Imaging and self-calibration

DARA Zambia 2018

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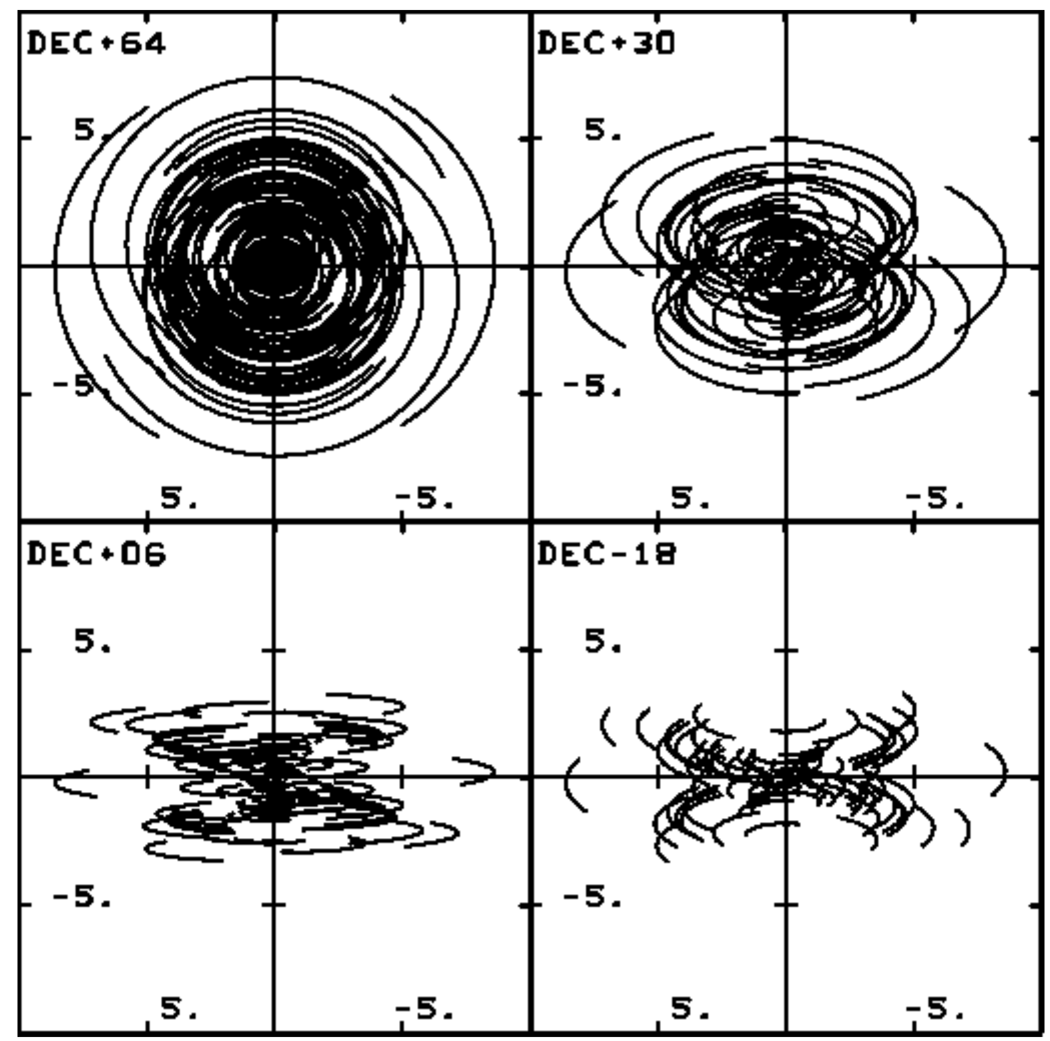
Image fidelity limitations

- **Incomplete u-v coverage** -> we have only sampled part of the u-v plane
- **Atmospheric problems** -> phase corruption, frequency-dependent
    - Can by corrected by phase referencing
    - Can be corrected by self-calibration if object is bright enough

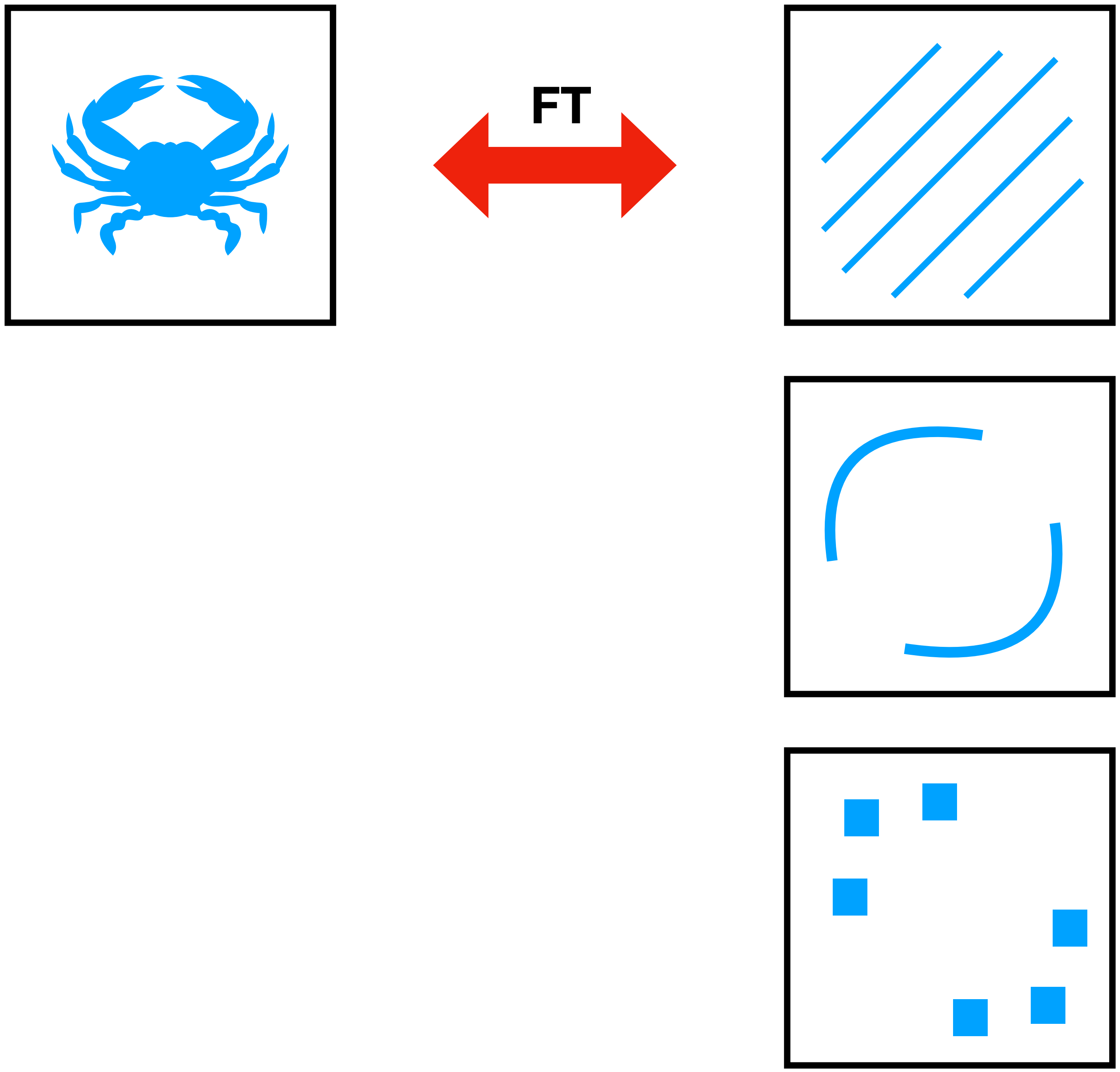
u-v limitations

- n telescopes -> ½ n(n-1) baselines
- Outer value of u-v limits resolution
- Inner value of u-v limits sensitivity to large-scale structures
- Density of u-v plane limits image fidelity



http://www.vlba.nrao.edu/astro/obstatus/1997-05-19/img24.gif

Image reconstruction



FT of source

Sampled on u-v tracks

Convolved with sampling fn

(+ interpolated onto a grid)

Image reconstruction

True source

'dirty beam'

'dirty map'

$$I'(l,m) = I(l,m) * S(l,m)$$

$\updownarrow$ FT $\qquad \updownarrow$ FT $\qquad \updownarrow$ FT

sampling fn

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

We measured this

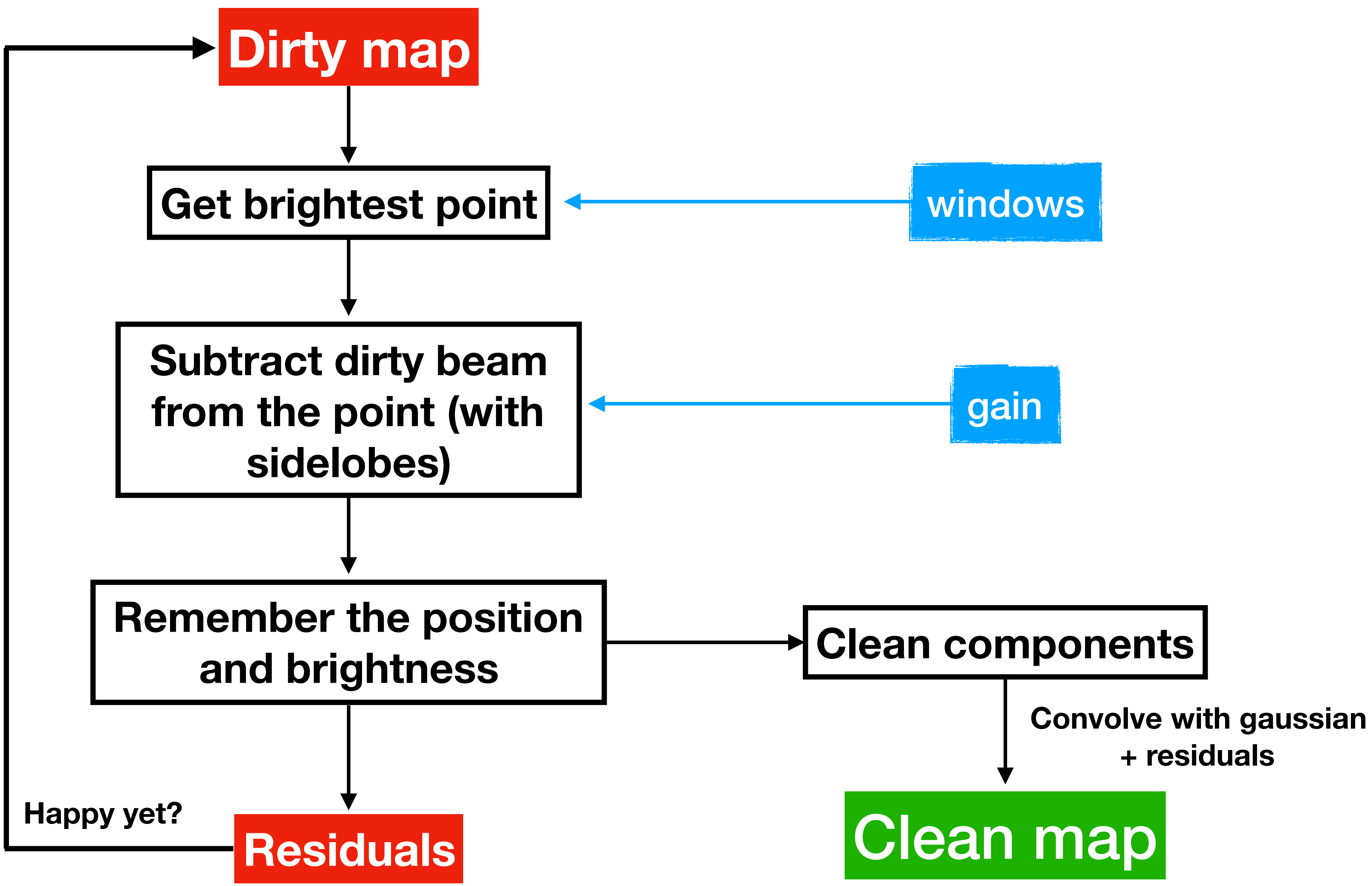
Deconvolution

- We have $I'(l,m)$, we need $I(l,m)$
- Main source of corruption is $S(u,v)$
- Dirty map assumes visibilities at unsampled points is zero
- Need to interpolate across unsampled points on u-v plane

Deconvolution

- Problem is to find a solution from the infinite possible maps that could be consistent with our data
- Need extra info on constraints…
- We use CLEAN algorithm: assume the sky can be represented by a number of point sources

Högbom CLEAN



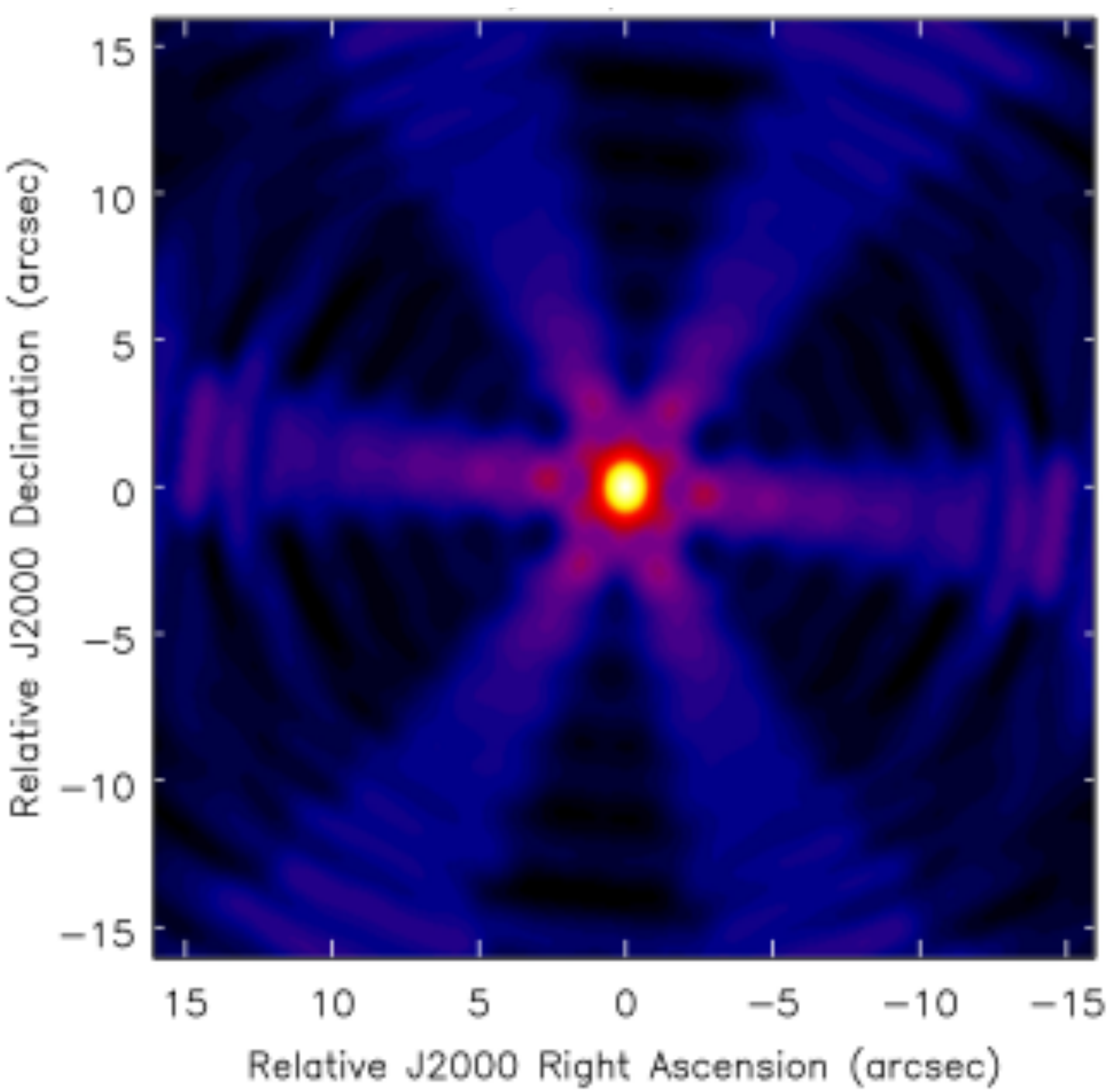
Clark CLEAN

- Algorithm has major and minor cycles
- Minor cycles loop and do subtractions from dirty map
- Major cycles do FT and subtract in u-v plane
- Done in u-v plane so no deconvolution

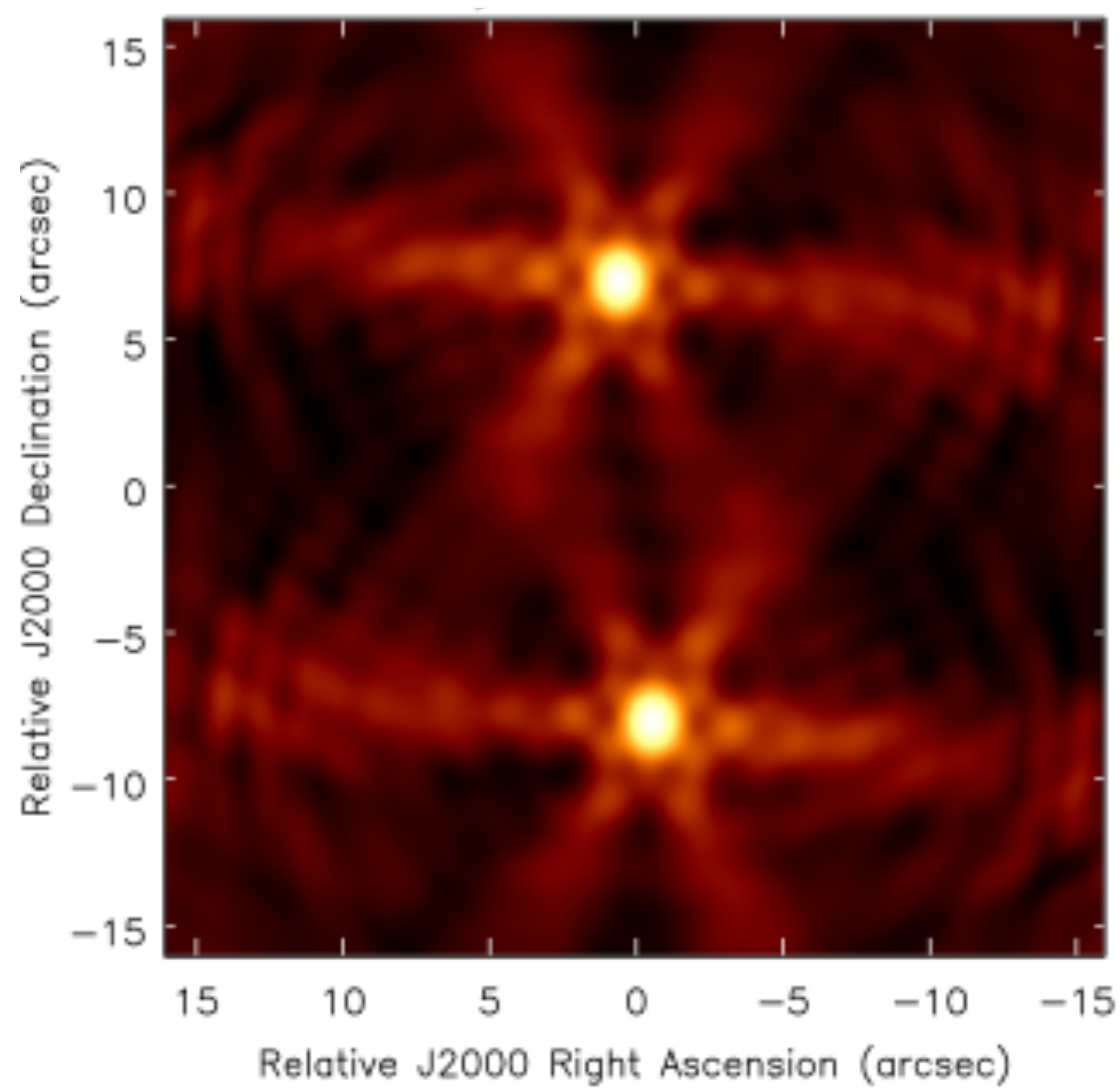
Deconvolution

JVLA simulation, 2hr observation targeting two 0.1 Jy point sources + some phase corruption

Dirty beam



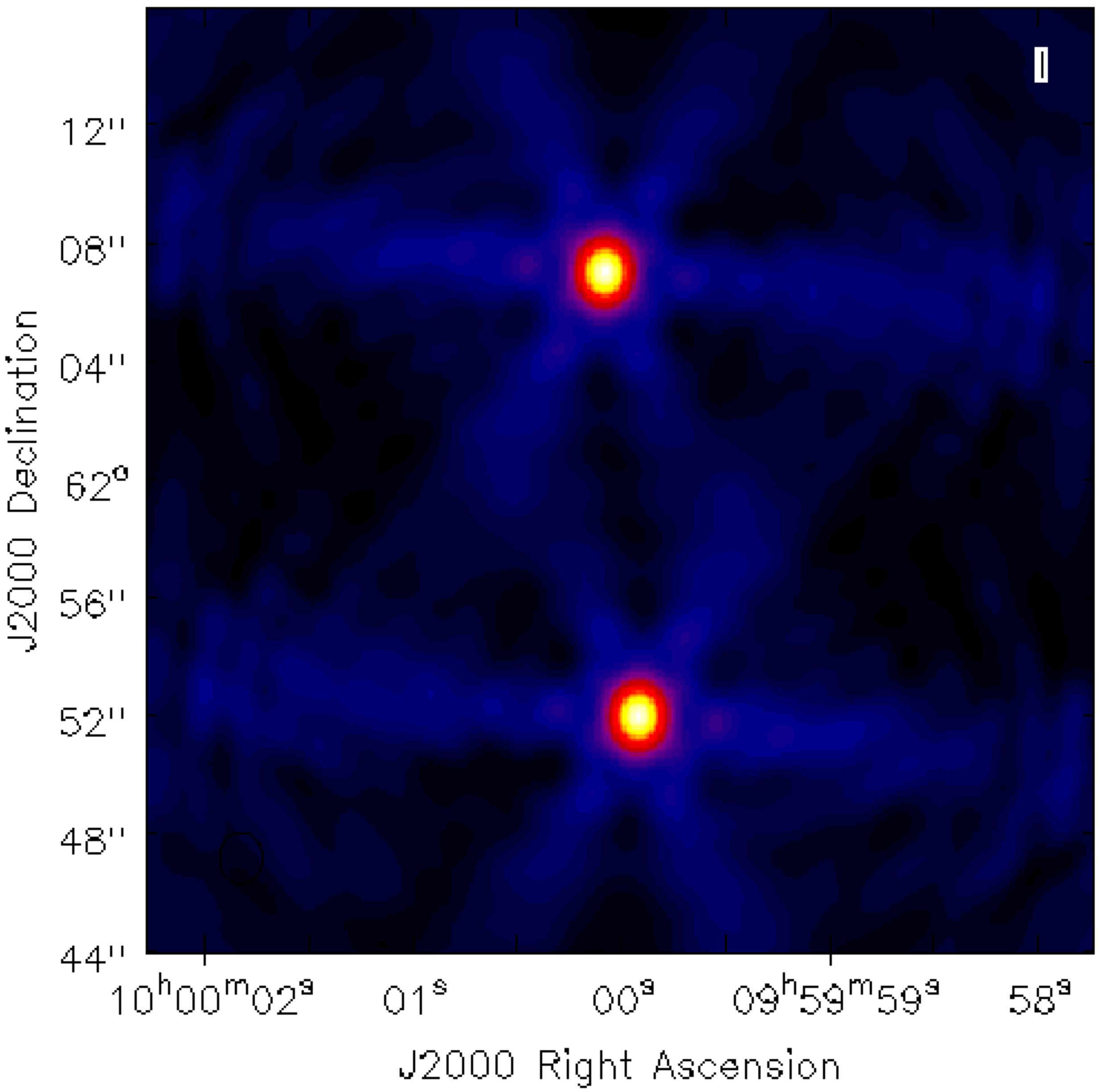
Dirty image



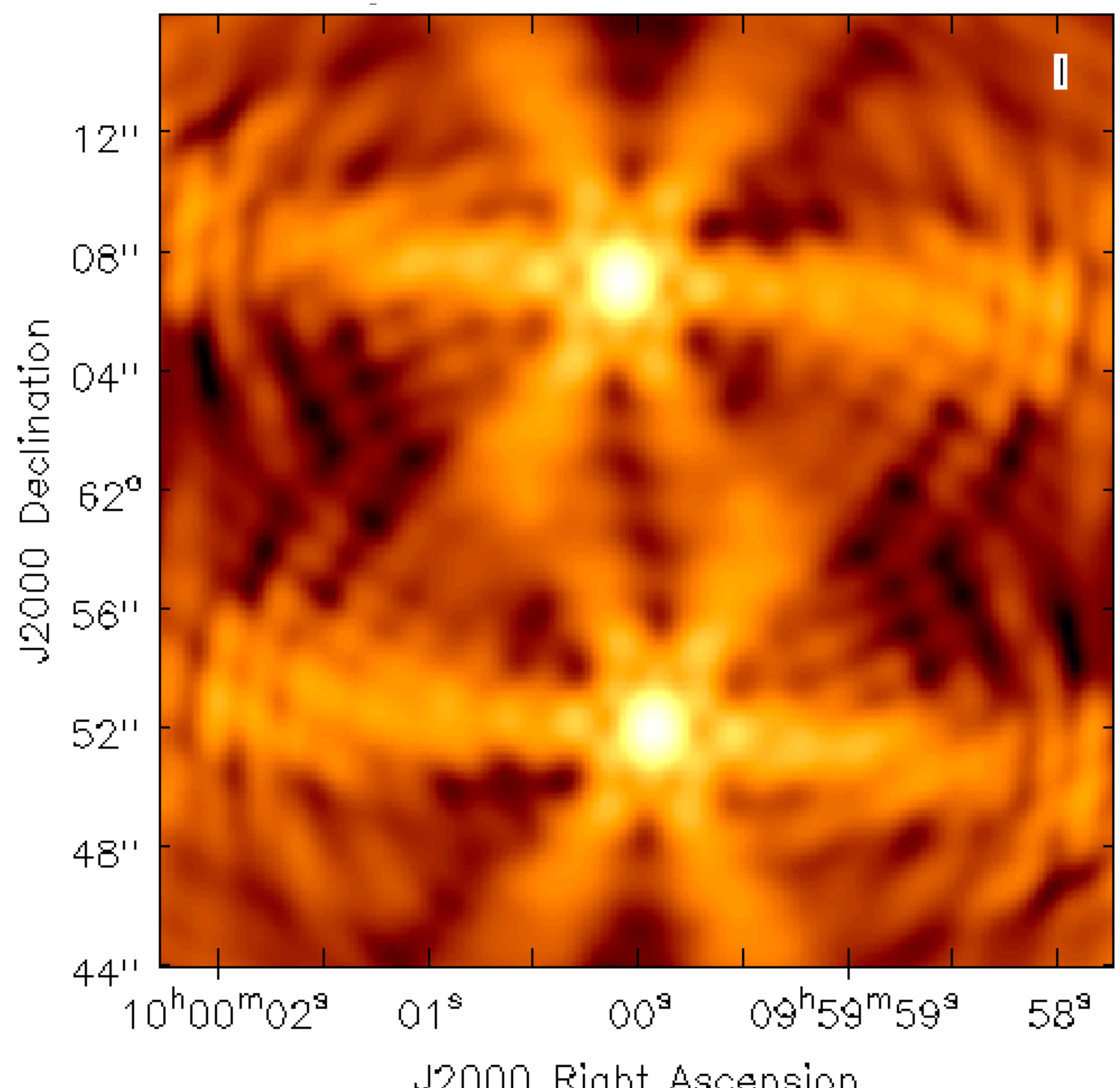
Deconvolution

CLEAN map (residual+CLEAN components) after 1 iteration

Clean image



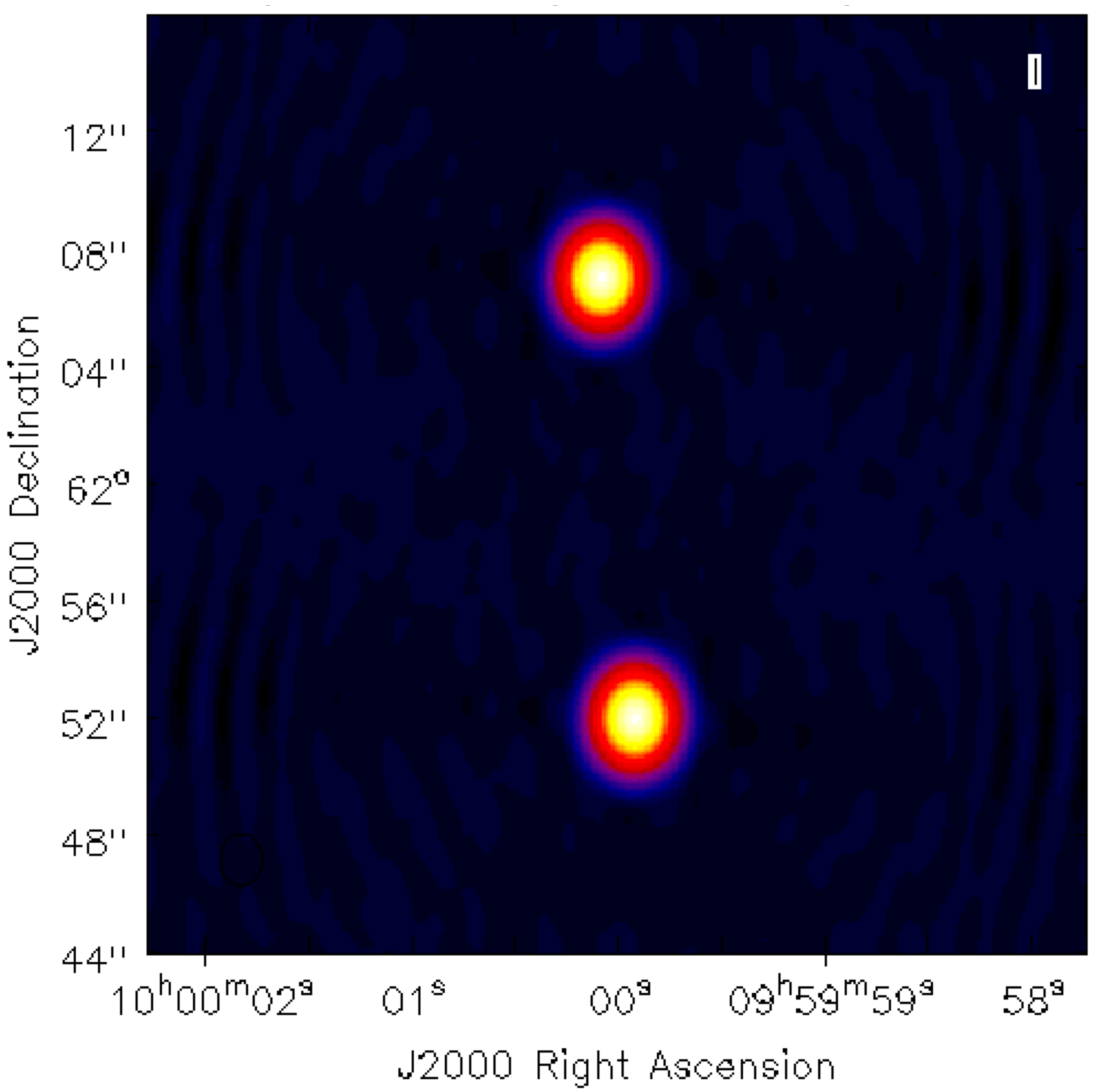
Residual



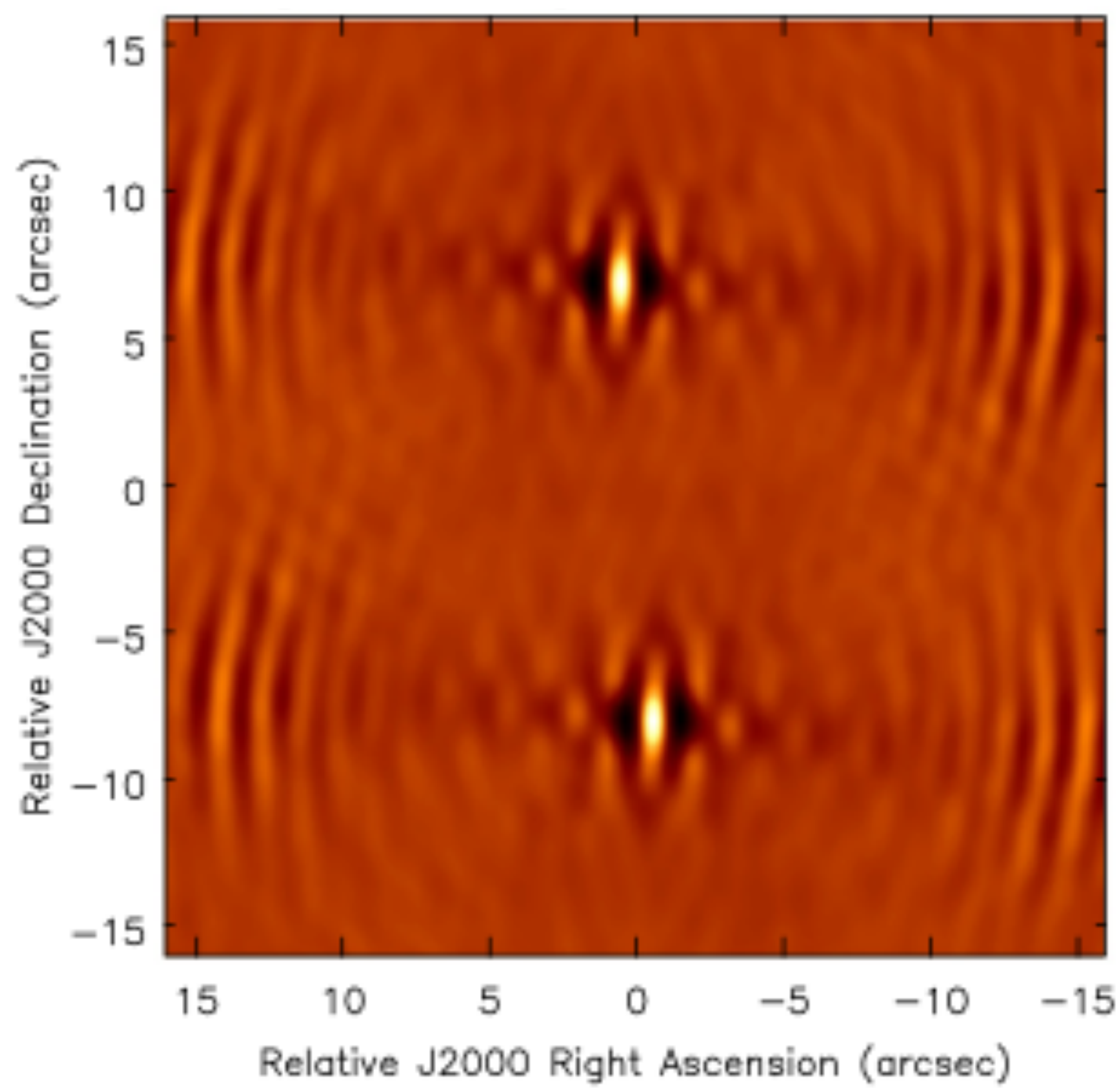
Deconvolution

CLEAN map (residual+CLEAN components) after 150 iterations

Clean image



Residual



Self-calibration

- We have corrected for incomplete u-v coverage, we also want to correct for atmosphere-induced errors

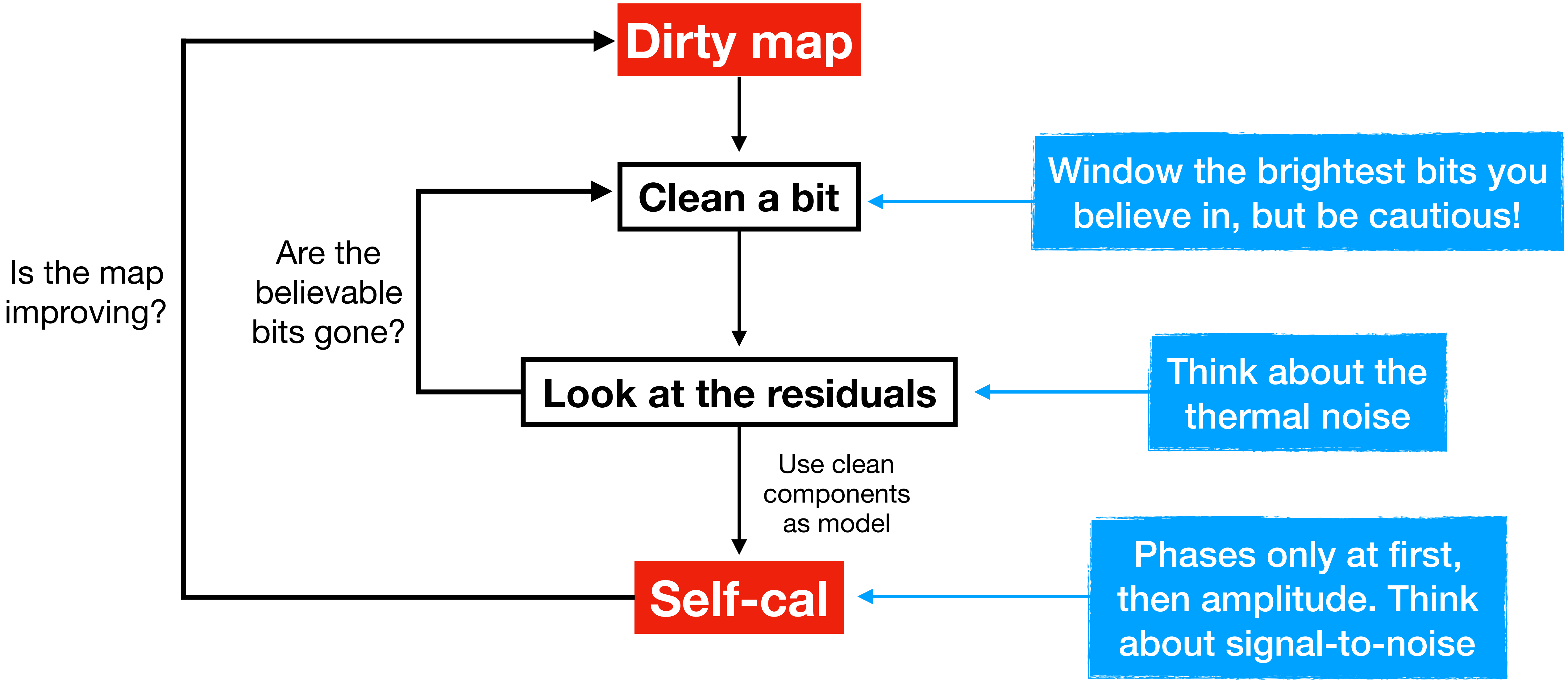
- Need model to correct -> can use CLEAN model!

    Solve for complex gain of each telescope
    $\overline{V}_{ij} = g_i\, g_j\, V_{ij}$
    Repeat for corrected visibilities

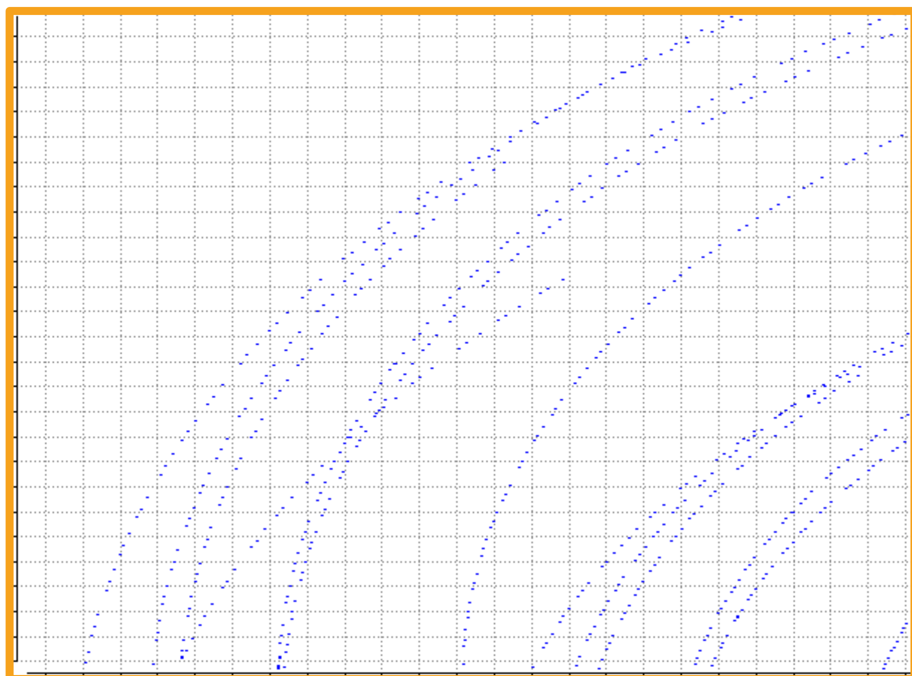
- Is this legitimate? Yes - errors associated to individual antennas. We have free parameters $g_i, g_j \ldots$ n_{tel} and n_{bas} constraints.

- Problem: need to have good signal-to-noise, lose absolute positional information

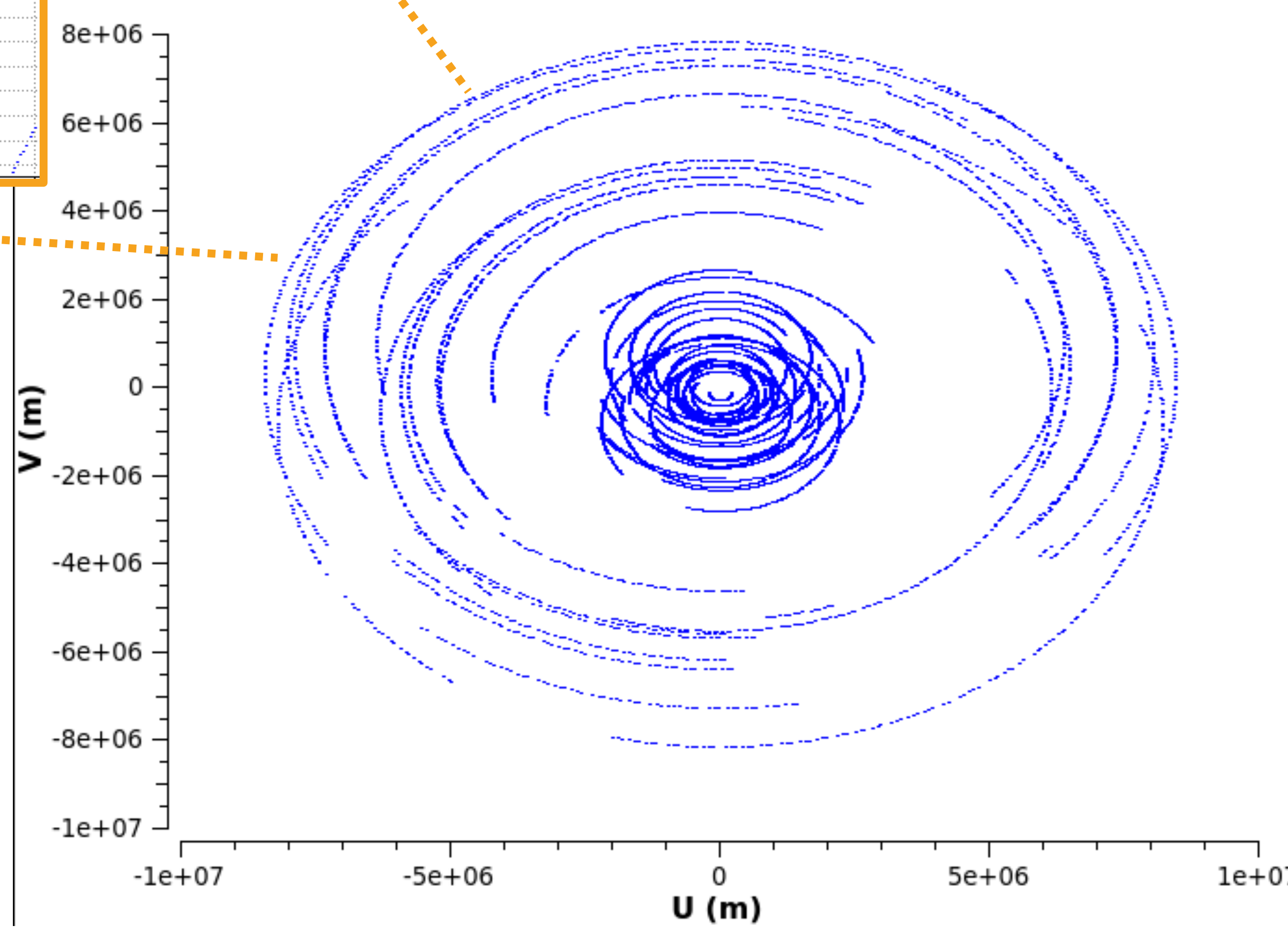
CLEAN & self-calibration in practice



Weighting visibilities

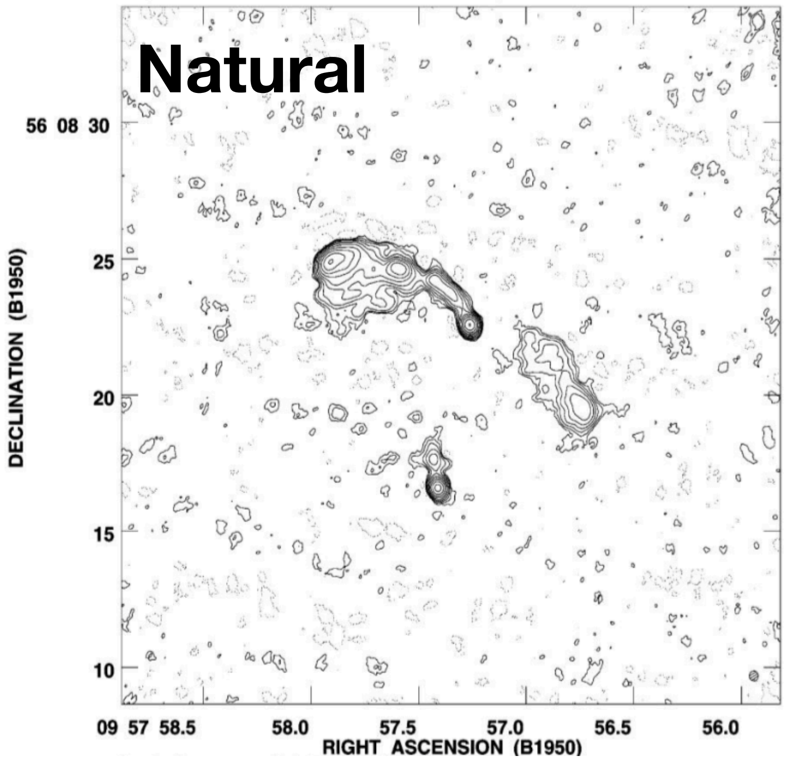


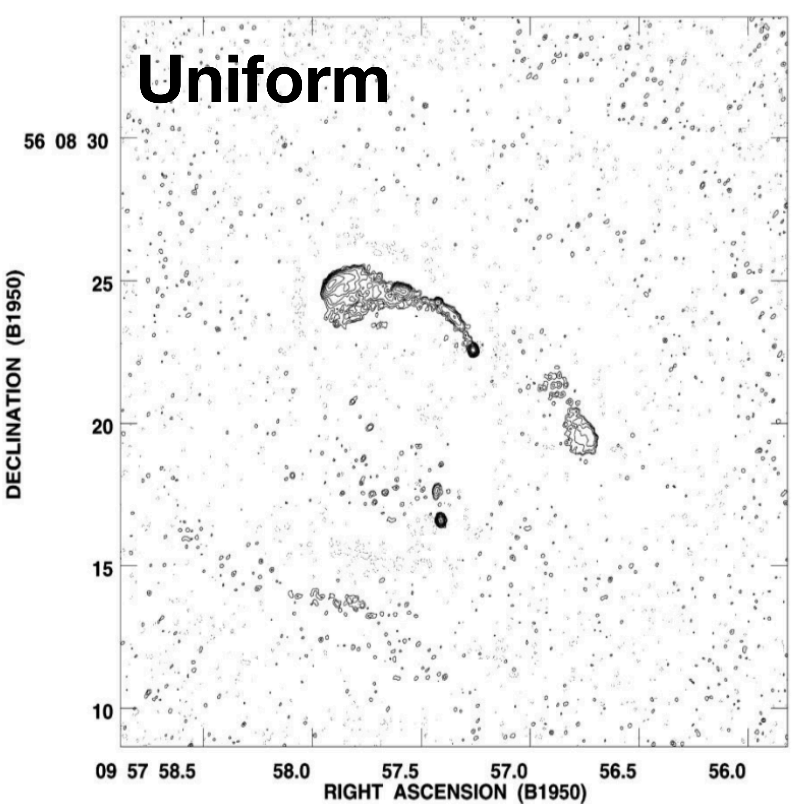
Fewer samples at outer points on uv plane - there are always more shorter baselines



- Data interpolated on 2^n grid
- **‘Natural’**: weights unmodified, depend on density of samples
- **‘Uniform’**: weights divided by local density of points
- **‘Briggs’**: a compromise between natural and uniform

Weighting visibilities





Natural weighted images have low spatial frequencies are weighted up (due to gridding) and gives:

- Best S/N
- Lower resolution

Uniform weighted images low have spatial frequencies weighted down and the data are not utilised optimally (may be subject to a deconvolution striping instability)
resulting in:

- Worse S/N
- Higher resolution

Compromise:

- **Briggs** (robust) weighting parameter -2 to +2. (next slide)

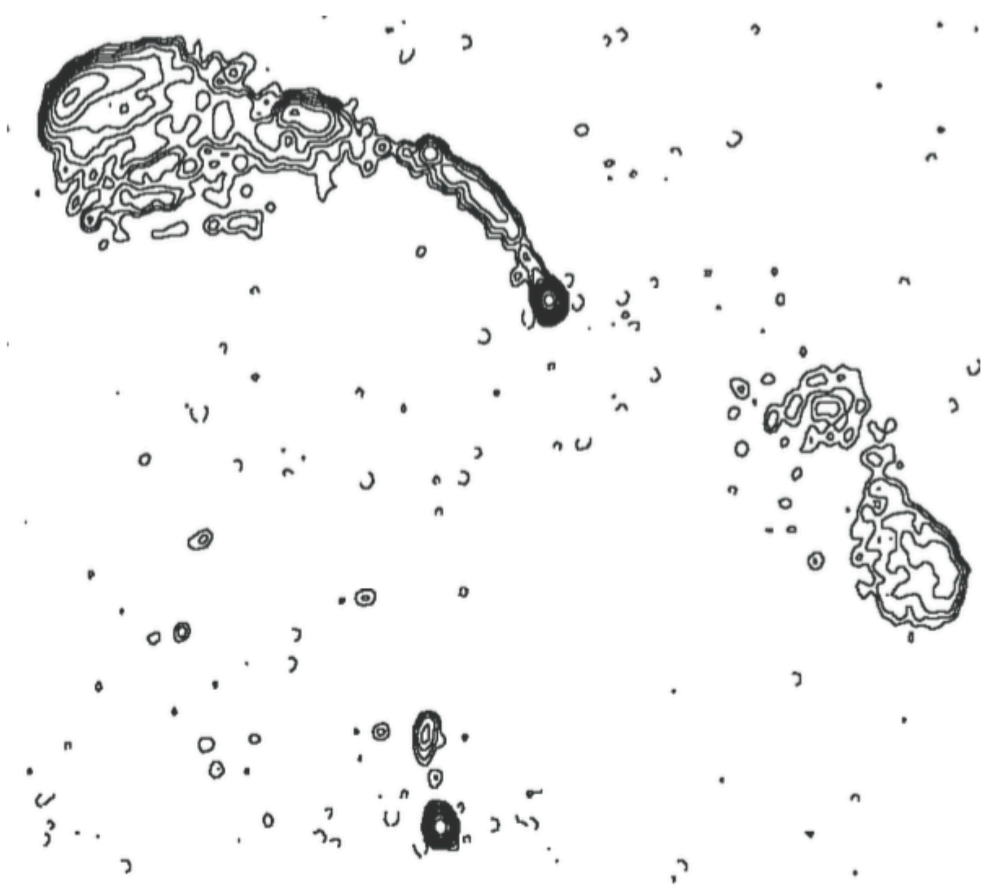
Implementation in CASA clean

```
weighting          =  'natural'        #  Weighting of uv (natural, uniform,
                                       #   briggs, ...)
```

Weighting visibilities

- Originally derived as a cure for striping – Natural weighting is immune and therefore most ‘robust’

Robust 0 image



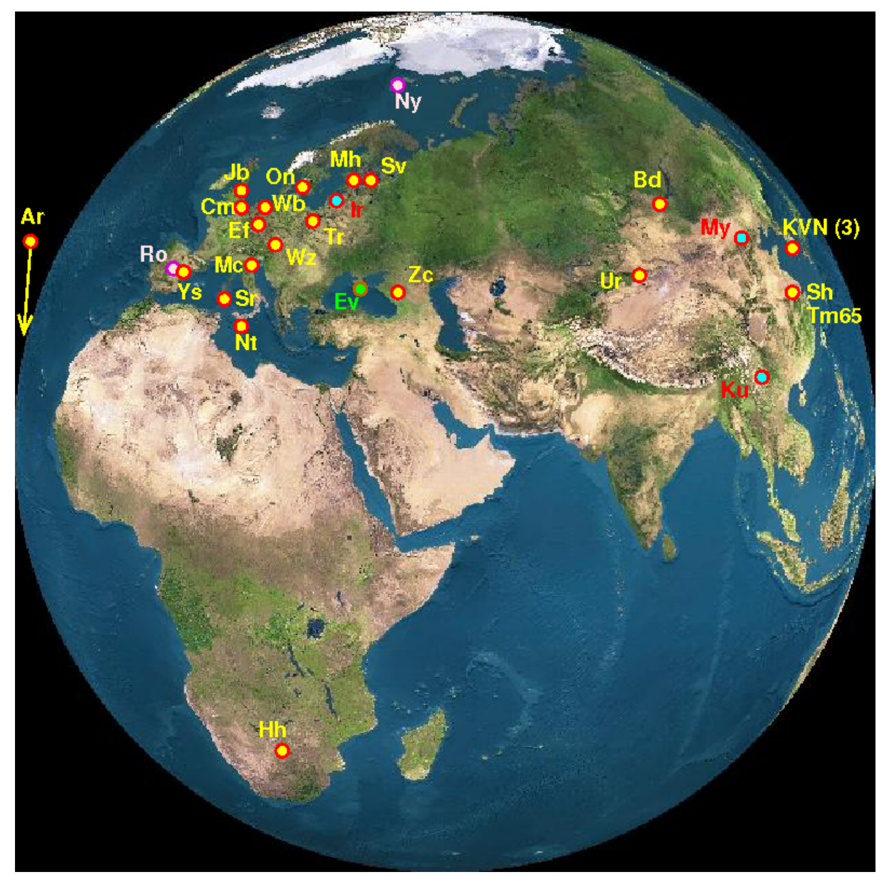
- Varies effective weighting as a function of local u-v weight density
  - Where weight density is low – effective weighting is natural
  - Where weight density is high – effective weighting is uniform

- Modifies the variations in effective weight found in uniform weighting → more efficient use of data & lower thermal noise

- ROBUST = – 2 is uniform
- ROBUST = + 2 is natural
- ROBUST = 0 is a good compromise

Weighting visibilities

- Many arrays are heterogeneous e.g. e-MERLIN, EVN & AVN (when built)
- To get the best S/N need to increase weighting on larger telescopes so they contribute more.
- Nb. this can change the resolution depending on the baseline distribution.



Field of view limitations

In order to image the entire primary beam you have to consider the following distorting effects:

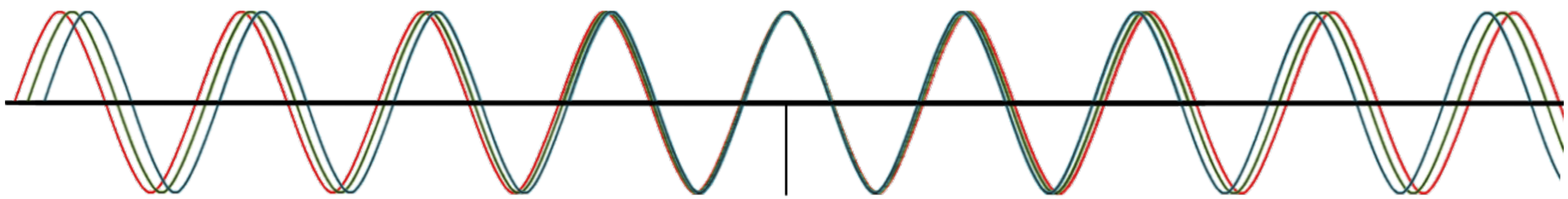
1. Bandwidth smearing

2. Time smearing

3. Non-coplanar baselines (or the ‘w’ term) - Covered in advanced imaging

4. Primary beam response

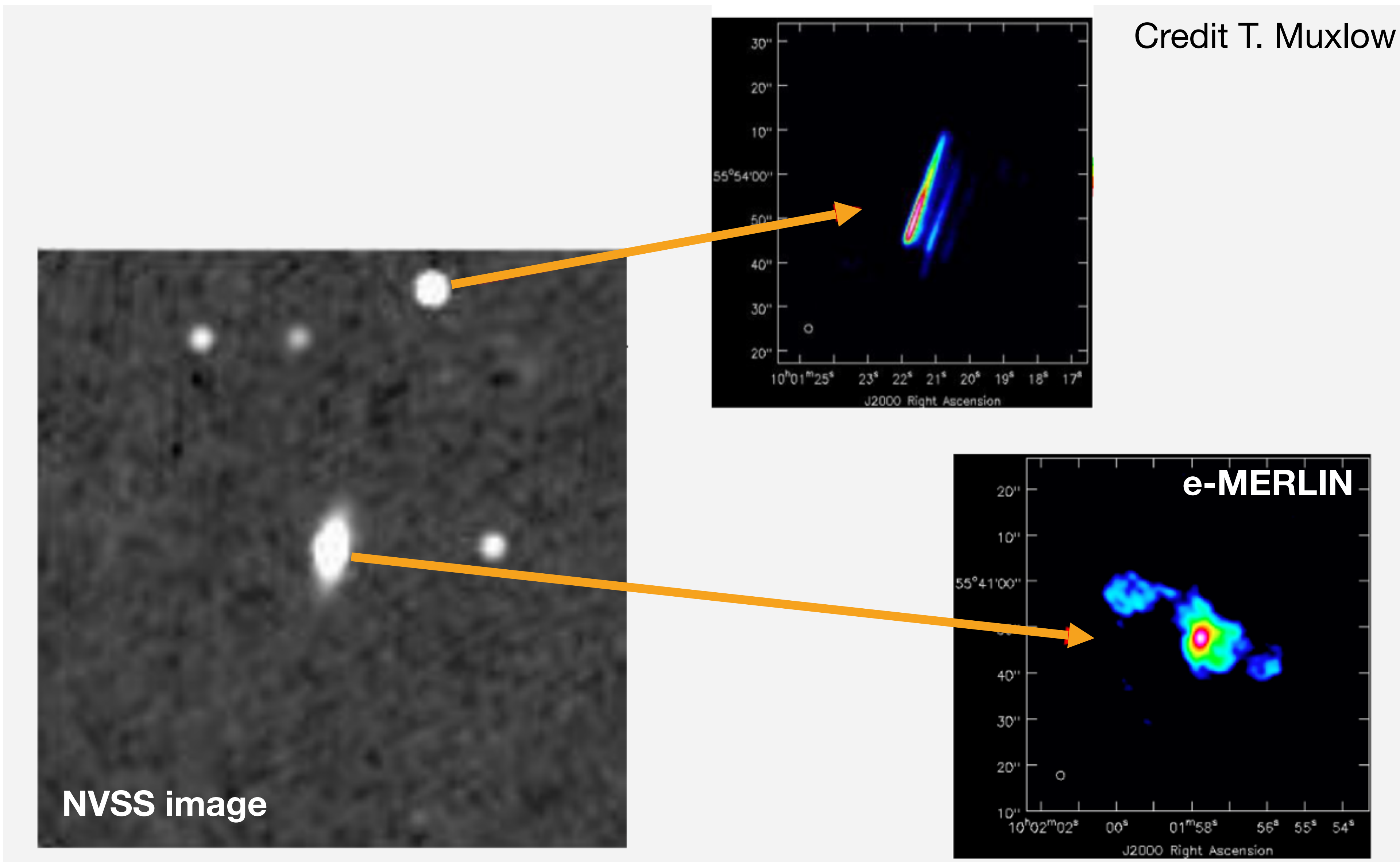
Bandwidth smearing



increasing radius ← pointing centre → increasing radius

- Data is not monochromatic: different frequencies go out of phase away from phase centre due to size of bandwidth
- Effect of BW smearing can be estimated by $\mathrm{FoV} \sim \frac{\lambda}{\Delta\lambda}\frac{\lambda}{B}$
- Help this by imaging with high spectral resolution, gridding separately before inversion

Bandwidth smearing



Effect is radial smearing, corresponding to radial extent of measurements in uv plane

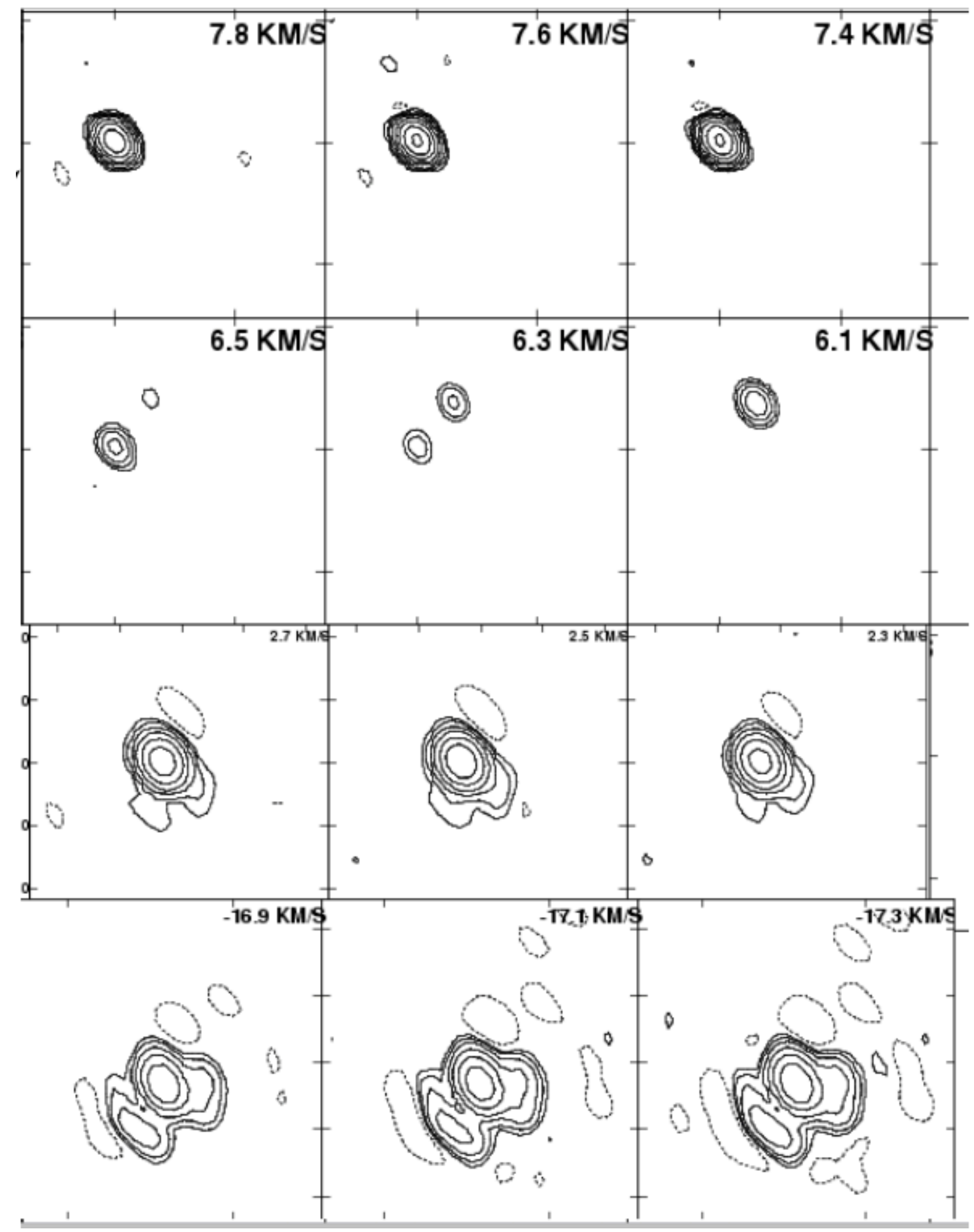
Time smearing

- Time-average smearing (de-correlation) produces tangential smearing

- Not easily parameterized. At declination +90° a simple case exists where percentage time smearing is given by:

$$\omega_e \delta t_{\mathrm{int}} \frac{\theta}{\theta_{\mathrm{HPBW}}}$$

- At other declinations, the effects are more complicated.



Credit N. Jackson

‘w’-term

Standard Fourier synthesis assumes coplanar arrays or small (l,m)
- Only true for E-W interferometers e.g. WSRT

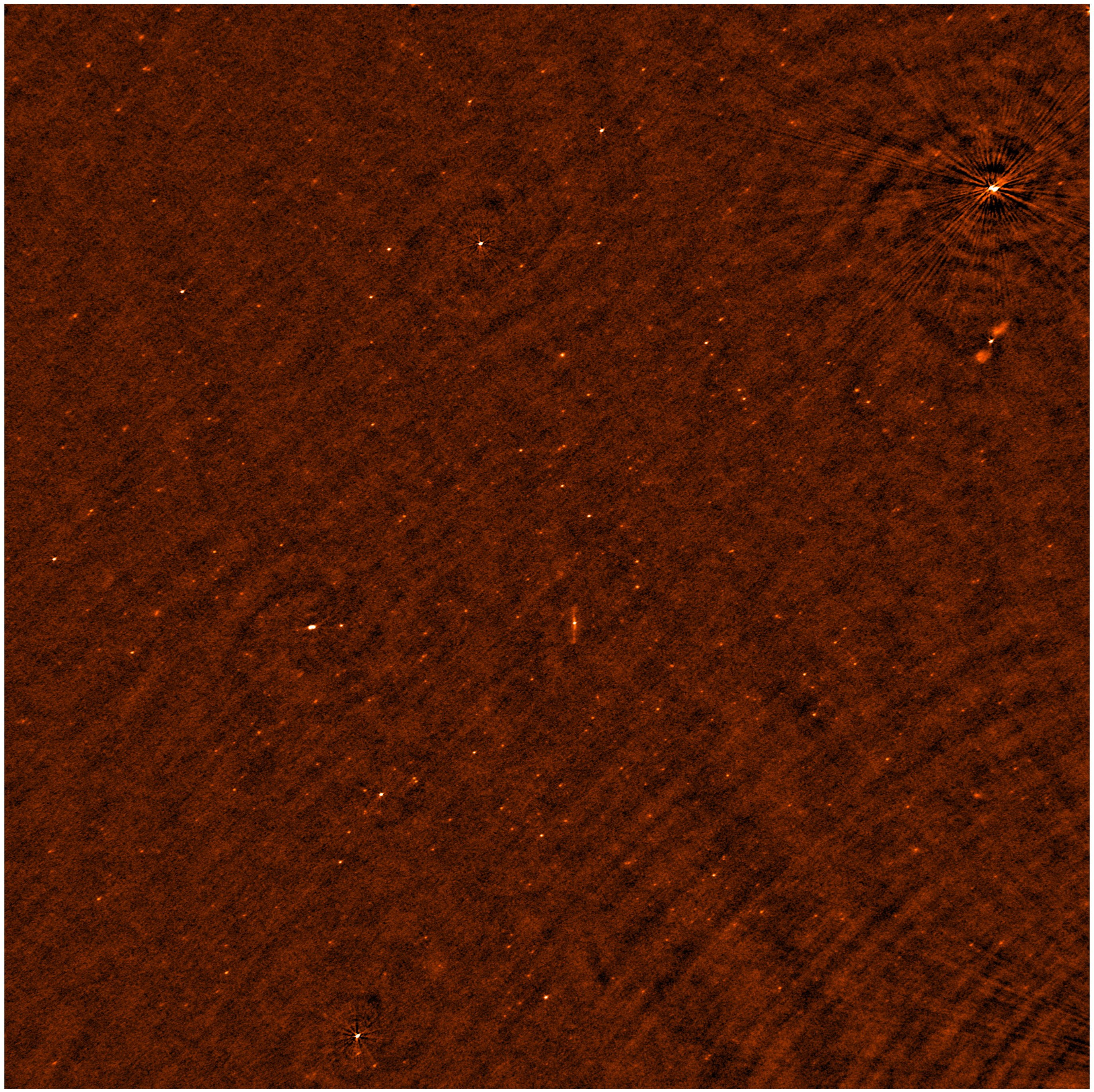
$$V(u,v,w) = \iint \frac{I(l,m)}{\sqrt{1-l^2-m^2}} e^{-2\pi i(ul+vm+w(\sqrt{1-l^2-m^2}-1))} dl dm$$

Need to take into account the ‘w’ term properly in wide-fields as errors increase quadratically with offset from phase-centre

Solution:

i. Faceting - split the field into multiple images to maintain l, m, w ~ 0 and stitch them together.
ii. w-projection - most used solution, project 3D sky brightness onto 2D tangent plane using w kernel.

Confusion



JVLA image of GOODS-N showing confusion from a 0.25Jy source to the SE. [Credit J. Radcliffe]

- Bright radio sources on the edge of the primary beam give rise to ripples in the centre of the field of view
- The primary beam is spectrally dependent, so image subtraction should include such corrections and be performed in full spectral-line mode
- Pointing errors introduce gain and phase changes on the edge of the primary beam

Signal-to-noise limitations

Noise level of a (perfect) homogeneous interferometer:

$$\text{Noise} = \frac{\sqrt{2}k_B T_{\text{sys}}}{\sqrt{n_b t \Delta\nu} A\eta}$$

where:
T_{sys} - system temperature [K]
n_b - number of baselines
t - integration time [s]
$\Delta\nu$ - bandwidth [Hz]
A - area of apertures [m]
η - aperture efficiency

Many factors increase noise level above this value:

- Confusion
- Calibration errors
- Bad data
- Non-closing data errors
- Deconvolution artefacts

Rarely get this from an image. Dependent of flagging accuracy, calibration & adequate deconvolution

CLEAN & self-calibration in practice

- Pixel size w.r.t. Nyquist rate
- Image size
- Weighting (natural, uniform, Briggs)
- Number of iterations (100=shallow, 5000=deep)
- Windows/Clean boxes
- Gain (typically 0.1)
- Noise level, SNR