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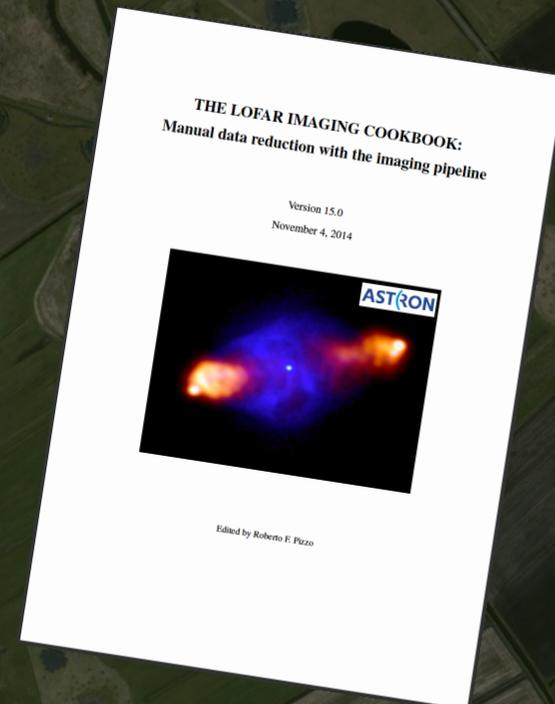
university of
 groningen

Calibrating LOFAR data

John McKean (ASTRON / Kapteyn
 Astronomical Institute, Groningen)

- **AIM:** This lecture aims to give a general overview to the calibration of LOFAR imaging synthesis data.
- **TOPICS:**
 - 1) The radio interferometric measurement equation (ME)
 - 2) The calibration strategy and Black Board Self-calibration (BBS)
 - 3) Sky models
 - 4) Beam models
 - 5) Direction dependent calibration
 - 6) Inspecting solutions
 - 7) Wide-bandwidth calibration
- **REFERENCE:** The LOFAR Imaging Cookbook

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- **RIME:** The radio interferometer measurement equation, as used by CASA etc. for the calibration,

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true visibility for
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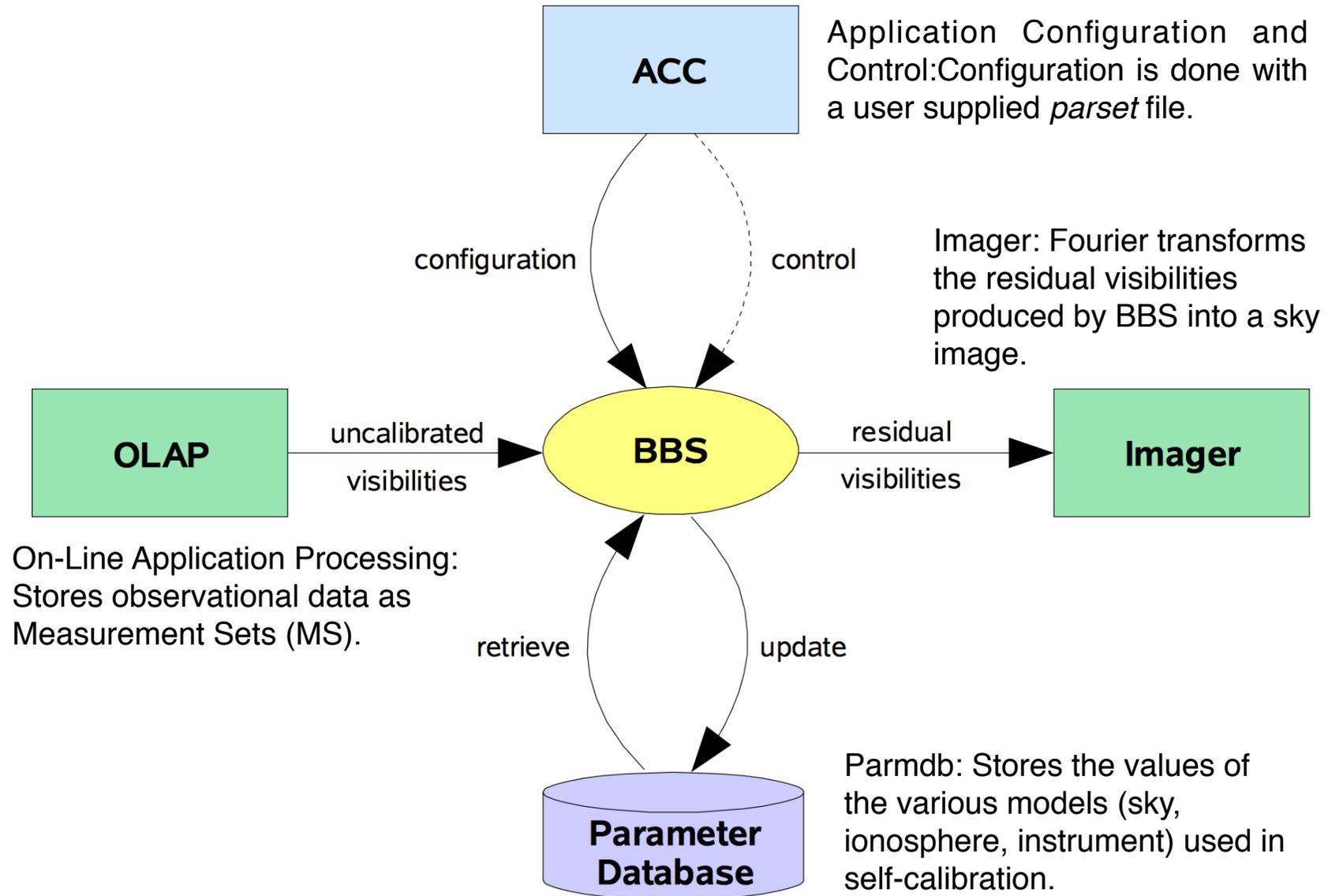
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- **Calibration** involves solving this inverse problem to determine what set of parameters are needed to minimise the difference between the *observed* visibilities and the *model* visibilities (our best guess at the *true* visibilities).

- **Black Board Self-calibration (BBS)** is a software package that is designed for the **calibration** and **simulation** of LOFAR data. Needed because:
 - 1) LOFAR data is very large (6 h observation can be >100 TB), needs to be processed in a distributed fashion.
 - 2) Must account for direction dependent effects.
- The term “Black Board” relates to the chosen architecture that has been implemented to control the calibration on a distributed cluster - many of the calculations are done on the local nodes, only management through databases is needed globally.
- BBS can be run in two ways:
 - Standalone: The calibration of 1 sub-band.
 - Global parameter estimation: The calibration of multiple sub-bands.

```
> calibrate-stand-alone -f <MS> <parset> <source catalog>
```



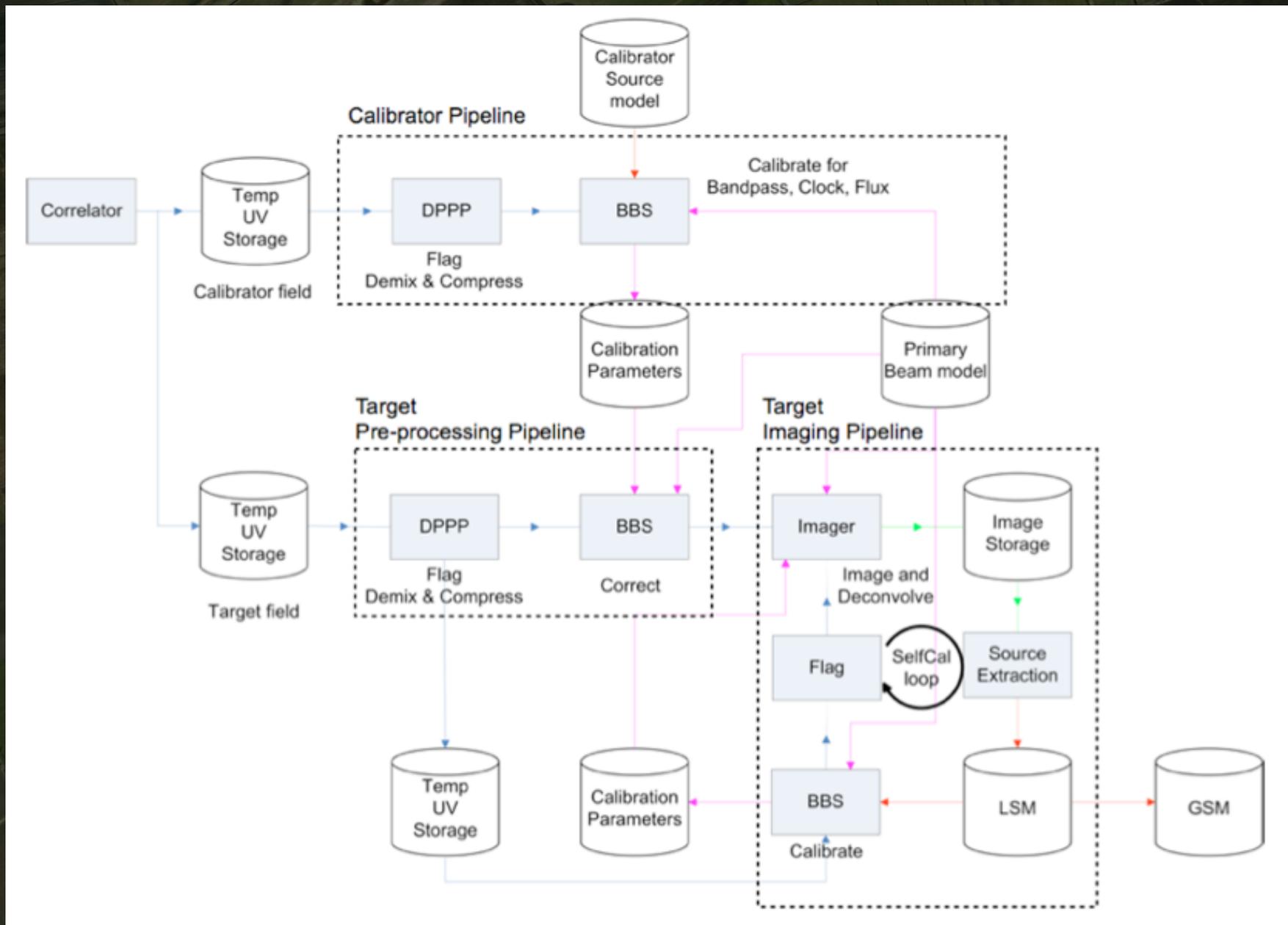
- The BBS kernel (the bit that does the work) can support an number of operations that are carried out locally on each compute node,
 1. **PREDICT**: Predict (simulate) visibilities based on a model that describes the sky, the environment (e.g. ionosphere), and the instrument.
 2. **SUBTRACT**: Predict visibilities for one or more source(s) and subtract the result from the observed visibilities.
 3. **CORRECT**: Correct the observed visibilities for a given reference (source) direction.
 4. **SHIFT**: Phase shift the observed visibilities to a different phase centre.
 5. **GENERATE EQUATIONS**: Generate condition equations in a form that can be fed to the solver. Condition equations relate the model parameters to the difference between the observed visibilities and the predicted visibilities (based on the model).
- This information is used globally to carry out the operation,
 6. **SOLVE**: Determines the calibration parameters.

```
Strategy.ChunkSize = 0
Strategy.Steps = [solve,correct]

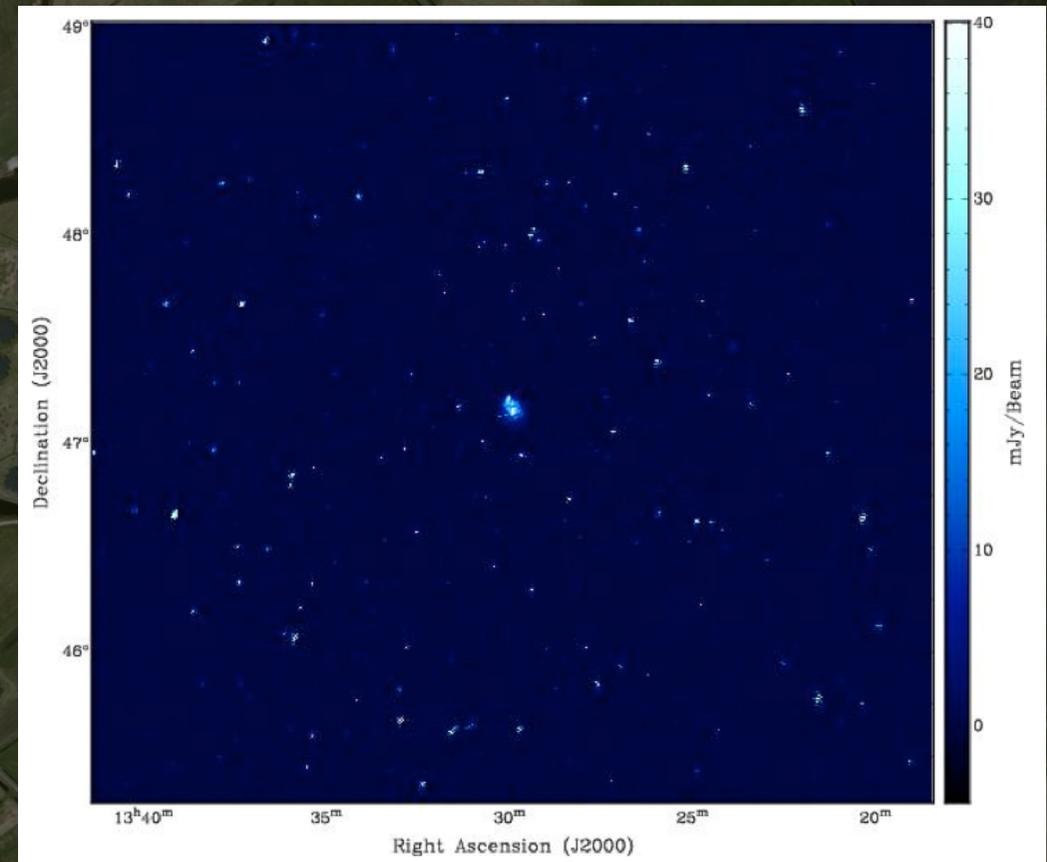
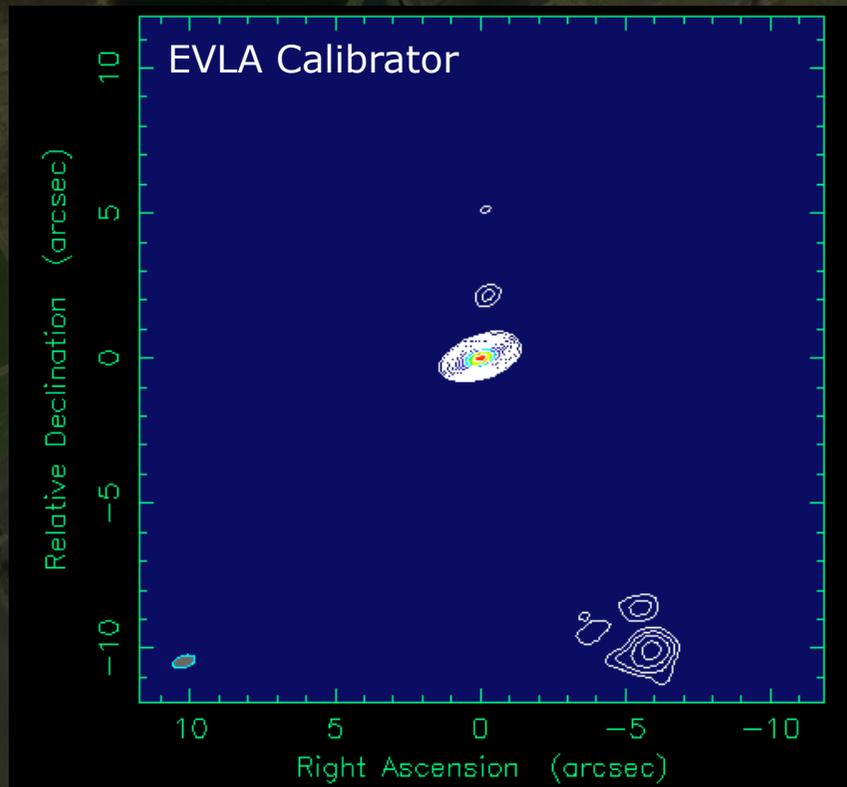
Step.solve.Operation = SOLVE
Step.solve.Model.Sources = [3c48]
Step.solve.Model.Gain.Enable = T
Step.solve.Model.Beam.Enable = T
Step.solve.Solve.Parms = ["Gain:0:0:*","Gain:1:1:*"]
Step.solve.Solve.CellSize.Freq = 0
Step.solve.Solve.CellSize.Time = 1
Step.solve.Solve.CellChunkSize = 10
Step.solve.Solve.Options.MaxIter = 50
Step.solve.Solve.Options.EpsValue = 1e-9
Step.solve.Solve.Options.EpsDerivative = 1e-9
Step.solve.Solve.Options.ColFactor = 1e-9
Step.solve.Solve.Options.LMFactor = 1.0
Step.solve.Solve.Options.BalancedEqs = F
Step.solve.Solve.Options.UseSVD = T

Step.correct.Operation = CORRECT
Step.correct.Model.Gain.Enable = T
Step.correct.Model.Beam.Enable = T
Step.correct.Model.Sources = [3c48]
Step.correct.Output.Column = CORRECTED_DATA
```

The standard imaging pipeline



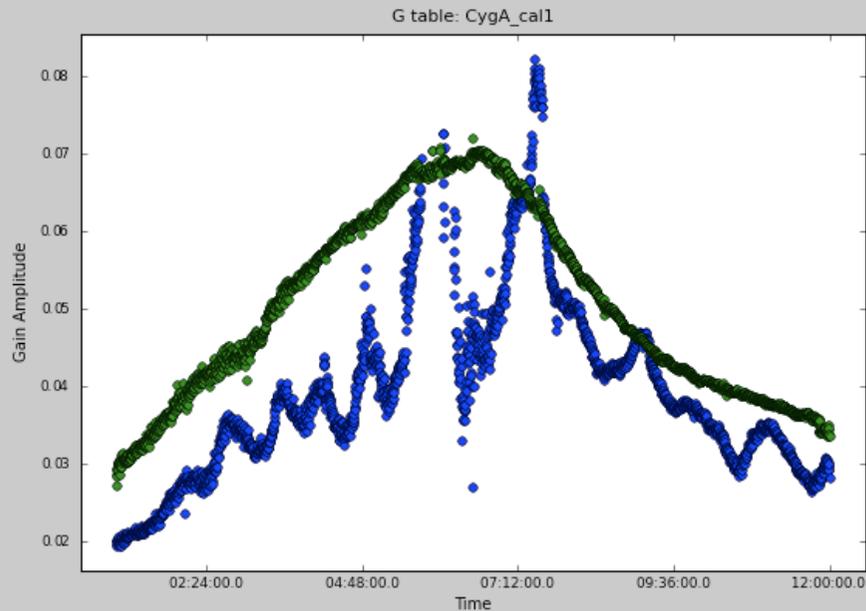
- To determine our calibration parameters (the elements in our Jones Matrices) we need to compare the *observed* (corrupted) visibilities with the *real* visibilities... need to use a model for the sky.



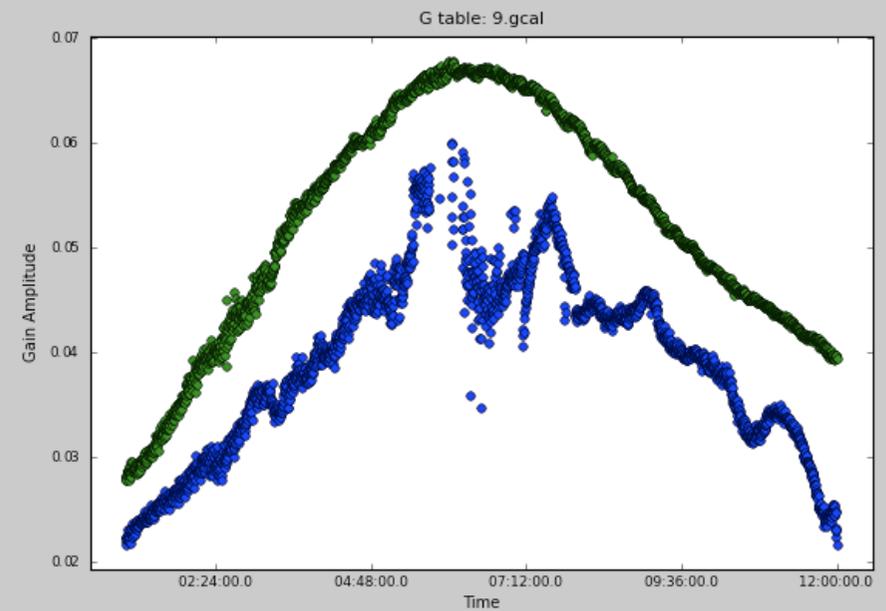
- In beam calibration can be used: **Good** because the amplitude and phase variations can be tracked over time, but **bad** because the model is complicated.

The effect of a poor model

- Need good models of structure on the smallest-scales to calibrate the 30--100 km Remote Stations - **Your calibration is only as good as your model!**



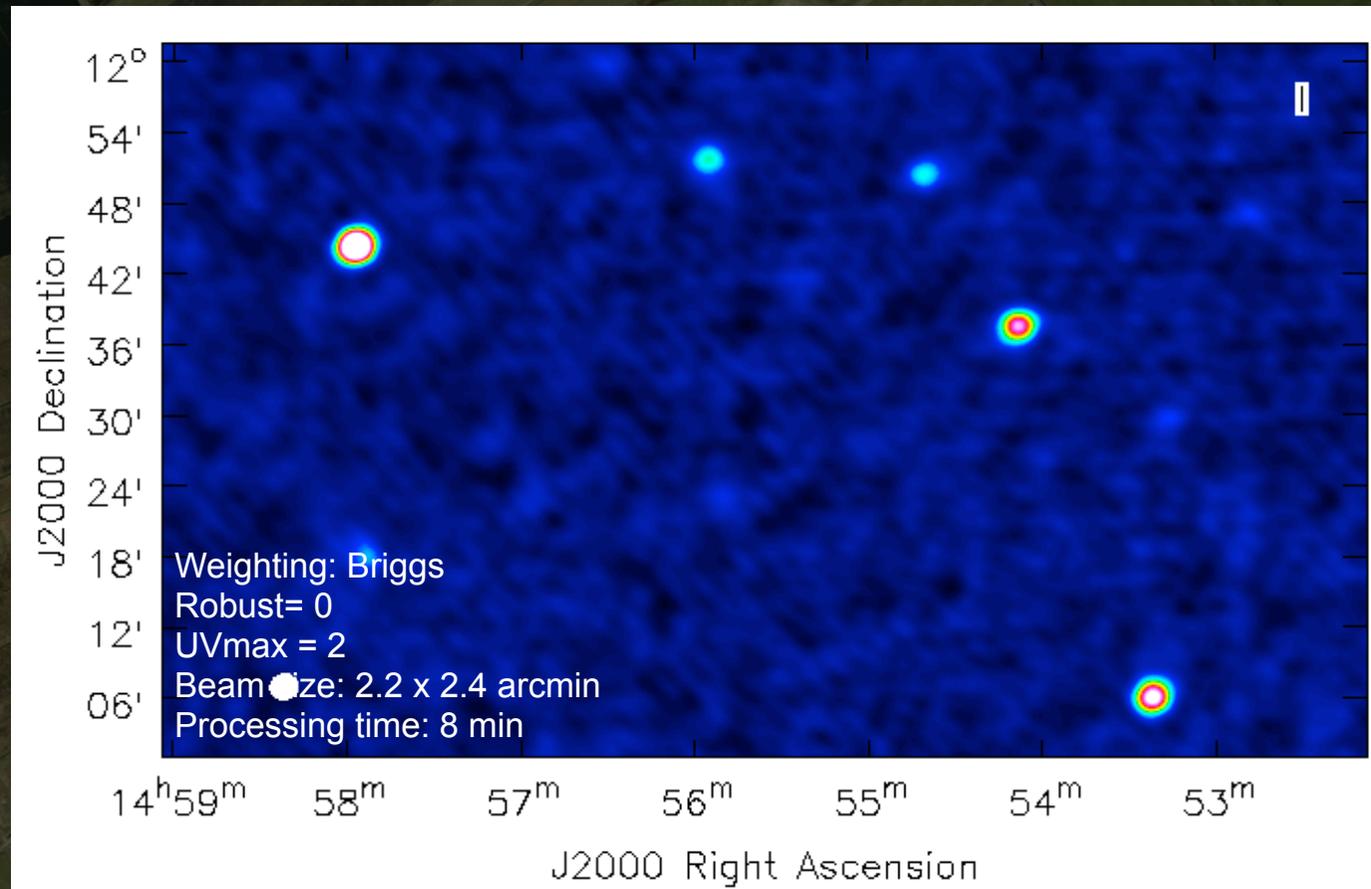
Initial Model



Better after self calibration

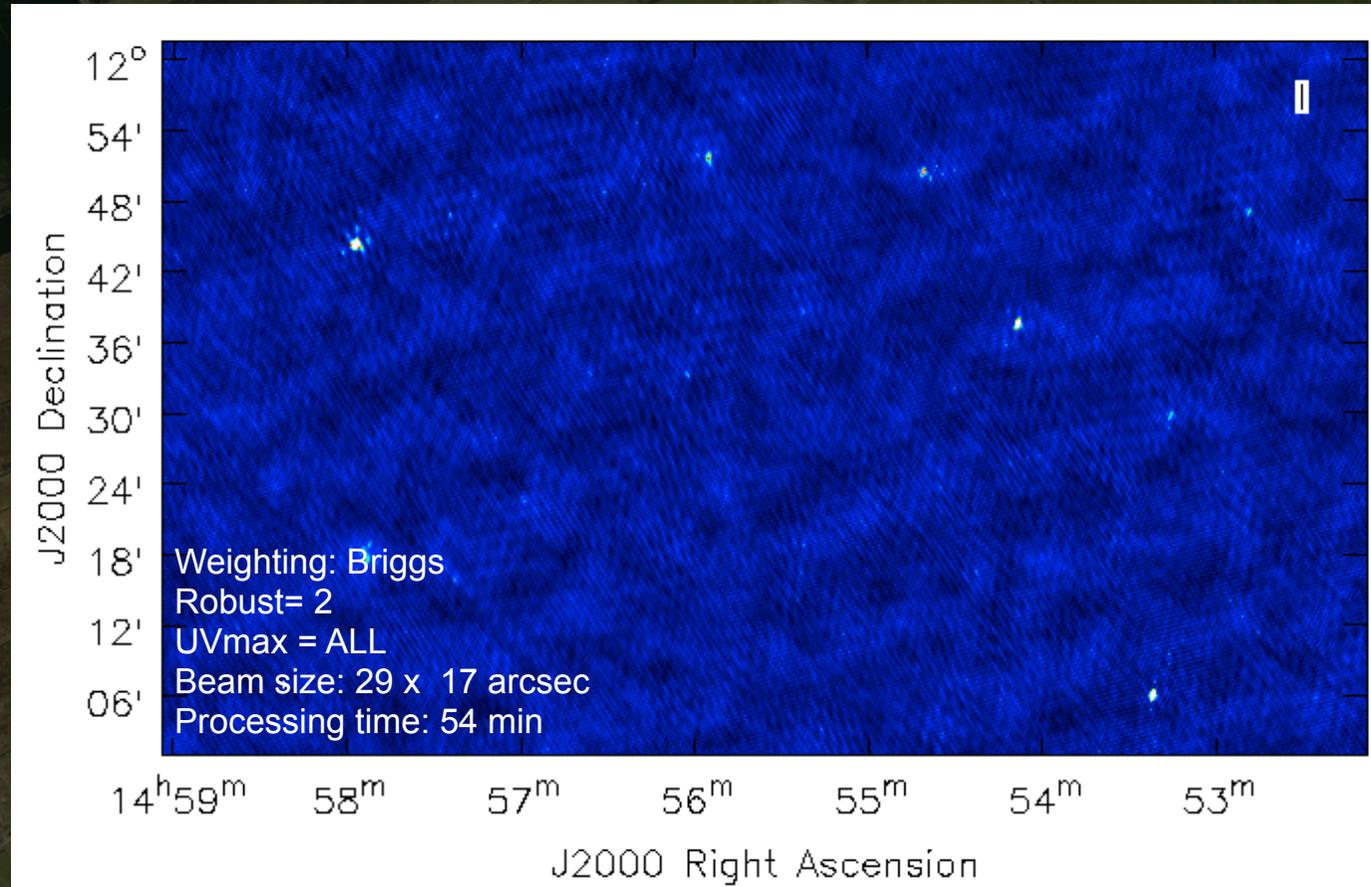
- Self-calibration can help a lot: N_{ant} unknowns $N_{ant}(N_{ant} - 1)/2$ constraints!
- A survey to establish the LOFAR initial sky model, that can be used for the first round of calibration available (use this as your starting model).

- The Multi-frequency Snapshot Sky Survey (MSSS; Heald et al. 2015) will provide an initial Global Sky Model (GSM) at 2 arcmin resolution (at 110-160 MHz).



- Re-process the 15 min of visibility data at full resolution to determine the best starting sky model for your observation (could save you a lot of time).

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- The sky model can be specified in two ways (#1 is favoured):
 1. A text file containing the properties of the sources (position, flux, size, spectral index, polarisation).

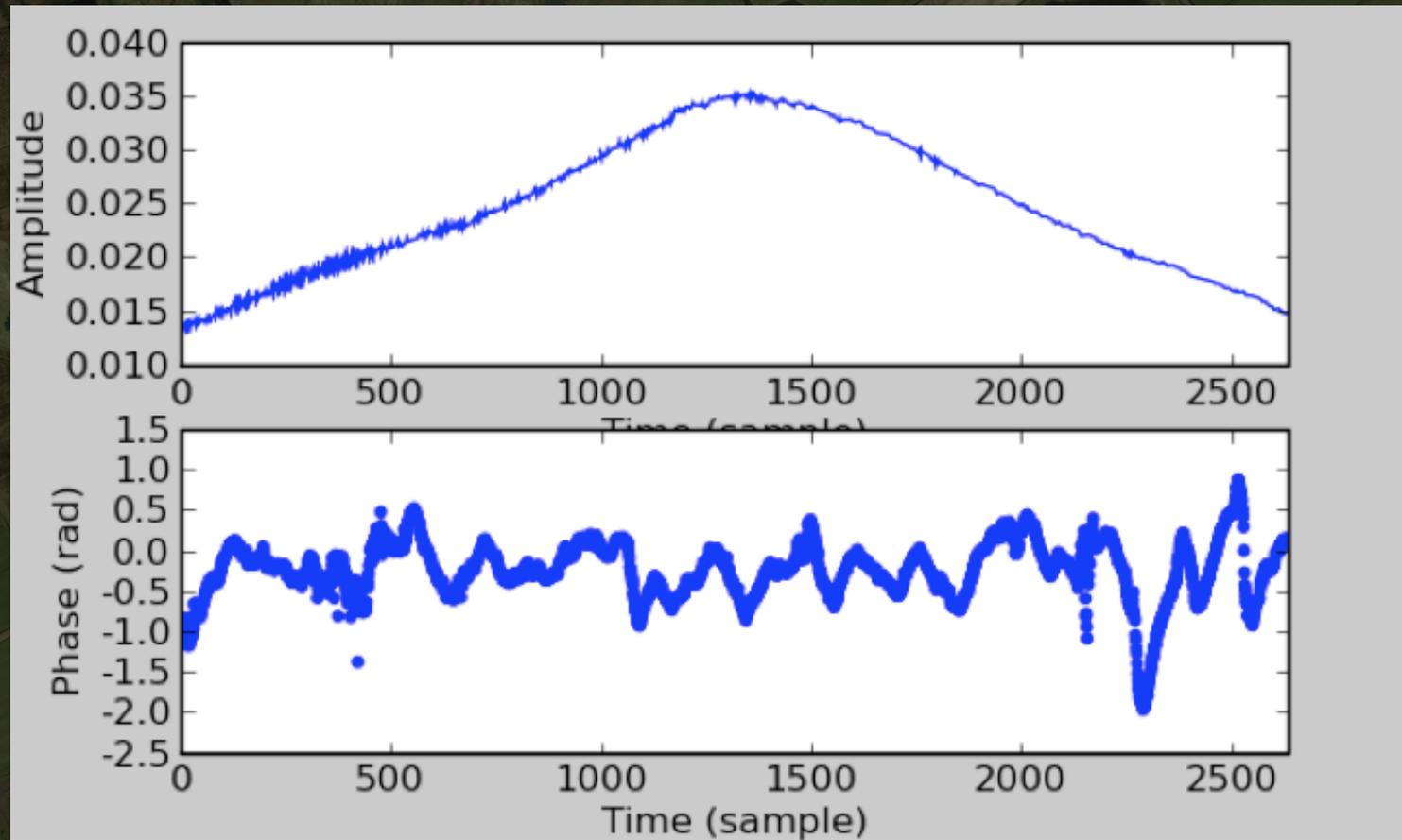
```
# (Name, Type, Ra, Dec, I) = format  
CygA.E, POINT, 19:59:31.60000, +40.43.48.3000, 1.25  
CygA.W, POINT, 19:59:25.00000, +40.44.15.7000, 1.0
```

2. As a model image (clean component, multi-scale clean, compressed sensing, Bayesian likelihood) which is directly converted to model visibilities with the PREDICT option within BBS.

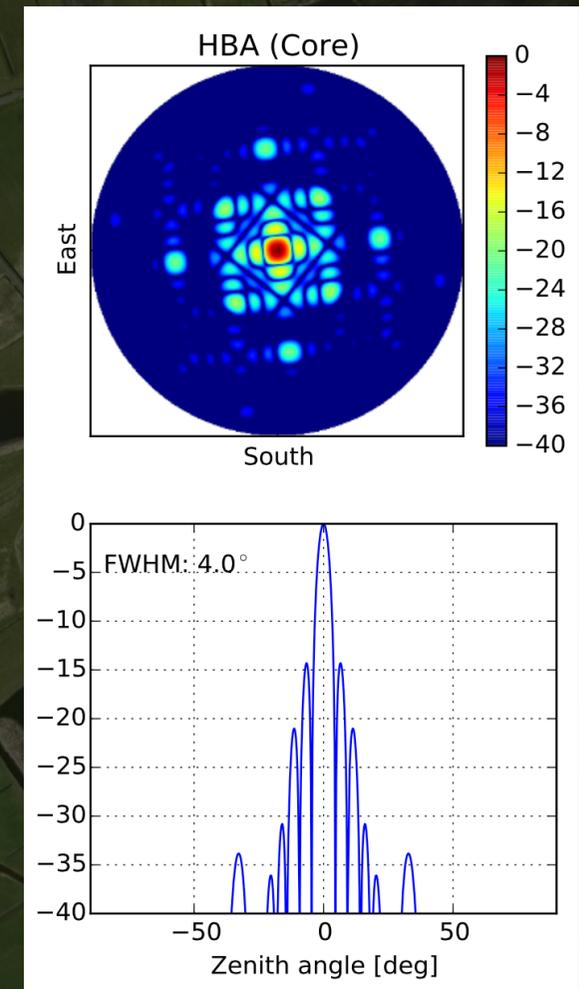
```
> addUV2MS -w 512 L24380SB030uv.MS.dppp.dppp $HOME/Images/3C196_5SBs.model
```

- Method two adds a new column to the MS that can be specified during the calibration. BUT, only should be used for complicated sources over a small field of view (direction dependent effects are lost).

- Unlike typical dish-based interferometers (e.g. JVLA, WSRT) the gain (amplitude) of the visibilities are not constant.
- This is due to the source moving through the beam (+atmosphere+ionosphere), effectively the change in the projected area of the station. Need beam correction in the calibration.



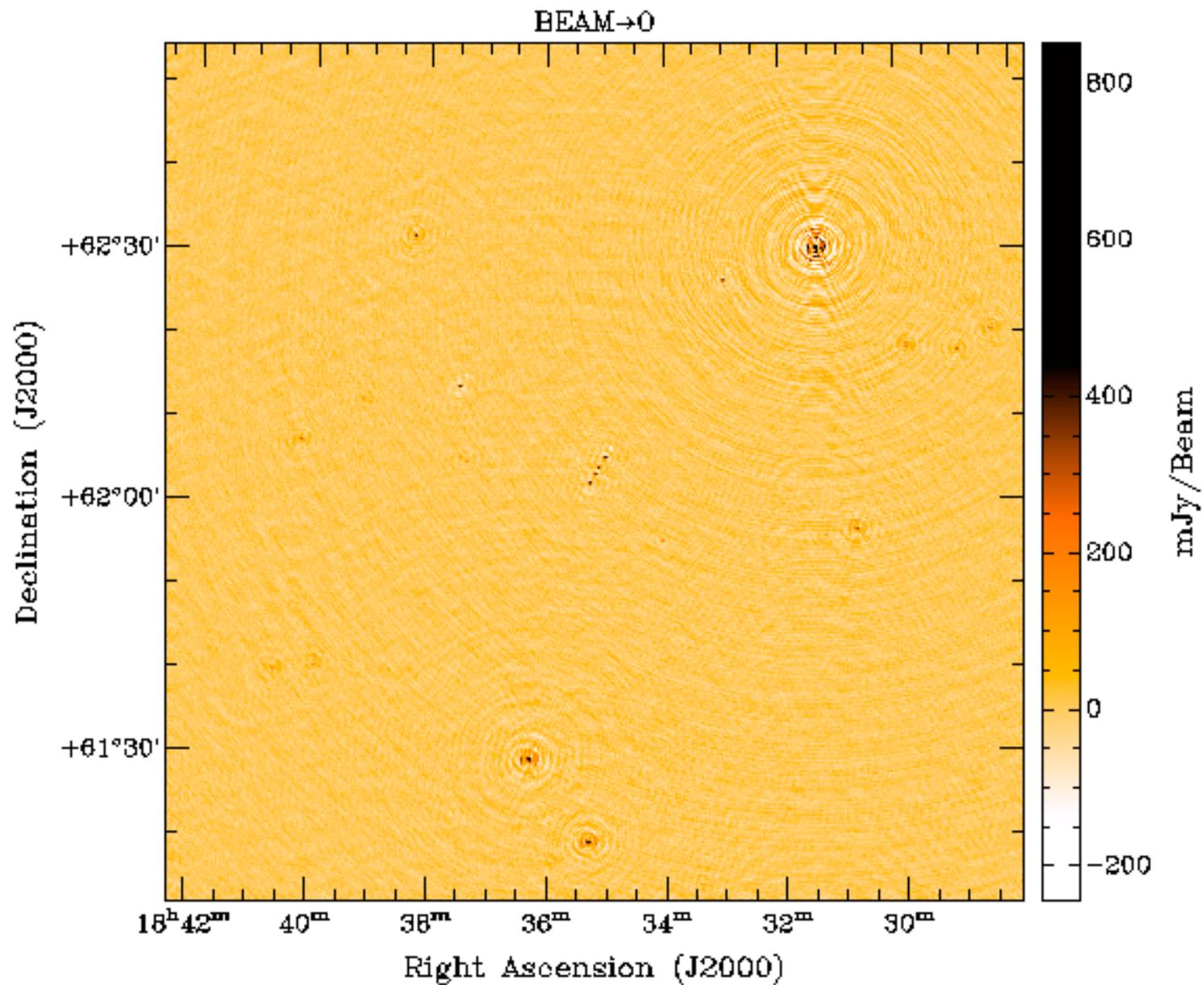
- The beam module emulates the distortions (attenuation) caused by the beam of the station.
 1. Element beam: response of a single dipole.
 2. Array Factor: Combined dipole response.
- Example of the HBA (core) station beam at 150 MHz (taken from MB's "Lots Of Flimsy Antenna Rigs" lecture.)
- Beam model is specified in the parset file.

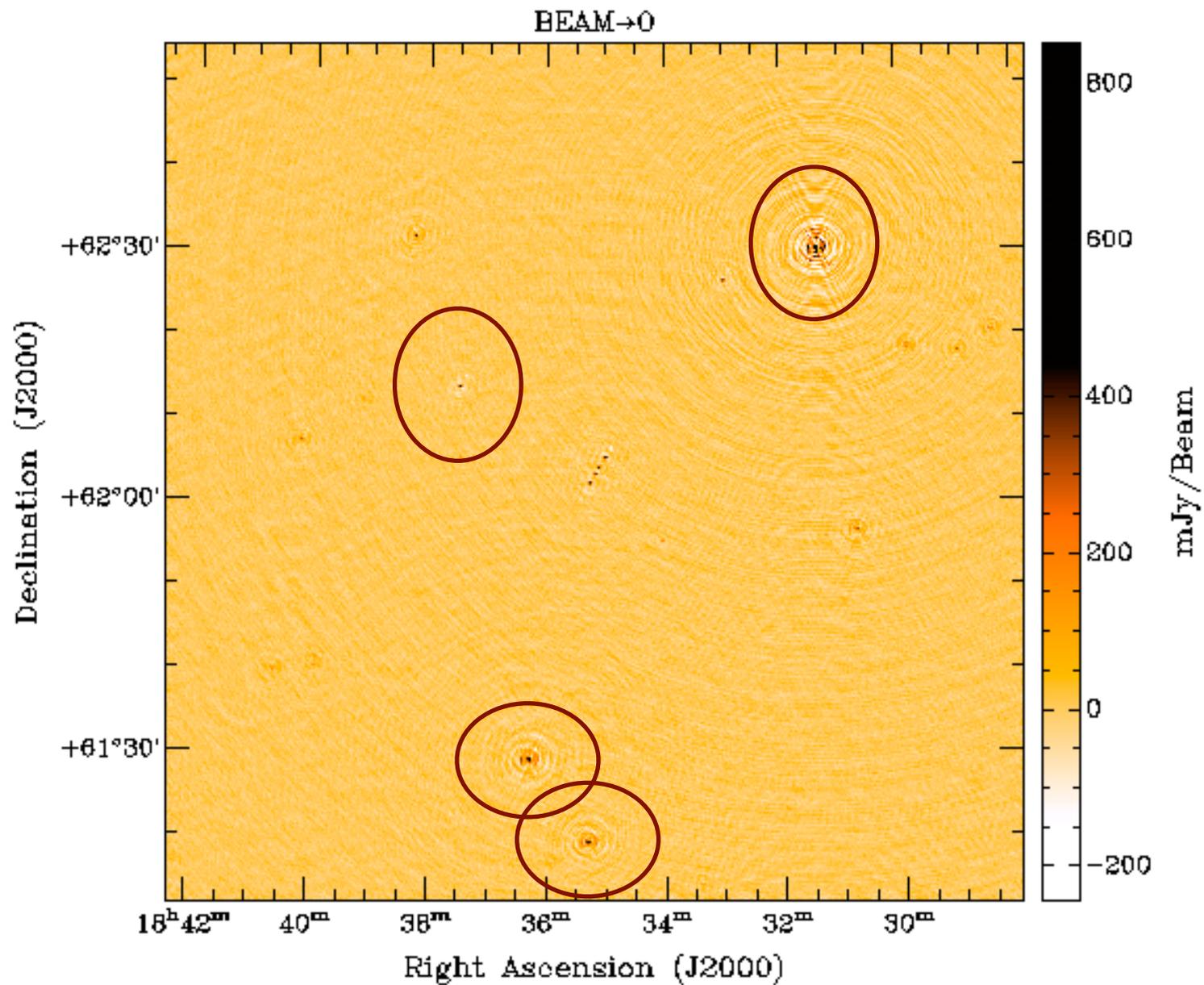


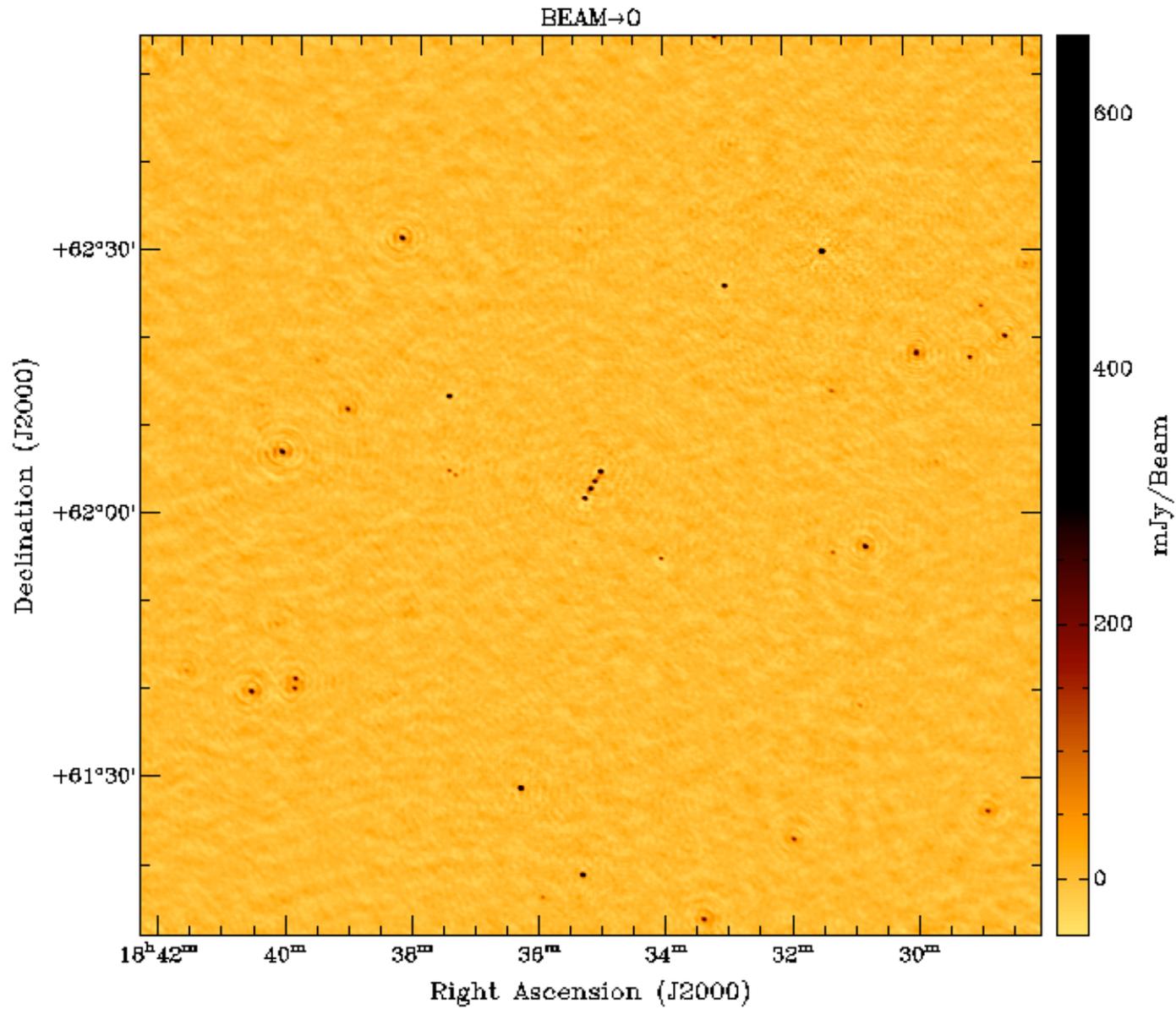
```
Model.Beam.Mode = ELEMENT      # only element beam
Model.Beam.Mode = ARRAY_FACTOR # only array factor
Model.Beam.Mode = DEFAULT      # both element beam and array factor (default)
```

- Calibration solves for the elements in the Jones matrices in one direction, but these solutions may not be valid over the wide field-of-view of our observations. This requires direction dependent solutions to be determined.
- In BBS, the sky is split into patches, and each patch is assumed to be satisfied by an direction independent solution, i.e. the patch is small enough that DDE's are negligible.

Effect	Description	
ScalarPhase	A phase that is equal for both dipoles	direction dependent
Rotation	Faraday Rotation without frequency dependency	direction dependent
FaradayRotation	Faraday Rotation	direction dependent
DirectionalTEC	TEC (ionosphere), see 6.7.5	direction dependent
Beam	The LOFAR beam model. See 6.6.1	direction dependent
DirectionalGain	Directional gain	direction dependent
CommonScalarPhase	Scalar Phase	direction independent
CommonRotation	Rotation	direction independent
TEC	TEC (ionosphere), see 6.7.5	direction independent
Gain	Gain	direction independent
Clock	Clock	direction independent





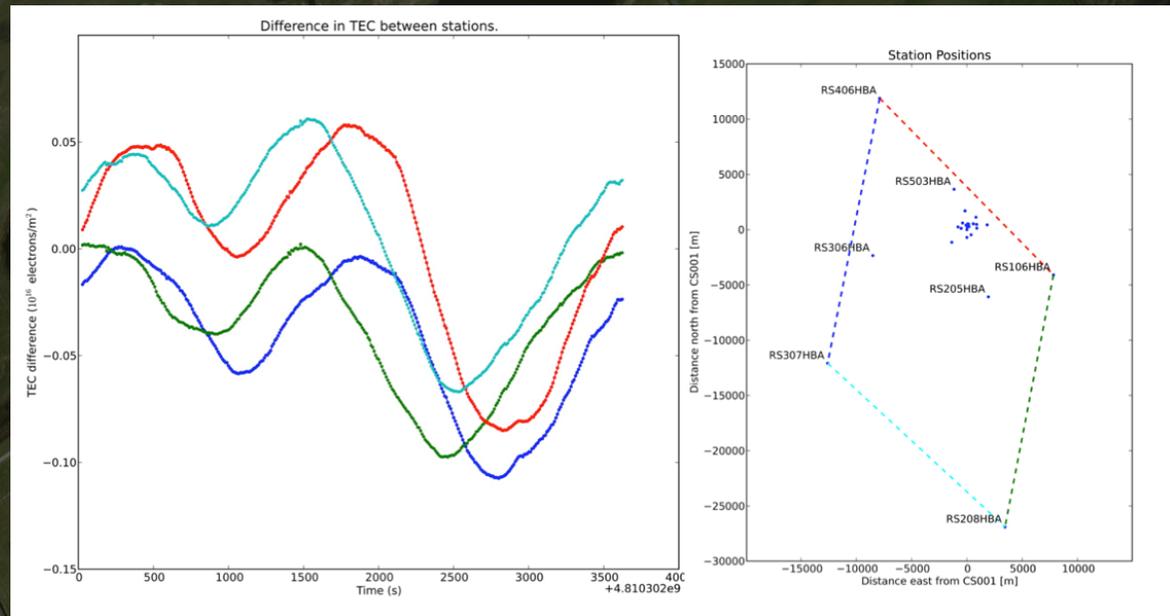


- Free electrons in the ionosphere can attenuate radio emission when the radiation frequency approaches the plasma frequency ($N_e \propto \nu^2$). Hence, the low frequency cut-off
- The ionosphere can also introduce a frequency dependent phase shift in the radio waves, and also varies with frequency

- Can solve for the differential TEC using our sky model (if we can separate the delay introduced by the clocks).

- See next lecture for details.

- Parameters included in the BBS parset file are,

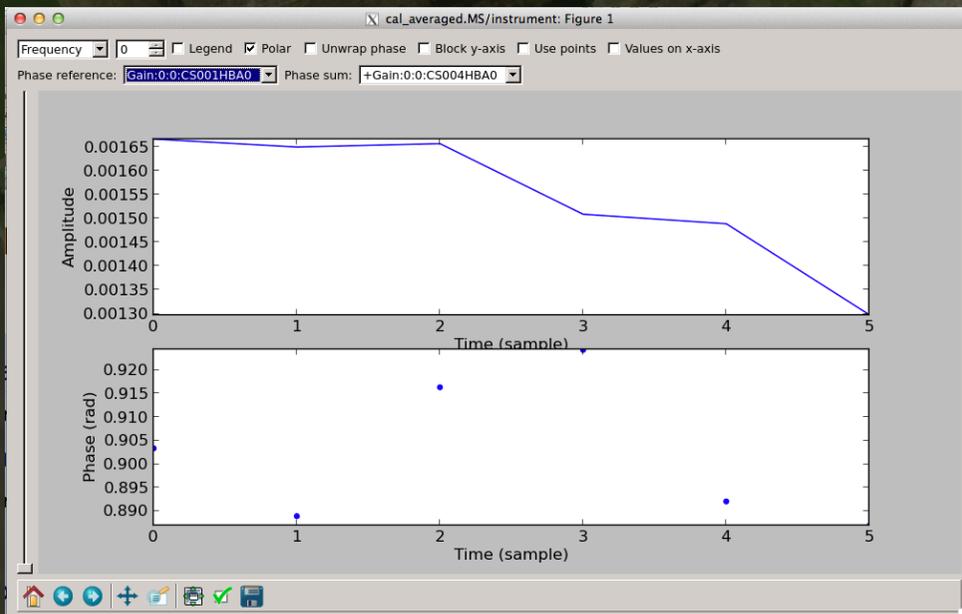


```
Step.<name>.Model.TEC.Enable = T  
Step.<name>.Solve.Parms = [TEC:*
```

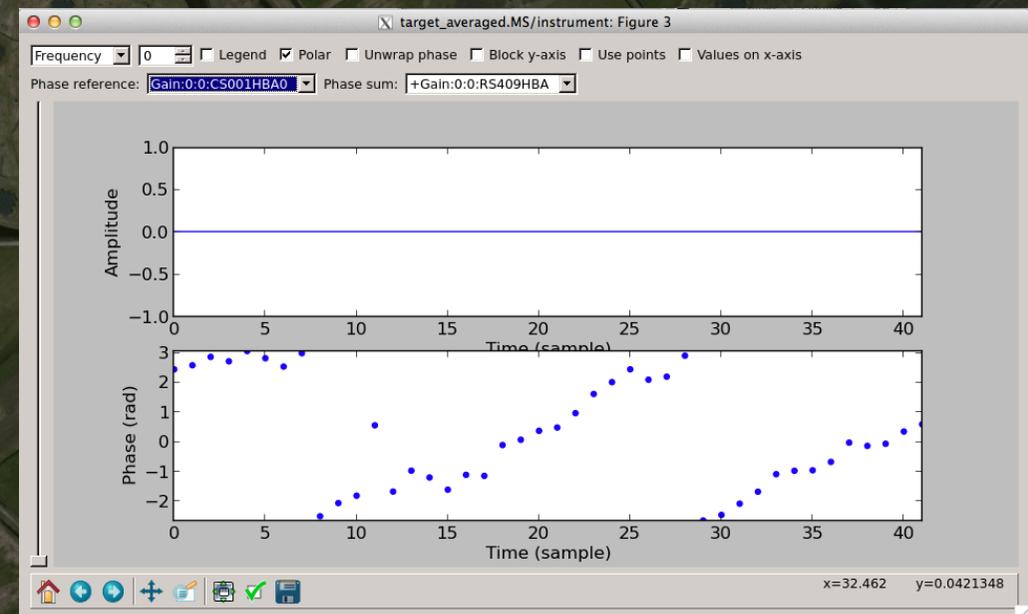
- A number of calibration strategies have been developed (see cookbook for details).
 1. **Gain calibration (direction independent):** Solves for a single direction amplitude and phase solution and applies this to the visibility data. Useful for targets that are bright objects in the field.
 2. **Gain calibration (direction dependent):** Solves for the amplitude and phase solution toward bright sources and subtracts them from the data, and then solves for the amplitude and phase solution toward the target field. Useful for calibrating targets that are faint objects in the field.
 3. **Gain Transfer:** Use the gain calibration from a strong calibrator field to calibrate the target field. Useful if there is no target field model, or if the target field has no bright sources in-beam. There are two methods.
 - A. Cycle between observations of a calibrator field and the target field to estimate the gain variations and transfer them to the target.
 - B. Use multi-beaming to simultaneously observe the calibrator field and target field (helps remove temporal variations).
- We will use gain transfer during the tutorial, this afternoon.

- Always check your solutions! This is done by plotting the amplitude and phase solutions for each station (direction) and flagging poor solutions (similar to what is done for other interferometric arrays).

```
> parmdbplot.py SB23.MS.dppp/instrument/
```



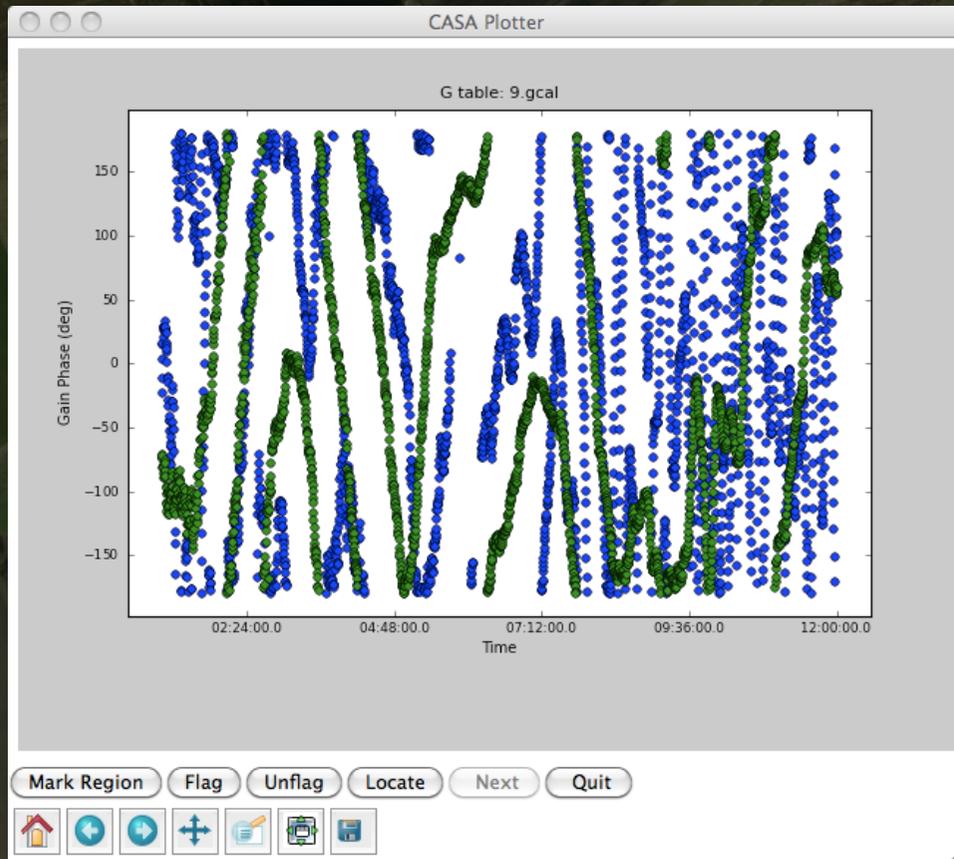
Calibrator



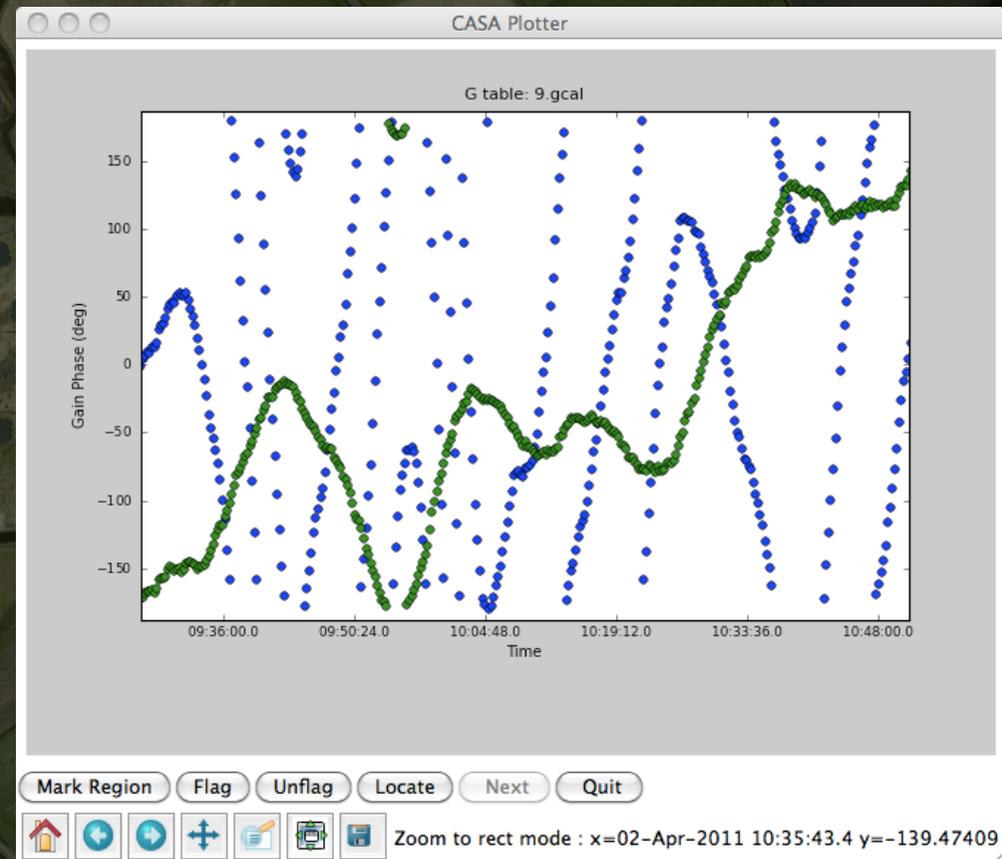
Target

Rapid phase variations

- Phases for RS503 (Green; 3 km from Superterp) and RS208 (Blue; 30 km from the Superterp).

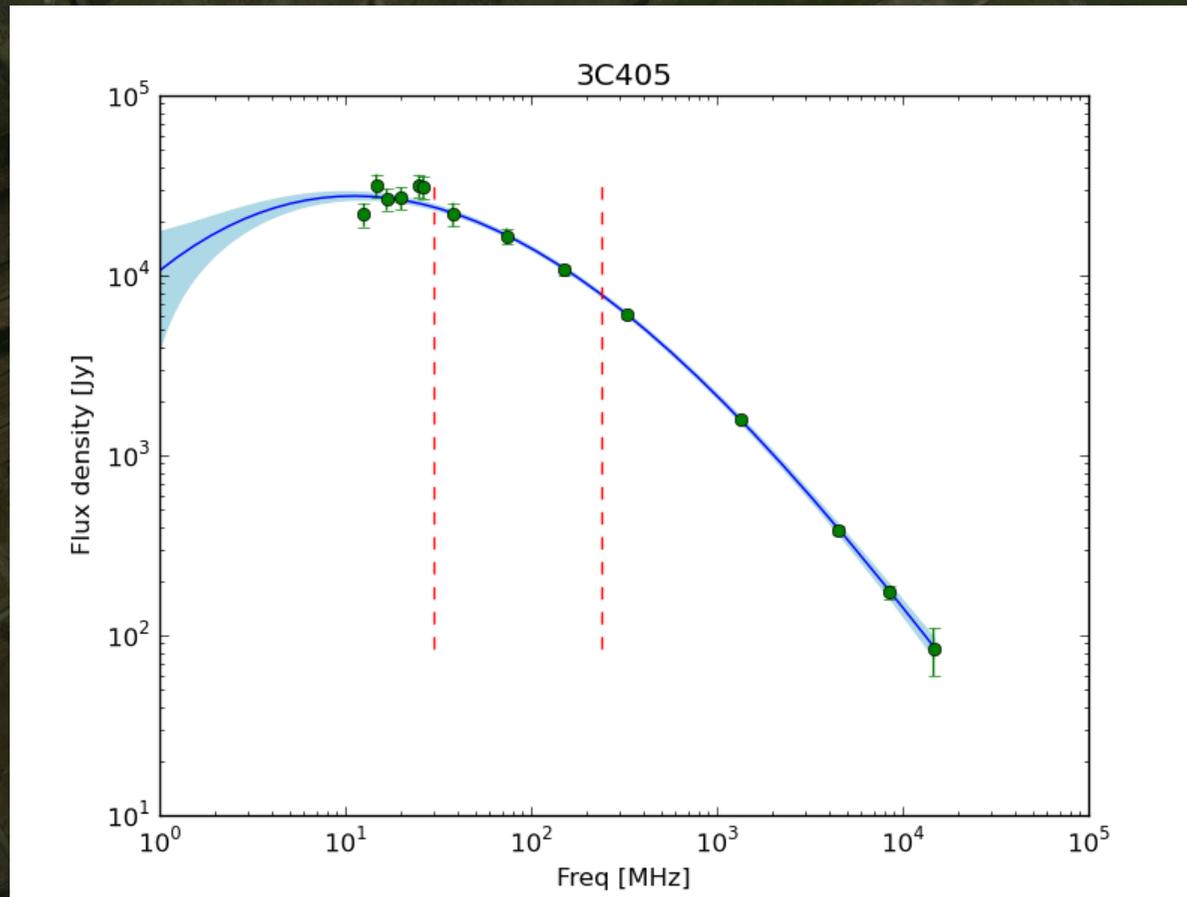


Phases change faster for longer baselines.

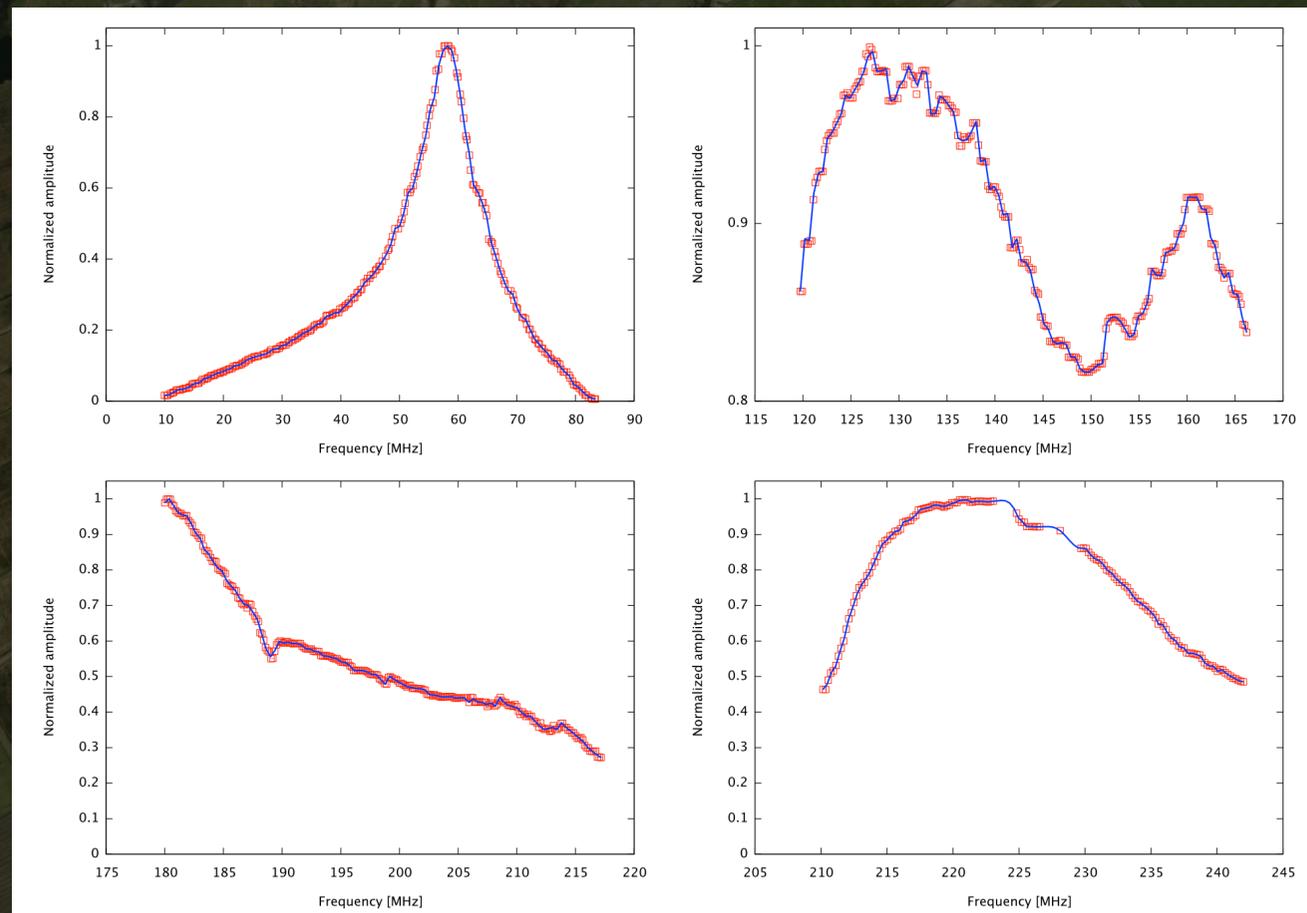


Still trace the changes for 15s visibility integration time.

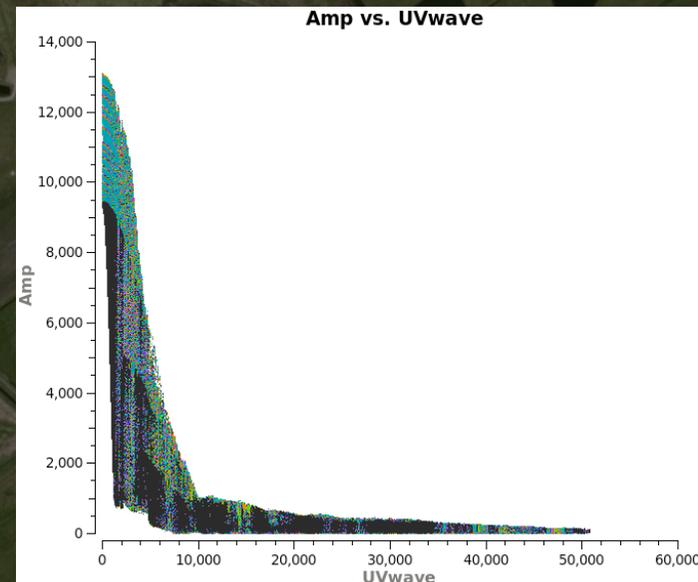
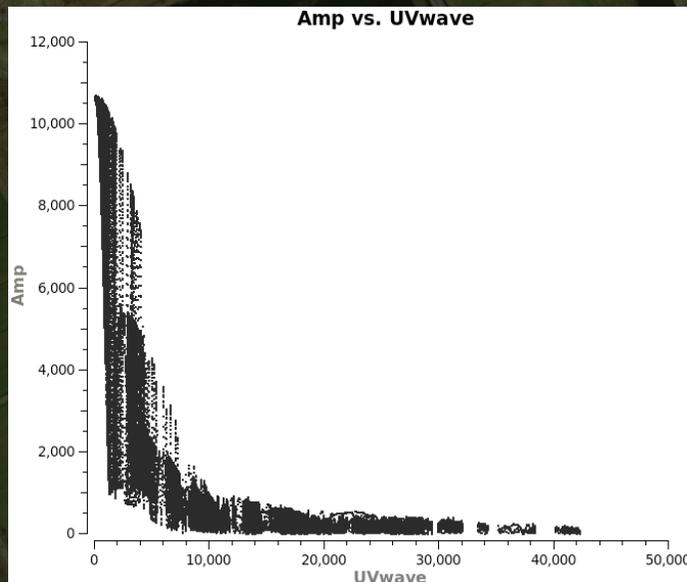
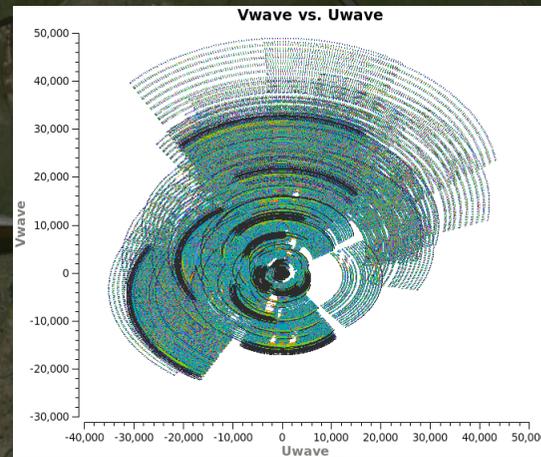
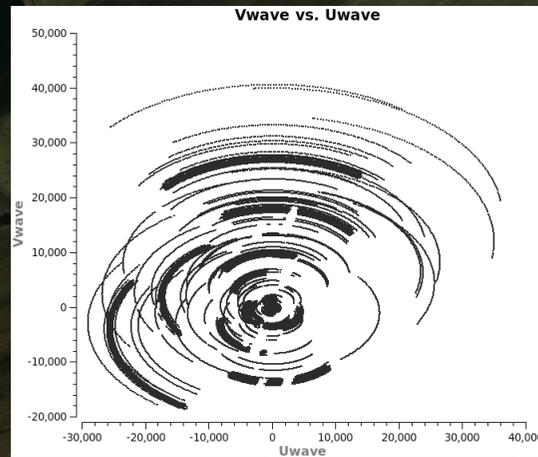
- If your target is very strong and has a well defined spectrum, it is possible to estimate the frequency dependence of the gains (e.g. Scaife & Heald 2012).
- In almost all cases, this is not possible, so we can apply our estimate of the global bandpass to our target data.



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- LOFAR will have large fractional bandwidths (~ 48 to 96 MHz bandwidth between 10 -- 250 MHz).



- MFS represents the sky emission in terms of a Taylor series about a reference frequency.

Taylor co-efficient images

(Rau & Cornwell 2011)

MS model image

$$I_{\nu}^m = \sum_{t=0}^{N_t-1} w_{\nu}^t I_t^{\text{sky}} \quad \text{where} \quad w_{\nu}^t = \left(\frac{\nu - \nu_0}{\nu_0} \right)^t$$

- A power model is used to describe the spectral dependence of the sky emission.

$$I_{\nu}^{\text{sky}} = I_{\nu_0}^{\text{sky}} \left(\frac{\nu}{\nu_0} \right)^{I_{\alpha}^{\text{sky}} + I_{\beta}^{\text{sky}} \log \left(\frac{\nu}{\nu_0} \right)}$$

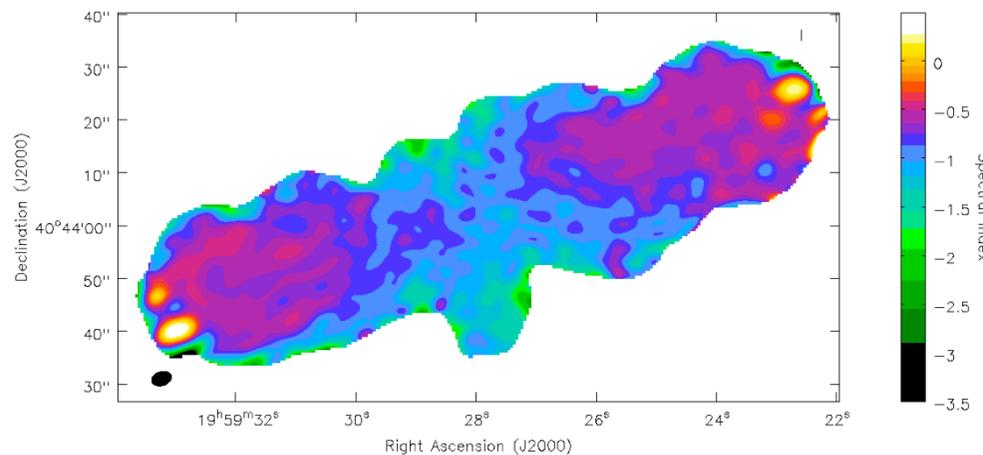
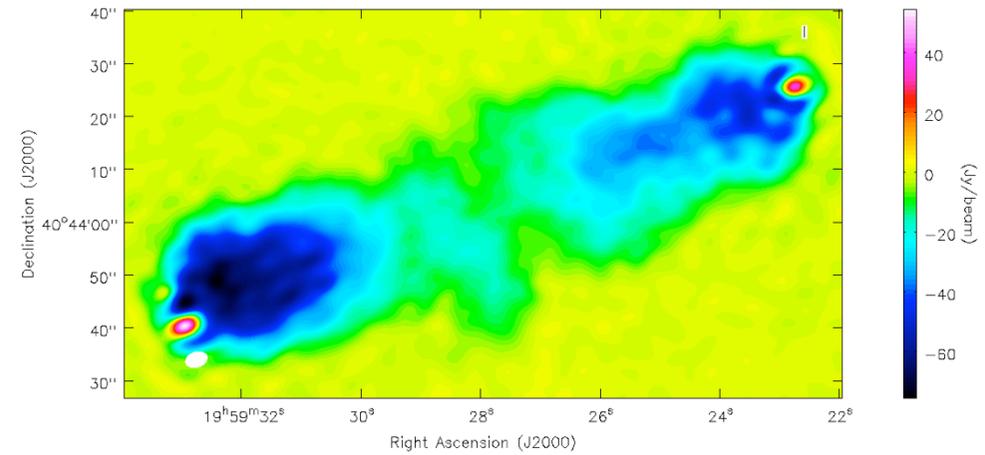
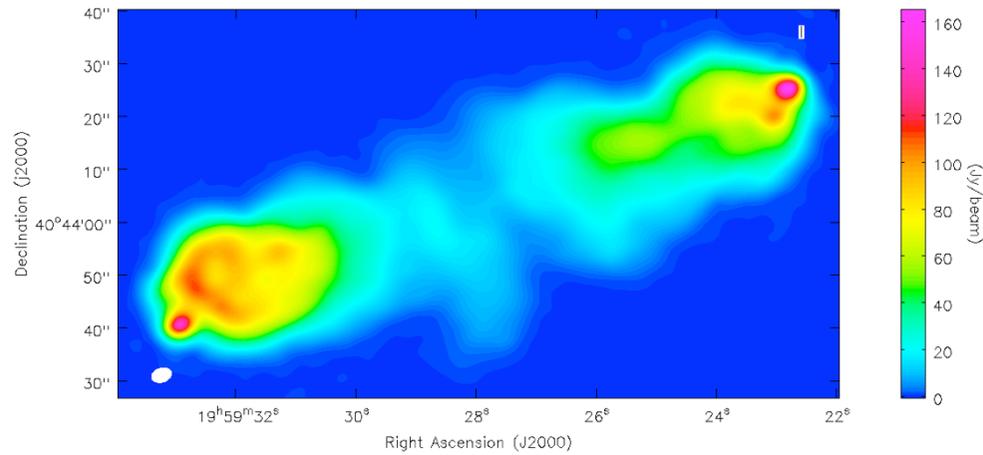
$$I_0^m = I_{\nu_0}^{\text{sky}} \quad ; \quad I_1^m = I_{\alpha}^{\text{sky}} I_{\nu_0}^{\text{sky}} \quad ; \quad I_2^m = \left(\frac{I_{\alpha}^{\text{sky}} (I_{\alpha}^{\text{sky}} - 1)}{2} + I_{\beta}^{\text{sky}} \right) I_{\nu_0}^{\text{sky}}$$

Imaging results



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- MS-MFS Imaging of Cygnus A (109 and 183 MHz), total bandwidth 27.5 MHz.

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