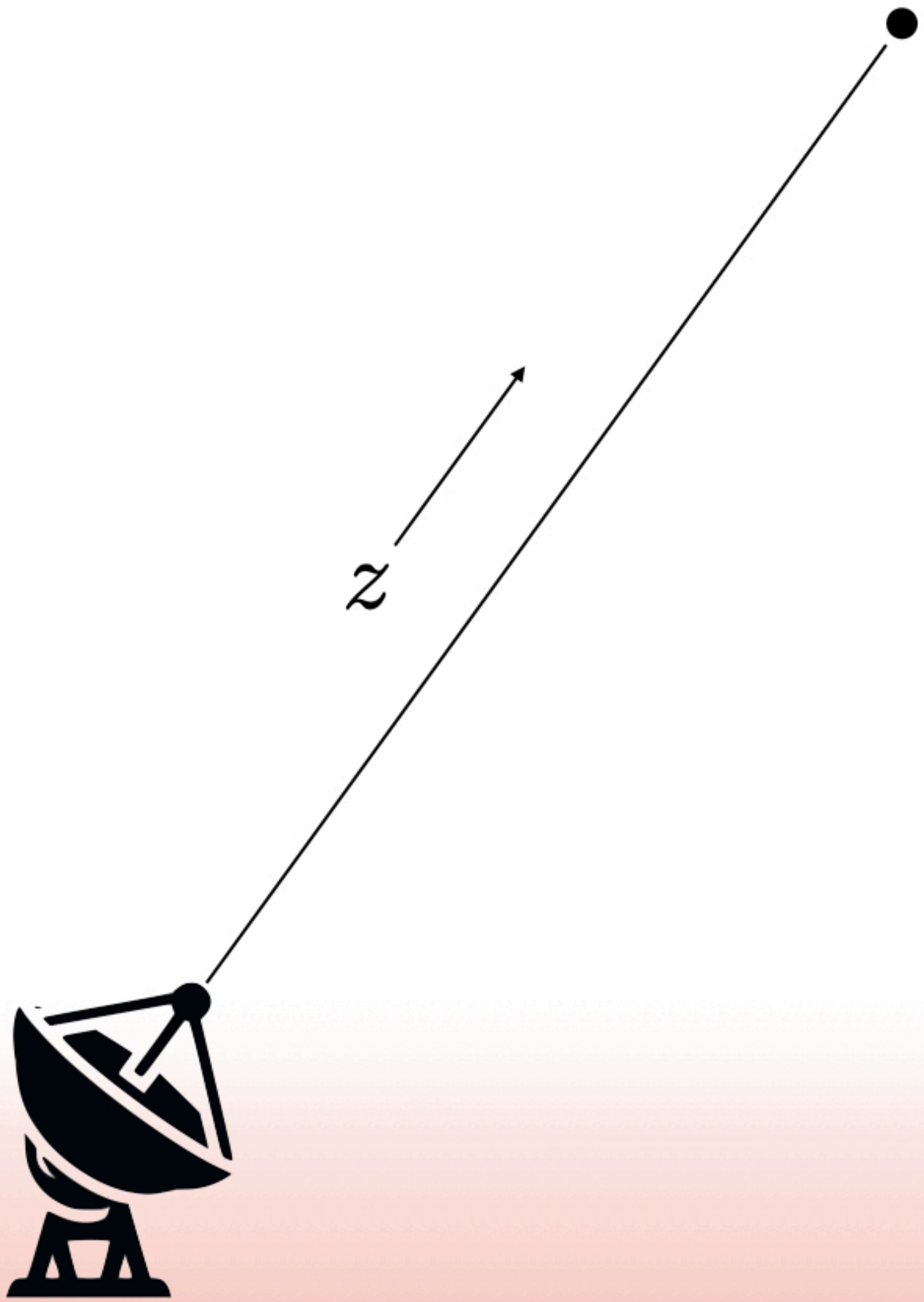
Correcting instrumental and propagation effects to ensure that all our antennas 'see' the same sky

Calibration and the Measurement Equation



(Smirnov, A&A, 2010)



The incoming planar electromagnetic wave propagating along direction ***z*** can be represented by a two-element complex vector, describing the state of the electric field in orthogonal directions ***x*** and ***y***:

$$\bar{e} = \begin{bmatrix} e_x \\ e_y \end{bmatrix}$$

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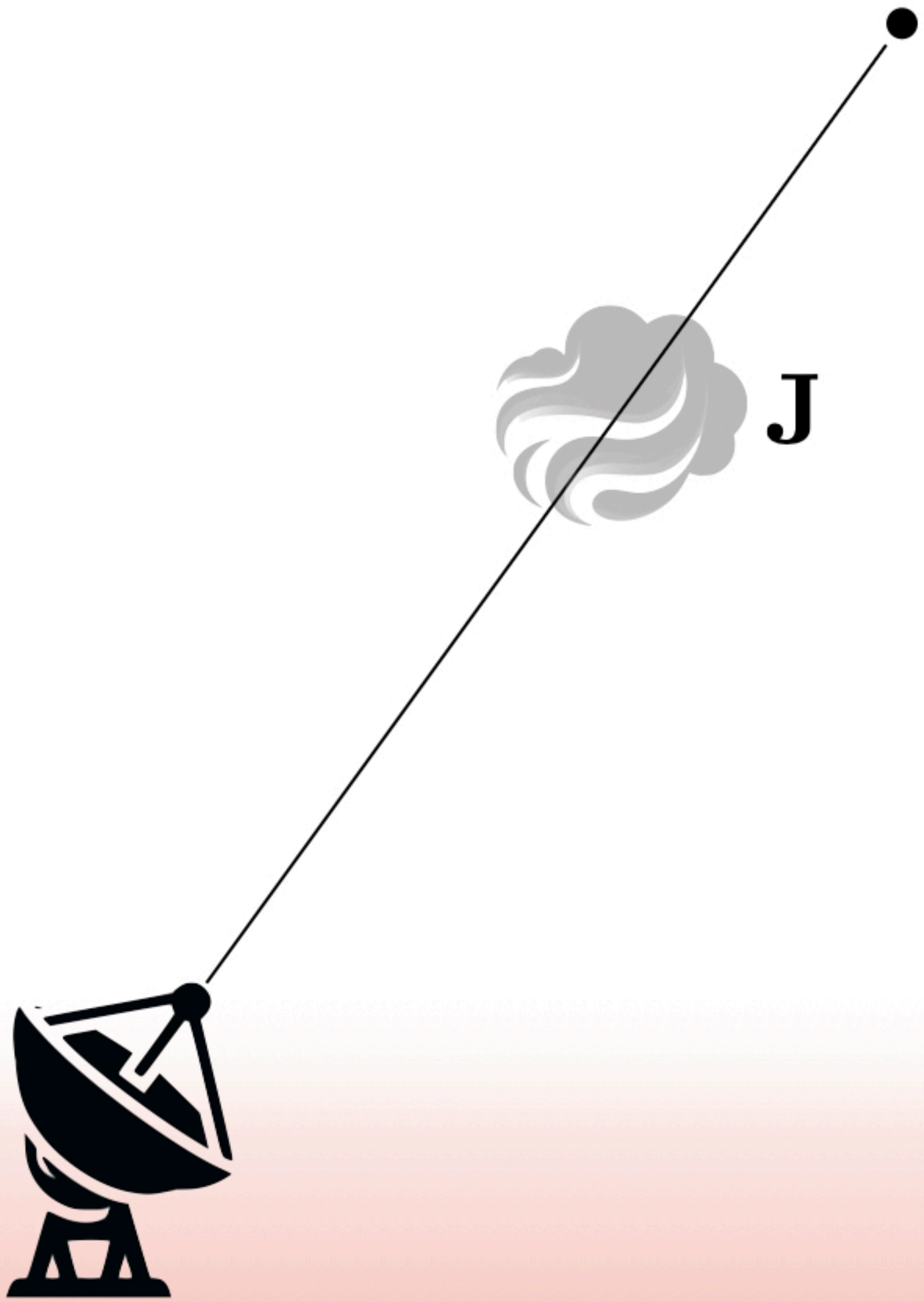

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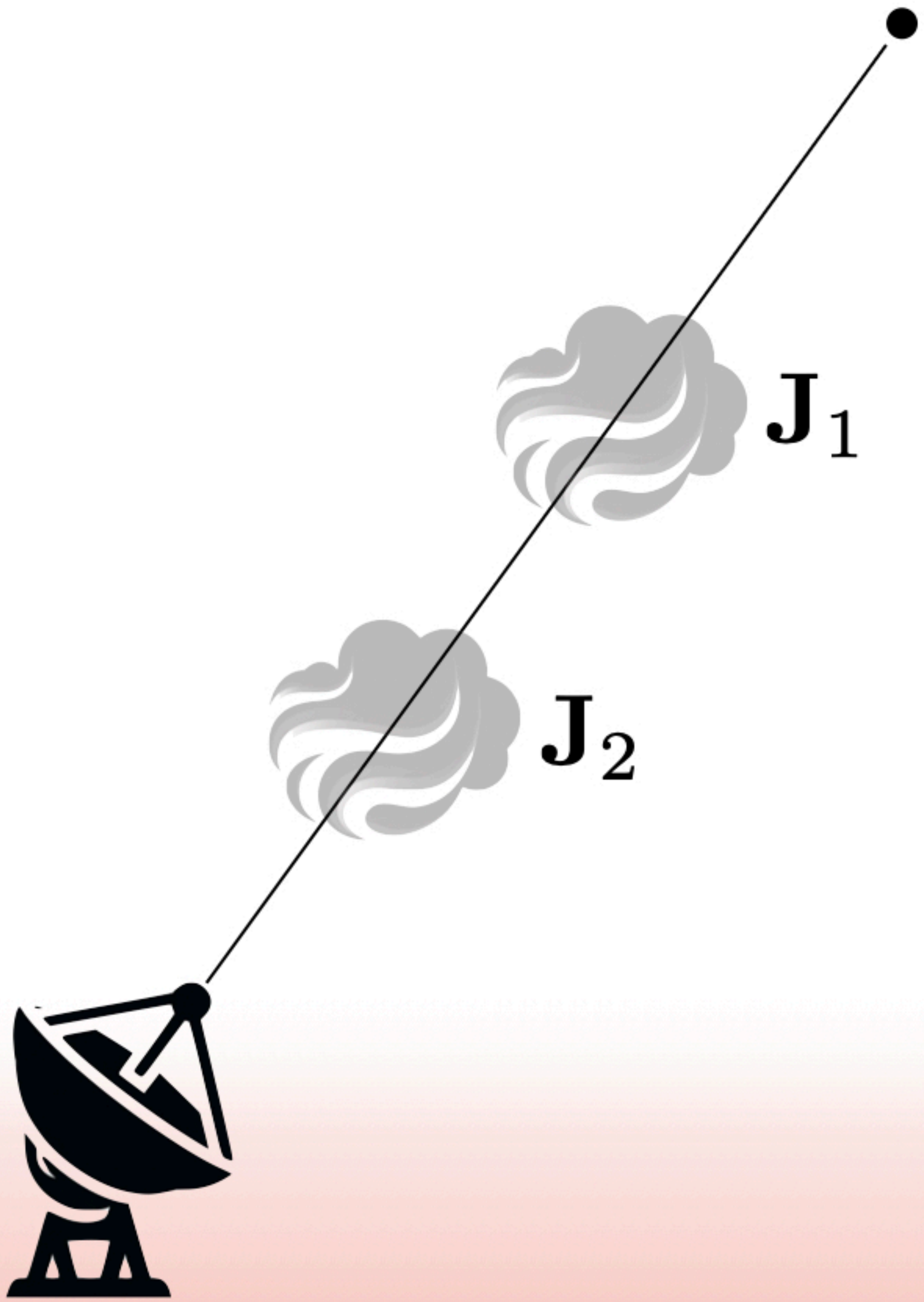
Physical effects that give rise to *linear* transformations along the signal path can be represented by a 2 × 2 matrix multiplication (Jones, 1941):

$$\bar{e}' = \mathbf{J}\bar{e}$$



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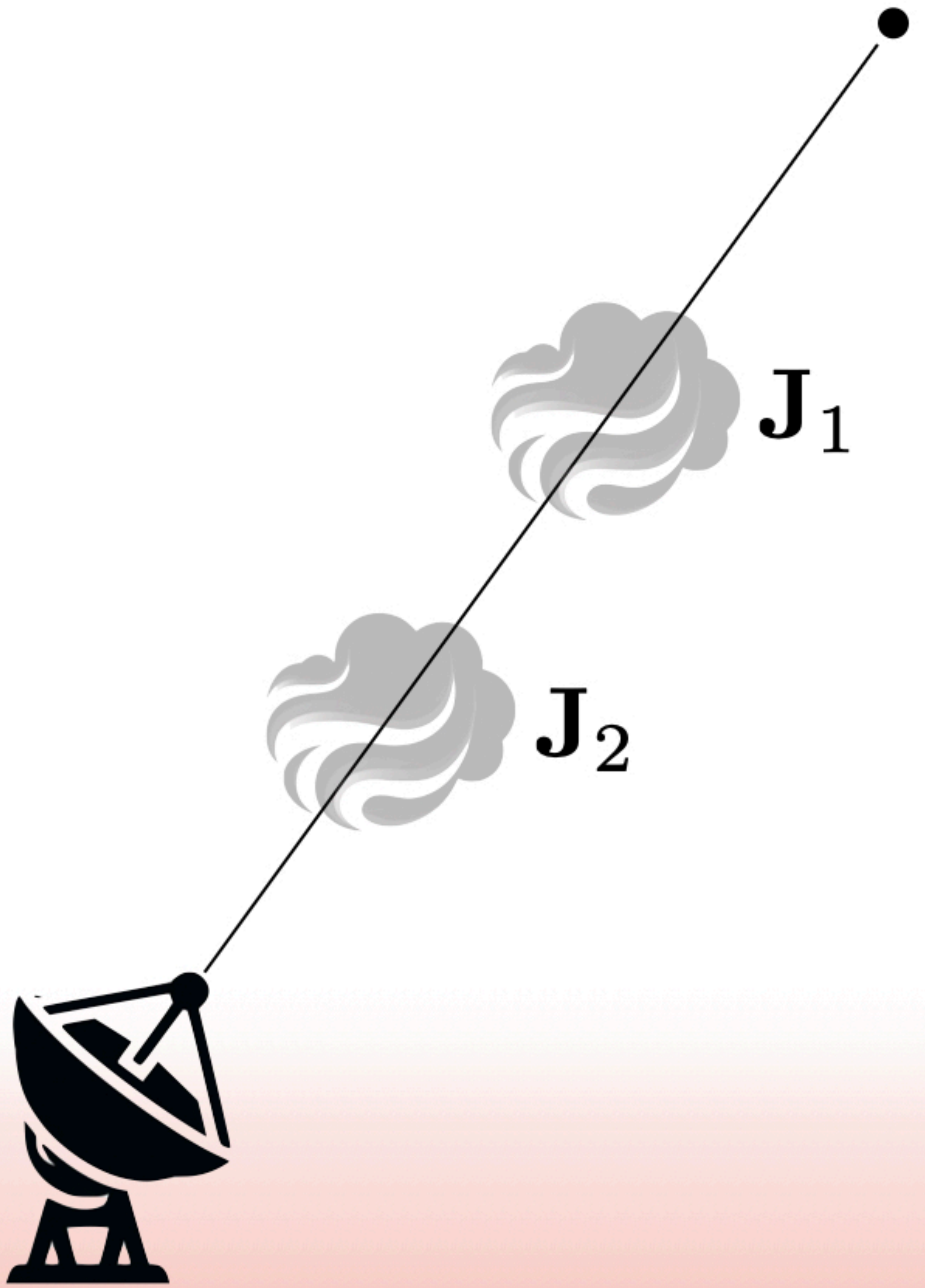
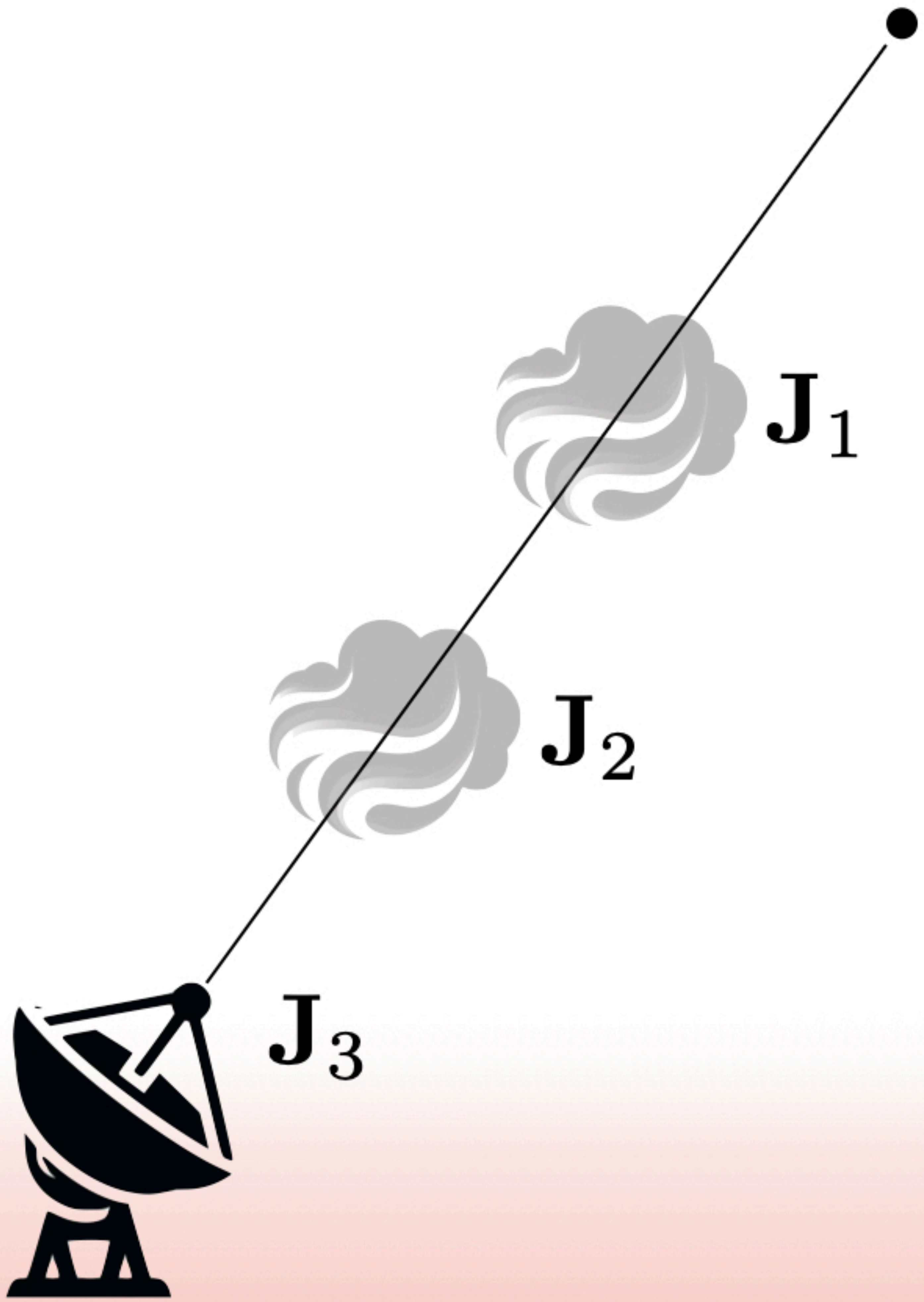
Multiple effects along the path have their own **Jones matrix**, for which the physical ordering must be preserved:

$$\bar{e}' = \mathbf{J}_n \ldots \mathbf{J}_2 \mathbf{J}_1 \bar{e} = \mathbf{J}\bar{e}$$



The incoming radio waves induce complex voltages at the antenna, typically in a pair of feeds ***a*** and ***b*** (which may be orthogonally-aligned linear dipoles, or circular feeds):

$$\bar{v} = \begin{bmatrix} v_a \\ v_b \end{bmatrix}$$



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A linear relationship between ***v*** and ***e*** can also be represented by a Jones matrix:

$$\bar{v} = \mathbf{J}\bar{e}$$

with **J** being the cumulative product of Jones matrices that relates ***v*** to **e**, and captures the propagation effects along the signal path.

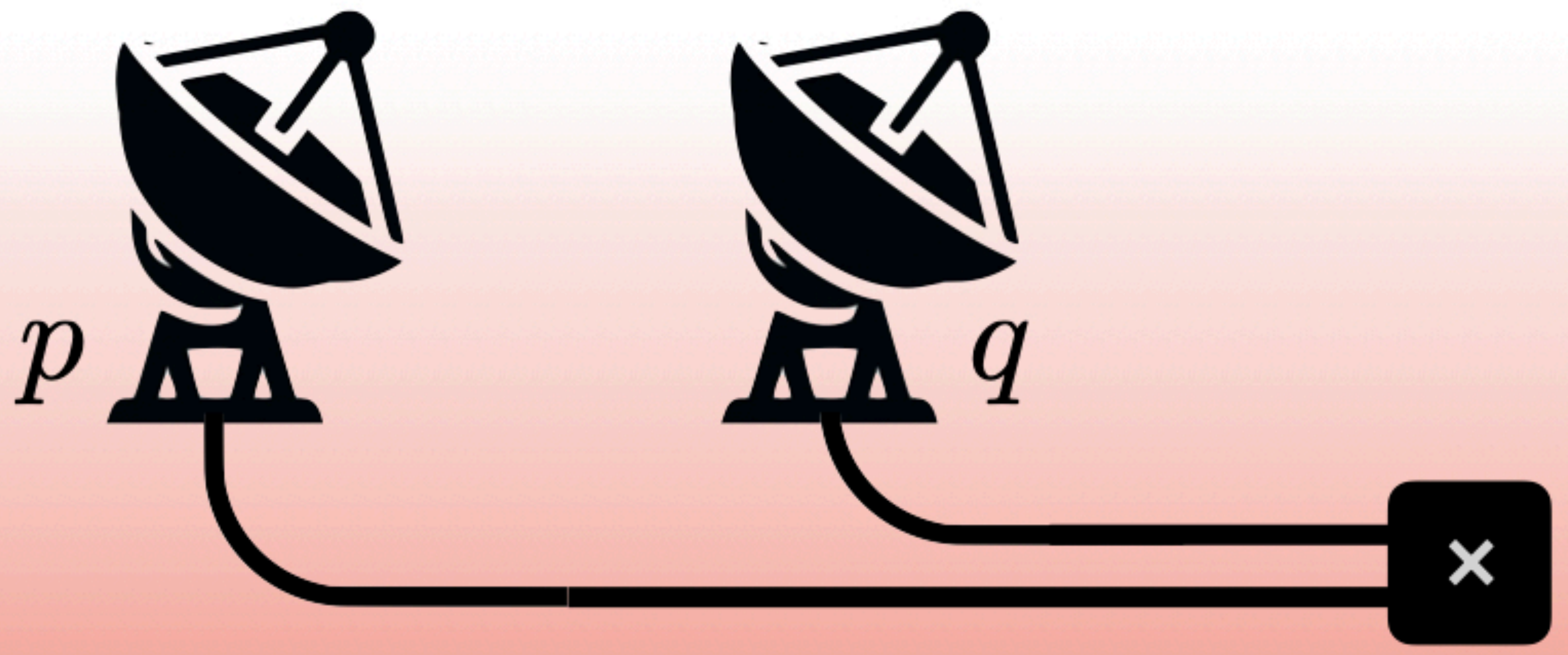
Two separate antennas *p* and *q* measure independent complex voltage vectors, which relate to the original signal **e** via the two different Jones chains for the two signal paths:

$$\bar{v}_p = \begin{bmatrix} v_{pa} \\ v_{pb} \end{bmatrix} = \mathbf{J}_p \begin{bmatrix} e_x \\ e_y \end{bmatrix}$$

$$\bar{v}_q = \begin{bmatrix} v_{qa} \\ v_{qb} \end{bmatrix} = \mathbf{J}_q \begin{bmatrix} e_x \\ e_y \end{bmatrix}$$

Radio interferometers work by correlating the voltages from antennas p and q, averaged over some small interval, equivalent to forming the outer product of voltage vectors $\boldsymbol{v_p}$ and $\boldsymbol{v_q}$:

$$\mathbf{V}_{pq} = \begin{pmatrix} < v_{pa} v_{qa}^* > & < v_{pa} v_{qb}^* > \\ < v_{pb} v_{qa}^* > & < v_{pb} v_{qb}^* > \end{pmatrix}$$



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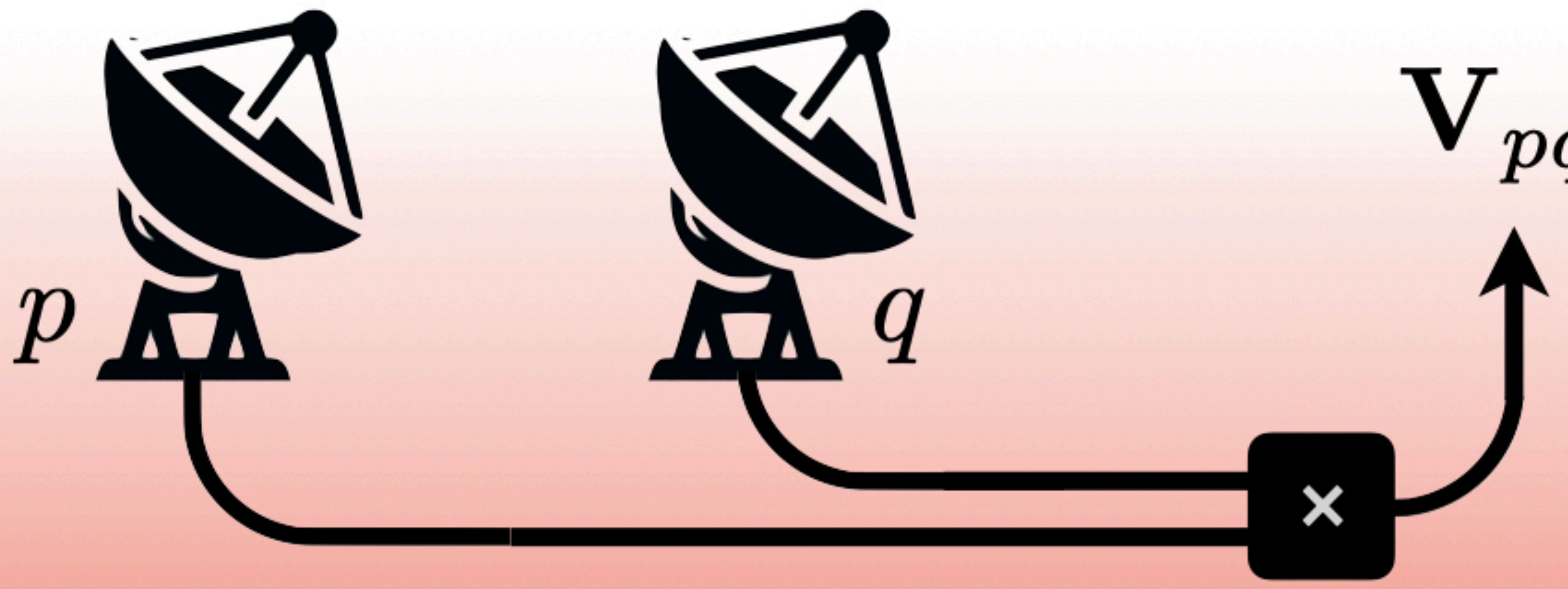
The **complex visibility** V_{pq} is thus a measurement related to the incoming electromagnetic wave **e**, corrupted by the total Jones chains along the differing paths to antennas *p* and *q*, assuming the Jones terms are constant across the averaging interval:

$$\mathbf{V}_{pq} = \mathbf{J}_p \begin{pmatrix} < e_x e_x^* > & < e_x e_y^* > \\ < e_y e_x^* > & < e_y e_y^* > \end{pmatrix} \mathbf{J}_q^H$$



The bracketed quantities:

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can be expressed in terms of four Stokes parameters:

$$\mathbf{V}_{pq} = \mathbf{J}_p \begin{pmatrix} I + Q & U + iV \\ U - iV & I - Q \end{pmatrix} \mathbf{J}_q^H$$

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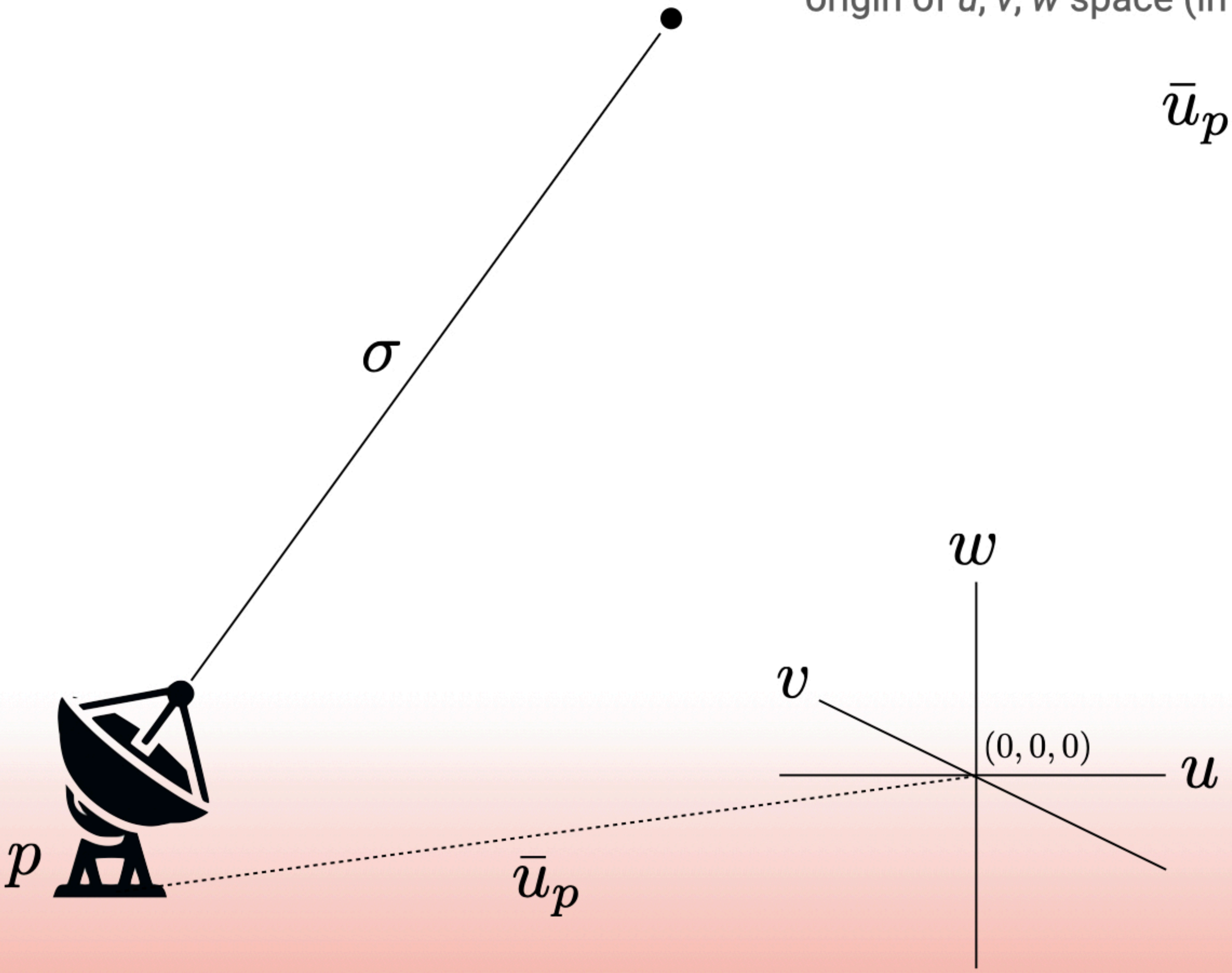
The complex visibility measurements thus give us information about the polarised radio sky, provided we can understand the Jones matrices.

Jones Matrices

A special scalar matrix

Antenna *p* has baseline coordinates u_p, v_p, w_p with respect to the origin of *u*, *v*, *w* space (in units of wavelength):

$$\bar{u}_p = (u_p, v_p, w_p)$$



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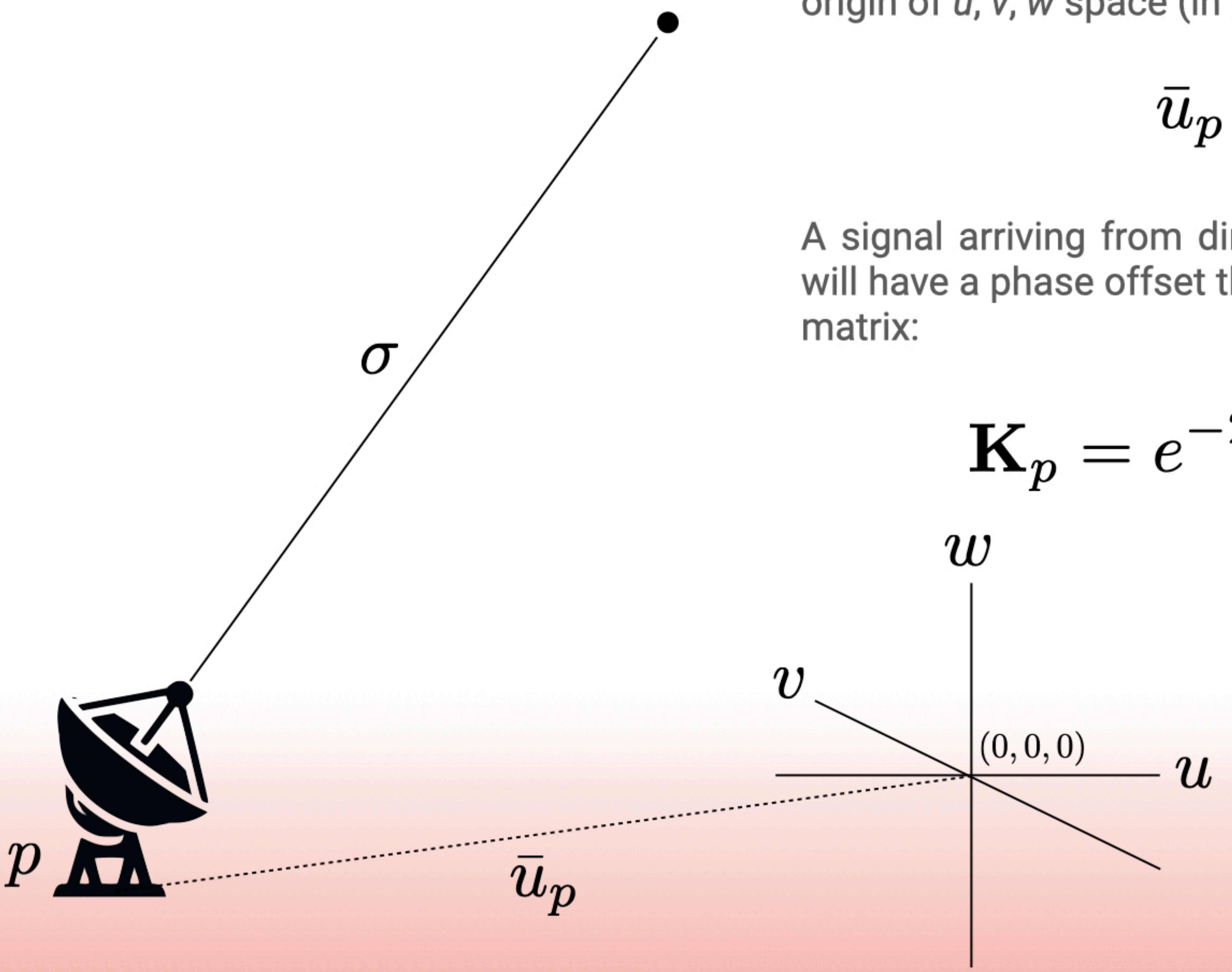
A signal arriving from direction σ with direction cosines *l*, *m*, *n* will have a phase offset that can be expressed as a scalar Jones matrix:

$$\mathbf{K}_p = e^{-2\pi i(u_p l + v_p m + w_p(n-1))}$$



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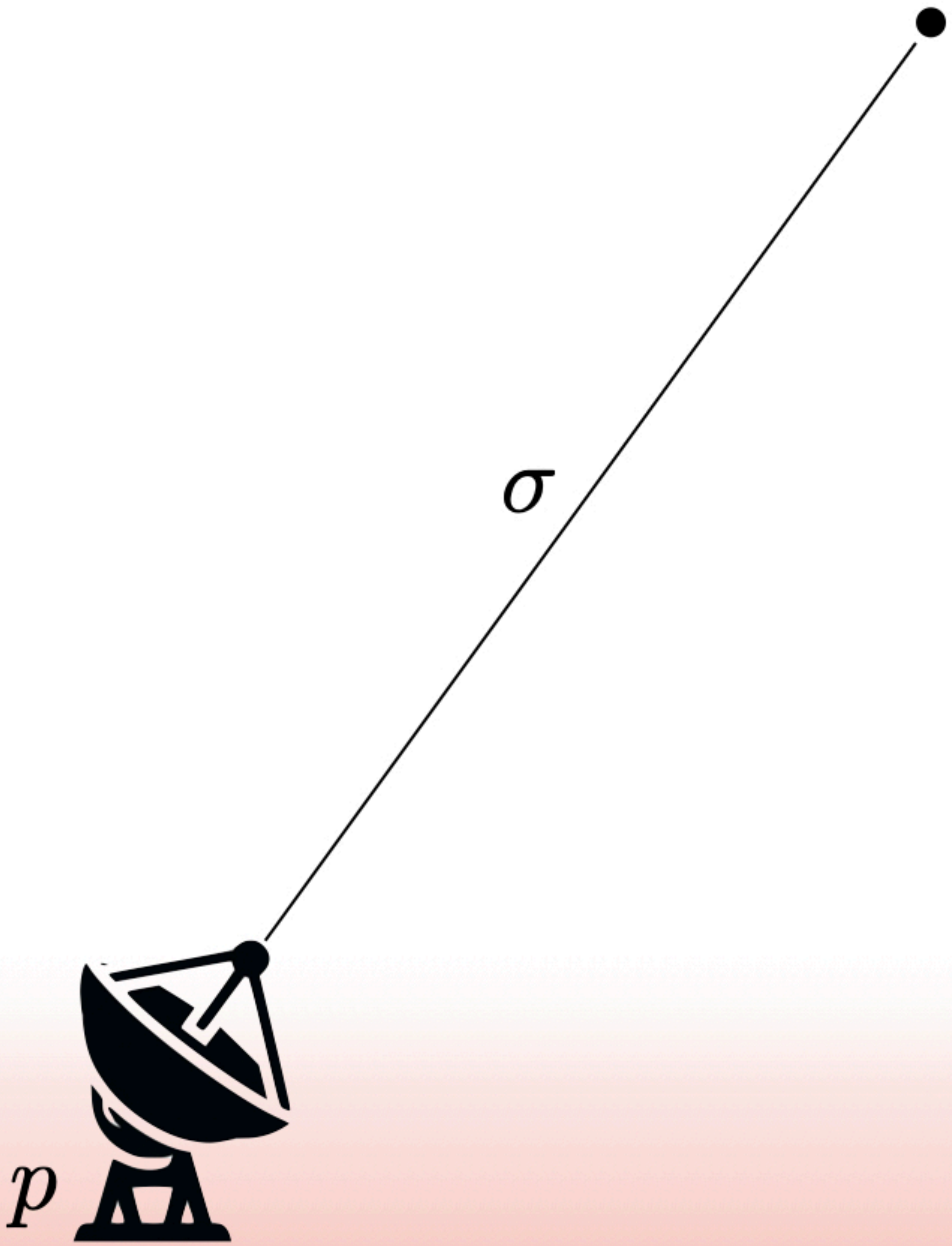

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(Does this look familiar?)

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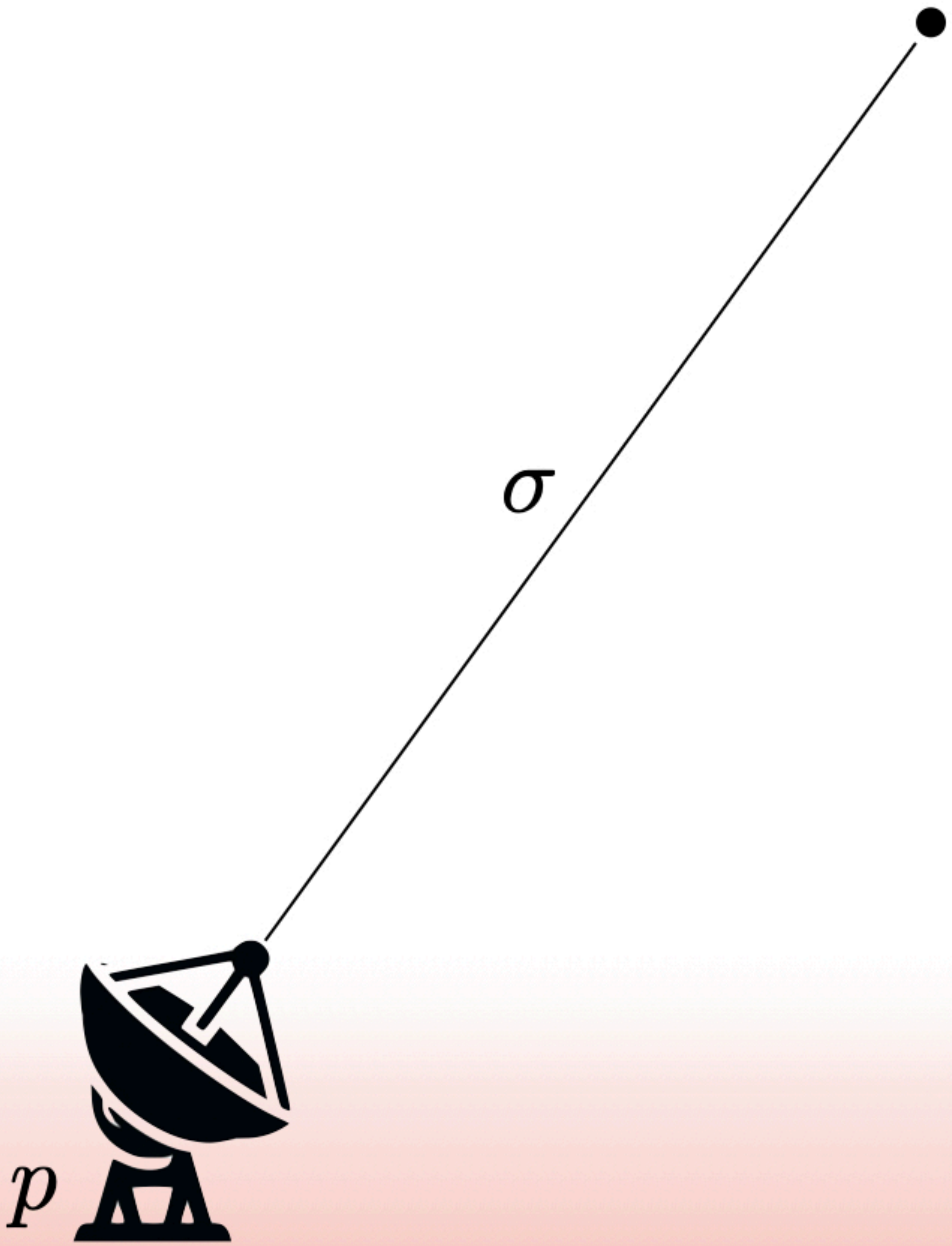

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In practice, the correlator introduces additional delay contributions in order to track a particular direction of interest on the sky.

This is known as the phase centre and is usually (but doesn't have to be) coincident with the direction that the antennas are tracking.

Our Measurement Equation for the baseline *p*, *q* now becomes:

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or by defining the "source coherency" $\boldsymbol{X}_{pq}$ as the product of the brightness matrix and the geometric delay terms for p and q, we obtain:

$$\mathbf{V}_{pq} = \mathbf{J}_p X_{pq} \mathbf{J}_q^H$$

for a baseline tracking a single point source corrupted by the Jones chains $\mathbf{J}_p$ and $\mathbf{J}_q$.

Links in the Jones chain

$$\mathbf{J}_p = \mathbf{K}_p\mathbf{B}_p\mathbf{G}_p\mathbf{D}_p\mathbf{E}_p\mathbf{X}_p\mathbf{P}_p\mathbf{T}_p\mathbf{Z}_p$$

$\mathbf{K}_p$	geometric delay
$\mathbf{B}_p$	bandpass
$\mathbf{G}_p$	electronic gains
$\mathbf{D}_p$	polarization leakage
$\mathbf{E}_p$	antenna primary beam response
$\mathbf{X}_p$	cross-hand phases
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Fundamental domains are:

$$\mathbf{E}_p = \mathbf{E}_p(l, m, \nu, t)$$

but we often assume that certain Jones matrices are only strong functions or a reduced set of these, e.g.:

$$\mathbf{B}_p = \mathbf{B}_p(\nu)$$

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Some of these will feature in more detail in the **Advanced Calibration** and **Polarisation** lectures.

I subjected you to all that because (IMO) calibration is best understood by this mathematical formalism, known as the Measurement Equation

$$\mathbf{V}_{pq} = \mathbf{J}_p X_{pq} \mathbf{J}_q^H$$

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Measure this

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Measure this

Predict this

Solve for these

$$\mathbf{V}_{pq} = \mathbf{J}_p X_{pq} \mathbf{J}_q^H$$

Measure this

Predict this

More generally, what calibration does is minimise the difference between the data (**D**) and the model (**M**), by evaluating the Measurement Equation and finding the best fitting instrumental (antenna-based) parameters (**G**):

$$\min_{\mathbf{G}} ||\mathbf{D} - \mathbf{G}\mathbf{M}\mathbf{G}^H||$$

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These important instrumental corrections are derived via observations of **calibrator sources**.

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There are two tiers of calibrators: **primary** and **secondary**. Their roles are different depending on what instrumental correction we are trying to derive. The strategy for observing them will depend on the characteristics of the array, the observing frequency, and what the demands of your science goals are.

Primary calibrators

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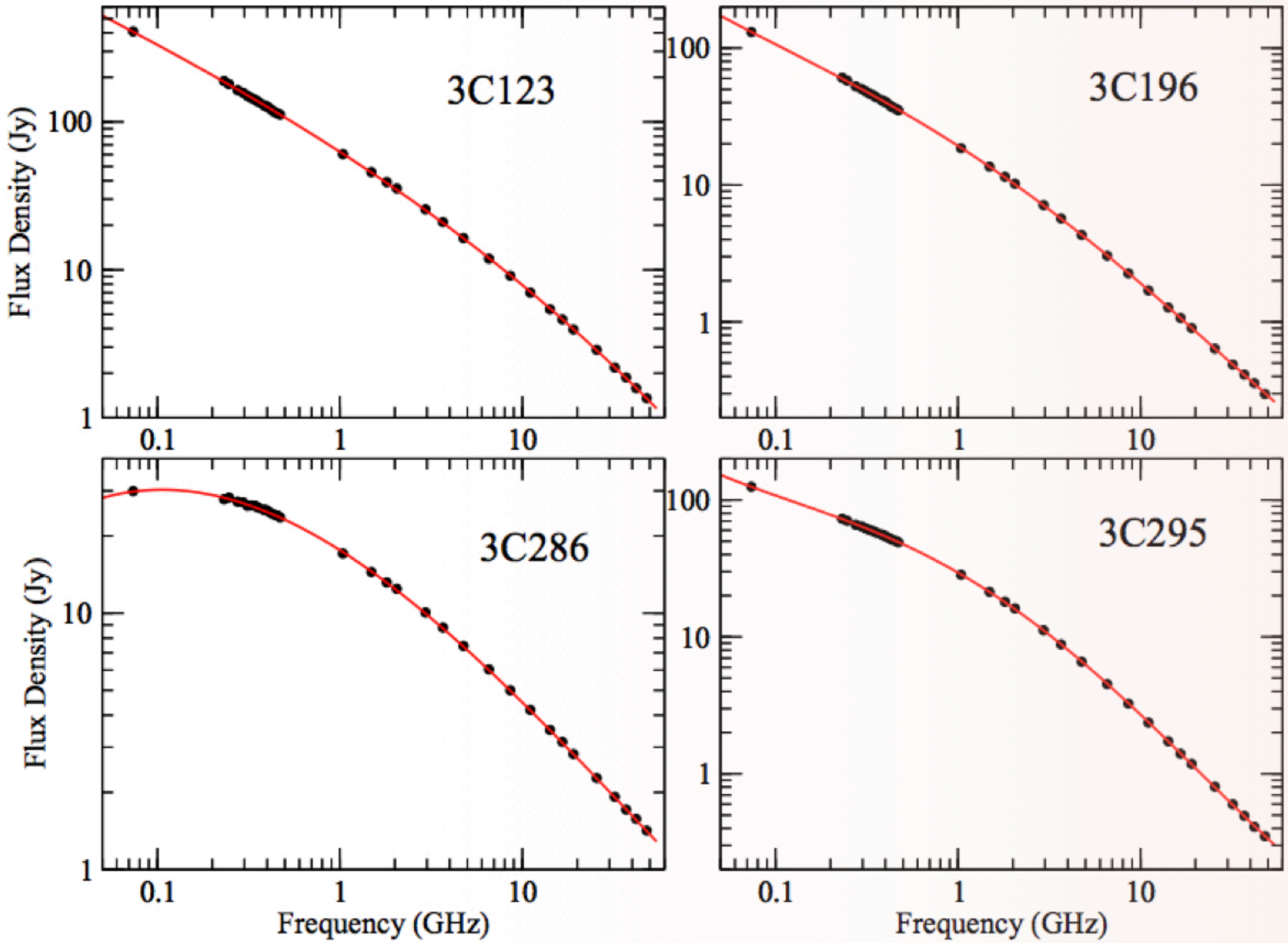
- Correct the instrumental response to polarised radio waves: the polarisation properties of the calibrator source must be precisely known (more on this in the polarimetry lecture).

Primary calibrators



Measured and modelled spectra of four 3C calibrator sources.

These four are stable to better than 1% over a 20 year timescale.

Perley & Butler
ApJSS, 2016

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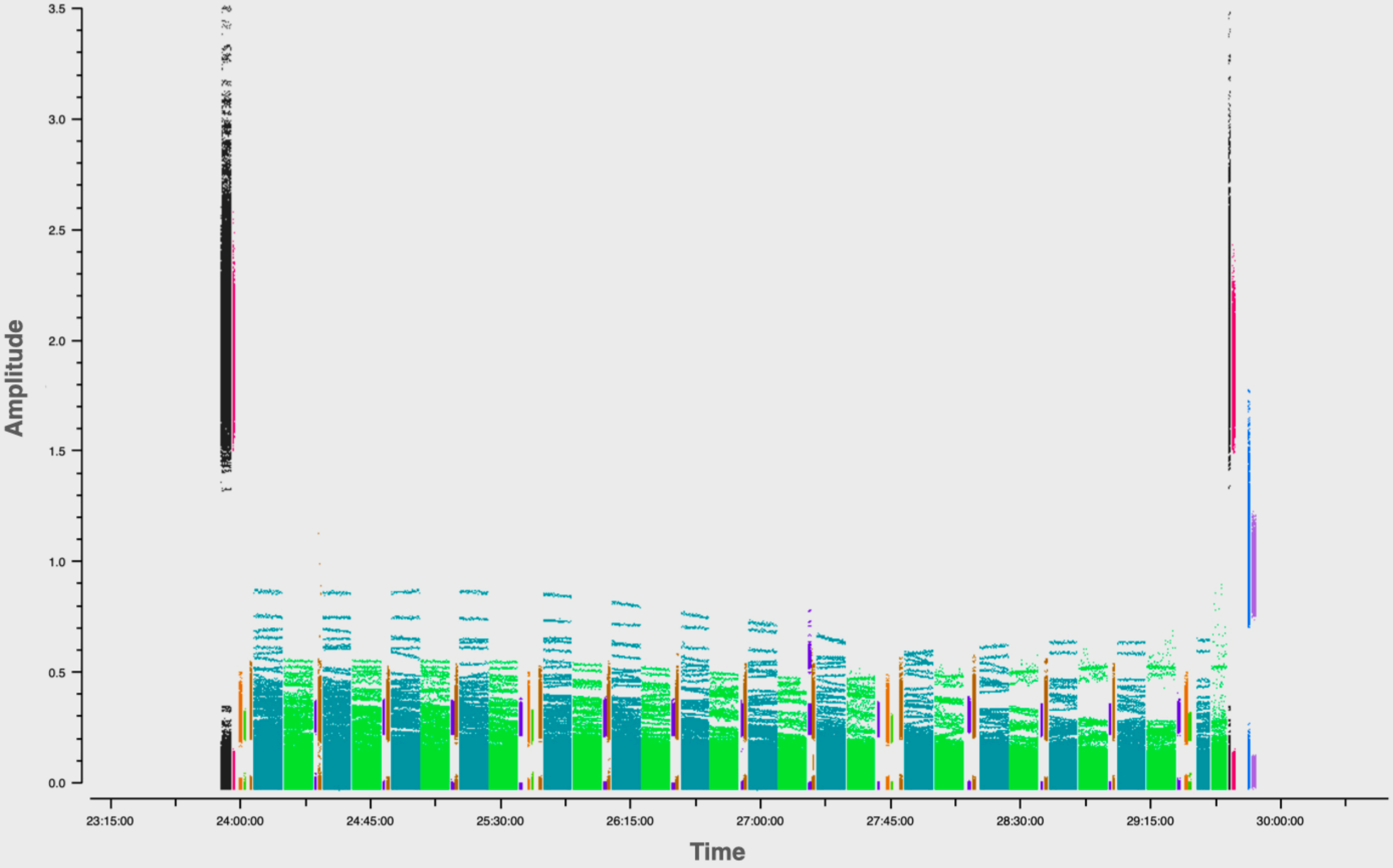
- Be wary of the spectral axis at this stage. SPWs in VLA / ALMA data will naturally handle it, this might not be the case for other instruments!

Anatomy of a scheduling block



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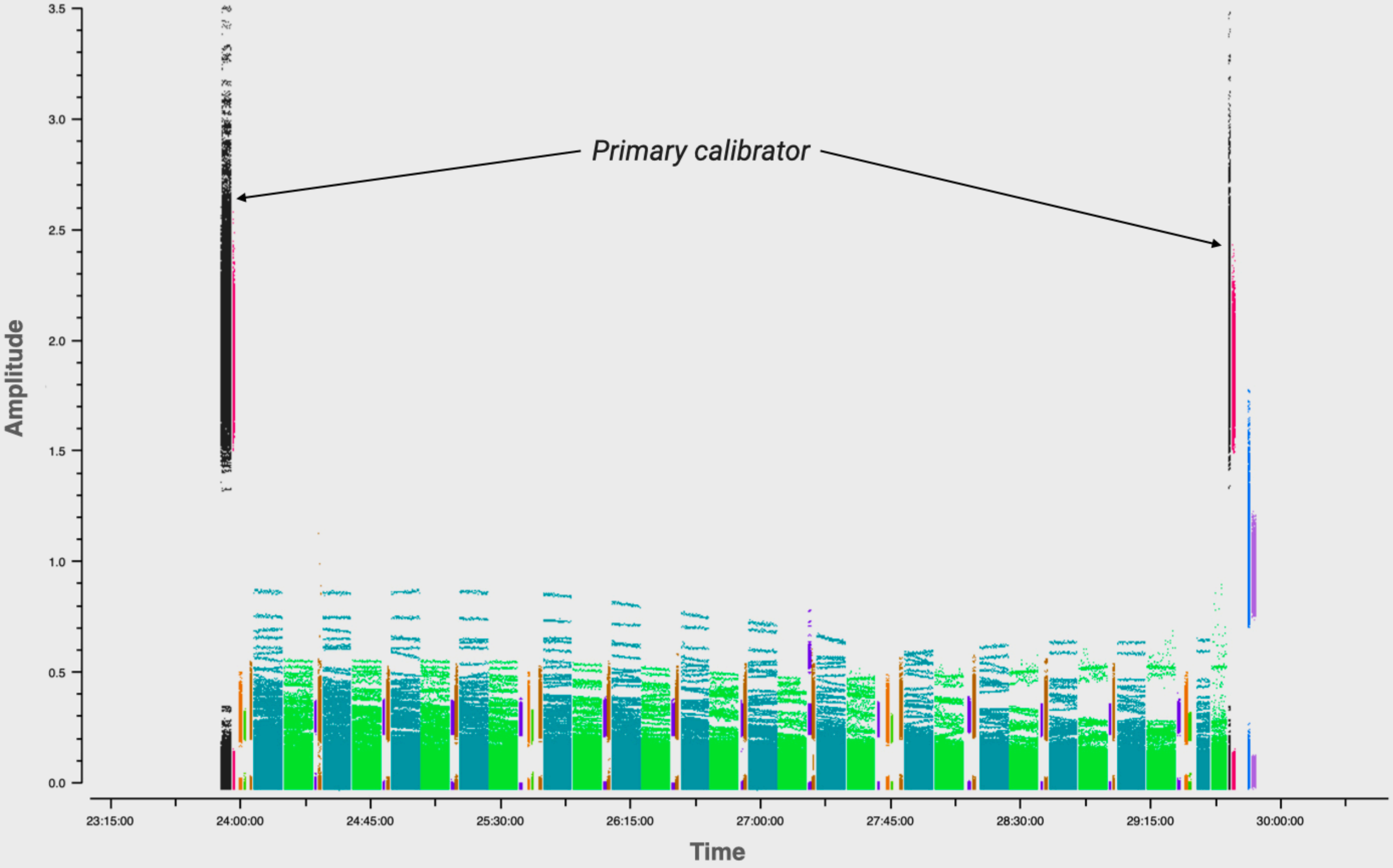

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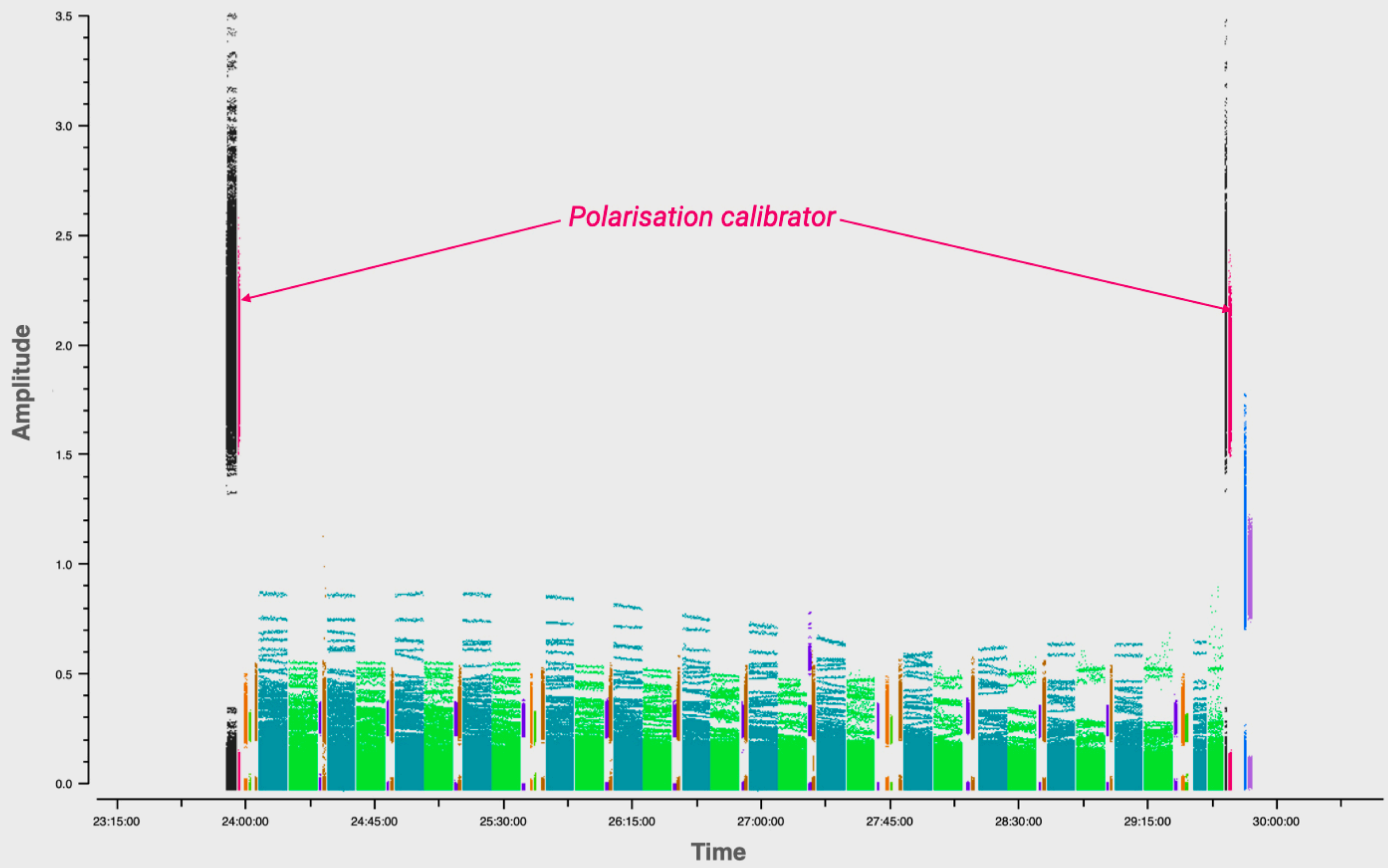

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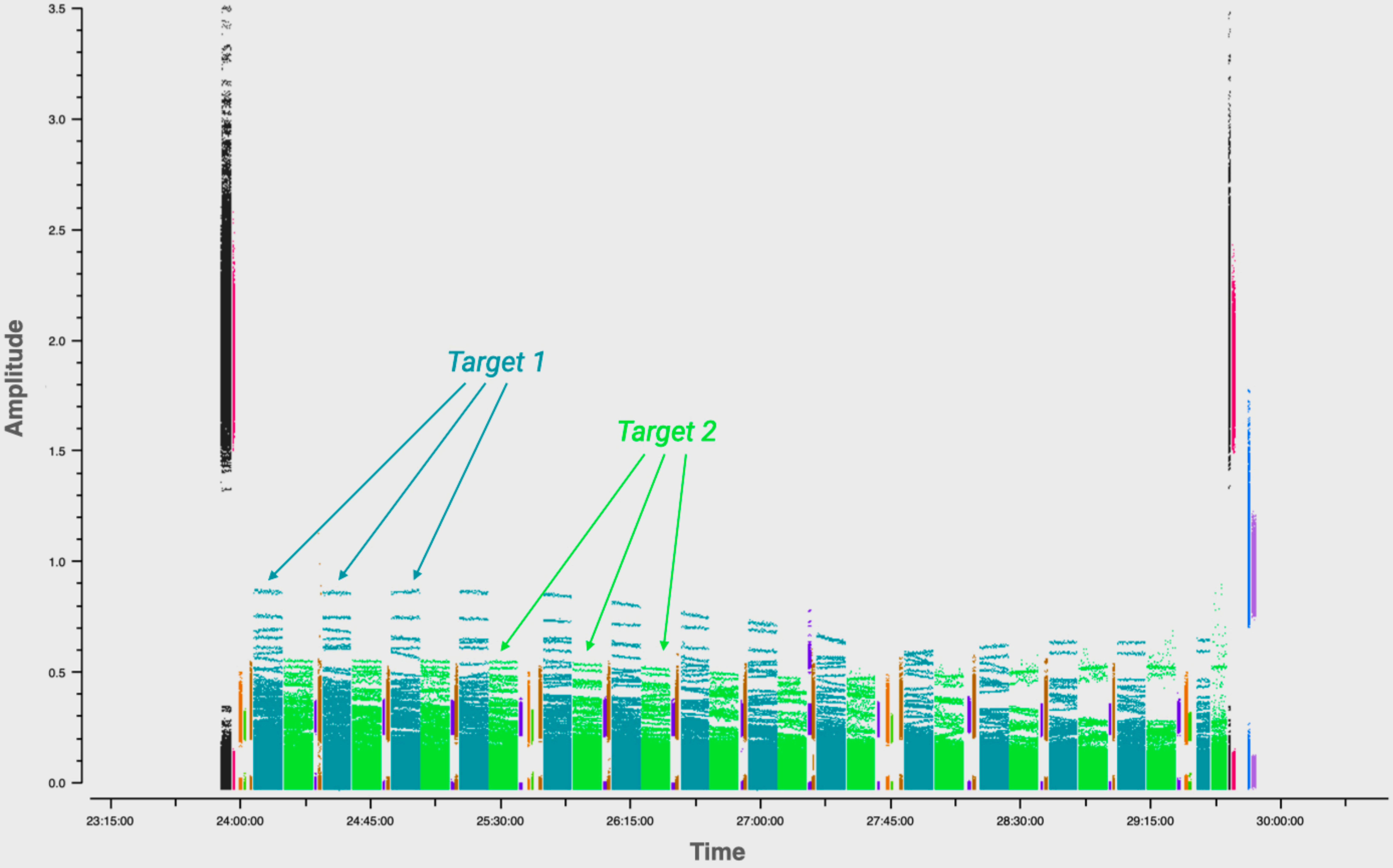

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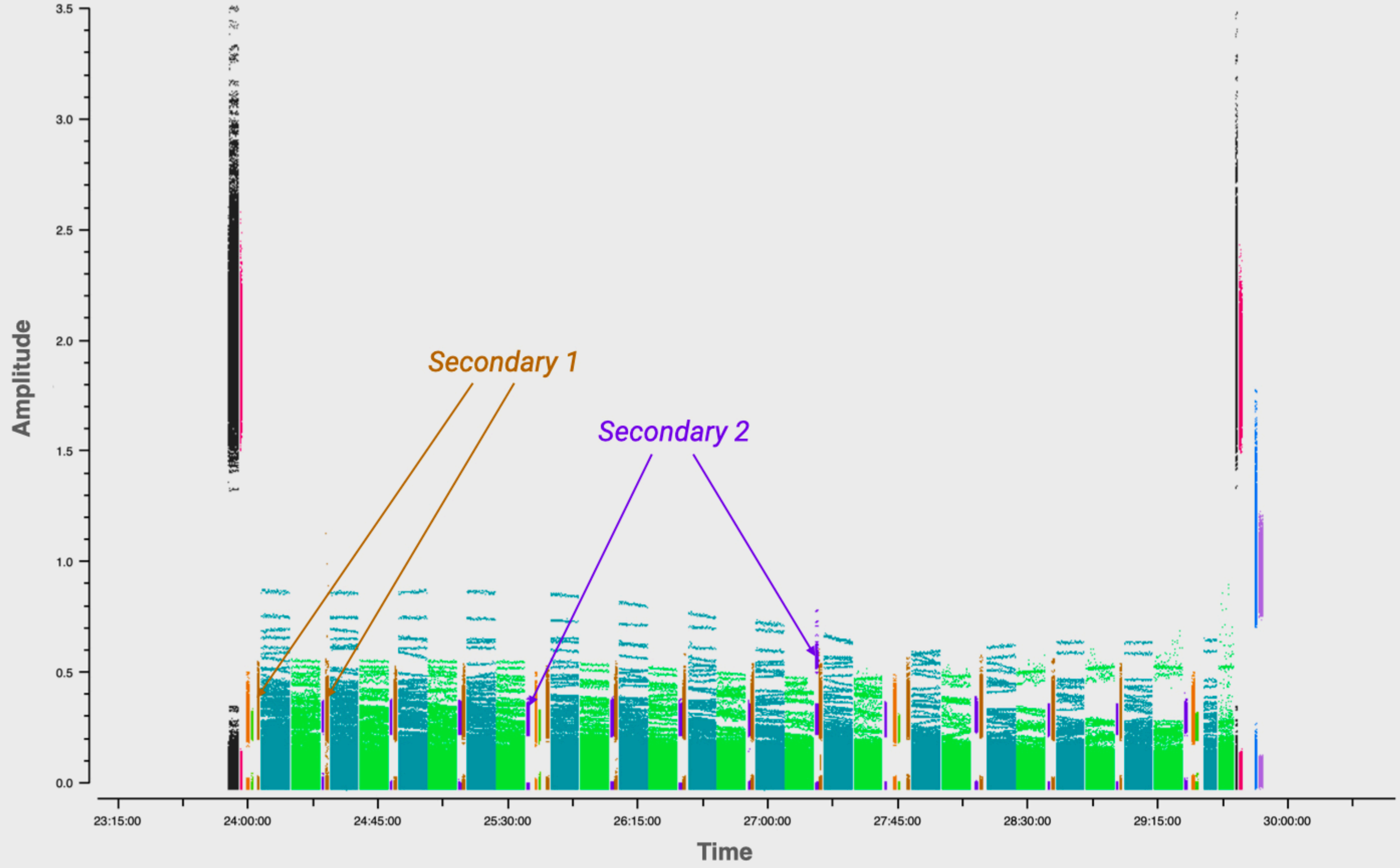

A Calibration Example

Supernova remnant 3C391

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- Demonstrating only a subset of the full observation:
    - ‘C1’ pointing only: `RA = 18h49m24.24s, Dec = −00d55m40.58s`
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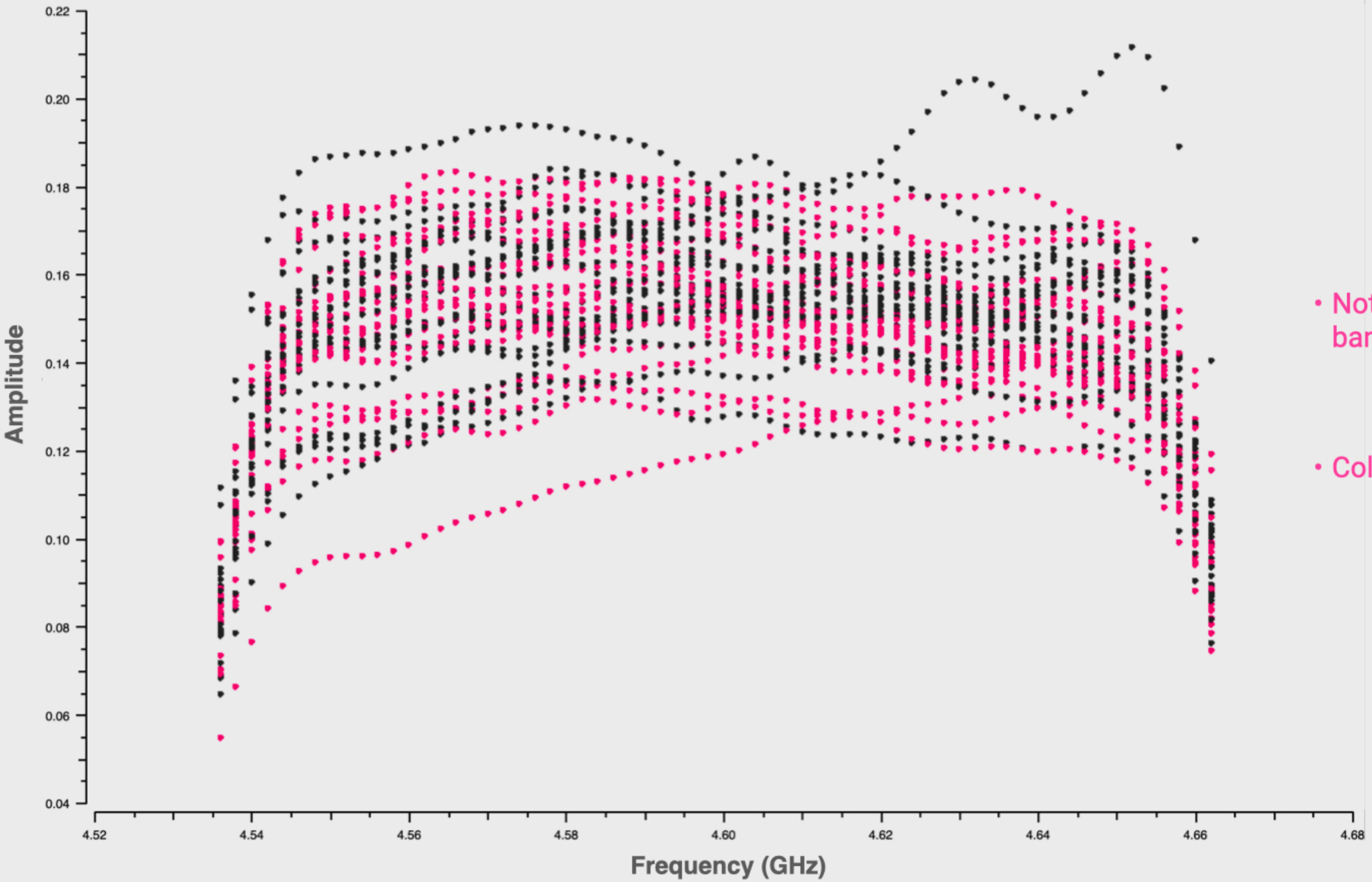
- Try it yourself: `https://casaguides.nrao.edu`

Bandpass solutions (B): amplitude vs frequency



- Note the smoothness of the solutions, bandpass table is not noise-dominated
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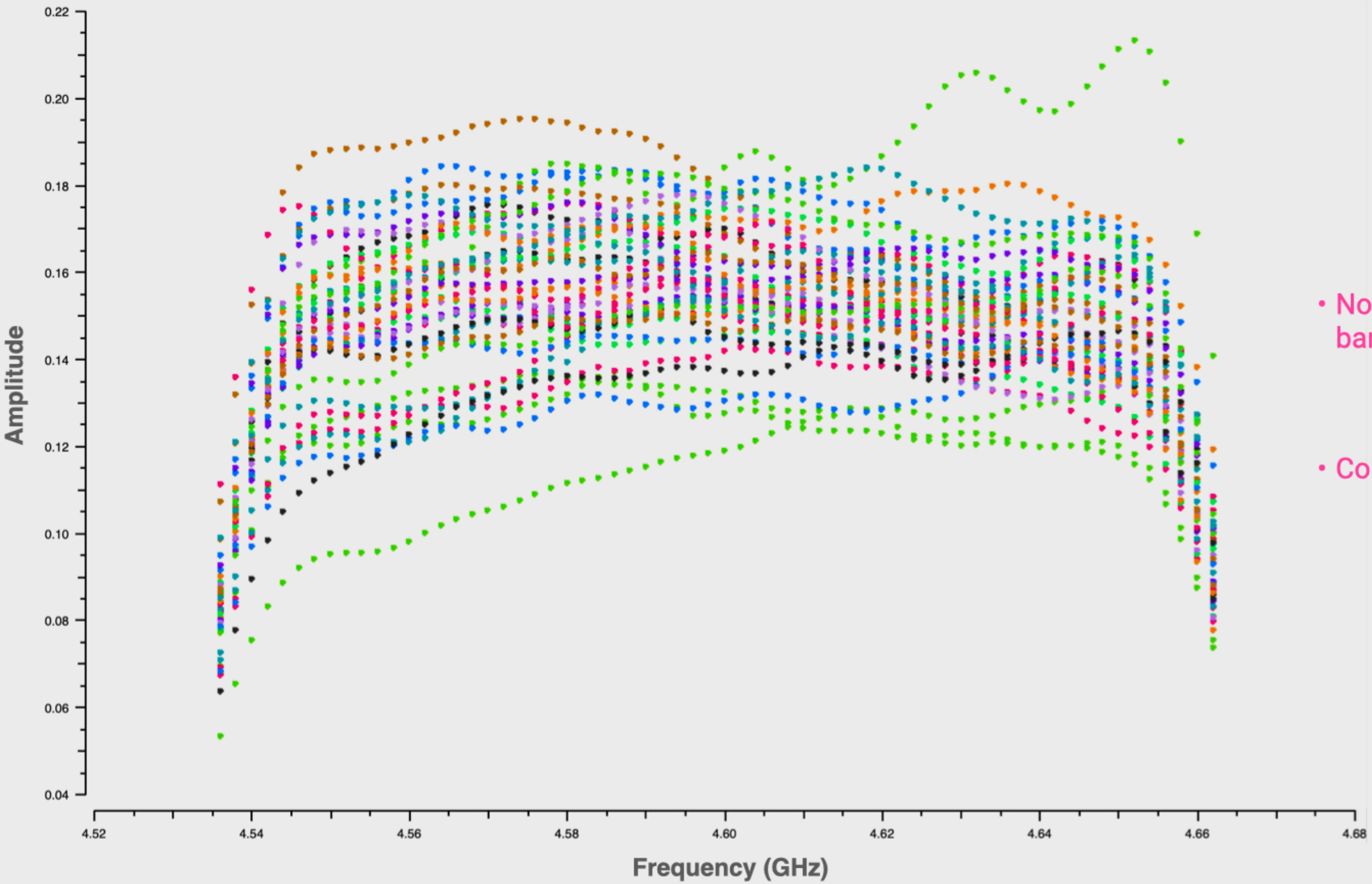
Bandpass solutions (B): amplitude vs frequency



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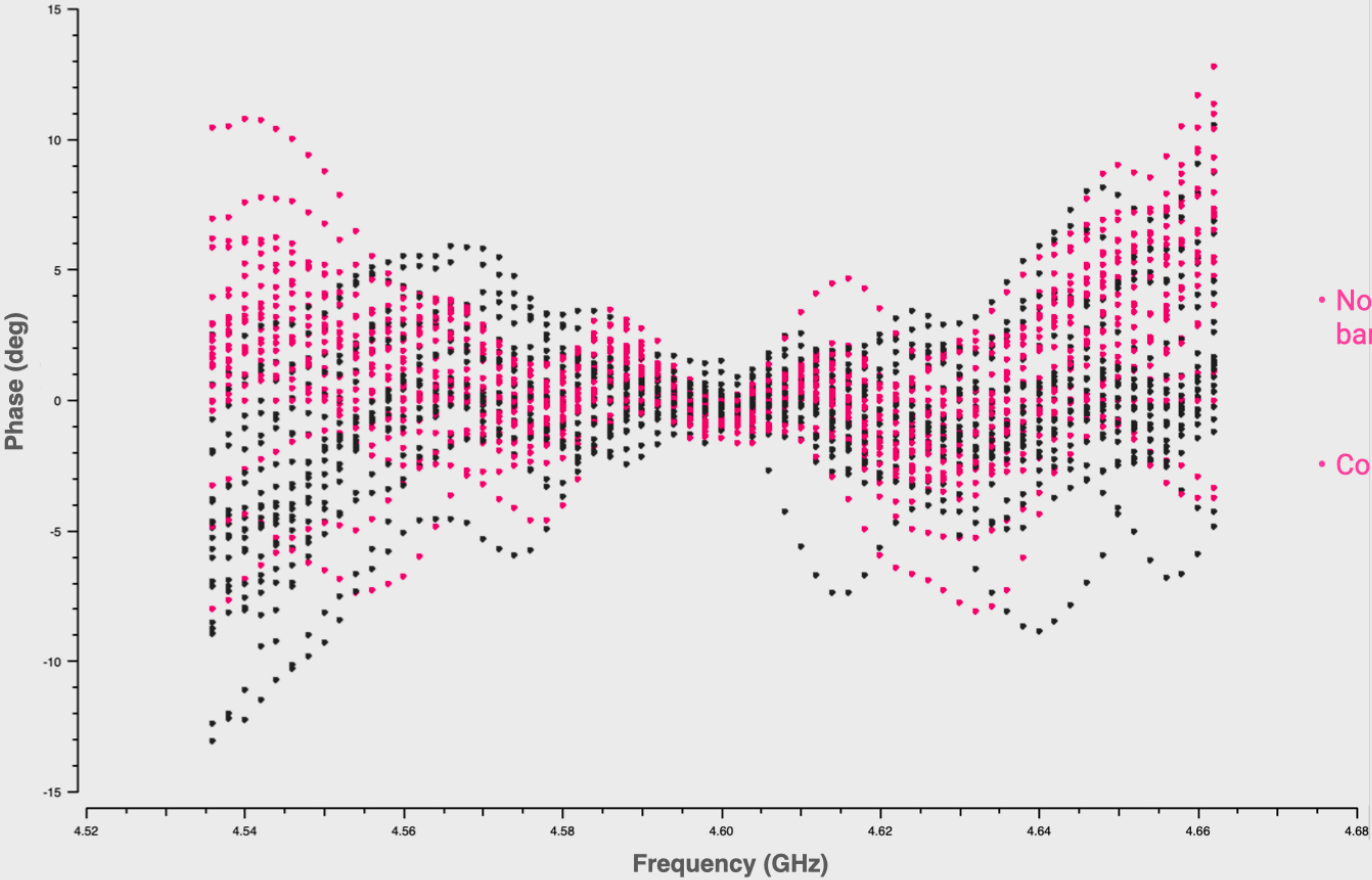
Bandpass solutions (B): phase vs frequency



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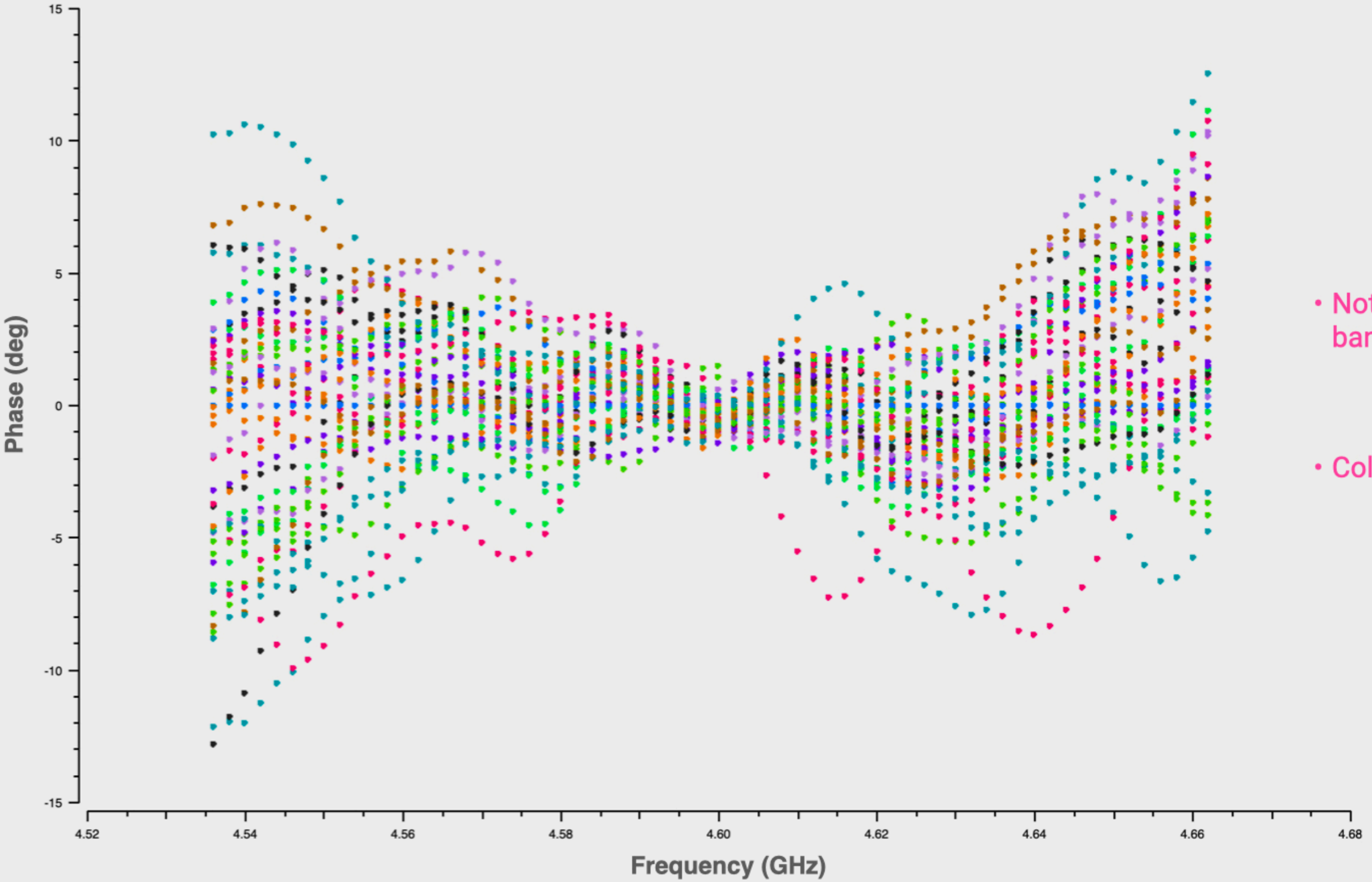

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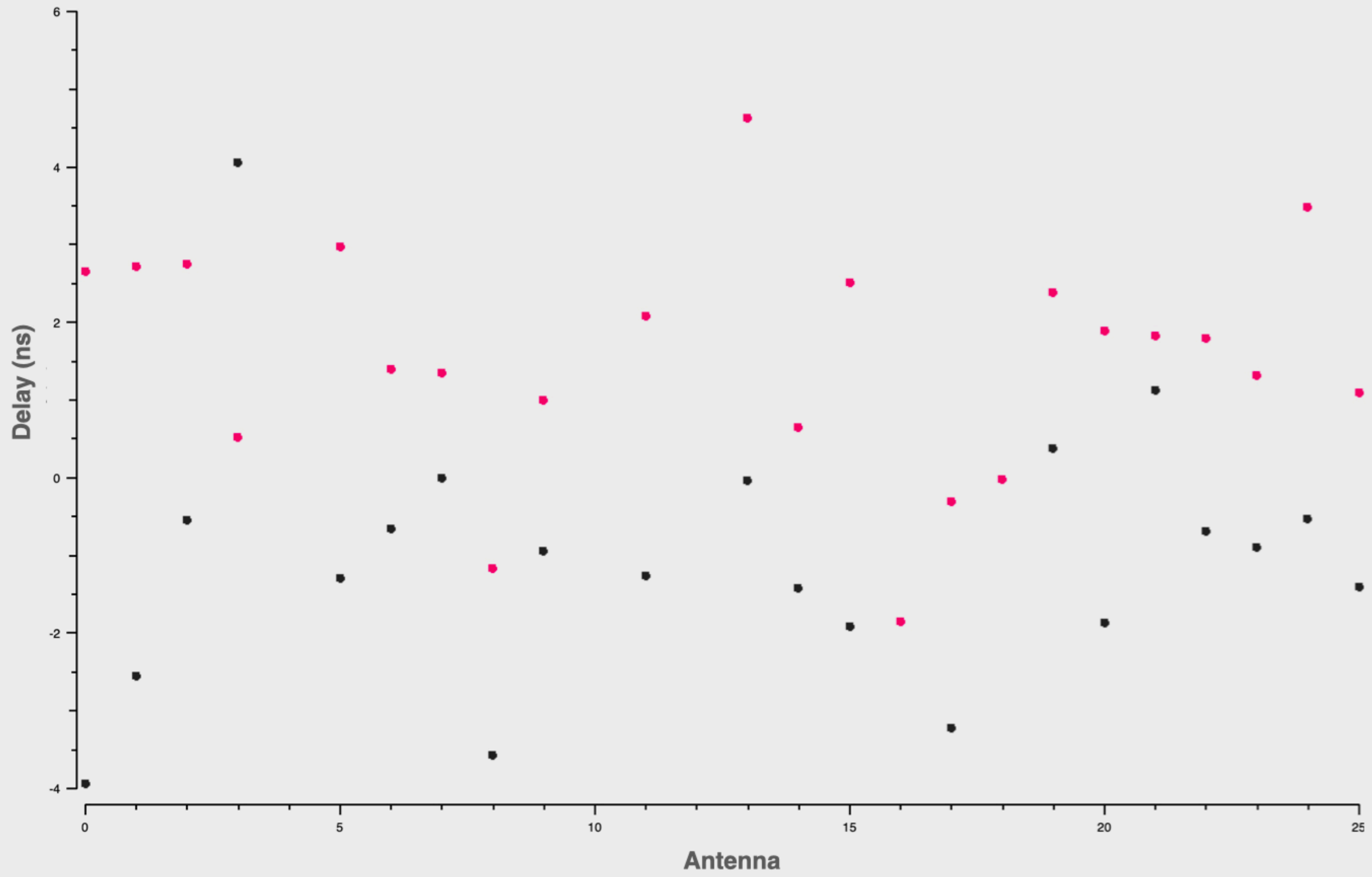
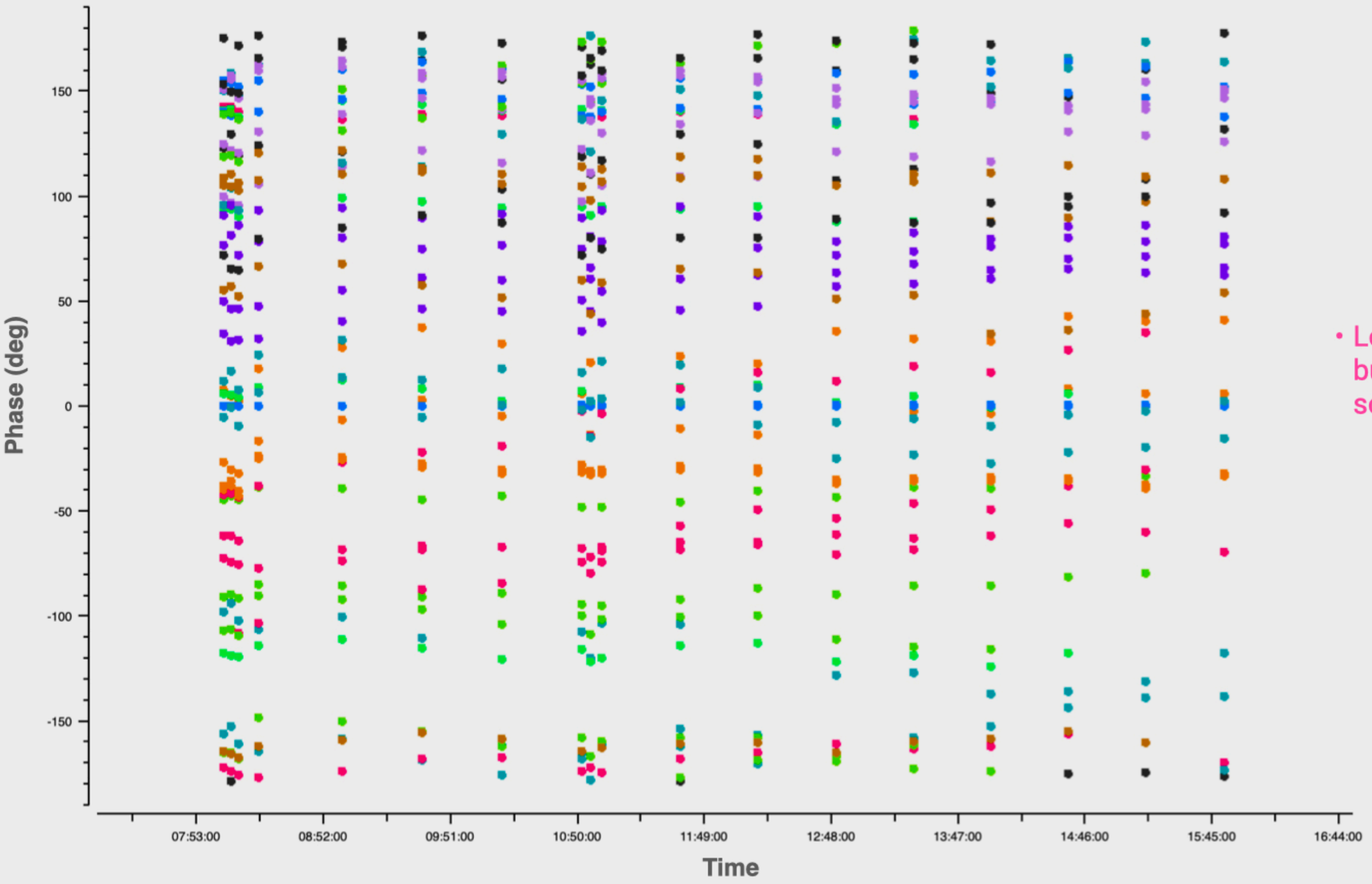
Delay solutions (K): delay vs antenna



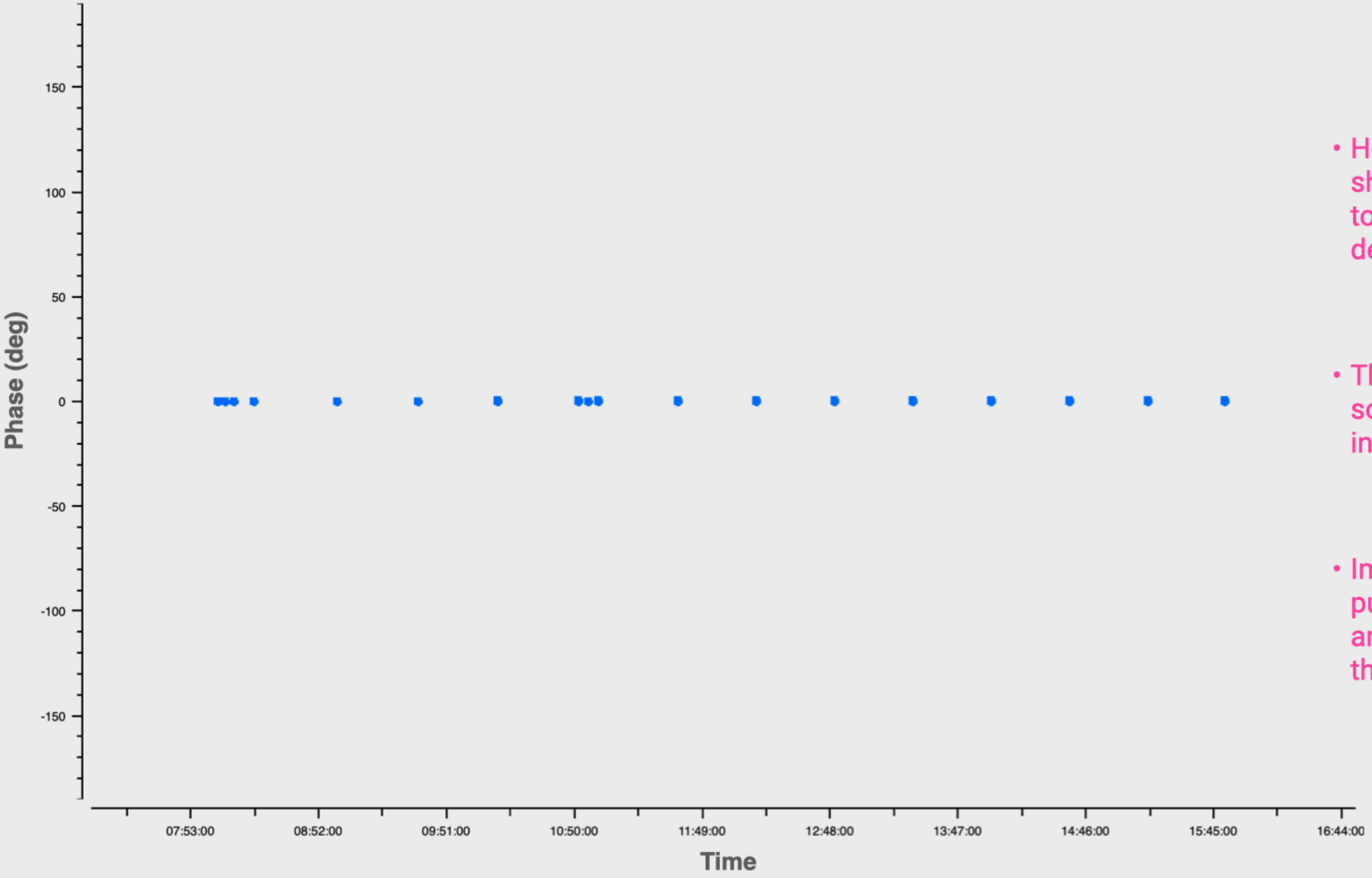
- Delay solutions are typically ~ns
- Generally no correlation from antenna to antenna
- This is a good product to visualise to spot egregiously bad antennas

Time dependent gains (G): phase vs time



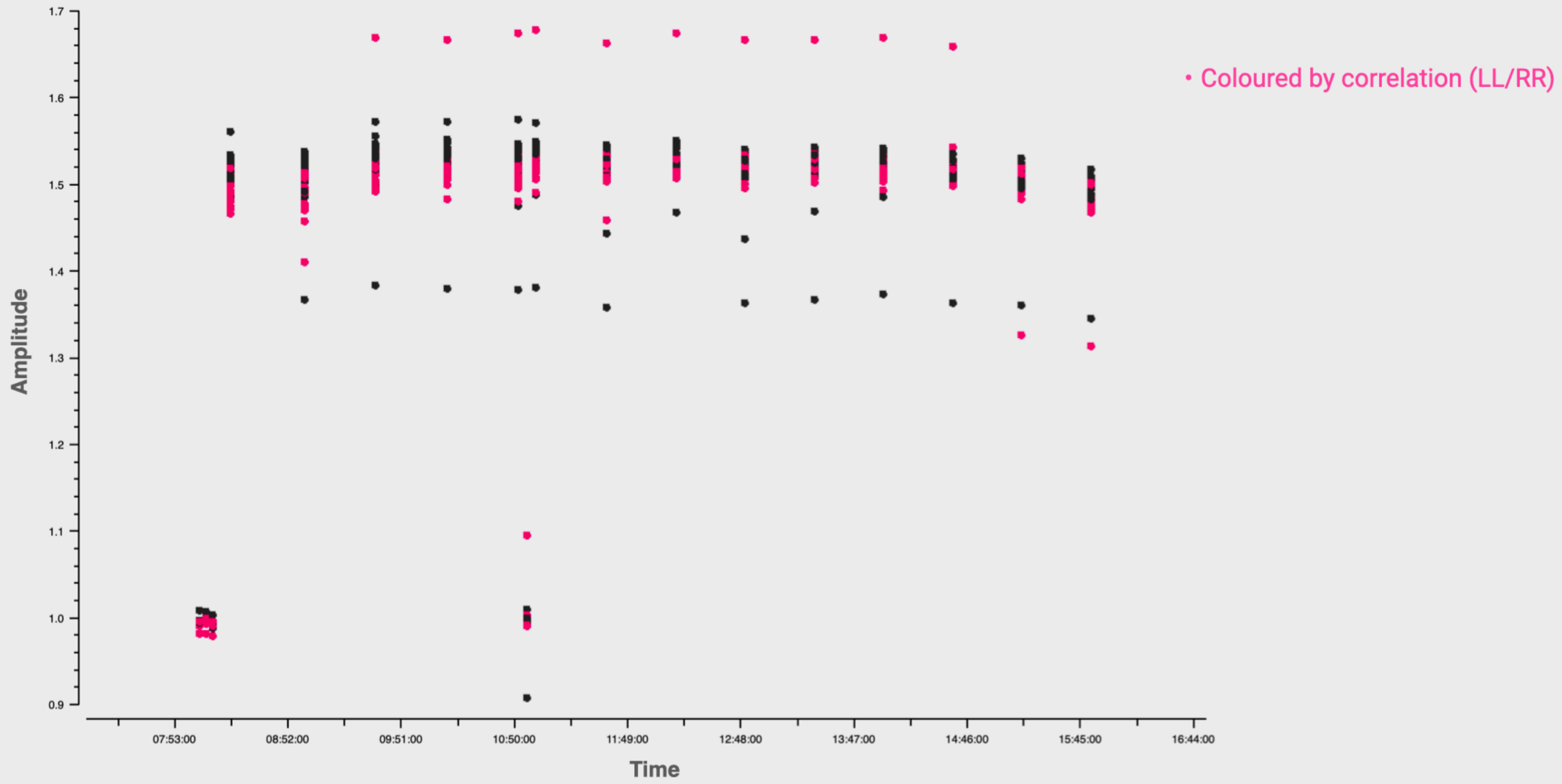
- Lots of scatter from antenna to antenna, but note that for a given antenna the solutions generally vary slowly with time

Time dependent gains (G): phase vs time



- Here only the reference antenna is shown. The phase of this antenna is fixed to zero, and all other antenna phases are determined with respect to this one.
- The phase component of the gain solutions for this antenna are absorbed into the solutions of the other antennas.
- Important to use a 'good' antenna for this purpose: i.e. its data are of good quality and the antenna is present throughout the observation.

Time dependent gains (G): amplitude vs time



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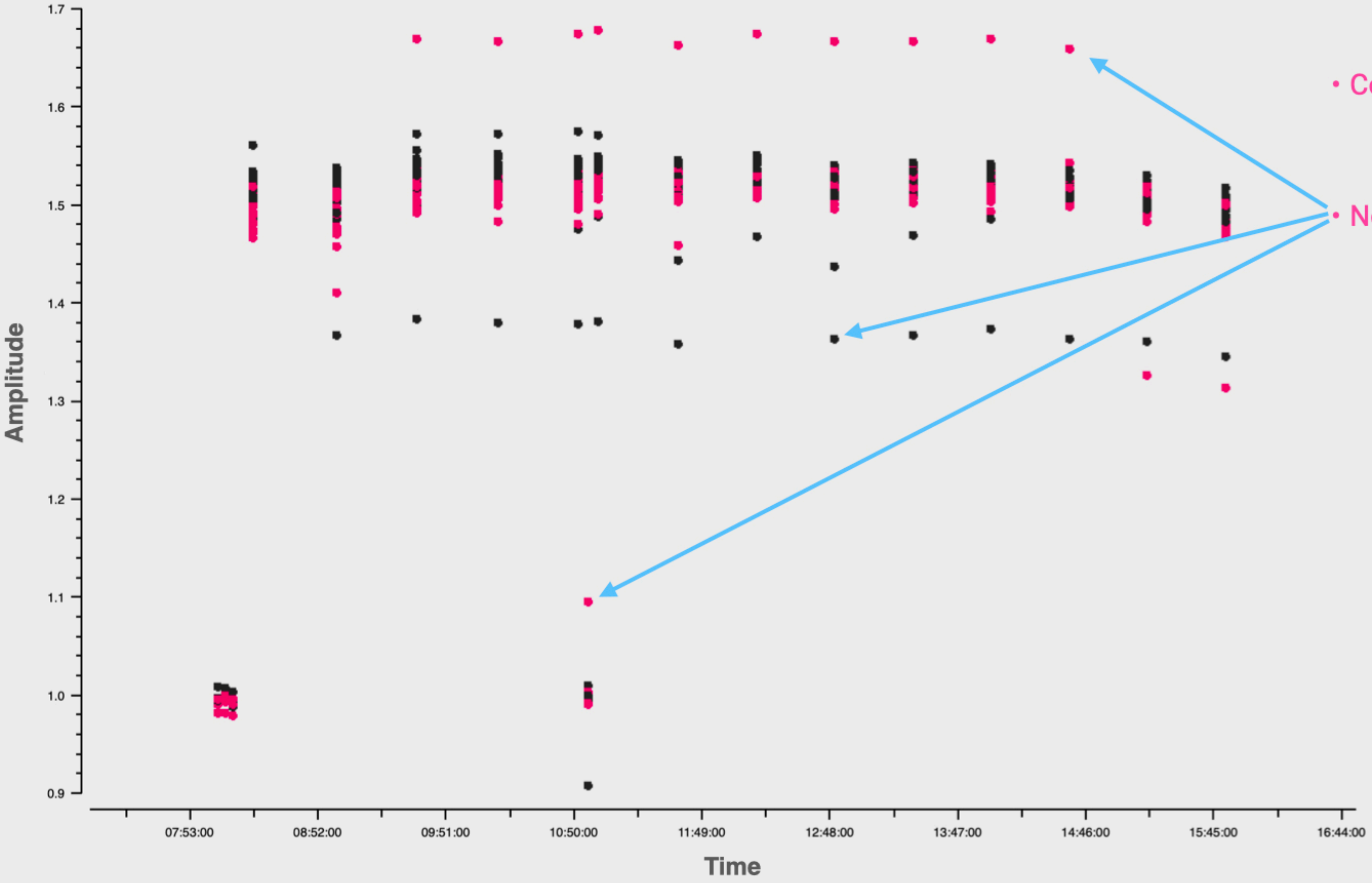

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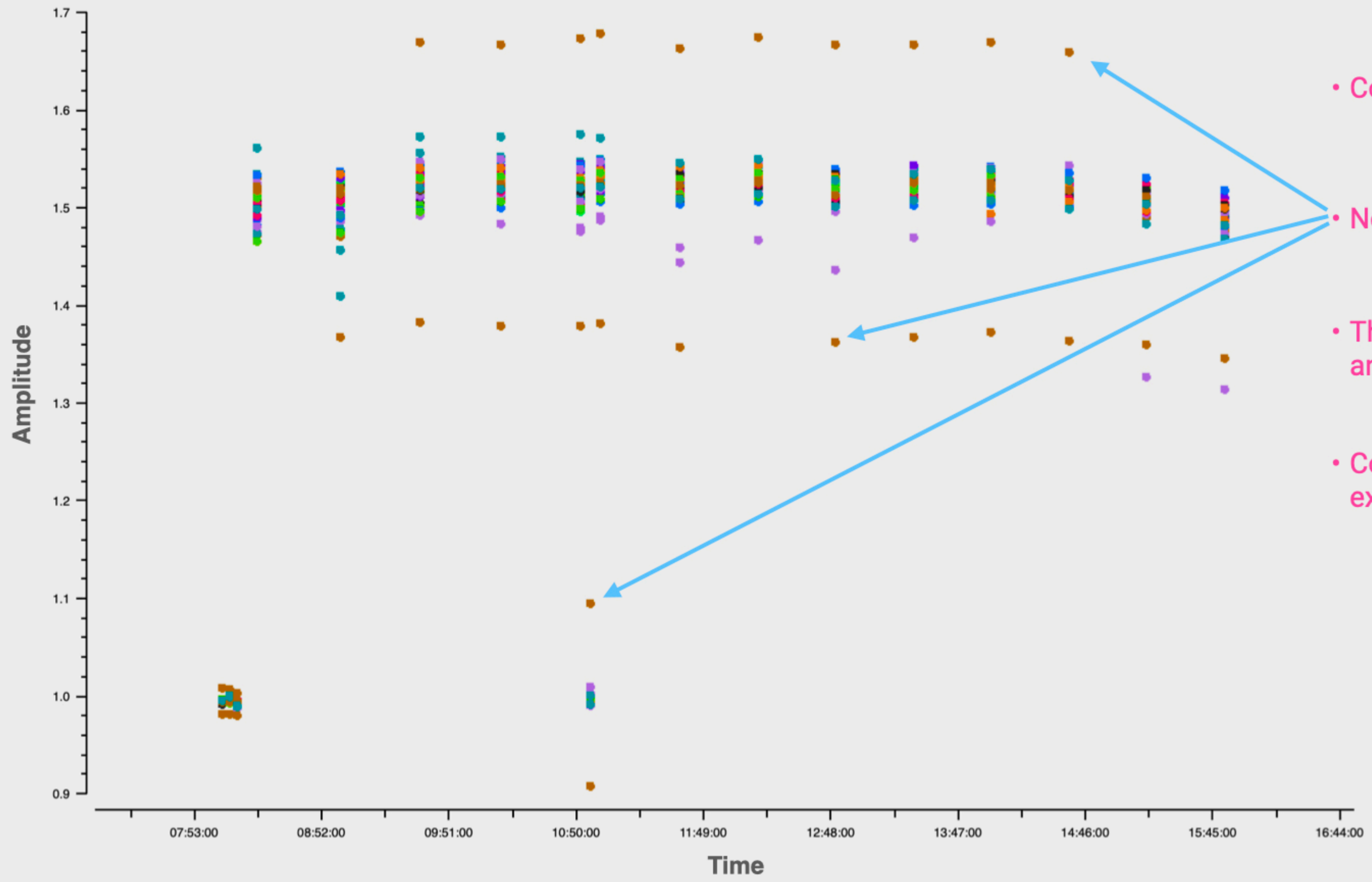
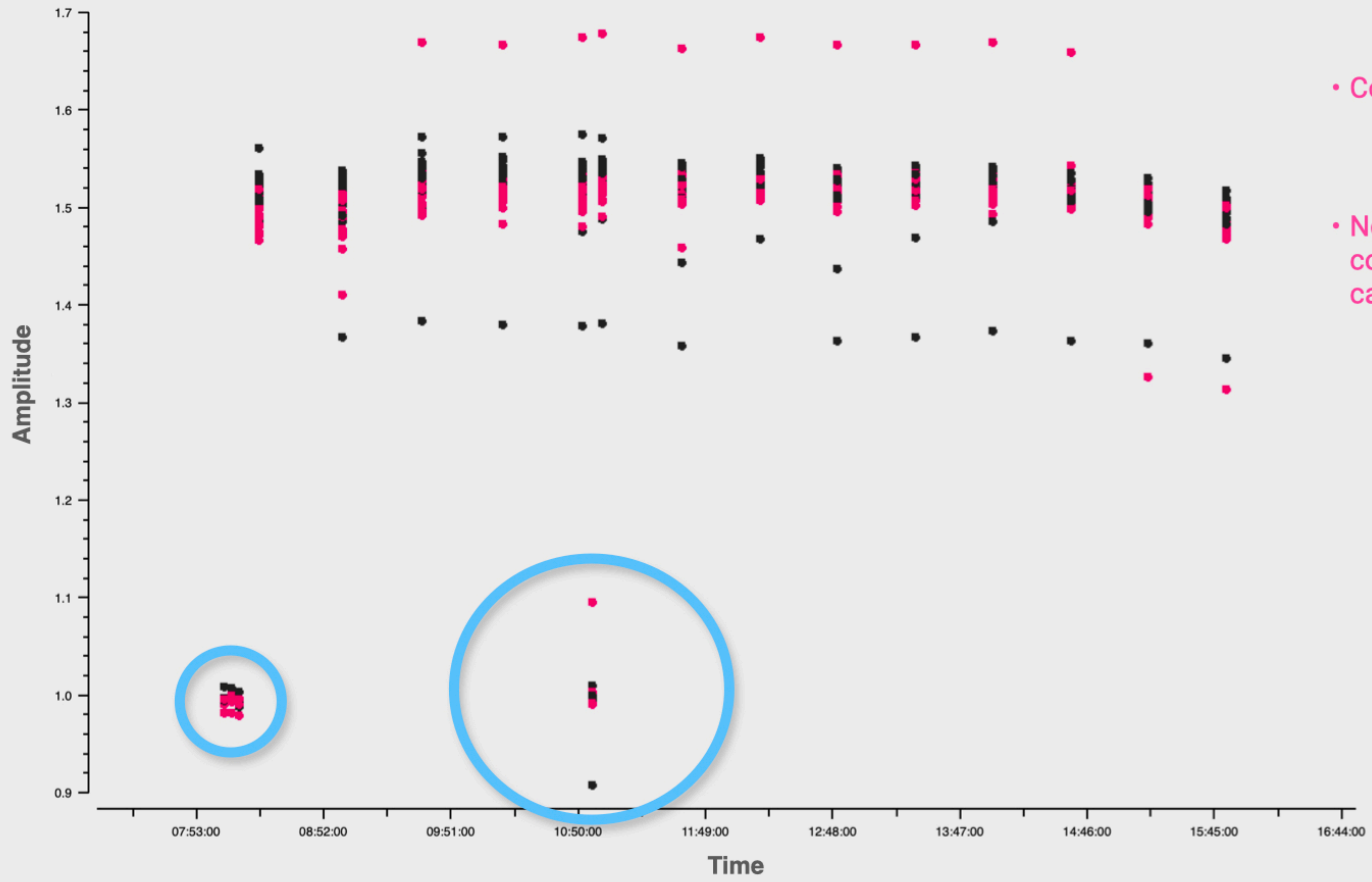
Time dependent gains (G): amplitude vs time



- Coloured by antenna
- Note the outlier points
- These mainly correspond to a single antenna
- Could be benign, but may warrant further examination

Time dependent gains (G): amplitude vs time



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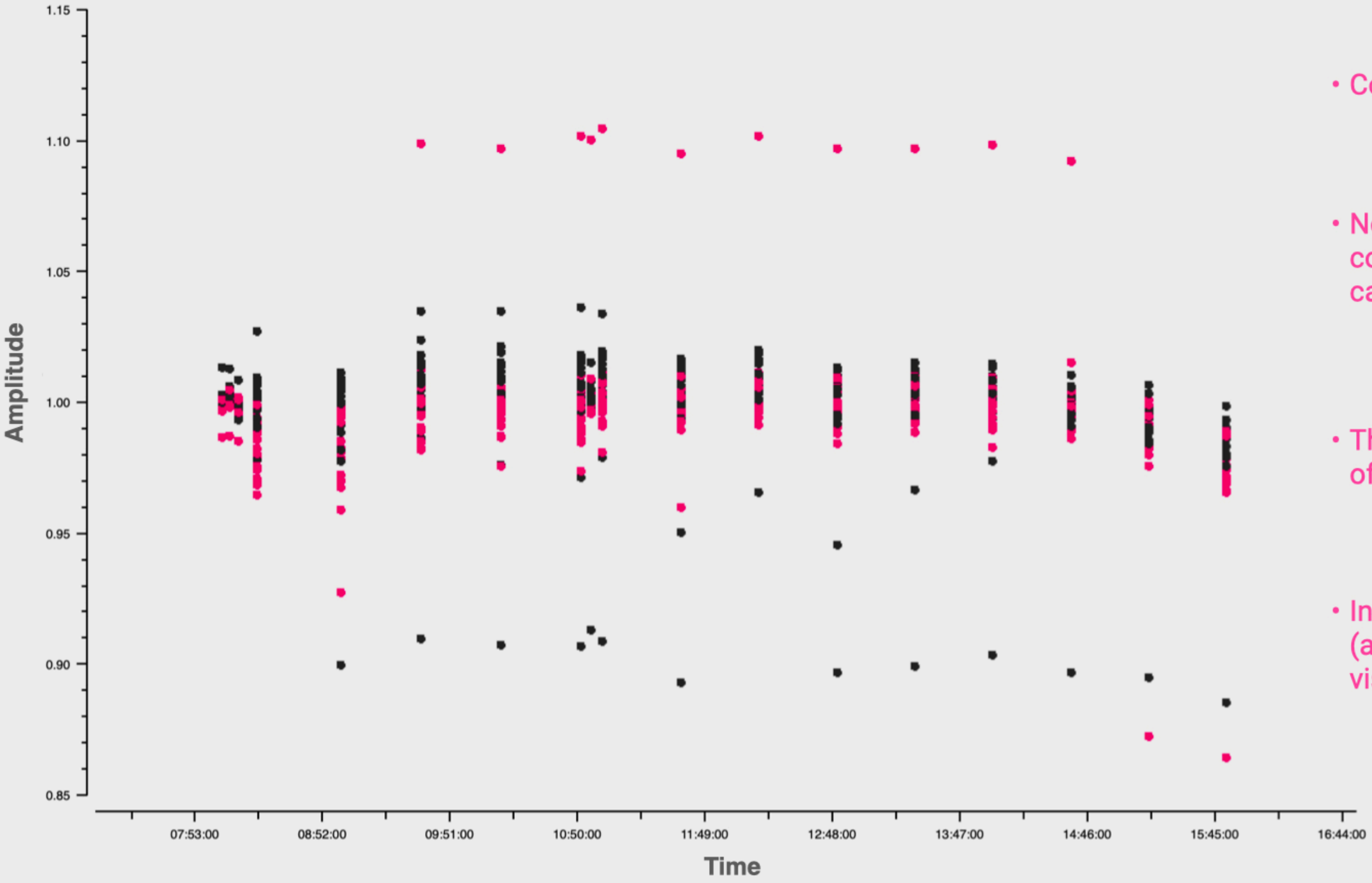
Fluxscale table: amplitude vs time



- Coloured by correlation (LL/RR)
- Note the offset between solutions that correspond to scans of the primary calibrator and those of the secondary
- These are corrected by scaling the gains of the secondary to those of the primary
- Instrumental gains are now aligned (although the suspicious antenna is still visible)

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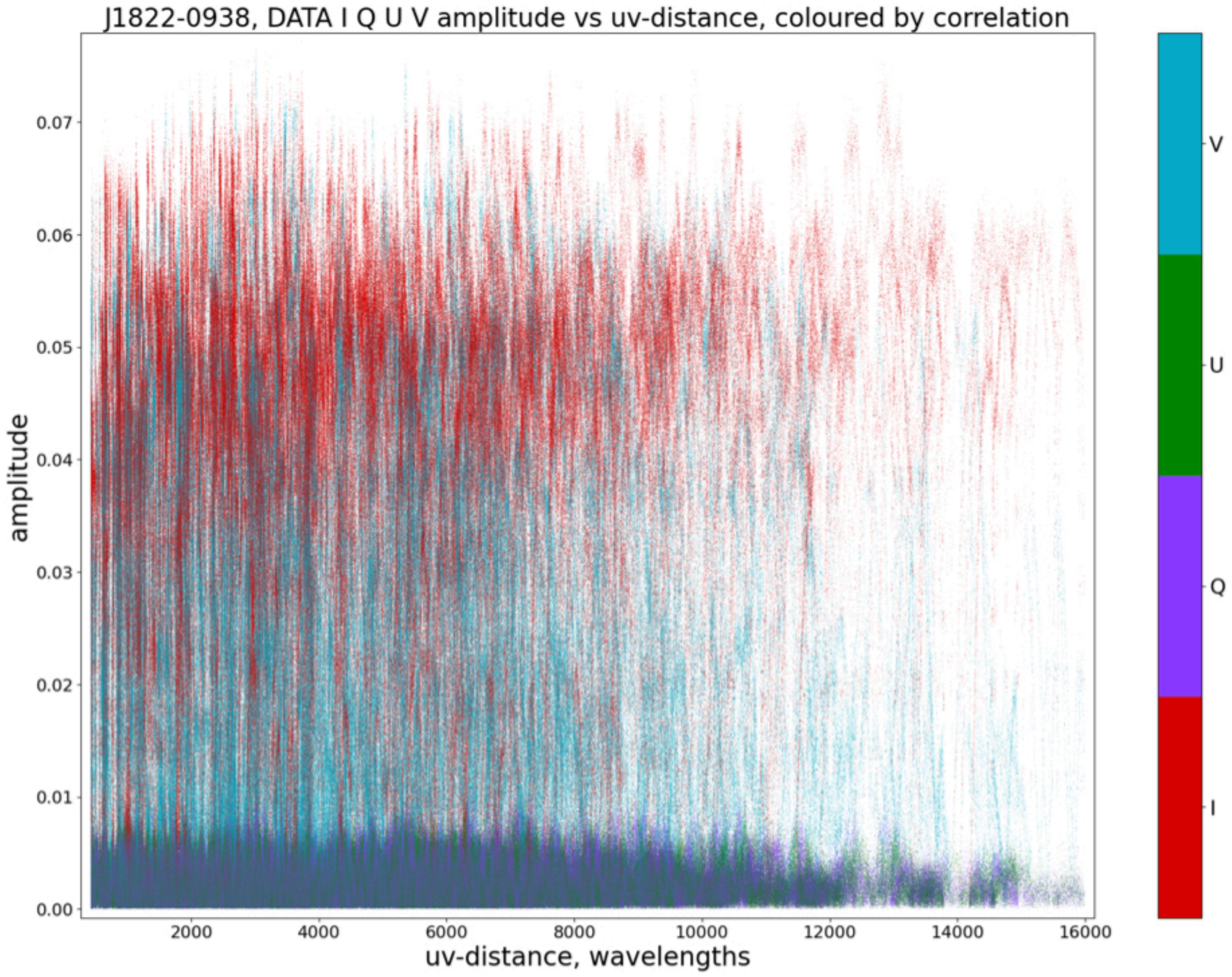
    - Outlying points should be investigated (improve data flagging and iterate the calibration)

Secondary calibrator (J1822—0938) visibilities: amplitude vs u,v distance



Uncalibrated

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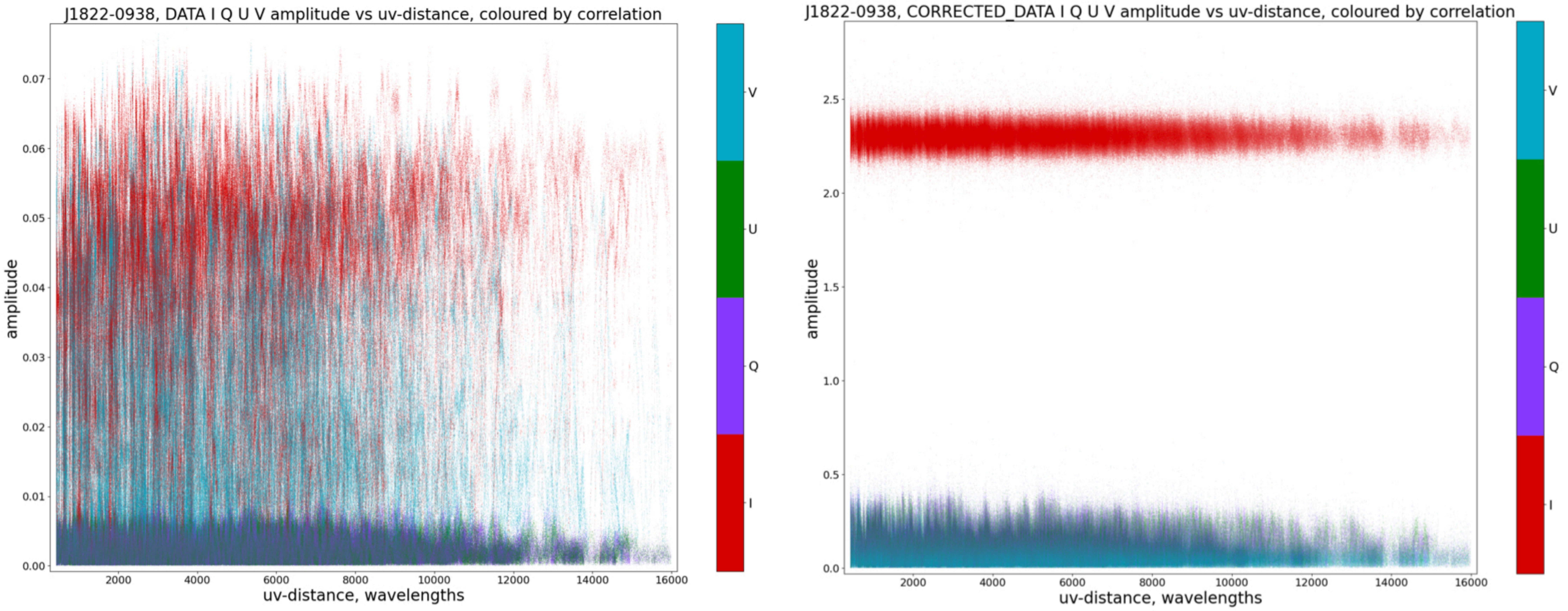
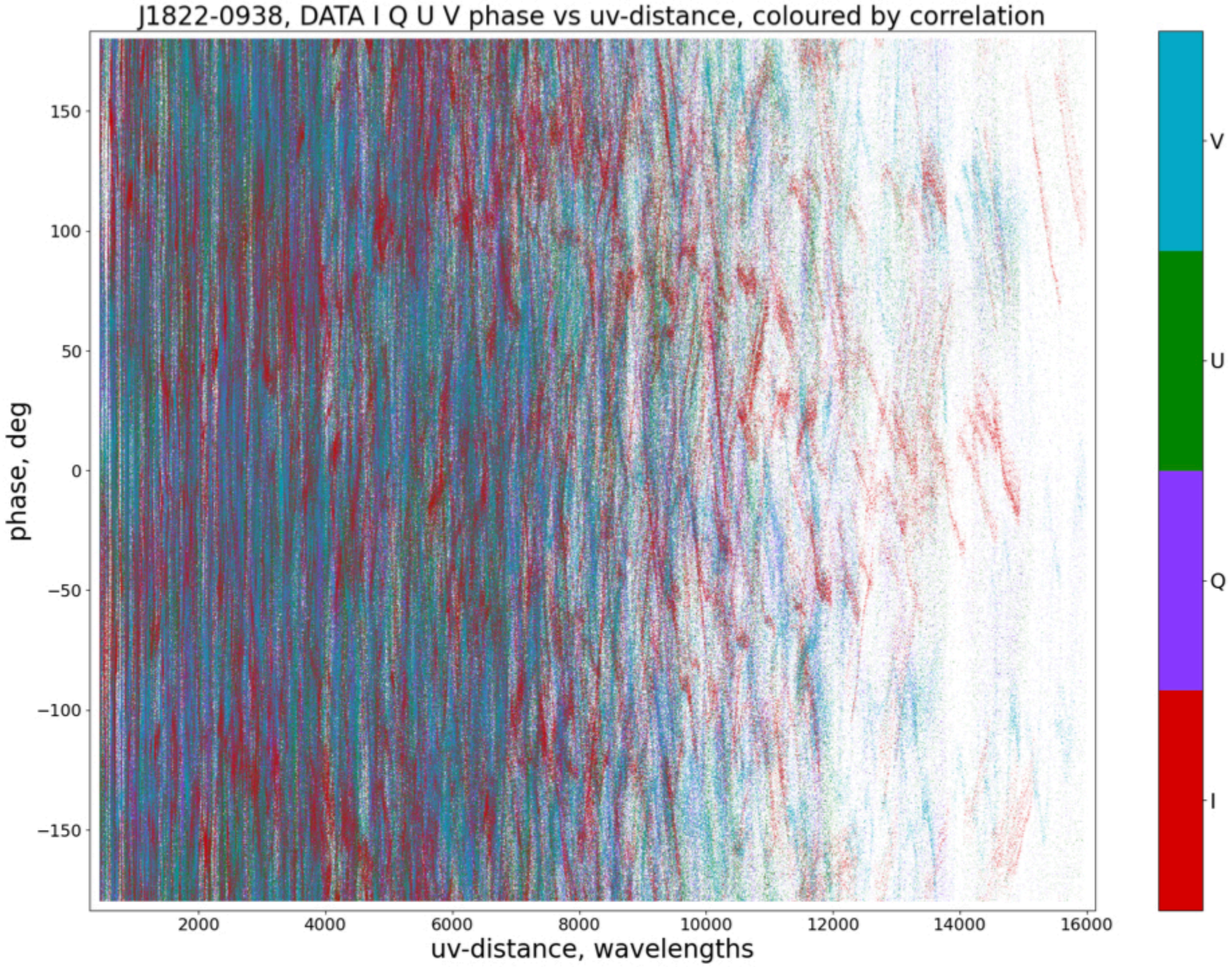


Uncalibrated

Calibrated

Secondary calibrator (J1822–0938) visibilities: phase vs u,v distance



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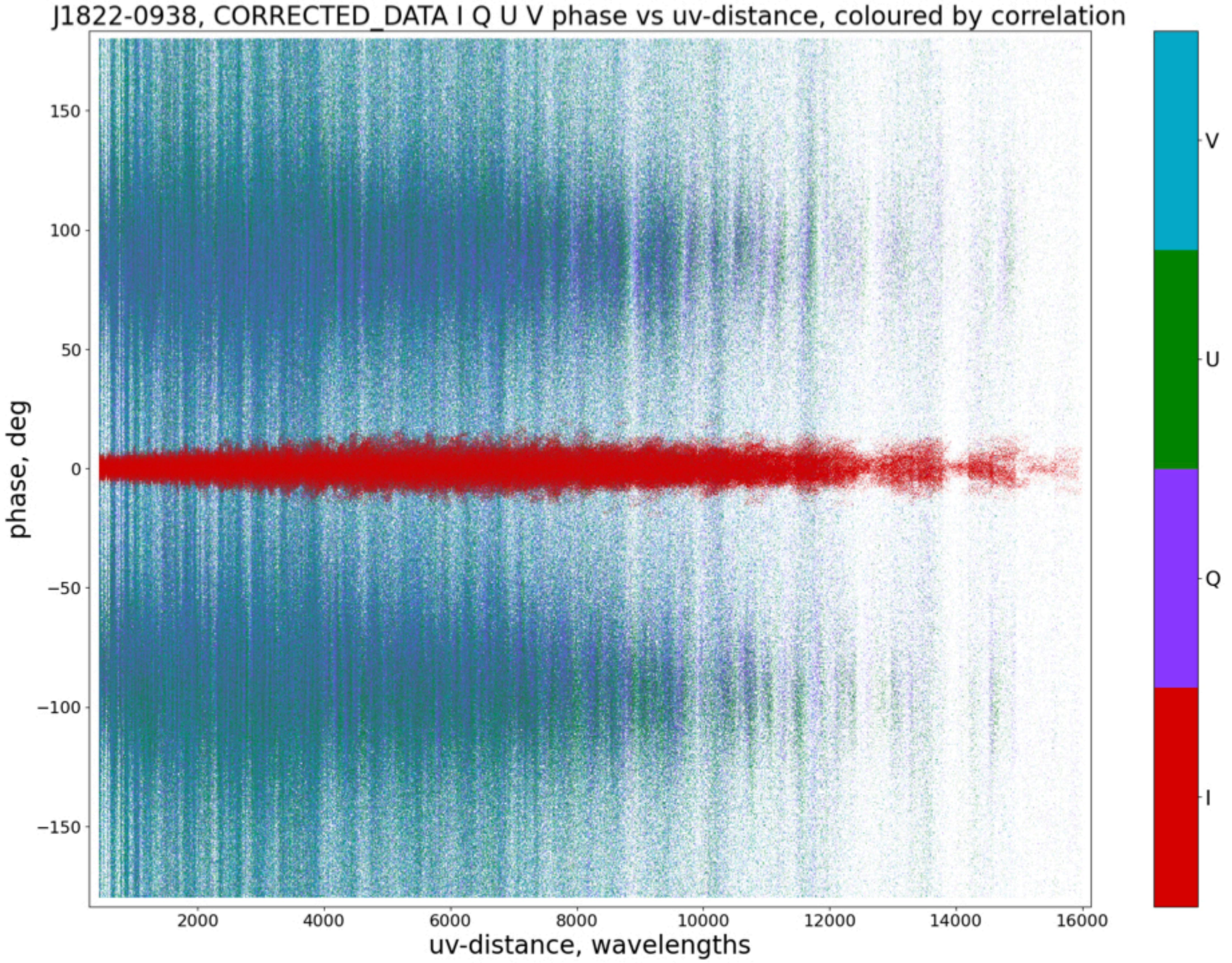

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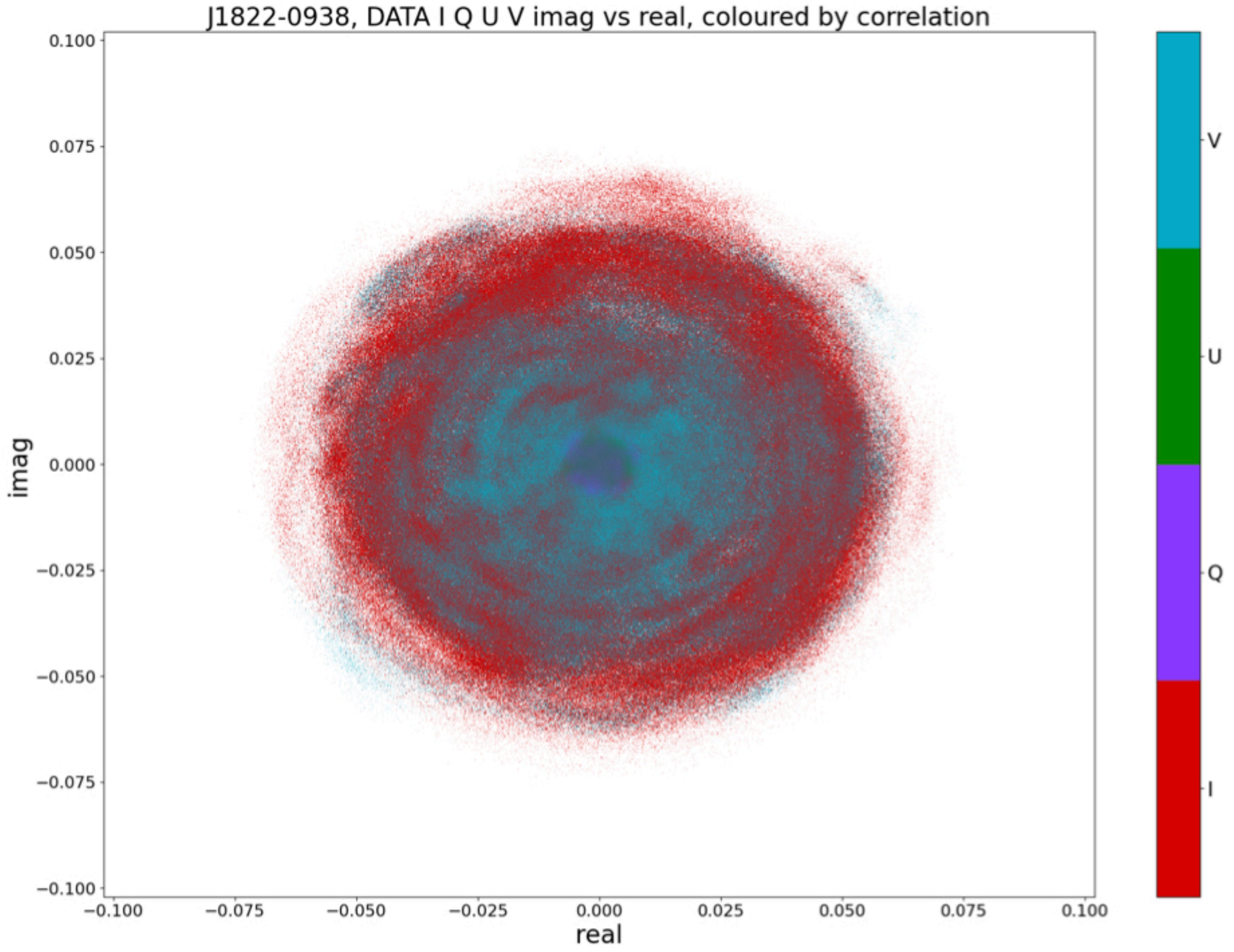
Secondary calibrator (J1822—0938) visibilities: imaginary vs real



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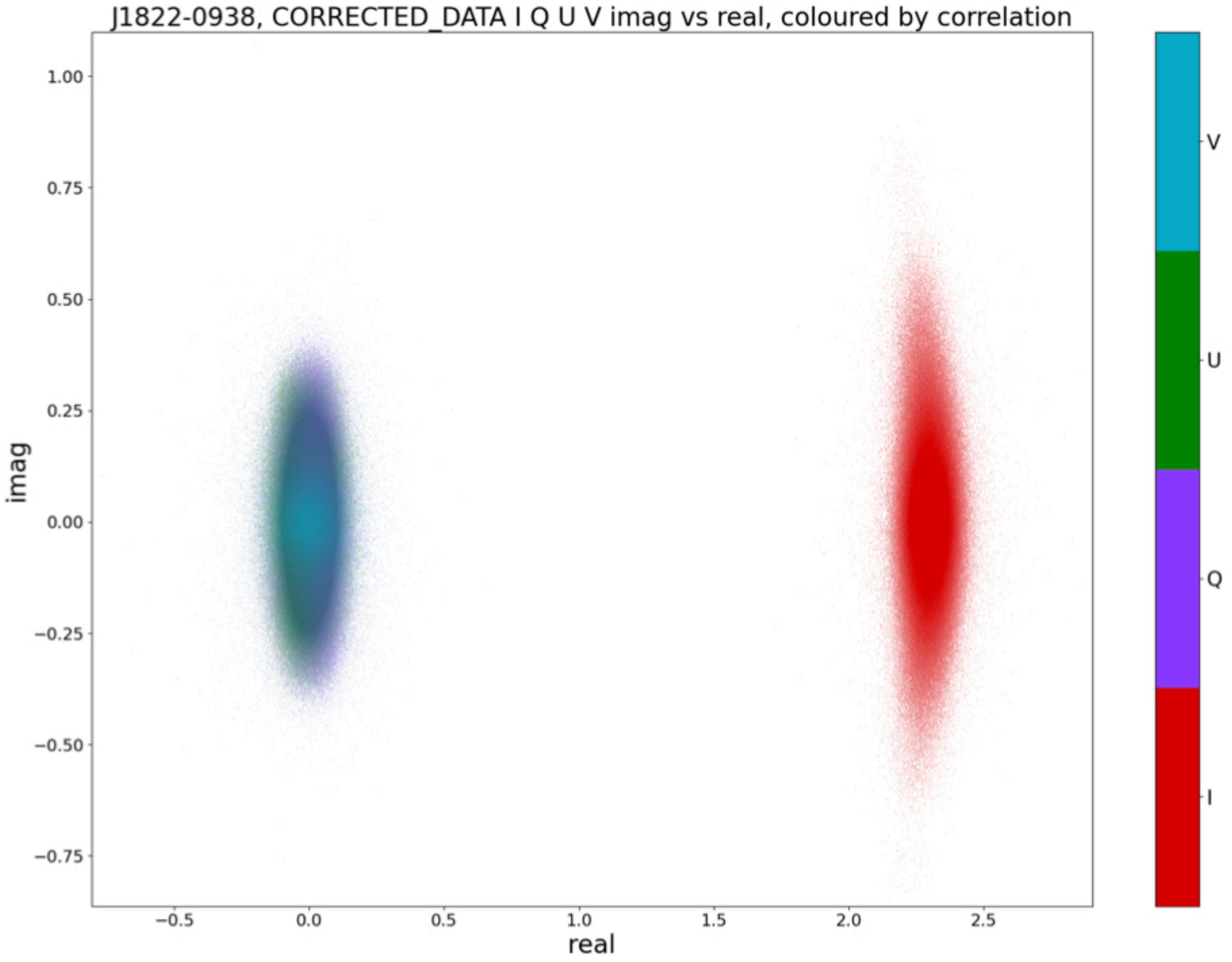
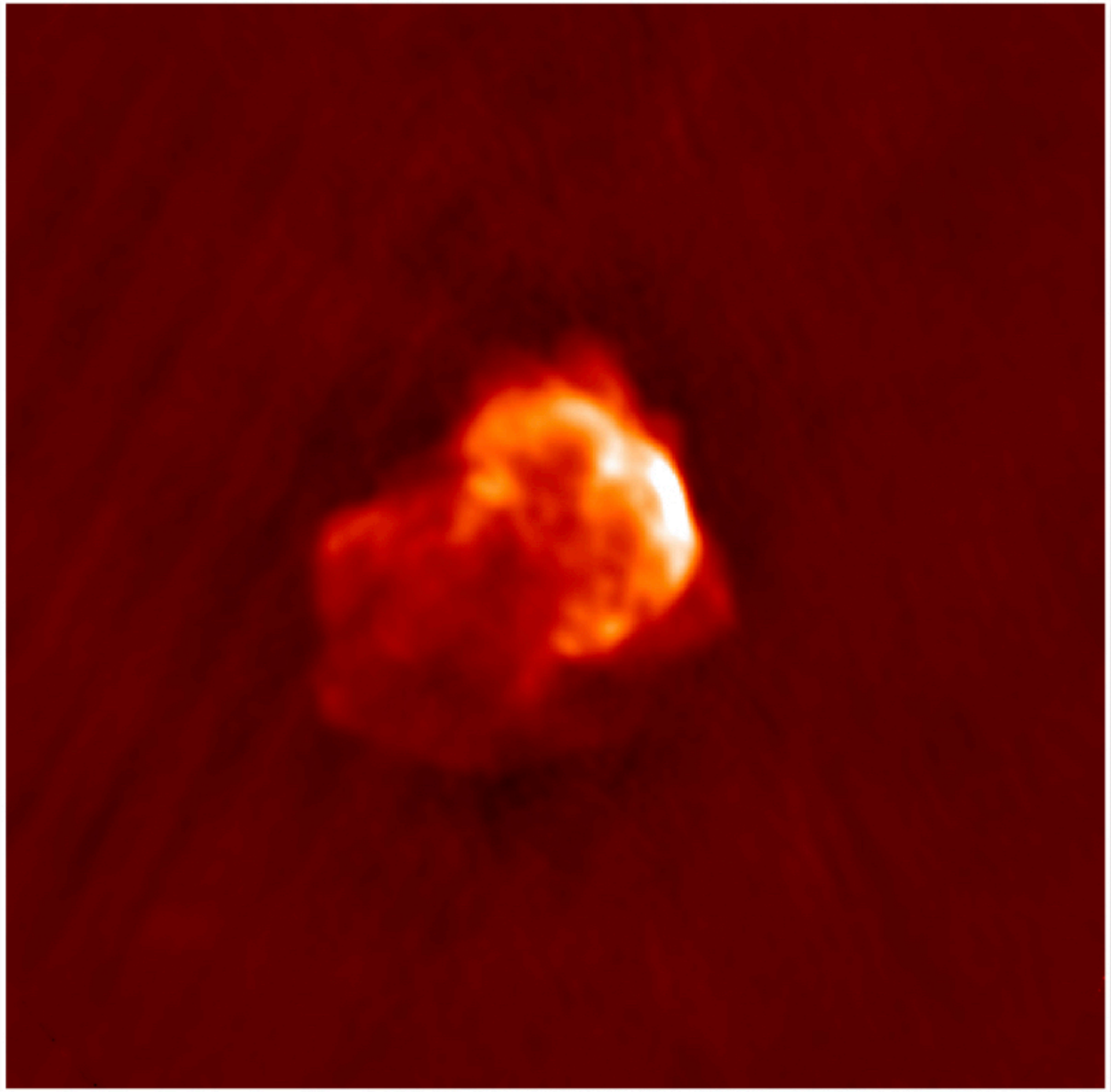


Calibrated

The calibrated target, and to summarise…

With proper calibration:
beautiful supernova remnant



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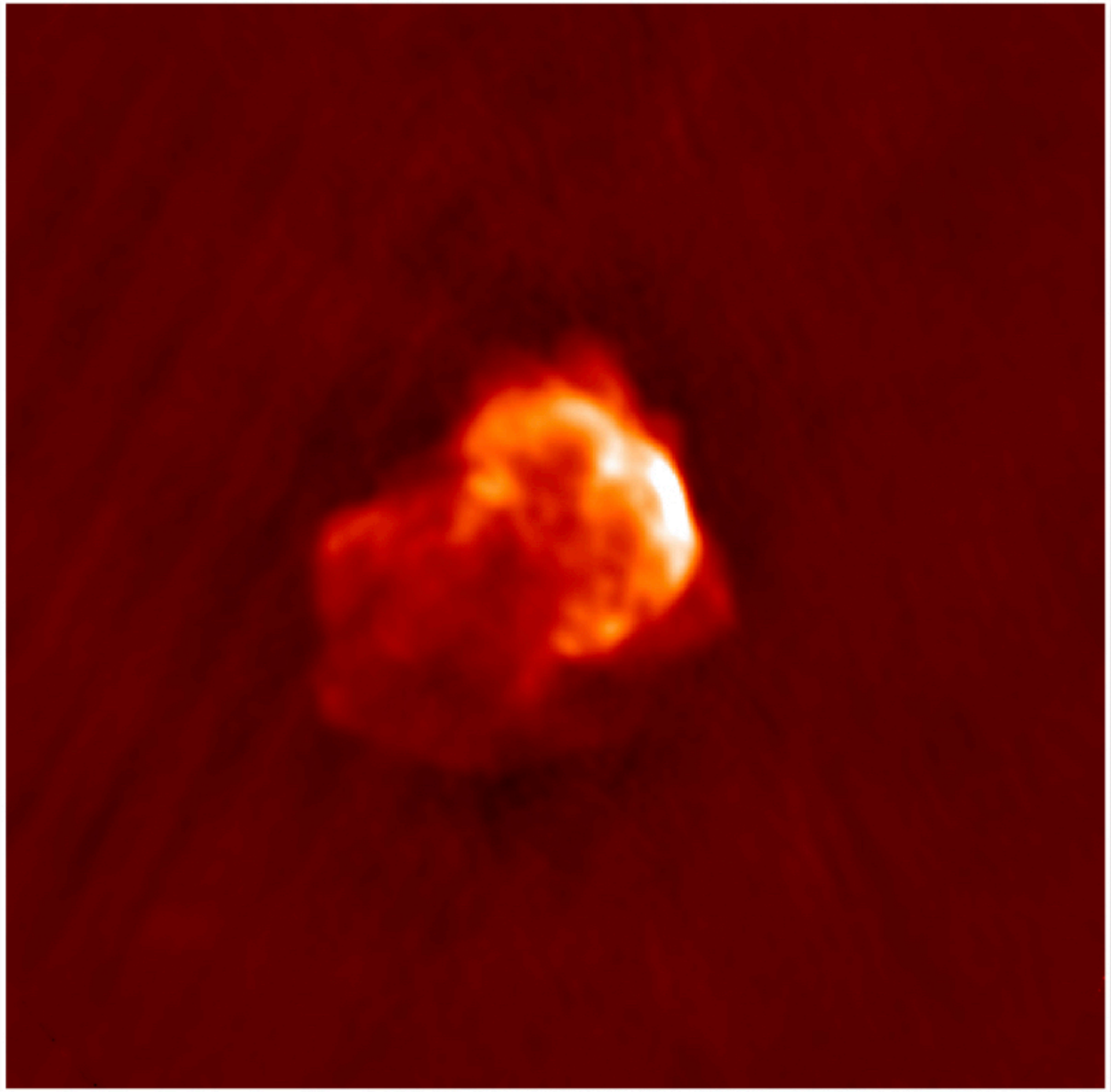

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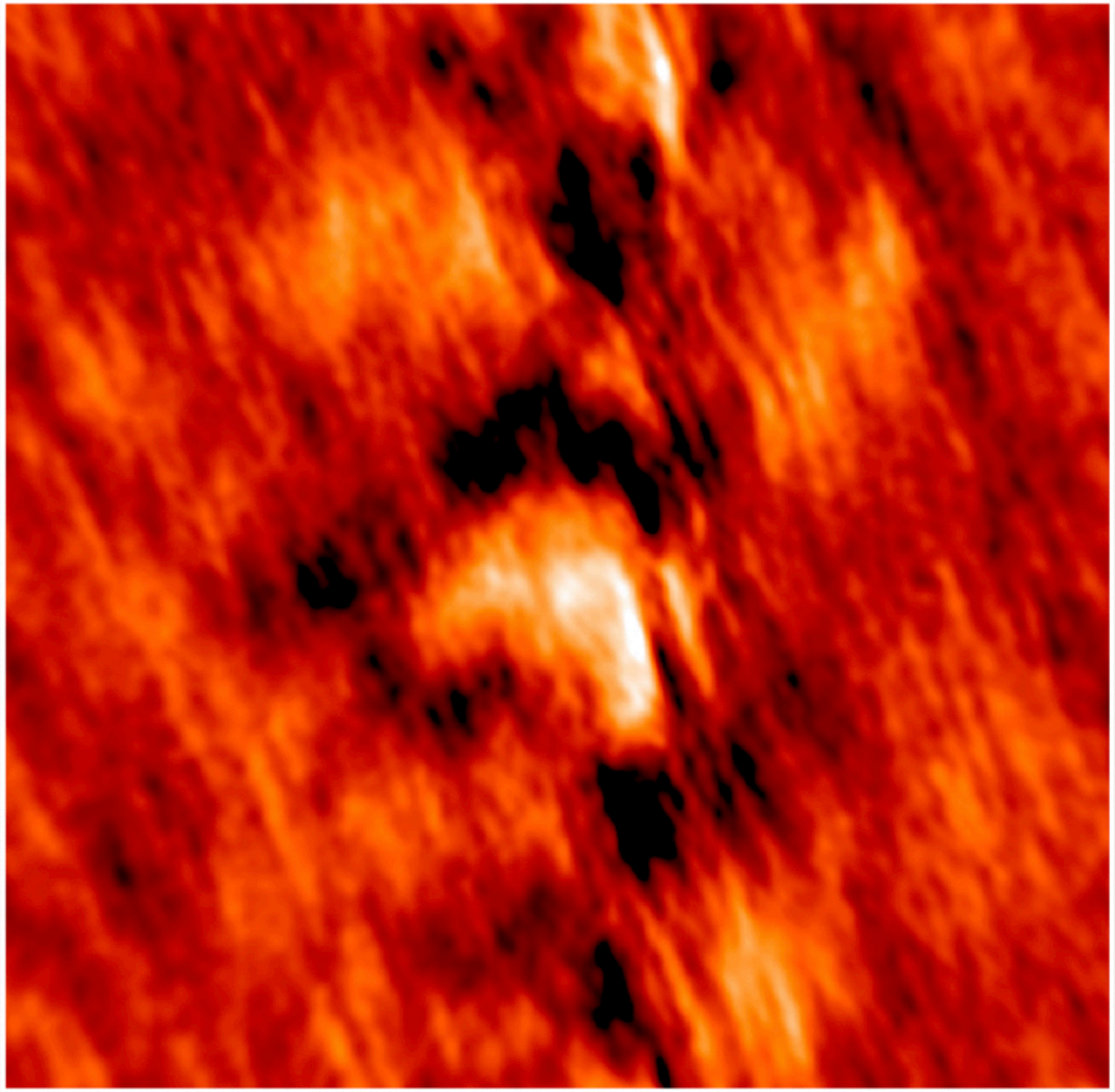

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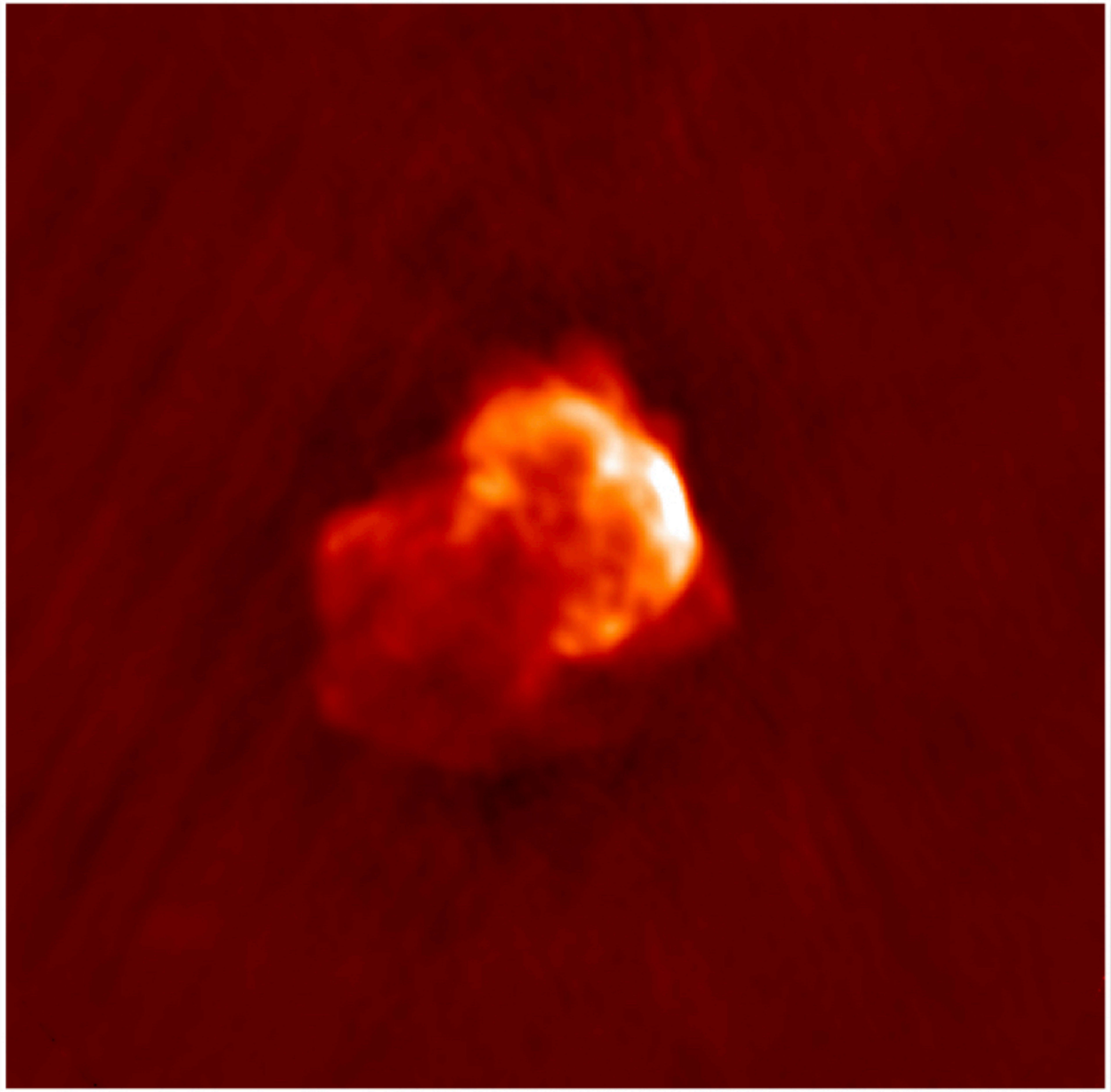

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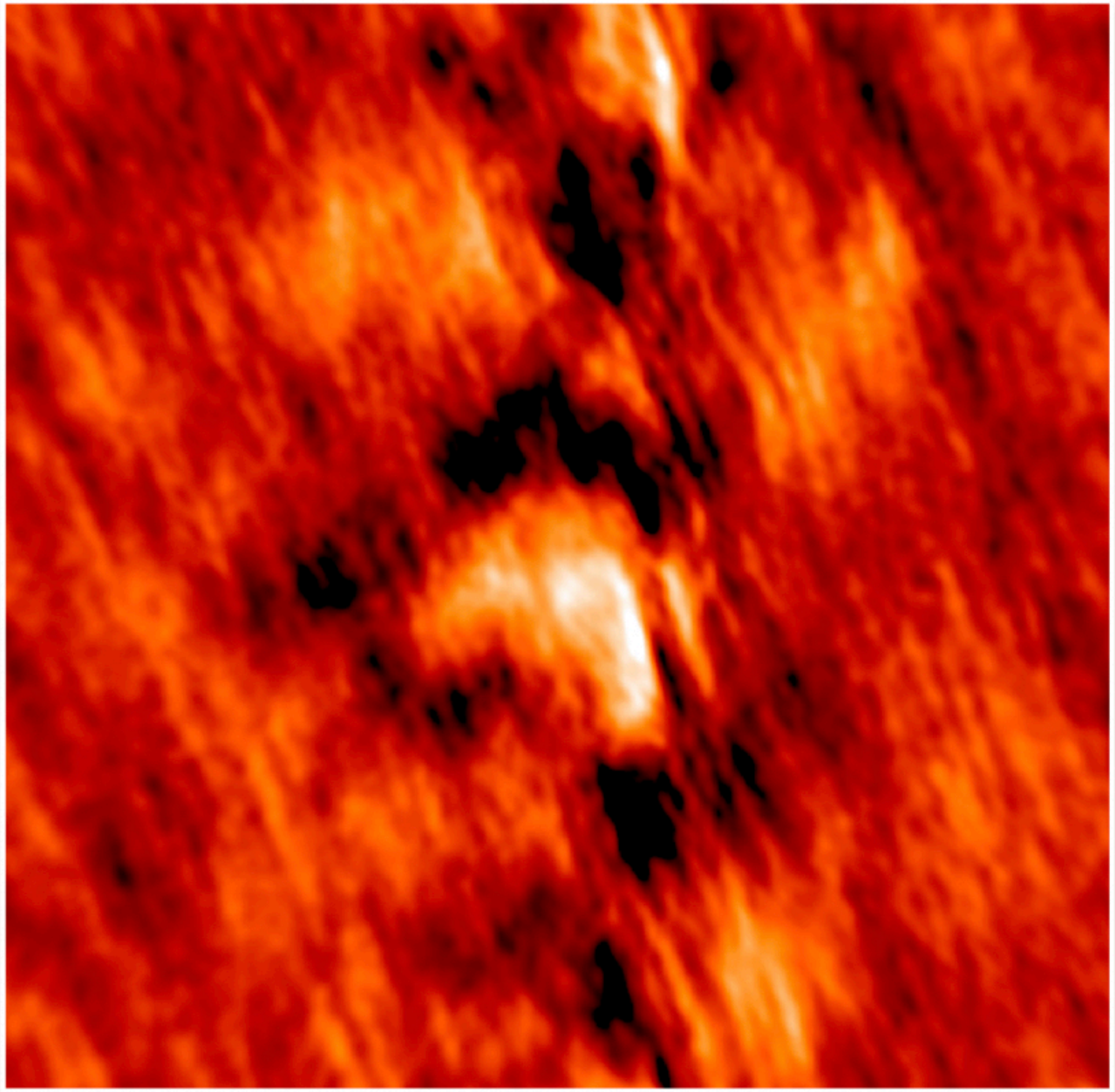

Calibration = good

“Why should I care? Isn’t there a pipeline for this stuff?”

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- If you do have to ask for help or advice (and we all do), then you will be better equipped to ask the right questions.