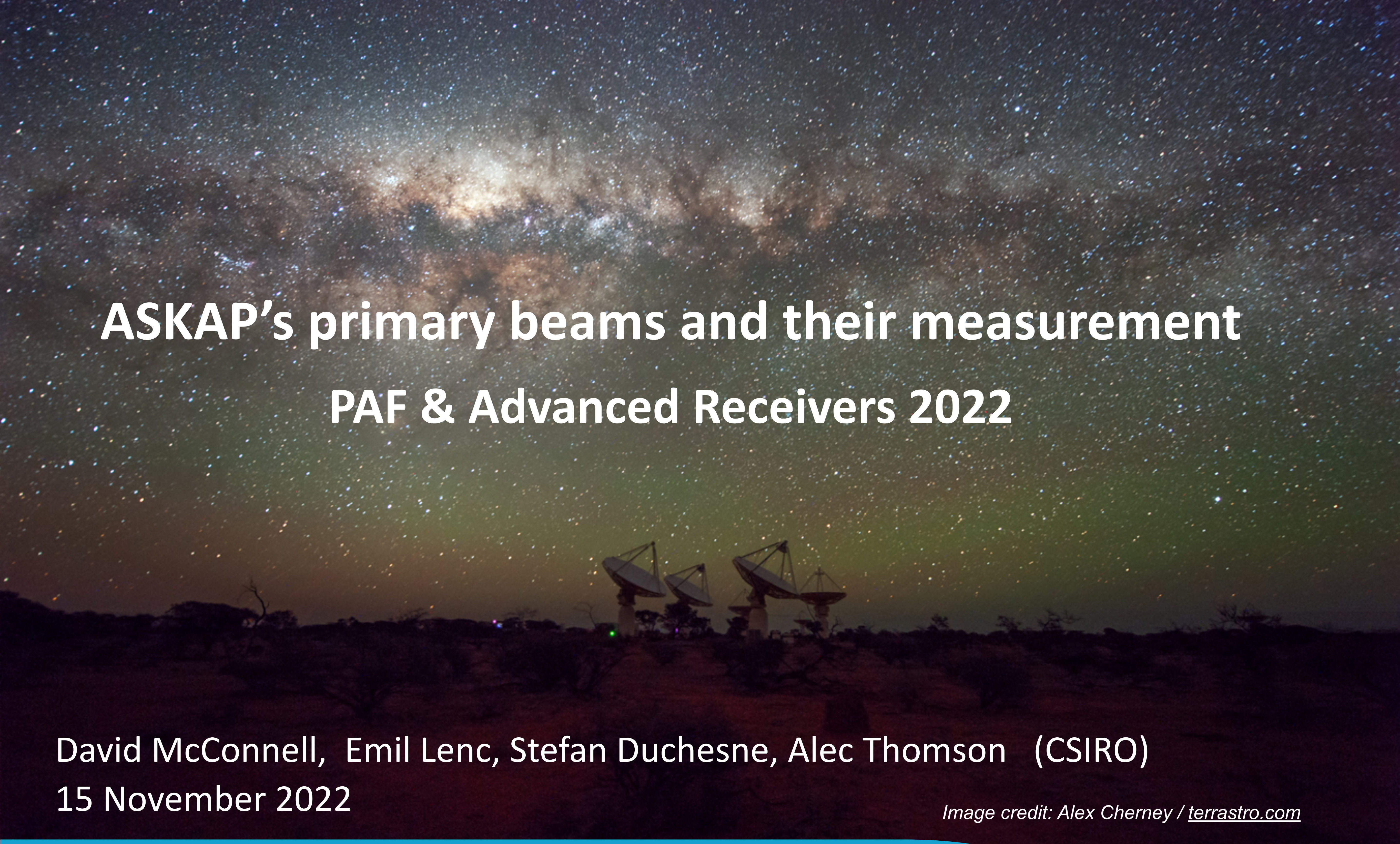


ASKAP's primary beams and their measurement

PAF & Advanced Receivers 2022

David McConnell, Emil Lenc, Stefan Duchesne, Alec Thomson (CSIRO)

15 November 2022

Image credit: Alex Cherney / terrastro.com

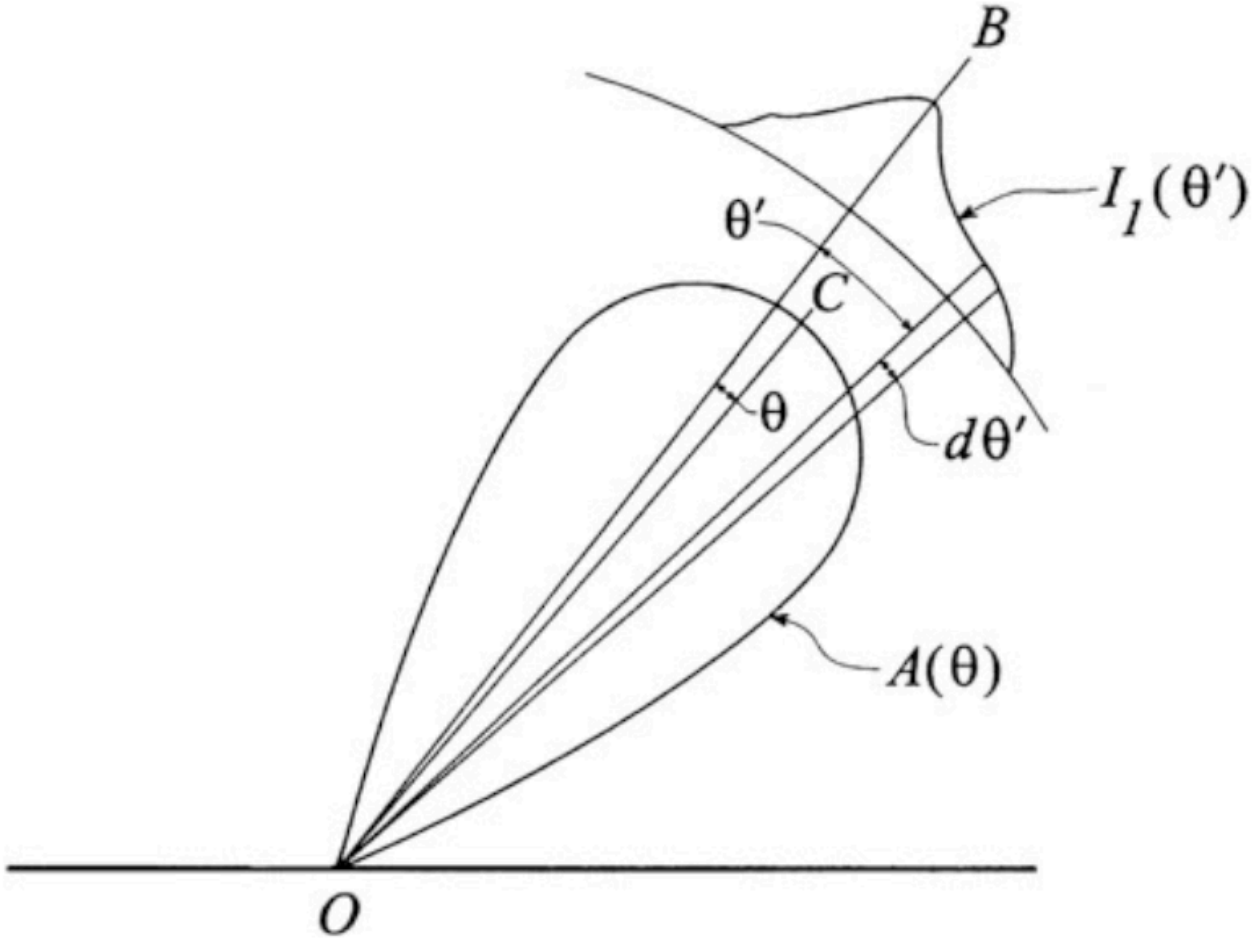
www.csiro.au

CSIRO

Introduction

- Importance of antenna reception pattern
  - Interpretation of receiver output
  - Including polarisation response

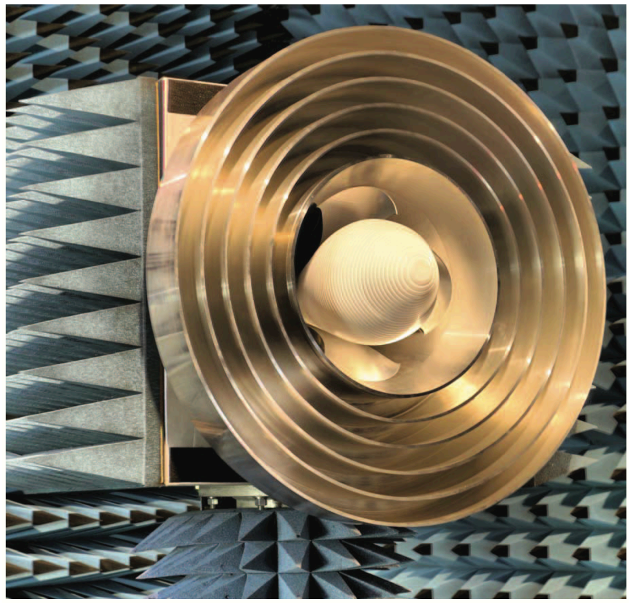
Fig. 2.5 The power pattern $A(\theta)$ of an antenna pointed in the direction OC, and the intensity profile of a source $I_1(\theta')$, used to illustrate the convolution relationship. The angle θ is measured with respect to the beam center OC. The profile of the source is a function of θ', measured with respect to the direction of the nominal position of the source OB.



From *Interferometry and Synthesis in Radio Astronomy*, Thompson, Moran and Swenson (2017)

Introduction

- Conventional receivers have stable reception patterns
  - Transducer normally inside a machined metal feed
    - Initial measurement of pattern
    - Subsequent occasional confirmation



Dunning, Bowen, Bourne, Hayman and Smith, *An ultra-wideband dielectrically loaded quad-ridged feed horn for radio astronomy*, 2015 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), Turin, 2015, pp. 787-790.

URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7300180&isnumber=7300131

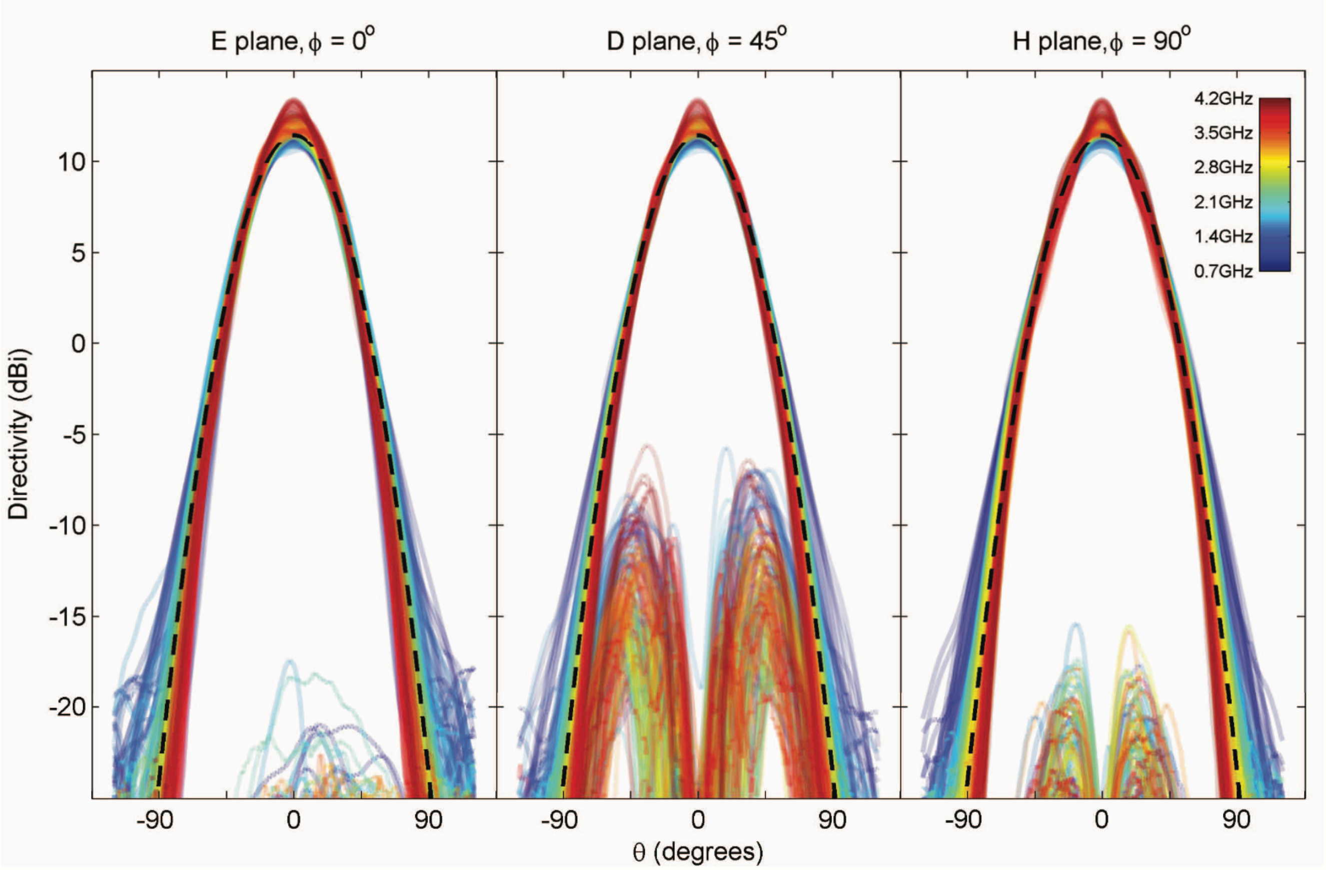
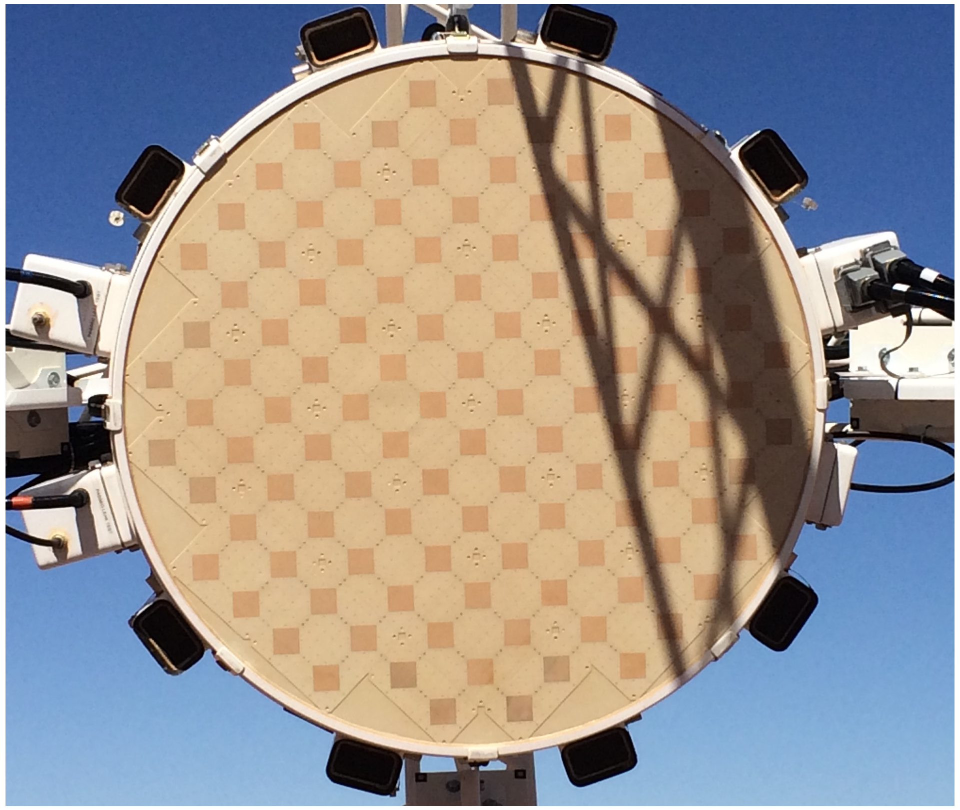


Figure 3. Co-polar and cross-polar directivity patterns of the feed horn. Each pane shows the performance of the feed over the 0.7-4.2GHz frequency range. The Gaussian pattern used to optimize the beam patterns is displayed in each plane as a reference (dashed, black).

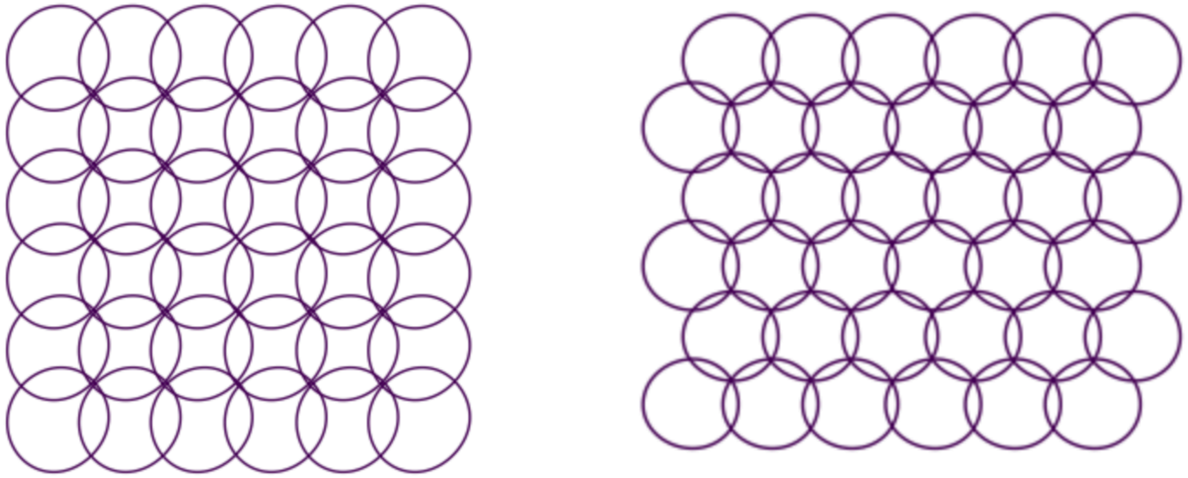
Introduction

- Synthetic beams from PAFs are
  - Less stable - dependence on many electronic components



ASKAP Mk II PAF Image credit: Steve Barker

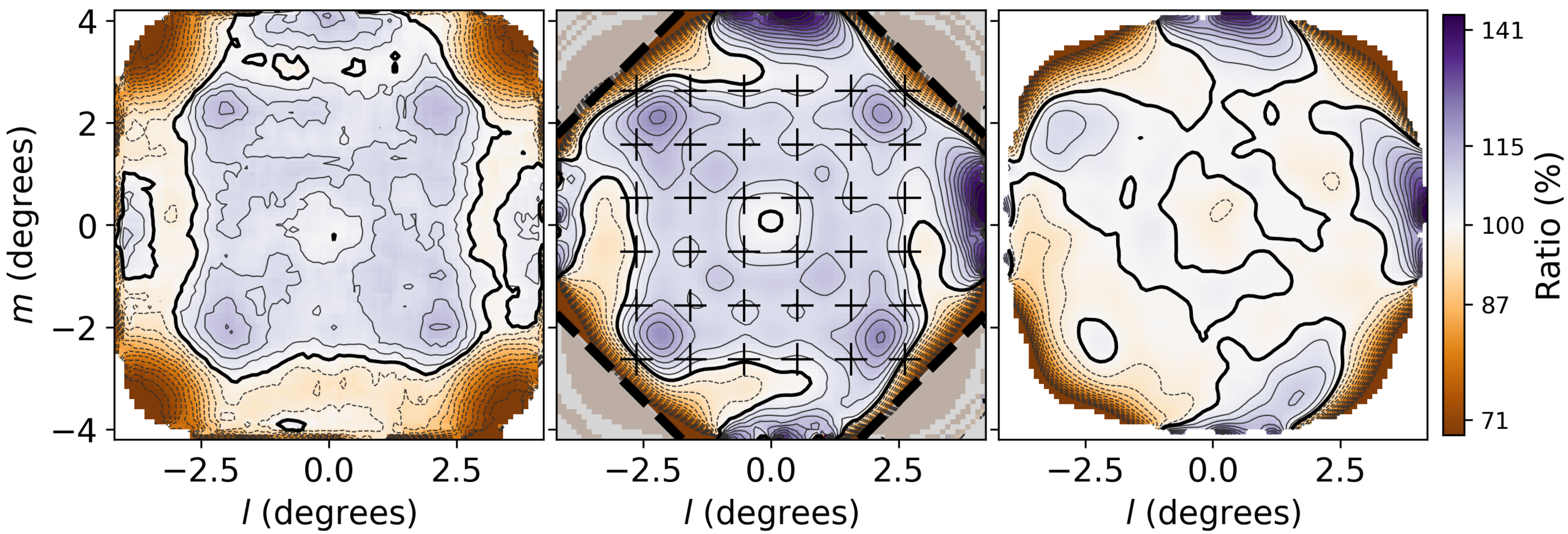
  - Are frequently reconfigured for different astronomical applications



Introduction

- Therefore successful astronomy demands routine measurement of patterns
- For ASKAP, we use holography
- The lesson from RACS:

(Rapid ASKAP Continuum Survey; McConnell et al., 2020)



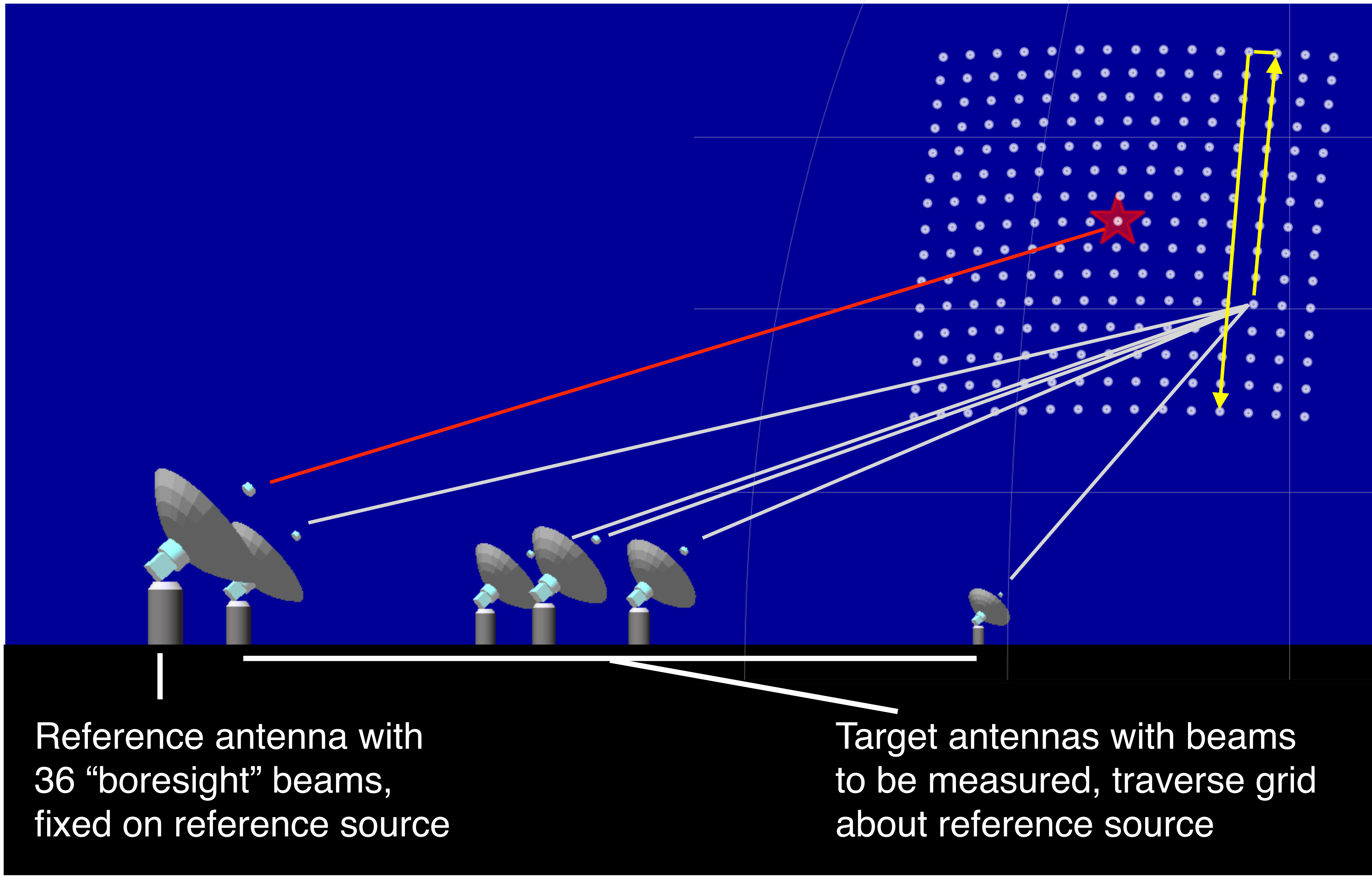
Observed flux scale over FoV

Scale inferred from holography measurements

Corrected

Measurement practice with ASKAP

- Sampling the data



The formalism

Measured electric field

$$\mathbf{E}' = \begin{pmatrix} E'_X \\ E'_Y \end{pmatrix} = \begin{pmatrix} a_1 & a_2 \\ a_3 & a_4 \end{pmatrix} \begin{pmatrix} E_X \\ E_X \end{pmatrix} = \mathbf{JE}$$

$$\mathbf{J}_{\text{gain}} = \begin{pmatrix} g_X & 0 \\ 0 & g_Y \end{pmatrix} \qquad \mathbf{J}_{\text{leak}} = \begin{pmatrix} 1 & D_X \\ D_Y & 1 \end{pmatrix}$$

Correlation between two antennas (coherency vector)

$$\mathbf{R}'_{ij} = \langle \mathbf{E}'_i \otimes \mathbf{E}'^*_j \rangle = \langle \mathbf{J}_i \mathbf{E}_i \otimes \mathbf{J}^*_j \mathbf{E}^*_j \rangle = \begin{pmatrix} R'_{XX} \\ R'_{XY} \\ R'_{YX} \\ R'_{YY} \end{pmatrix}_{ij}$$

$$\mathbf{R}'_{ij} = (\mathbf{J}_i \otimes \mathbf{J}^*_j)\mathbf{R}_{ij}$$

$$\mathbf{R}'_{ij} = \begin{pmatrix} g_{iX} g^*_{jX} & g_{iX} g^*_{jX} D^*_{jX} & g_{iX} g^*_{jX} D_{iX} & g_{iX} g^*_{jX} D_{iX} D^*_{jX} \\ g_{iX} g^*_{jY} D^*_{jY} & g_{iX} g^*_{jY} & g_{iX} g^*_{jY} D_{iX} D^*_{jY} & g_{iX} g^*_{jY} D_{iX} \\ g_{iY} g^*_{jX} D_{iY} & g_{iY} g^*_{jX} D_{iY} D^*_{jX} & g_{iY} g^*_{jX} & g_{iY} g^*_{jX} D*_{jX} \\ g_{iY} g^*_{jY} D_{iY} D^*_{jY} & g_{iY} g^*_{jY} D_{iY} & g_{iY} g^*_{jY} D^*_{jY} & g_{iY} g^*_{jY} \end{pmatrix} \mathbf{R}_{ij}$$

The formalism

$$\mathbf{R}'_{ij} = \begin{pmatrix} g_{iX}g^*_{jX} & g_{iX}g^*_{jX}D^*_{jX} & g_{iX}g^*_{jX}D_{iX} & g_{iX}g^*_{jX}D_{iX}D^*_{jX} \\ g_{iX}g^*_{jY}D^*_{jY} & g_{iX}g^*_{jY} & g_{iX}g^*_{jY}D_{iX}D^*_{jY} & g_{iX}g^*_{jY}D_{iX} \\ g_{iY}g^*_{jX}D_{iY} & g_{iY}g^*_{jX}D_{iY}D^*_{jX} & g_{iY}g^*_{jX} & g_{iY}g^*_{jX}D*_{jX} \\ g_{iY}g^*_{jY}D_{iY}D^*_{jY} & g_{iY}g^*_{jY}D_{iY} & g_{iY}g^*_{jY}D^*_{jY} & g_{iY}g^*_{jY} \end{pmatrix} \mathbf{R}_{ij}$$

Let antennas *i, j* be the reference and target.

Antenna *i* is fixed in the reference source

Assume g_{iX}, g_{iY} constant and $D_{iX}, D_{iY} = 0$

Assume reference source is unpolarised so $\boldsymbol{R}_{ij} = (R_{XX}, 0, 0, R_{YY})$

$$\begin{aligned} R'_{XX} &= R_{XX}g_{iX}g^*_{jX} \\ R'_{XY} &= R_{XX}g_{iX}g^*_{jY}D^*_{jY} \\ R'_{YX} &= R_{YY}g_{iY}g^*_{jX}D^*_{jX} \\ R'_{YY} &= R_{YY}g_{iY}g^*_{jY} \end{aligned}$$

The formalism

$$R'_{XX} = R_{XX} g_{iX} g^*_{jX}$$
$$R'_{XY} = R_{XX} g_{iX} g^*_{jY} D^*_{jY}$$
$$R'_{YX} = R_{YY} g_{iY} g^*_{jX} D^*_{jX}$$
$$R'_{YY} = R_{YY} g_{iY} g^*_{jY}$$

For the target antennas, the apparent gain is a function of angular coordinates

$$g_j = g_j(l,m)$$

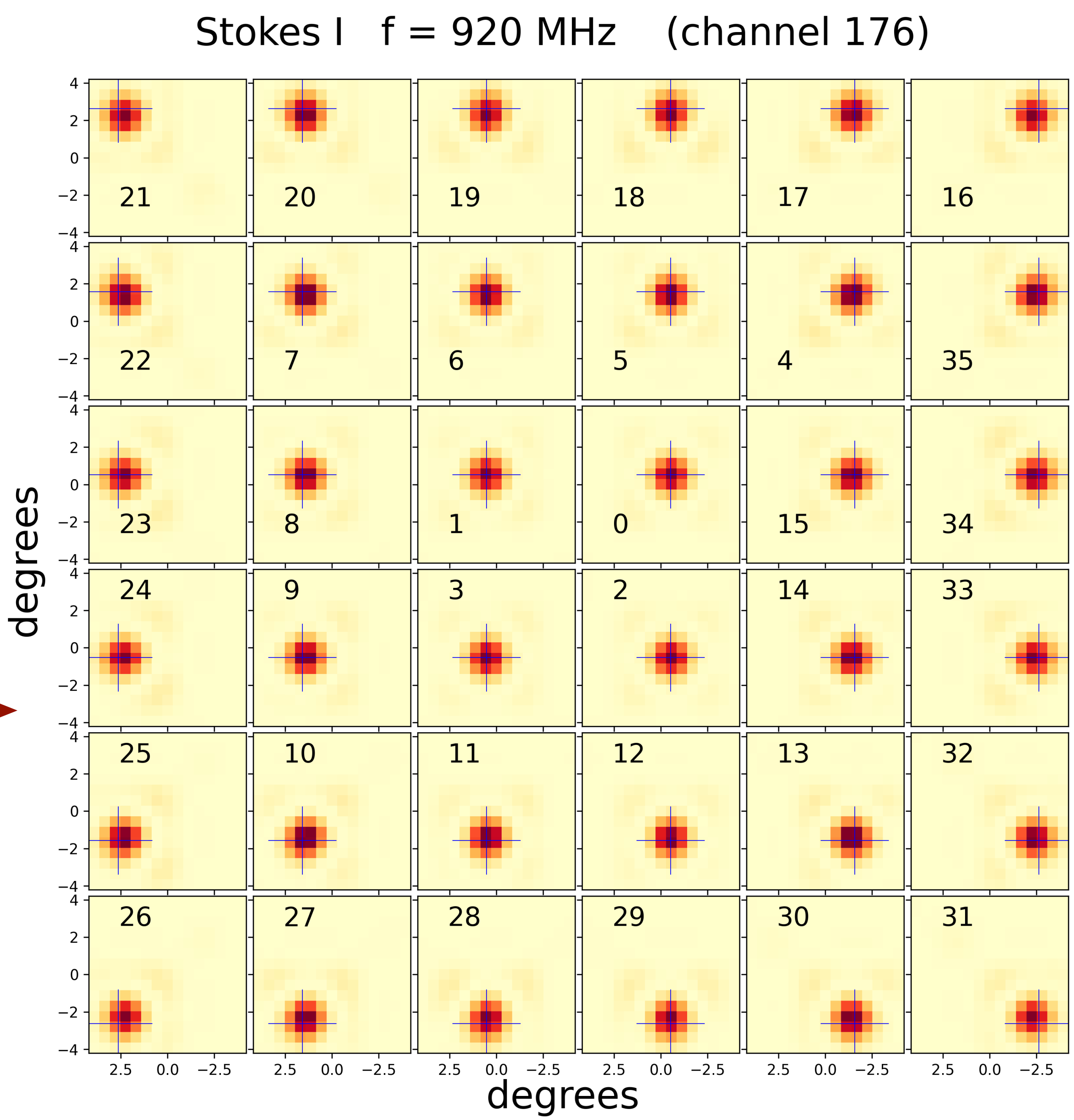
So we can normalise the R' quantities by their values at the beam centre:

$$\mathcal{R}'_{XX}(l,m) = \frac{R_{XX} g_{iX} g^*_{jX}(l,m)}{R_{XX} g_{iX} g^*_{jX}(0,0)} = \frac{g^*_{jX}(l,m)}{g^*_{jX}(0,0)}$$

Conversion to relative power images in Stokes (I,Q,U,V)

The procedure

- Select correlations between reference and each target antenna
- For each antenna, beam and frequency channel, normalise the image by its value at beam centre
- Convert to power in (I,Q,U,V)
- Detect and flag bad data
- Form mean over antennas from good data.
- Interpolate over missing frequencies and write output.
- Output used by LINMOS for constructing astronomical images



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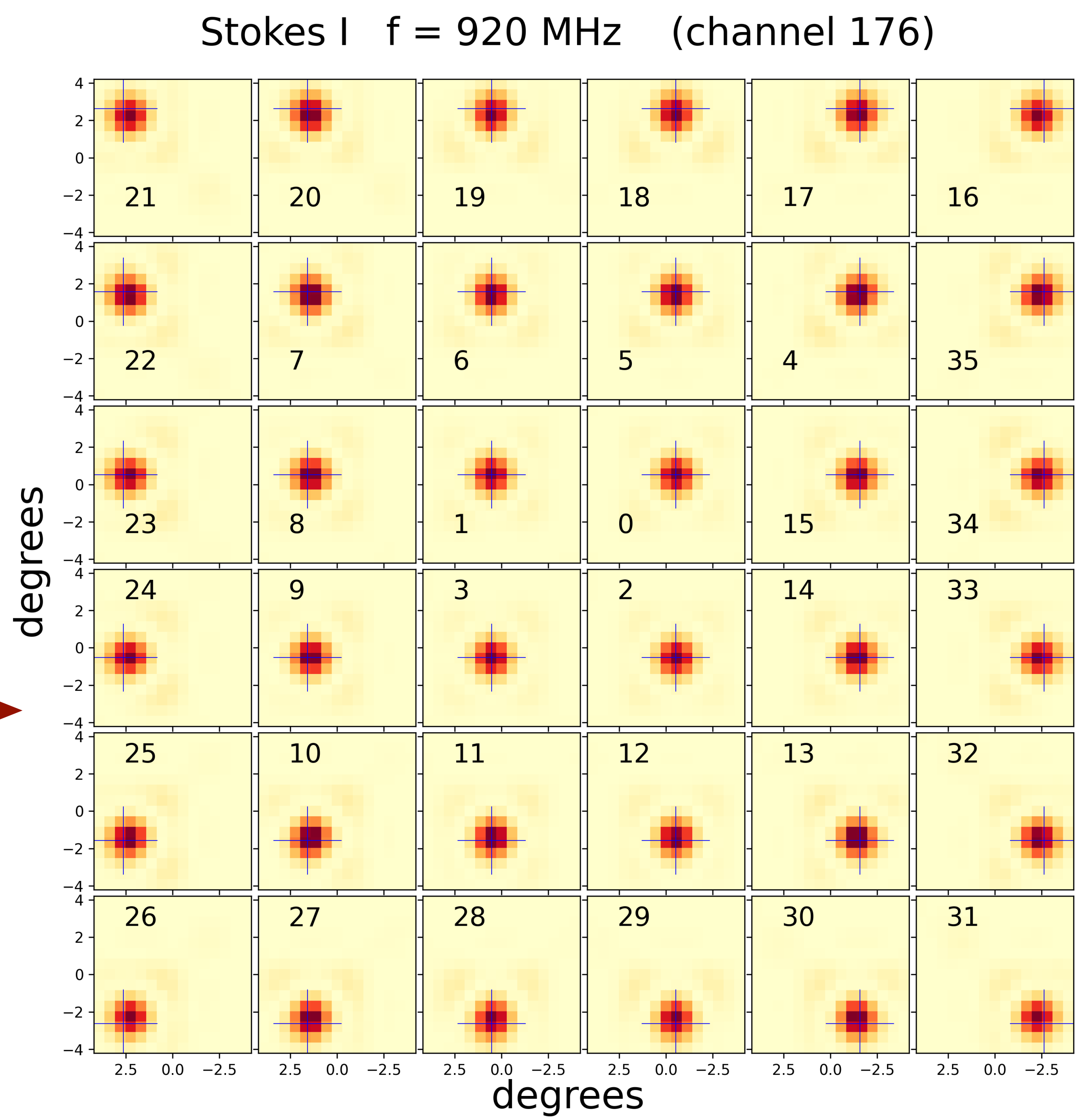

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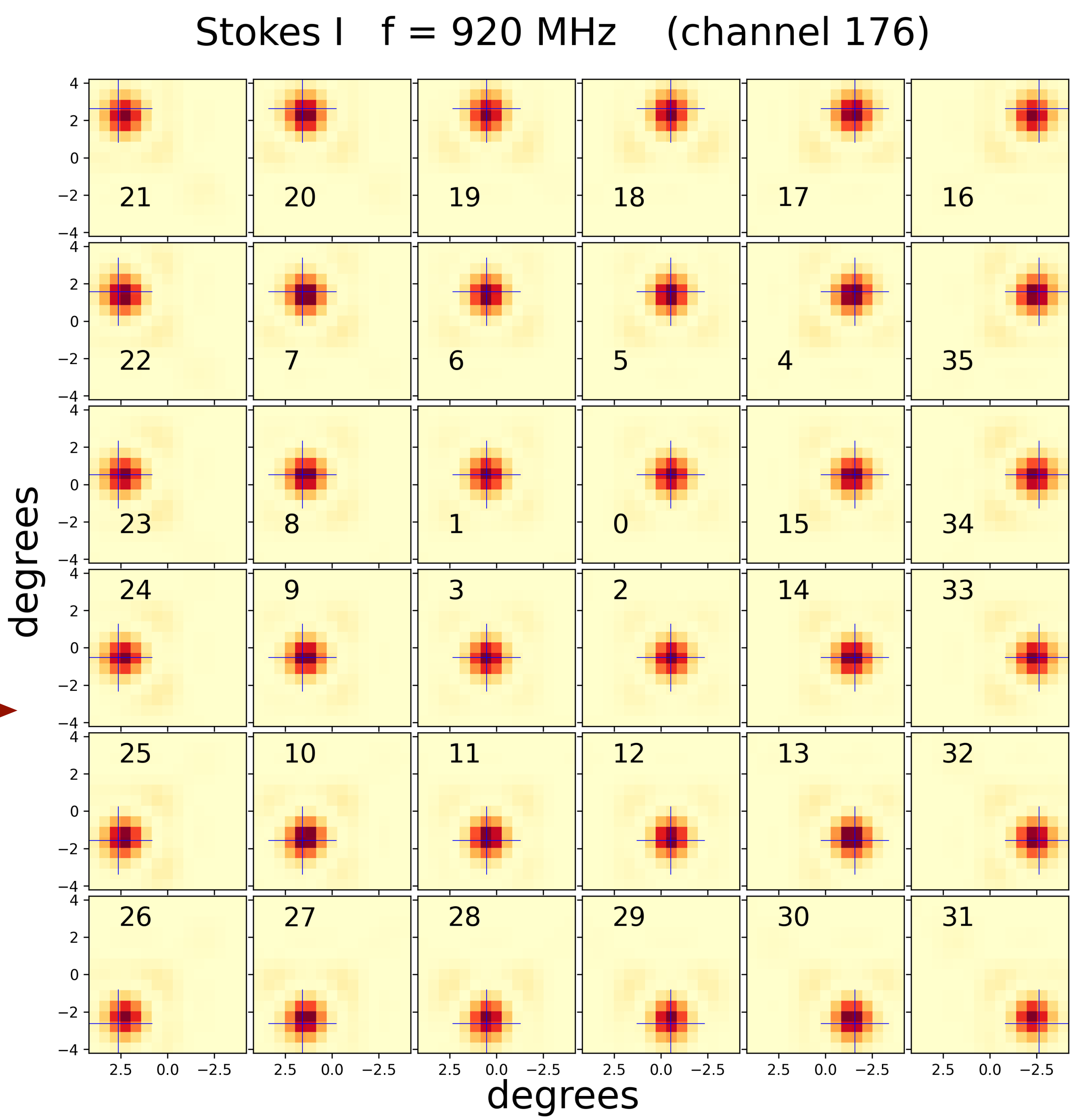
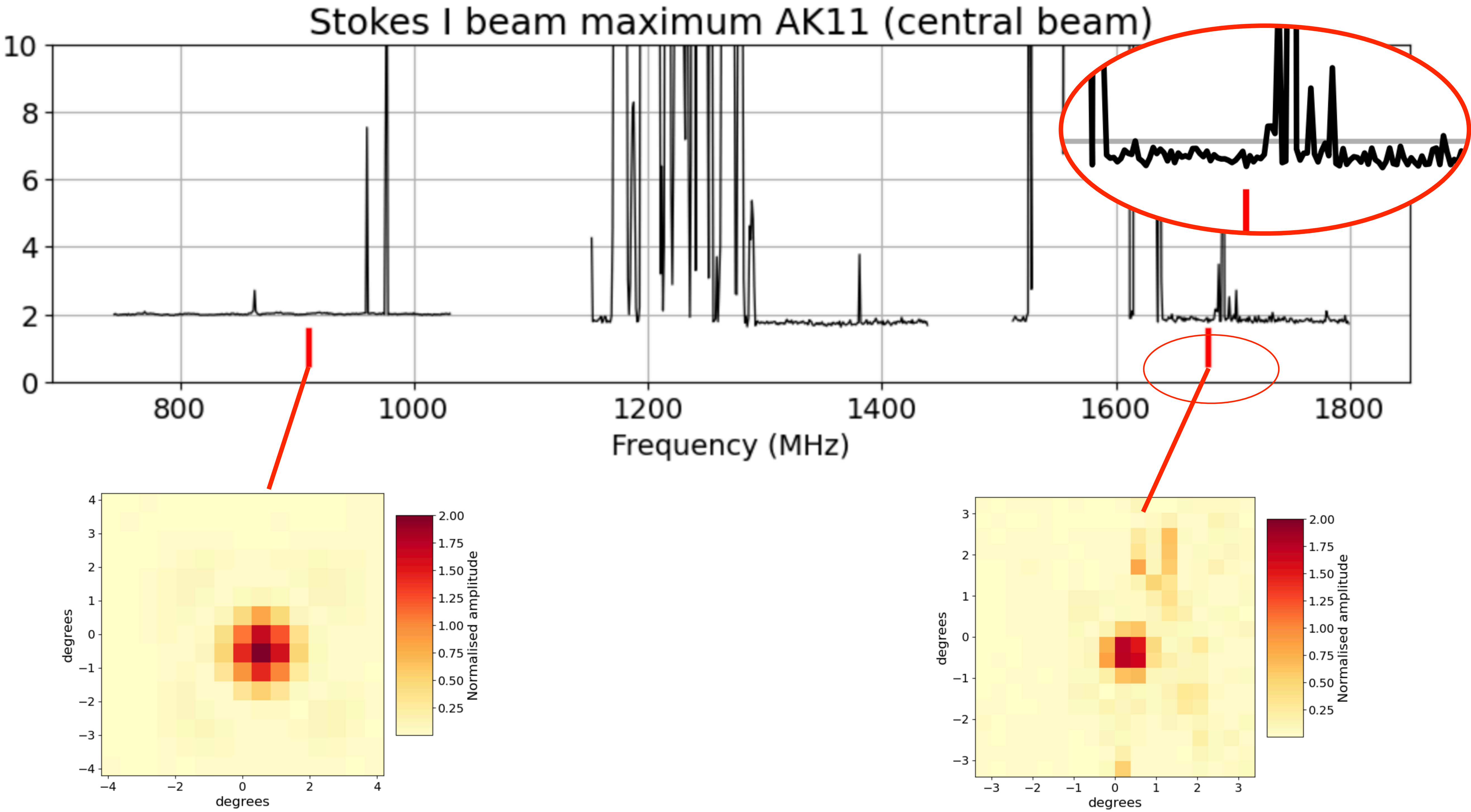


Detecting bad data - anomalous amplitudes

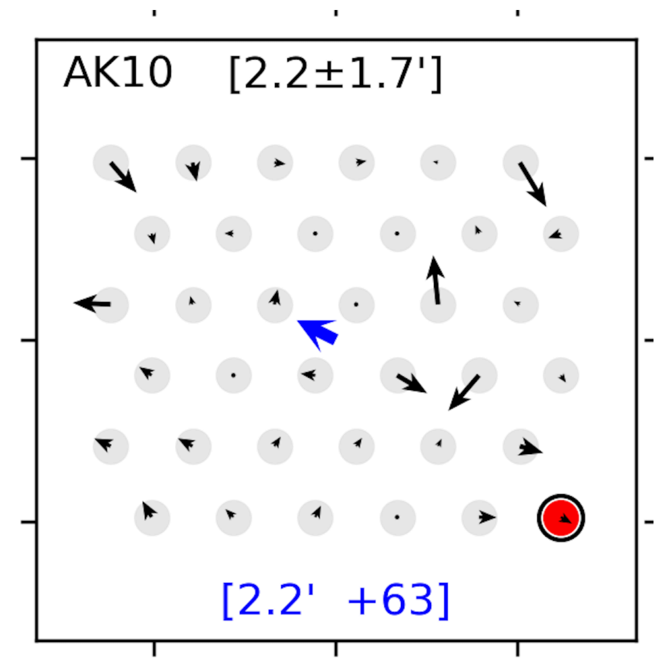


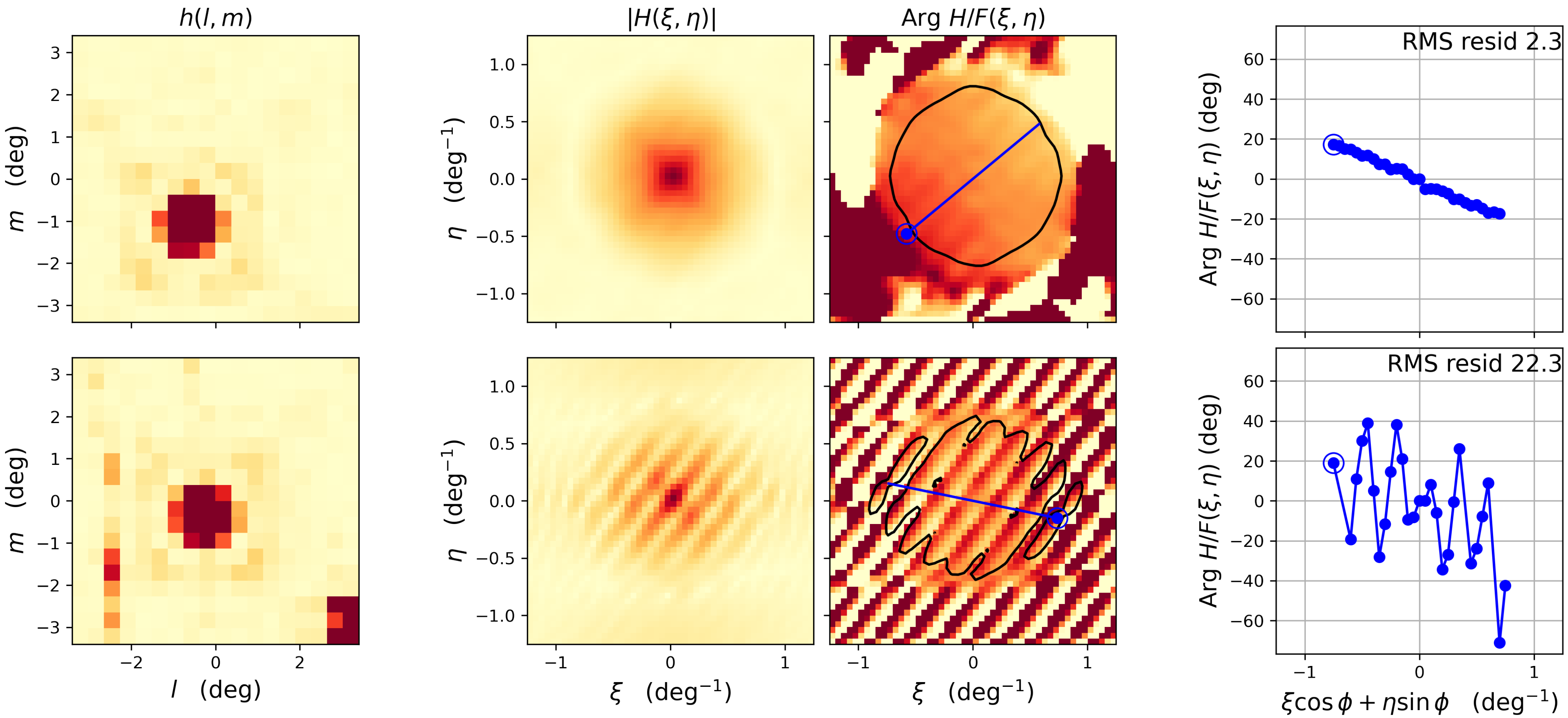
Detecting bad data - beam shapes, positions

Absolute position error

Fitted beam amplitude

Goodness of fit to phase slope



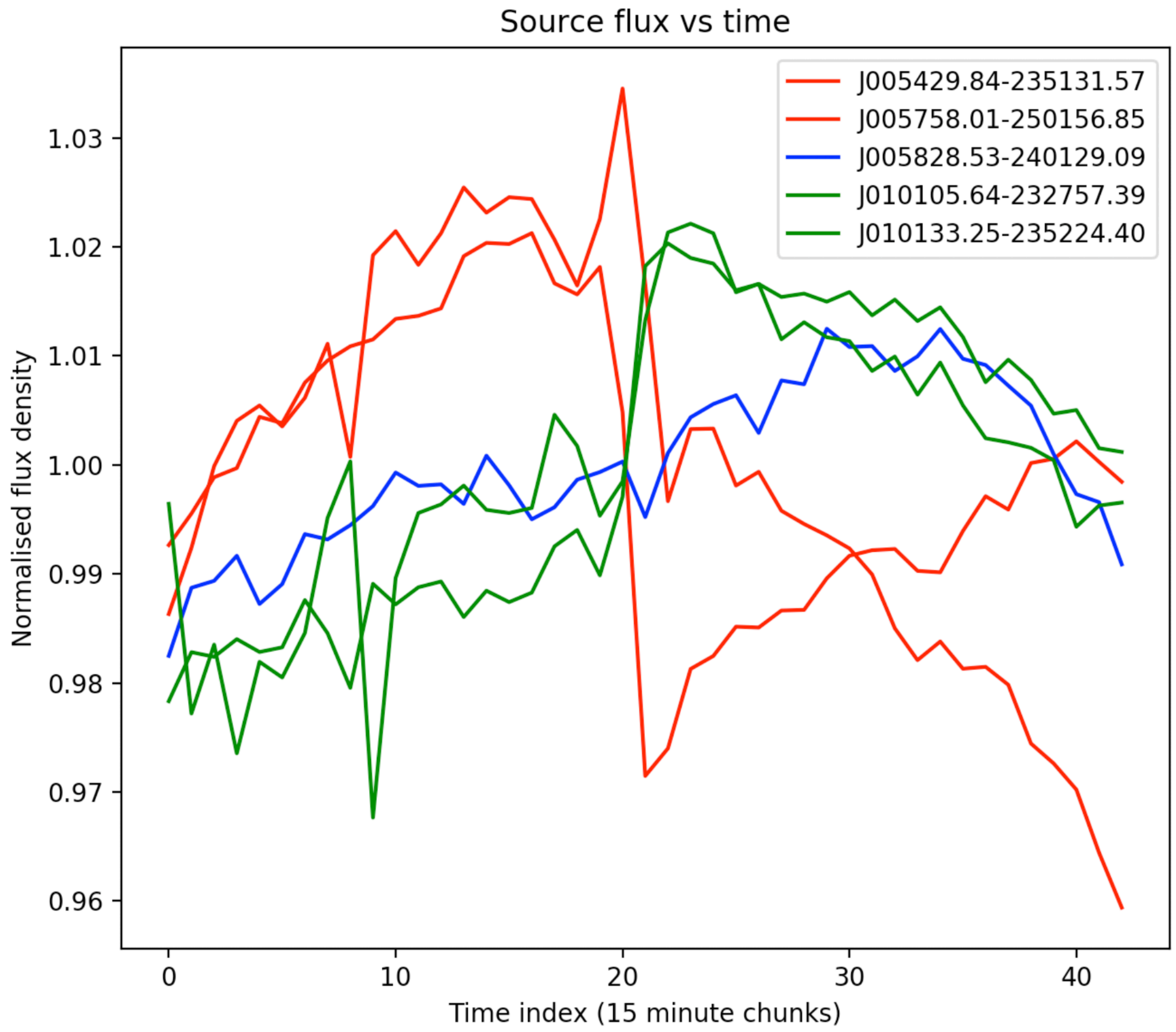


PASS

FAIL

The mysterious case of the variable sources

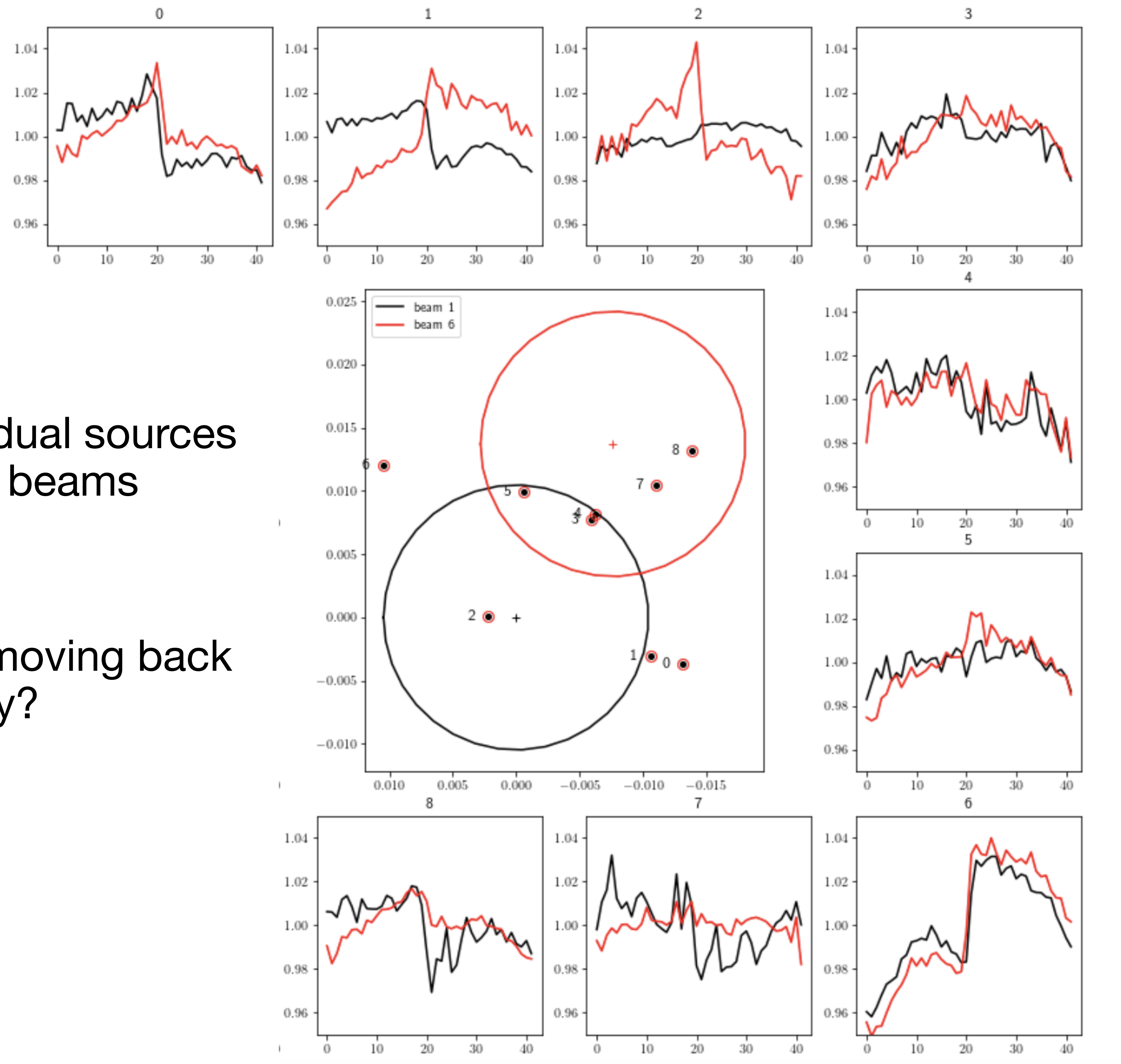
- Time series analysis of LIGO follow-up field by Yuanming Wang (USyd)



The case of the variable sources

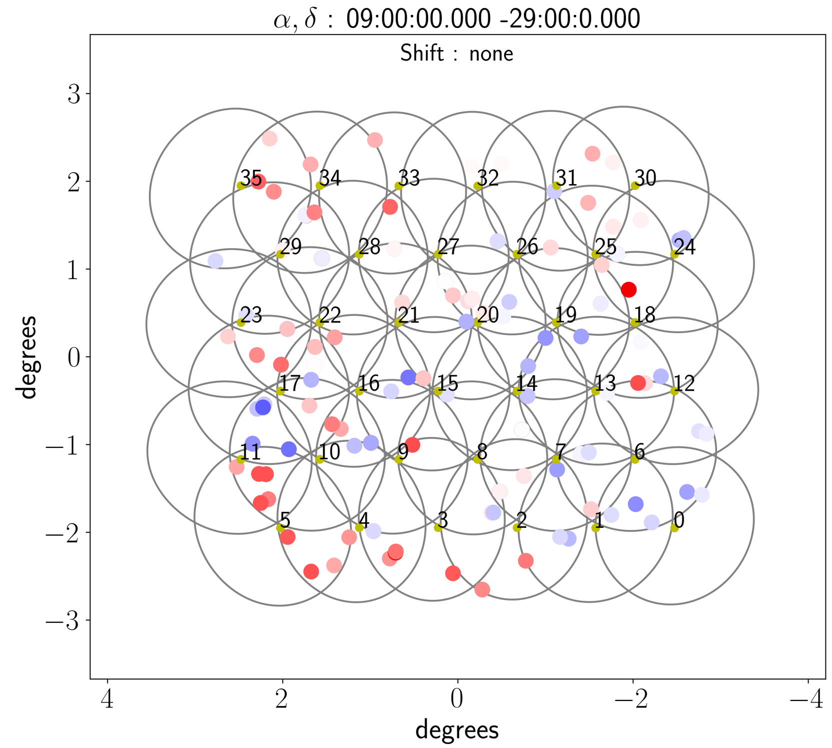
The apparent flux of individual sources observed though adjacent beams behaved differently.

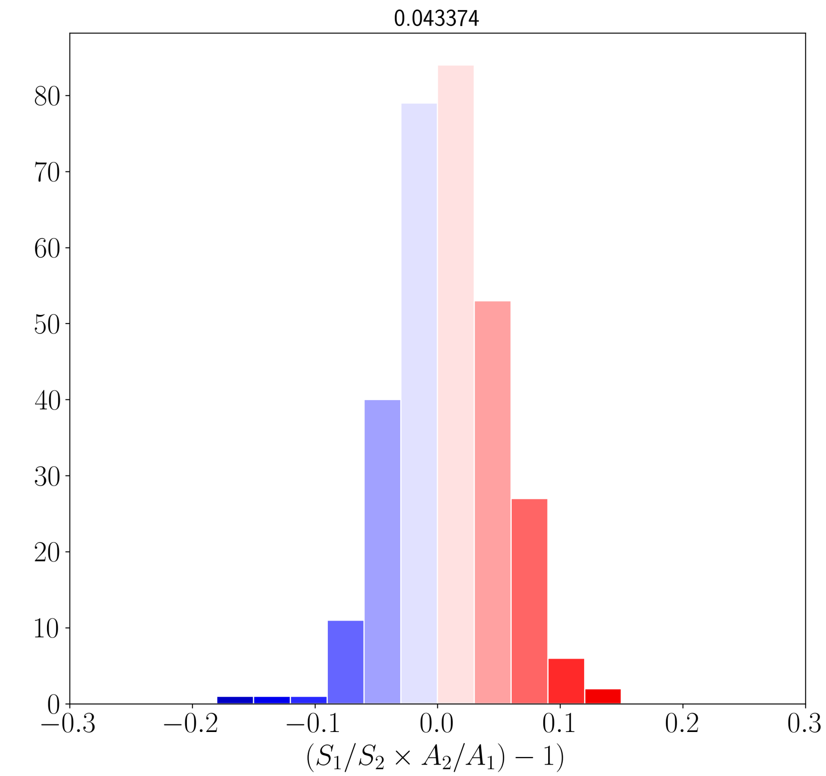
Perhaps the beams were moving back and forth relative to the sky?

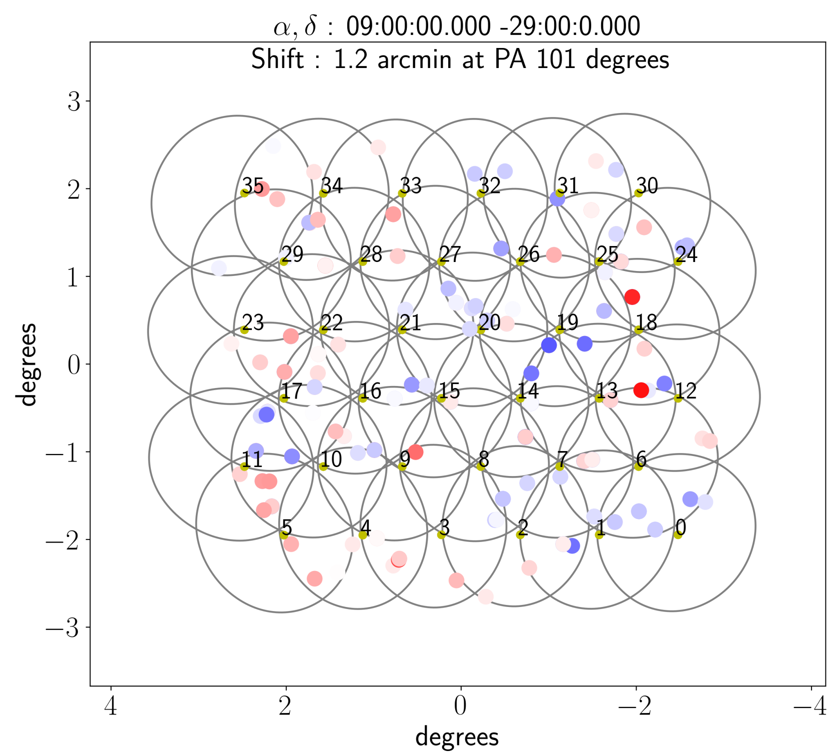


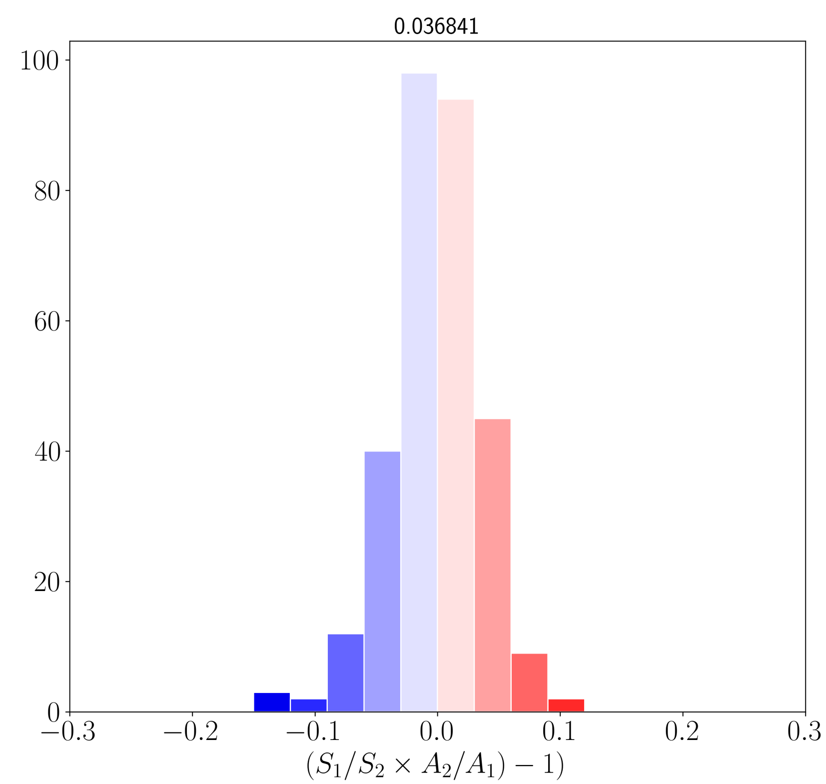
The case of the variable sources

Indeed, we found that the discrepancies between flux-densities of sources in adjacent beams could be minimised with a bulk shift of all beams.

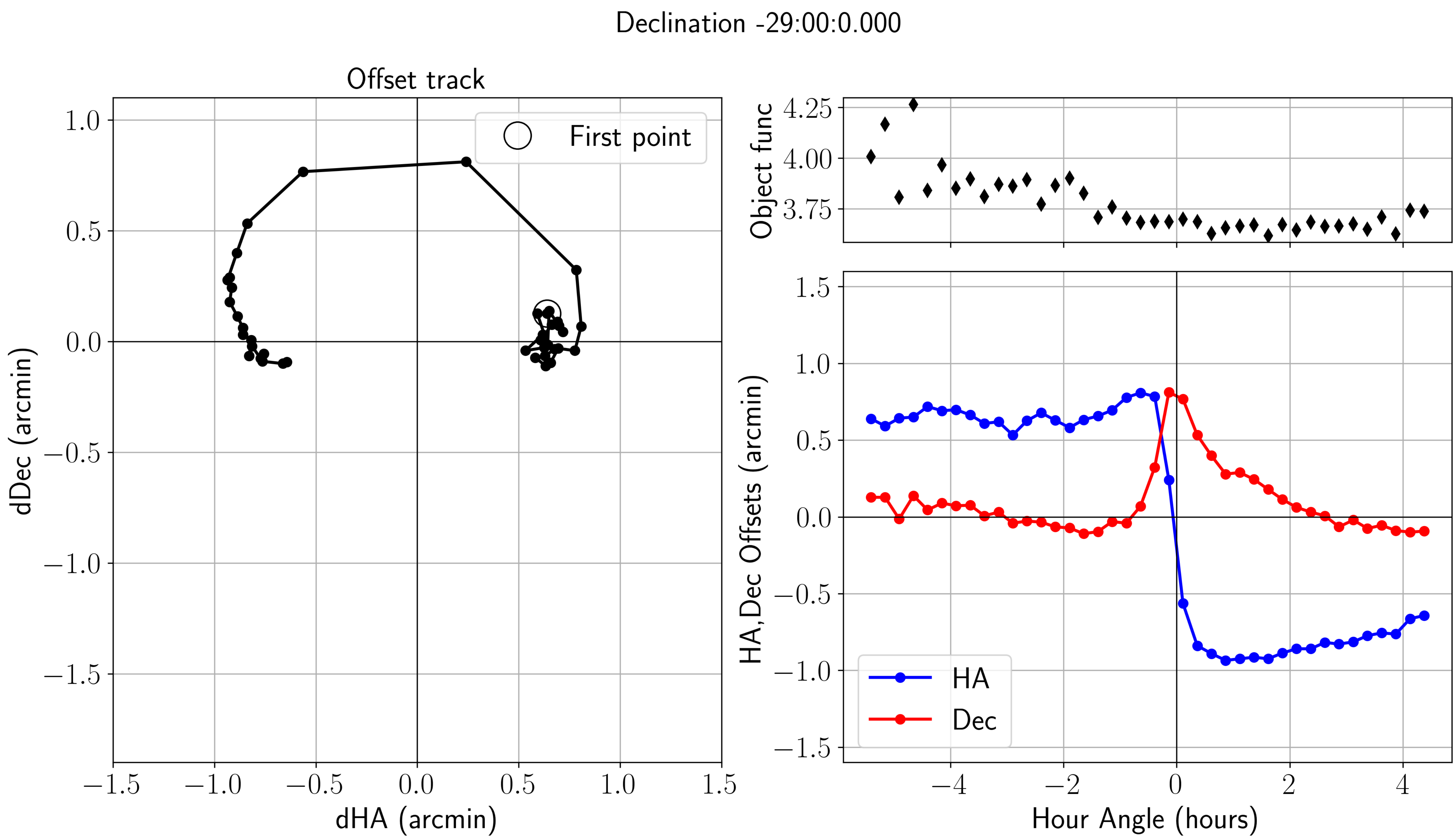








The case of the variable sources



The Future

- Improved telescope control to enable faster measurement and/ or larger or finer sampling grid
- Use of individual antenna patterns (not array-wide mean)
  - -> A-projection
- Larger grid would give better measurement of dish illumination pattern - enable A-projection imaging.

We acknowledge the Wajarri Yamatji people
as the traditional owners of the observatory site.