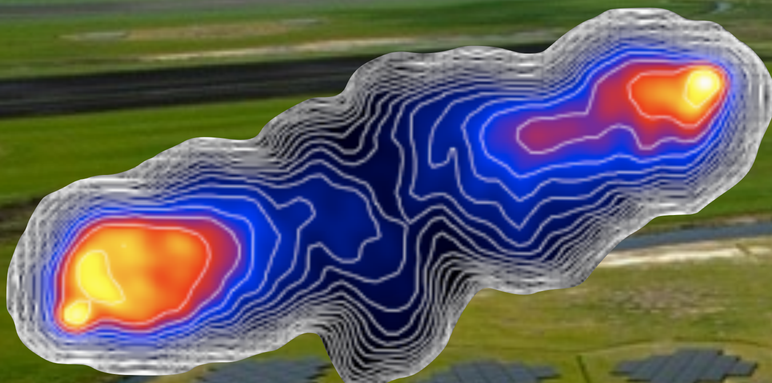
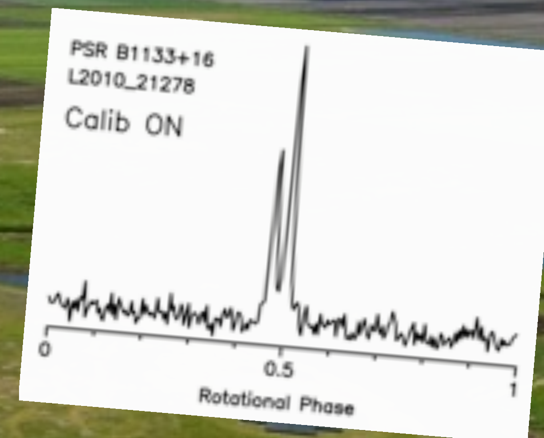
Netherlands Institute for Radio Astronomy





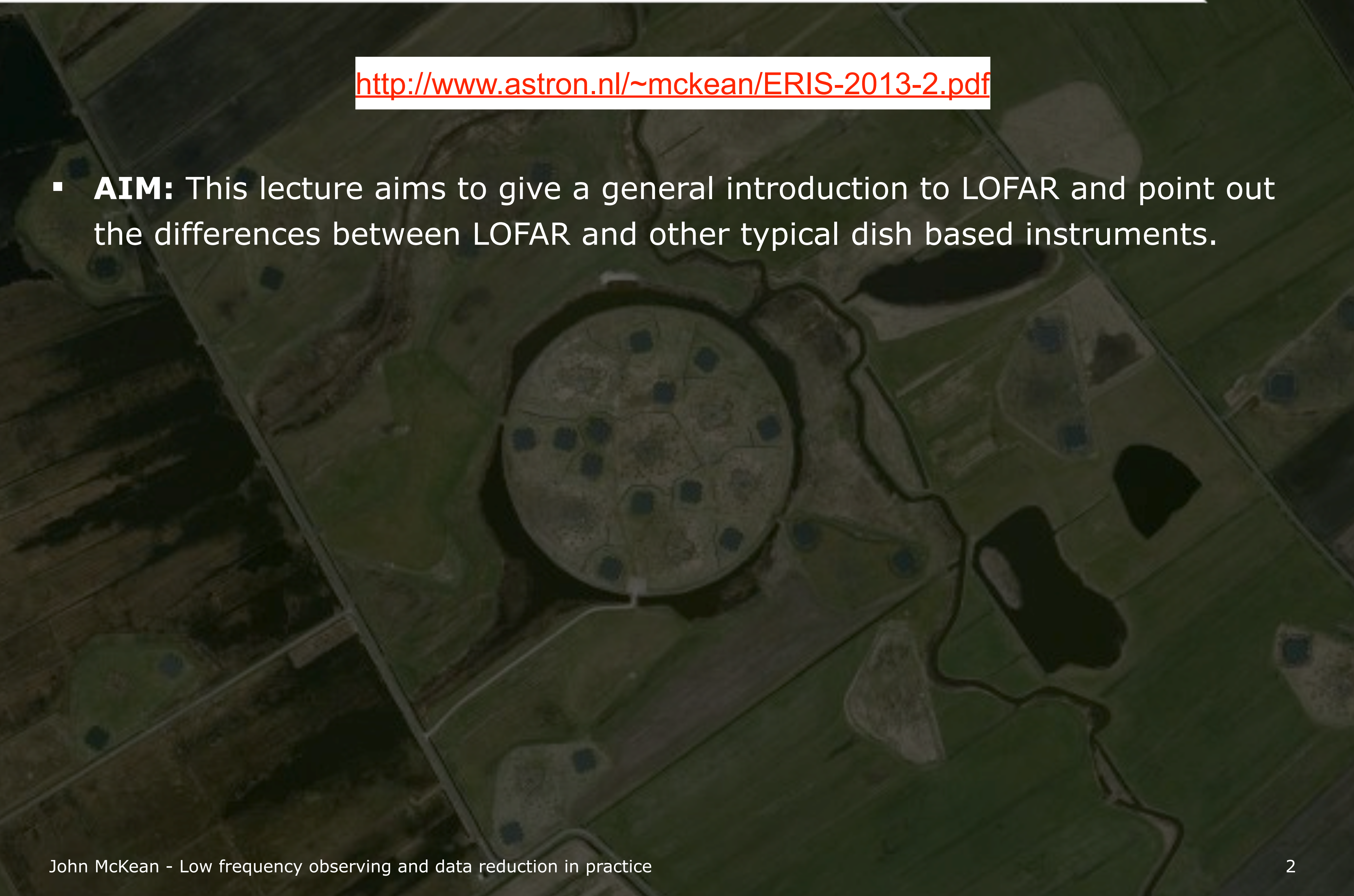
Low frequency observing and data reduction in practice

John McKean (ASTRON)

Preamble

http://www.astron.nl/~mckean/ERIS-2013-2.pdf

Preamble



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- **AIM:** This lecture aims to give a general introduction to LOFAR and point out the differences between LOFAR and other typical dish based instruments.

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  - The Low Frequency Array

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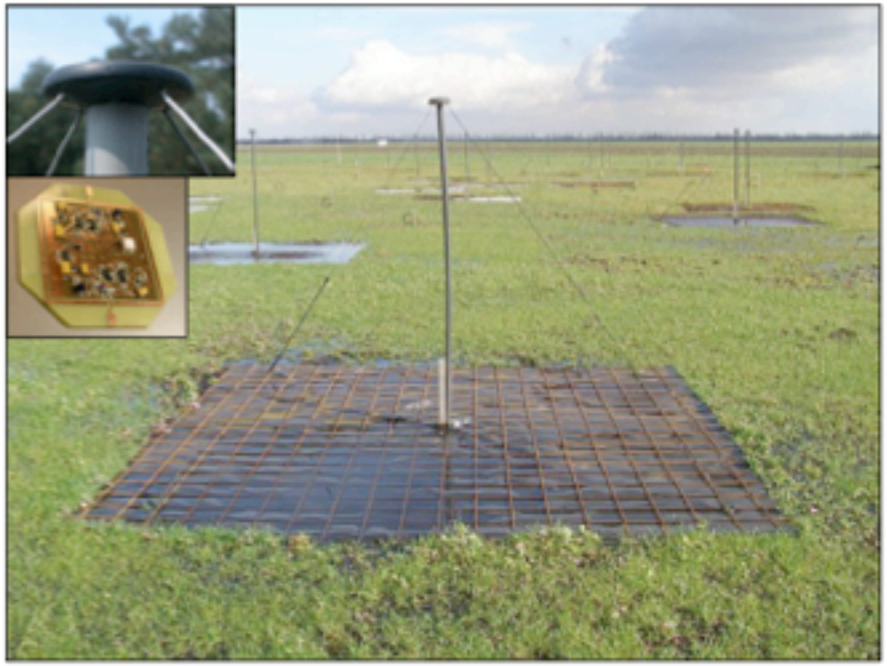
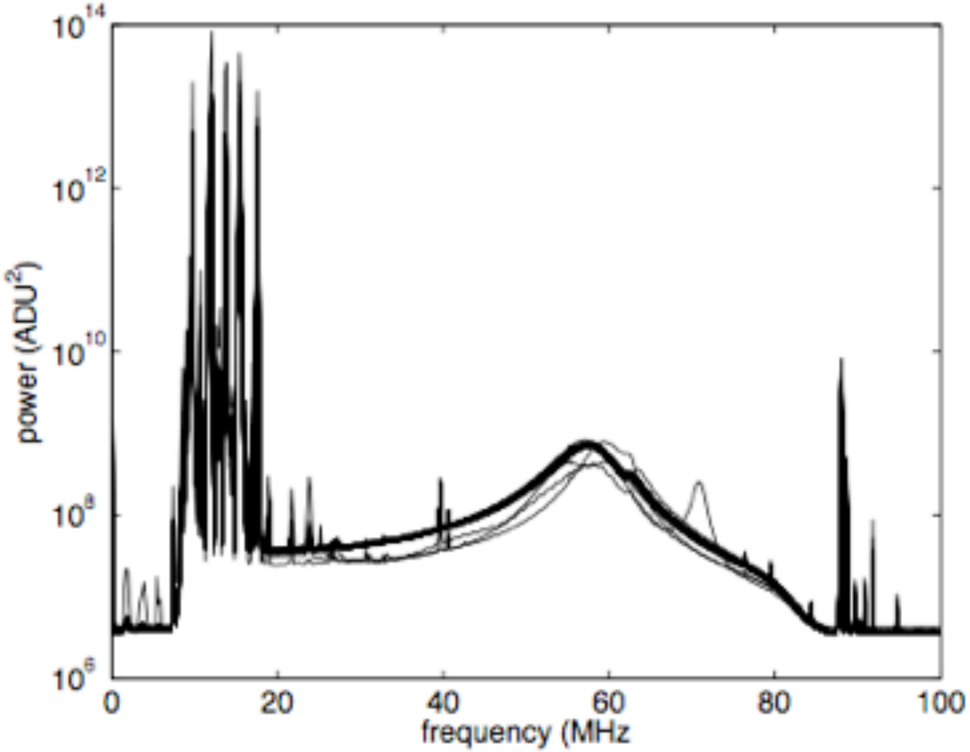
The Low Frequency Array - Key Facts

- The International LOFAR Telescope (ILT) is being built in the Netherlands, Germany, France, UK and Sweden (~€50M construction + running costs).
- Operating frequency is 10 -- 250 MHz.
- 1 beam with up to 96 MHz total bandwidth, split into 488 sub-bands with 256 Channels (8-bit mode).
- <488 beams on the sky with ~0.2 MHz bandwidth.
- 1700--7 deg^2 field-of-view.
- Low Band Antenna (LBA; Area ~ 75200 m^2; T_{rec} ~ 500 K; 10-90 MHz).
- High Band Antenna (HBA; Area ~ 57000 m^2; T_{rec} ~ 160 K; 110-240 MHz).
- Correlated by an IBM BlueG/P supercomputer.

Low Band Antenna (LBA)

- **LBA antennas:** Cap containing the low noise amplifiers (LNAs), copper wires receive two orthogonal *linear* polarisations, ground plate.
- Low cost, high durability (15 year operation), whole sky coverage.

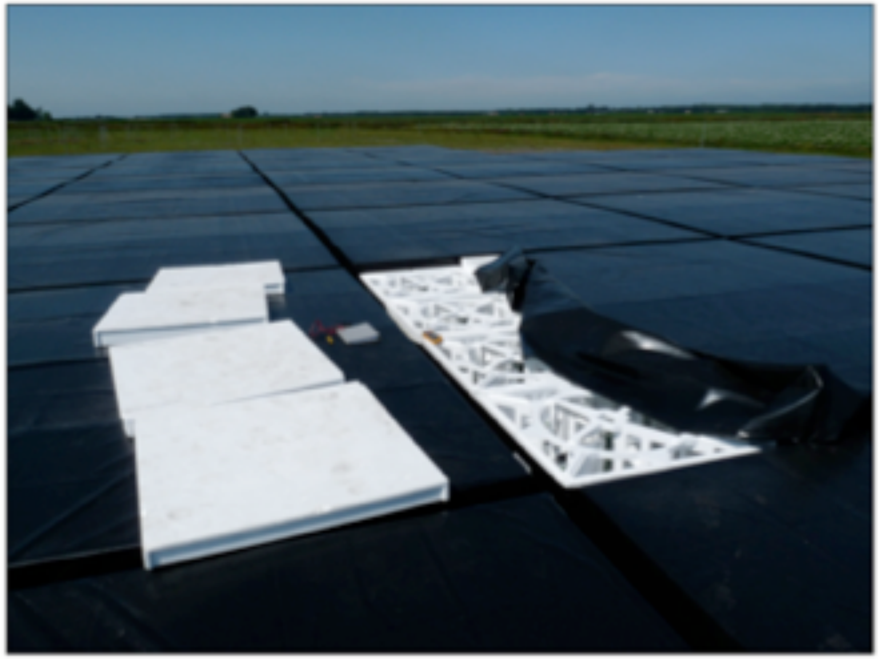


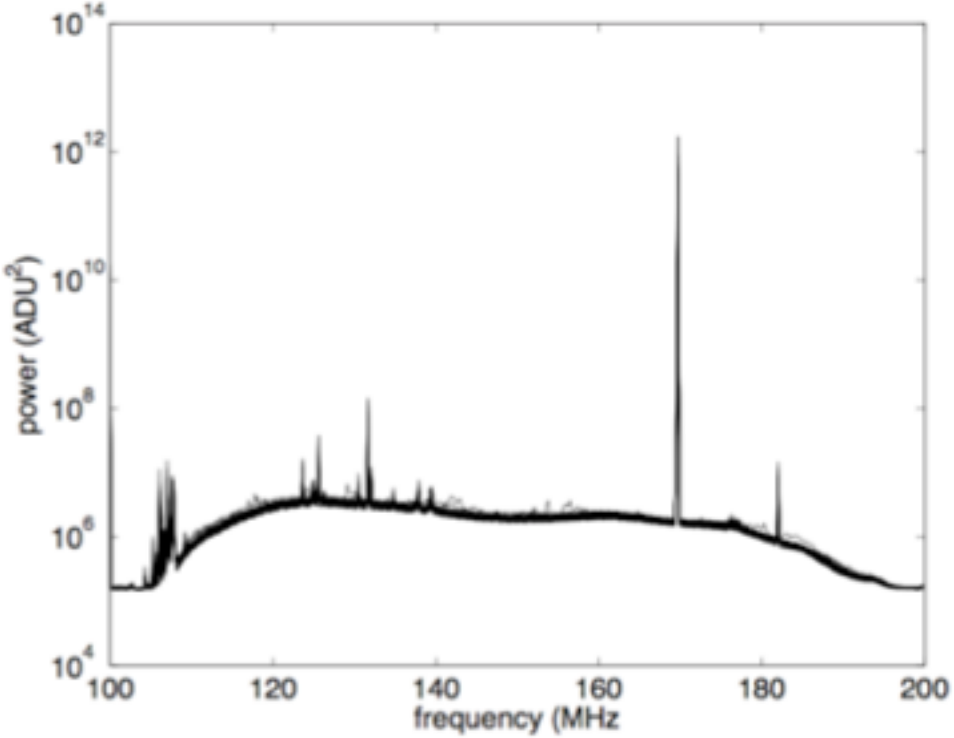


- **The response curve:** There is a peak close to the resonance frequency (52 MHz) - dipole arms are 1.38 m long.

High Band Antenna (HBA)

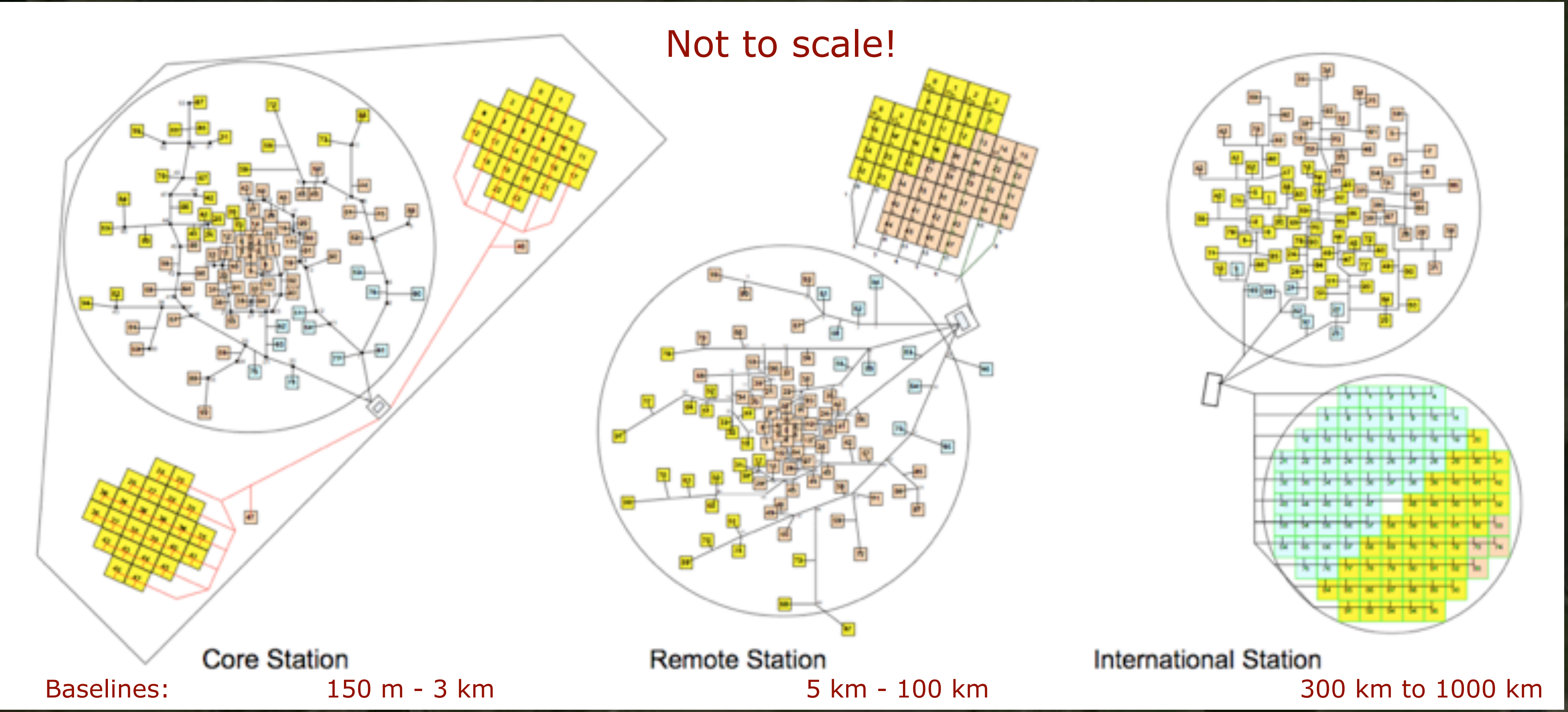
- **HBA antennas:** Each tile consists of 4 x 4 dual *linear* polarisation aluminium dipoles, housed in a polystyrene structure, covered by polypropylene sheets.
- Dipoles are combined to form a single "tile beam".





- **The response curve:** There is a smoother response over the main HBA observing band.

Stations



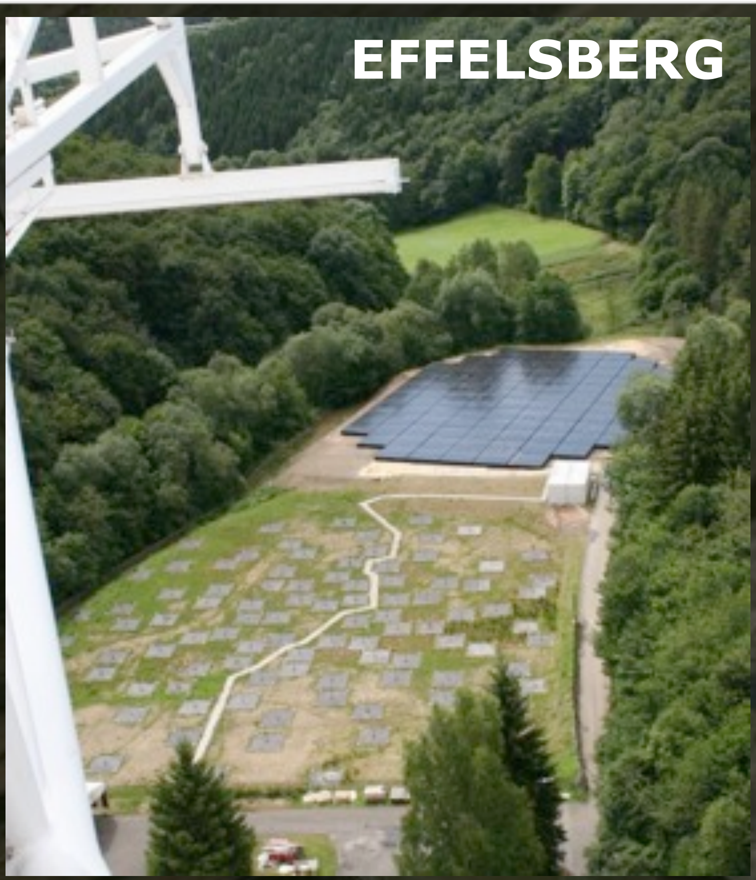
- **Three types:** Core (24), Remote (14) and International (8 so far).
- Different beam shapes
- Different sensitivities

} 48/96 LBA dipoles used for Core + Remote stations.

Core stations (24)

6 station superterp (300 m)

International Stations (8)



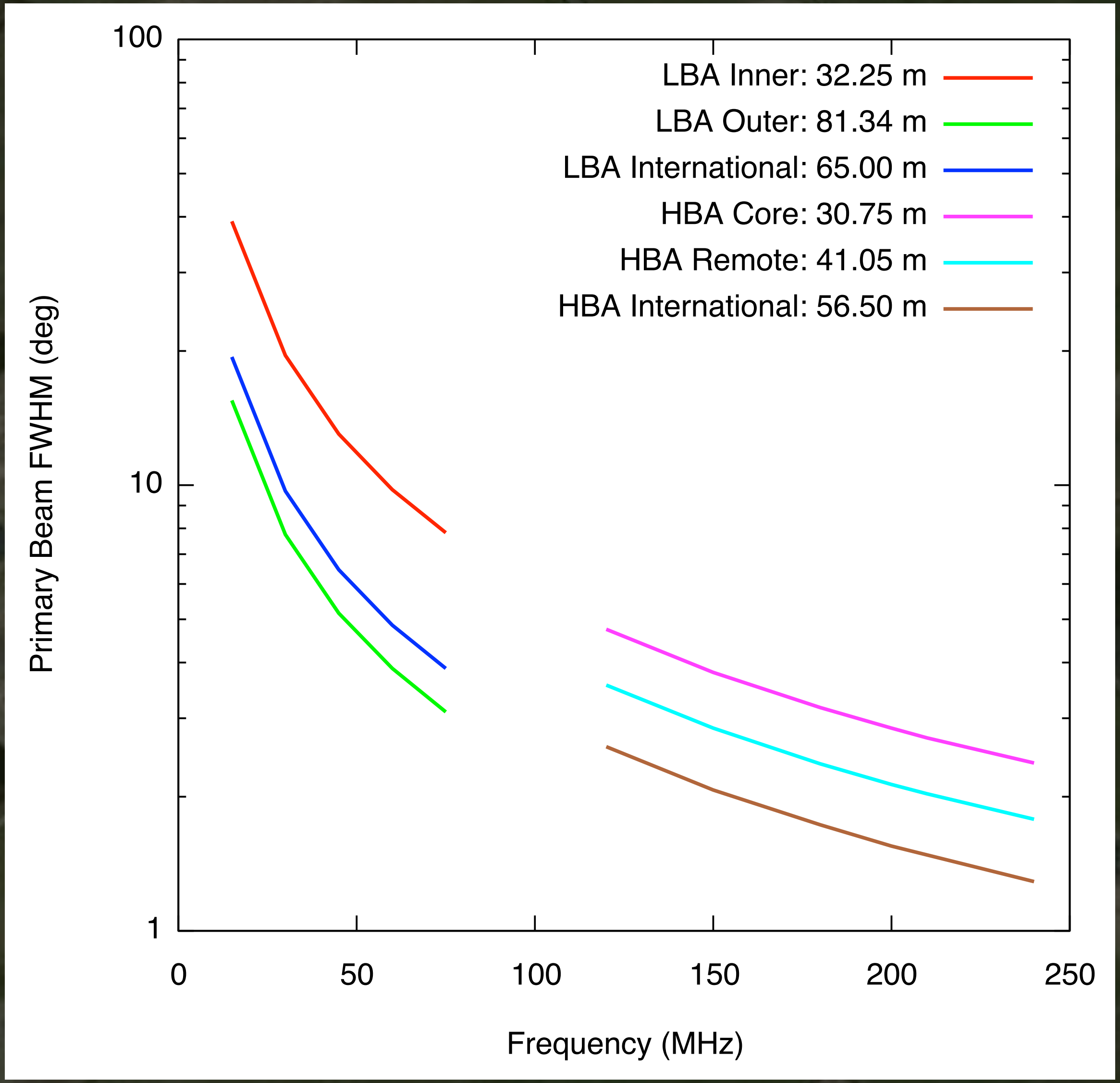
Field-of-View (FWHM v Freq.)

- LOFAR will have an unprecedented field-of-view.

$$\text{FWHM [rad]} = \alpha \, \frac{\lambda}{D}$$

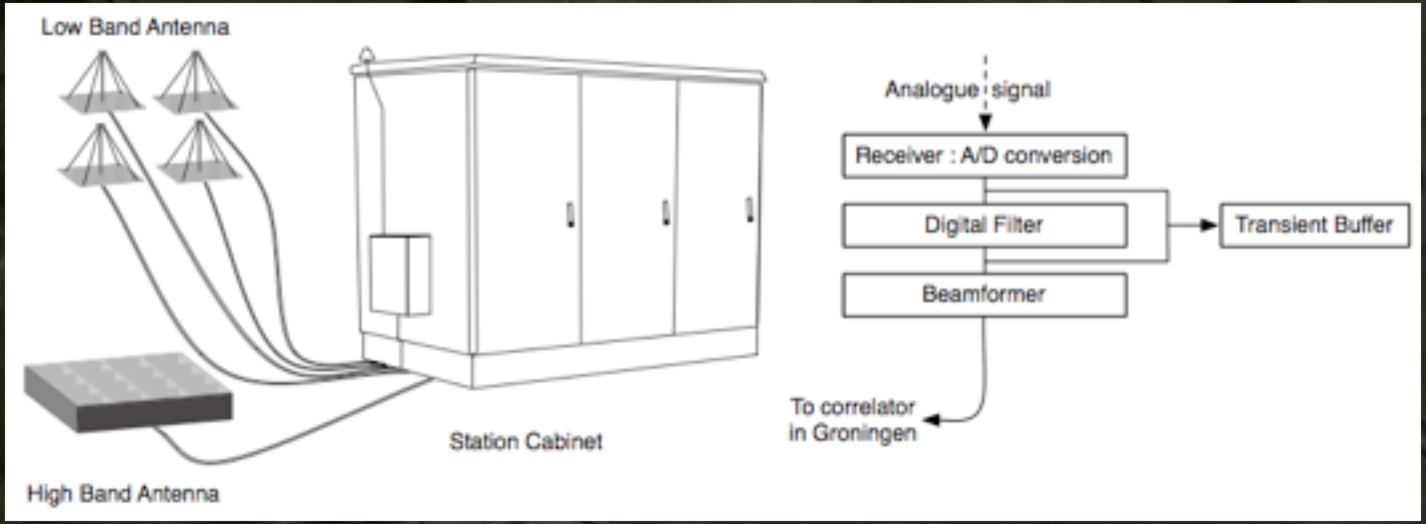
- Where α depends on the tapering used at the station level.

$$\text{FoV} = \pi \left(\frac{\text{FWHM}}{2} \right)^2$$



Central cabinets

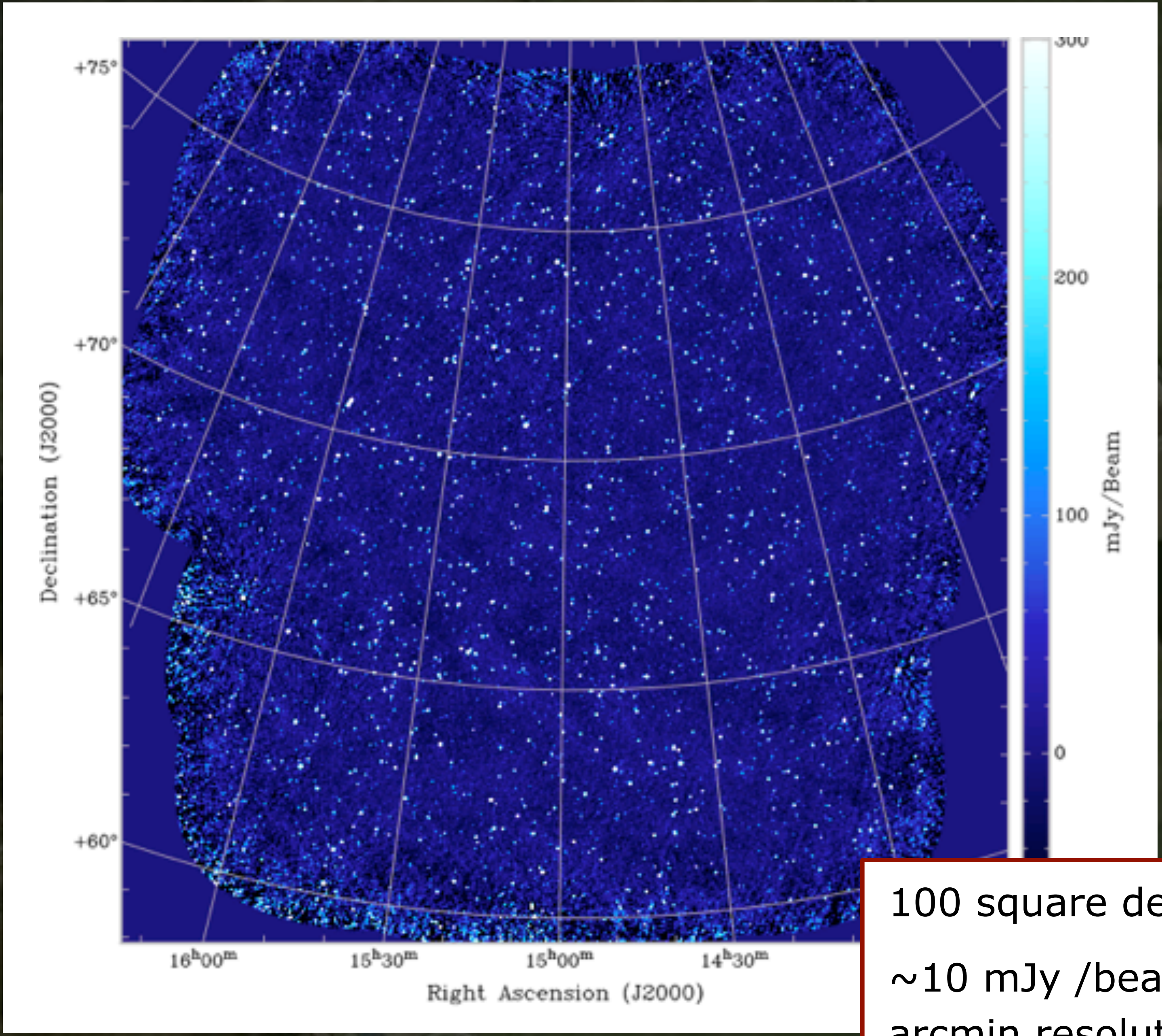
- **Receiver Control Units (RCU):** Input antenna voltages are converted to base-band frequencies, amplified, filtered and digitised.
- Receive signals up to 40 dB - important for removing RFI signals.
- Sampling clocks at 200 MHz or 160 MHz (flexible selection of frequency bands).
- **Remote Station Processing (RSP):** Separate the signal into 512 sub-bands of 156 or 195 kHz width (clock dependent).
- Carries out phase-rotation based beam-forming by multiplying with a set of complex weights that correspond to the geometrical delay for pointing.



Beam-forming

- Unlike standard telescopes, LOFAR has no moving parts.
- Pointing is achieved by combining the beams from each individual element (antenna or tile), at the station level, using different complex weights.
- Combine many stations to form a tied array.
- <488 beams can be formed, increasing survey speed, efficiency, calibration.

Wide field imaging (MSSS -- MVF)



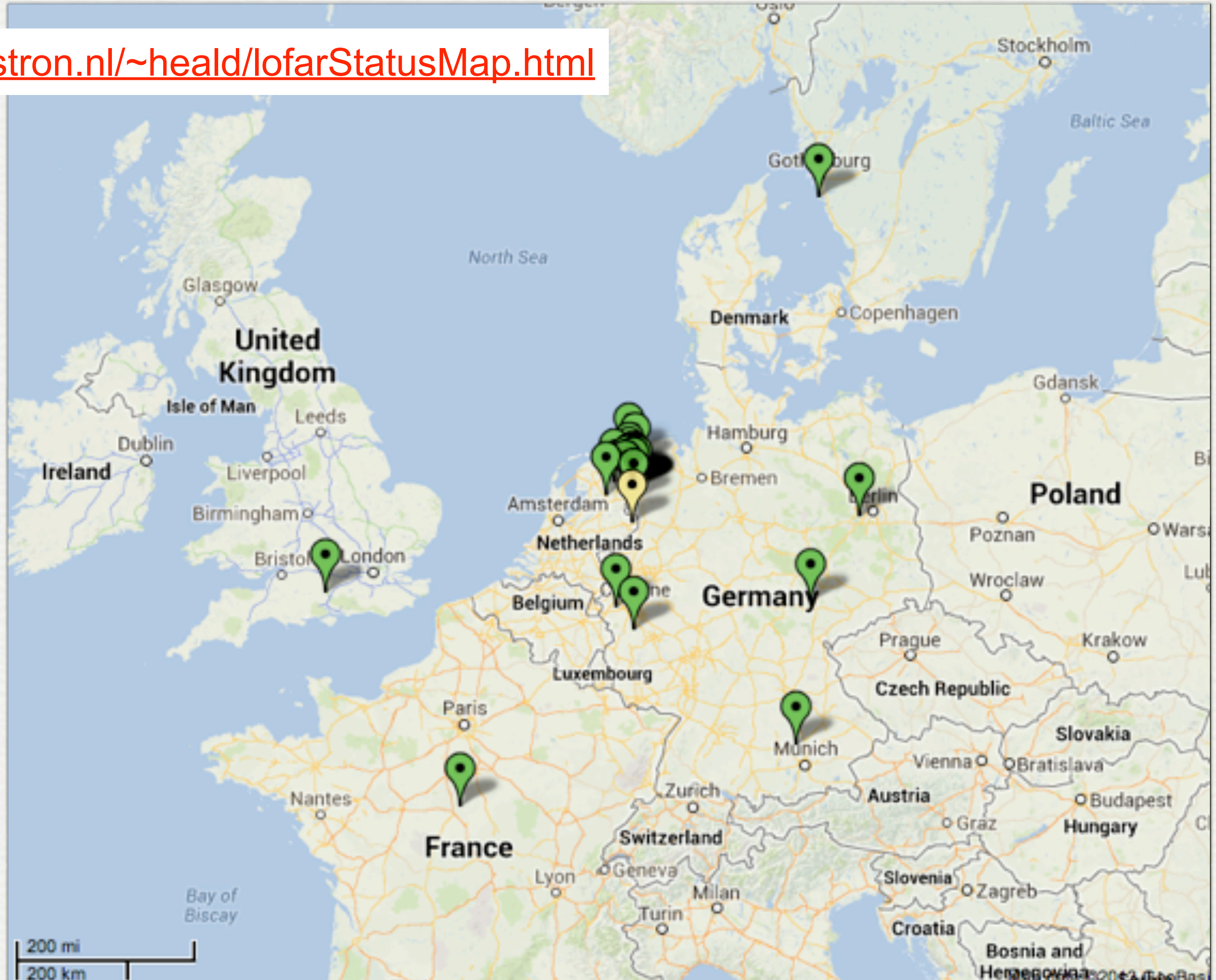
100 square degree

~10 mJy /beam [2 arcmin resolution]

A Pan-European Array (ILT 46)

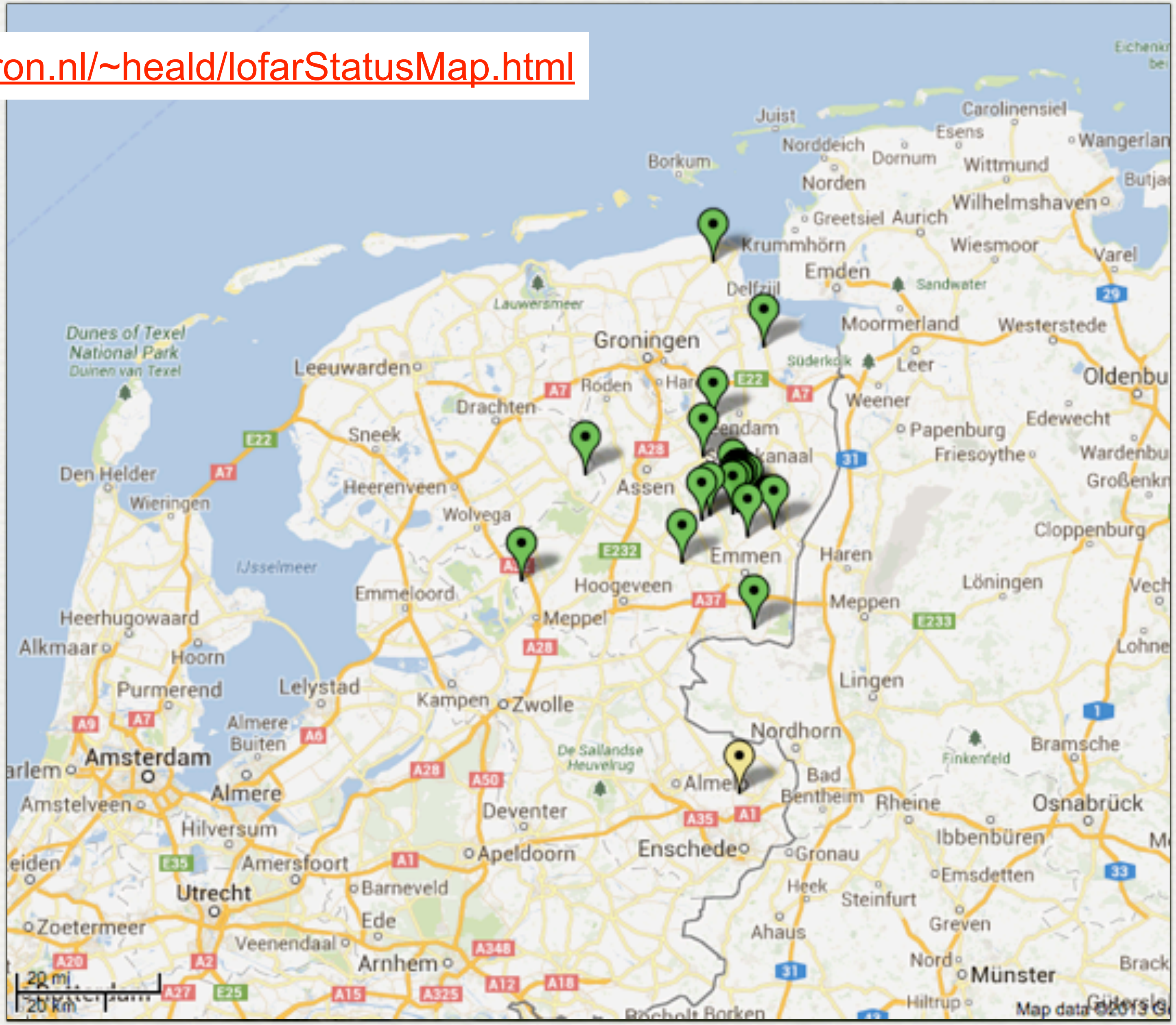
ASTRON

http://www.astron.nl/~heald/lofarStatusMap.html



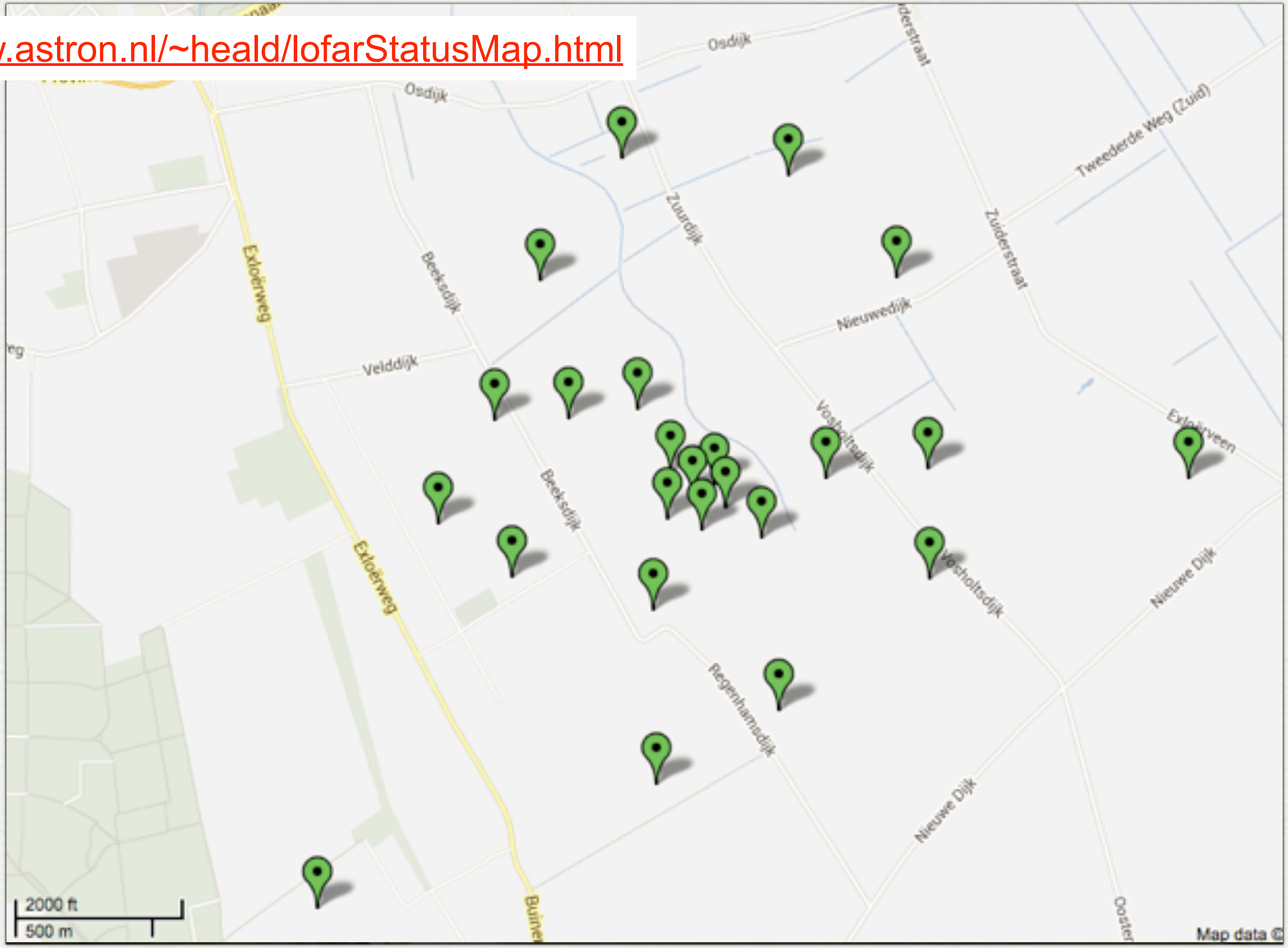
The Dutch Array (LOFAR-NL 38)

http://www.astron.nl/~heald/lofarStatusMap.html

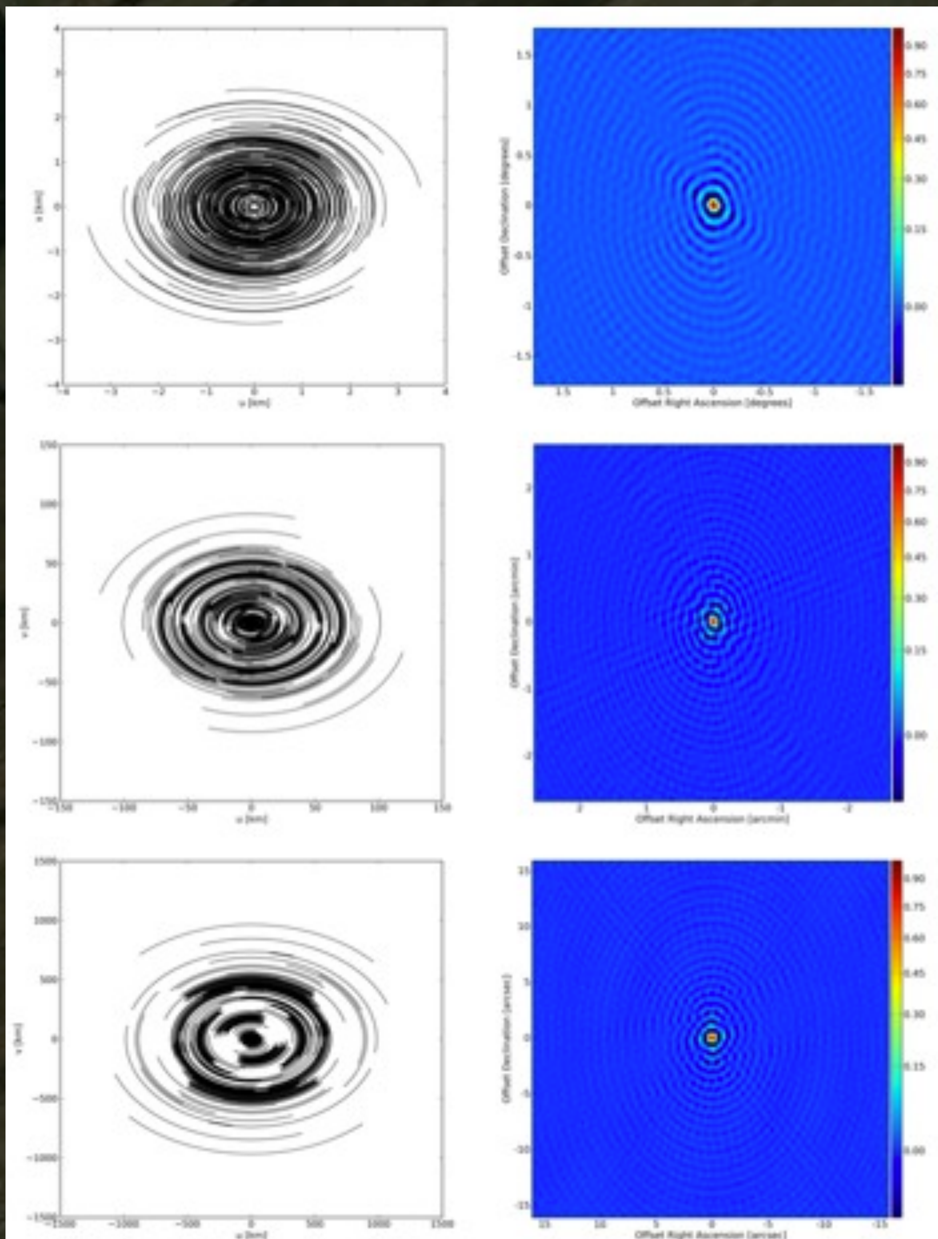


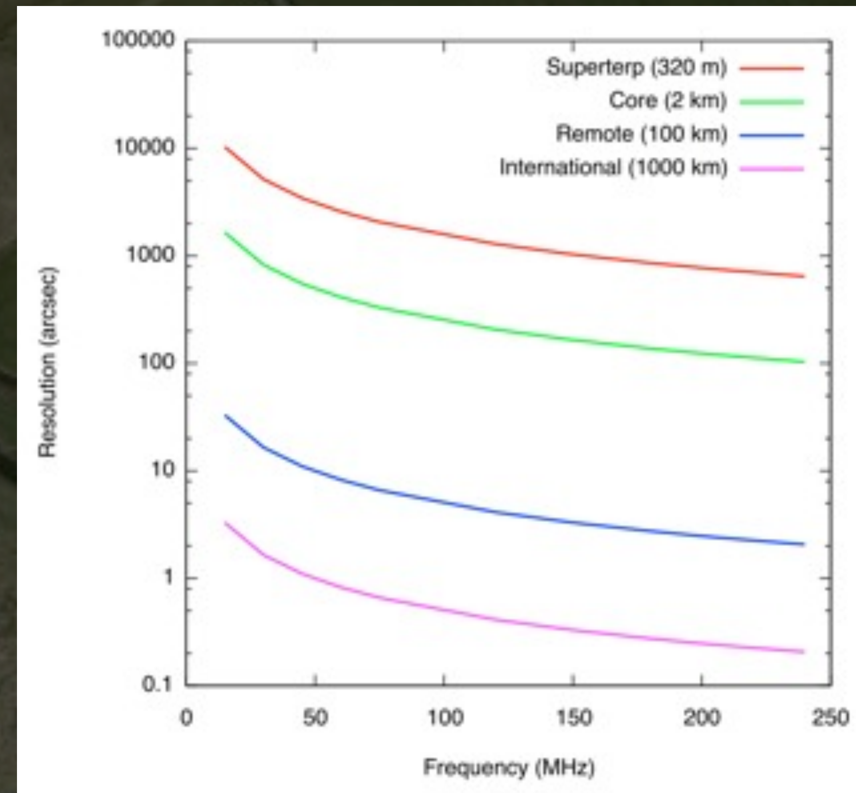
The Core Array (24)

http://www.astron.nl/~heald/lofarStatusMap.html



UV coverage and angular resolution

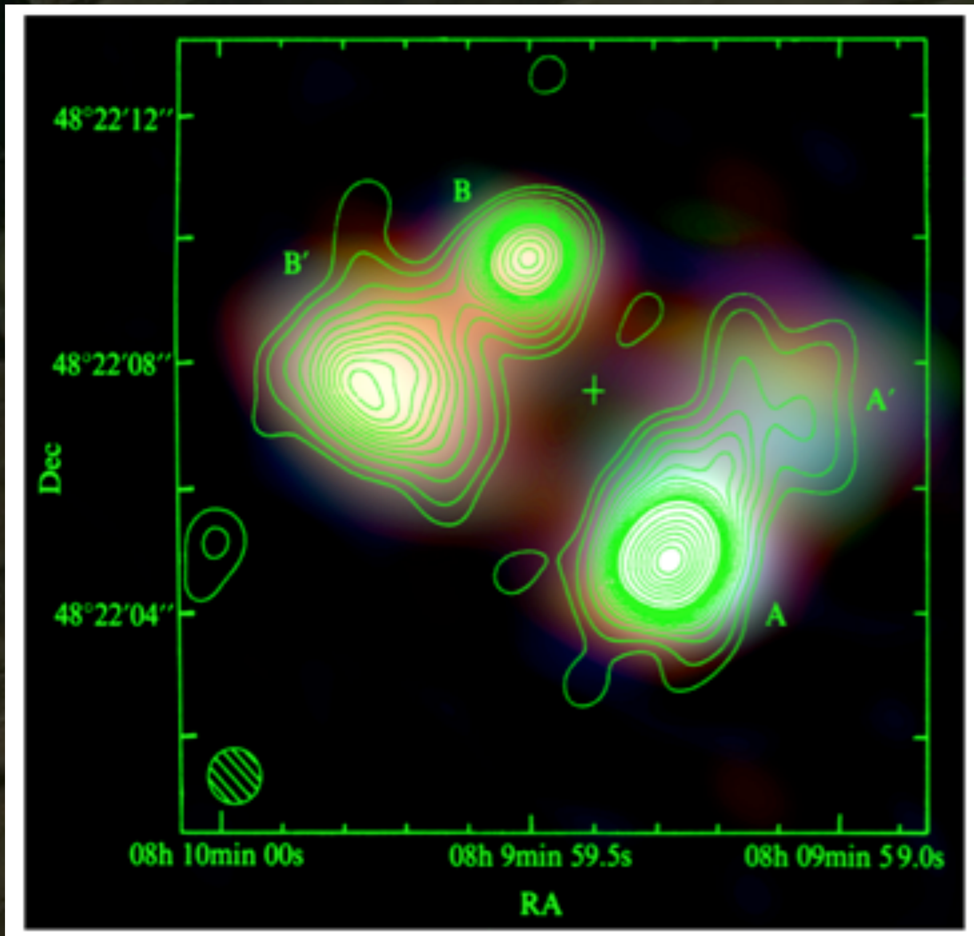


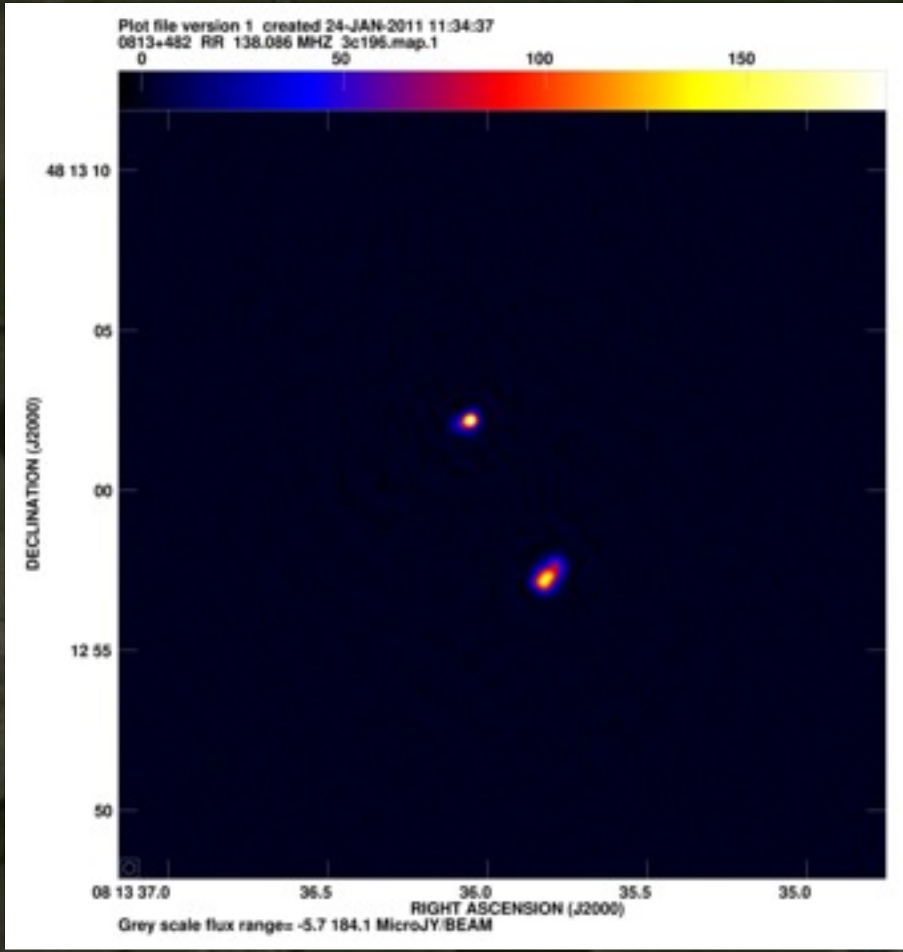


$$\mathrm{FWHM}\ [\mathrm{rad}] = \alpha\ \frac{\lambda}{D}$$

- Where α depends on the data weighting of the visibilities (e.g., 0.8 for uniform weighting).

LOFAR VLBI imaging of 3C196





- LBA image of 3C196 with MERLIN 408 MHz contours overlaid.
- **1.2 arcsec beam**

- HBA image of 3C196 resolves the double structure.
- **0.35 arcsec beam**

Olaf Wucknitz

The dipole SEFD

- The System Equivalent Flux Density is,

$$S_{\mathrm{sys}} = \frac{2\eta k}{A_{\mathrm{eff}}} T_{\mathrm{sys}}$$

- The system temperature is,

$$T_{\mathrm{sys}} = T_{\mathrm{rec}} + T_{\mathrm{sky}}$$

- The sky temperature is dominated by the Galactic emission (LBA: 320000-1000 K and HBA: 630-80 K),

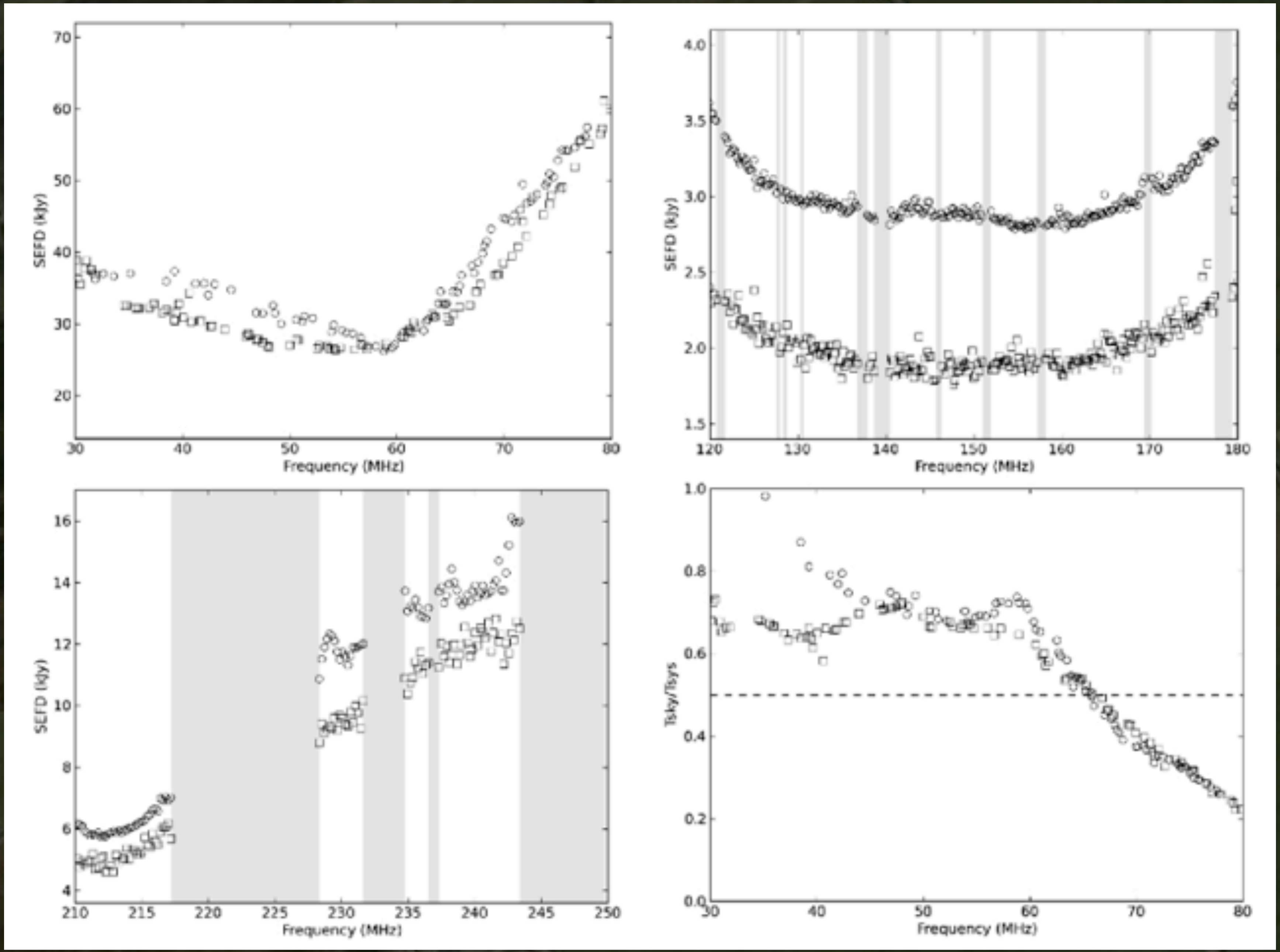
$$T_{\mathrm{sky}} = T_{\mathrm{S_0}}\,\lambda^{2.55}$$

- The minimum effective areas of the dipoles are defined by the observing wavelength and the separation between the dipoles,

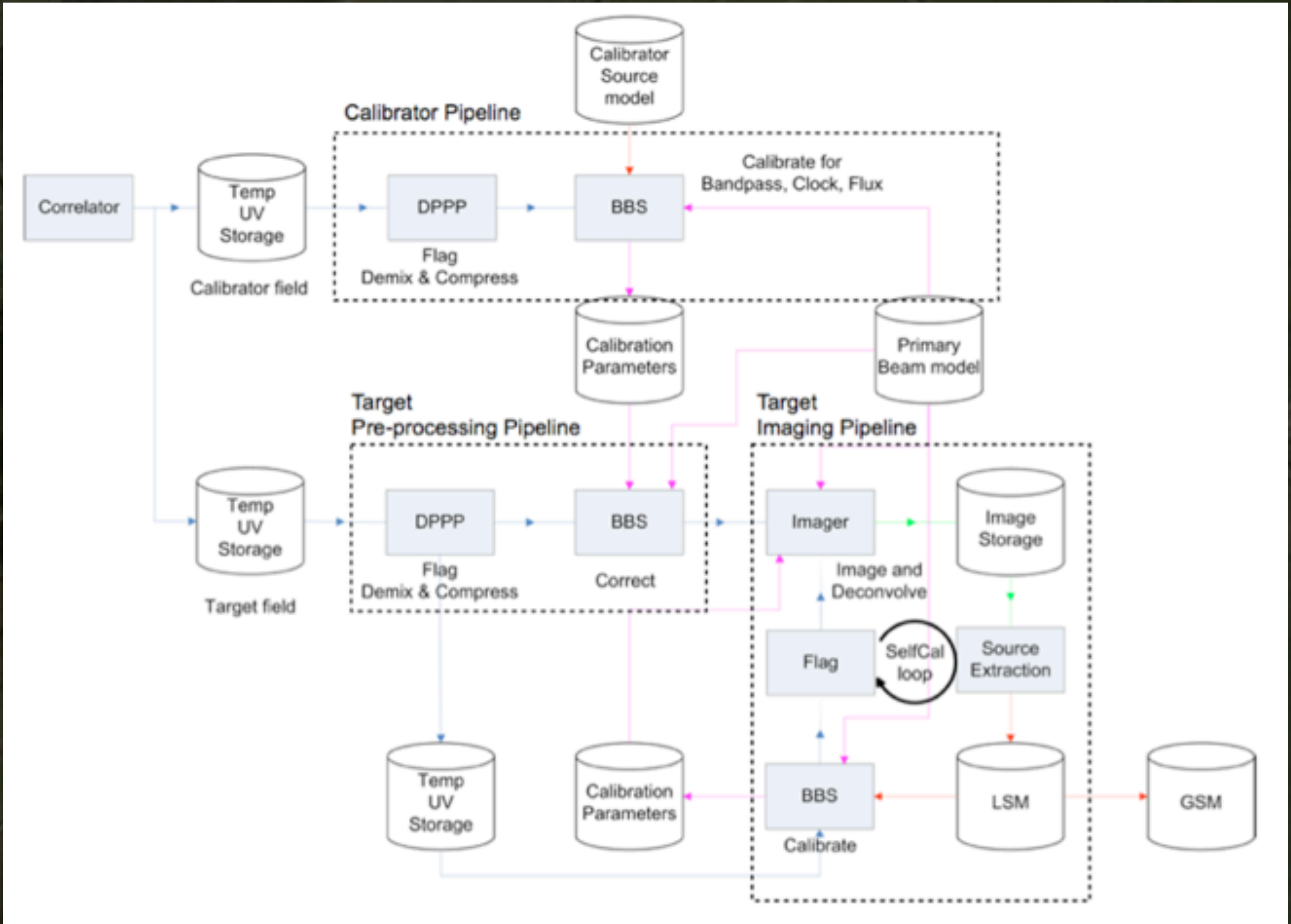
$$A_{\mathrm{eff,dipole}} = \min\left\{\frac{\lambda^2}{3}, \frac{\pi d^2}{4}\right\}$$

$$A_{\mathrm{eff,dipole}} = \min\left\{\frac{\lambda^2}{3}, \frac{25}{16}\right\}$$

Array sensitivity



Data analysis pipeline



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Data Volumes

- Like many new instruments, LOFAR will also investigate data handling management.

- **Interferometric Data**

Data Vol = Ba * P * T * C * S * Be * (bytes/T + overhead)

Ba = baselines = **2556** (for HBA Dual) or **1128** (for HBA Single).

P = Polarisations = 4 (XX, YY, XL, LX).

T = Time Samples = 21600 (for 6h observations and 1 s visibility averaging).

C = Channels = 256

S = Sub-bands = 244

Be = 1

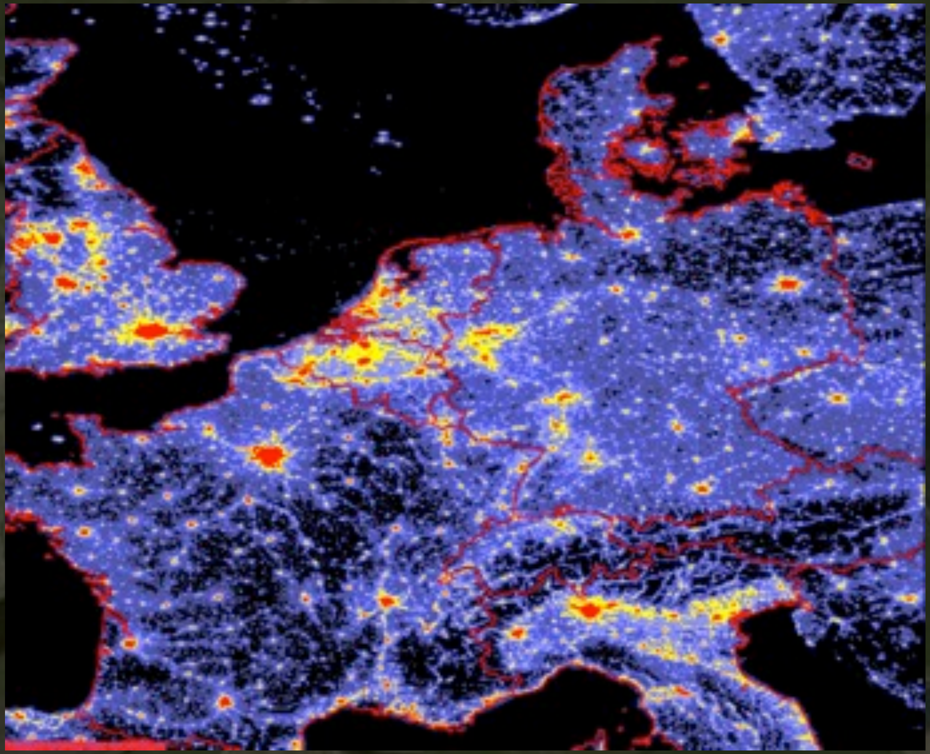
bytes/Sa + overhead = 8 + 0.2

Data Vol = 113 Tb **Need data processing cluster!**

Radio frequency interference

ASTRON

- Europe is a highly populated area - lots of radio frequency interference!



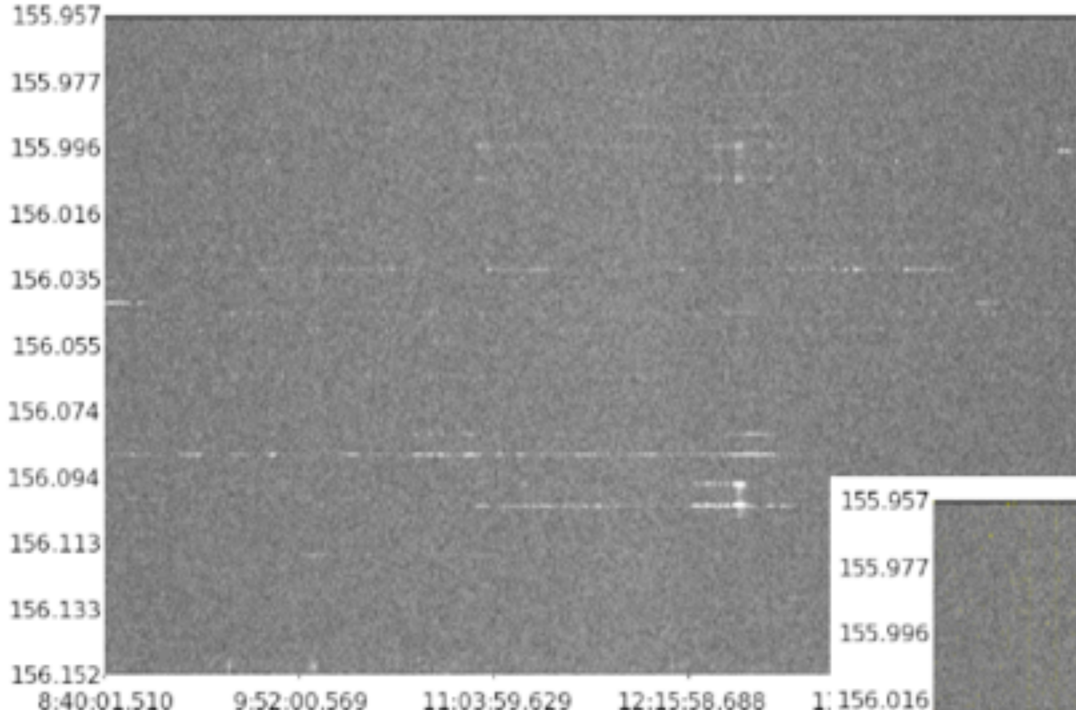
- LOFAR mitigates RFI by

  i) having a small time and frequency resolution (1s; 763 Hz).

  ii) having 40 dB receiver units to stop saturation/spill over to other channels

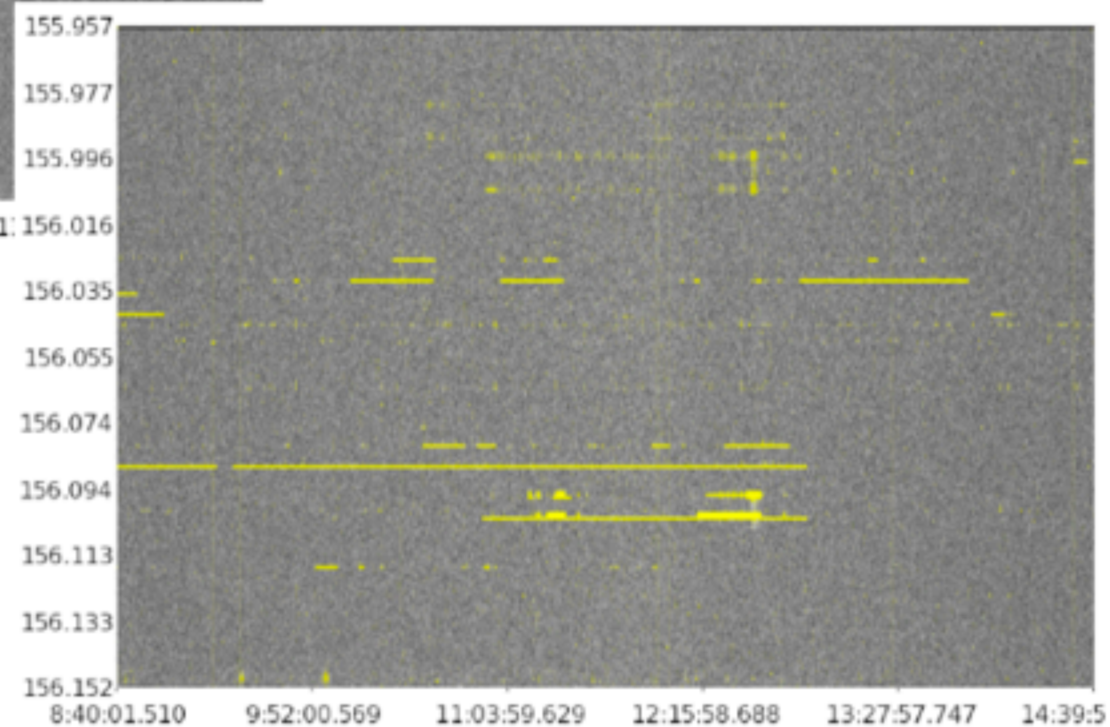
  iii) having digital filters to remove signals at < 30 MHz, 80--110 MHz.

Radio frequency interference



AOflagger (Offringa et al.2012).

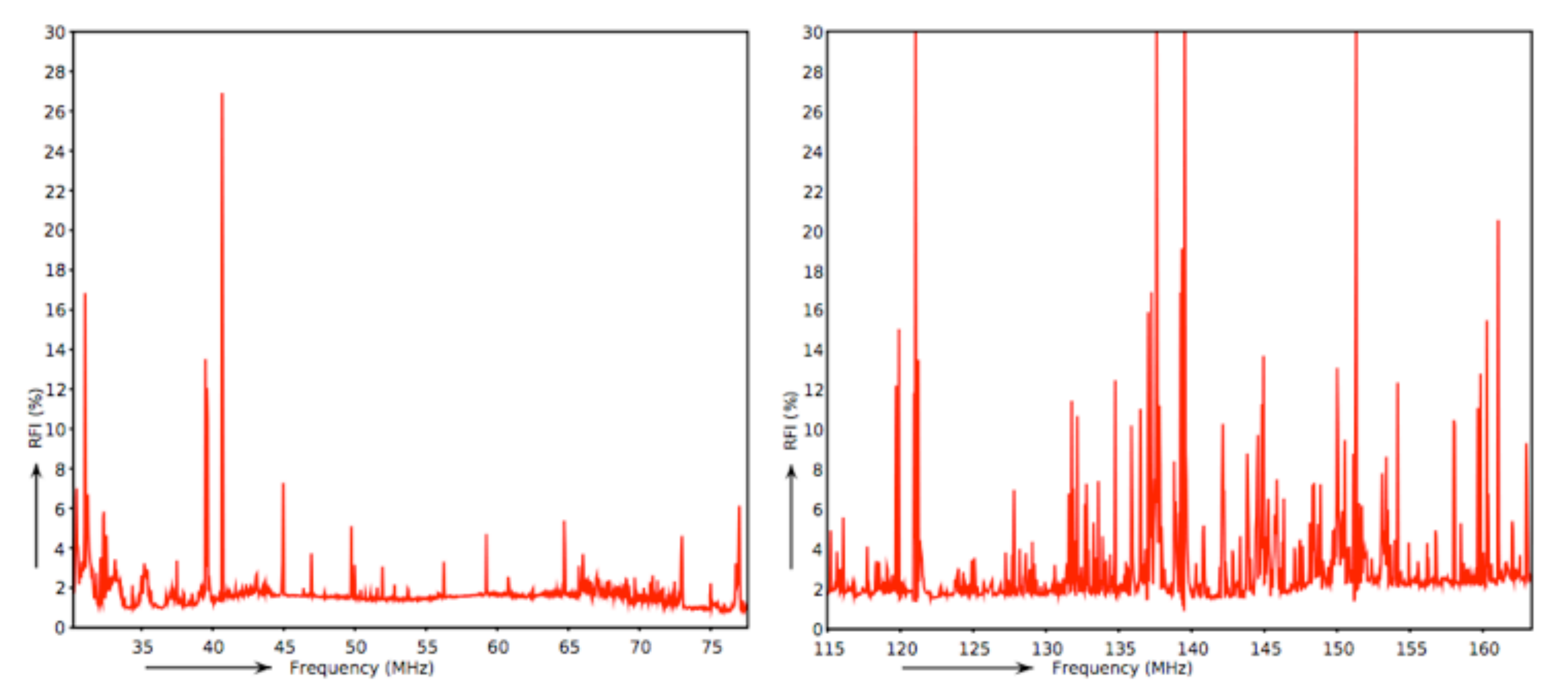
- fits a surface to the time-frequency plane to identify RFI.



- Iteratively defines the threshold.
- Low level of false-positive RFI detections
- Struggles with very broad-band RFI.

Radio frequency interference

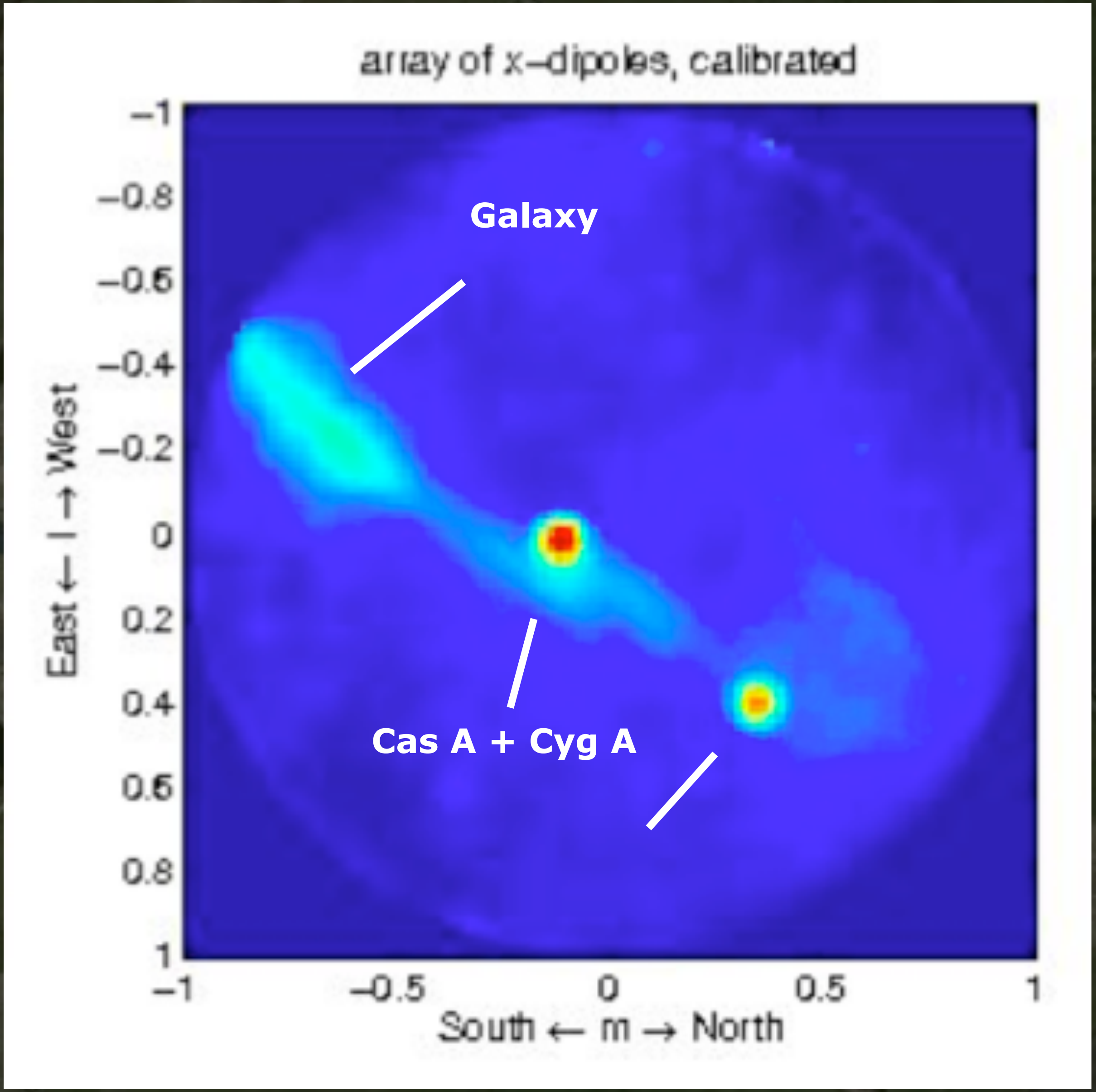
(Offringa et al. 2012, 2013)



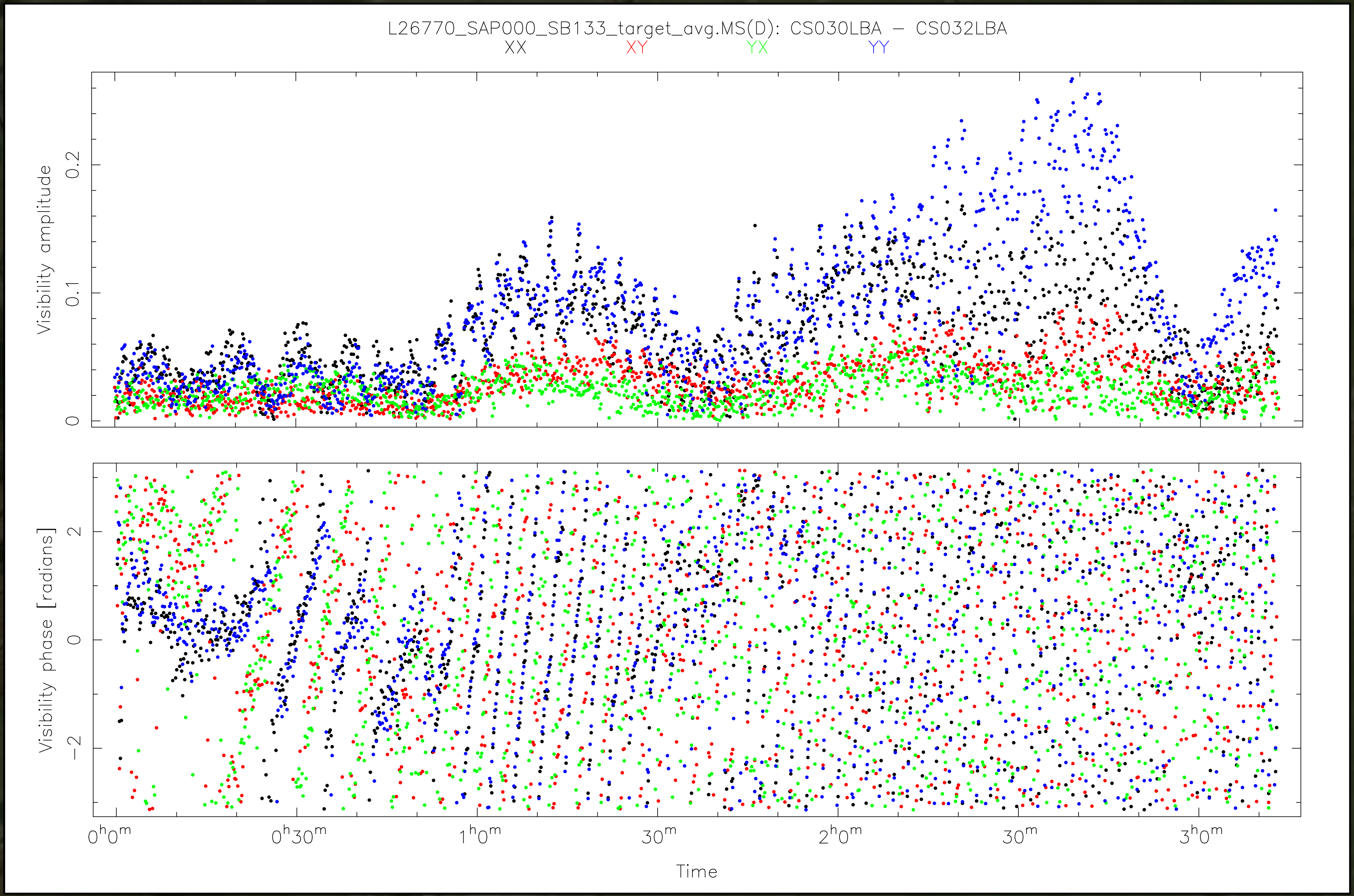
- RFI occupancy is low and day / night results are consistent.
  - LBA: 1.8%
  - HBA: 3.2%

Bright confusing sources

- The dipoles see the whole sky.
- Cygnus A and Cassiopeia A dominate the radio sky for LOFAR.

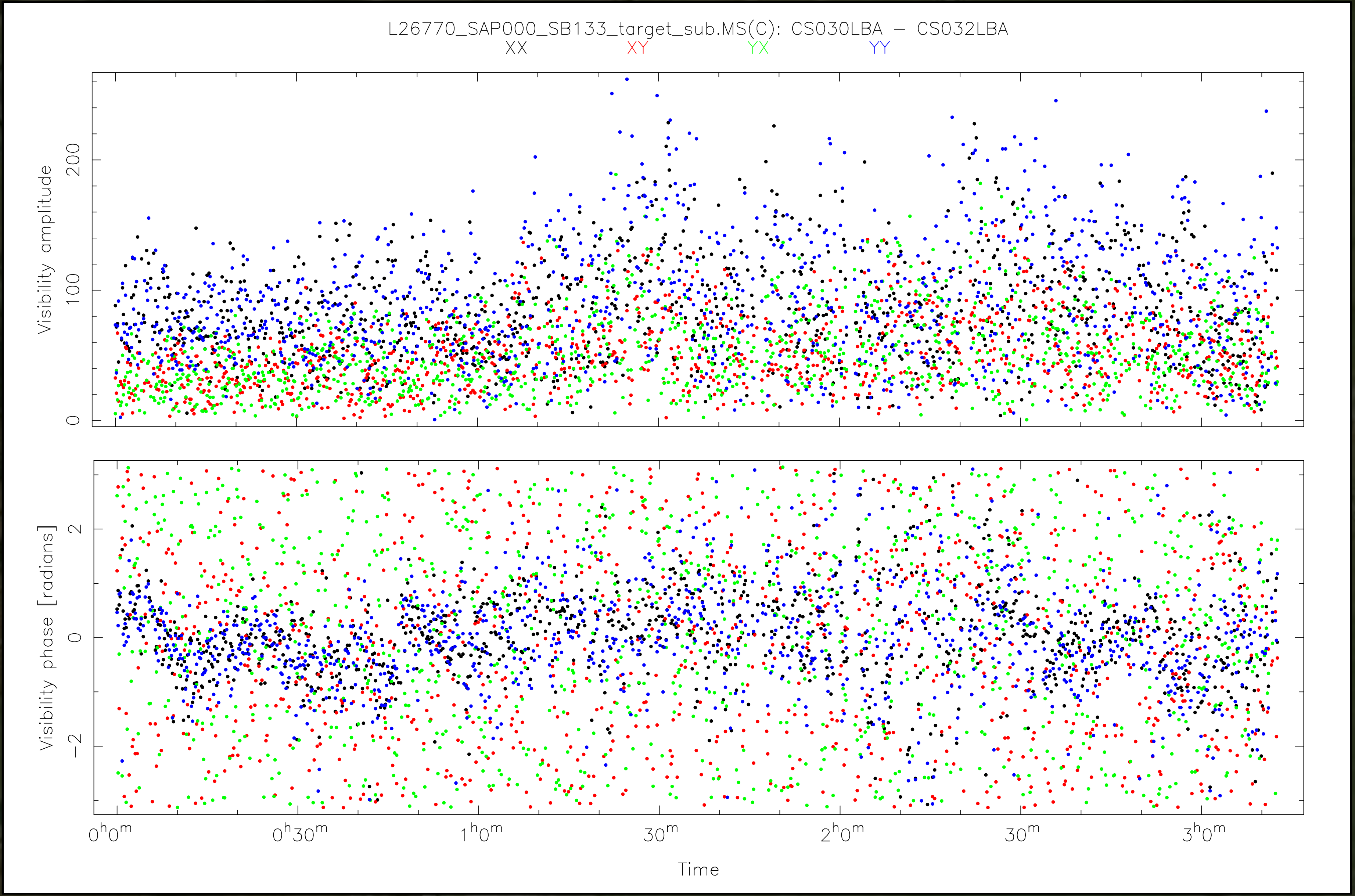


Bright confusing sources



George Heald

De-mixing



George Heald

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Calibration

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

$$V_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\mathrm{true}}$$

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true visibility for ant. *i* and *j*

Calibration

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Observed visibility for ant. *i* and *j*

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Baseline based, non closing errors

true visibility for ant. *i* and *j*

Calibration

ASTRON

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Baseline based, non closing errors

Gain amplitude and phase

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Errors due to elevation

Observed visibility for ant. *i* and *j*

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true visibility for ant. *i* and *j*

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- Observed visibility for ant. *i* and *j* (V_{ij}^{obs})
- Baseline based, non closing errors (M_{ij})
- Gain amplitude and phase (G_{ij})
- Errors due to elevation (E_{ij})
- Opacity and path length variation (T_{ij})
- true visibility for ant. *i* and *j* (V_{ij}^{true})

Calibration

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Baseline based, non closing errors

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Opacity and path length variation

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Change in paralactic angle

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Instrumental polarisation

Change in paralactic angle

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Bandpass response

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Baseline based, non closing errors

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Opacity and path length variation

true visibility for ant. *i* and *j*

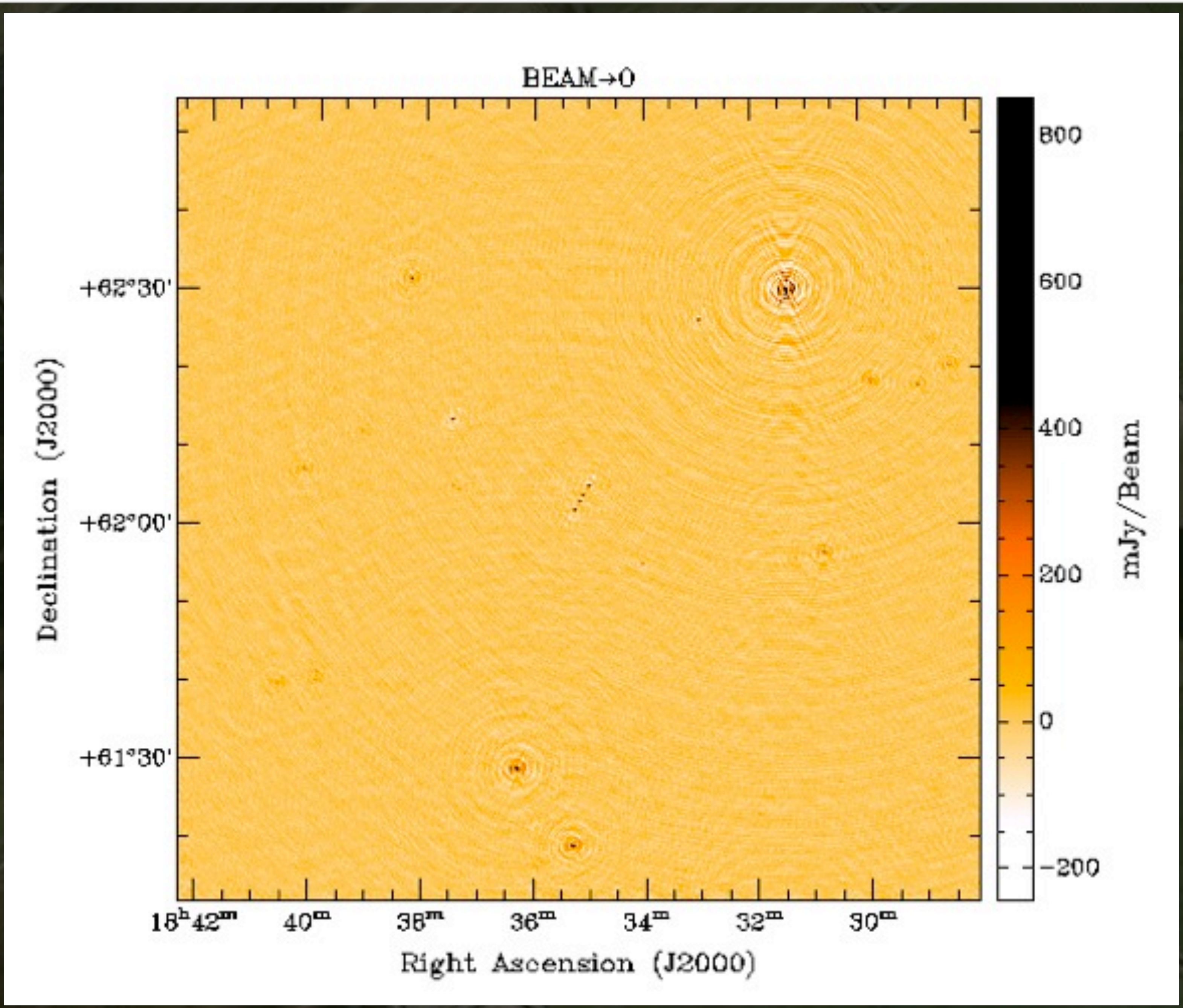
Bandpass response

Instrumental polarisation

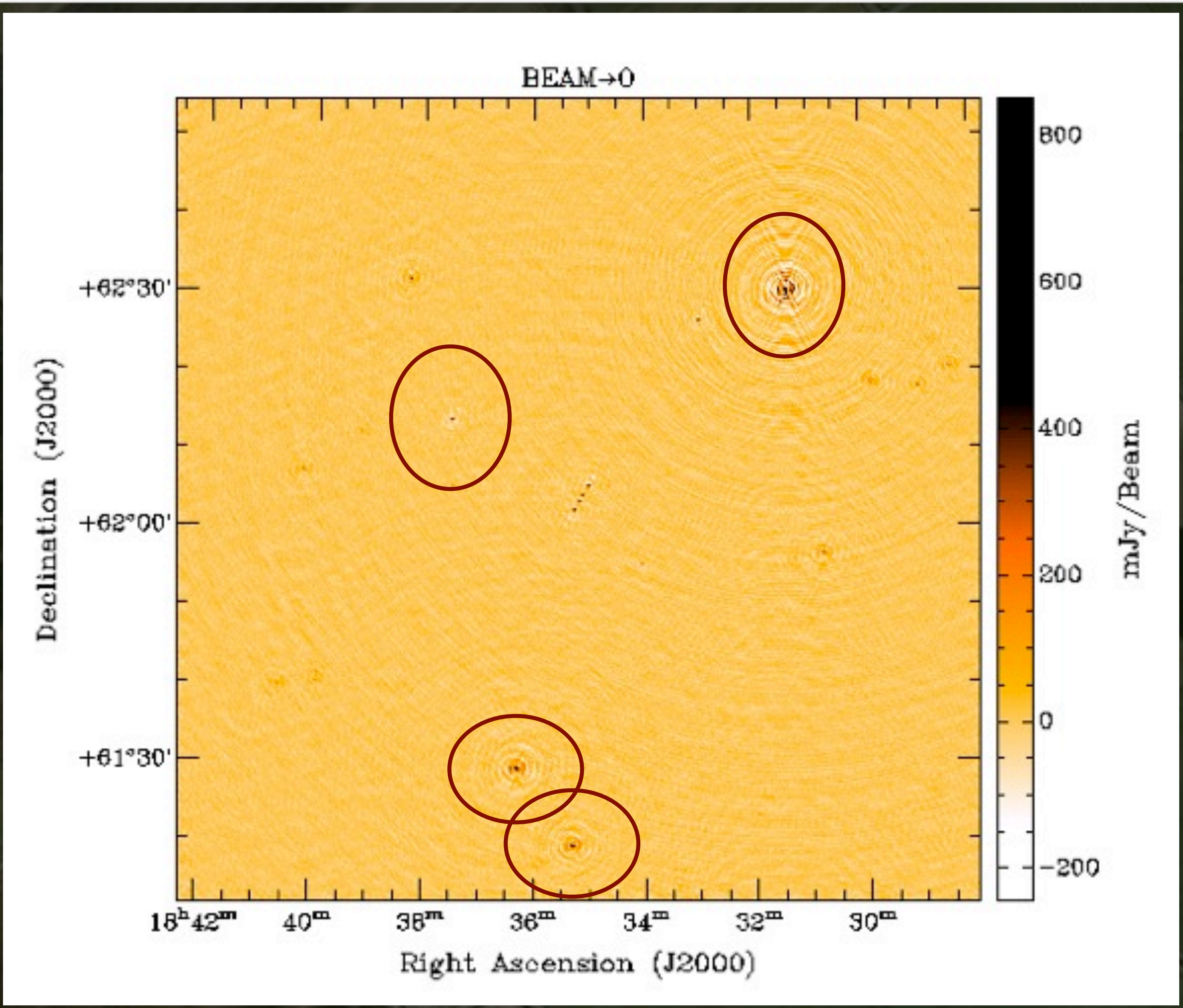
Change in paralactic angle

- Jones (2 x 2) matrices only valid for solving in one direction.
- Is that ok? LOFAR is just an interferometer.

Direction dependent effects



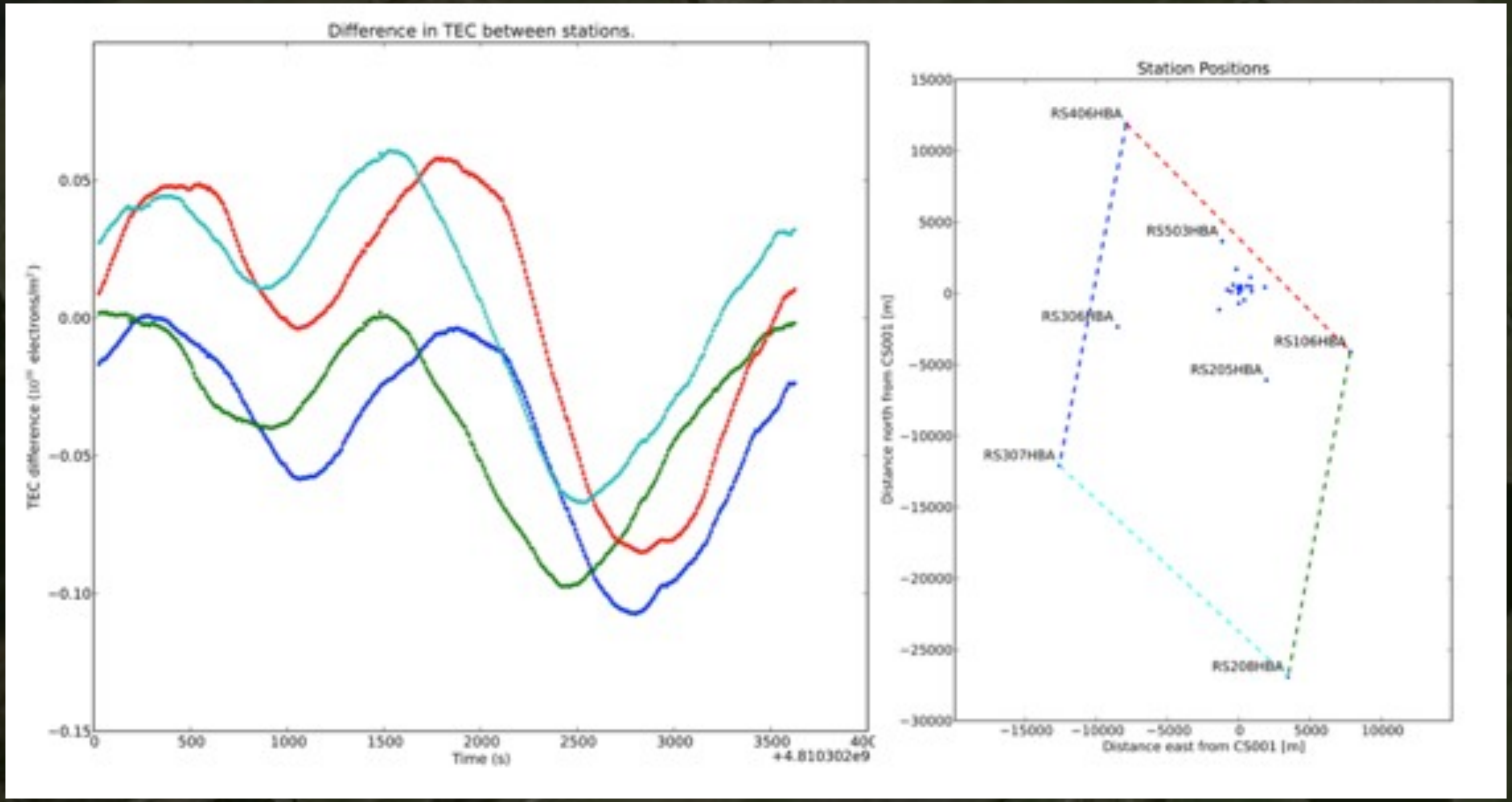
Direction dependent effects



Ionosphere

- Yes, but LOFAR is a low-frequency interferometer, so the ionosphere is highly variable!

Mark Aartsen

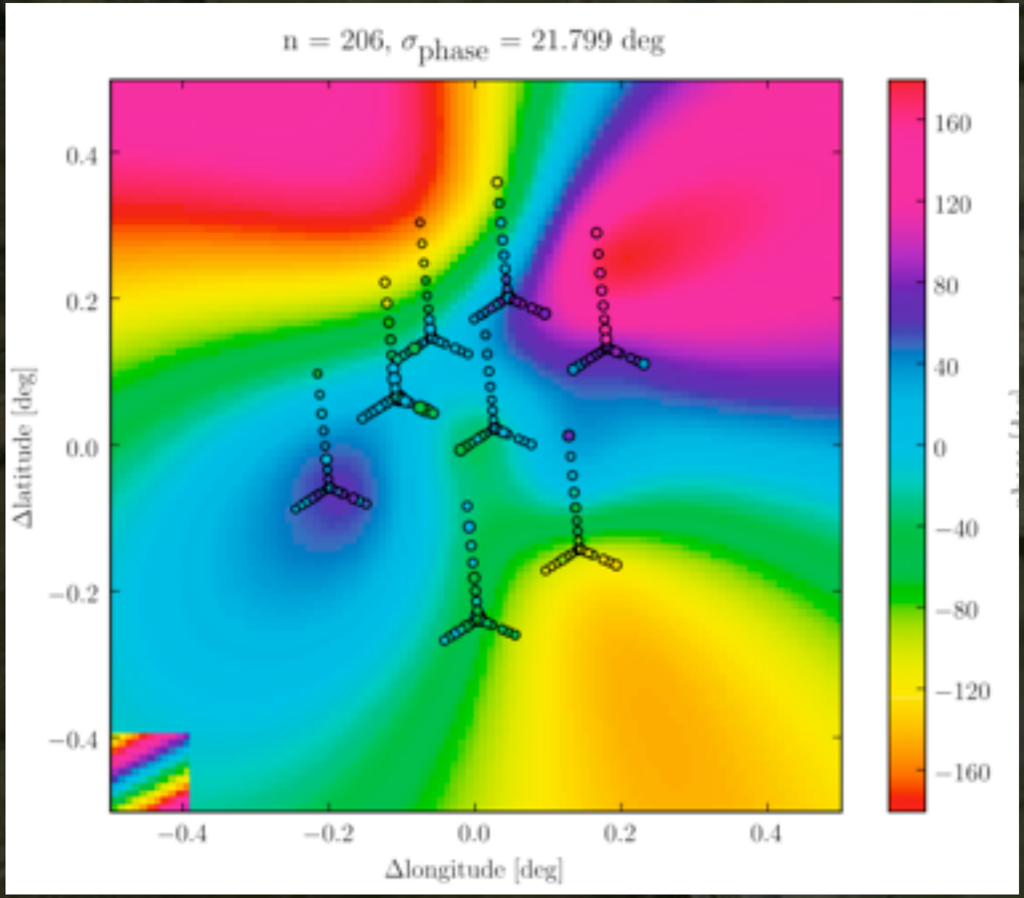


- The recent detection of the motion of an ionospheric wave over the LOFAR remote stations.
- *So what, the same is the case for other interferometers.*

Ionosphere

- Yes, but LOFAR is a low-frequency interferometer, the wide fields of view (many degrees!) mean we are observing through different parts of the ionosphere.

Different gains (amplitudes and phases over the field of view)

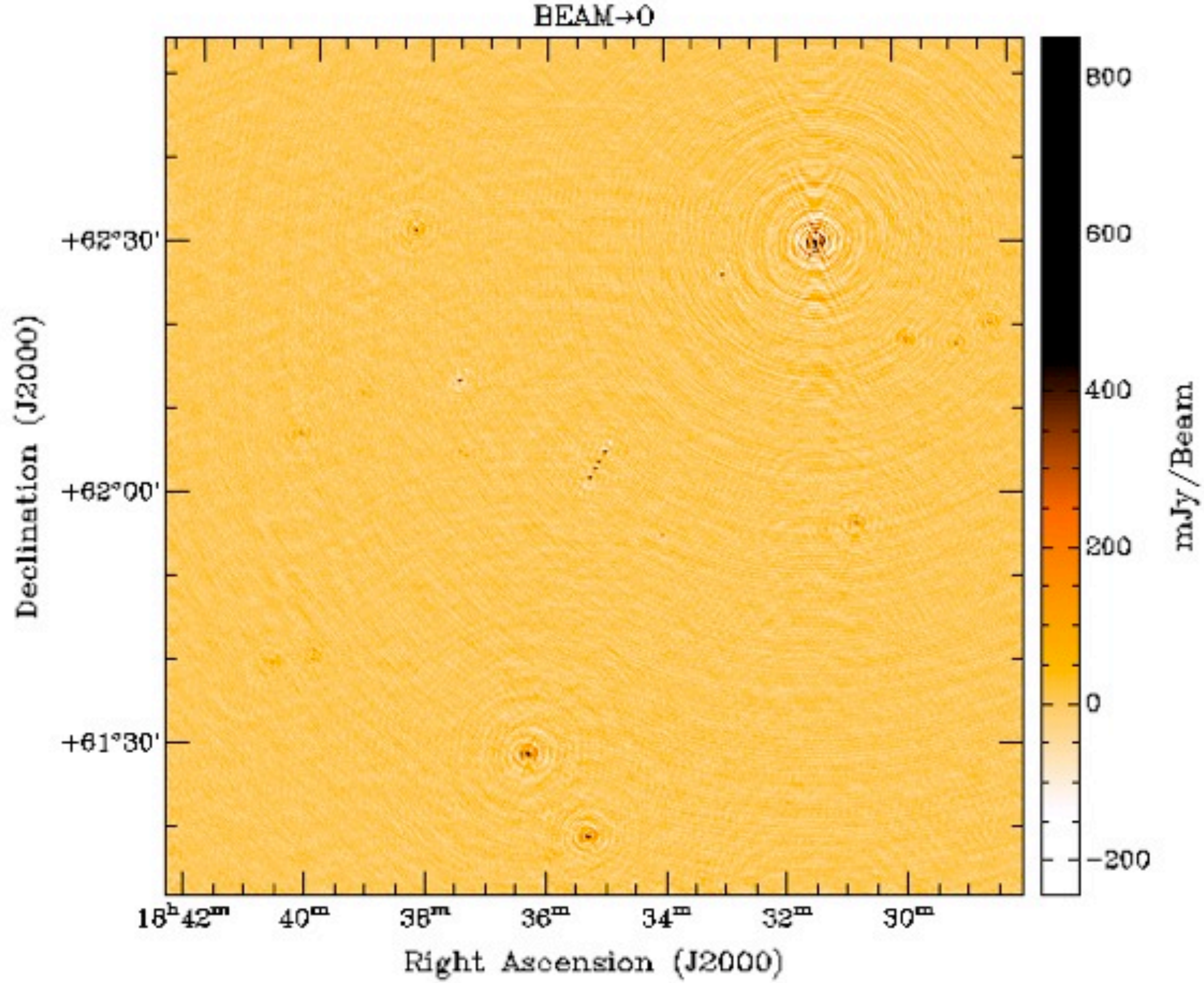


- Observations of 8 sources with the VLA at 74 MHz (10 degree FoV).
- The solutions for each antenna toward each source are used to create a phase screen.
- Direction dependent calibration needed.

Intema et al. (2009)

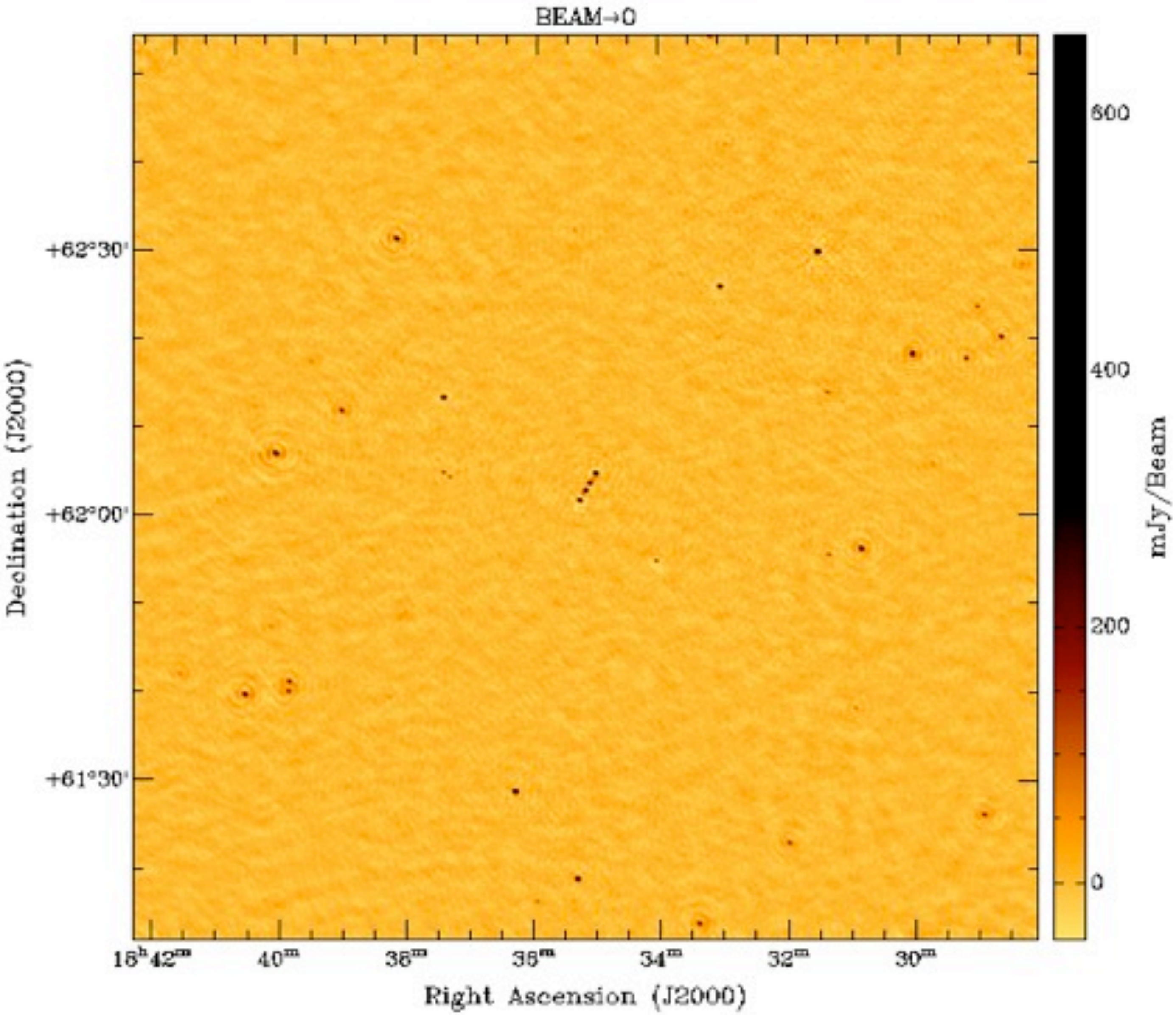
Calibration

Manu Orru'



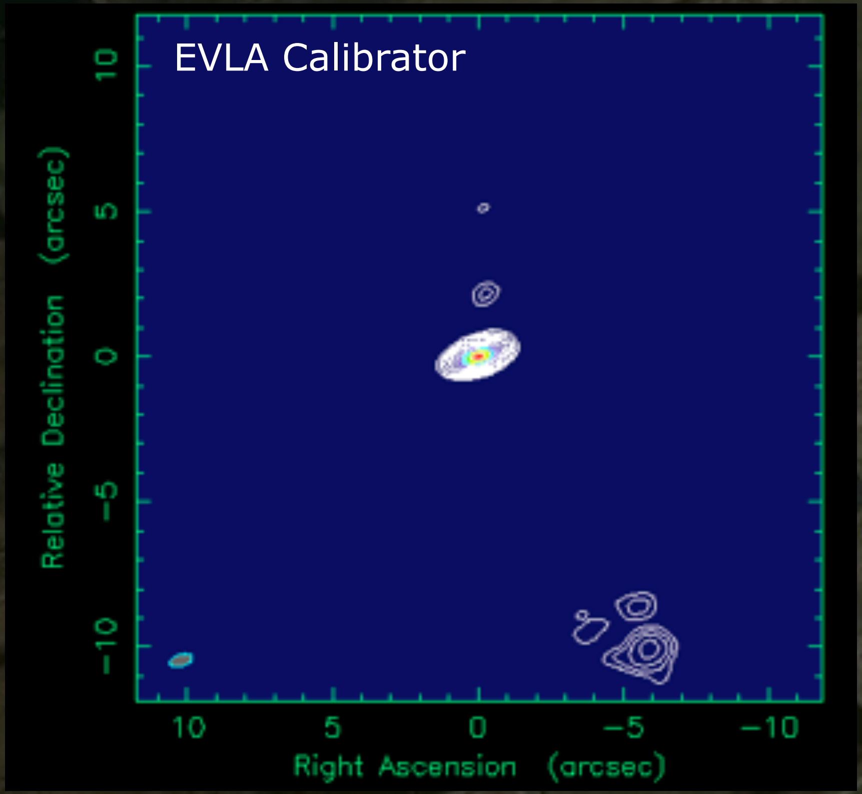
Calibration

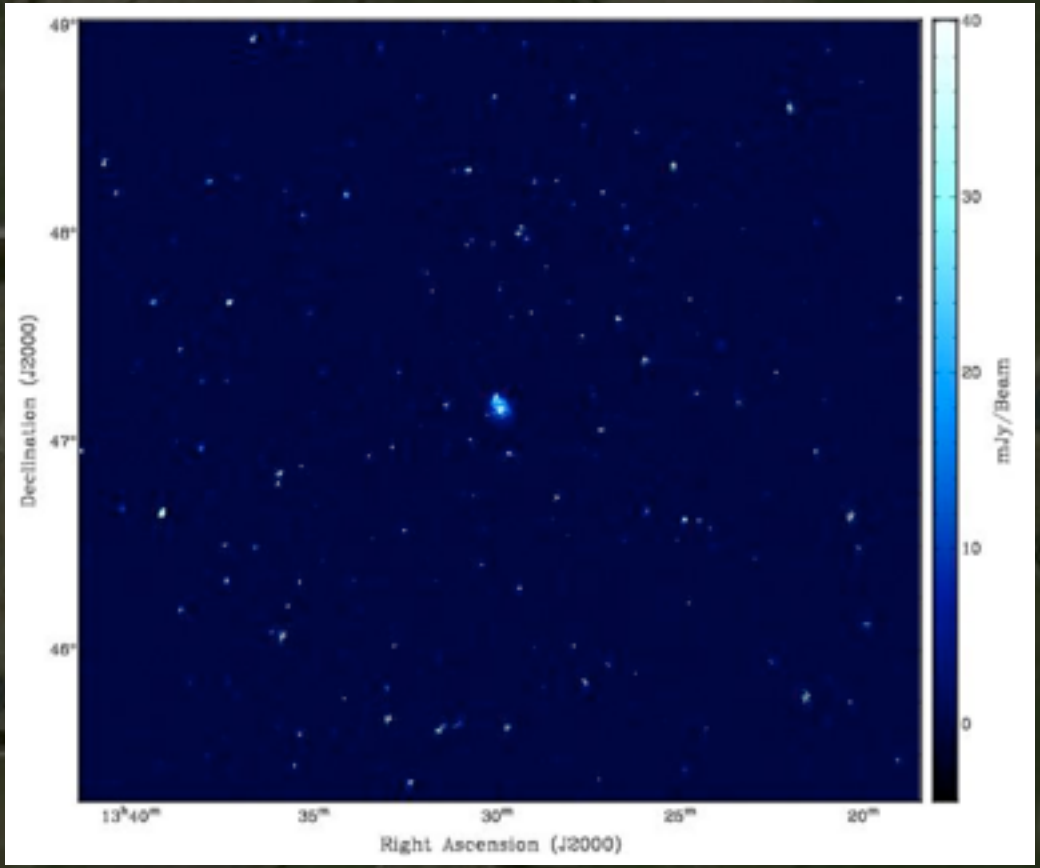
Manu Orru'



Your sky calibration model

- The visibility function is not dominated by a single source (for most cases).



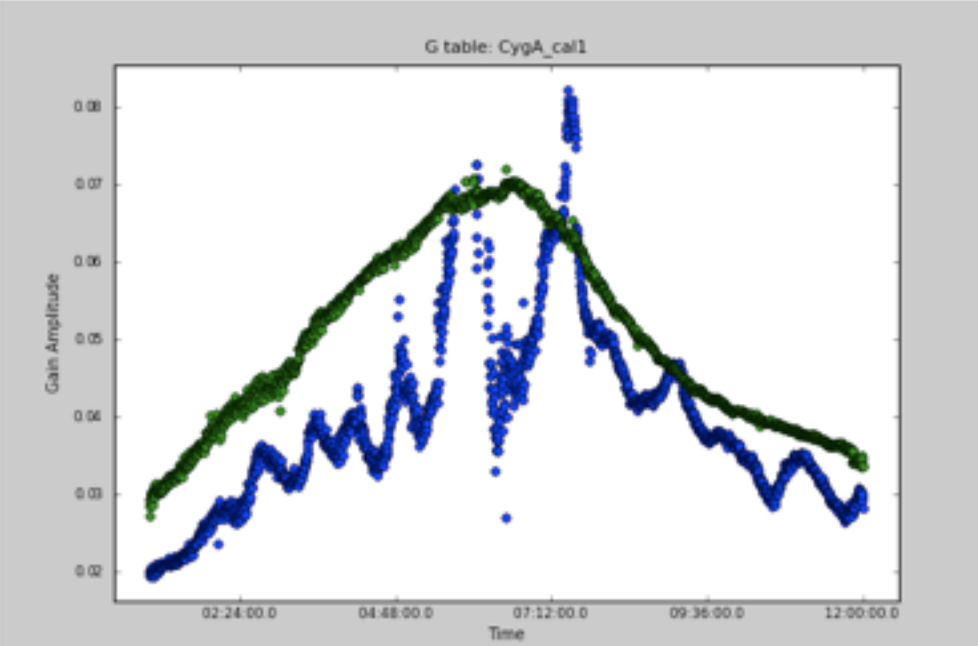


- In beam calibration with the dominant sources in the field is used.

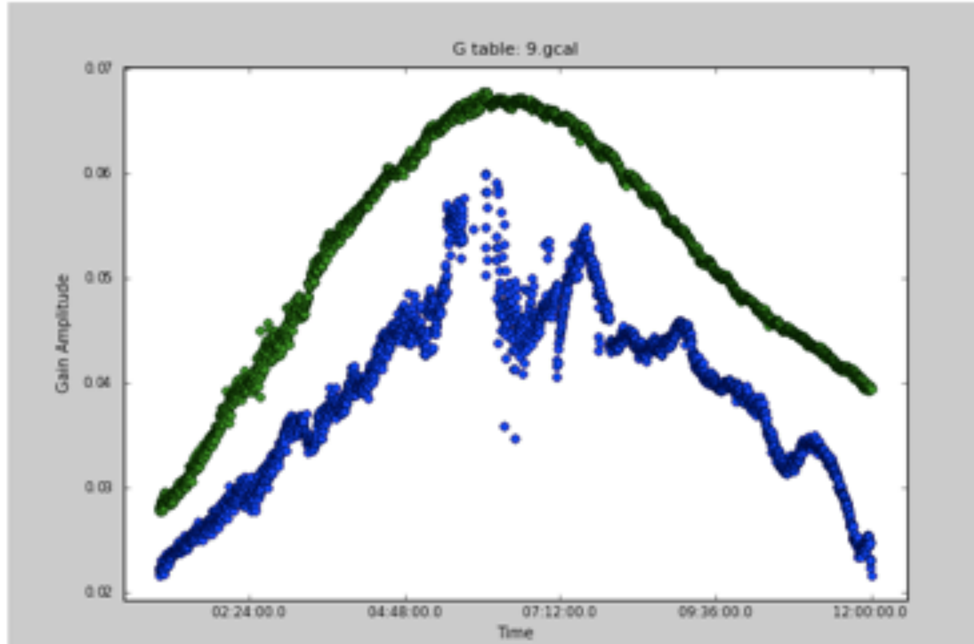
  Good since it gives the amplitude and phase for the target field as a continuous function of time.

Improve the sky model with selfcal

- 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

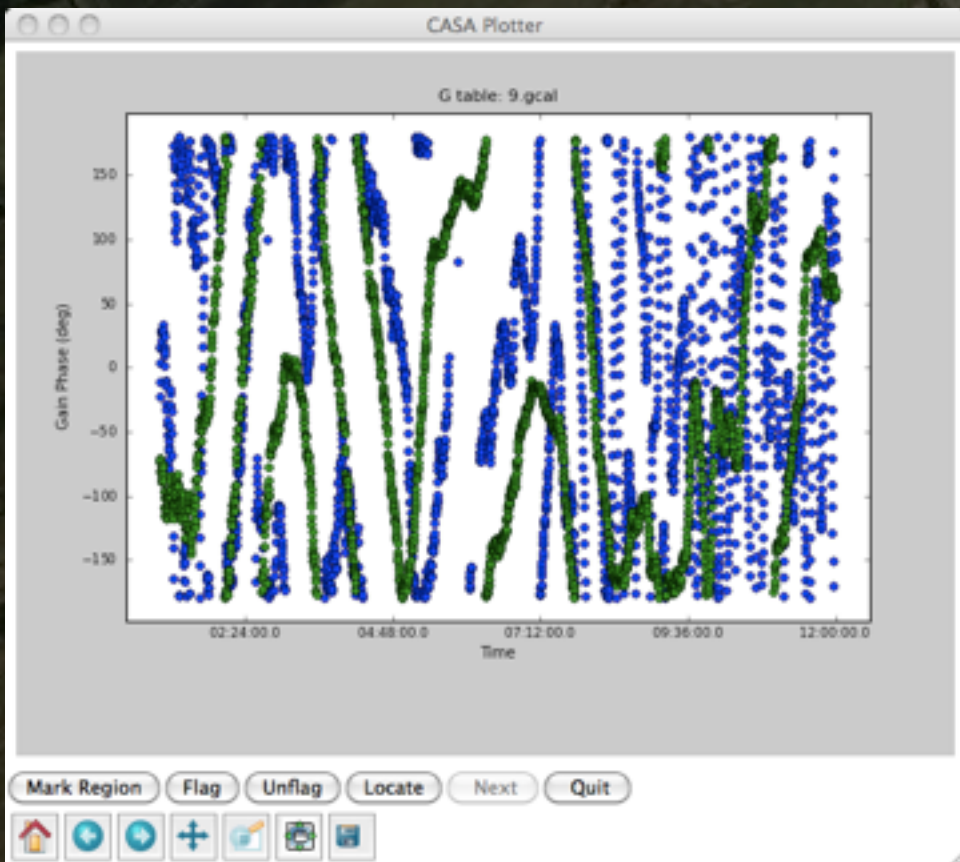


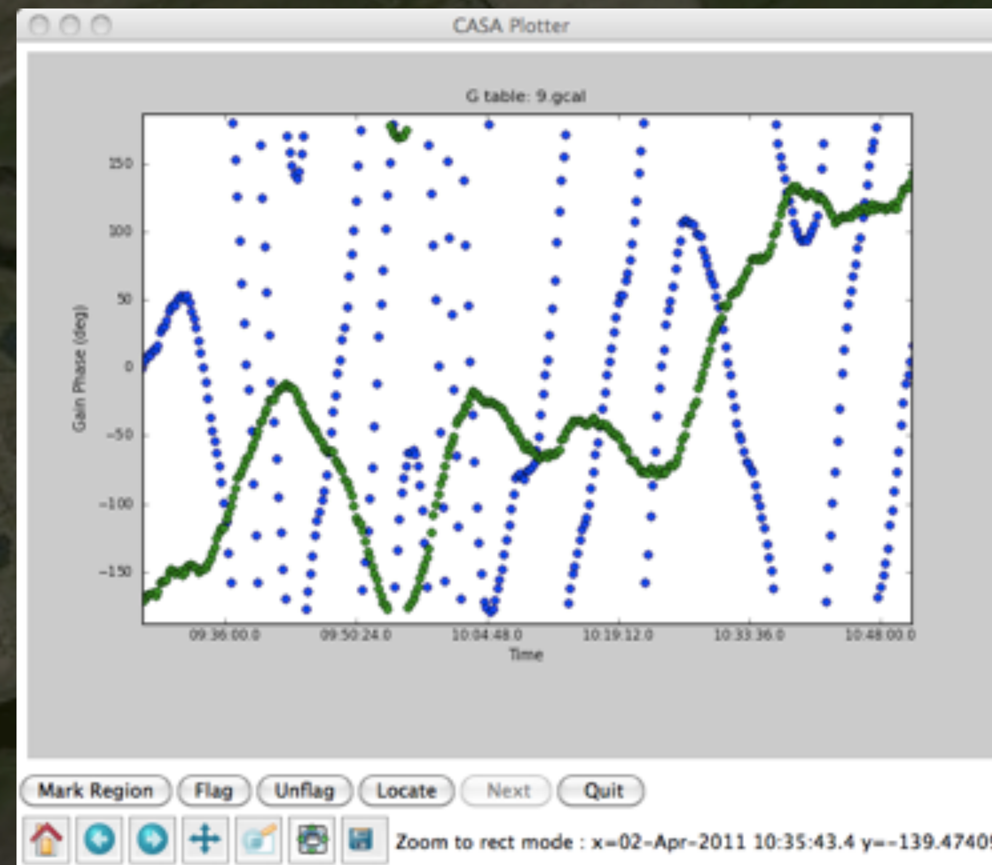
Better after self calibration

- Selfcal call helps a lot: N_{ant} unknowns $N_{ant}(N_{ant} - 1)/2$ constaints!
- A survey to establish the LOFAR initial sky model, that can be used for the first round of calibration will soon start (MSSS).

Phase Solutions

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





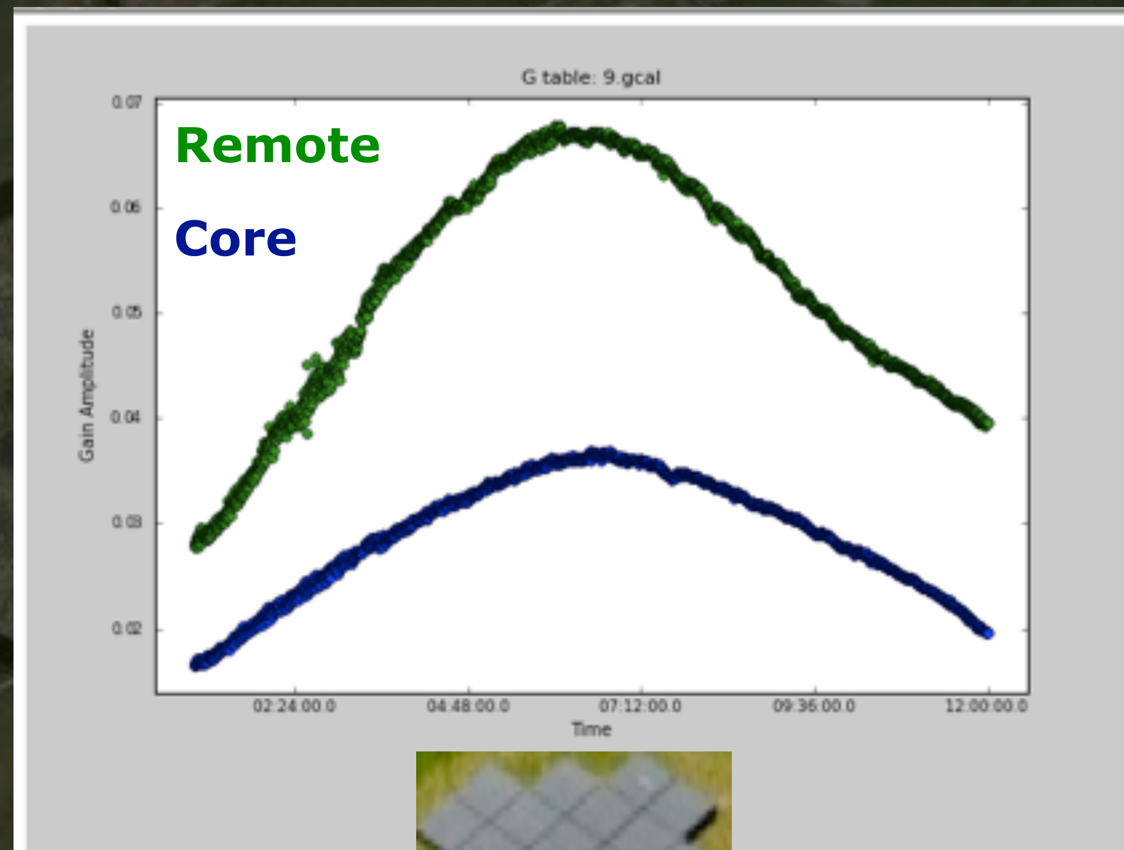
- Phases change faster for longer baselines.
- Still trace the changes for 15s visibility integration time.

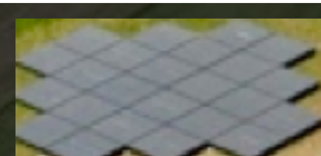
The station beam

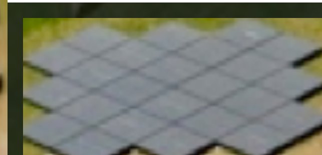
- The amplitude gain for dishes, which track a source over the sky, typically vary by a few percent over an observation.

- For LOFAR, the gains change over time because the projected area of the station changes with respect to the source.

- Core, Remote and International stations have different areas, so the amplitude gain is also different.







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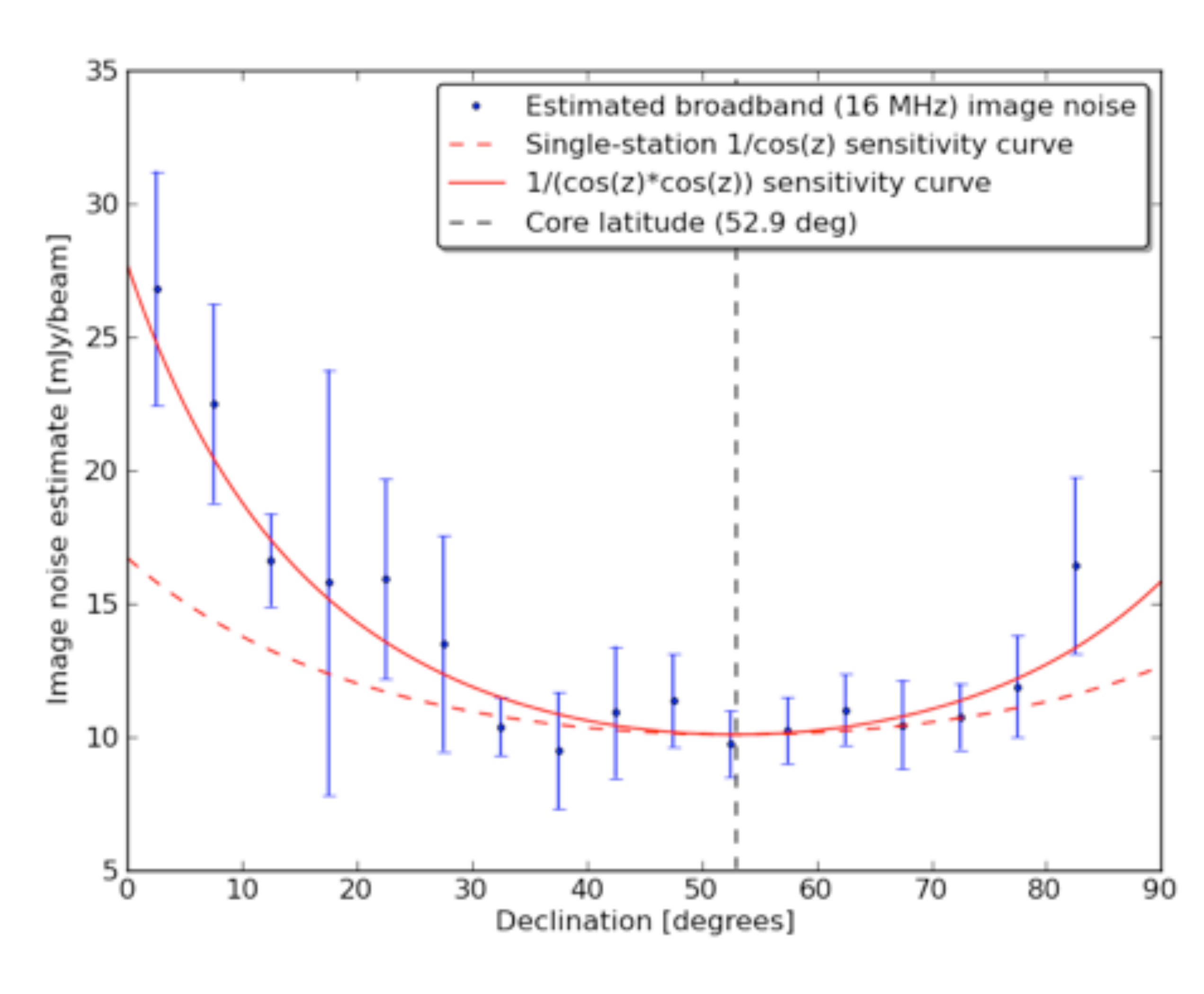

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Wide field imaging

- The aim of imaging is to determine an accurate surface brightness distribution (positions and flux-densities) of the sky.

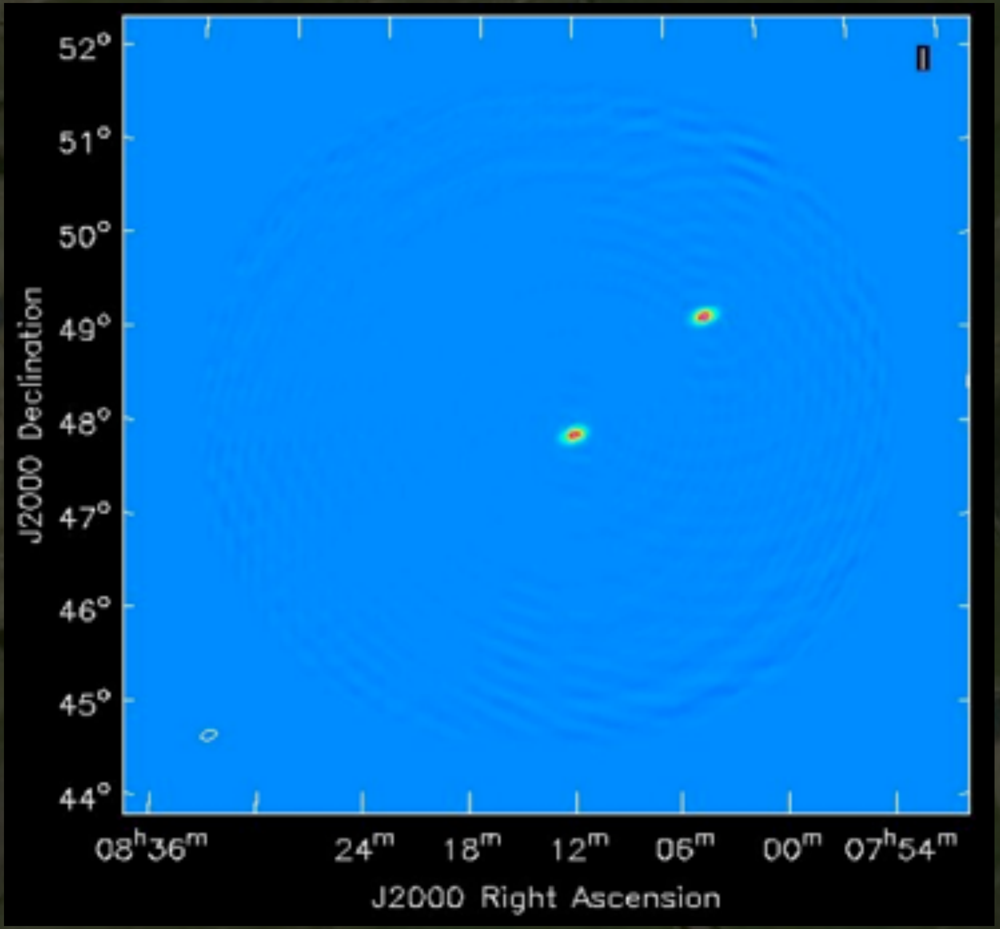
- We need:

  i) w-projection because the 2-d approximation does not hold over wide fields of view

  ii) a-projection because the LOFAR beam is constantly changing.

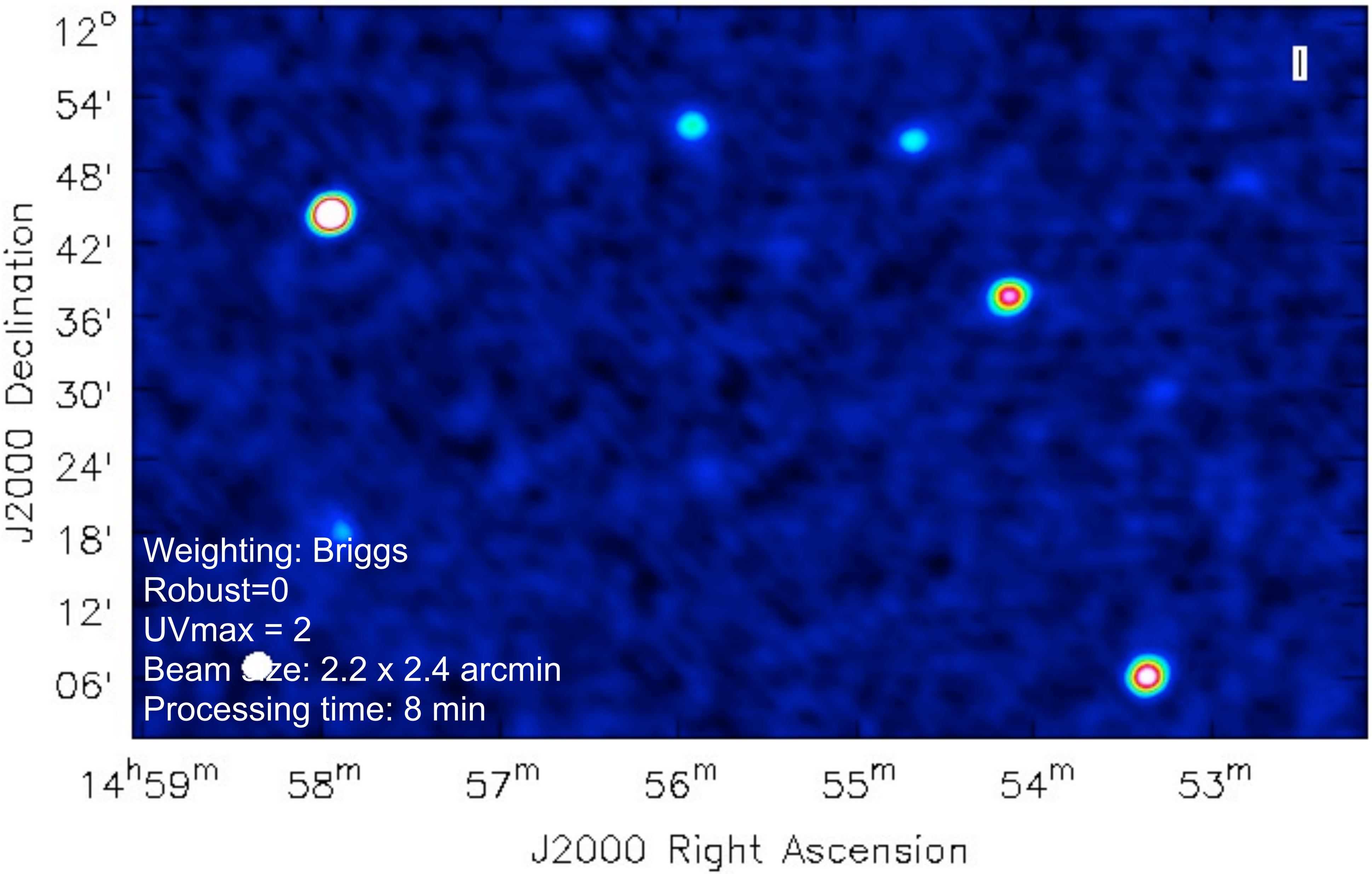
  => AW-Imager.

- Limits the dynamic range of images, and allows for self-calibration.
- Simulations show flux-densities recovered at the 1% level.

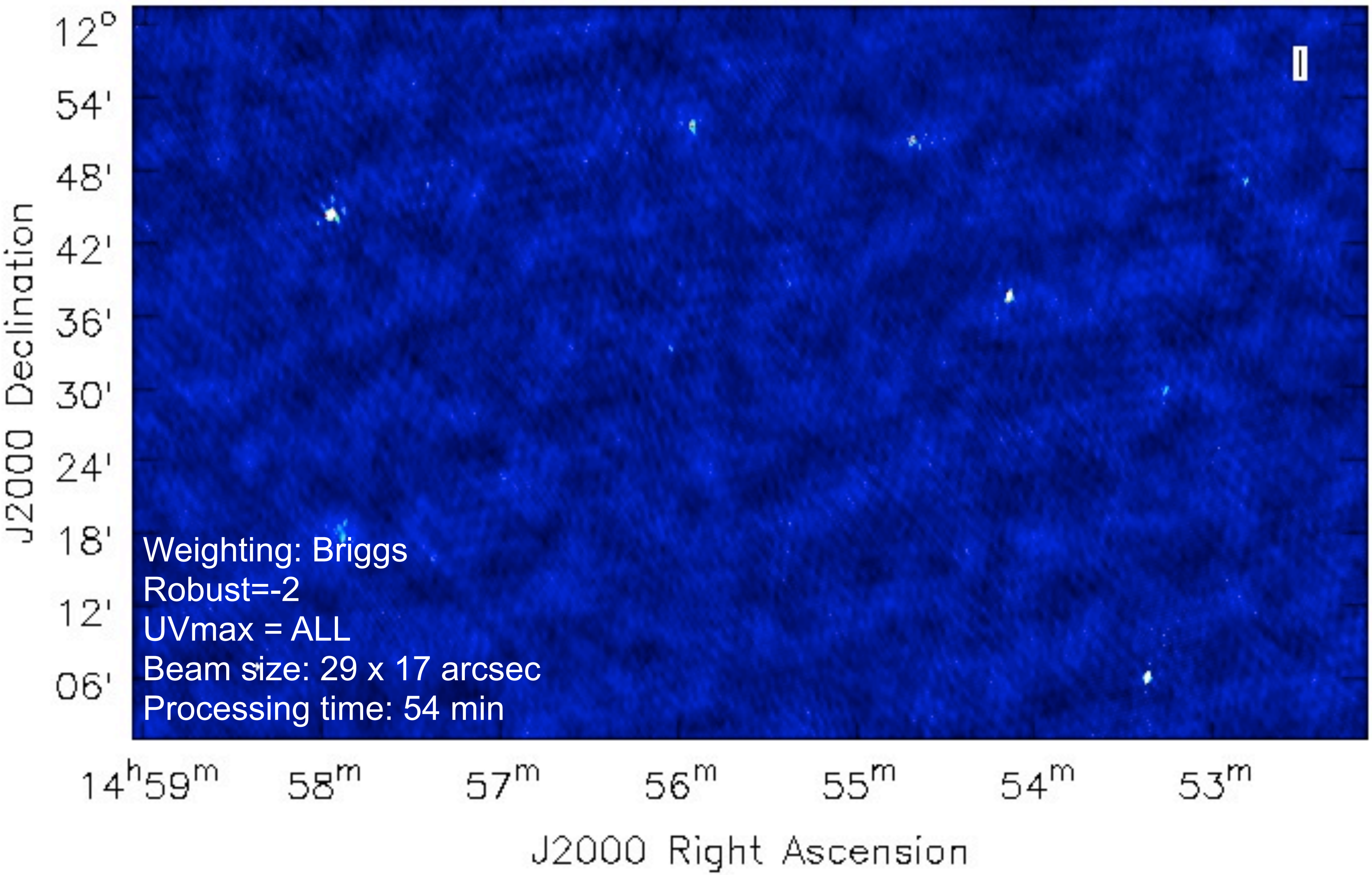


Tasse et al. (2013)

Wide field imaging

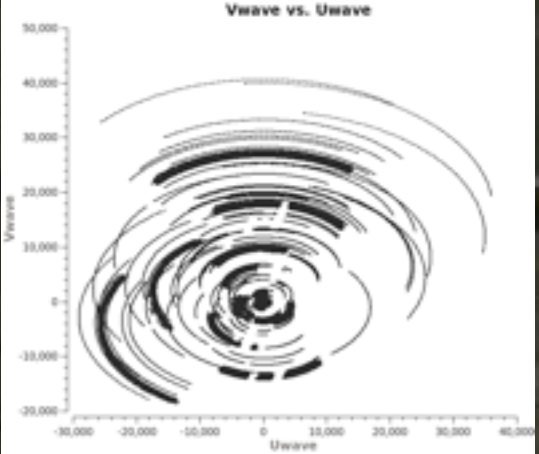


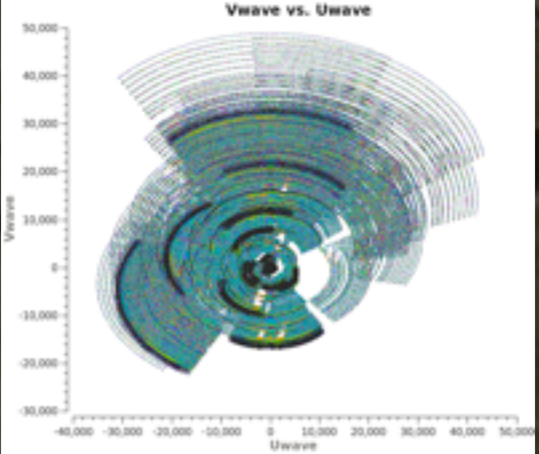
Wide field imaging

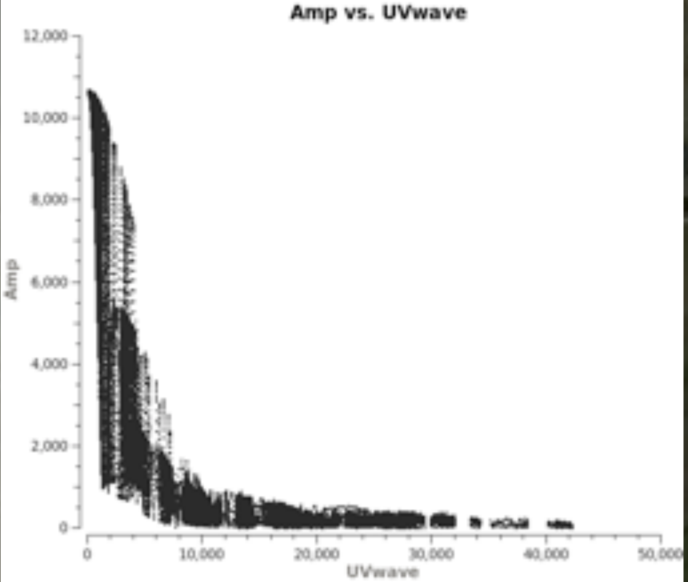


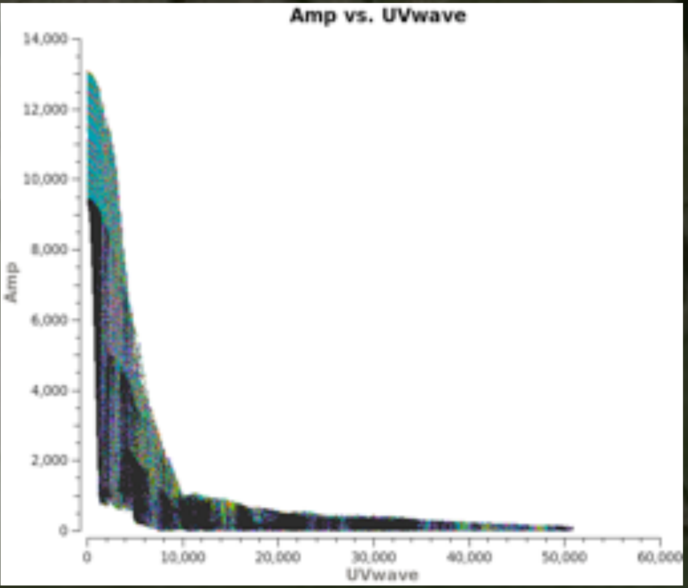
Dealing with large bandwidths

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









Multi-Frequency Synthesis (MFS)

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

(Rau & Cornwell 2011)

Taylor co-efficient images

MS model image

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

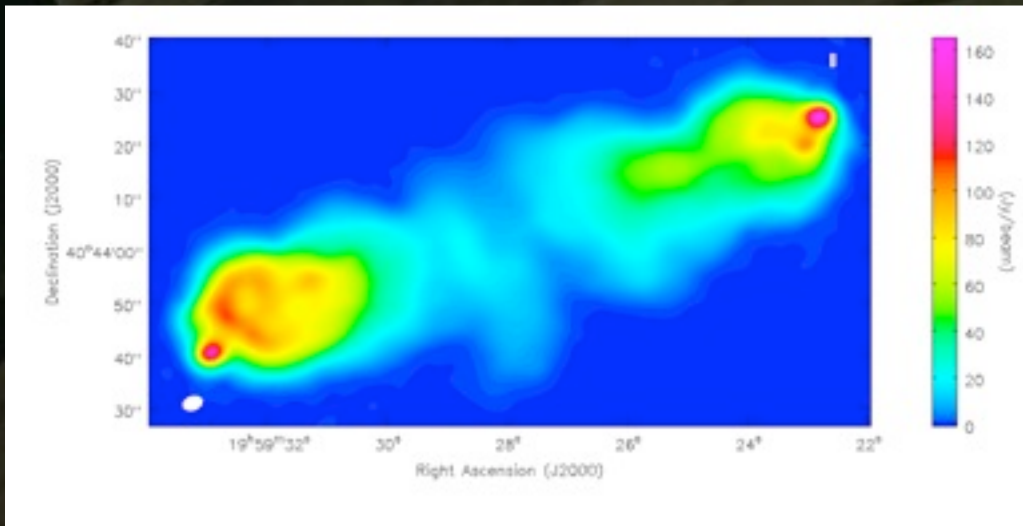
- A power model is used to describe the spectral dependence of the sky emission.

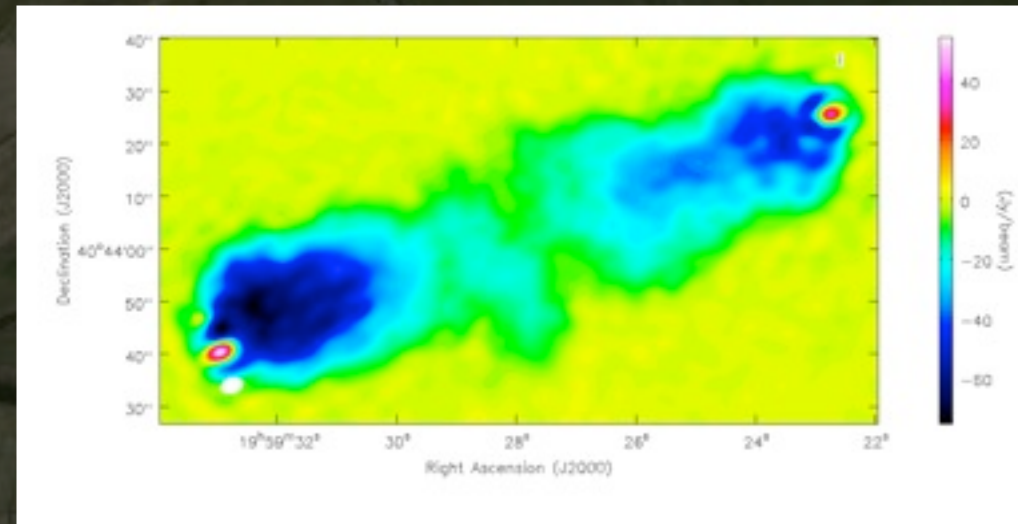
$$I_\nu^{\mathrm{sky}} = I_{\nu_0}^{\mathrm{sky}} \left(\frac{\nu}{\nu_0}\right)^{I_\alpha^{\mathrm{sky}} + I_\beta^{\mathrm{sky}} \log\left(\frac{\nu}{\nu_0}\right)}$$

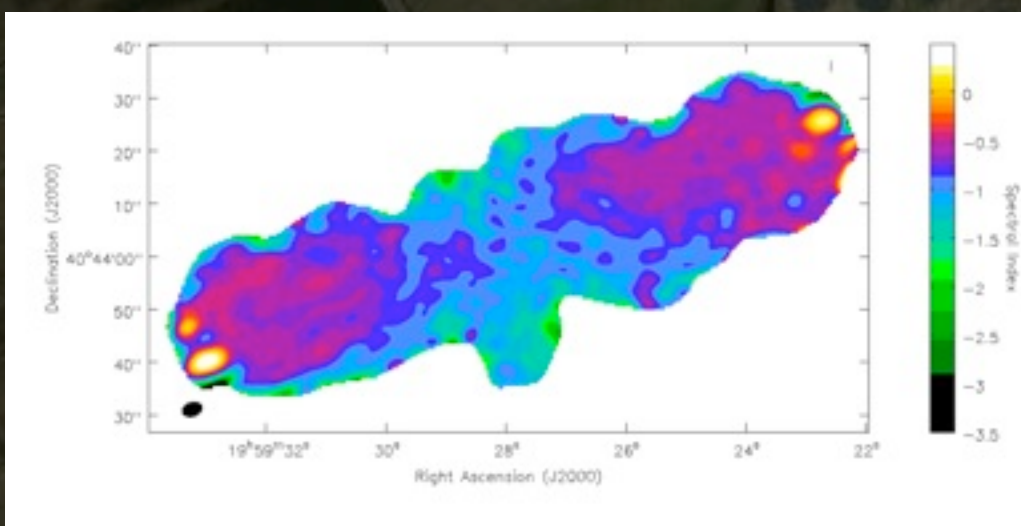
$$I_0^m = I_{\nu_0}^{\mathrm{sky}} \;;\; I_1^m = I_\alpha^{\mathrm{sky}} I_{\nu_0}^{\mathrm{sky}} \;;\; I_2^m = \left(\frac{I_\alpha^{\mathrm{sky}}(I_\alpha^{\mathrm{sky}} - 1)}{2} + I_\beta^{\mathrm{sky}}\right) I_{\nu_0}^{\mathrm{sky}}$$

Imaging results

ASTRON







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

Contents

Summary

- LOFAR is almost fully constructed.
- Imaging data over the 10-250 MHz frequency range, data with the long baselines and wide-field data has been taken to test the system during commissioning - looking good so far!
- Special care needs to be taken in the analysis of LOFAR data due to
  - Data size, RFI.
  - Direction dependent effects.
  - Need for wide-field imaging (aw-projection).
- Enjoy getting your hands on LOFAR data after coffee!