Netherlands Institute for Radio Astronomy

Error Recognition in LOFAR Data

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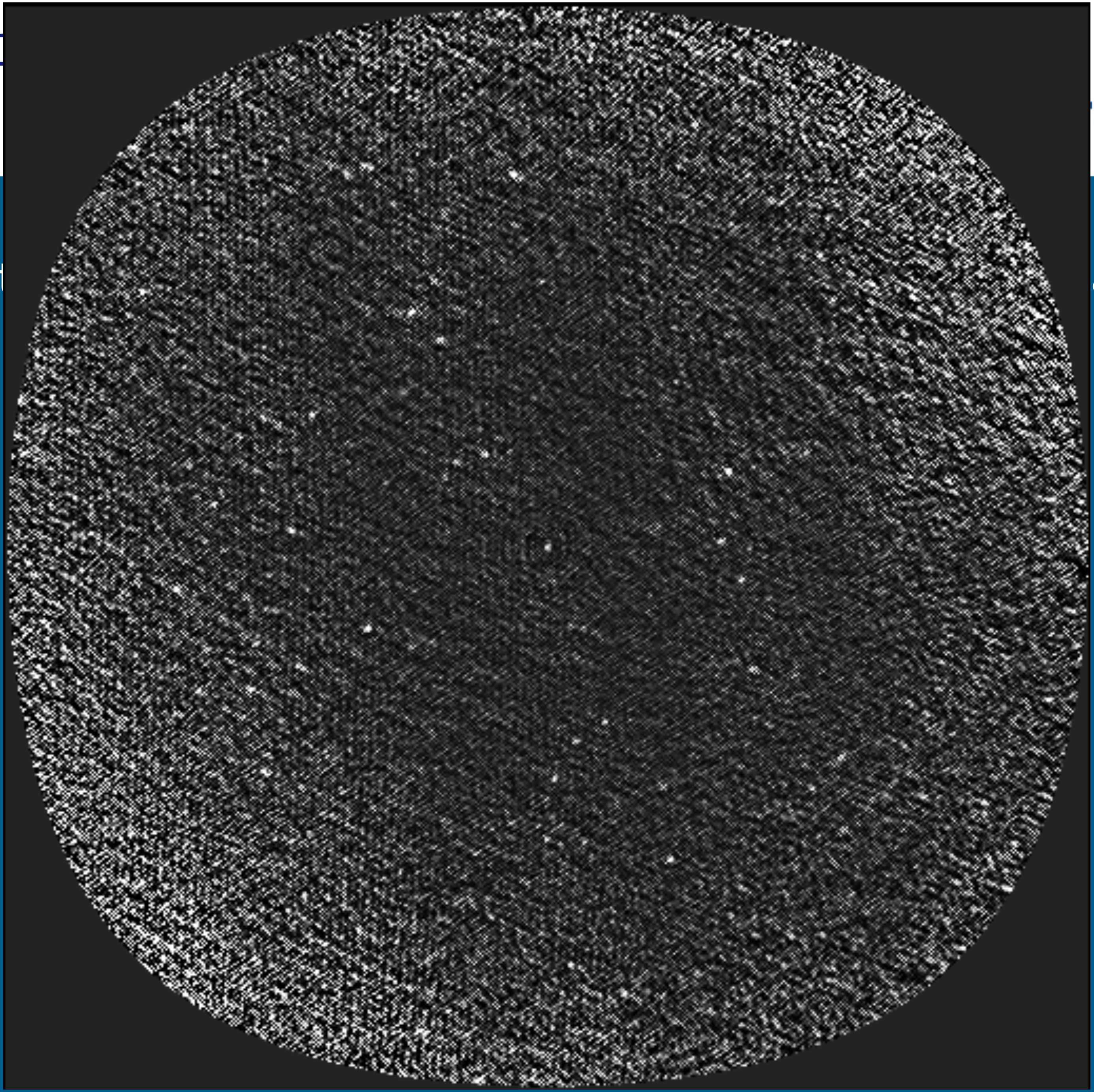
(With thanks to R. Ekers, R. Laing, G. Taylor, J. Stevens and others who I have borrowed/stolen slides from)

Step 1: make an image

- Now that your data is nicely calibrated, let’s make an image!

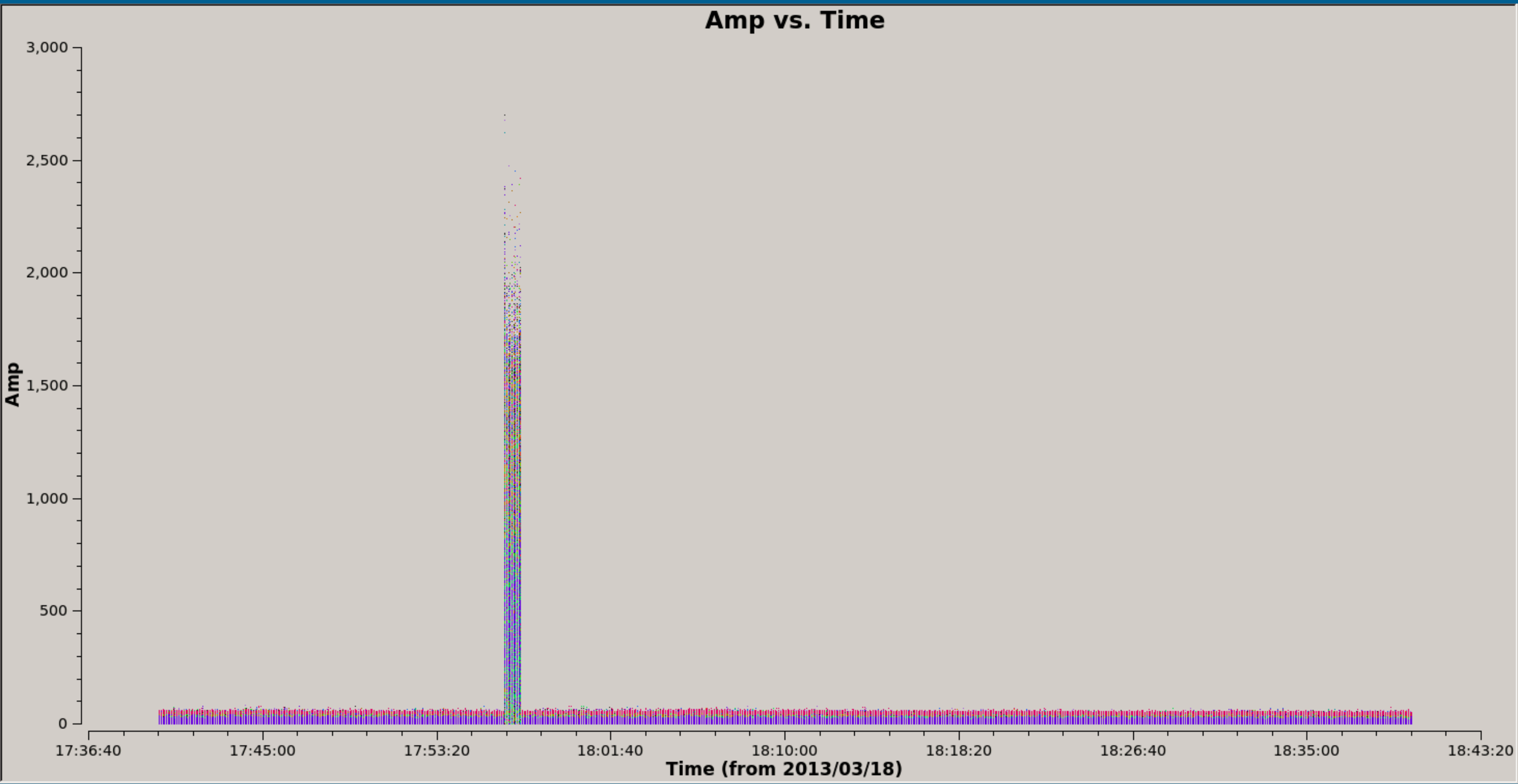
Step :

- Now t ... age!

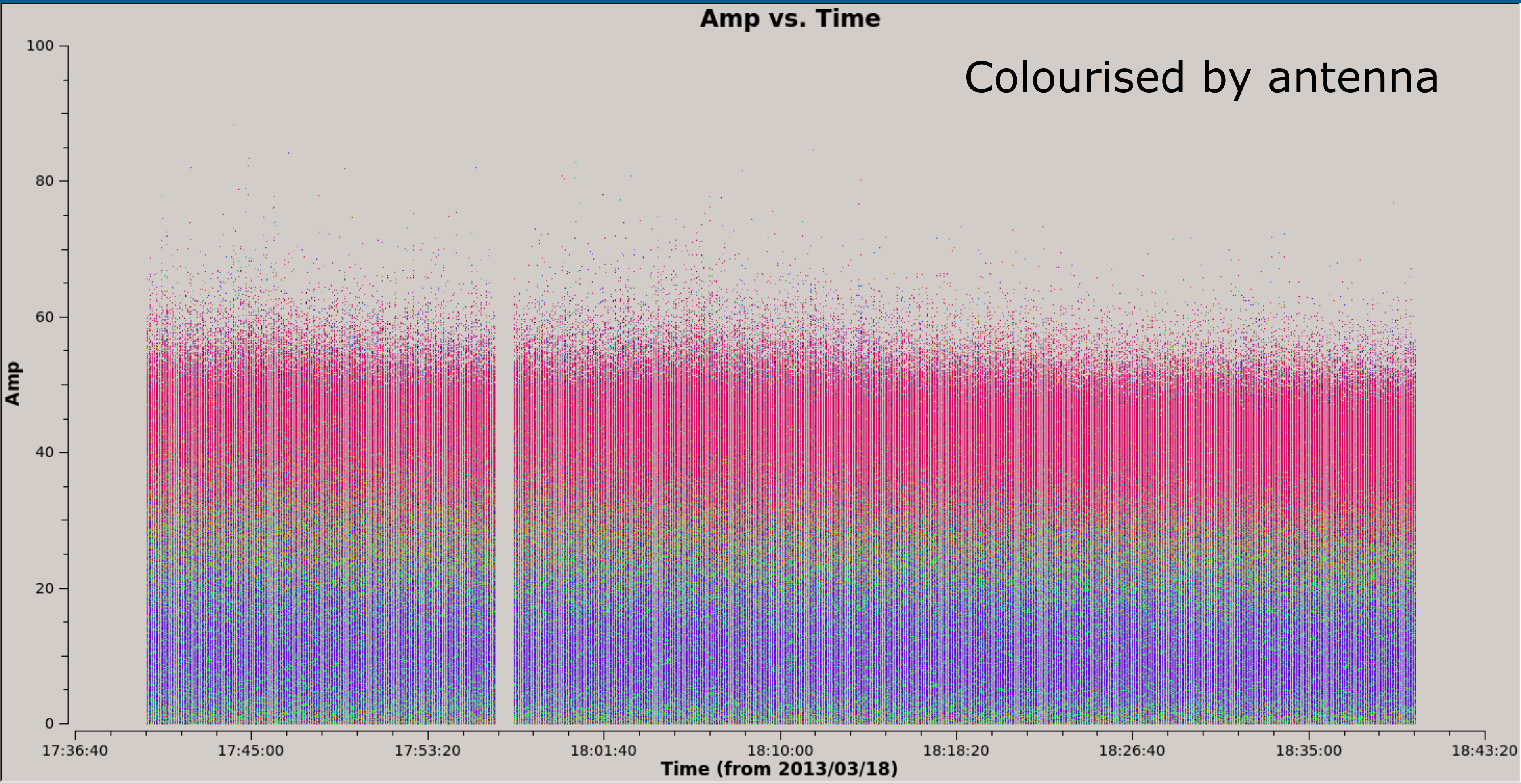


What went wrong??

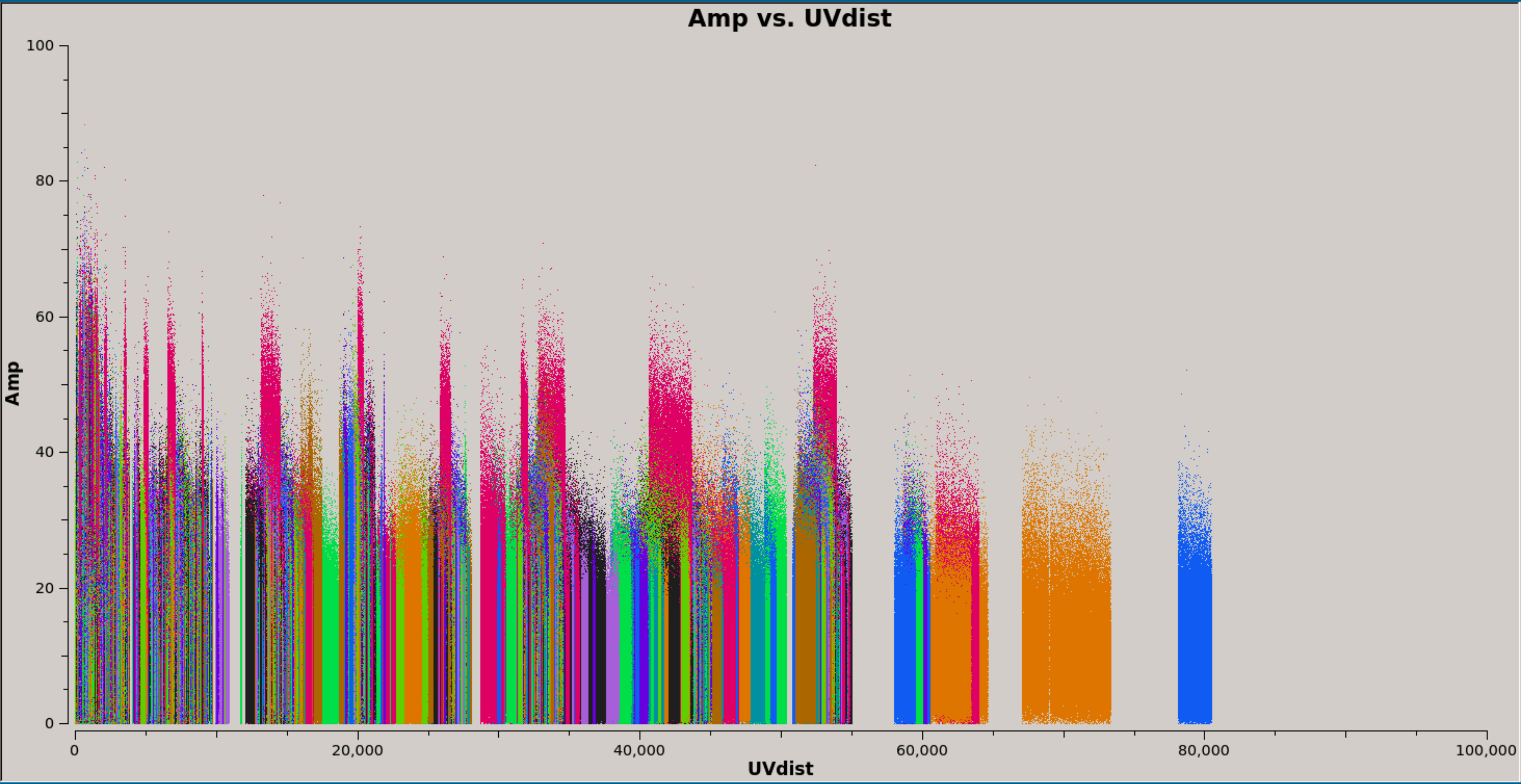
- First check: look for bad data in the u,v plane.



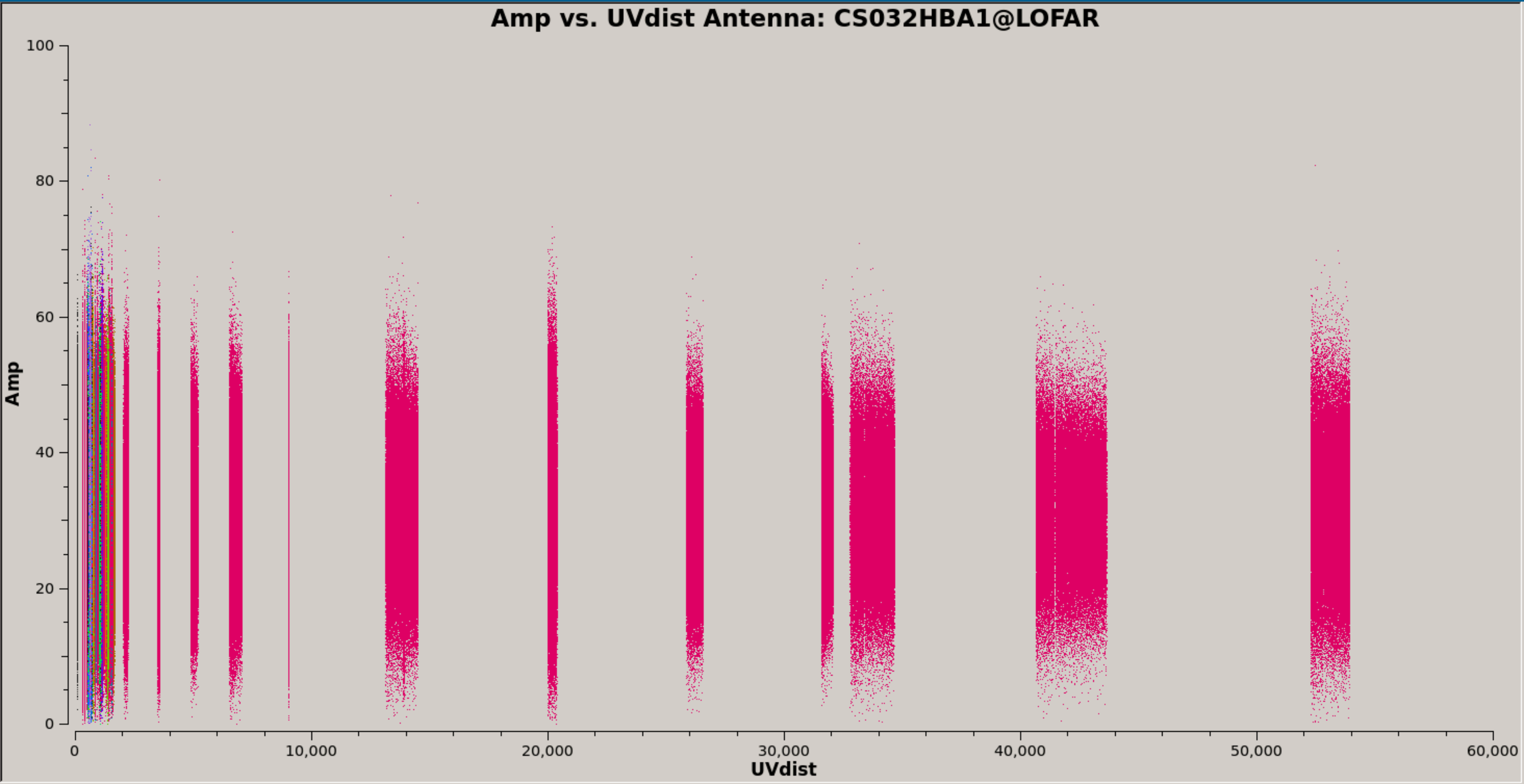
Finding bad data in the u,v plane



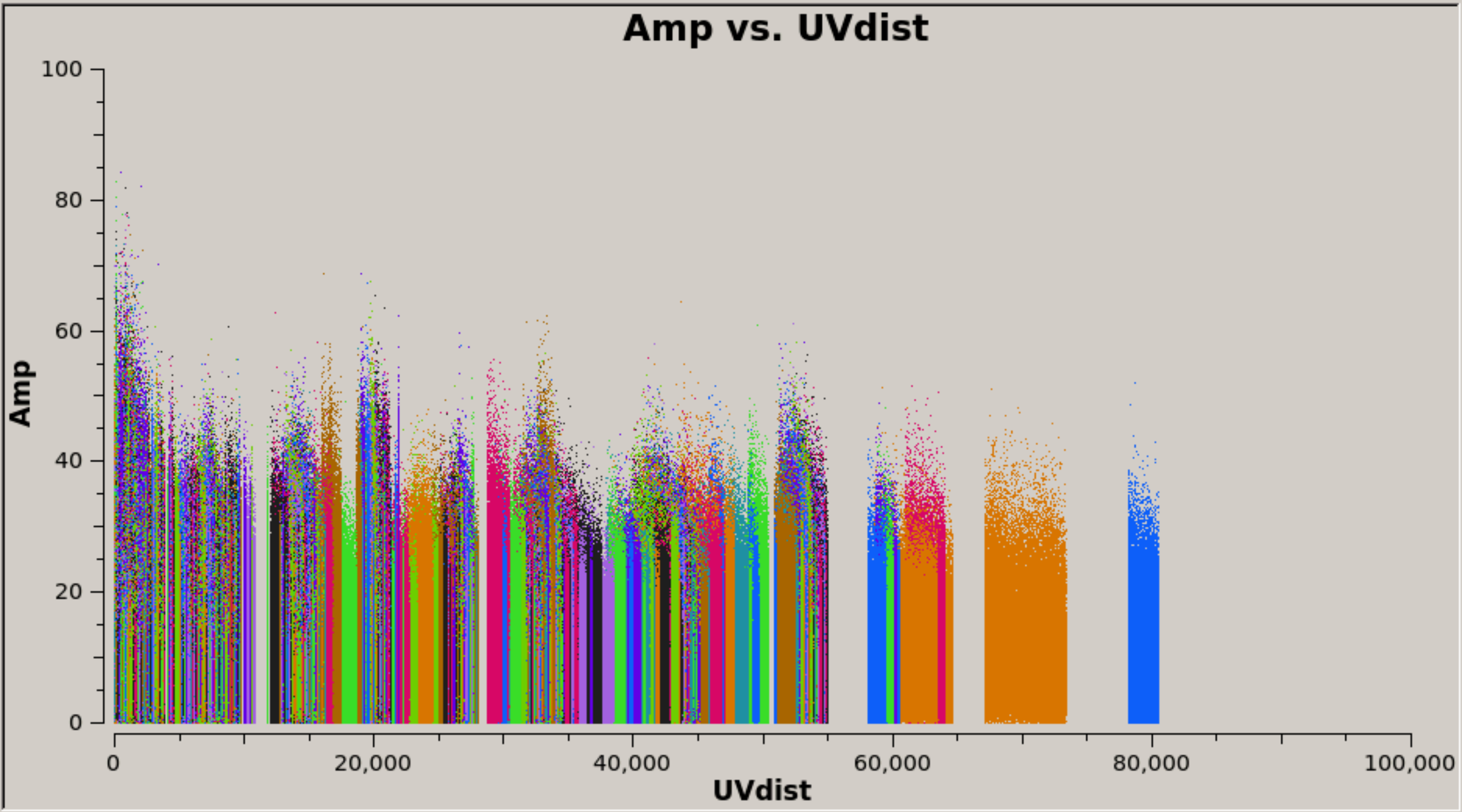
Finding bad data in the u,v plane



Finding bad data in the u,v plane



Finding bad data in the u,v plane



u,v plane or image plane?

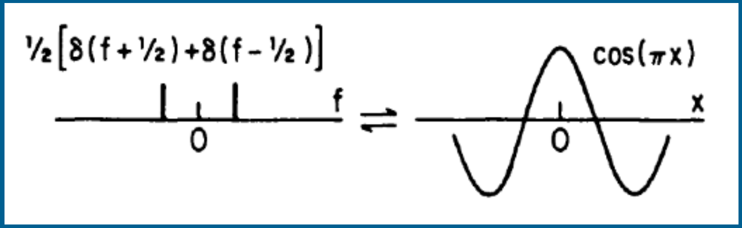
- Can easily identify large errors in the u,v plane, but it's often difficult to find smaller errors
  - Particularly true with LOFAR where many sources in the field of view make interpreting uvdist plots difficult!

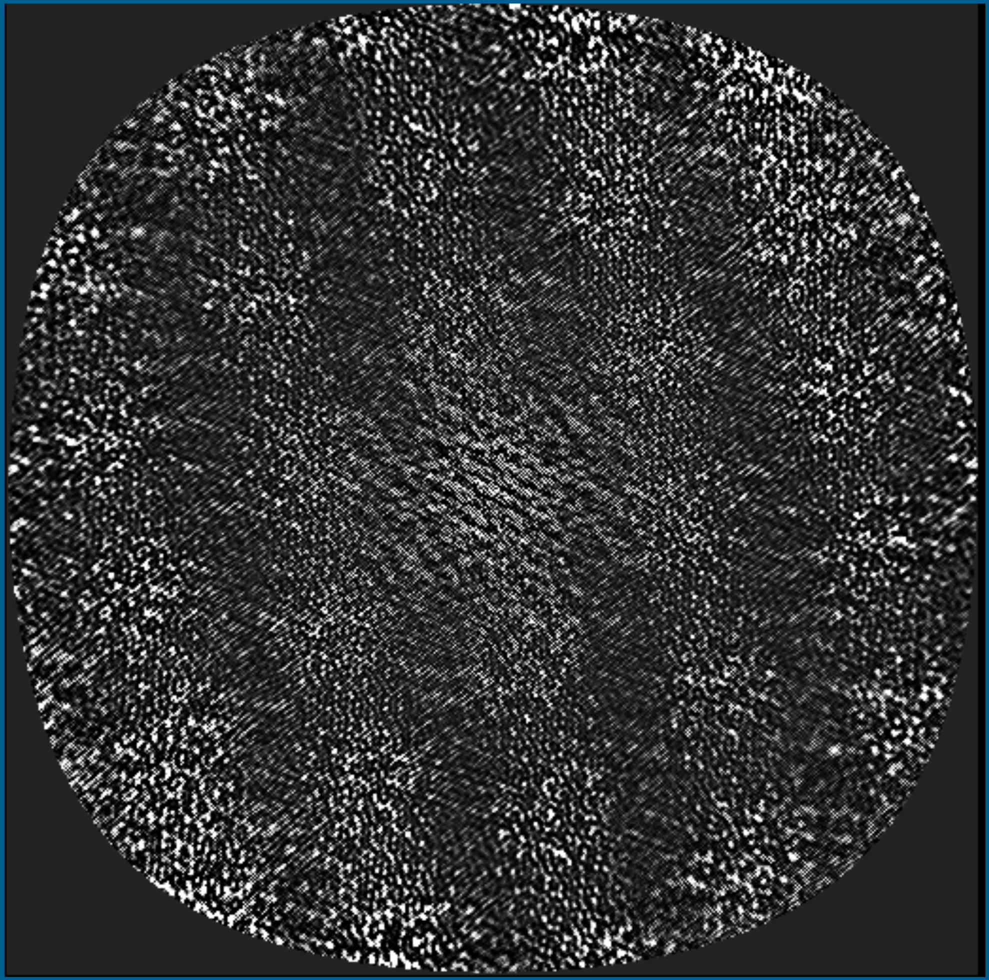
- Remember: errors also obey the Fourier transform relation
  - Large errors in the u,v plane can be virtually insignificant in the image plane
  - Likewise, small undetectable defects in the u,v plane can be very obvious in the image plane

- Goal is to get good image – not always worth being a perfectionist about the u,v data…

Recognising calibration errors in the image plane

- Can use our knowledge of Fourier transform pairs to our advantage
    - Look for patterns/ symmetries

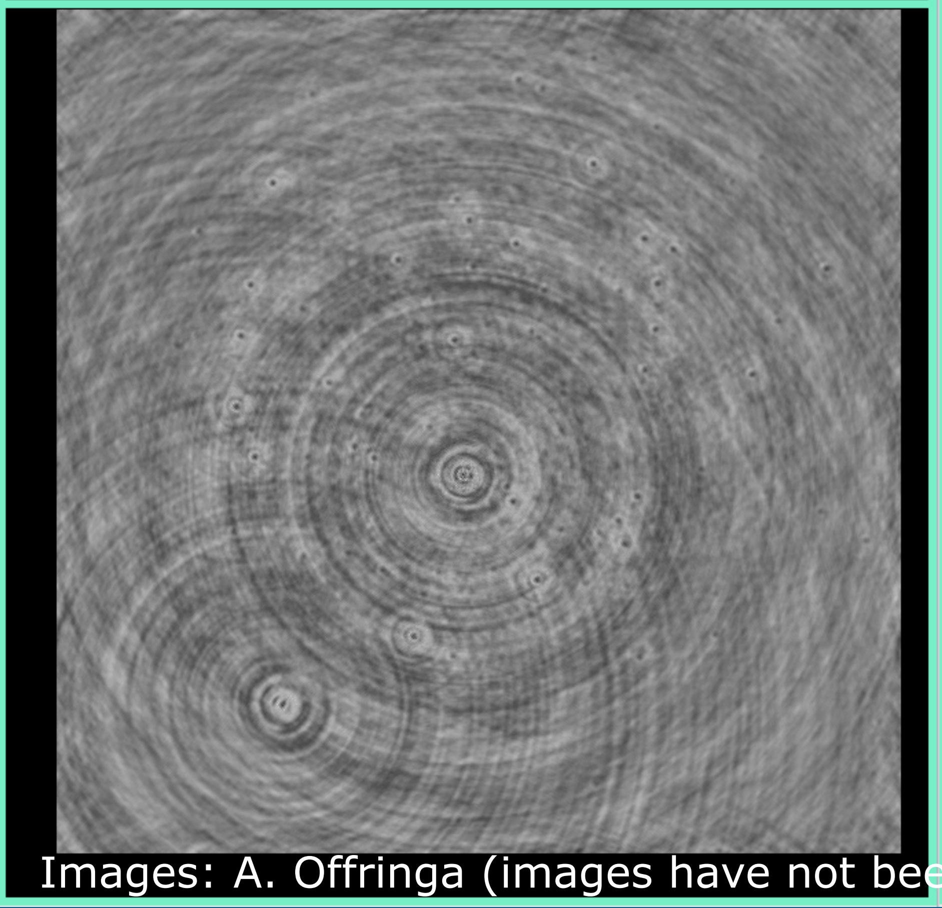




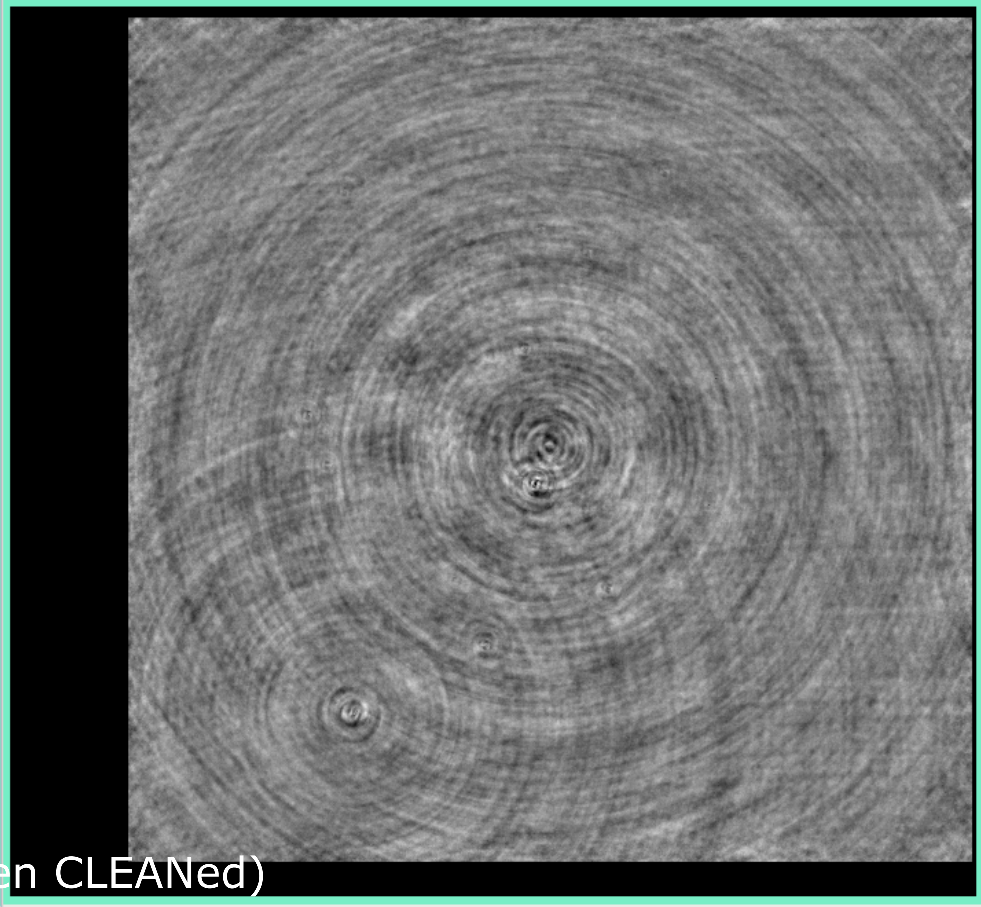
Recognising calibration errors in the image plane

- Another example of RFI (NCP observations):

No RFI



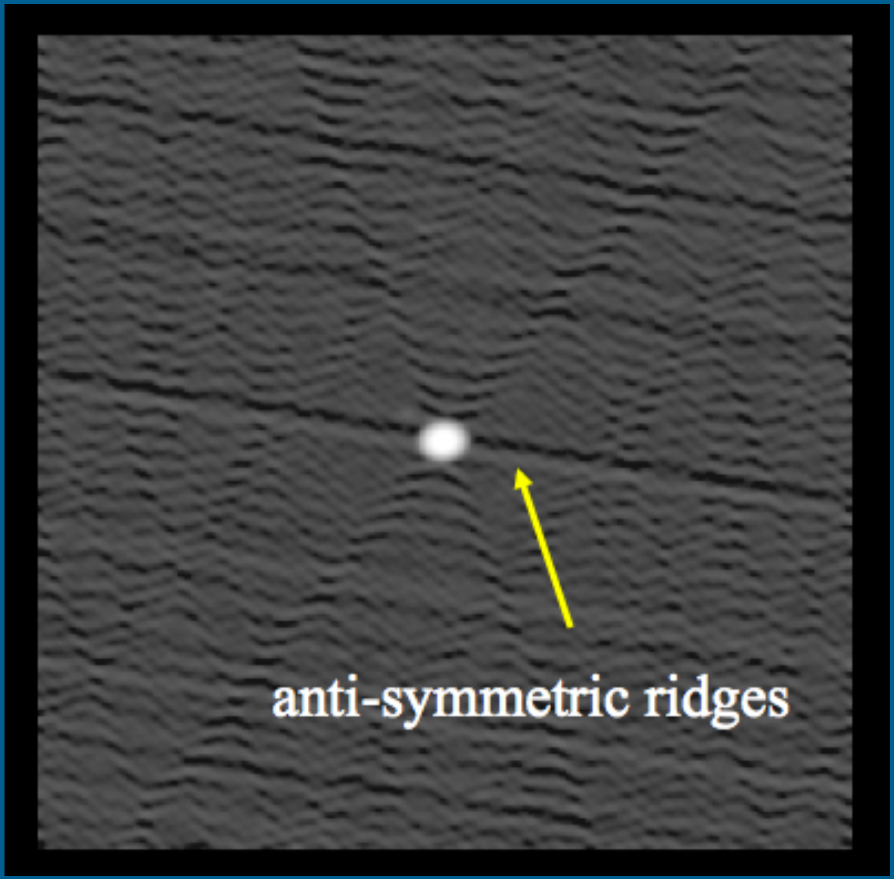
RFI centred at the pole



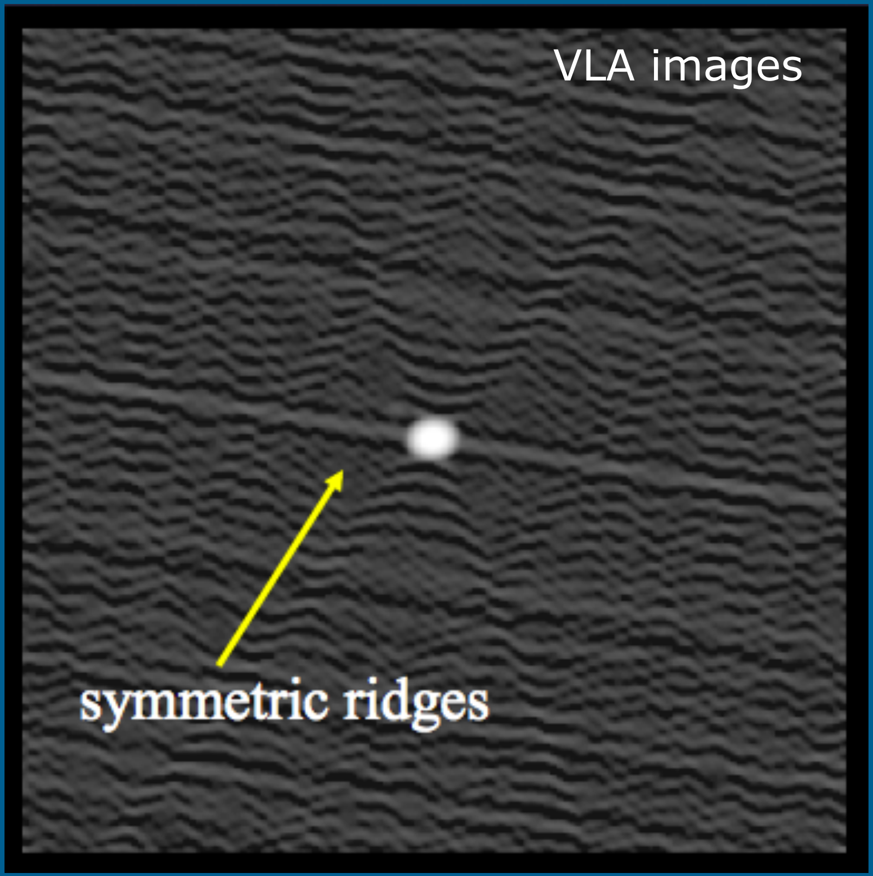
Images: A. Offringa (images have not been CLEANed)

Recognising calibration errors in the image plane

10 deg phase error for
one antenna at one time



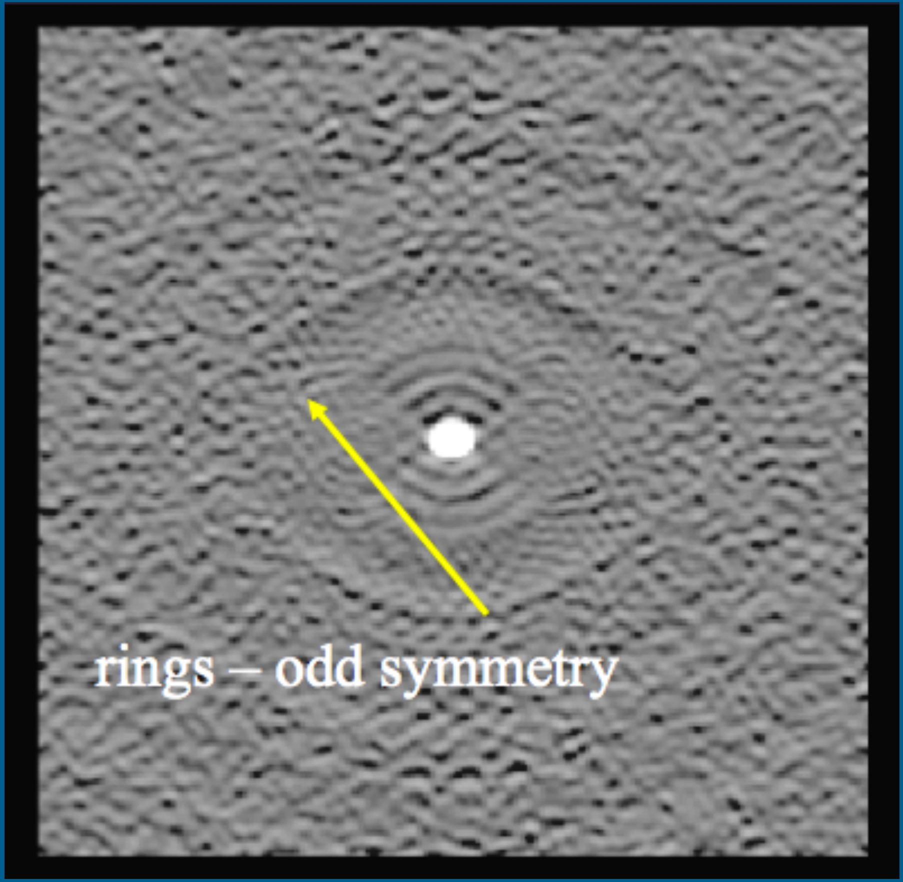
20% amplitude error for
one antenna at one time



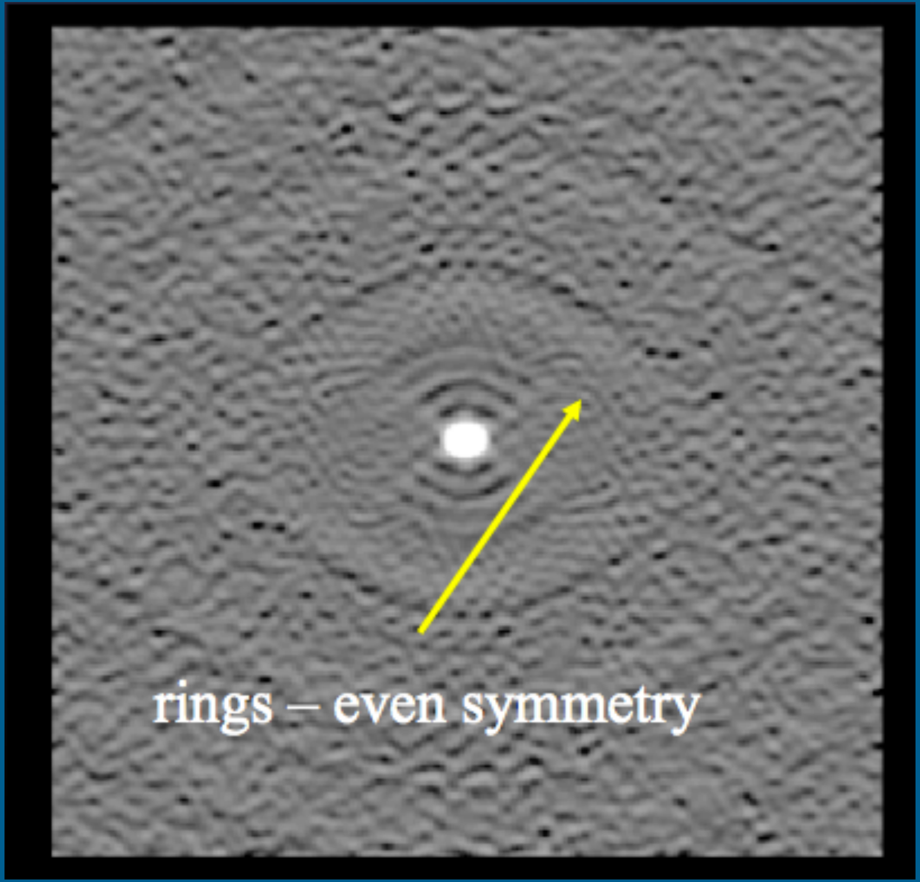
Images from Taylor lecture from 2014 NRAO synthesis imaging workshop

Recognising calibration errors in the image plane

10 deg phase error for one antenna at all times



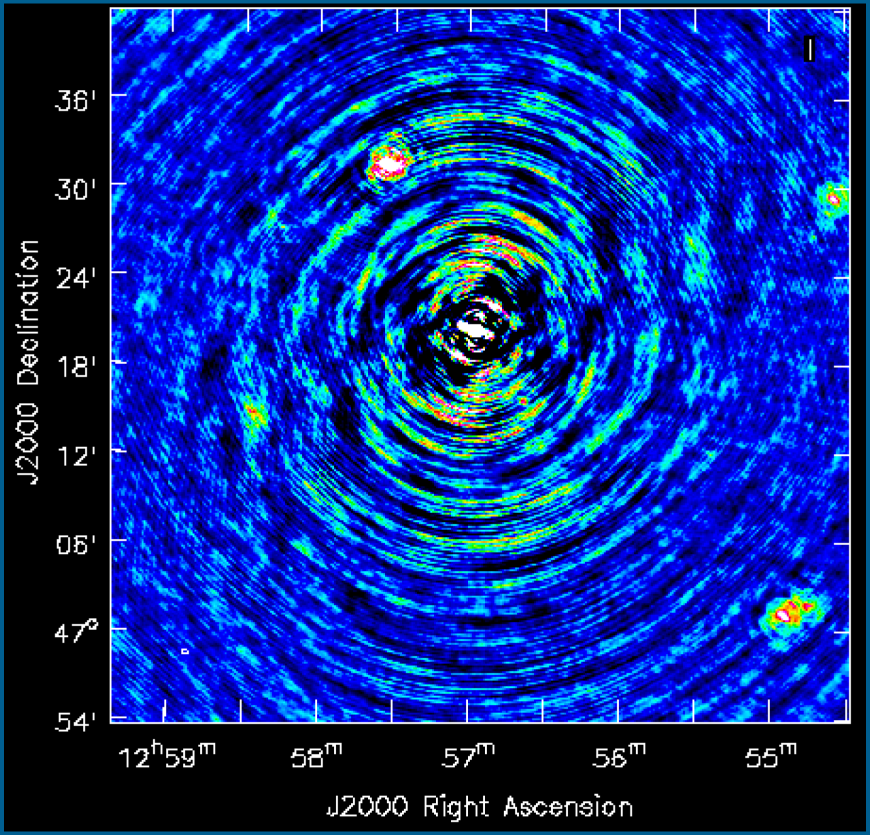
20% amplitude error for one antenna at all times

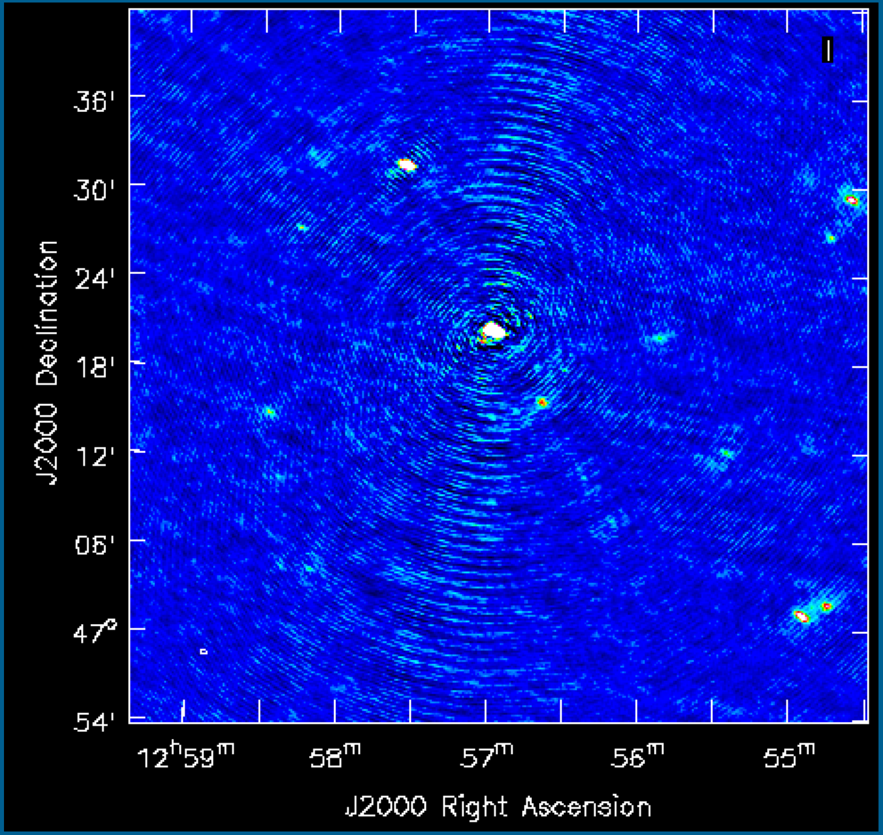


Images from Taylor lecture from 2014 NRAO synthesis imaging workshop

Recognising calibration errors in the image plane

A LOFAR example…





Images: T. Shimwell

Recognising imaging errors

- Deconvolution errors:
- Negative bowls around sources
  - Missing short spacings?

  (not usually an issue for LOFAR, plenty of short baselines)

  - Haven't CLEANed deep enough?

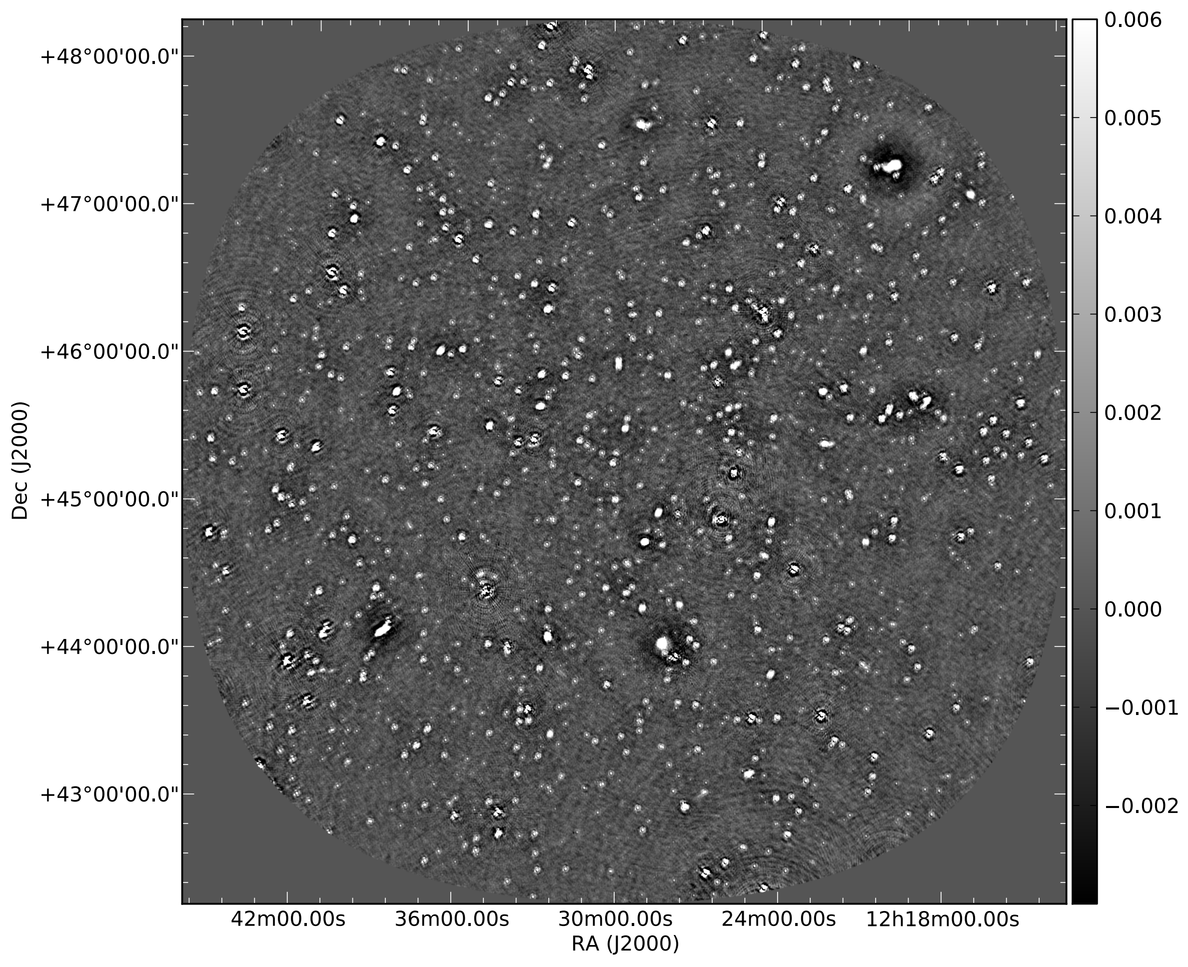
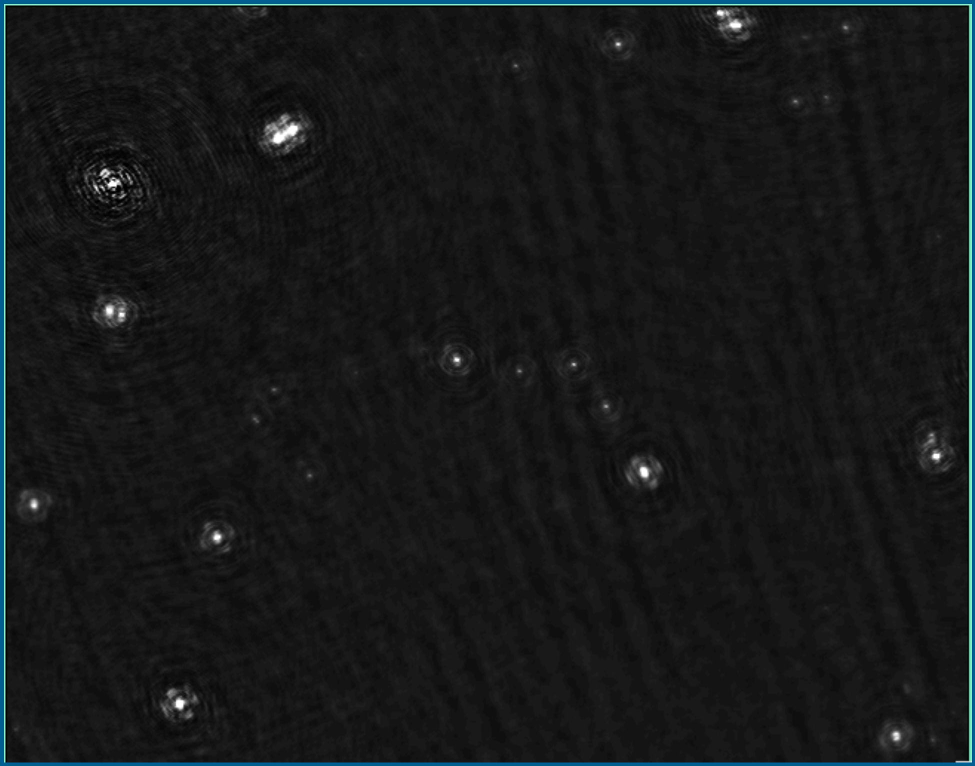
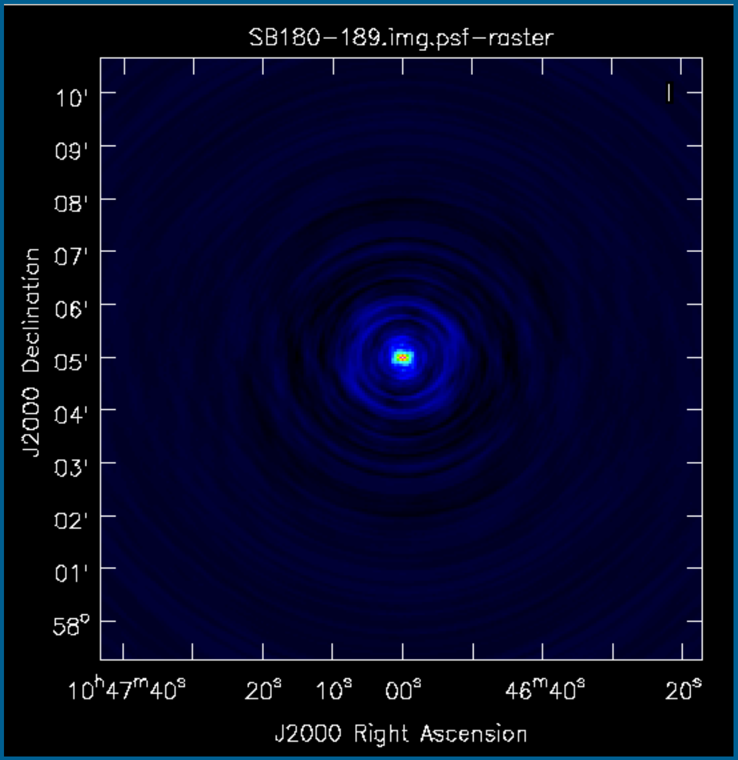


Image: T. Shimwell

Recognising imaging errors

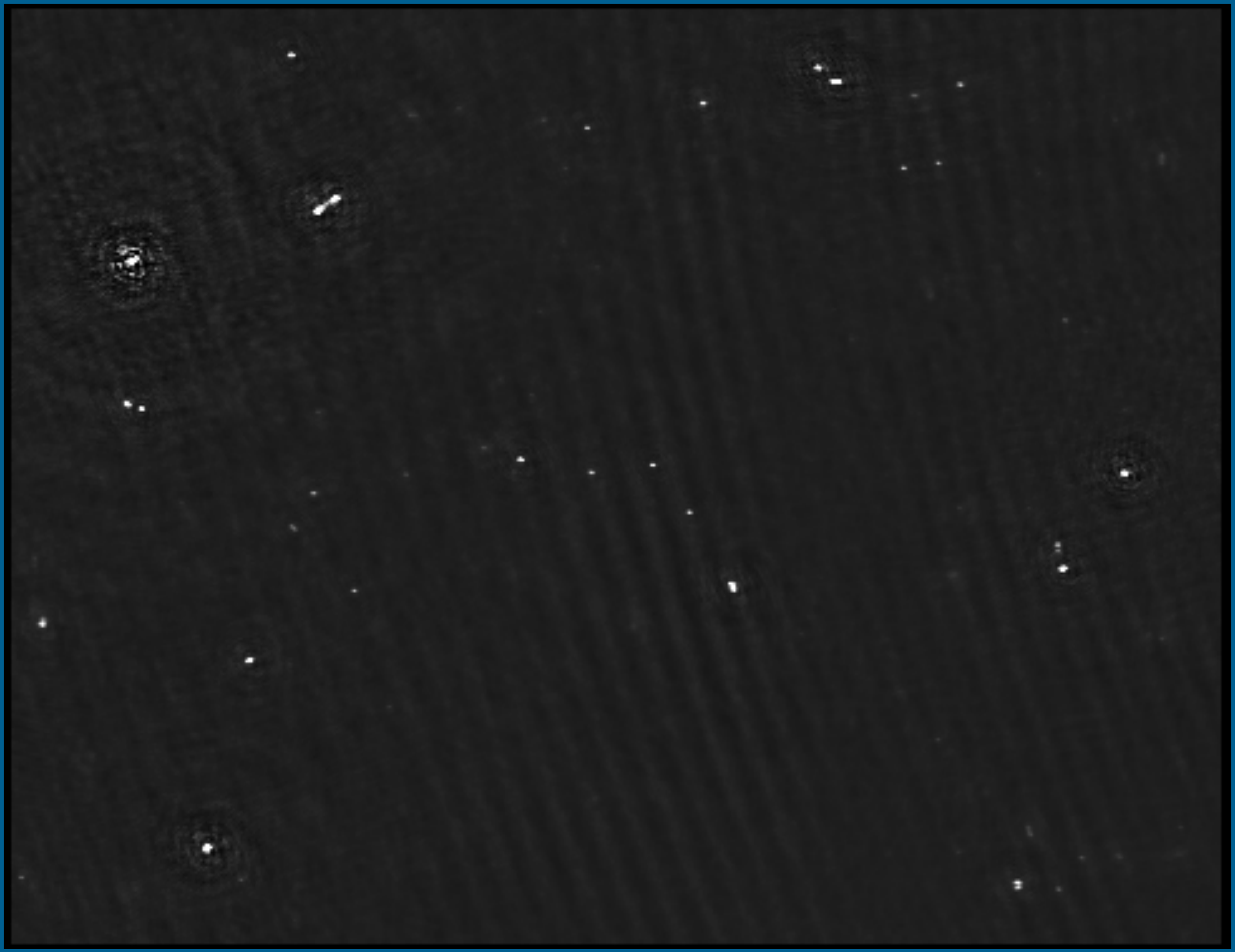




- Do your artifacts look similar to the psf (dirty beam)?
  - Need to clean deeper!
  - Use clean masks around sources to only clean where you need to

Recognising imaging errors

After using CLEAN masks:



Multiscale and mfs clean

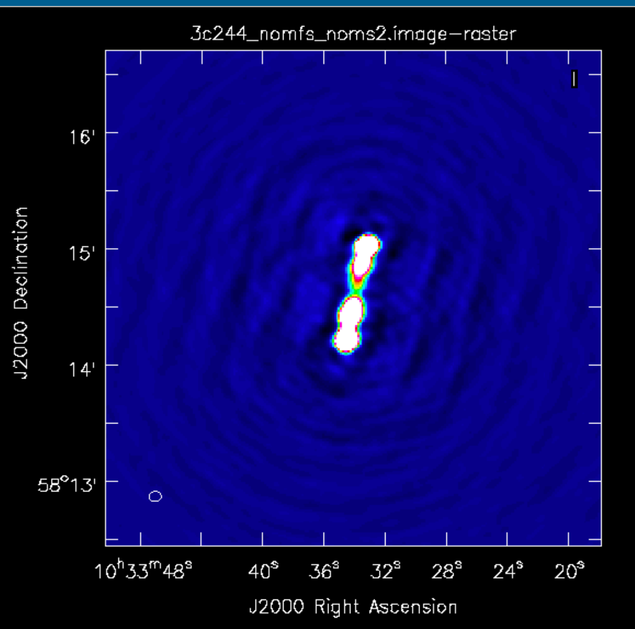
- The deconvolution algorithm you choose will also affects the image quality:
  - Imaging extended, diffuse emission:

    -> multiscale CLEAN
  - Combining many spectral channels:

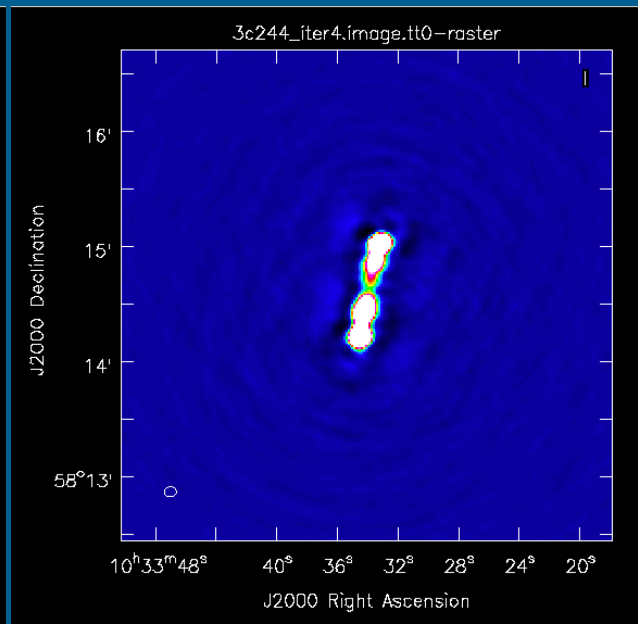
    -> mfs CLEAN (accounts for the spectral index)

Multiscale and mfs clean

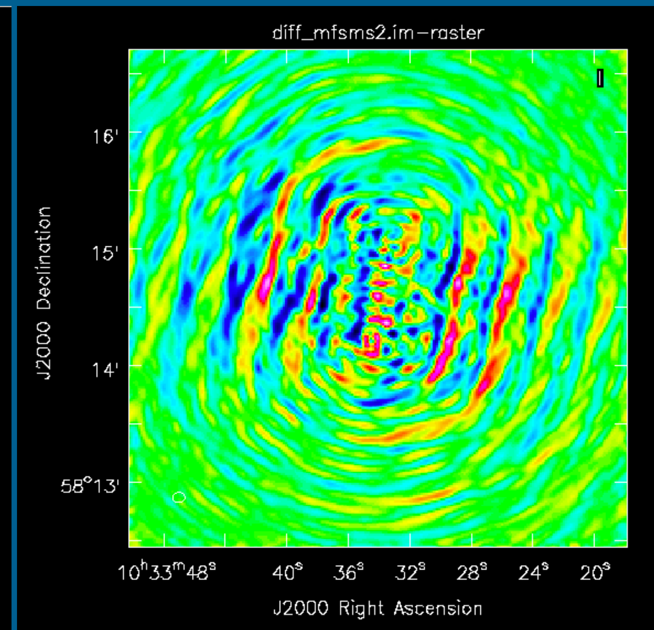
Normal CLEAN



ms-mfs CLEAN



Difference image

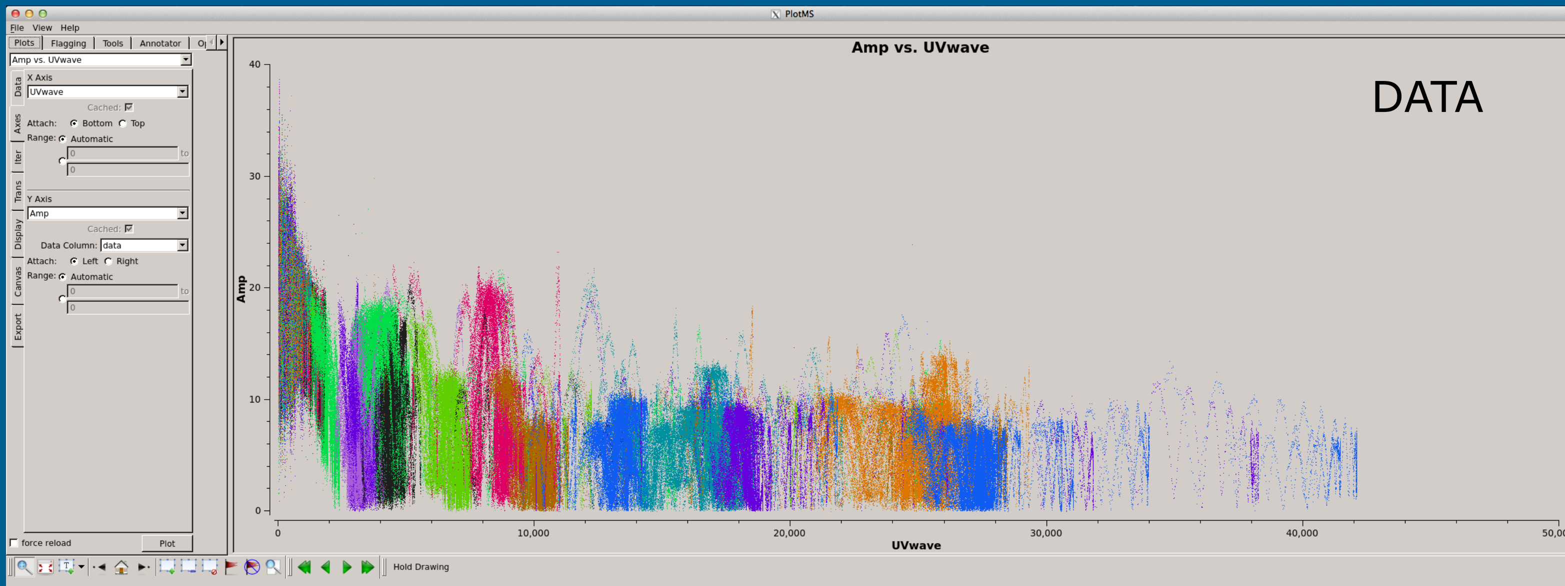


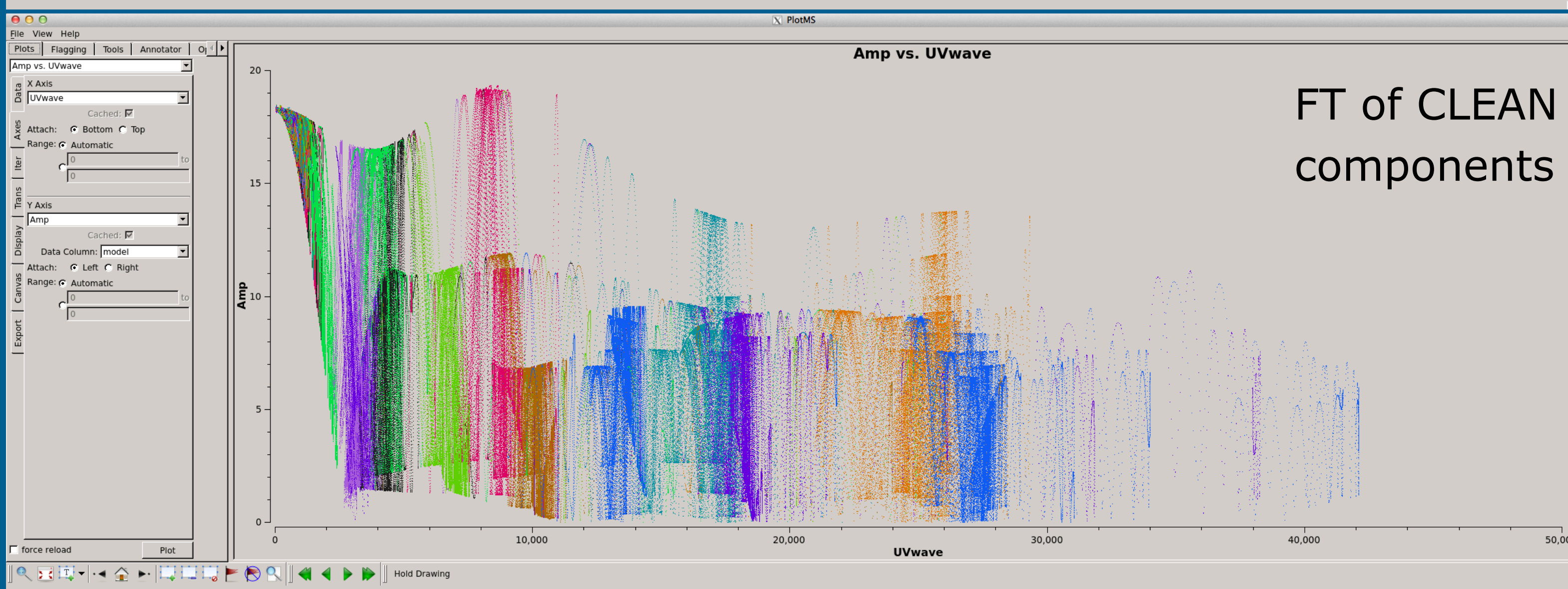
- BUT… multiscale + mfs clean computationally expensive!
- AWimager2.0 will have these functionalities, still being tested.

Does the model fit the data?

- Still have artifacts in the image that you can’t diagnose?
- The skymodel plays a very important role in calibrating and imaging the data
    - If you put a wrong model in you’ll get the wrong information out!
- Try simulating the skymodel to compare with the image
    - Can do this with the predict step in BBS
- OR from your image, FT the clean components into the MODEL column to compare the visibilities

Does the model fit the data?





Wide-field imaging effects

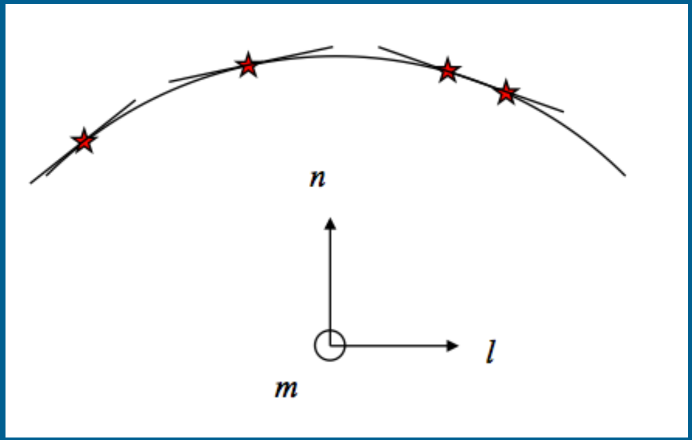
- Many of the difficulties associated with imaging LOFAR data are due to the large field of view.
- Extra things to worry about for wide-field imaging:
    - includes non-coplanar array (w-term) effects
    - Primary Beam changes with time and frequency
    - Also have wide bandwidths – need to be careful of bandwidth and time-averaging smearing
    - Direction dependent effects (looking through different patches of ionosphere – particularly important at low frequencies!
    - Requires enormous computing power
    - All of these issues will limit the dynamic range and image fidelity if not accounted for properly!

W-projection effects

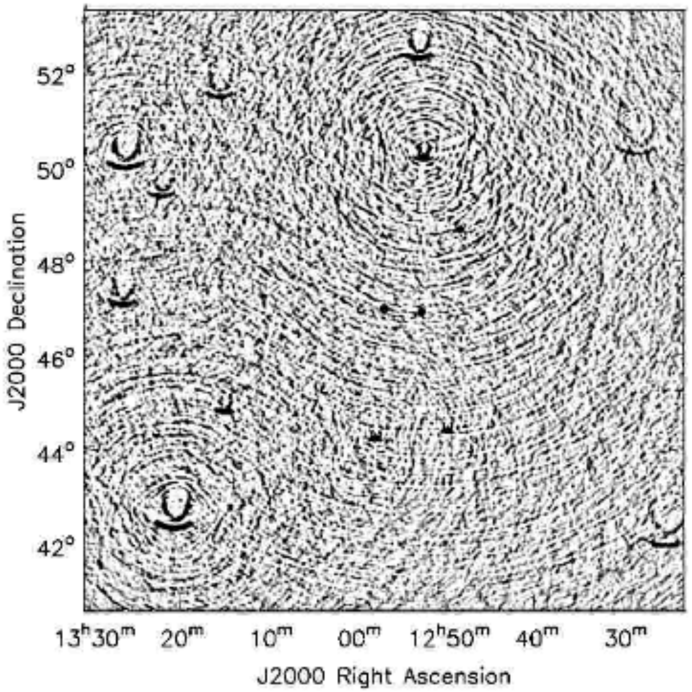
- The w-term describes the deviation from a perfect plane:

$$V(u,v,w) = \int\int I(l,m)\, e^{-2\pi i[ul+vm+\boxed{w(\sqrt{1-l^2-m^2}-1)}]}\, dl\, dm$$

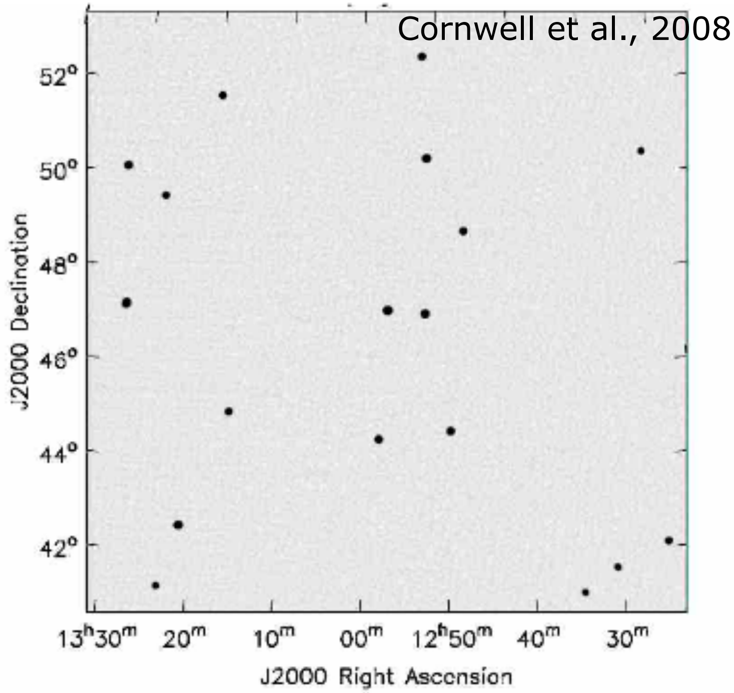
- When imaging large fields, 2-d approximation is not valid (i.e. can no longer assume the sky is flat)
- Imaging algorithms exist to take the w-term into account
  - LOFAR uses w-projection algorithm -> projects data onto w=0 plane



W-projection effects



(a) standard Fourier transform



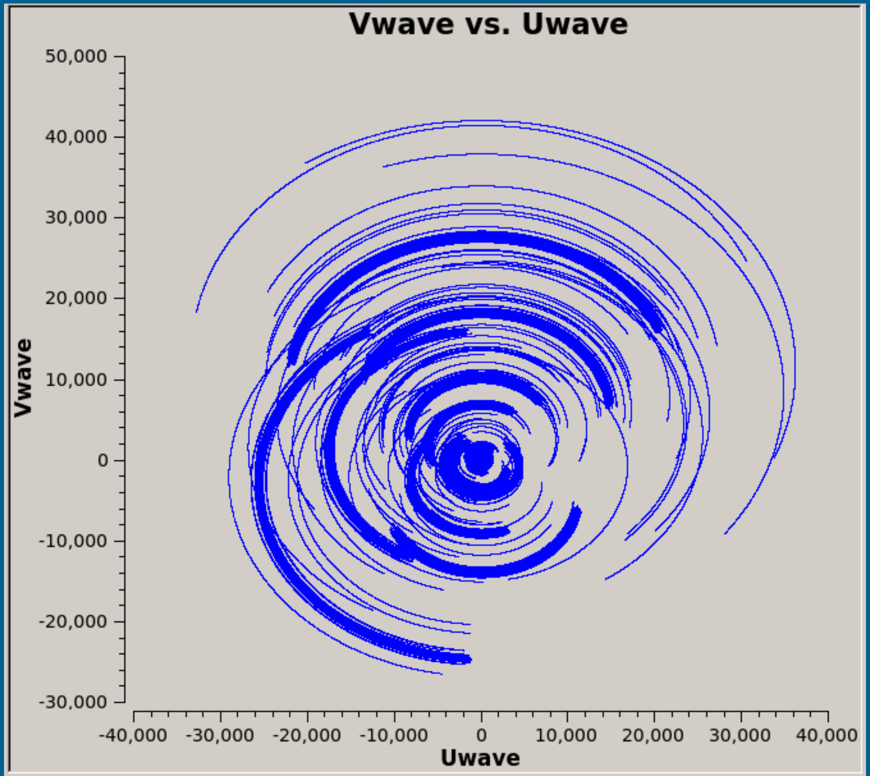
(c) W-projection (128 $\tilde{G}_T$ planes)

- In addition, LOFAR beam is also constantly changing -> need a-projection
  - A-projection and w-projection done in Awimager (see Bas' talk tomorrow)

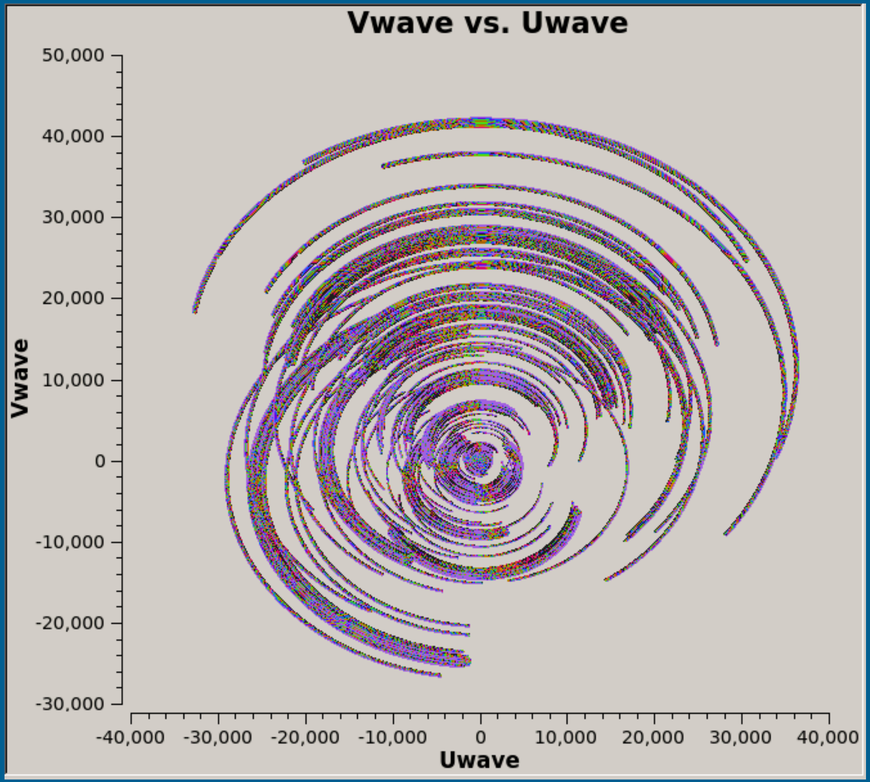
Imaging with wide-bandwidths

Let's look at the u,v coverage of LOFAR for different bandwidths:

1 subband

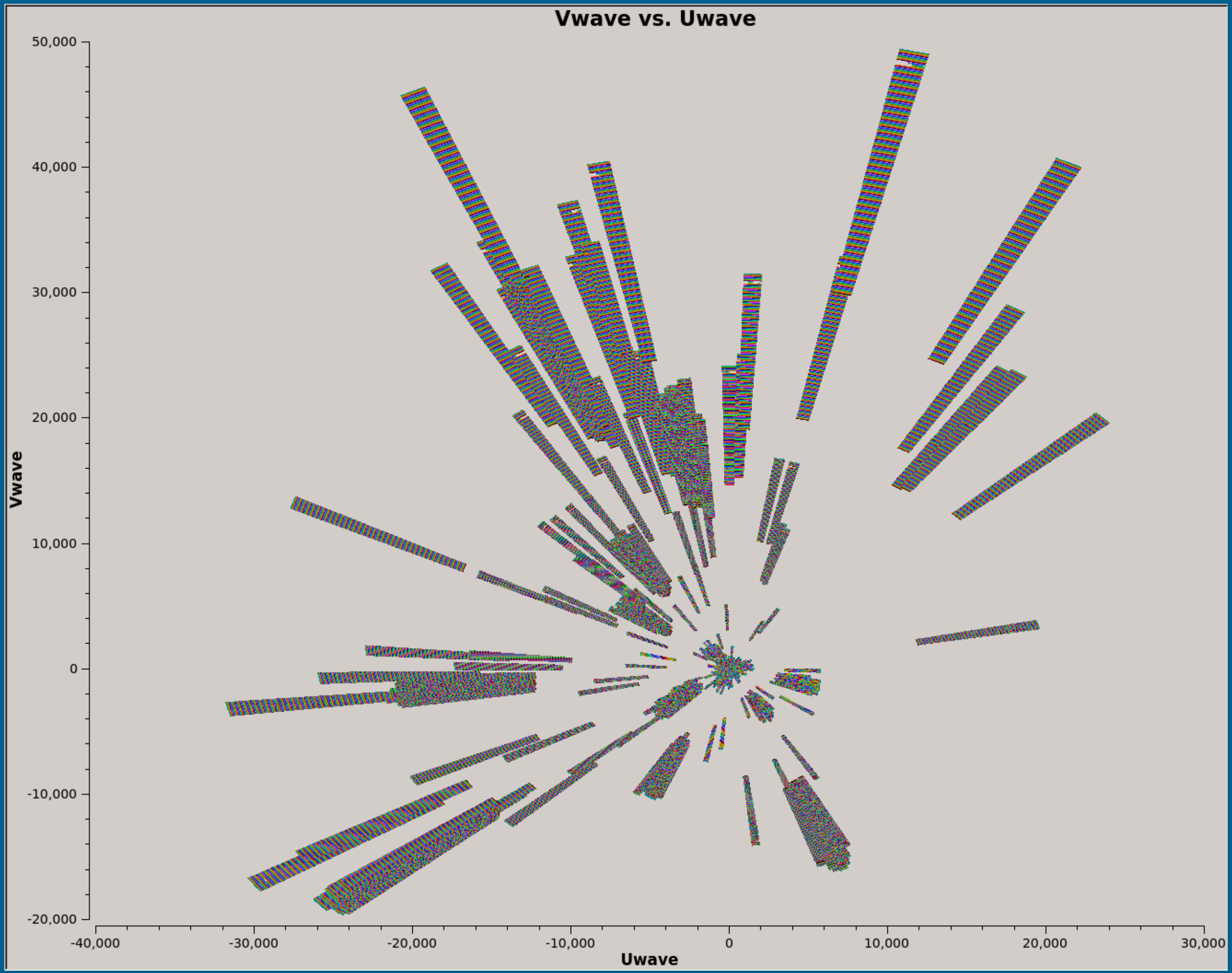


10 subbands (2 MHz bandwidth)



Imaging with wide-bandwidths

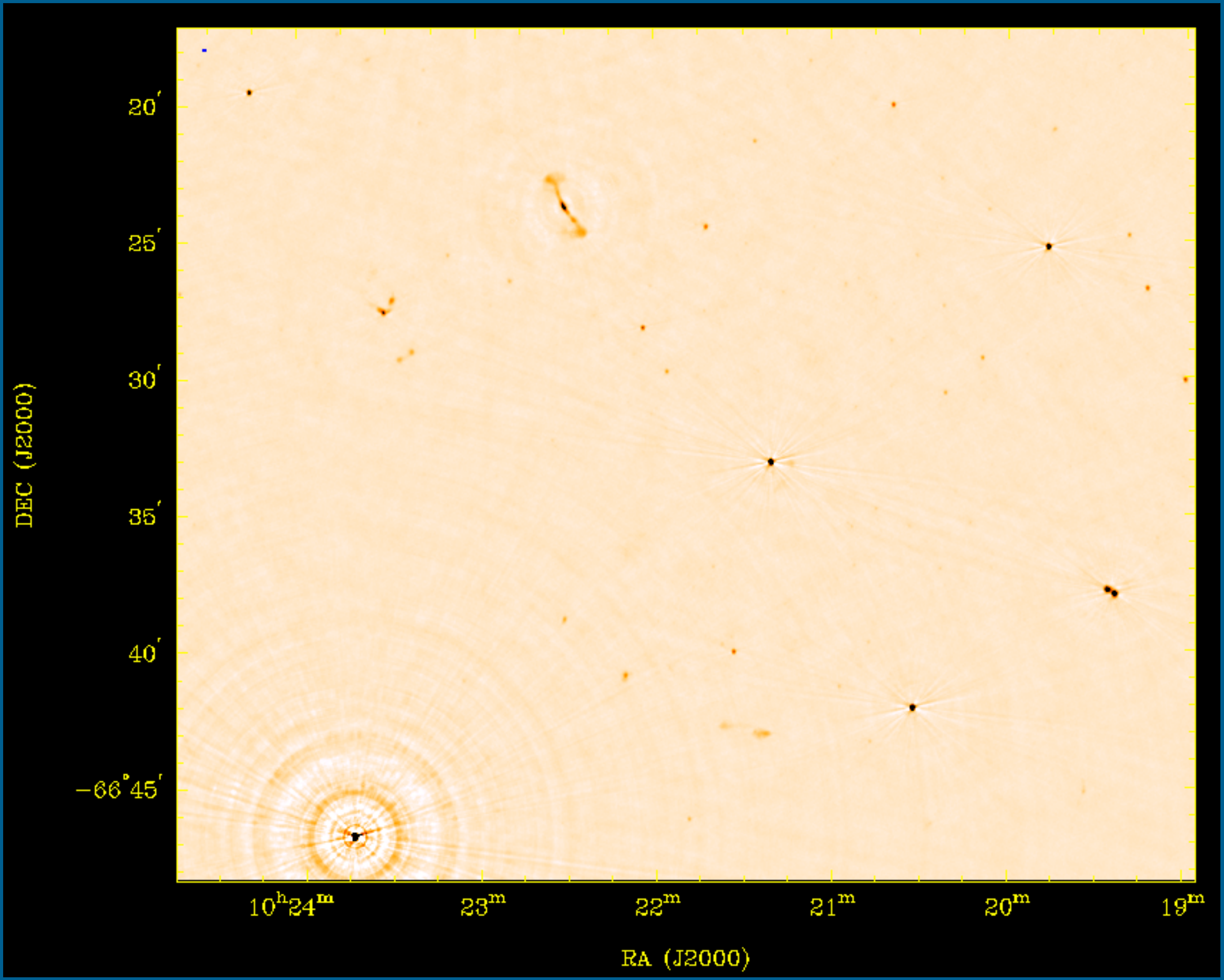
366 subbands (70 MHz bandwidth) – 10 mins of data



Bandwidth smearing and time-smearing

- When making an image, the visibilities are gridded as if they were monochromatic (i.e. all same frequency)
  - This means that if we average too much, sources will be smeared in the radial direction
  - This effect gets larger the further the sources are from the phase centre

Bandwidth smearing and time-smearing



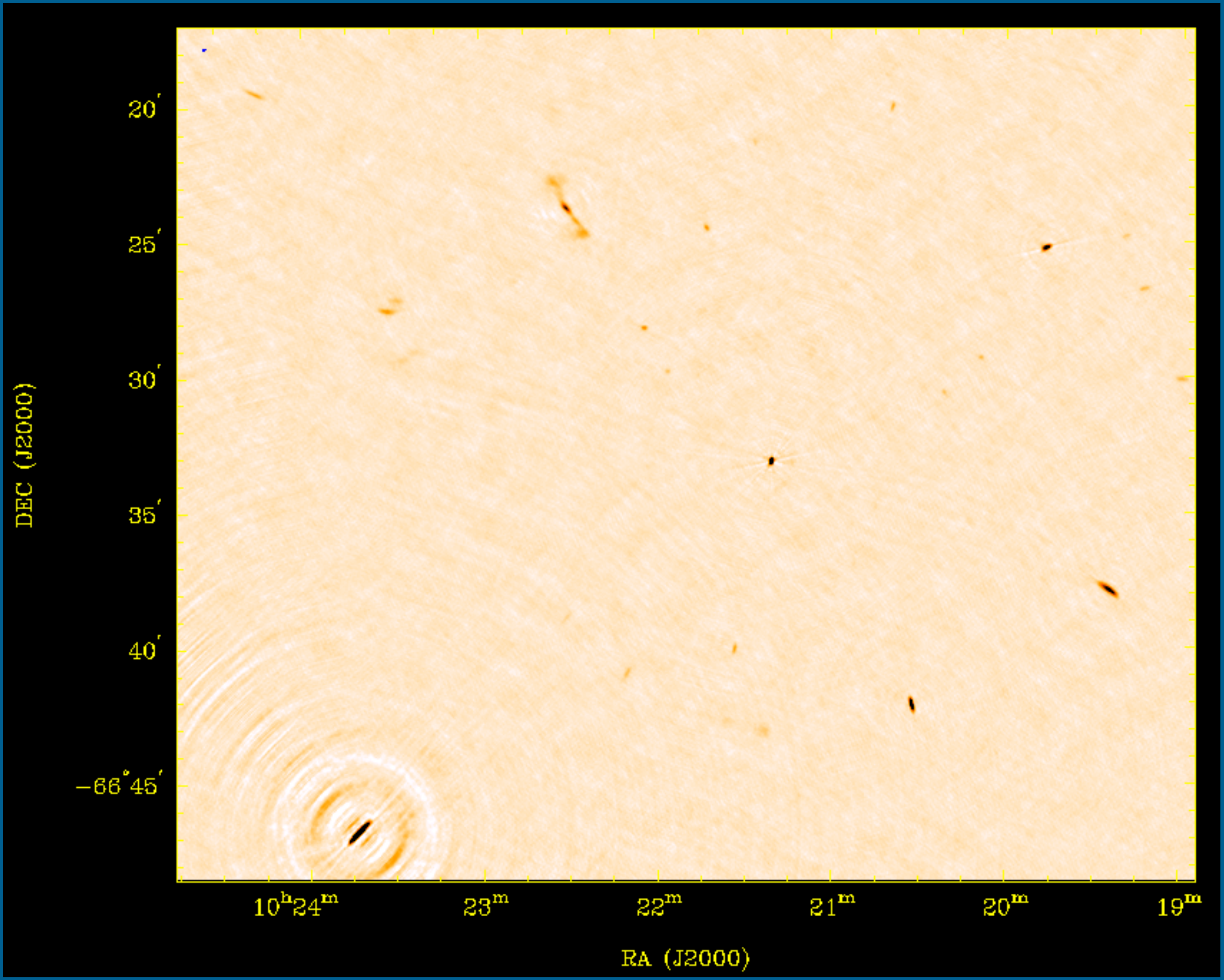
ATCA image

2048 channel bandwidth (~2 GHz)

2048 x 1 MHz channels

Image: J. Stevens

Bandwidth smearing and time-smearing



ATCA image

2048 channel bandwidth (~2 GHz)

32 x 64 MHz channels

Image: J. Stevens

Bandwidth smearing and time-smearing

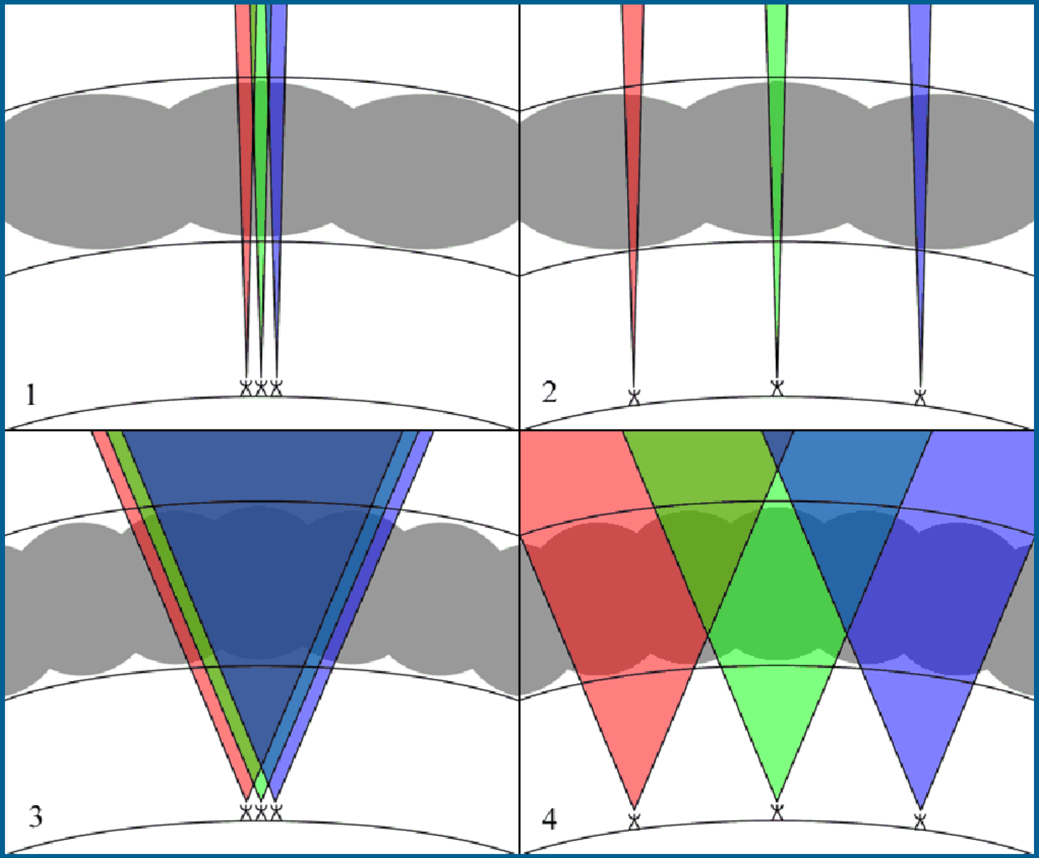
- The same thing happens if you average too heavily in time, but instead the sources are smeared in the tangential direction

- Bandwidth smearing and time-averaging smearing aren't unique to wide-field imaging, but effects become more pronounced as you move away from the phase centre

- LOFAR's large field of view means we have to be careful of both these effects
  - Need small channel widths (to avoid bandwidth smearing)
  - Need rapid correlator dumps (to avoid time smearing)

    -> this is why LOFAR data rates are so huge!

Direction dependent effects



Intema et al., 2009

- Each antenna looks through different patch of ionosphere
- Phases change across the antenna aperture
- Need to calibrate different directions separately

  -> direction-dependent calibration

Direction dependent effects

After direction-independent calibration and selfcal:

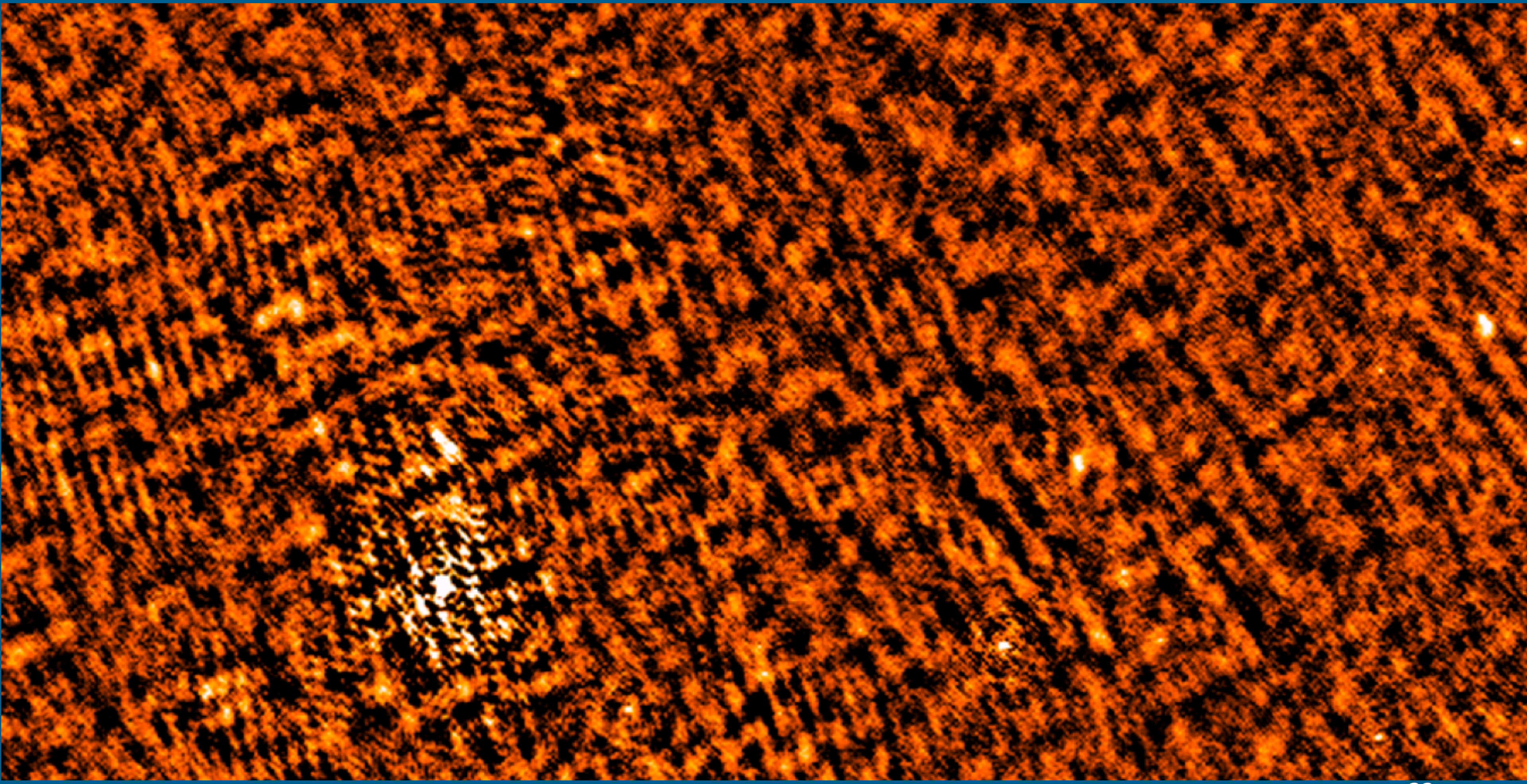
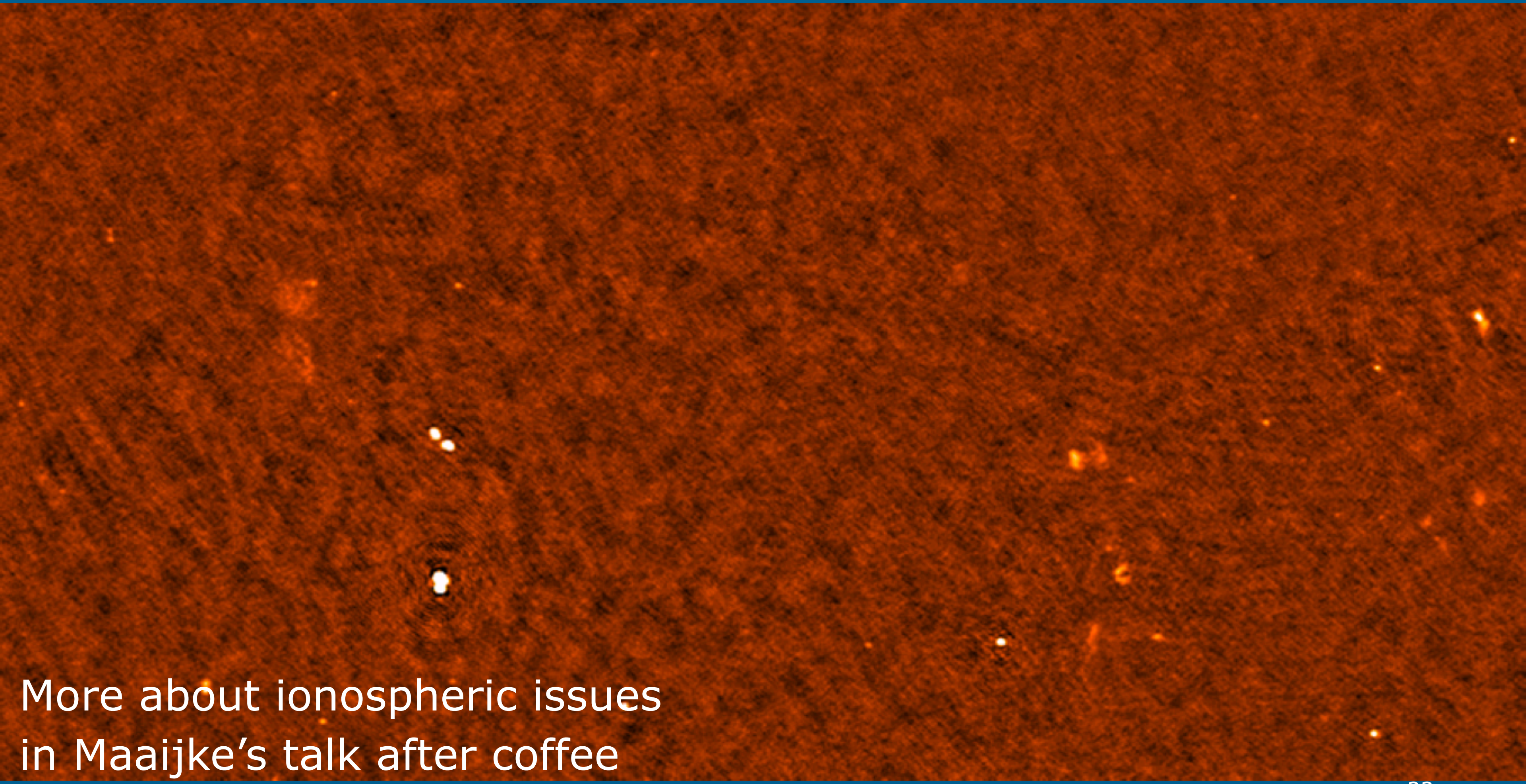


Image credit: R. van Weeren

Direction dependent effects

After direction-dependent calibration:

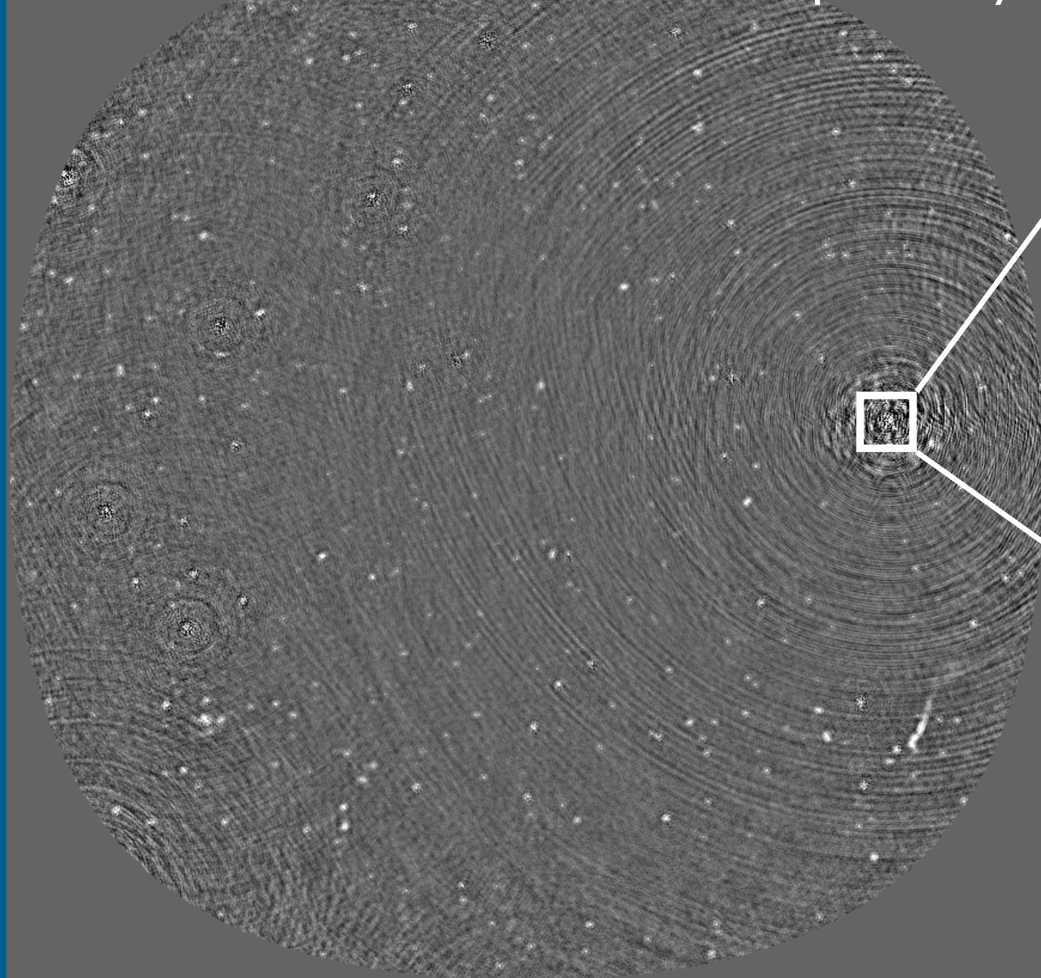


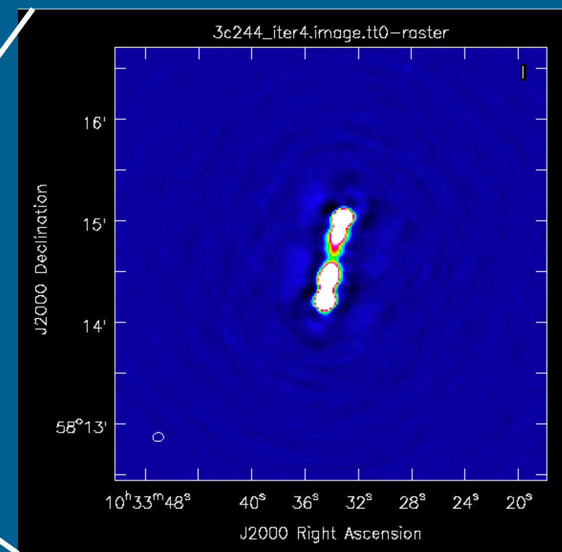
More about ionospheric issues
in Maaijke’s talk after coffee

Image credit: R. van Weeren

Bright sources in the field

- With a large field of view there's a good chance a bright source could be in or near the primary beam





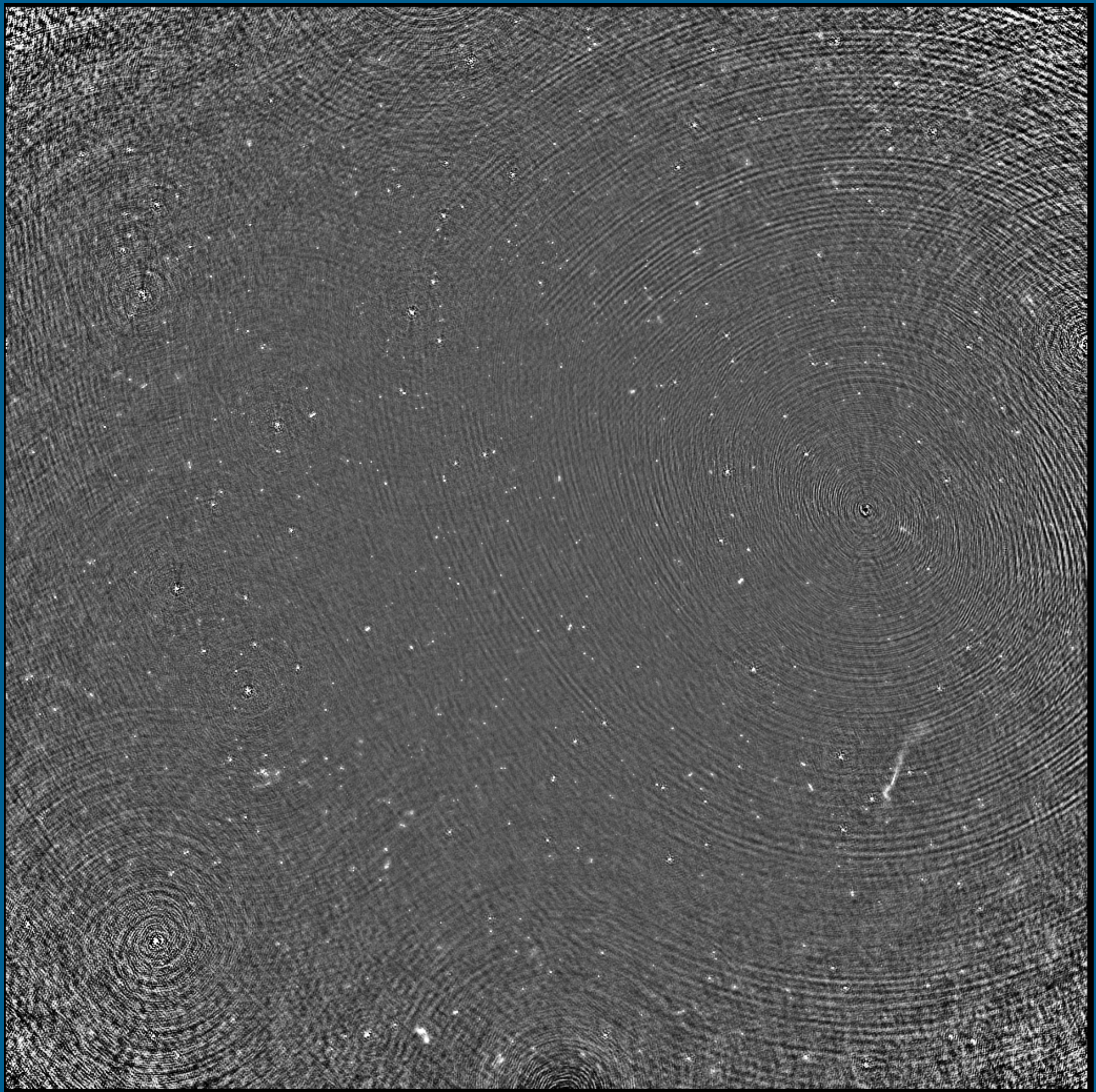
3C244.1
~35 Jy, 2 degrees from the pointing centre

Aside: Peeling 101

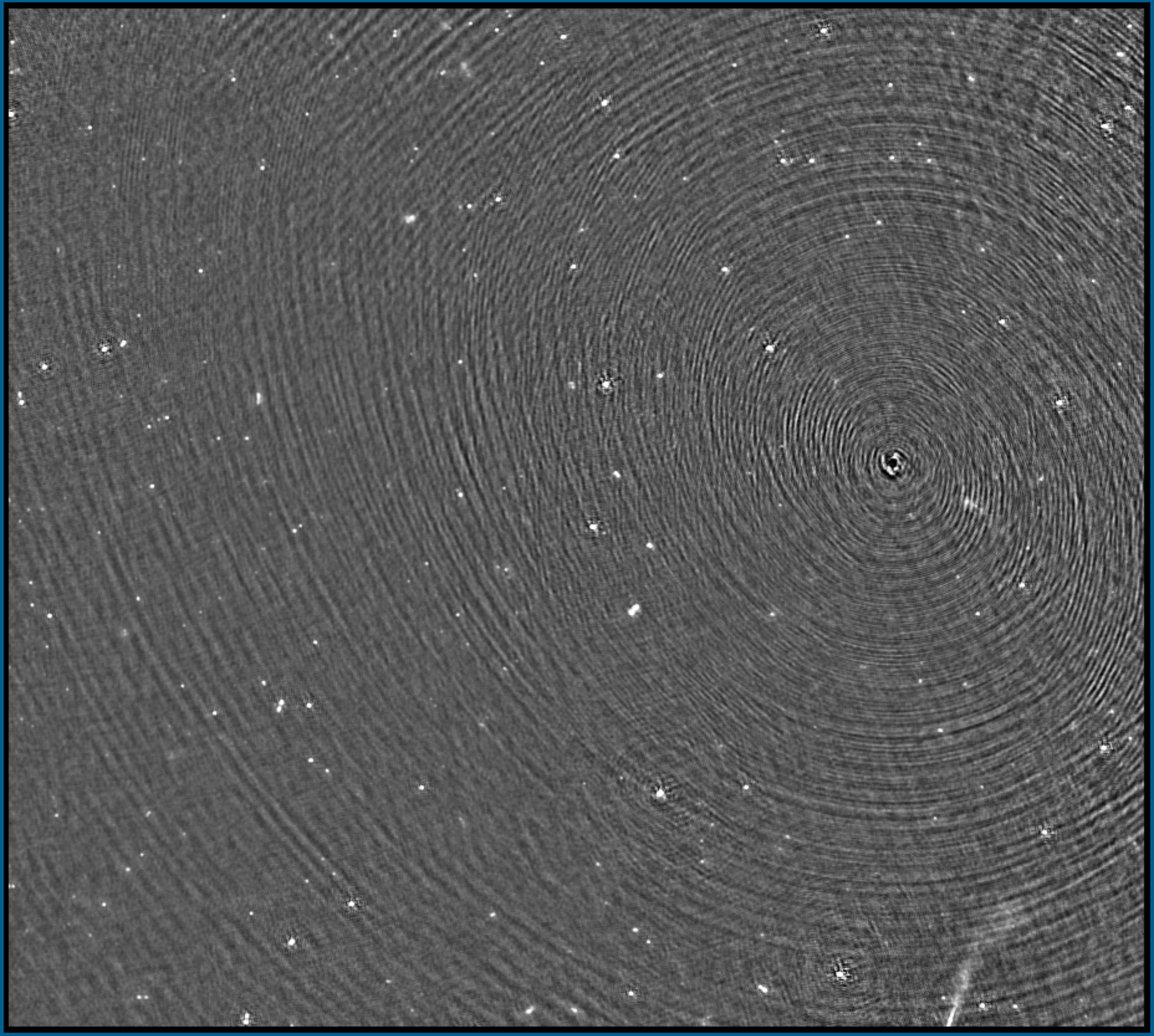
- To peel sources properly need to start with data that has been calibrated as best it can be (and also have a good skymodel)
  - 1. Subtract all other sources in the field
  - 2. Direction-dependent calibration towards the bright source
  - 3. Subtract bright source
  - 4. Add back all other sources
  - 5. Another round of phase calibration (optional)

Bright sources in the field

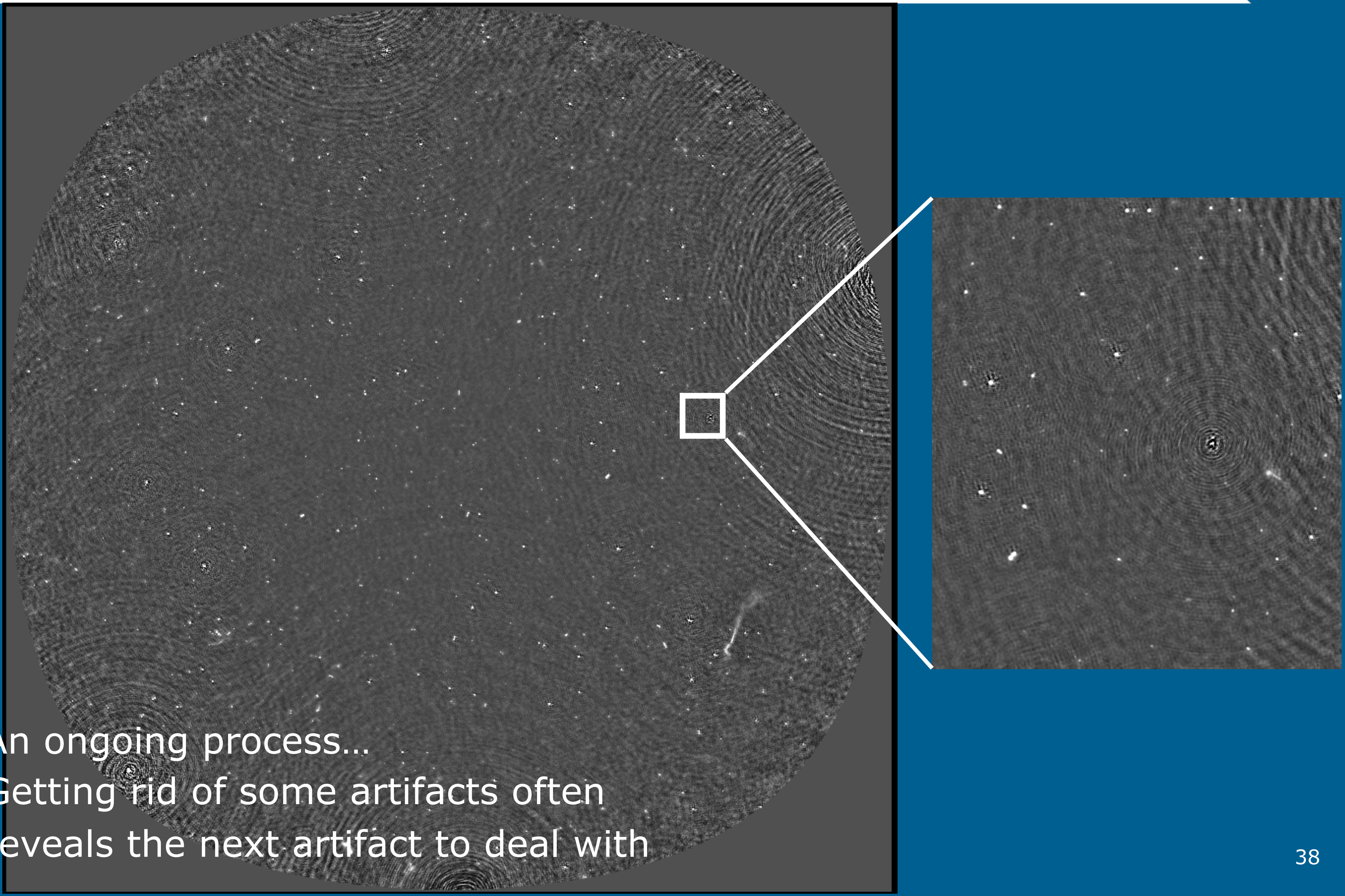
- If the data isn't calibrated properly when peeling artifacts will still remain



Bright sources in the field



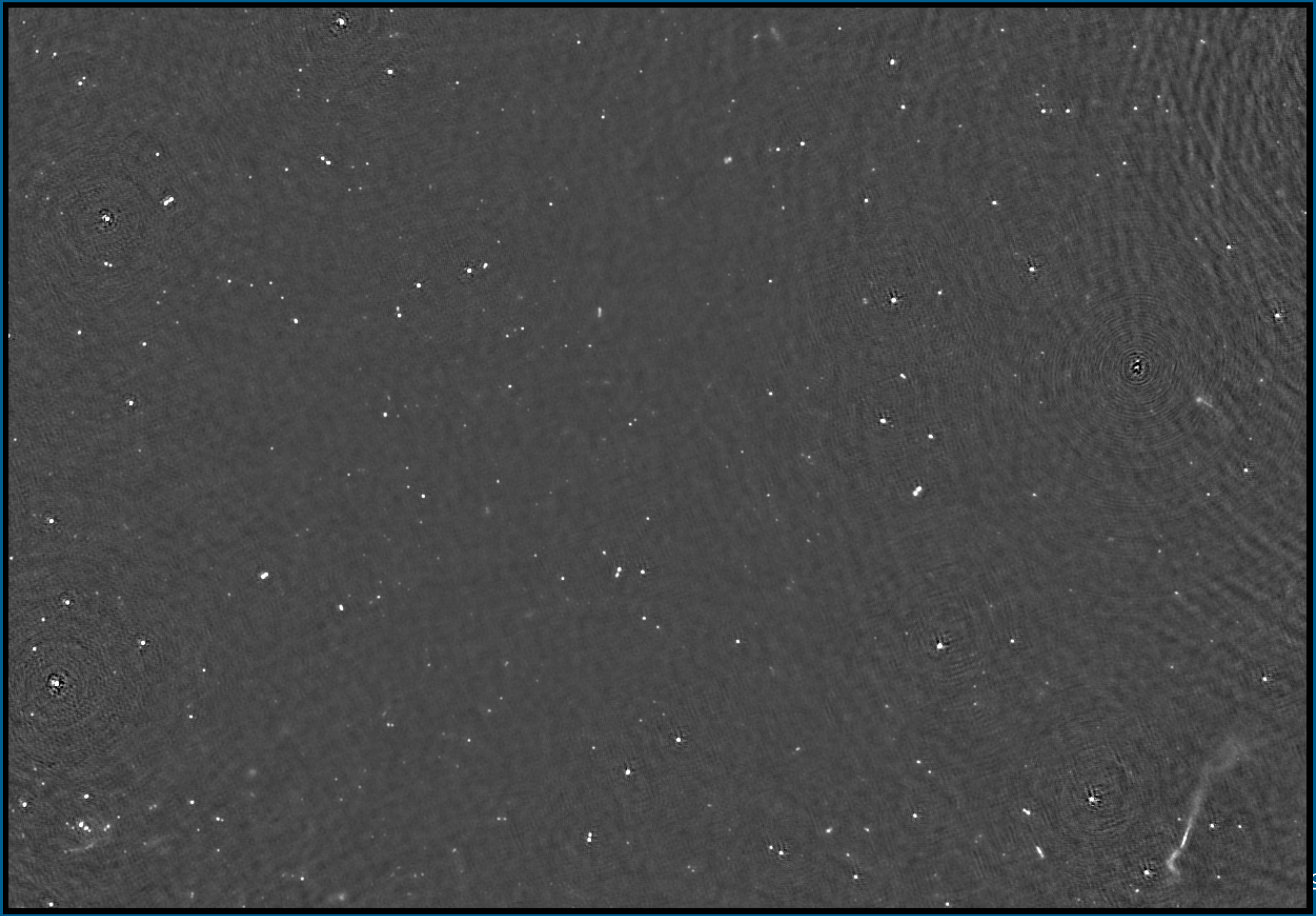
Bright sources in the field



An ongoing process…

Getting rid of some artifacts often reveals the next artifact to deal with

Once you've checked all these things you (hopefully) have a perfect image!



Once you've checked all these things you (hopefully) have a perfect image!

Once you've checked all these things you (hopefully) have a perfect image!

…almost

Can you do science with it?

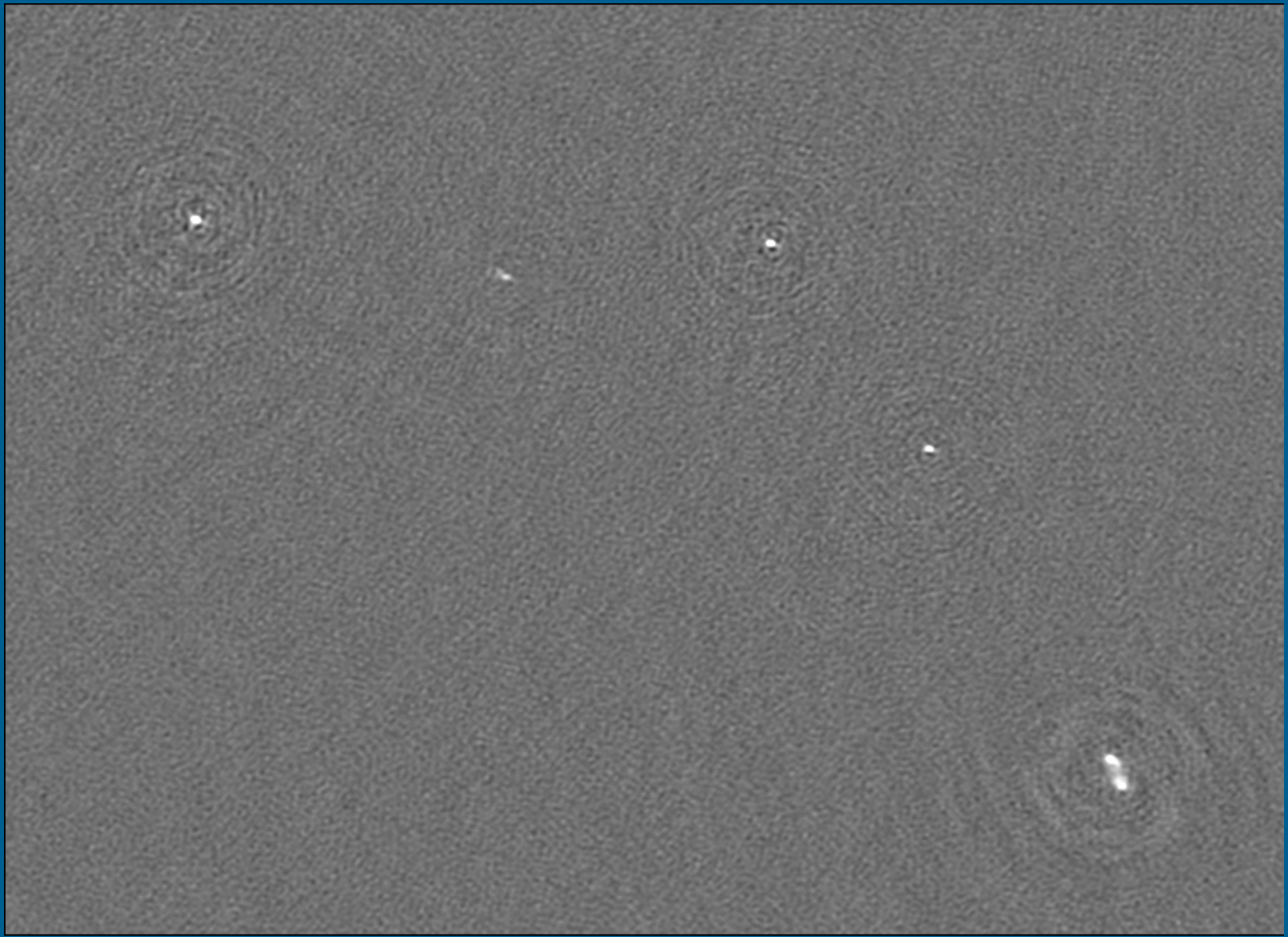
- If your fluxes or positions are wrong then it is useless!

- Check fluxes by comparing with other surveys

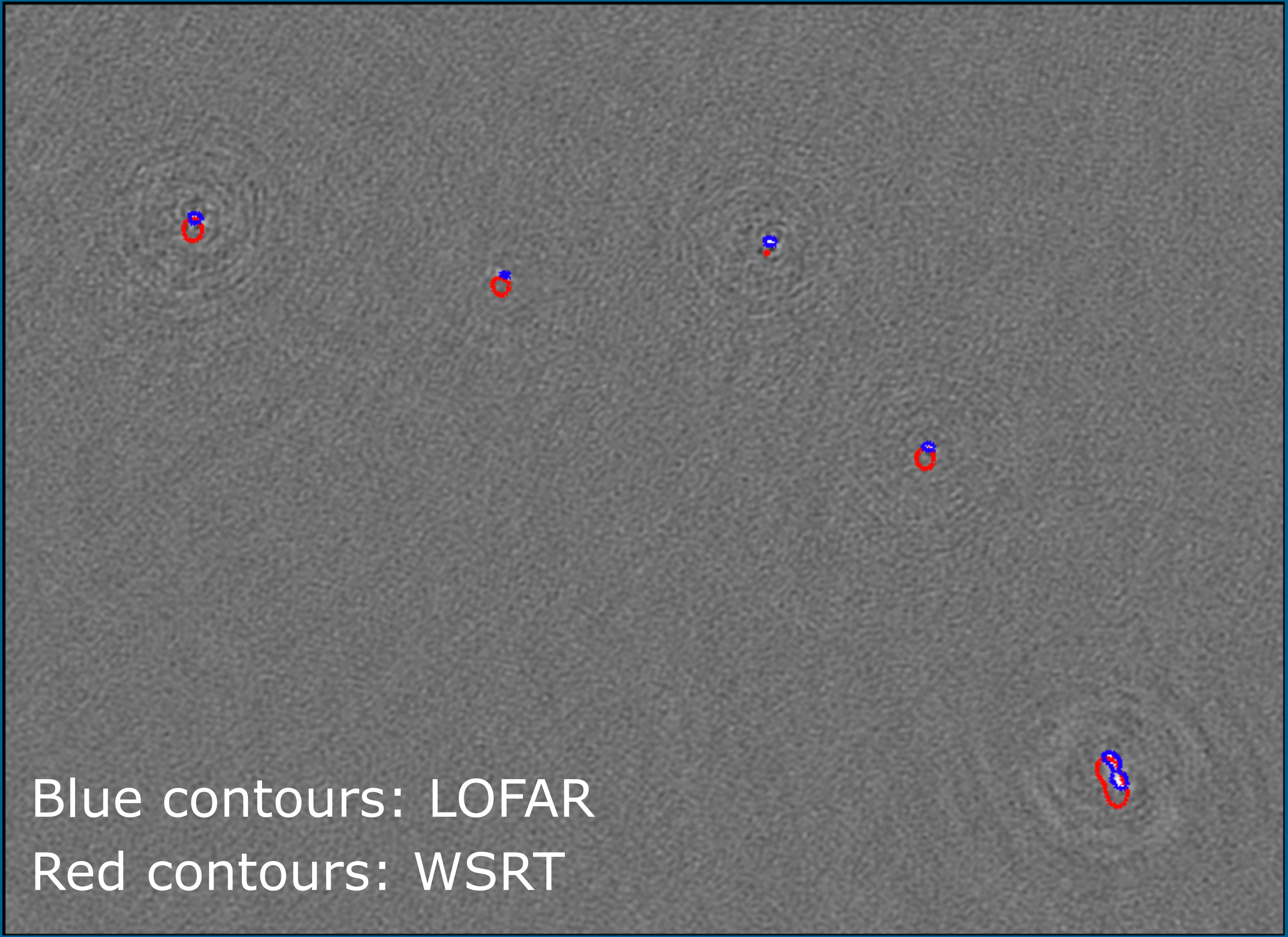
  e.g. 7C at 151 MHz, VLSS at 74 MHz, MSSS

  - Careful of the different resolutions!
- Check positions (especially if doing selfcal!)
  - Overlays/contour plots with whatever other data you can find
- Other checks:
  - does the noise go down as expected when combining in either time or frequency?
  - can you extract the number of sources you expect?

Can you do science with it?



Can you do science with it?



Summary

- Errors obey Fourier transform relation – use this to your advantage!

- Image artifacts can either come from bad u,v data which needs to be flagged, OR due to the deconvolution algorithm used -> choose wisely

- If still in doubt, try FT back into visibility space to compare

  -> make sure you have the best skymodel possible

Summary

- Beware of widefield imaging effects:
  - Need to use W-projection and A-projection
  - Be careful not to average too heavily, can lead to bandwidth or time-smearing
  - Direction dependent effects
  - Are there any bright sources in the field you need to peel?

- Can you do science with it?
  - Check the flux scale and source positions!

Tips for getting a good image

- First flag obviously bad data in the u,v plane
- Make large, low resolution image first
  - Identify potential issues (i.e. bright sources in the field)
  - First check of flux scale (7C/VLSS good catalogues to crossmatch with, in the future MSSS)
  - Check that you have the best input skymodel possible
- Start with a subset of data to reduce manually and work out the best strategy

  -> once you've figured out the best way to reduce your data can write a script to do the rest, but remember to still check the data after different steps!

References

- VLA white book – Chapters 15, 18, 19
- Lectures from previous synthesis imaging schools
    - ERIS 2013 (http://www.astron.nl/eris2013/lectures.php)
    - NRAO synthesis imaging workshop 2014 (https://science.nrao.edu/science/meetings/2014/14th-synthesis-imaging-workshop/lectures)
    - CSIRO radio astronomy school (http://www.atnf.csiro.au/research/radio-school/2014/index.html)
- Papers on w-projection and a-projection (Cornwell+ 2008; Bhatnagar+ 2008,2013; Offringa+ 2014)
- Papers on direction-dependent calibration (Intema+ 2009,2014)