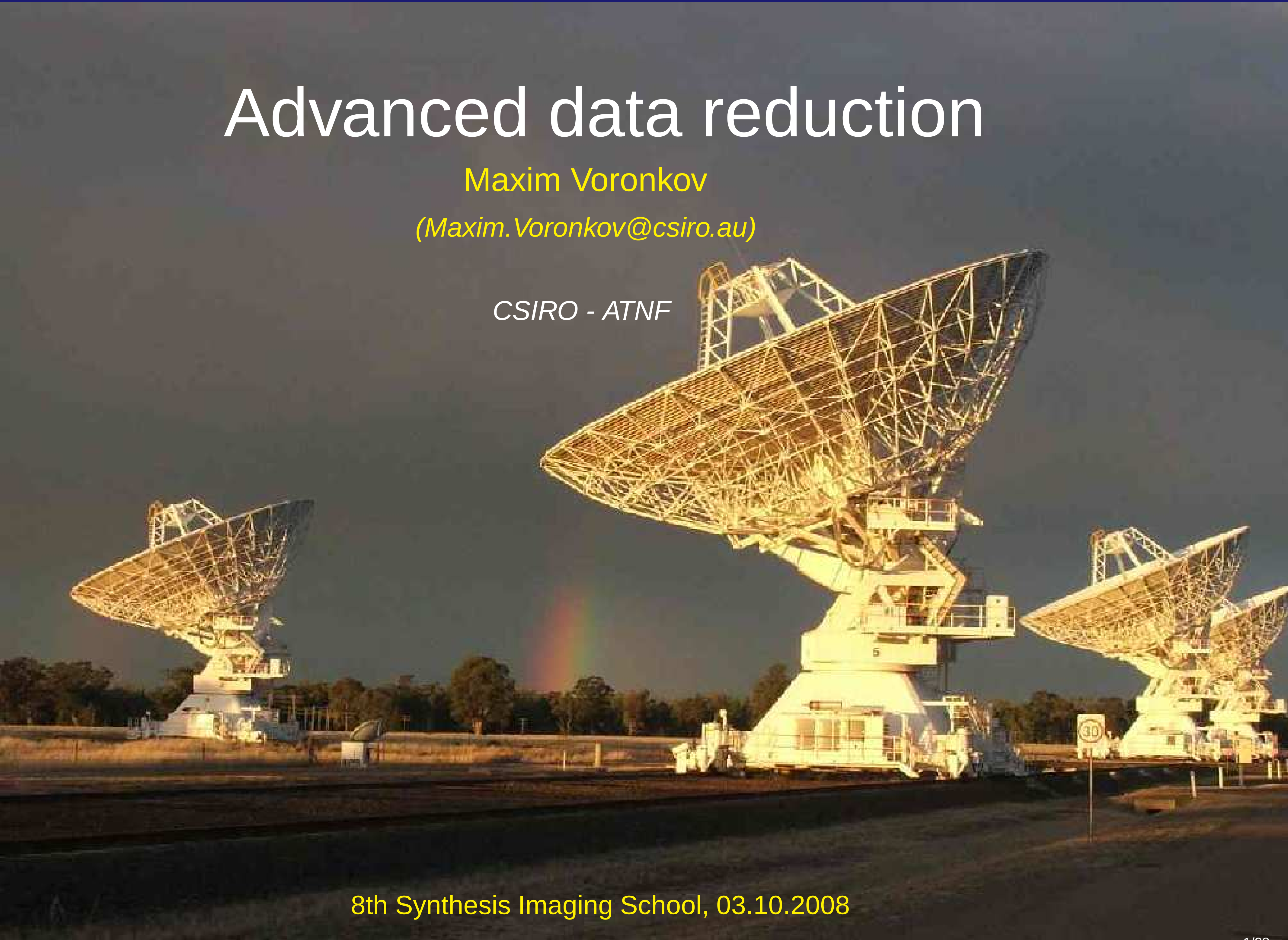
Advanced data reduction

Maxim Voronkov

(Maxim.Voronkov@csiro.au)

CSIRO - ATNF



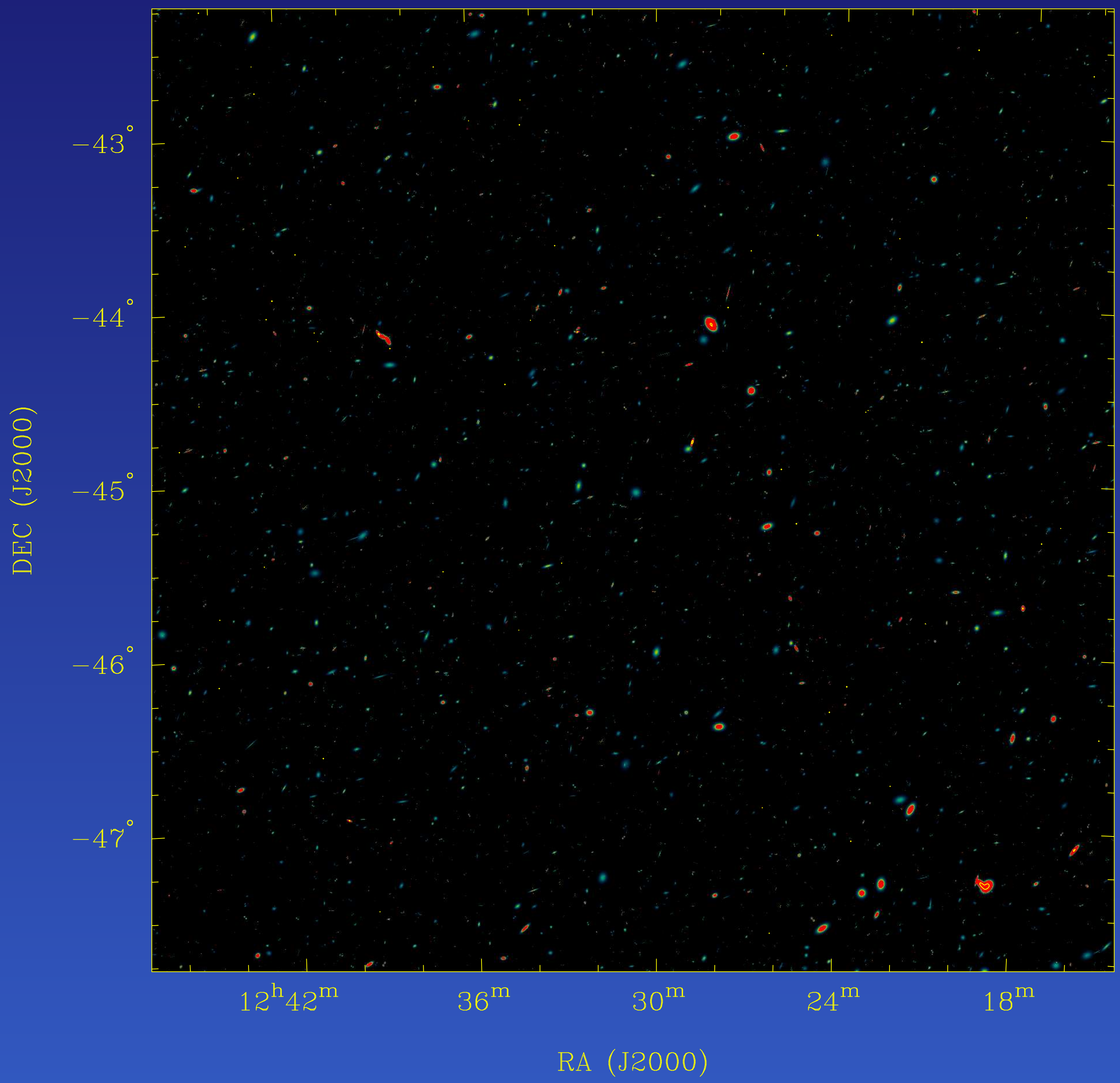
8th Synthesis Imaging School, 03.10.2008

This talk is about algorithms

But it is not a collection of recipes for data reduction

- Various wide-field effects and the problems they cause
- Algorithms to deal with these effects
- Examples from advanced data reduction tutorials

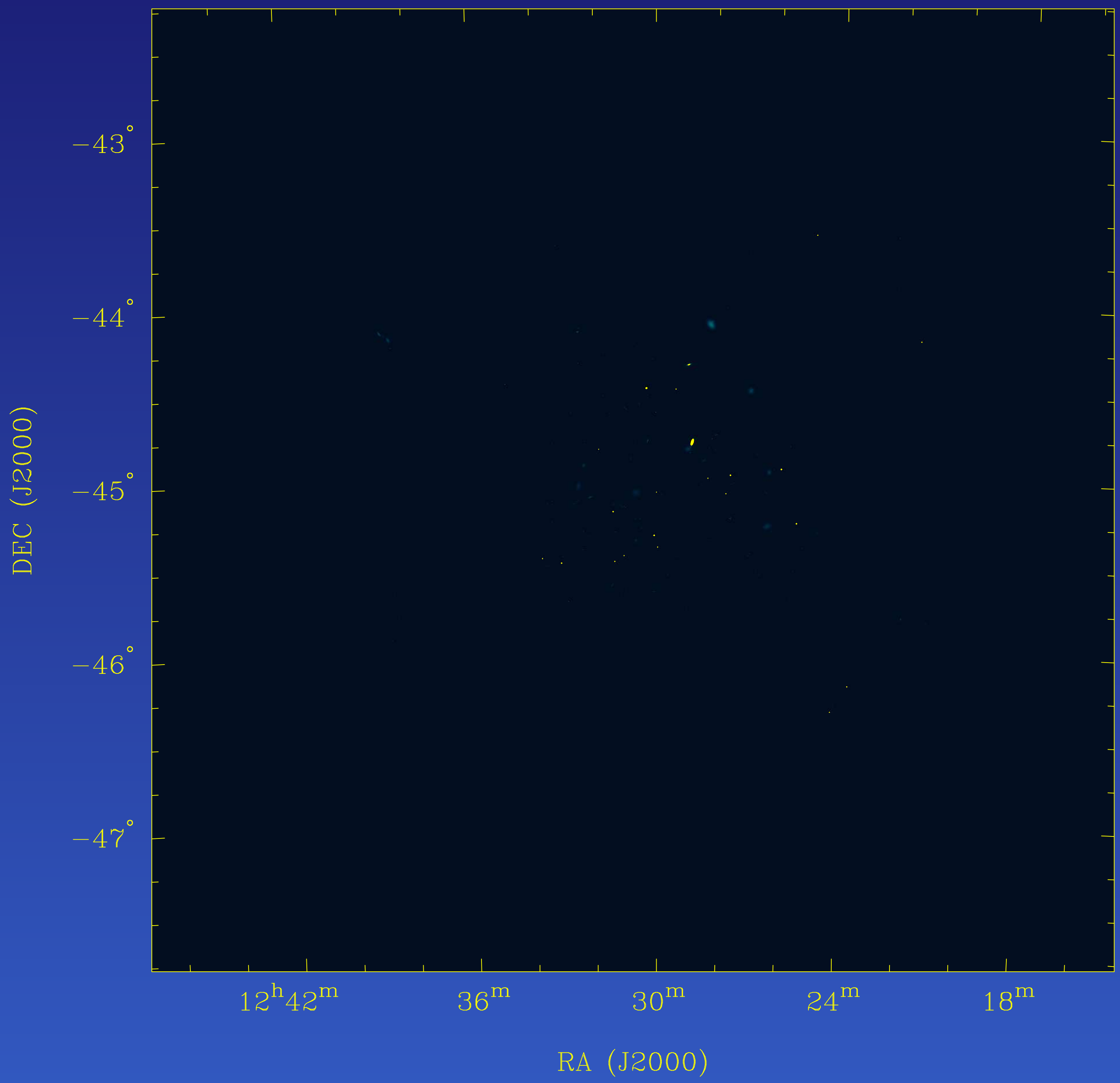
Instantaneous field of view



- Describes the area of the sky seen in one go
- Primary beam limits the field of view
- Useful FoV is largely the main beam. Strong sources could be seen through sidelobes
- The larger the antenna, the smaller the field of view

⇐ Model sky which spans roughly the field of view of ASKAP

Instantaneous field of view



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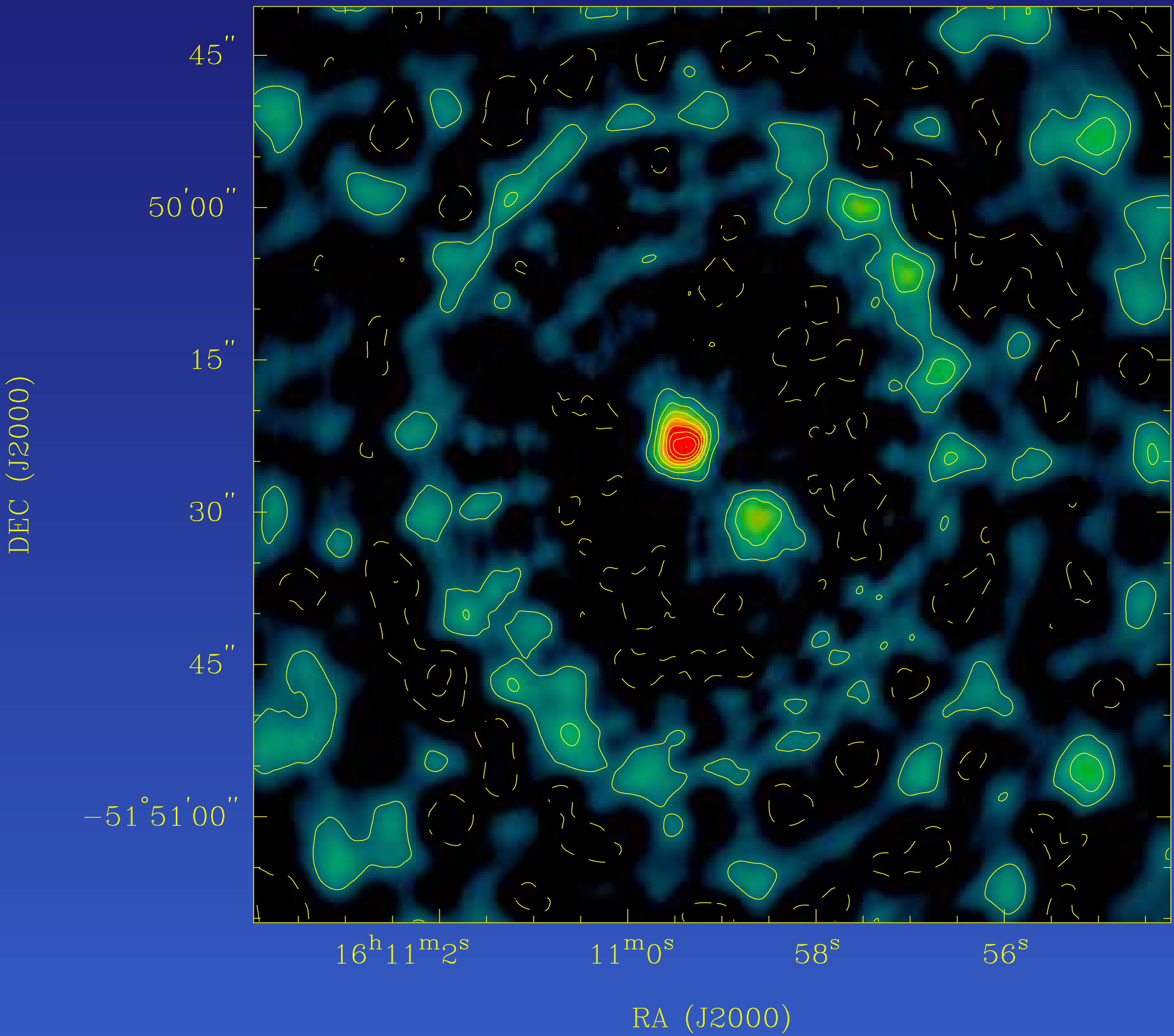
⇐ Same sky seen by an ATCA antenna

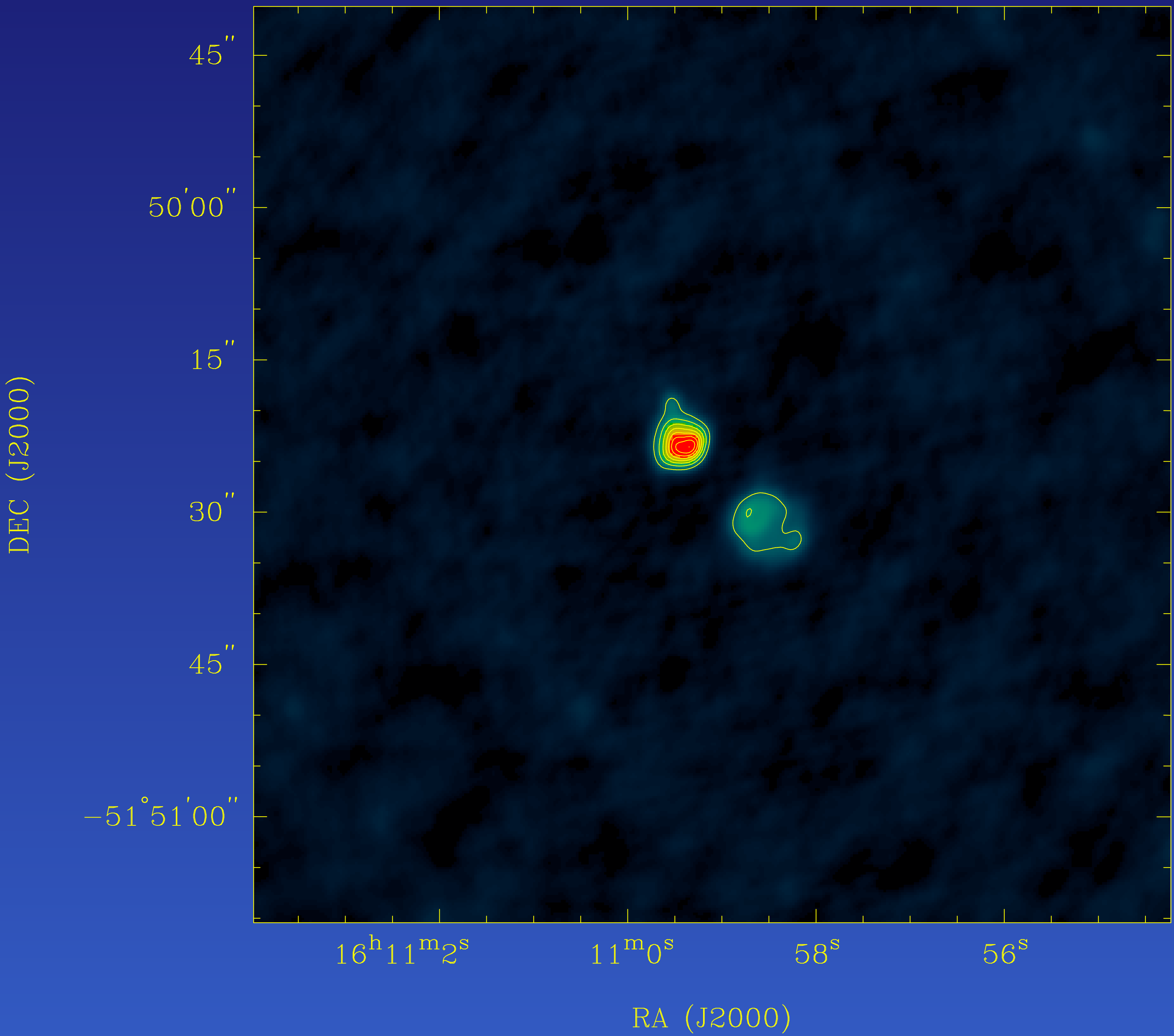
A concept of the dynamic range



- Each real source causes artefacts
- Hard to study weak sources in the presence of strong ones
- Dynamic range describes the relative sidelobe level with respect to the peak brightness in the image

⇐ ATCA dirty image of two HII regions

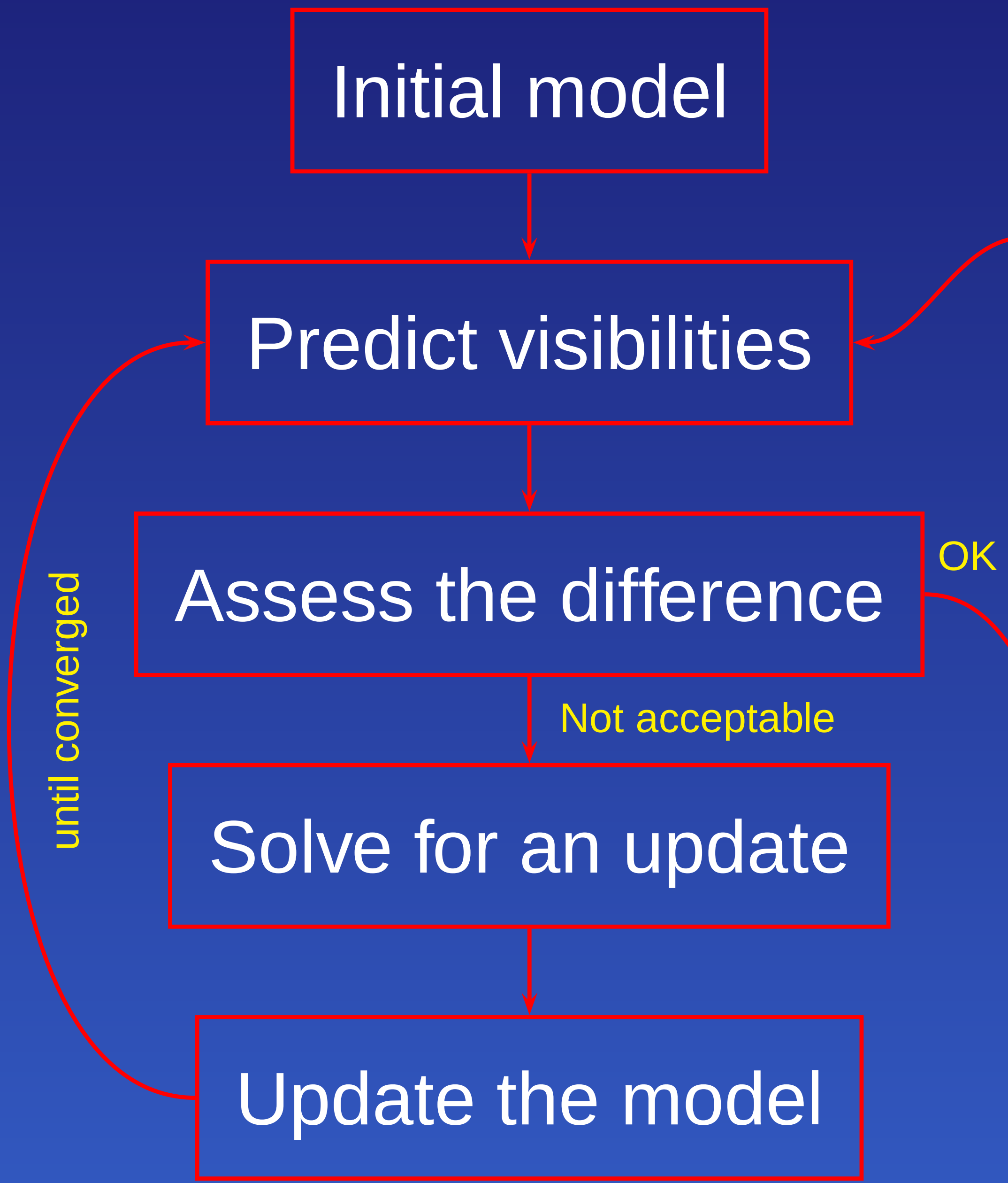
A concept of the dynamic range



- Each real source causes artefacts
- Hard to study weak sources in the presence of strong ones
- Dynamic range describes the relative sidelobe level with respect to the peak brightness in the image

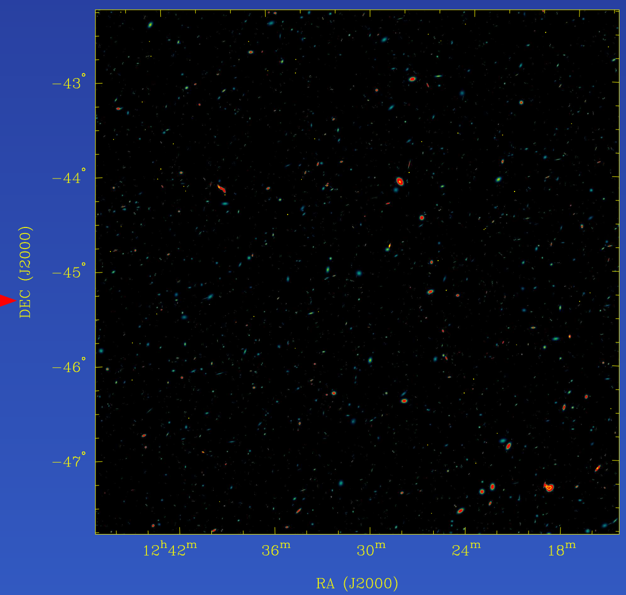
⇐ Cleaned ATCA image of two HII regions

Flow-chart of an imaging algorithm



- Need an iterative procedure for reverse problem (visibilities to image)
- Forward problem (image to visibilities or prediction) can be done accurately
- Accuracy depends on the measurement equation assumed
- FT = simplest measurement equation:

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



Approximations to the measurement equation

- Fourier Transform is the simplest form of the measurement equation:

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

- Using it we assume that the sky is flat (in other words the sky is 2D), which is fine for a small field of view

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$\Leftarrow$ An illustration for our assumption

strictly speaking it is valid if

- we're looking straight up, or
- the interferometer is East-West, or
- there is no diurnal motion

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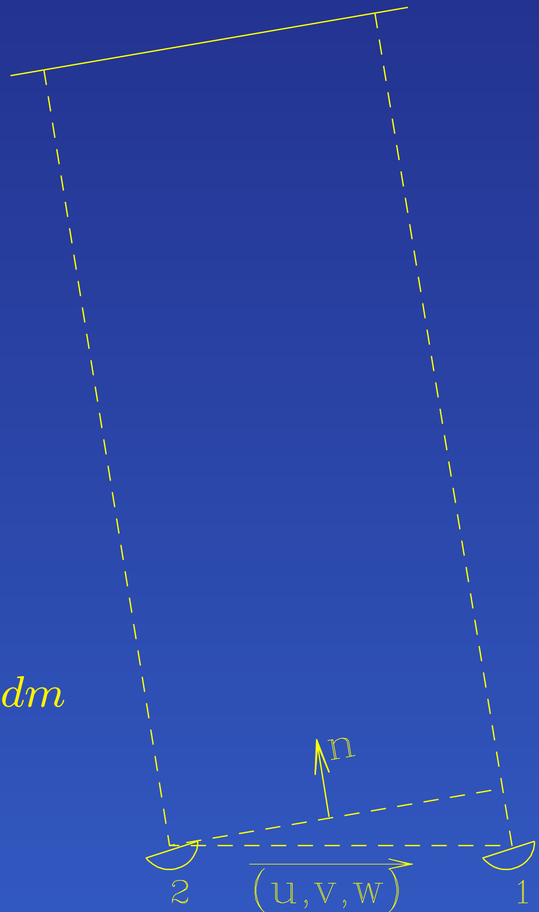


$$V(u,v,w) = \int\int \frac{I(l,m)e^{-2\pi i(ul+vm+w(\sqrt{1-l^2-m^2}-1))}}{\sqrt{1-l^2-m^2}}\, dl\, dm$$

Co-planar array: w is a linear combination of u and v $\Rightarrow$ shift

Illustration of the w-term effect: uncorrected

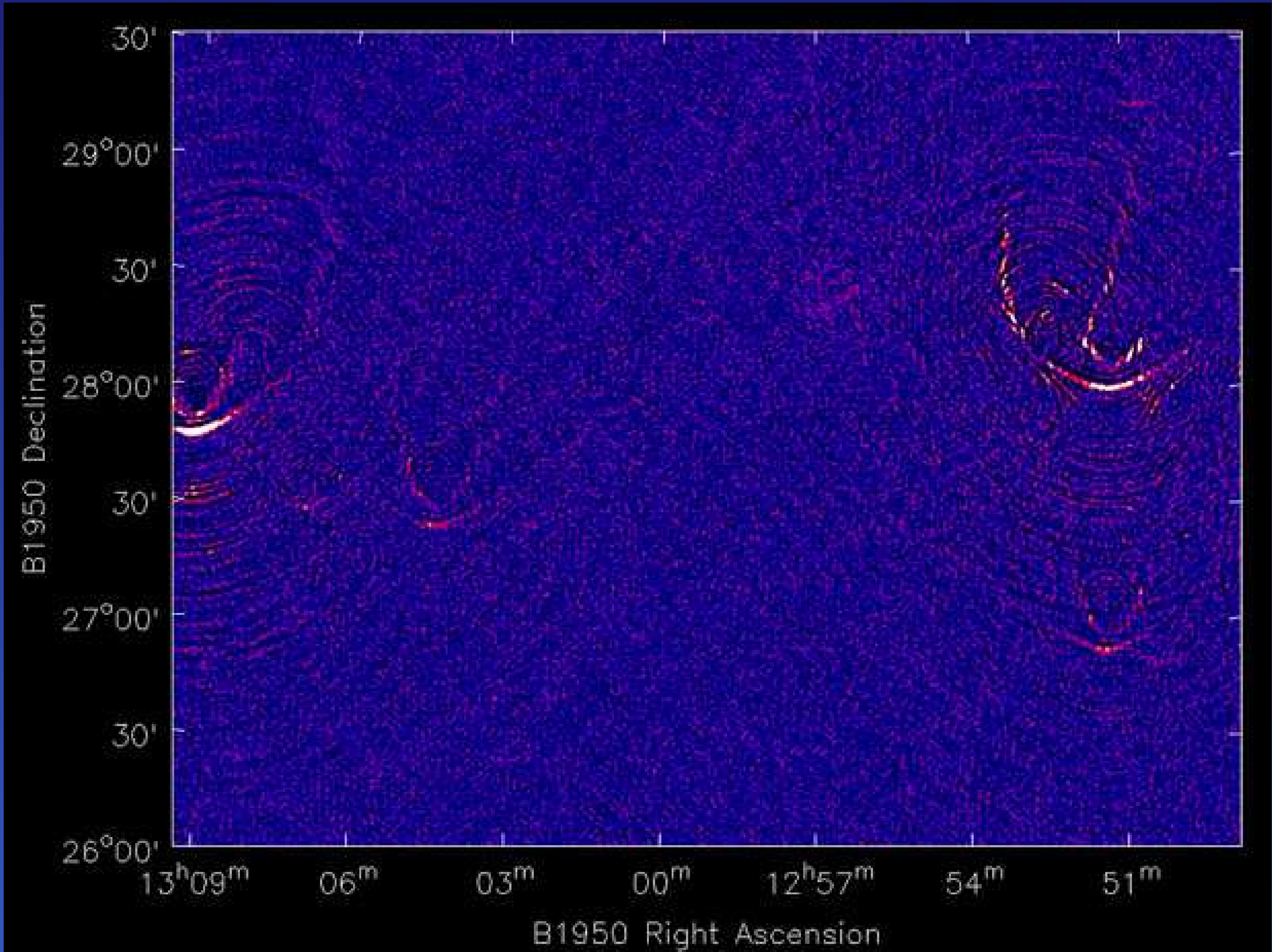


Image credit: Tim Cornwell

Illustration of the w-term effect: corrected

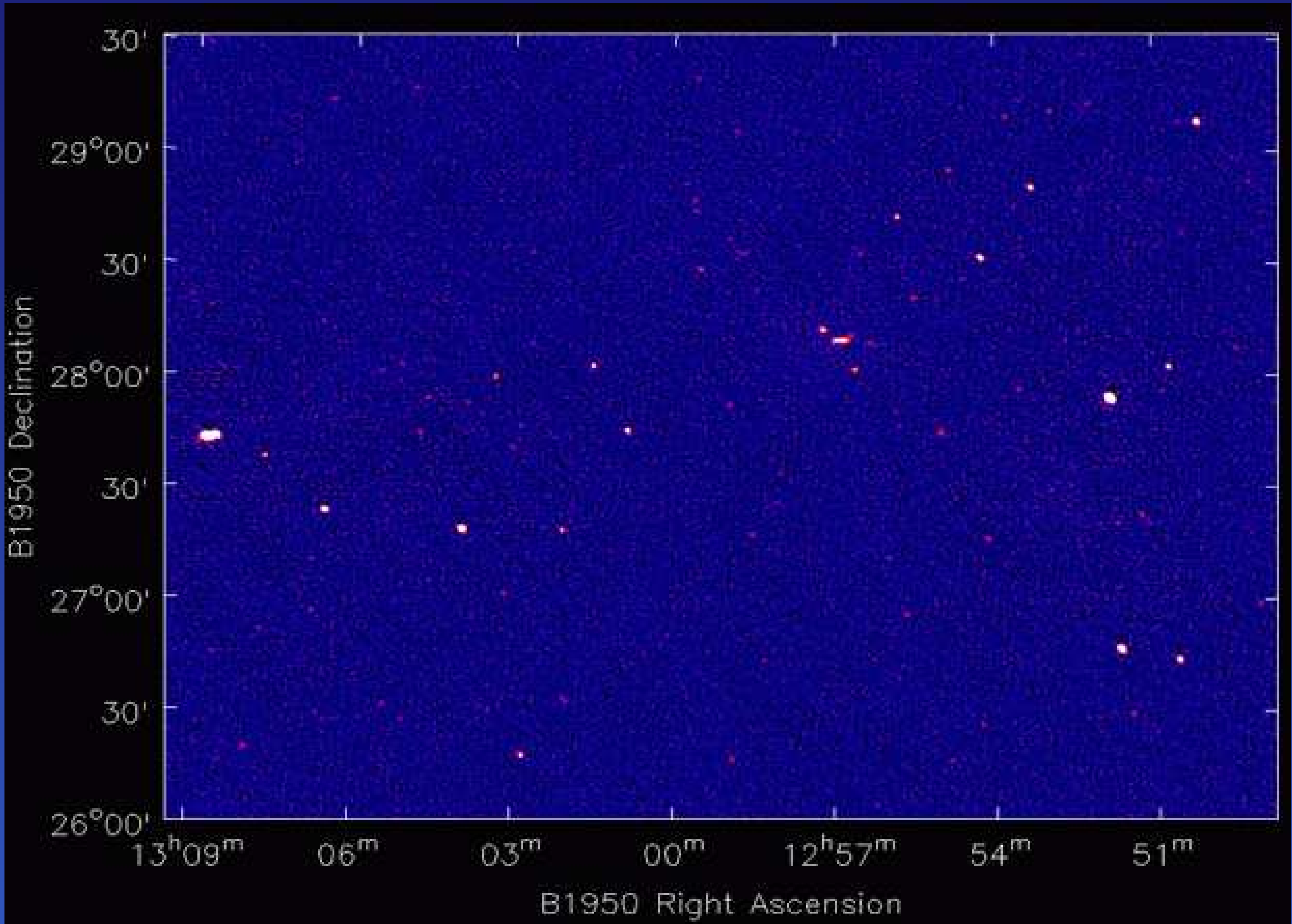


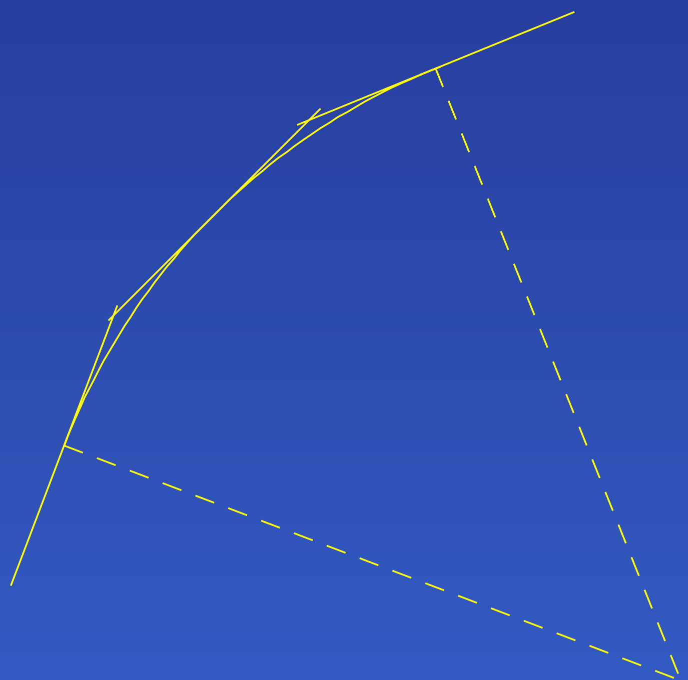
Image credit: Tim Cornwell

Faceted approach

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

- We can ignore the w-term if $\sqrt{\lambda B} \ll D$
- The whole field of view is split into a number of facets, where a normal 2D Fourier transform can be used

$$V(u,v,w) = \sum_k e^{-2\pi i(u_k l_k + v_k m_k + w_k(\sqrt{1-l_k^2-m_k^2}-1))} \times \int\int \frac{I_k(l,m)e^{-2\pi i(u_k(l-l_k)+v_k(m-m_k))}}{\sqrt{1-(l-l_k)^2-(m-m_k)^2}}\,dl\;dm$$



- Number of facets is $const \times \frac{\lambda B}{D^2}$
- uv-facets are also possible and even give better results

W-Projection

- See Cornwell et al. (astro-ph/0807.4161)

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

- Multiplication ⇒ convolution in the conjugate space

$$V(u,v,w) = V(u,v,w=0) \otimes G(u,v,w)$$

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

$$G(u,v,w) = \frac{i}{w} e^{-\pi i\left(\frac{u^2+v^2}{w}\right)}$$

- Convolution is done during the imaging anyway
- Convolution functions for w-projection have a larger support

Physical sense: Fresnel diffraction

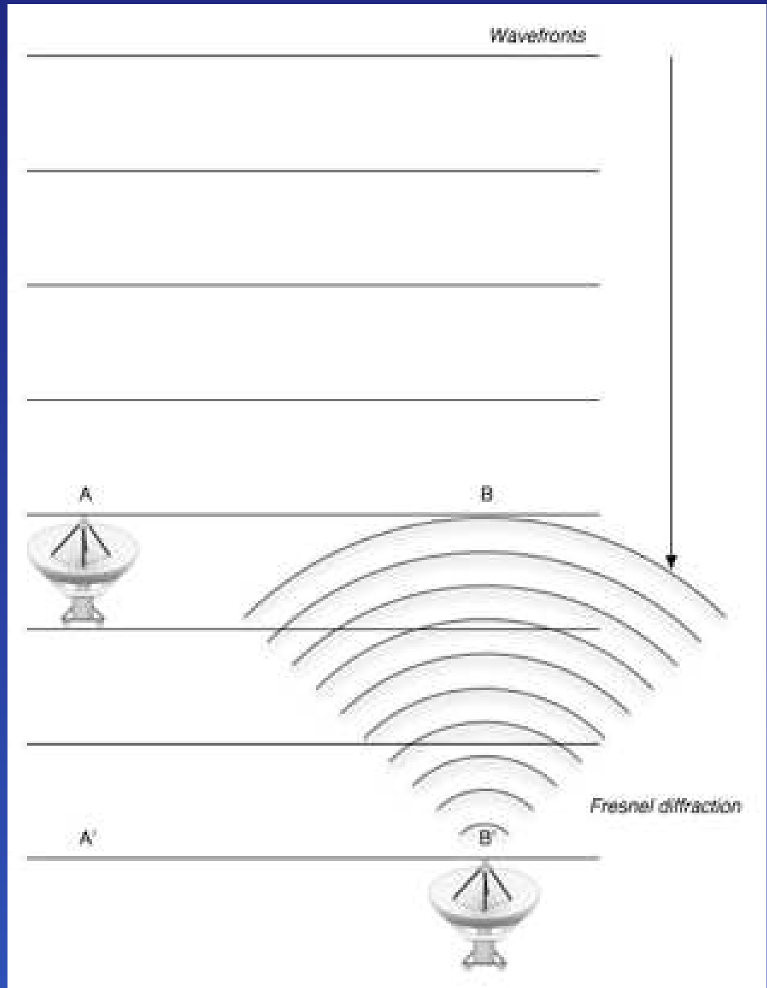


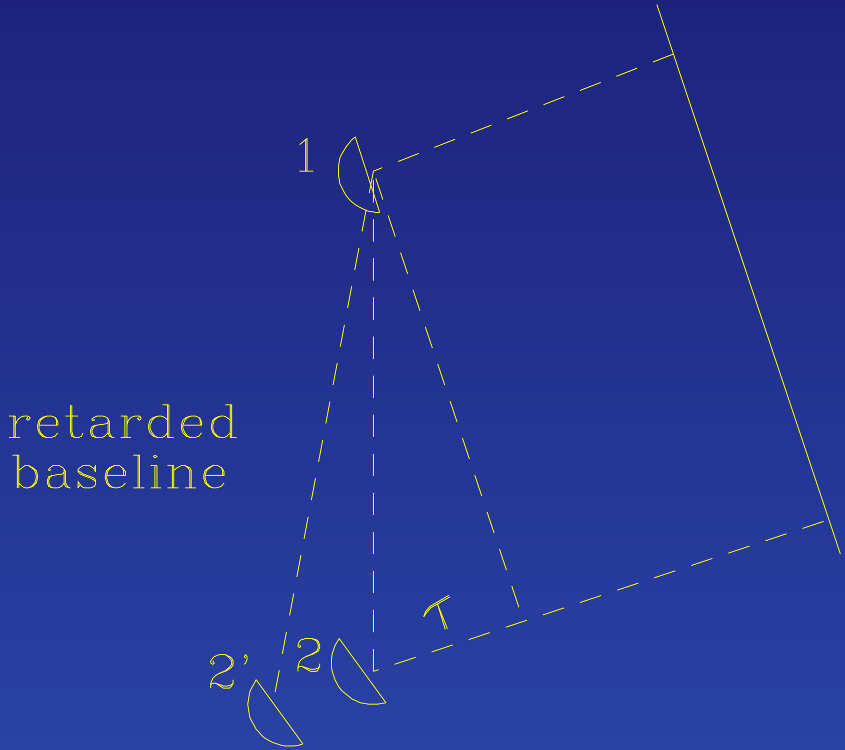
Image credit: Tim Cornwell

Fresnel scale is $\sqrt{\lambda B}$

What limits the dynamic range?

- *Inadequate approximation of the measurement equation*
- Improvement is possible by using more sophisticated algorithms
- But... the price paid is a higher computing cost

Another geometrical effect - retarded baselines

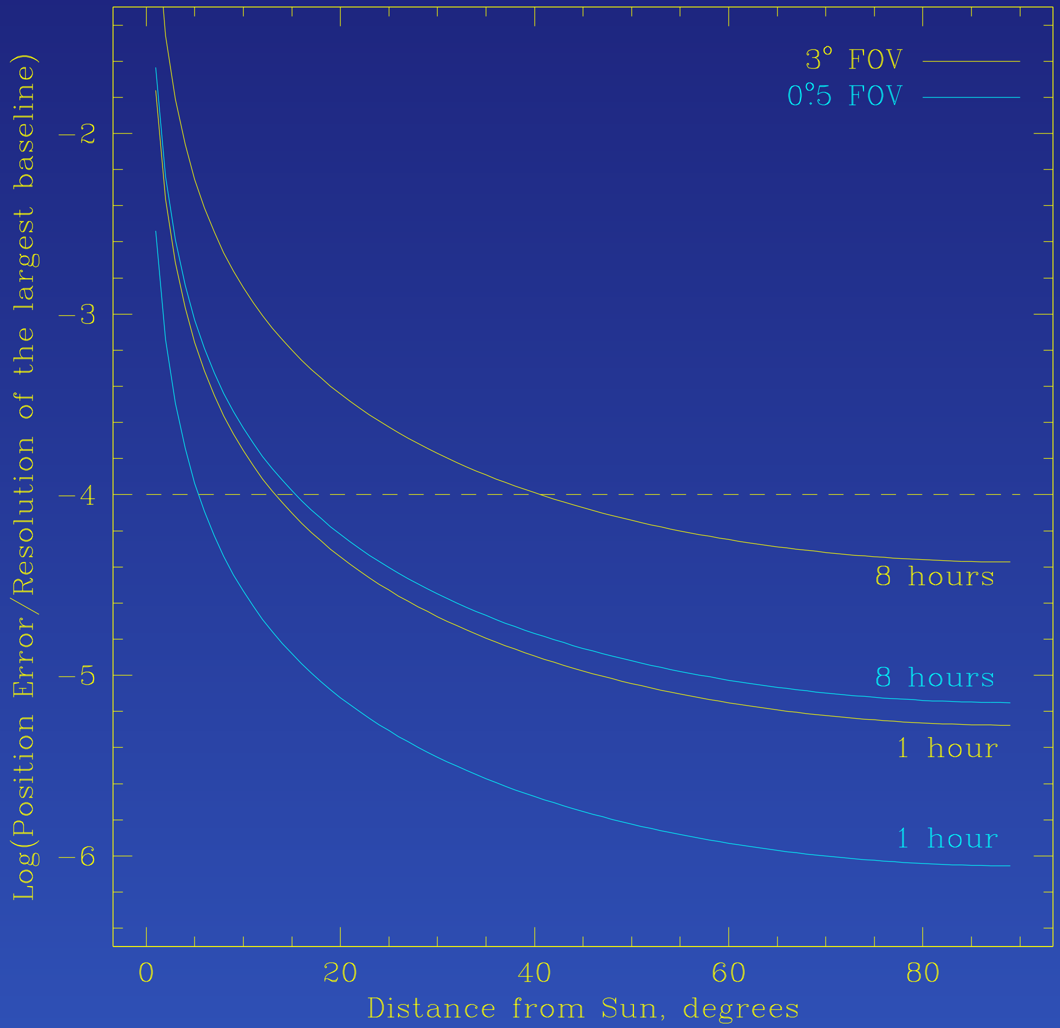


- Antennae are not stationary!
- By the time the wavefront reaches the second antenna it moves a bit
- To the first order the effect is the light aberration
- Non-inertial reference frame means the effect changes in time
- Differential effect across the field of view can affect the dynamic range in the SKA regime
- Algorithms similar to the faceting or W-projection can help

The following is only an approximation:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \frac{1}{\lambda} \begin{pmatrix} \sin H & \cos H & 0 \\ -\sin\delta\cos H & \sin\delta\sin H & \cos\delta \\ \cos\delta\cos H & -\cos\delta\sin H & \sin\delta \end{pmatrix} \begin{pmatrix} L_X \\ L_Y \\ L_Z \end{pmatrix}$$

One more (minor) challenge for SKA



- Differential gravitational bending $\longrightarrow$ time-dependent distortion
- First order estimate for position accuracy, short observations ($\ll 1$ year)

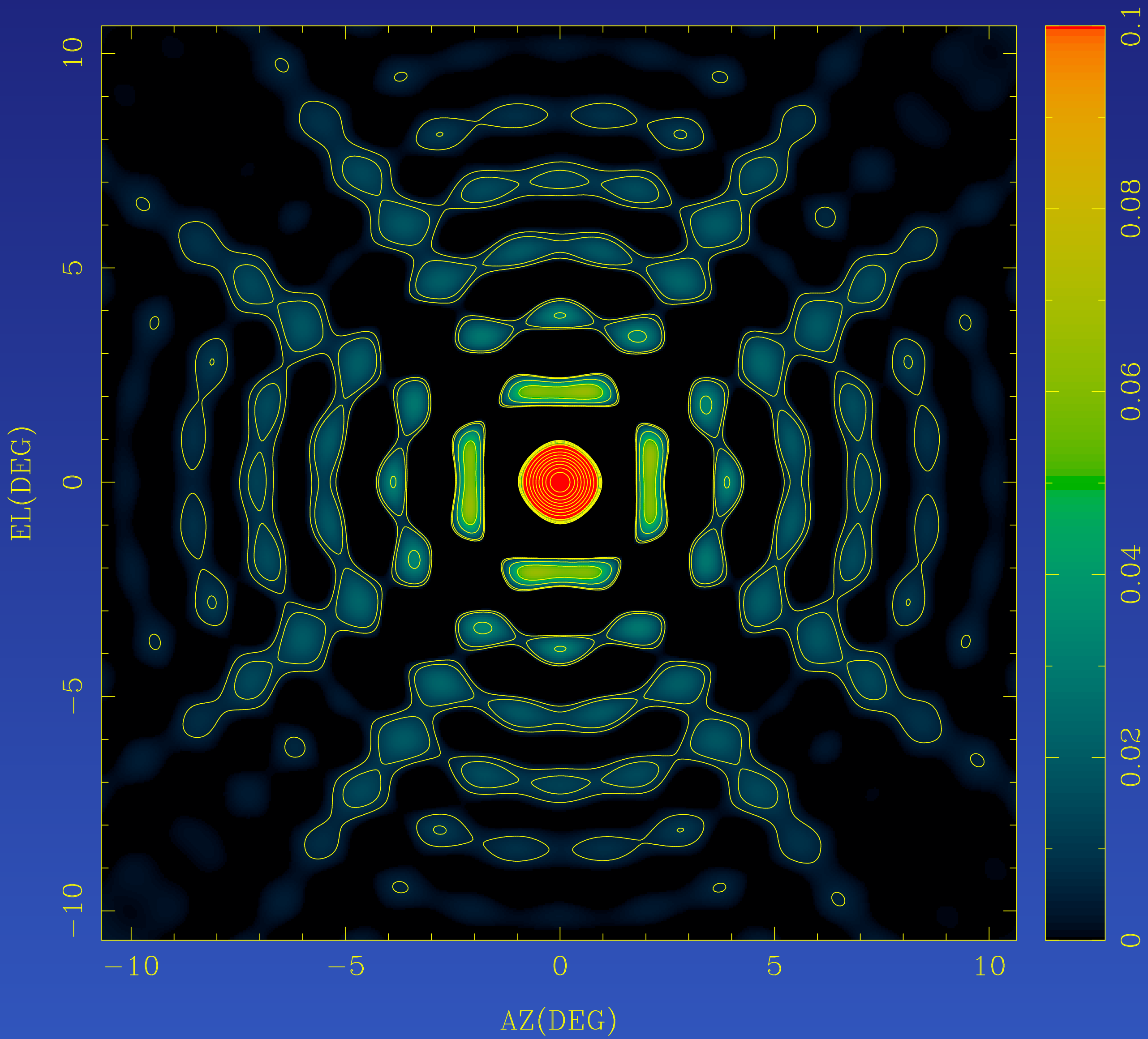
$$\varepsilon = \frac{2(1+\gamma ppn) G M_{\odot} \Delta\phi}{c^2 R \sin^2 \phi_0} \dot{\phi}_0 t_{obs},$$

ϕ_0, $\dot{\phi}_0$ – the angular separation between the phase centre and the Sun and its rate

$\Delta\phi$ – the source distance from the phase centre

γppn – post-Newtonian parameter (=1 in GR)

Primary beam

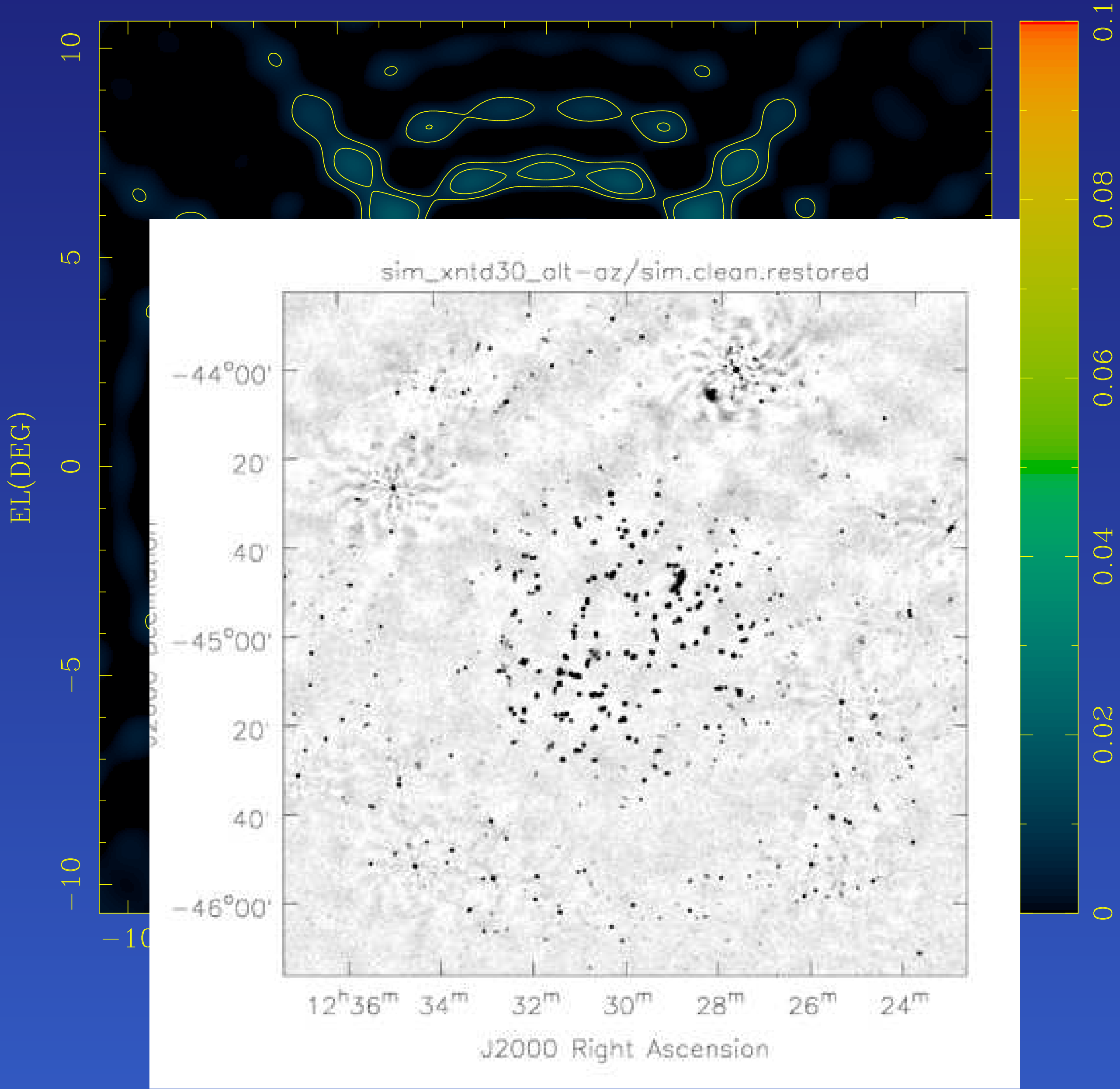


- Rotation of the primary beam causes artefacts
- Mainly due to sources in sidelobes

Possible solutions:

- Equatorial or sky mount
- Field rotator
- Electronic rotation
- Correct in software
- Good uv-coverage can also help!

Primary beam



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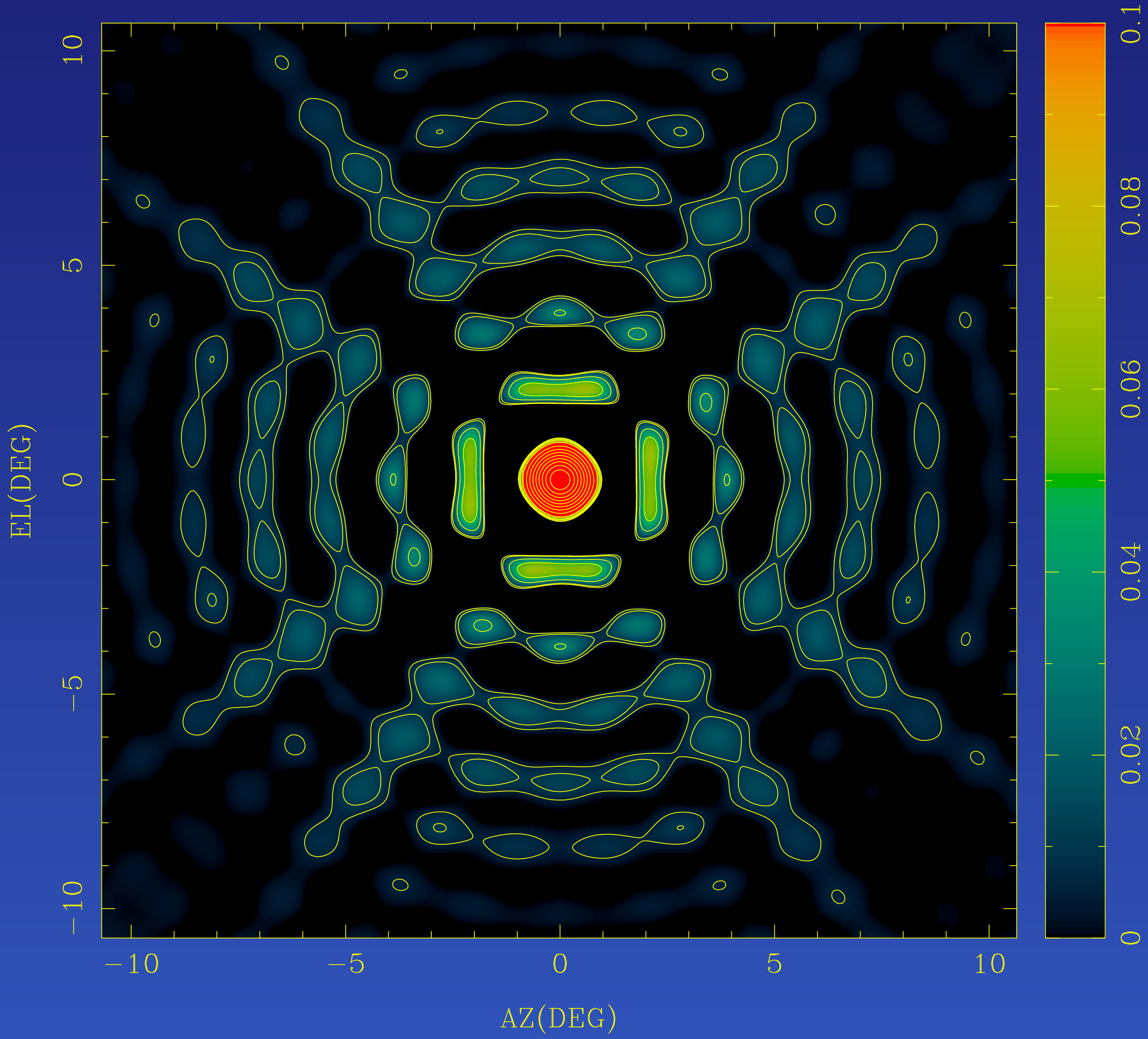
Tim Cornwell's simulations of ASKAP with an Alt-Az mount

Primary beam

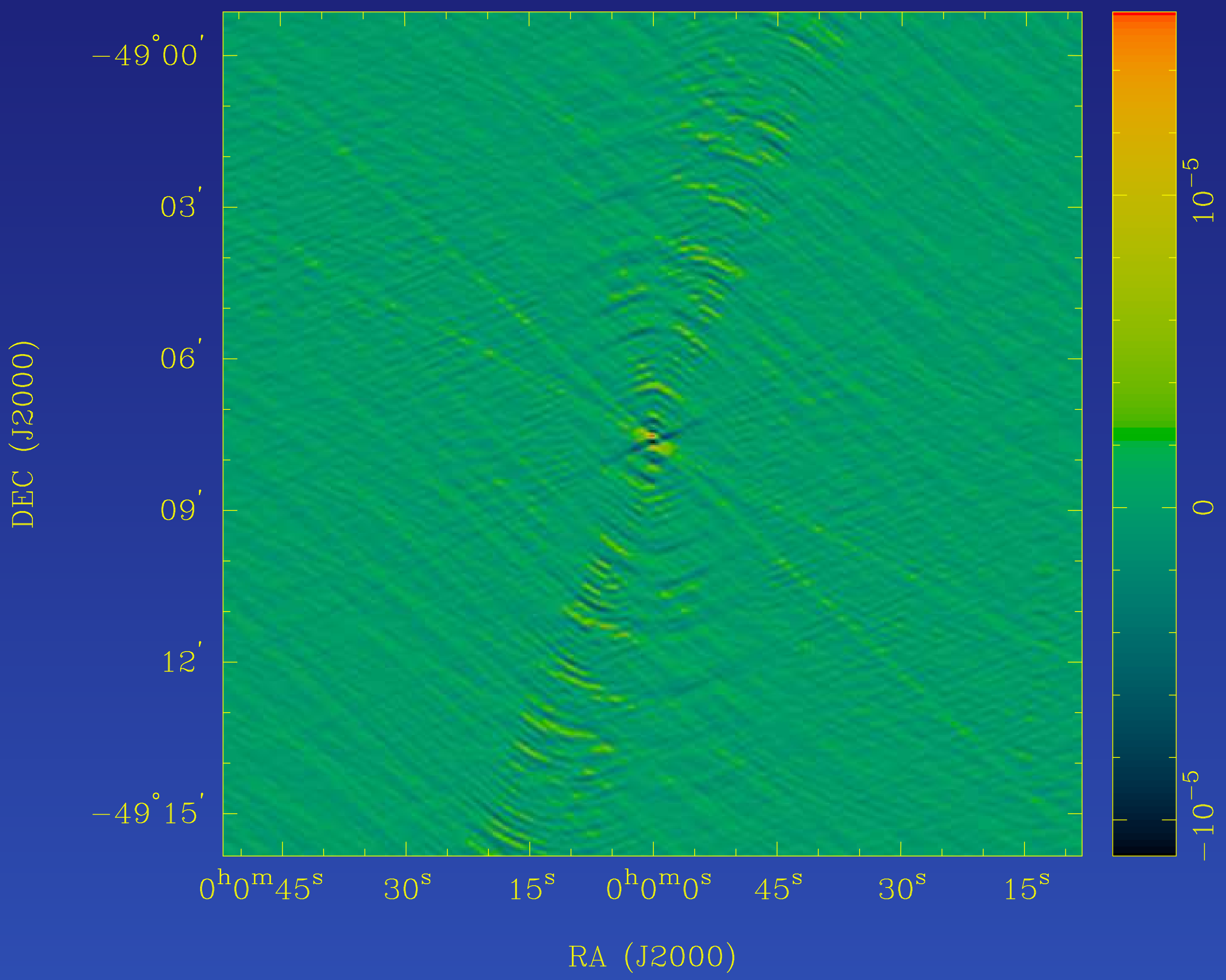


- Strictly speaking we should be dealing with voltage patterns (E_1 and E_2 for the first and the second antenna) rather than primary beams (A)

$$A(\theta,\varphi) = E_1(\theta,\varphi)E_2^*(\theta,\varphi)$$

- Pointing errors cause both amplitude and phase variations of sources

Pointing errors



- Cause amplitude and phase variations
- More significant away from the pointing centre
- Good uv-coverage can minimize the problem!
- ATCA simulations: the effect can be ignored unless we need a dynamic range higher than 5×10^4.

- Bhatnagar et al. (2004), EVLA Memo #84 $\Rightarrow$ we can solve for pointing errors and correct them to some degree
- Multi-feed systems: solve on-the-fly

Peeling algorithm

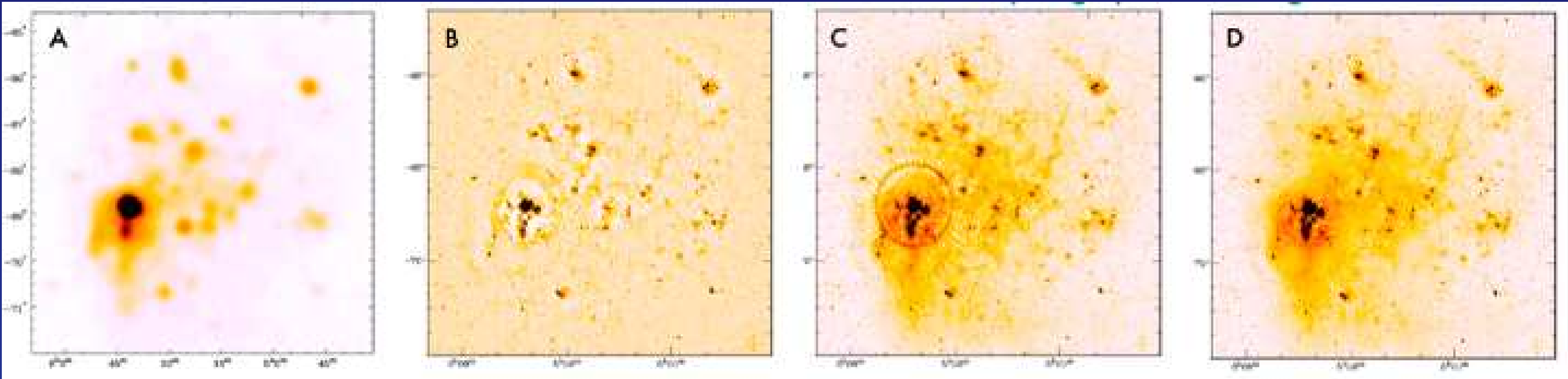


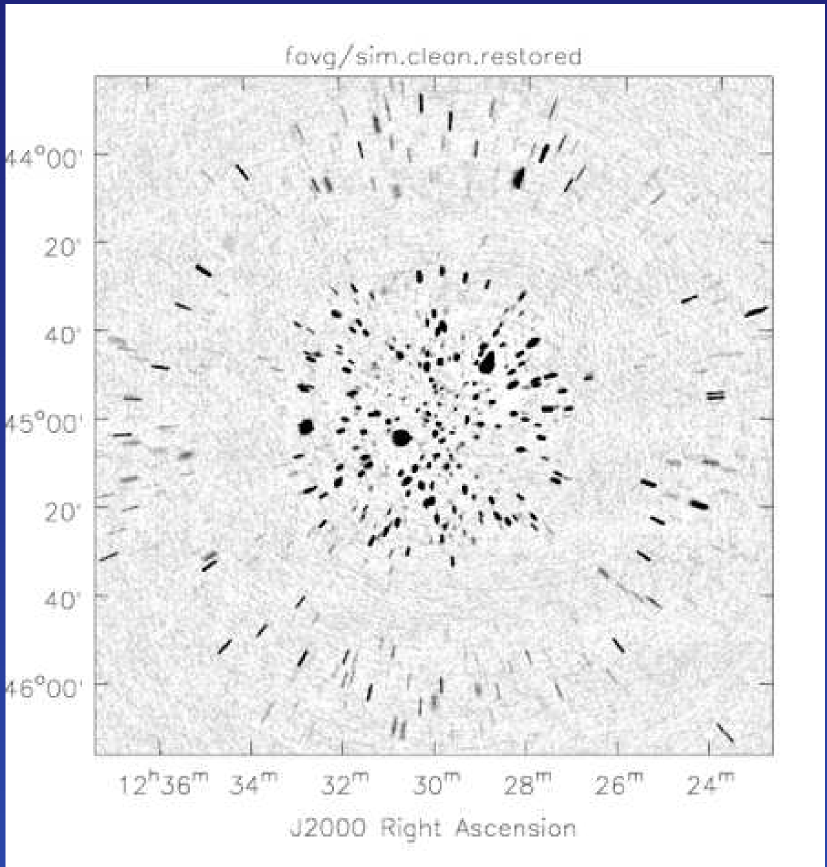
Figure 2 a) Parkes map b) ATCA mosaic c) Original ATCA+Parkes mosaic d) ATCA+Parkes mosaic after peeling technique applied.

Image credit: Tim Cornwell

- All these weak effects are a nuisance. It's too hard to put all of them into the measurement equation.
- Usually a number of sources causing problems is small and they are rather compact $\Rightarrow$ peeling is the solution

- Self-calibrate separately for different parts of the image
- Subtract the source out, iterate if necessary
- Time varying "local" gains account for weak effects not present in the measurement equation.

Bandwidth and time averaging smearing



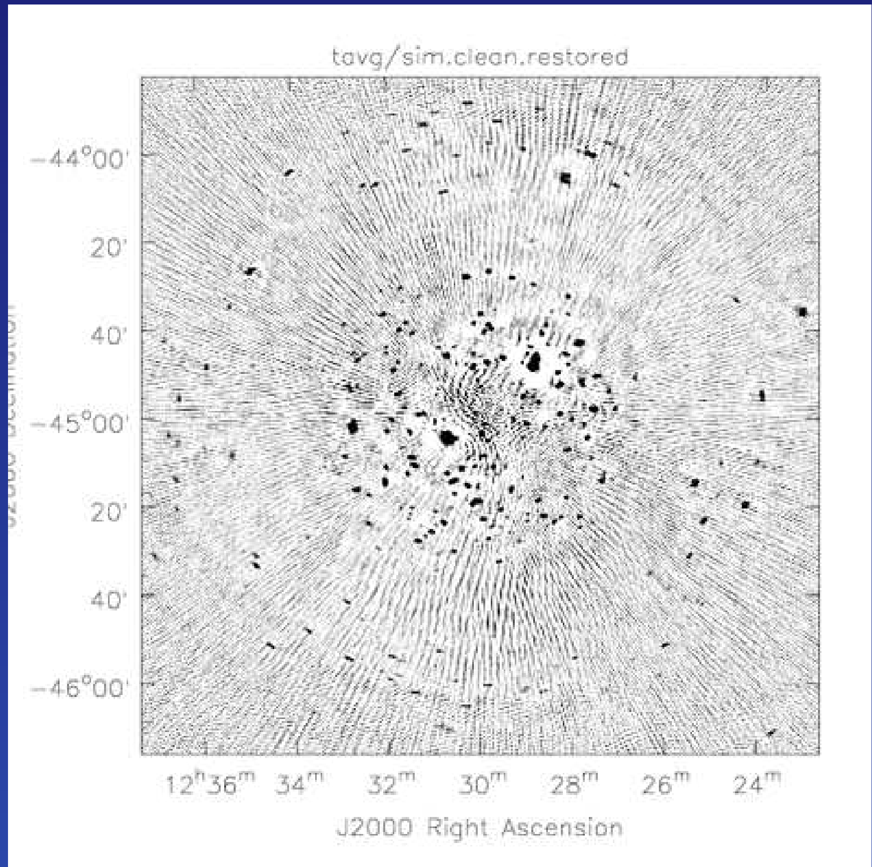


Image credit: Tim Cornwell

- Cause: averaging too much in the uv-plane
  - Frequency change scales u and v measured in wavelengths
  - Time change cause rotation to a different point on the uv-track
- Solution: reobserve with a higher spectral resolution or a finer sampling in time

Summary

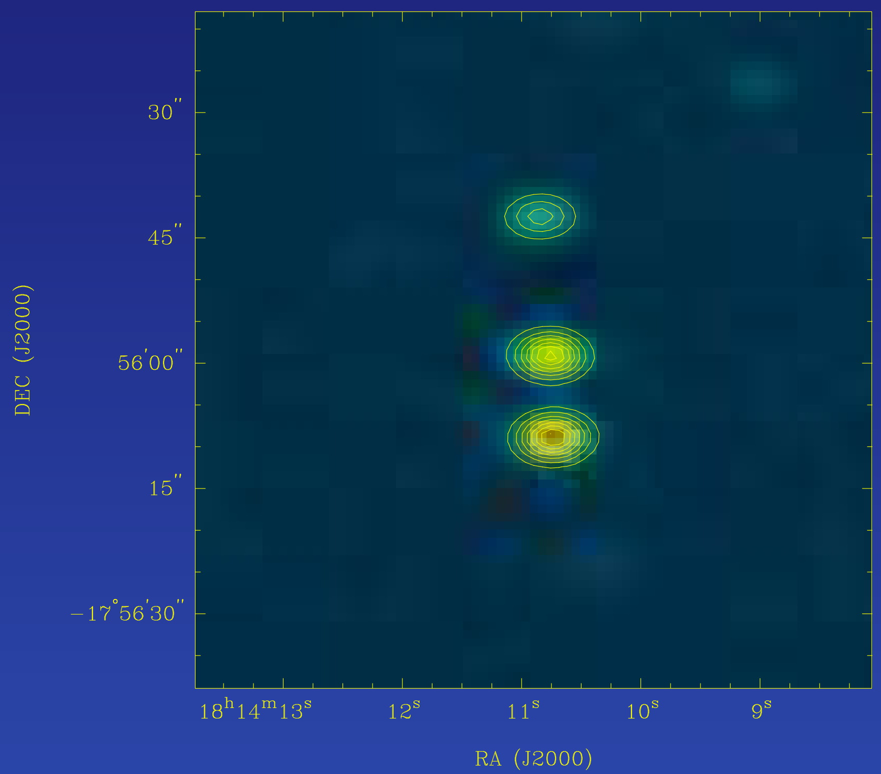
- Dynamic range is limited because the measurement equation is wrong!
- The problems become more difficult for large baselines and large field of view
- Wide-field effects can be a limiting factor for the new telescopes like ASKAP and SKA
- Nice algorithms already exist (peeling, w-projection) and the new ones are under development
- Many more effects exist (e.g. ionosphere is a big topic by itself)!

What went wrong?

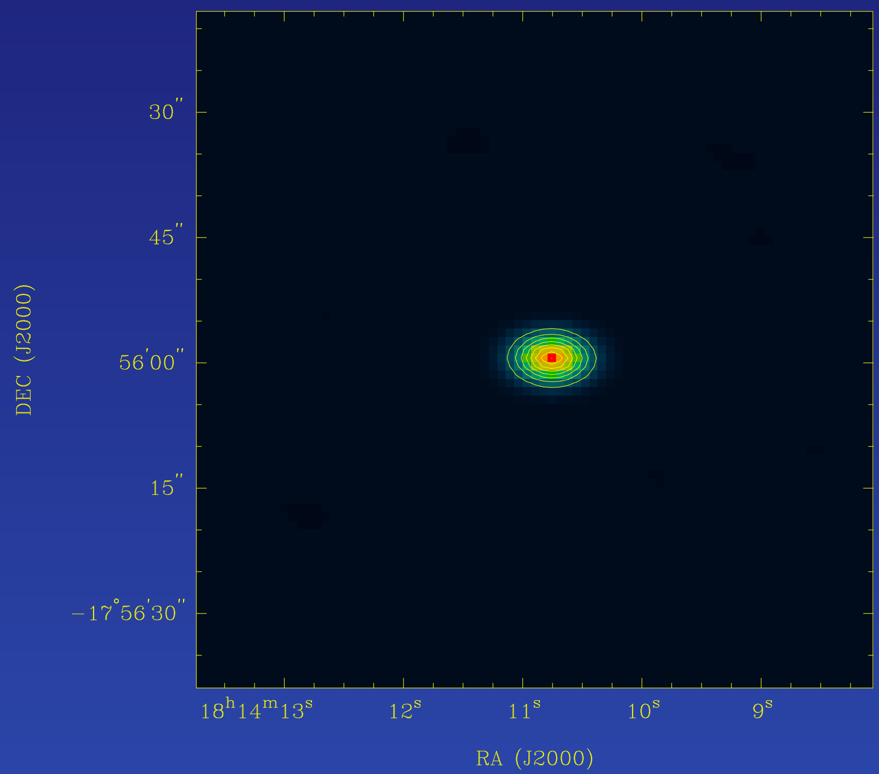
Review of the advanced data reduction tutorials

Advanced tutorial 1

After calibration on 1730-130

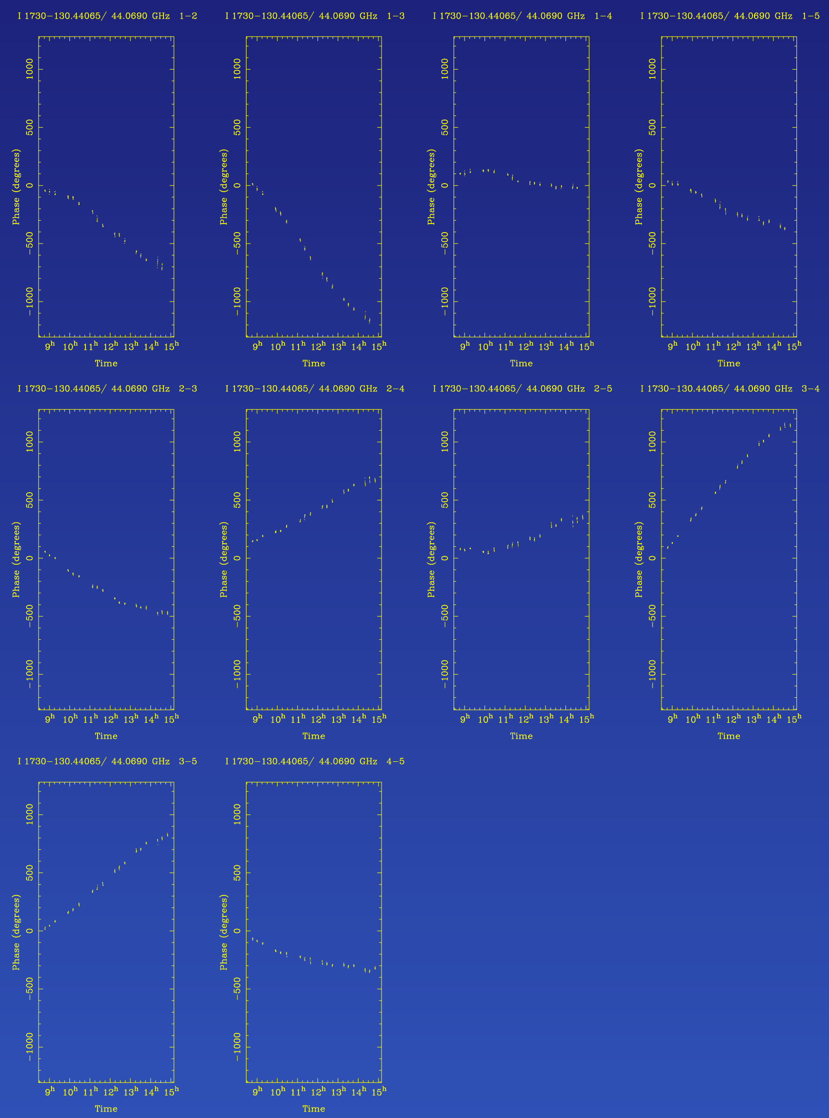


After selfcal



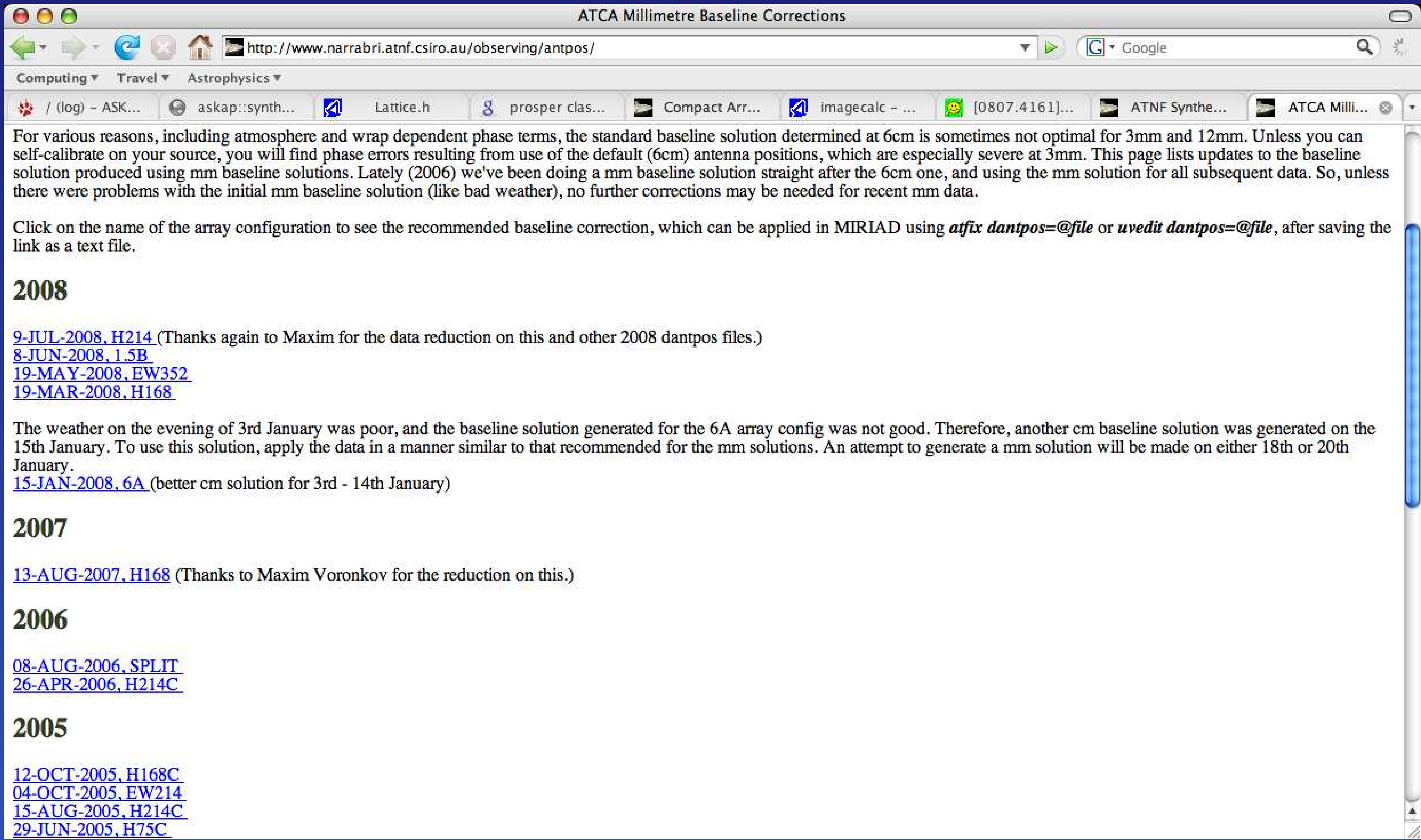
- Images of the 44 GHz methanol maser in W33-Met
- A number of spots after ordinary calibration using 1730-130 peak at exactly the same velocity
- This structure looks spurious and the self-calibration makes a single blob out of it.

Is it a weather or antenna position errors?



- Secondary calibrator phases look reasonable
- Log book doesn't mention any obvious errors or bad weather
- Seeing monitor output looks reasonable
- Worth considering antenna position errors!
- Unless a number of calibrators all over the sky has been observed it is hard to solve for updates of antenna positions

Where to look for updated antenna locations (baseline solution)?



For various reasons, including atmosphere and wrap dependent phase terms, the standard baseline solution determined at 6cm is sometimes not optimal for 3mm and 12mm. Unless you can self-calibrate on your source, you will find phase errors resulting from use of the default (6cm) antenna positions, which are especially severe at 3mm. This page lists updates to the baseline solution produced using mm baseline solutions. Lately (2006) we've been doing a mm baseline solution straight after the 6cm one, and using the mm solution for all subsequent data. So, unless there were problems with the initial mm baseline solution (like bad weather), no further corrections may be needed for recent mm data.

Click on the name of the array configuration to see the recommended baseline correction, which can be applied in MIRIAD using ***atfix dantpos=@file*** or ***uvedit dantpos=@file***, after saving the link as a text file.

2008

9-JUL-2008, H214 (Thanks again to Maxim for the data reduction on this and other 2008 dantpos files.)
8-JUN-2008, 1.5B
19-MAY-2008, EW352
19-MAR-2008, H168

The weather on the evening of 3rd January was poor, and the baseline solution generated for the 6A array config was not good. Therefore, another cm baseline solution was generated on the 15th January. To use this solution, apply the data in a manner similar to that recommended for the mm solutions. An attempt to generate a mm solution will be made on either 18th or 20th January.
15-JAN-2008, 6A (better cm solution for 3rd - 14th January)

2007

13-AUG-2007, H168 (Thanks to Maxim Voronkov for the reduction on this.)

2006

08-AUG-2006, SPLIT
26-APR-2006, H214C

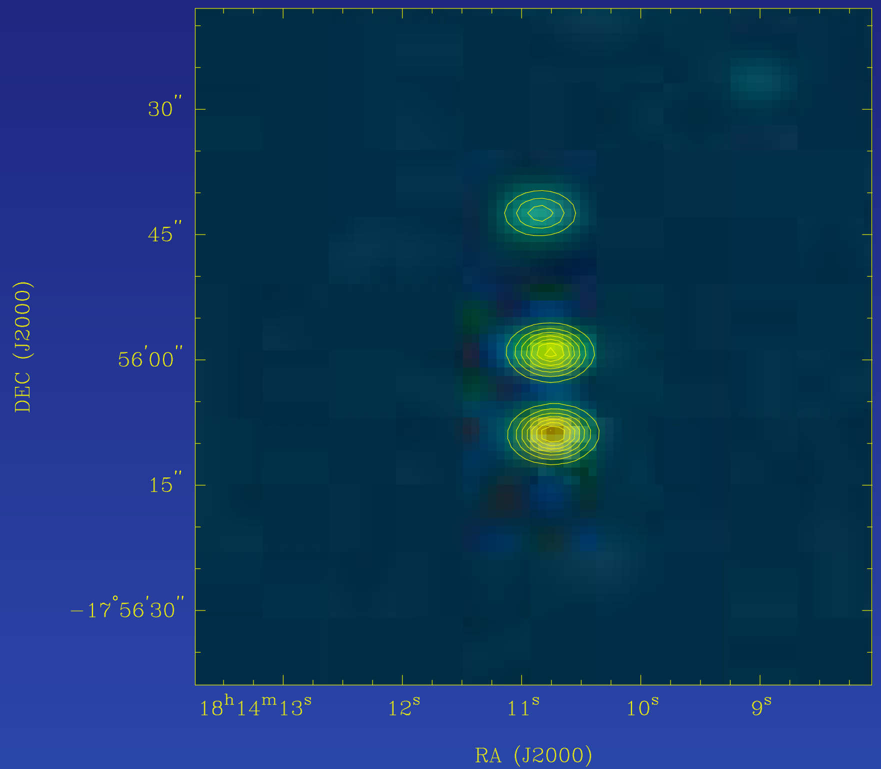
2005

12-OCT-2005, H168C
04-OCT-2005, EW214
15-AUG-2005, H214C
29-JUN-2005, H75C

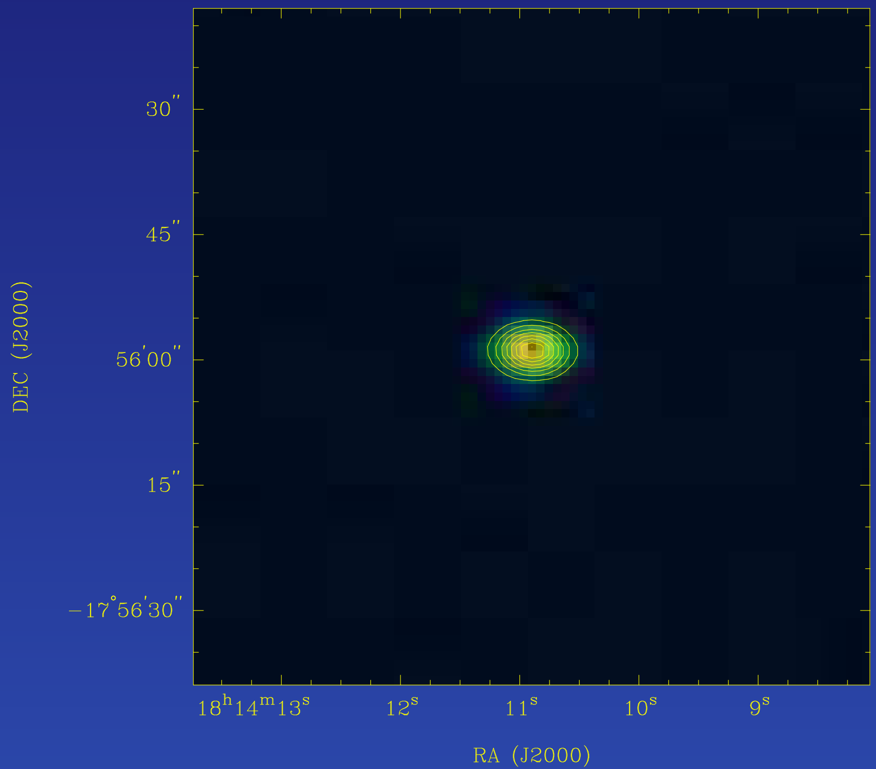
If no solution is available and you suspect that antenna positions have a significant error, it is worth asking someone local....

Processing with more accurate antenna positions

Before *atfix*



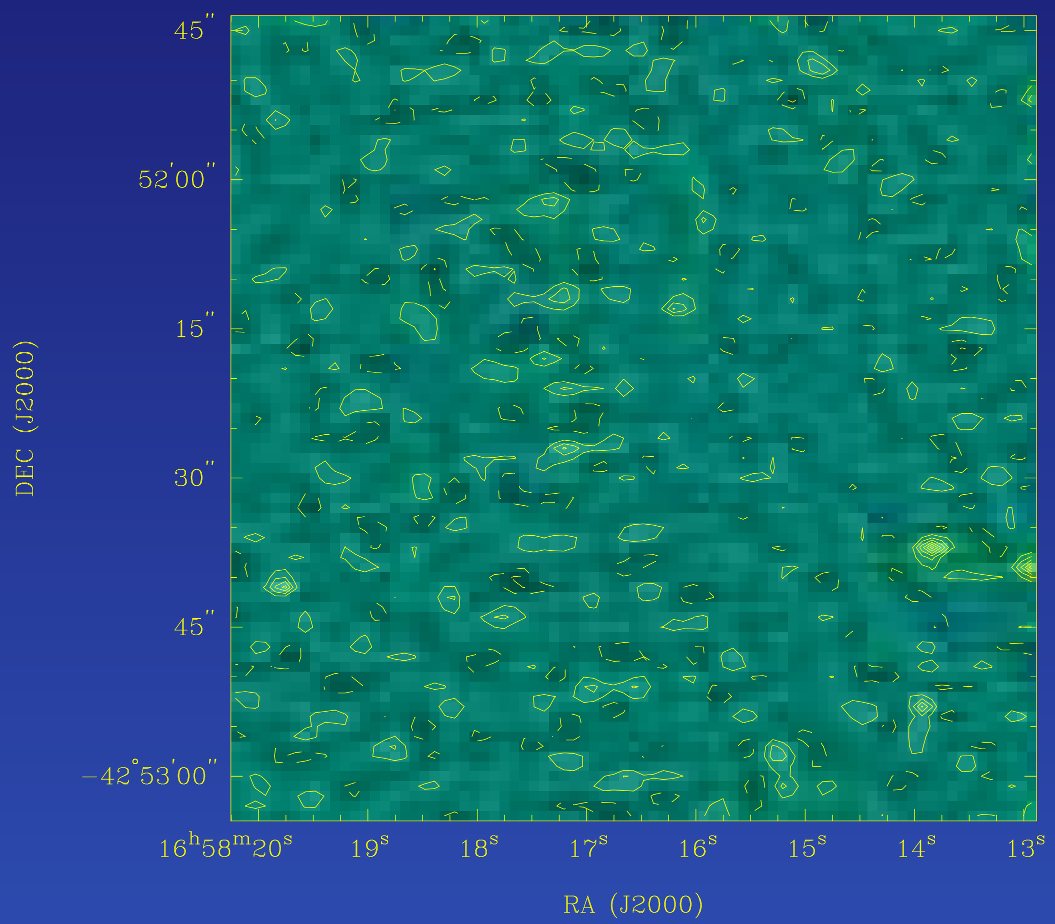
After *atfix*



$$\begin{pmatrix} \Delta u \\ \Delta v \\ \Delta w \end{pmatrix} = \frac{1}{\lambda} \begin{pmatrix} \sin H & \cos H & 0 \\ -\sin\delta\cos H & \sin\delta\sin H & \cos\delta \\ \cos\delta\cos H & -\cos\delta\sin H & \sin\delta \end{pmatrix} \begin{pmatrix} \Delta L_X \\ \Delta L_Y \\ \Delta L_Z \end{pmatrix}$$

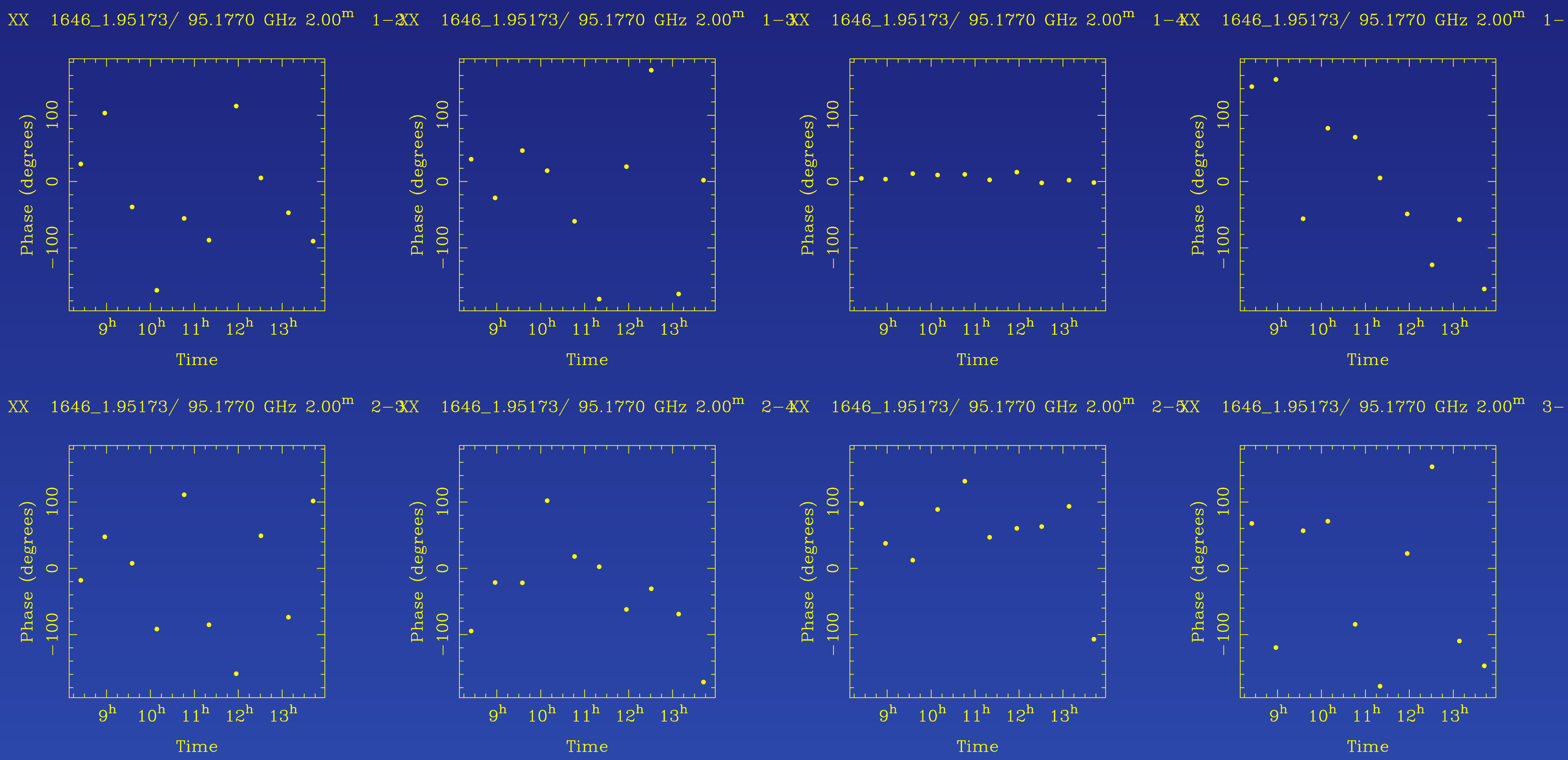
Fourier integral got an additional phase term $e^{-2\pi i(\Delta u l + \Delta v m)}$

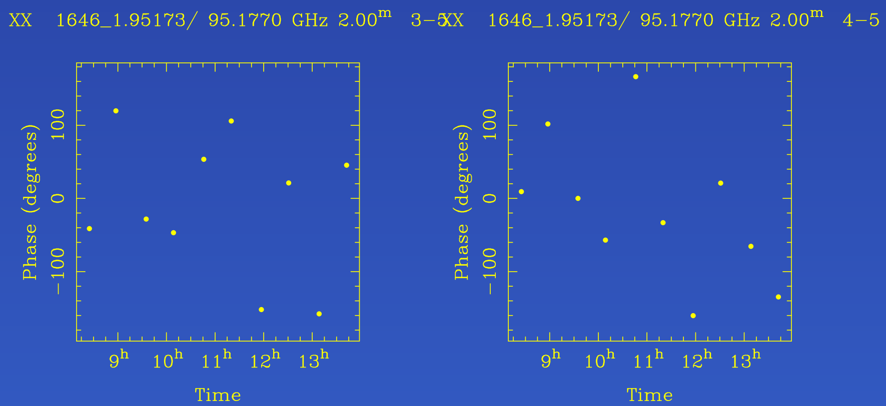
Advanced tutorial 2



- Image of the 95 GHz methanol maser in G343.12-0.06 following a blind data reduction
- But no one should have gone that far!

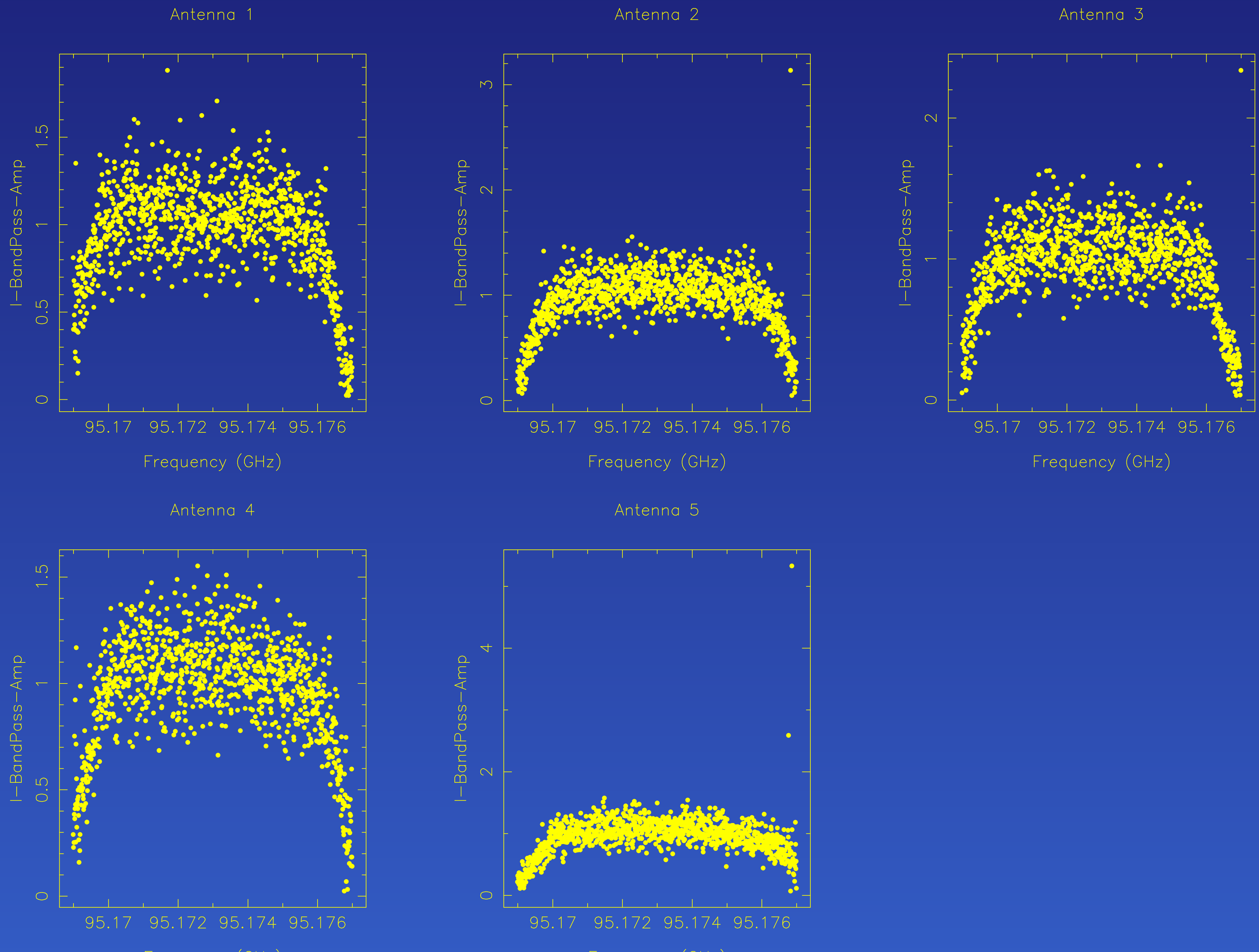
Calibrator phases (1646-50)



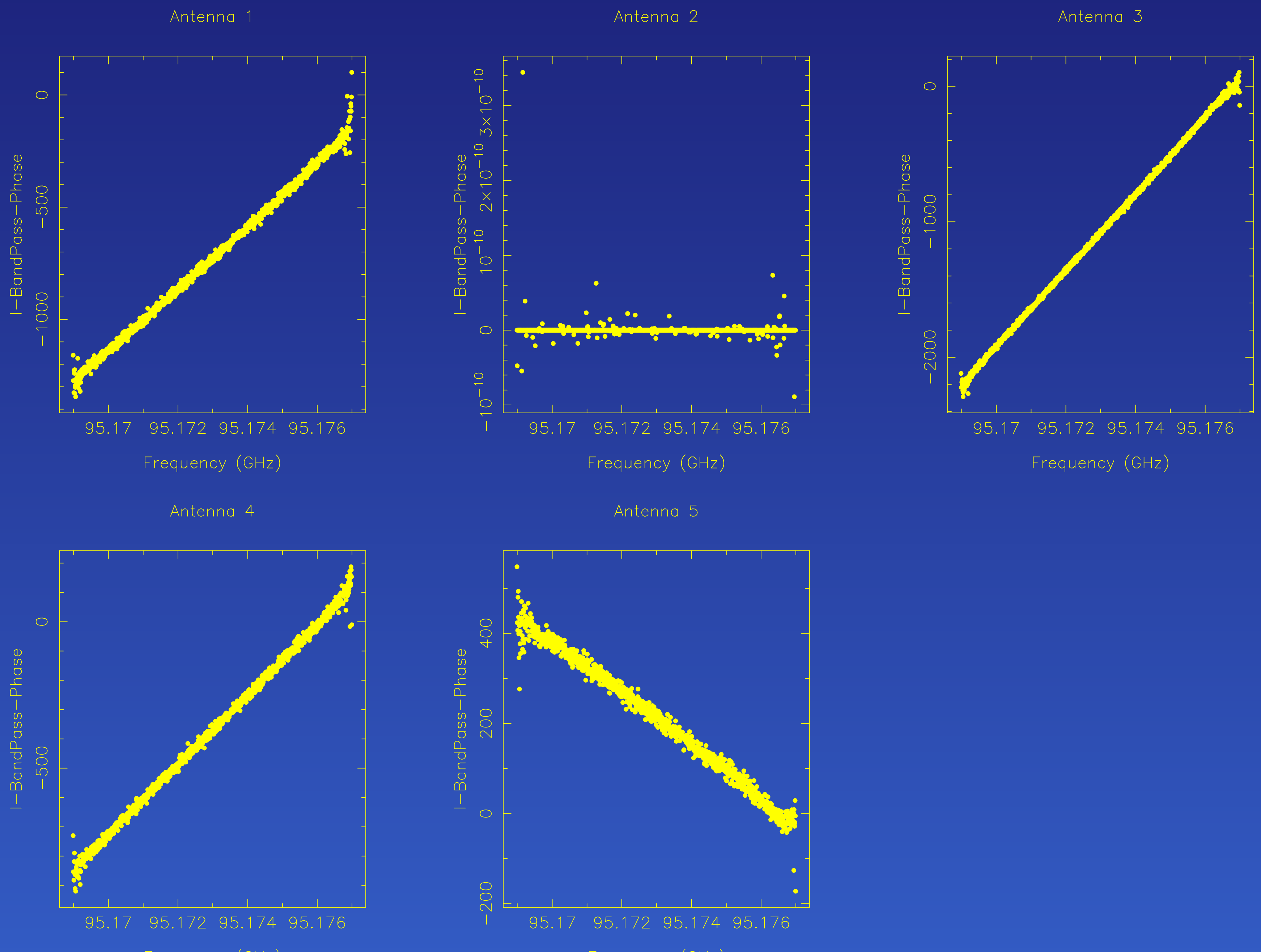


$$\tilde{V}_{12} = g_1(\nu) g_2^*(\nu) g_1 g_2^* V_{12}$$

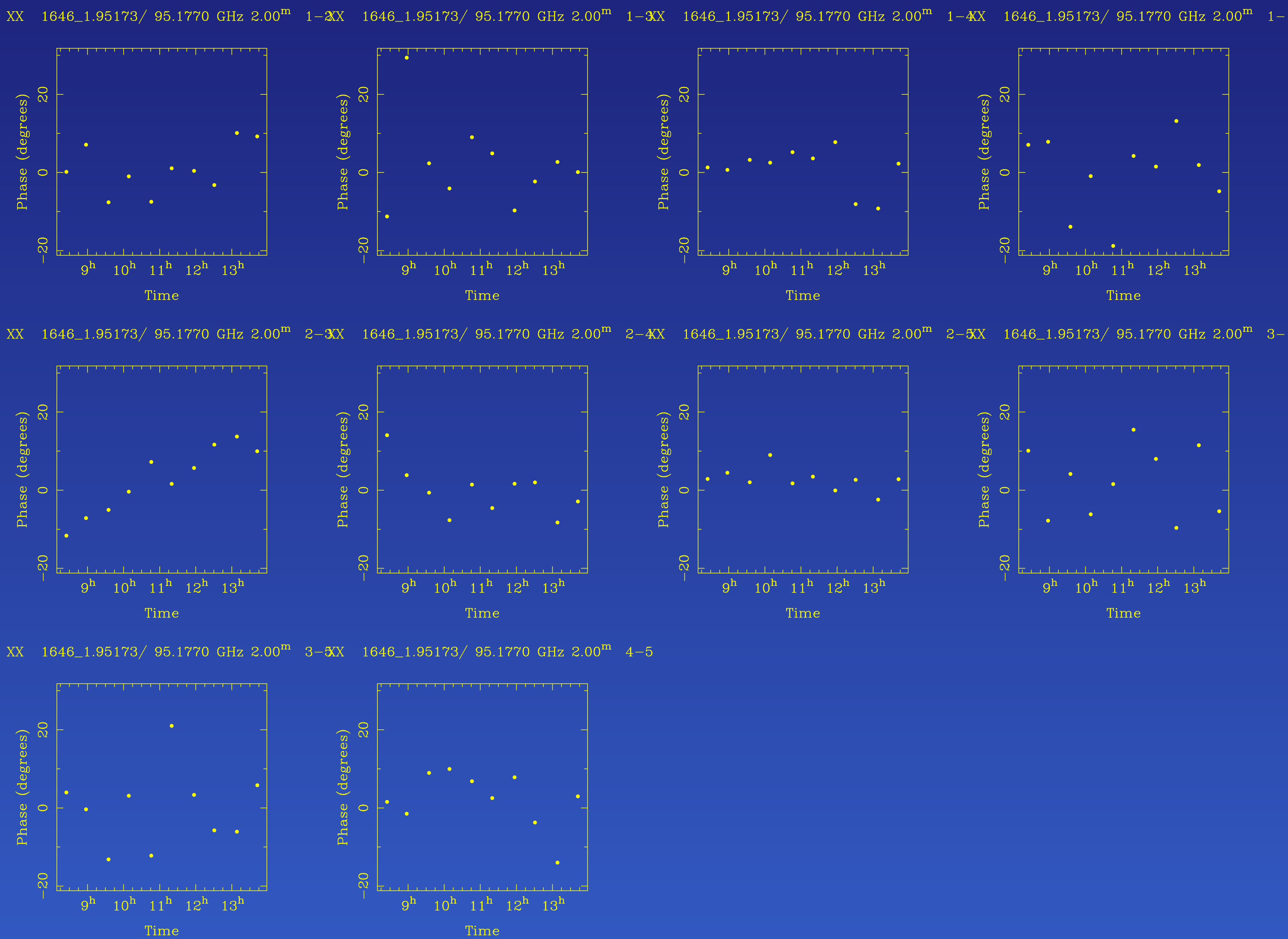
Bandpass amplitudes (1921-293)



Bandpass amplitudes (1921-293)

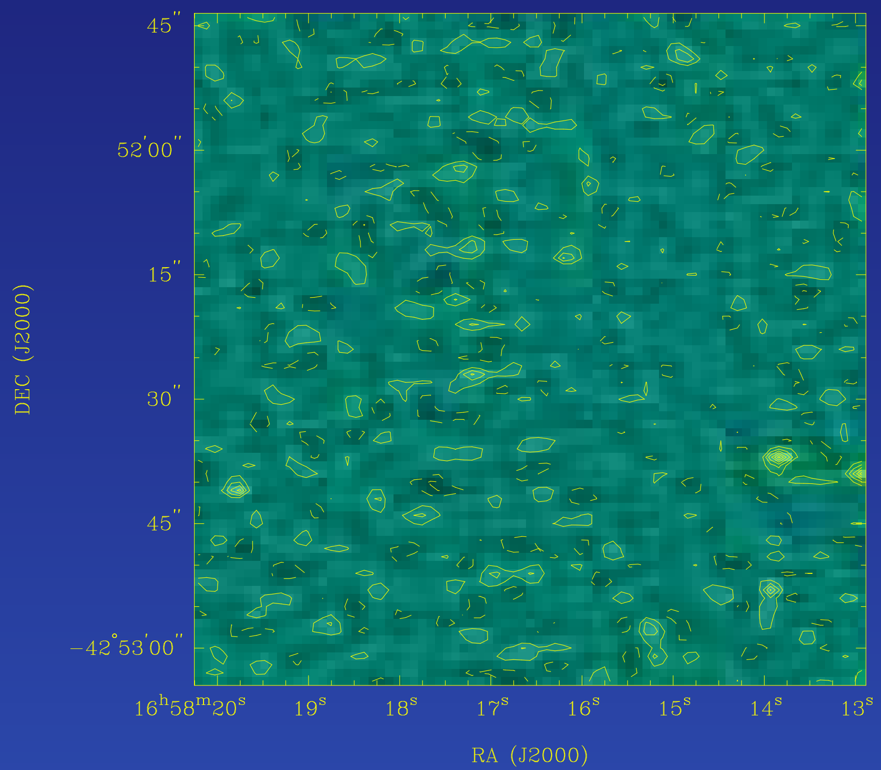


Calibrator (1646-50) phases after bandpass correction

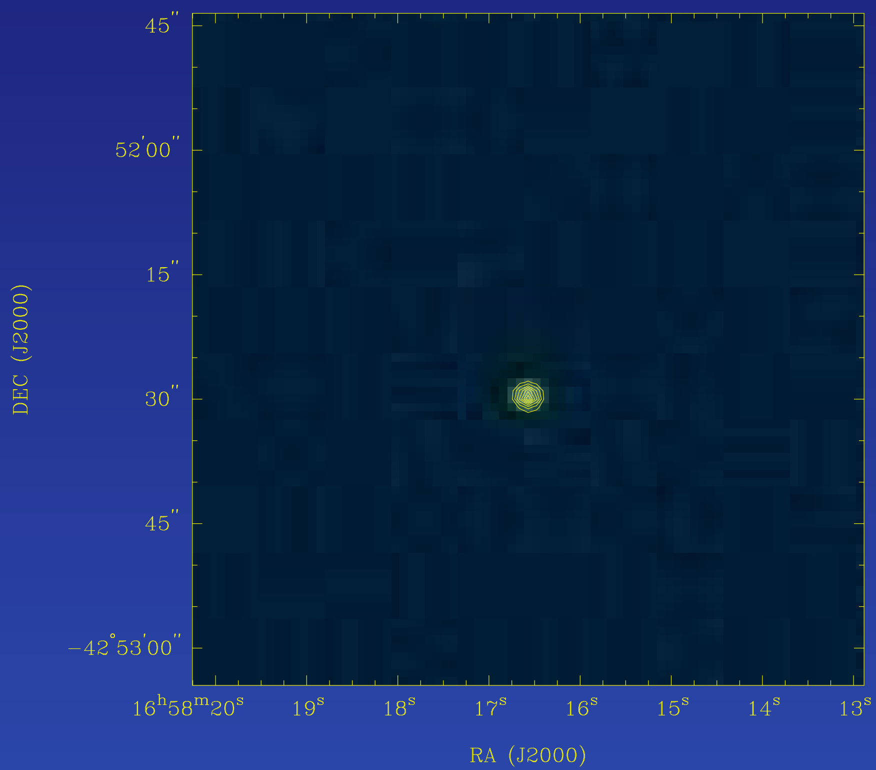


Processing with and without bandpass

Without bandpass



With bandpass



- Message: include observation of a bandpass calibrator even if you don't need it for your science!