Netherlands Institute for Radio Astronomy

Low frequency interferometry (and advanced calibration)

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- (ASTRON and Kapteyn Astronomical Institute)

Preamble

- **AIM:** This lecture aims to give a general introduction to low frequency astronomy, focusing on the issues that you must consider and the differences with observations with other telescopes.

- **OUTLINE:**

1. The Low Frequency Array (LOFAR)
2. Direction dependent effects I. - The beam
3. Direction dependent effects II. - The atmosphere
4. Spectral dependence of calibration

Contents

1. The Low Frequency Array

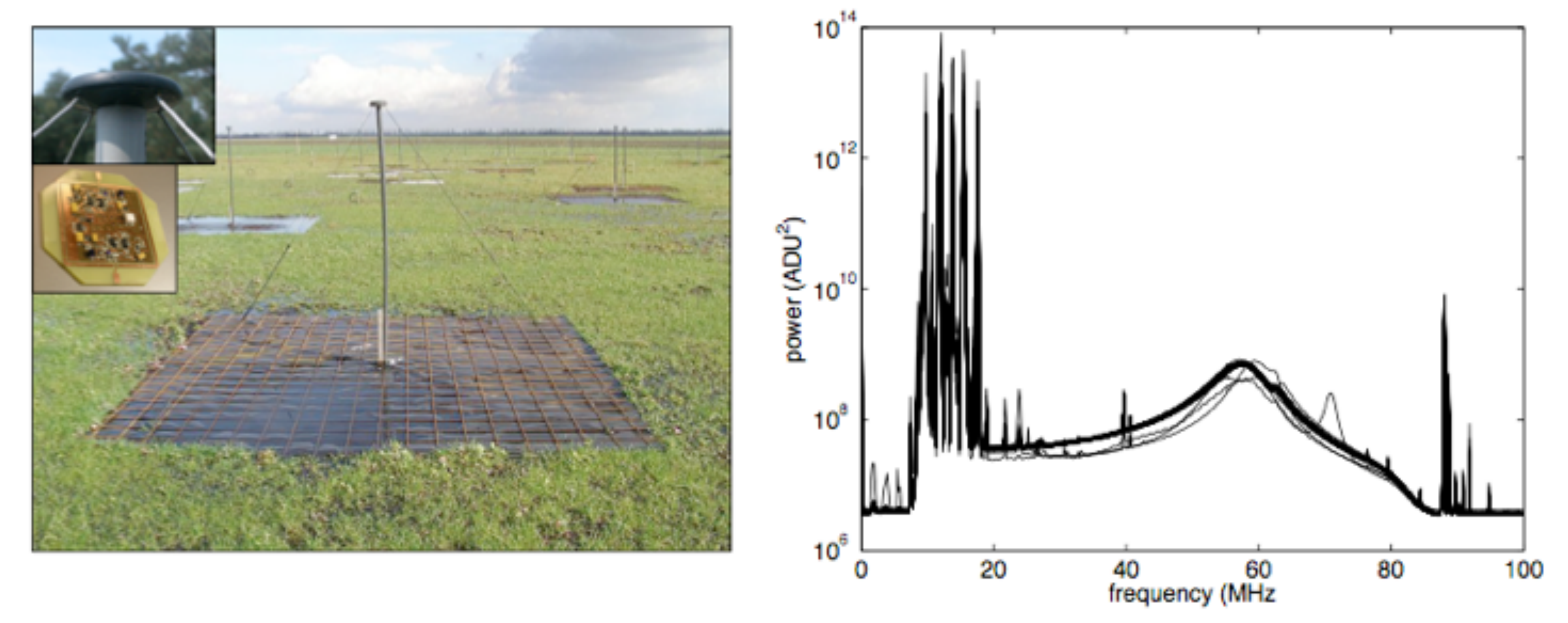
The Low Frequency Array - Key Facts

- The International LOFAR Telescope (ILT) is being built in the Netherlands, Germany, France, UK, Sweden and Poland (~€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 with a software correlator in Groningen.

Low Band Antenna (LBA)

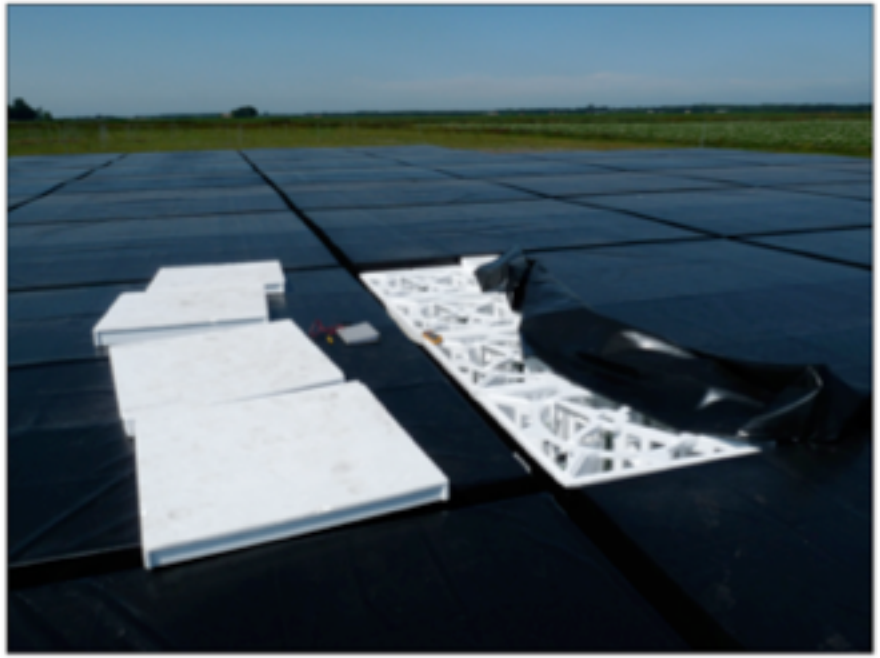
- **LBA antennas:** Cap containing the low noise amplifiers (LNAs), copper wires receive two orthogonal *linear* polarisations (XX and YY), ground plate.
- Low cost, high durability (15 year operation), whole sky coverage.

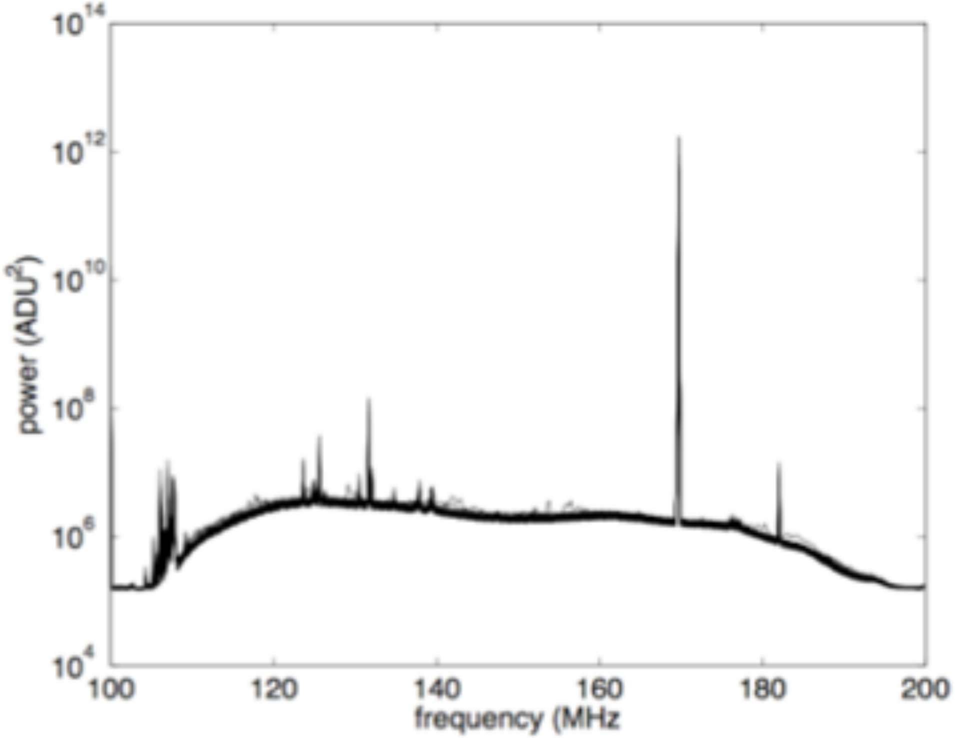


- **The response curve:** There is a peak close to the resonance frequency (52 MHz) - dipole arms are 1.38 m long.

High Band Antenna (HBA)

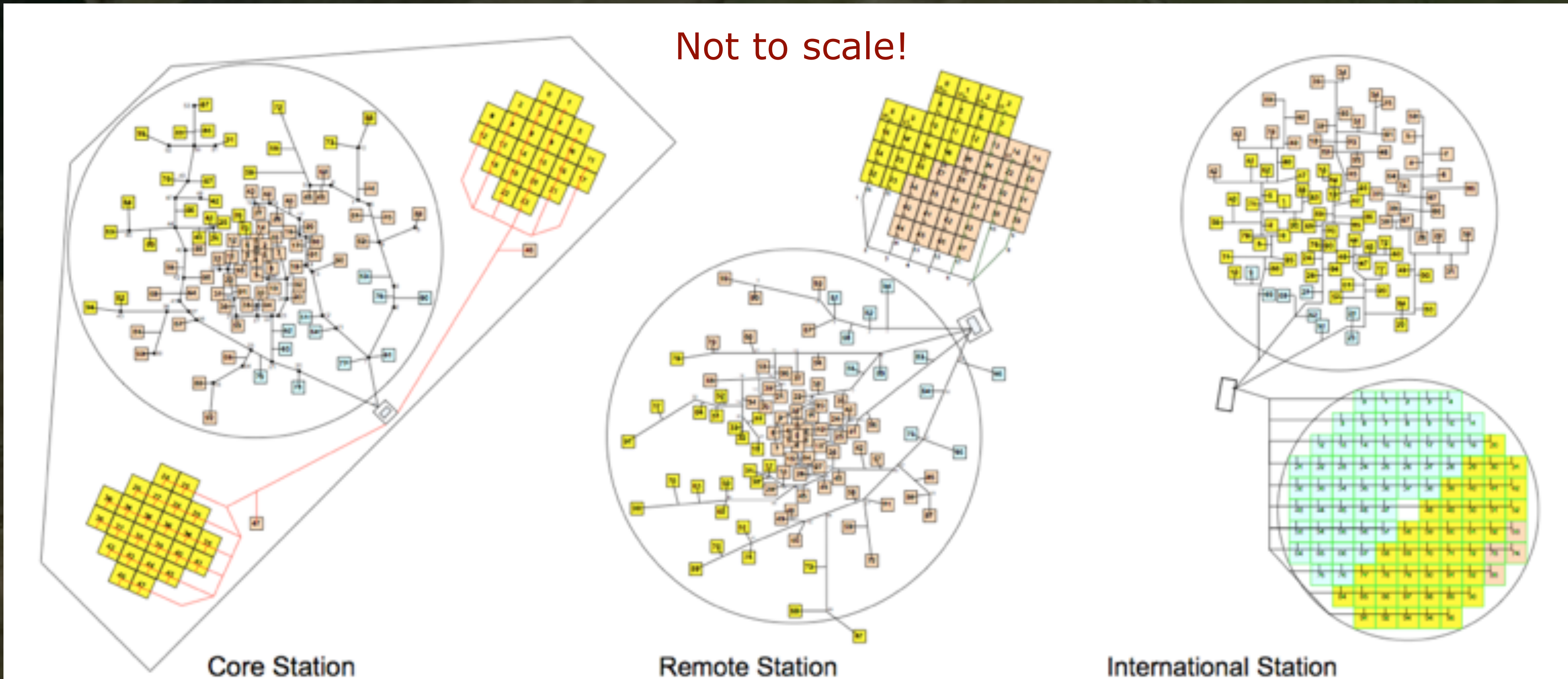
- **HBA antennas:** Each tile consists of 4 x 4 dual *linear* polarisation aluminium dipoles, housed in a polystyrene structure, covered by polypropylene sheets.
- Dipoles are combined to form a single “tile beam”.





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

Stations



Baselines: 150 m - 3 km | 5 km - 100 km | 300 km to 1000 km

- **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)

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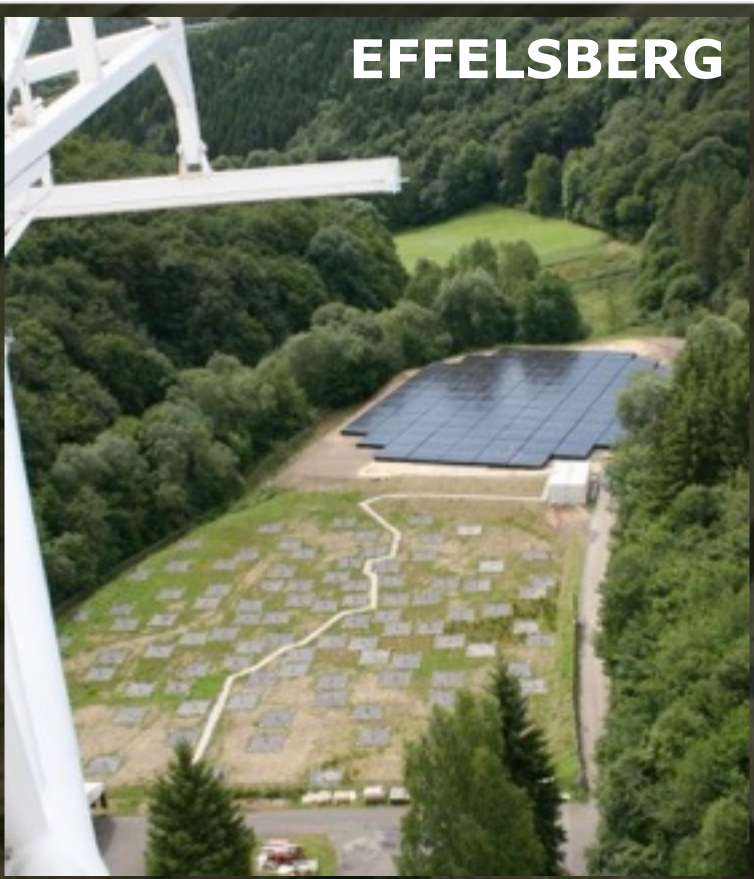
International Stations (8)



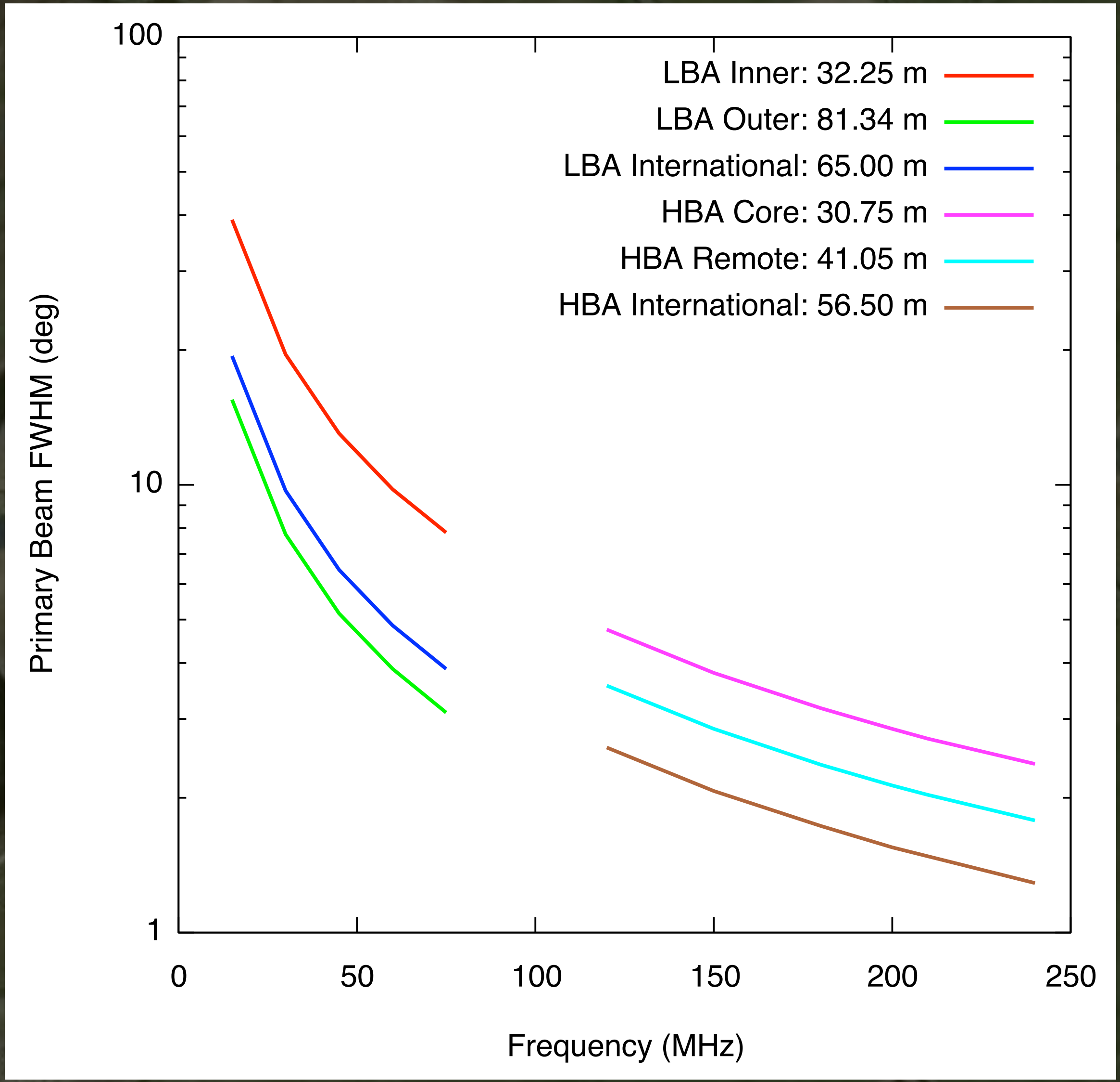
Field-of-View (FWHM v Freq.)

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

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

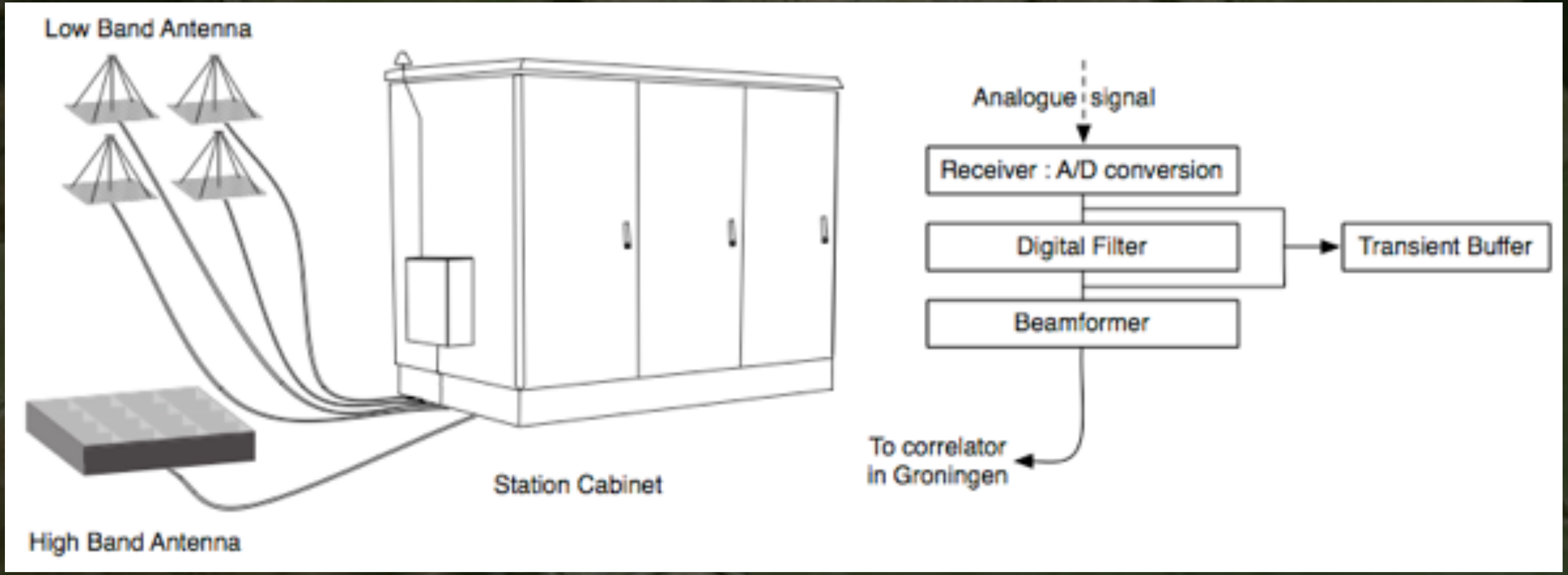
- Where α depends on the tapering used at the station level.

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



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.



A Pan-European Array (ILT 46)

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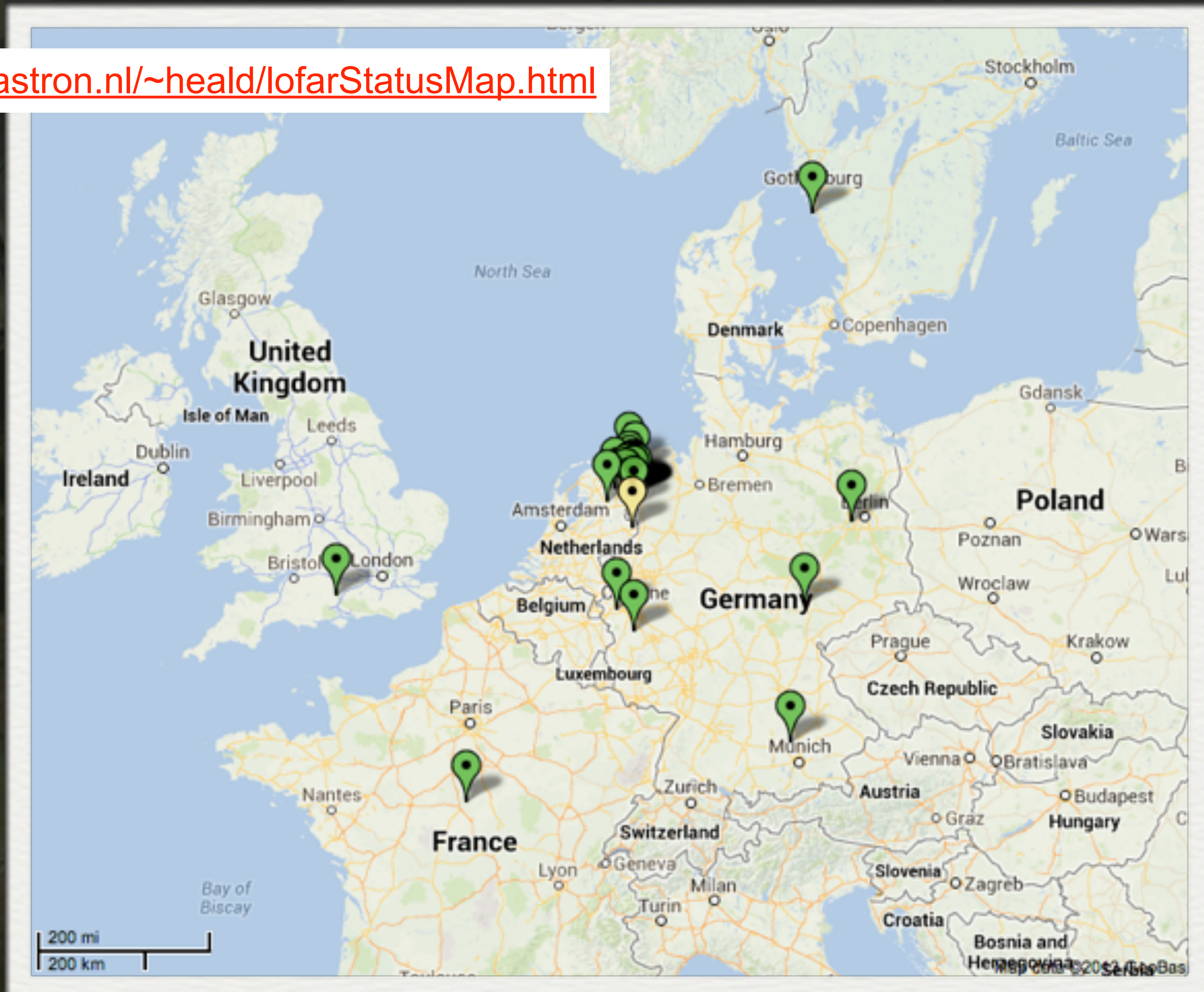
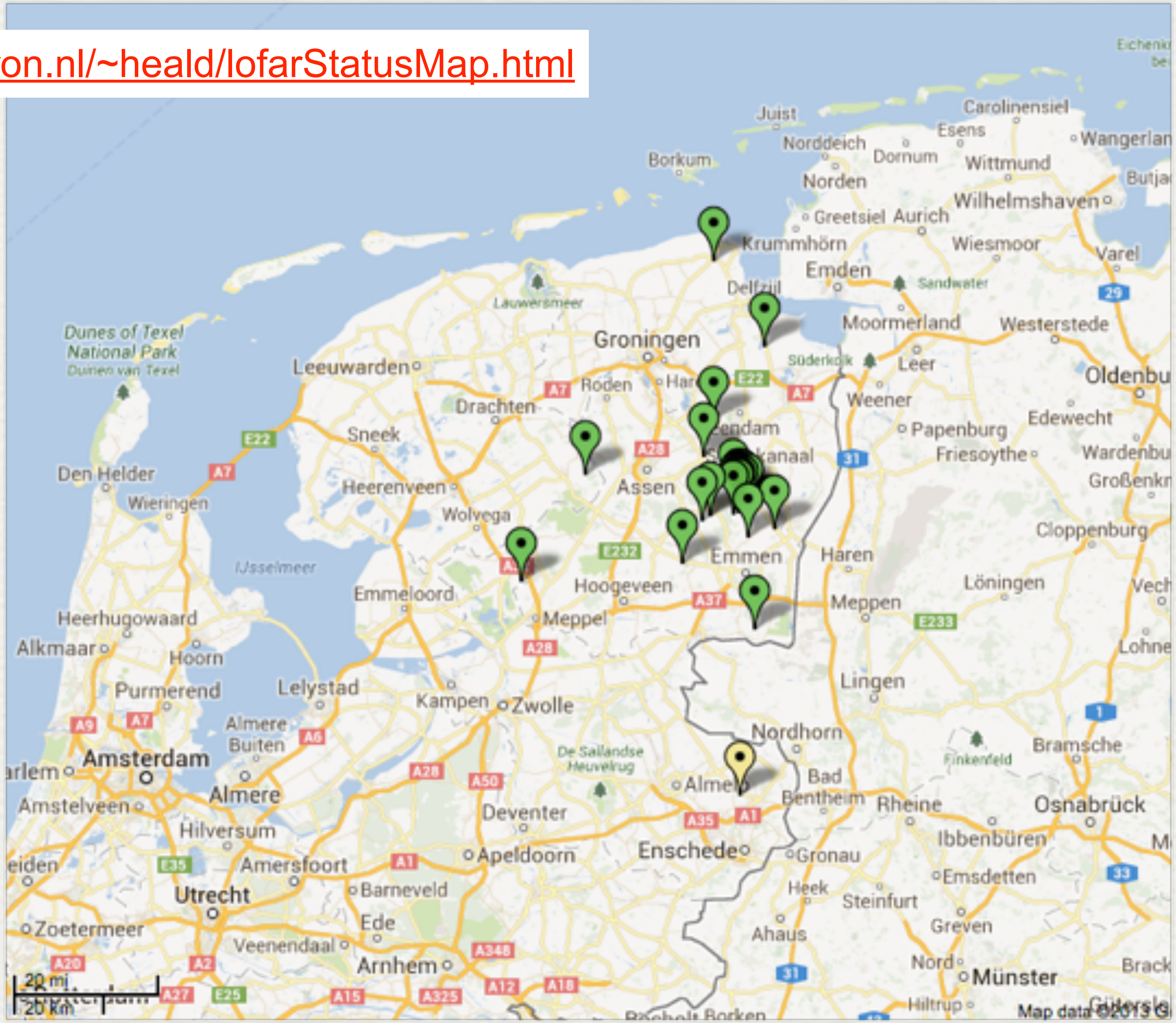
http://www.astron.nl/~heald/lofarStatusMap.html



The Dutch Array (LOFAR-NL 38)

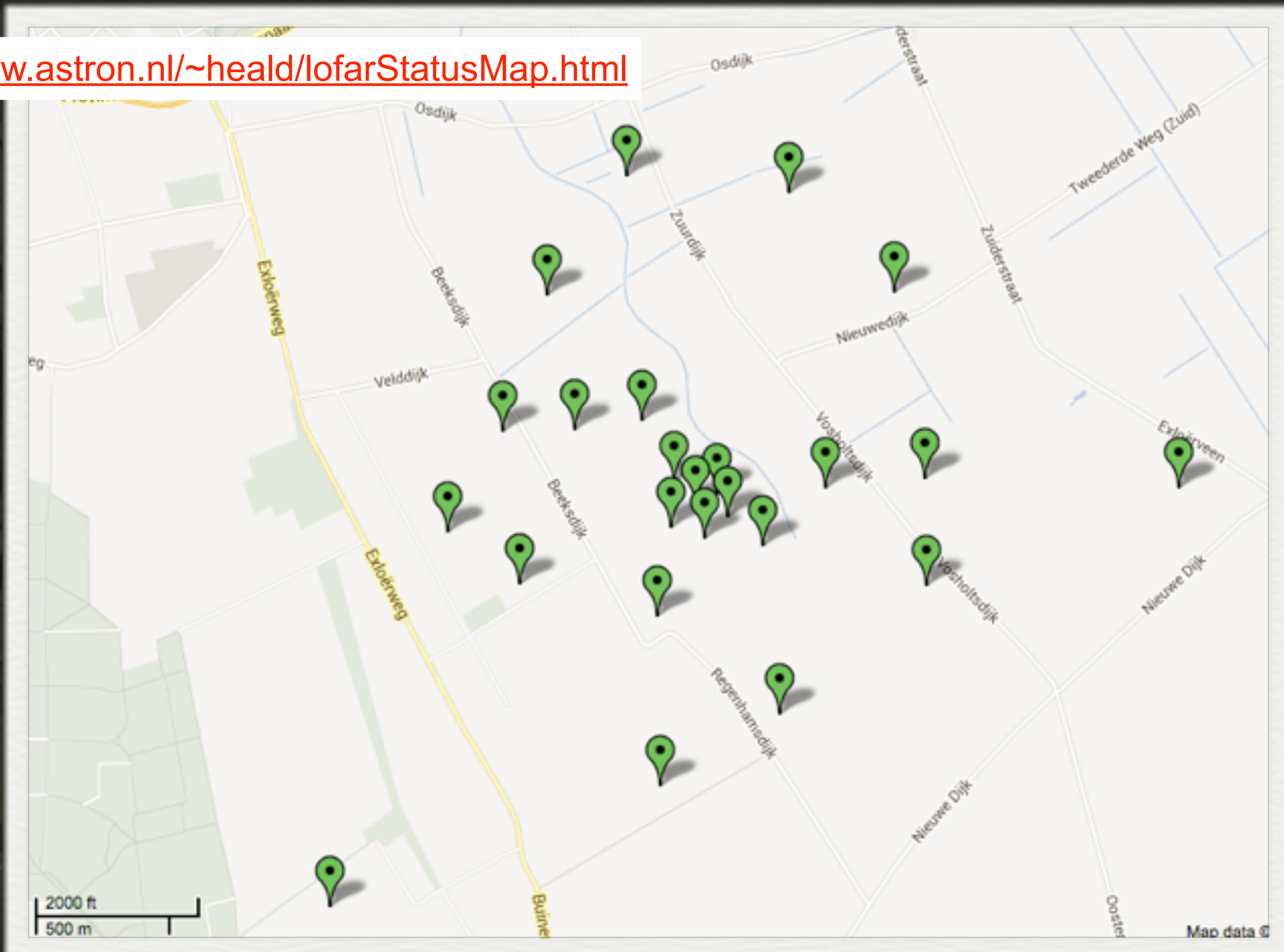
ASTRON

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

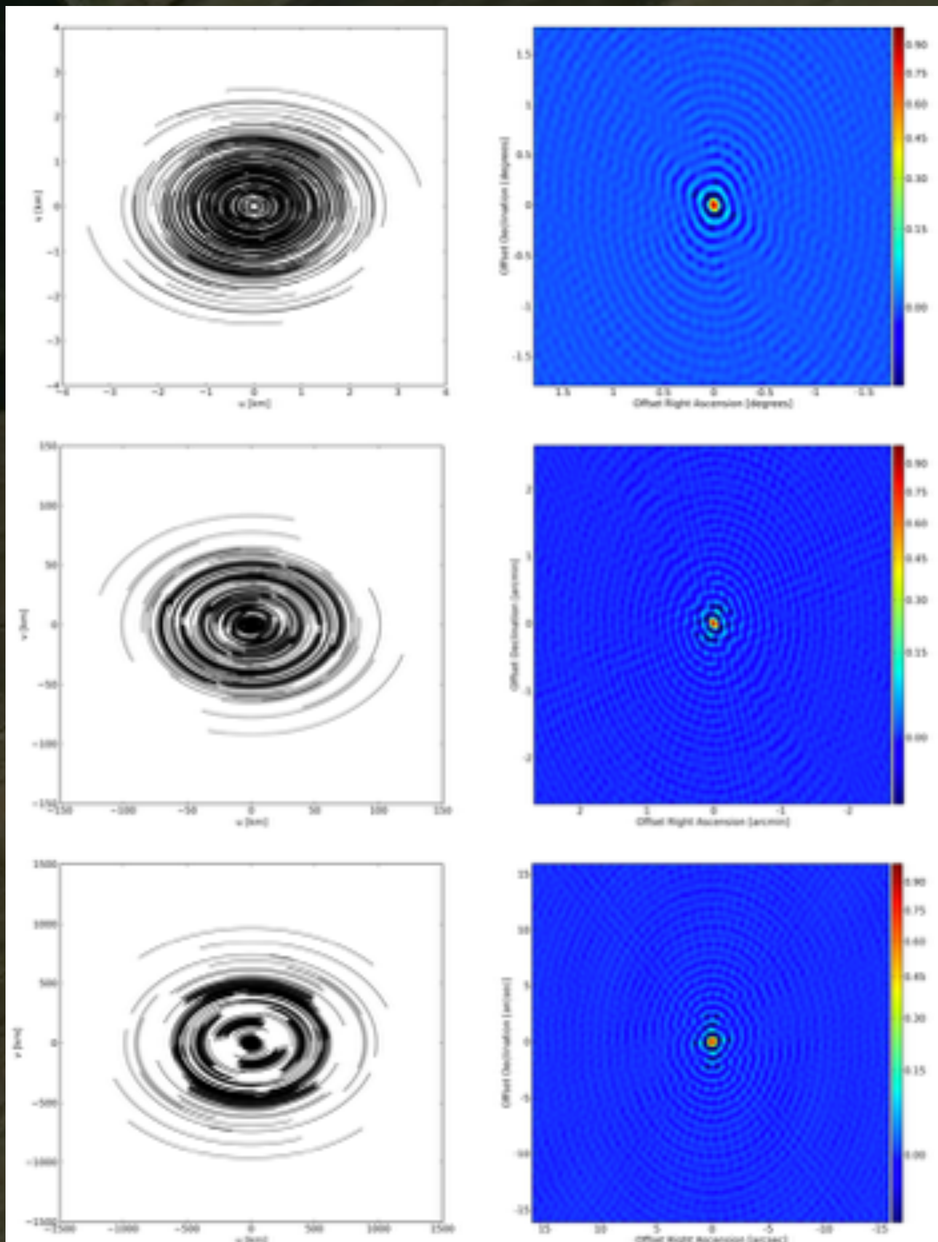


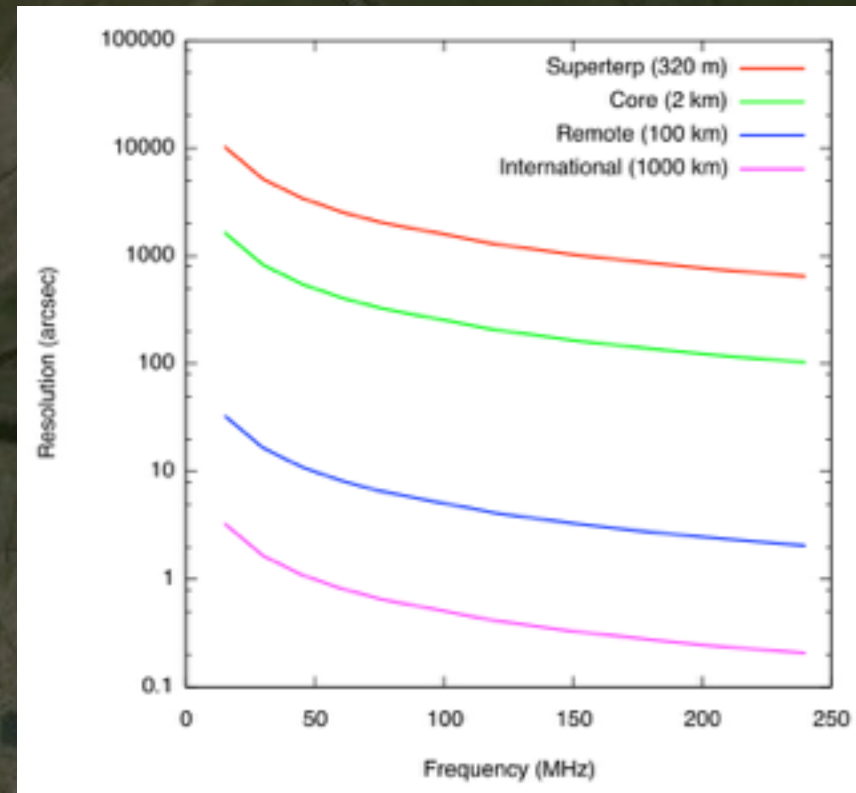
The Core Array (24)

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



UV coverage and angular resolution

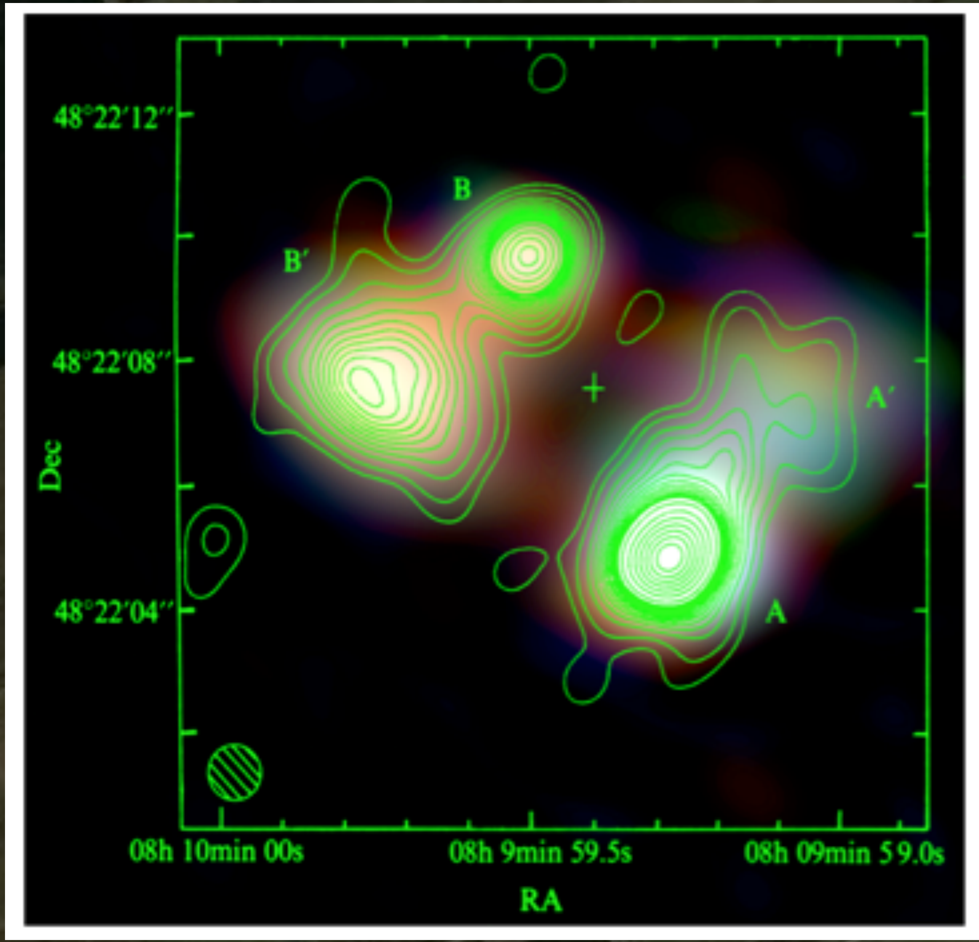


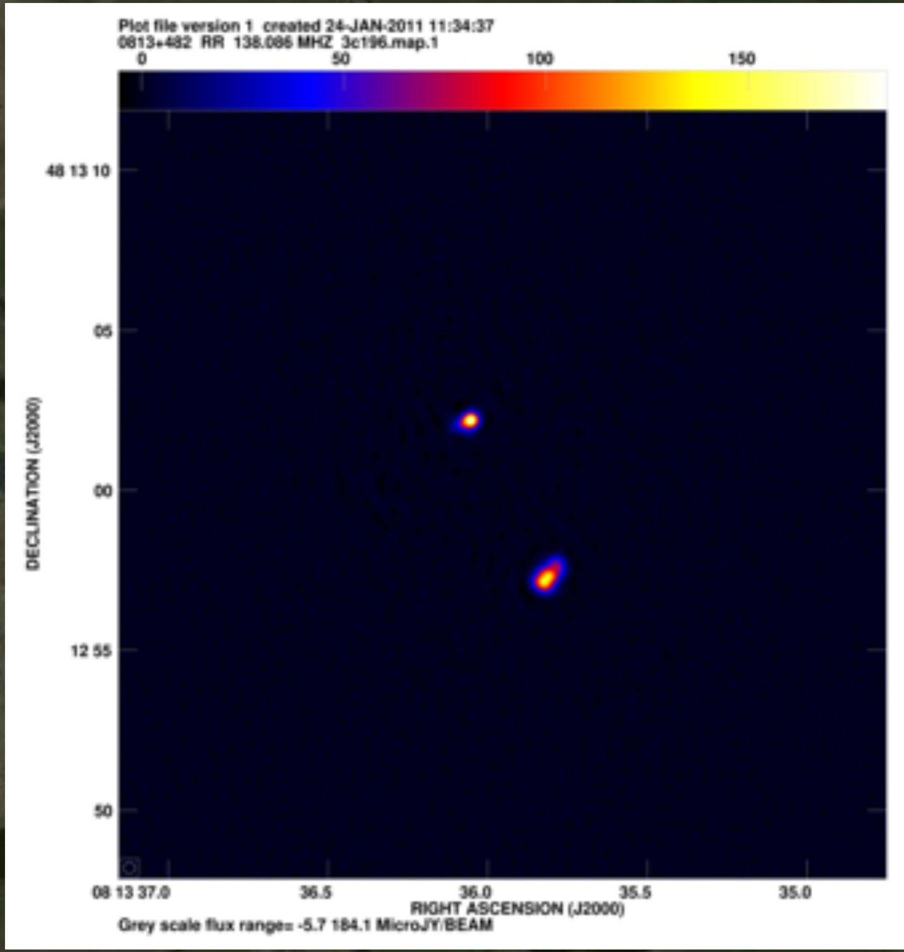


$$\text{FWHM [rad]} = \alpha \, \frac{\lambda}{D}$$

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

LOFAR VLBI imaging of 3C196





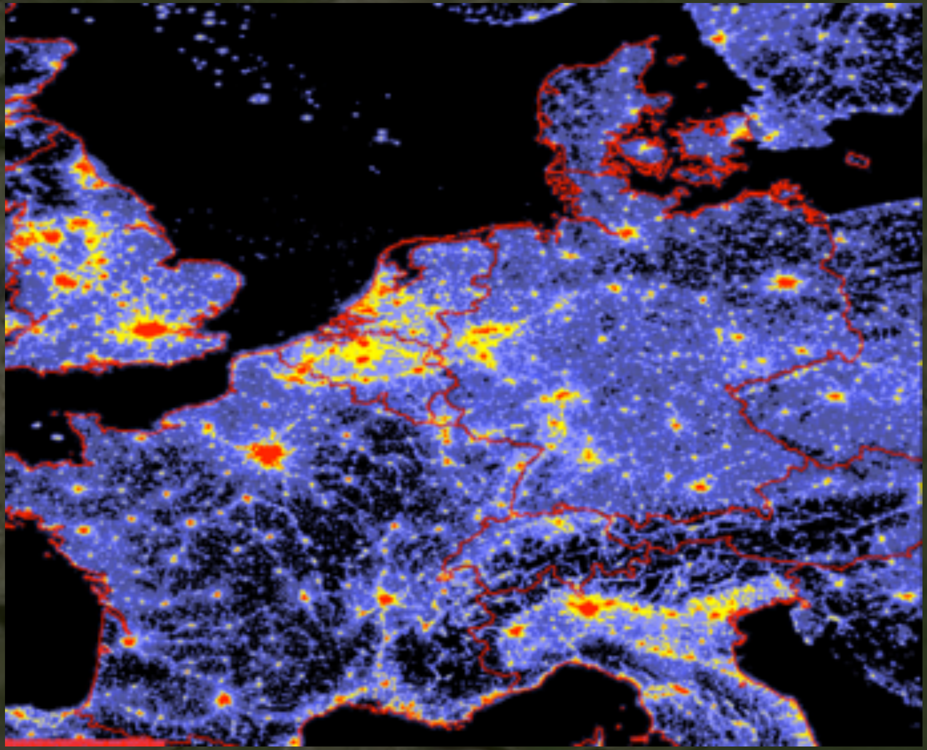
- LBA image of 3C196 with MERLIN 408 MHz contours overlaid.
- **1.2 arcsec beam**

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

Olaf Wucknitz

Radio frequency interference

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



- LOFAR mitigates RFI by

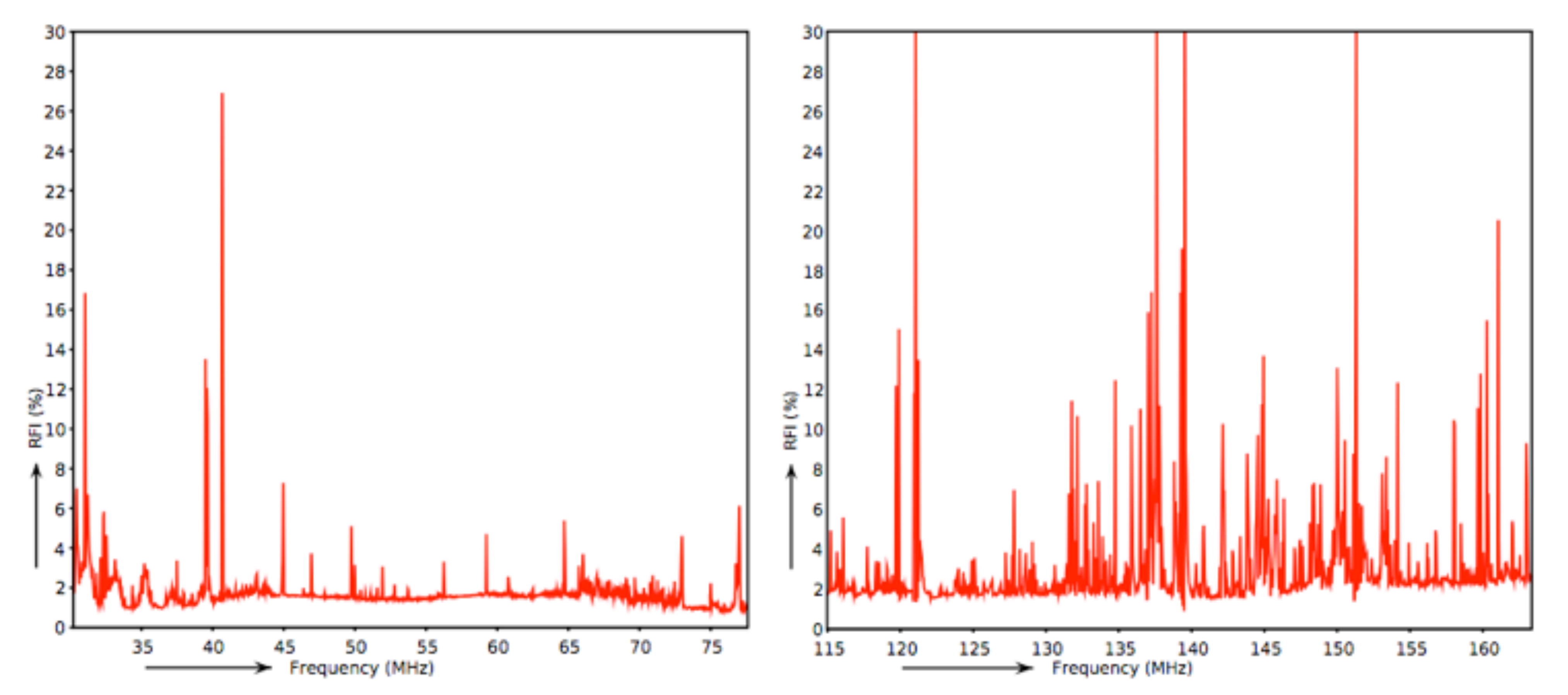
  i) having a small time and frequency resolution (1s; 763 Hz).

  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

(Offringa et al. 2012, 2013)



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

Contents

2. Direction dependent effects. I - The beam

Wide field imaging is fun!

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Imaging wide-fields is useful for,

1) Efficient all-sky survey
2) Looking for rare objects

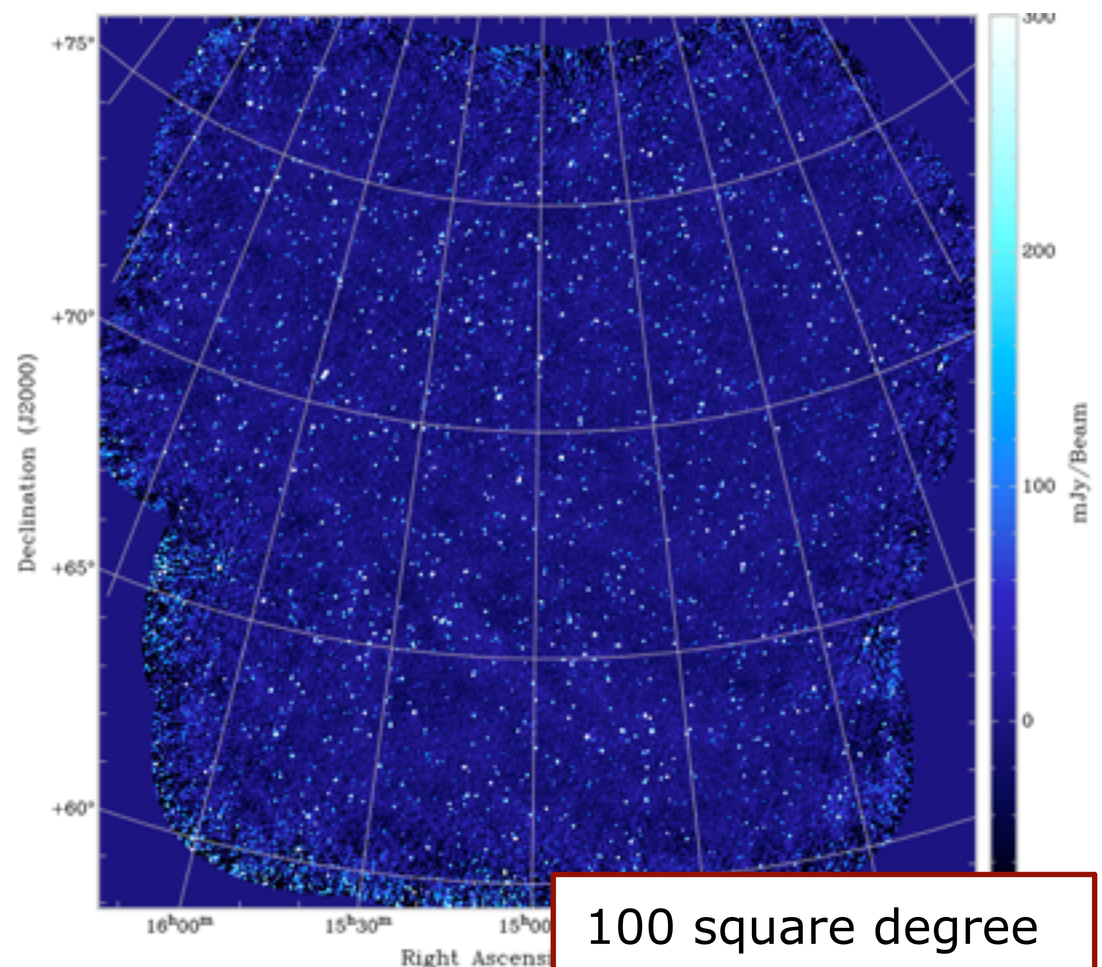
Wide-fields introduce many issues for a good calibration,

1) Variable beam power as a function of position results in a more complicated amplitude calibration.
2) The phase solutions in one direction cannot be applied to another.
3) Sky model is more complicated (many sources).

An error in your model can be absorbed in the calibration

$$\vec{V}_{ij} = J_{ij}\vec{V}_{ij}^{\mathrm{IDEAL}}$$

LOFAR MSSS SVF; *George Heald*



100 square degree

~10 mJy /beam [2 arcmin resolution]

Pointing an aperture array

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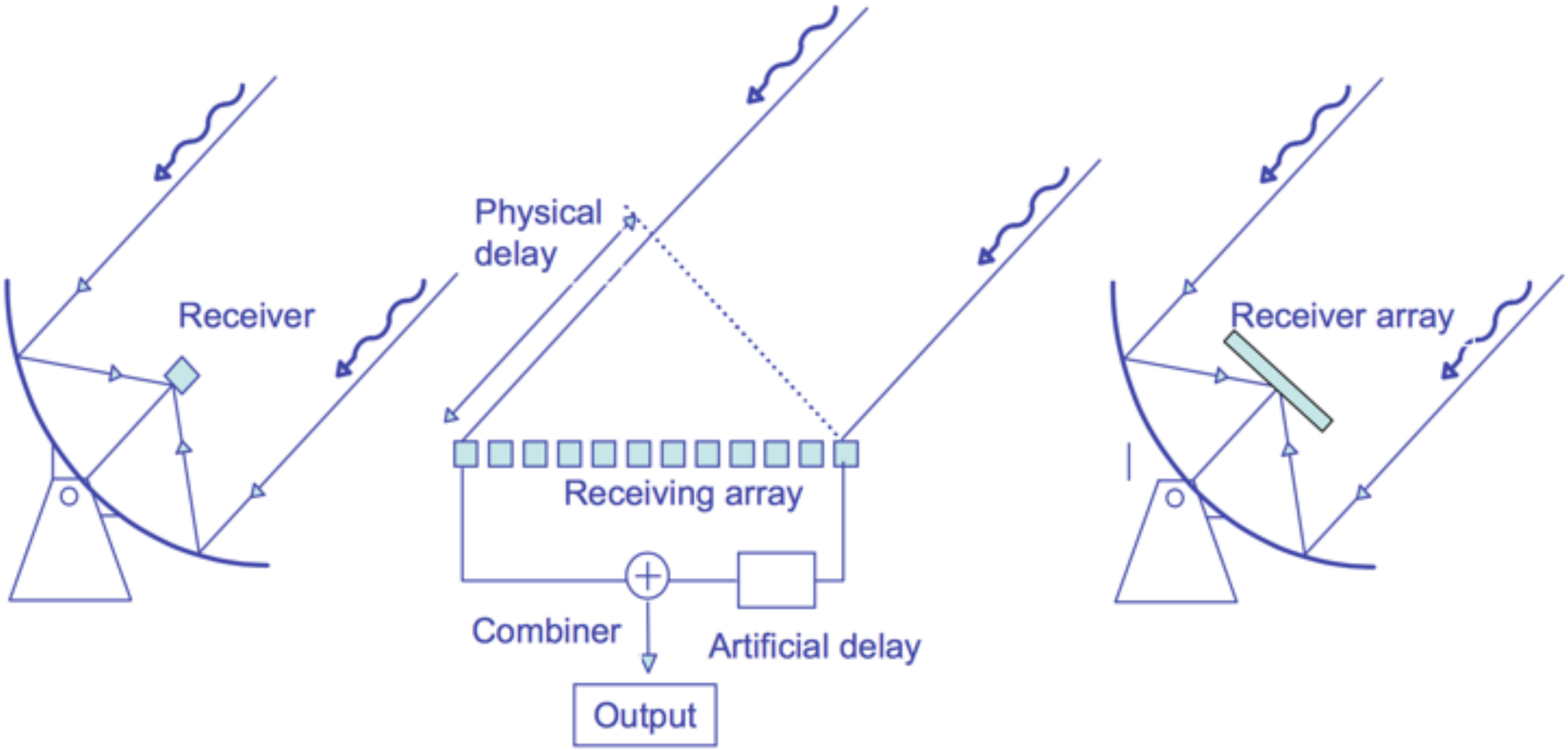
Single pixel | Aperture Array | Phased Array Feed (PAF)



Parabolic reflector (mechanical) | Aperture array (electronic) | Reflector + receiver array (mechanical + electronic)

The delay that we add will coherently add the different elements of an aperture array in one direction, and suppress the emission from other directions.

Beam-forming

- Unlike standard telescopes, phase arrays have 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 (LOFAR), increasing survey speed, efficiency, calibration.

Beam-forming

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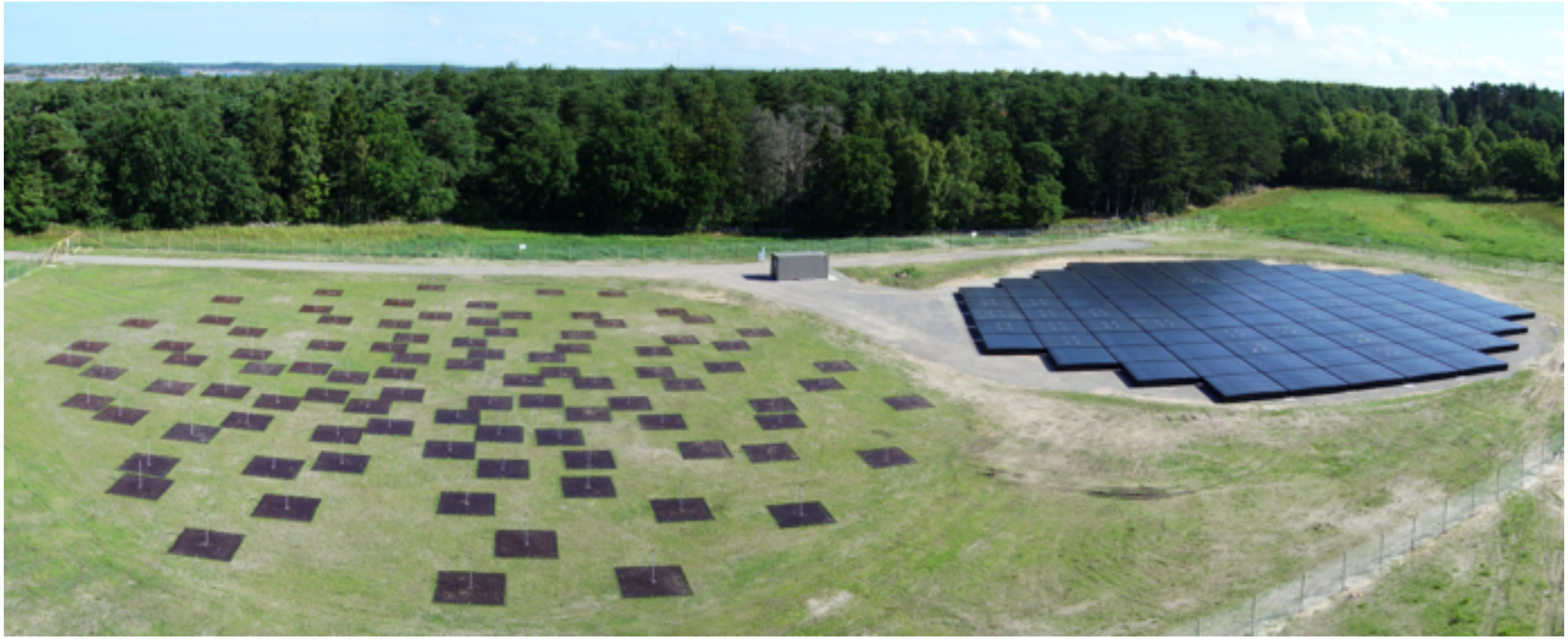
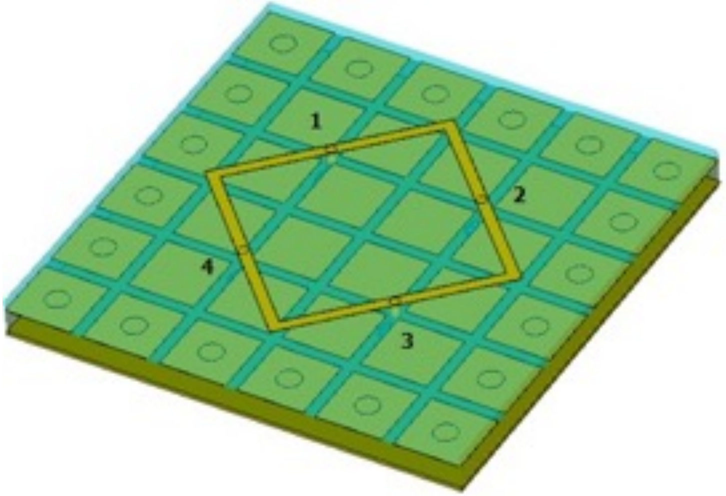
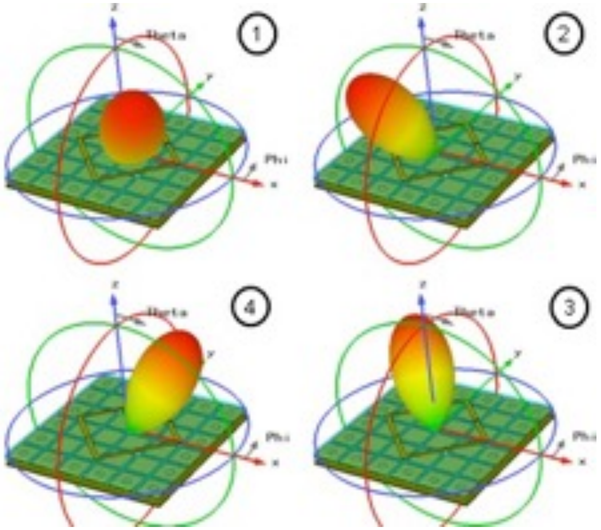
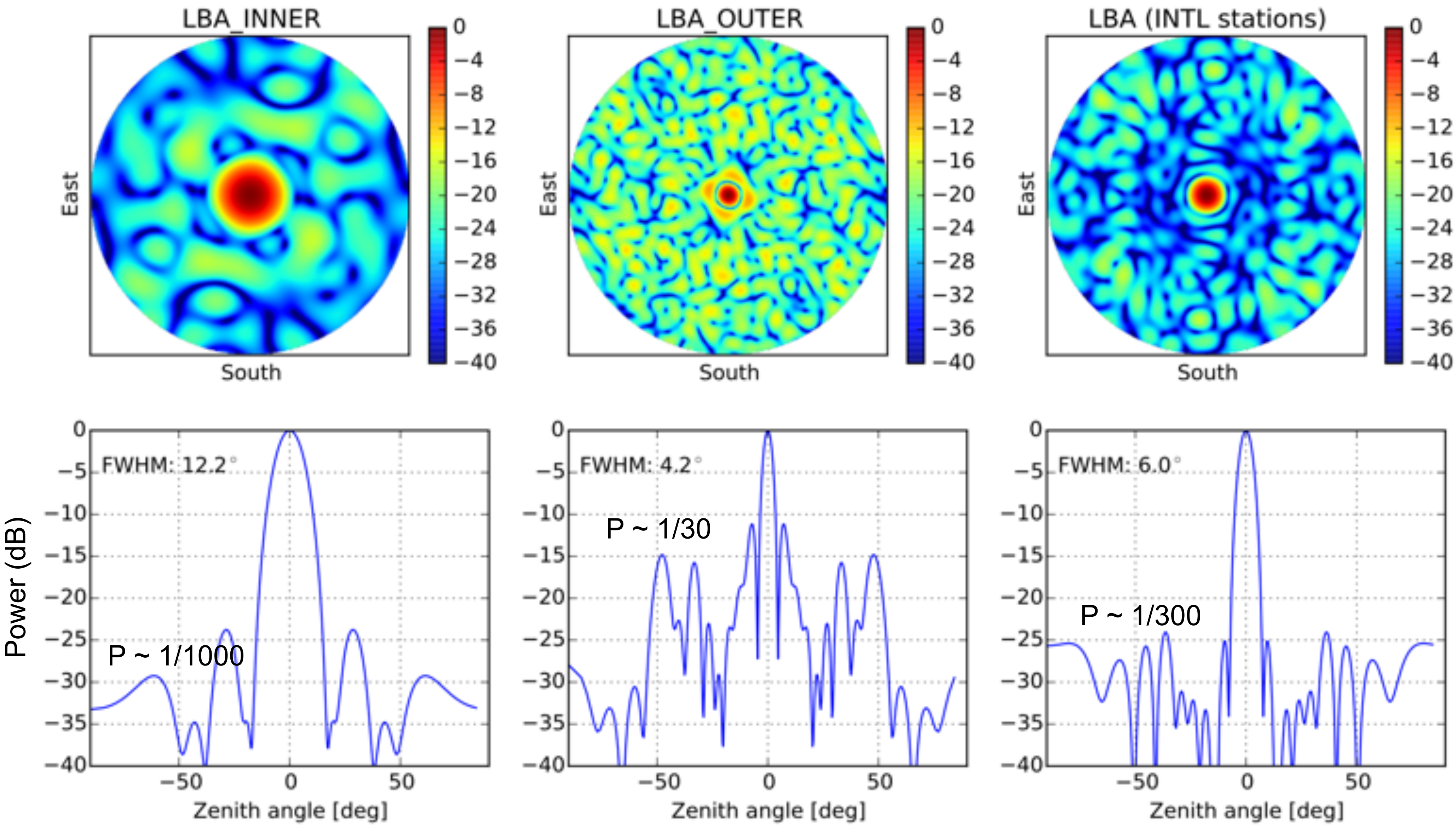




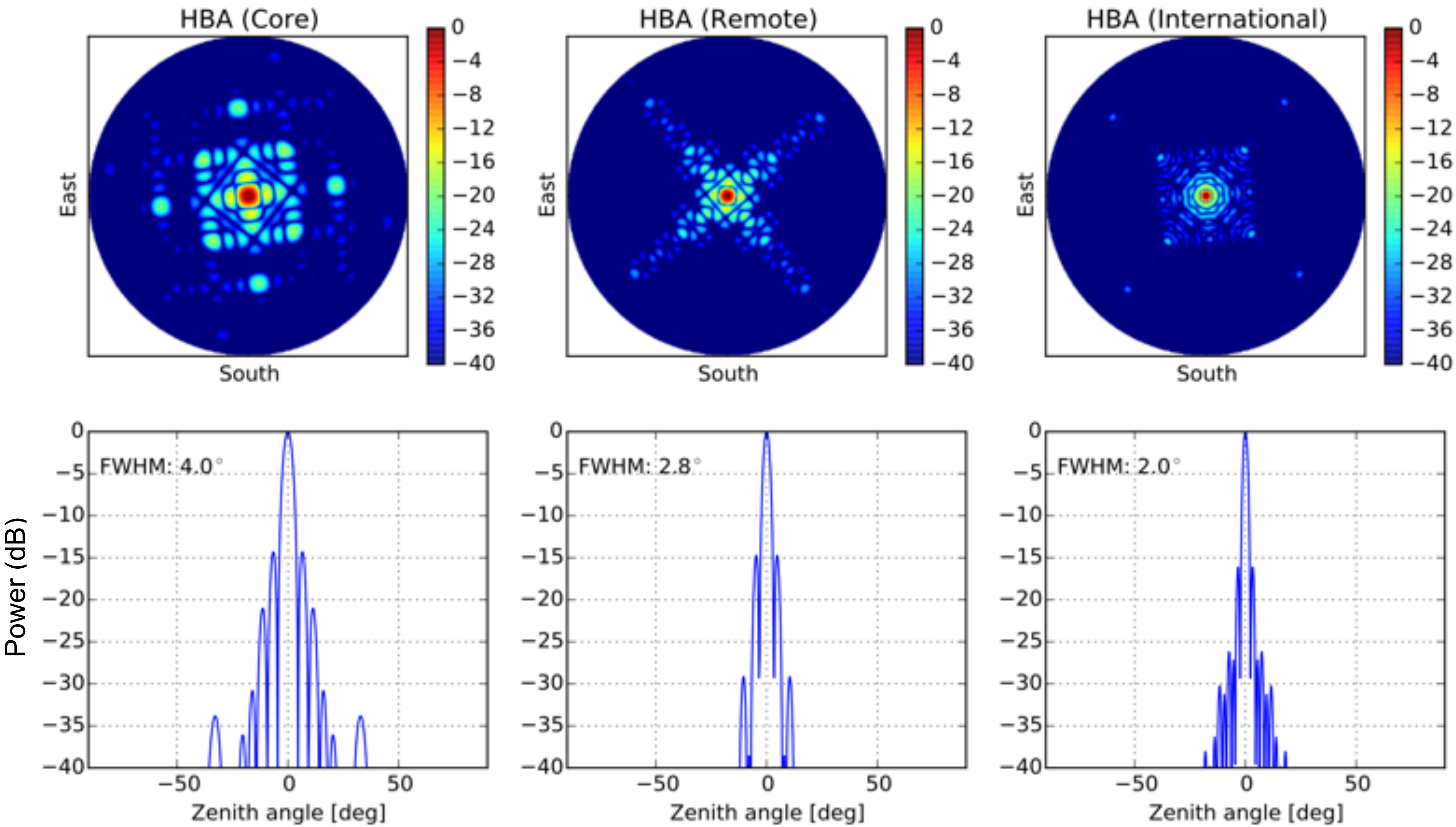


Example of the LOFAR LBA beam



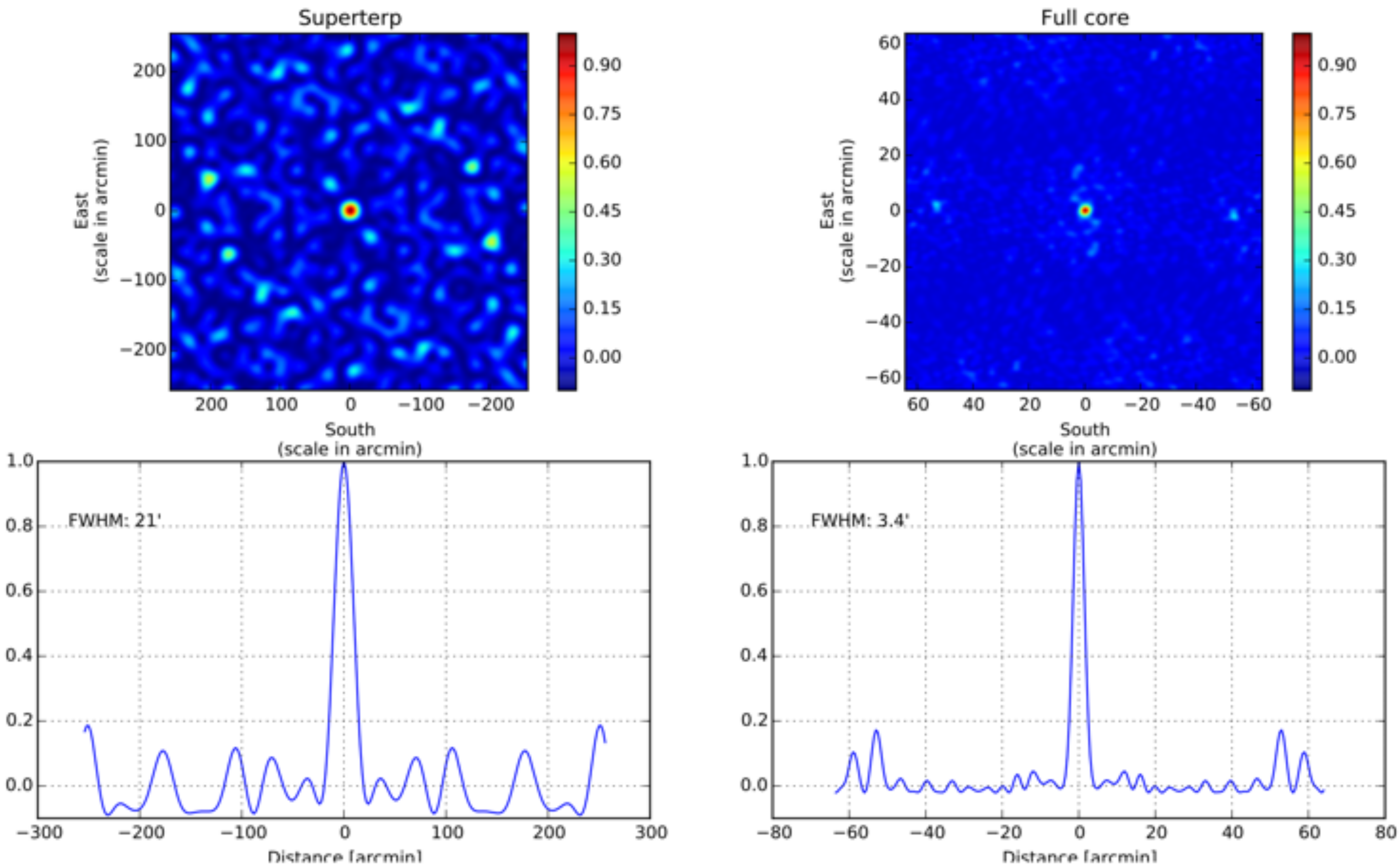
Michiel Brentjens

Example of the LOFAR HBA beam



Michiel Brentjens

Example of LOFAR beam combined



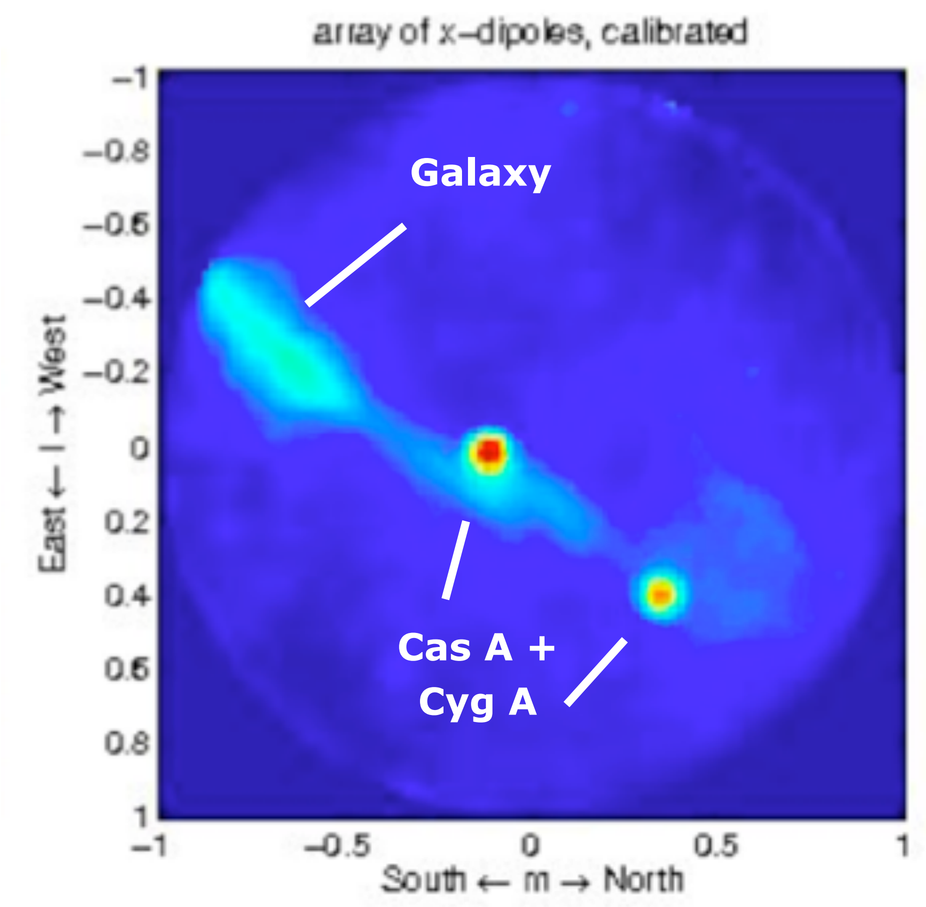
Michiel Brentjens

What happens with a large beam?

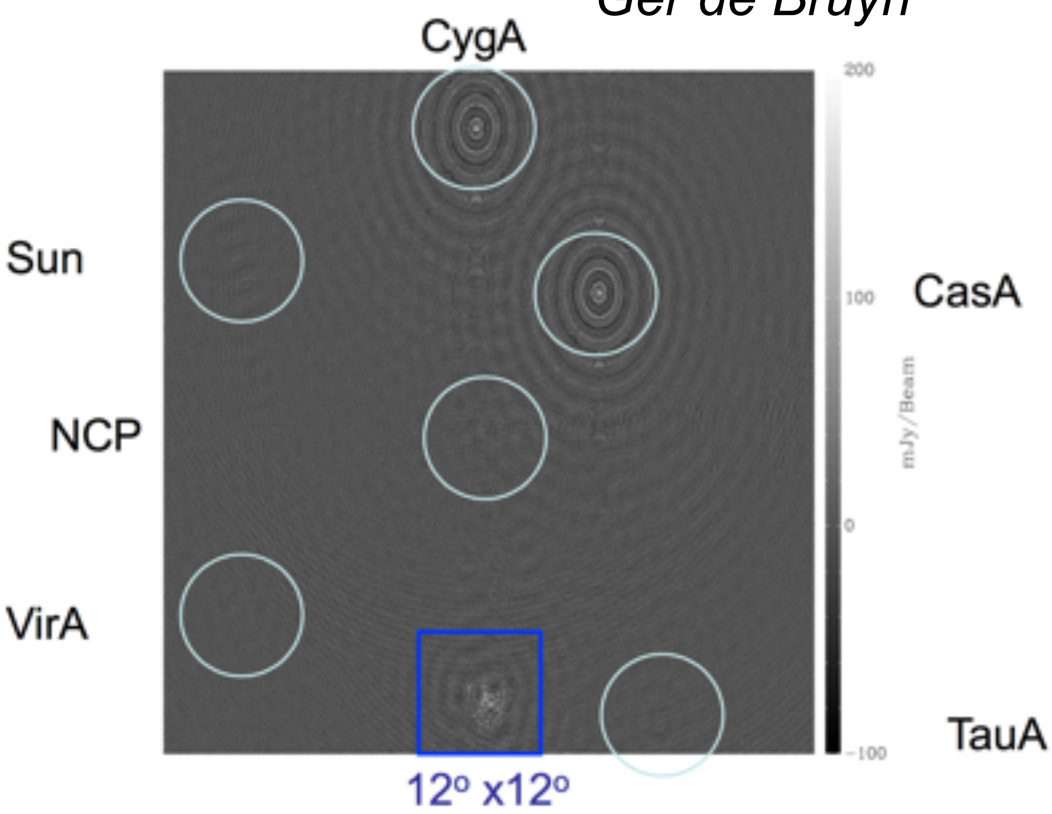
A large beam means that you can survey much larger areas of the sky

- **Great** for surveys, transients
- **Bad** if you are not interested in the sky that is off-axis

Ger de Bruyn



Single LBA station image



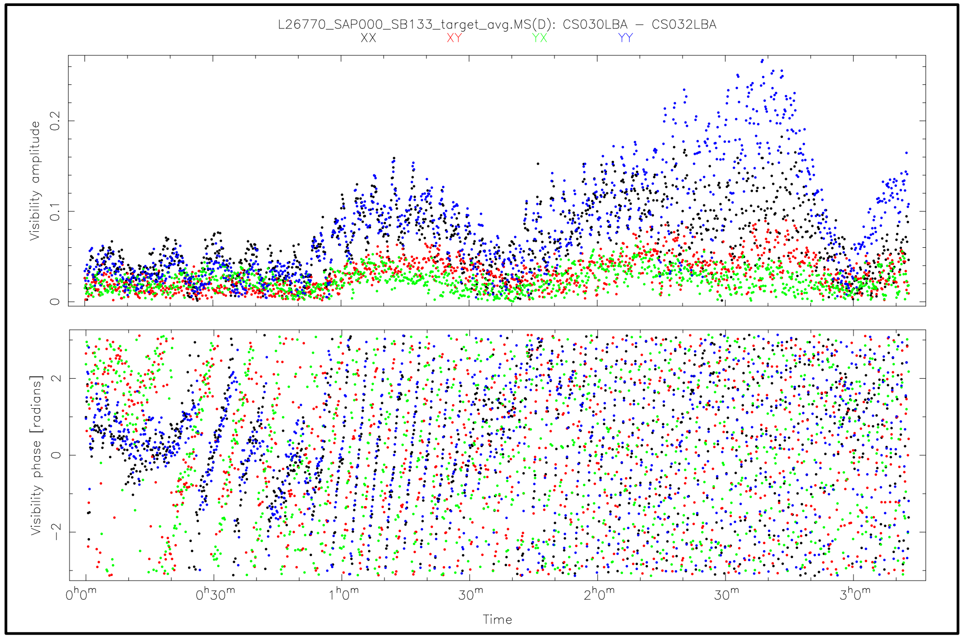
WSRT (25-m dish array) at 150 MHz

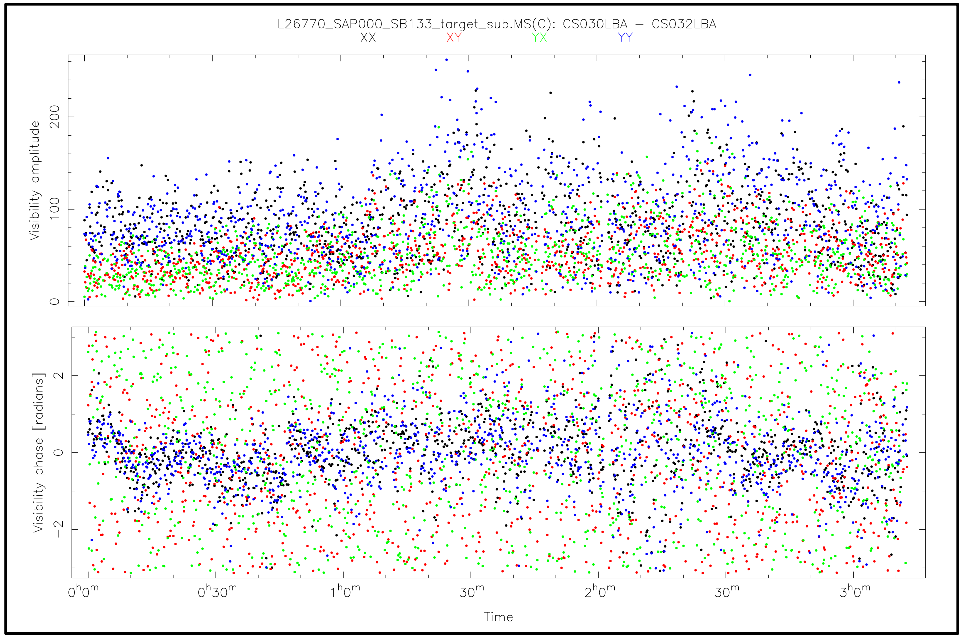
Bright off-axis sources

Cygnus A and Cas A are about 20000 Jy at 60 MHz.

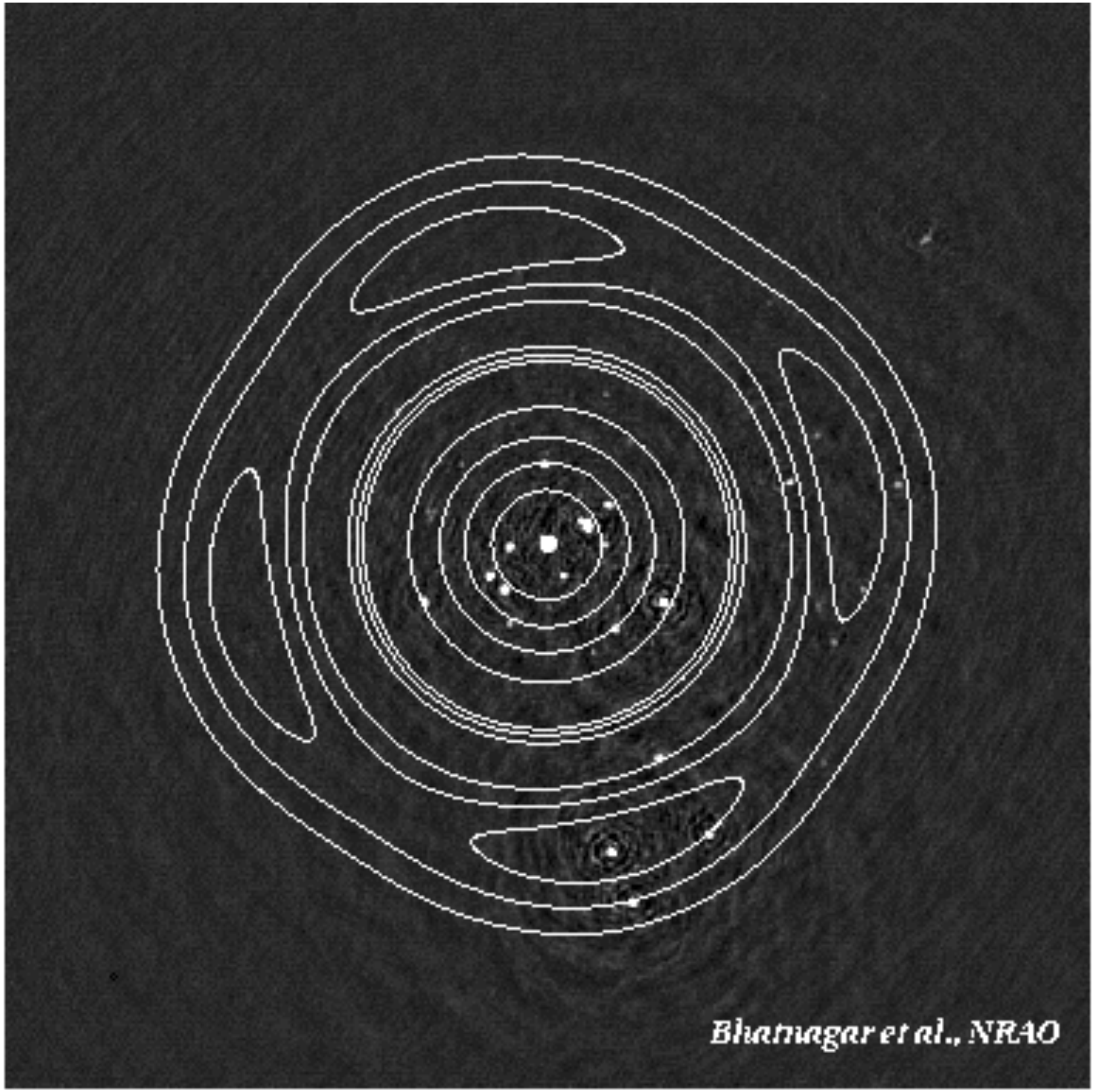
Even far from your target, they can dominate the visibility function (side-lobes at 1/15 to 1/1000).

Solution, phase shift to the their locations, self-calibrate using good models and subtract them from the target visibility data

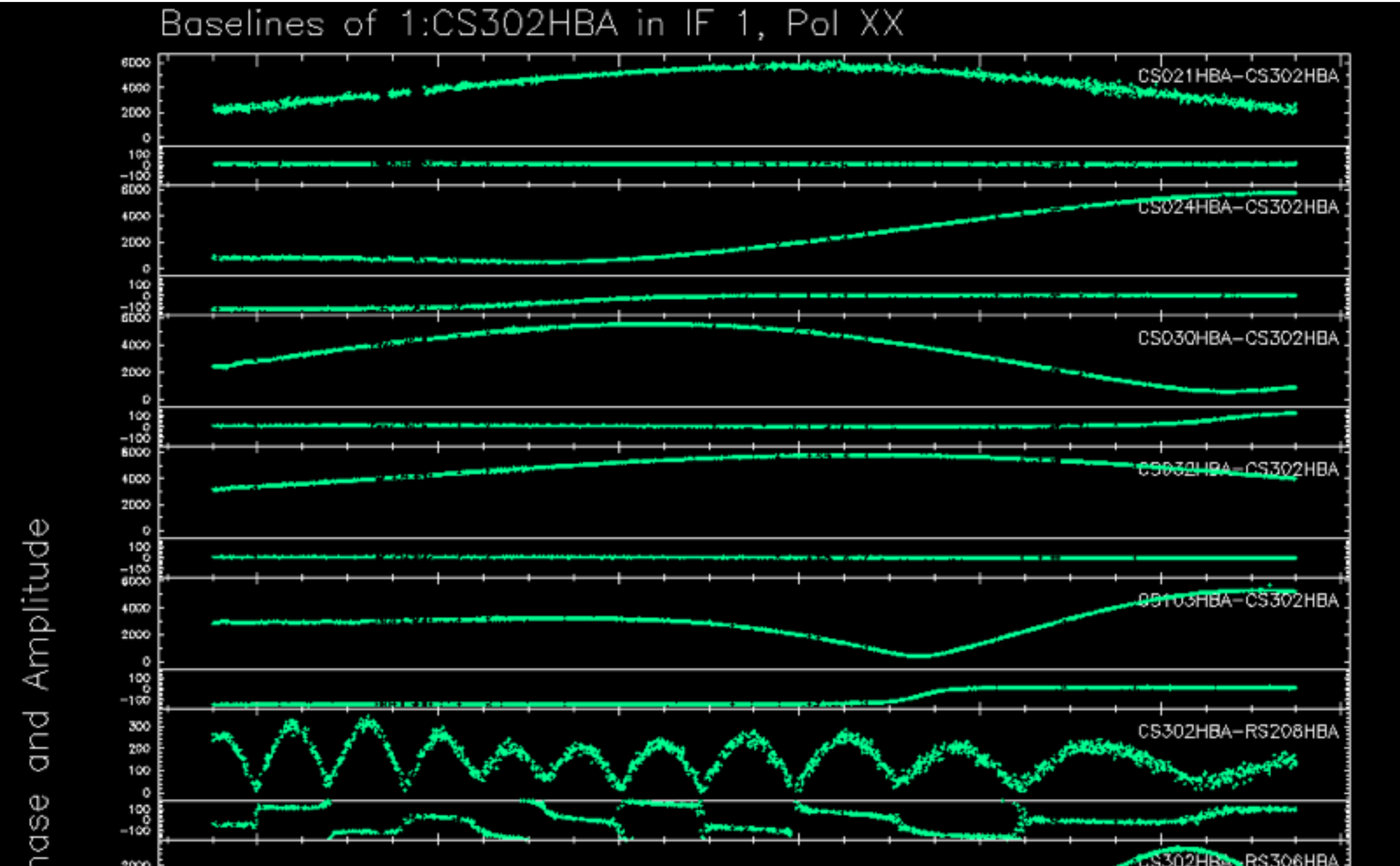




The beam is not constant with time



The beam is not constant with time



Correcting for the beam

Variable beams as a function of time mean that the contribution from each source will vary over time to the visibilities (must convolve sky model with beam model).

$$V_\nu(u,v) = \int\int A_\nu(l,m) I_\nu(l,m) e^{-2\pi i(ul+lm)} dl dm$$

More sophisticated calibration that includes the beam (a-projection is being implemented in CASA for the JVLA).

Issues:

1) How well do we know the beam? Recall, the beam is the FT of the aperture. What happens if a dipole stops working?

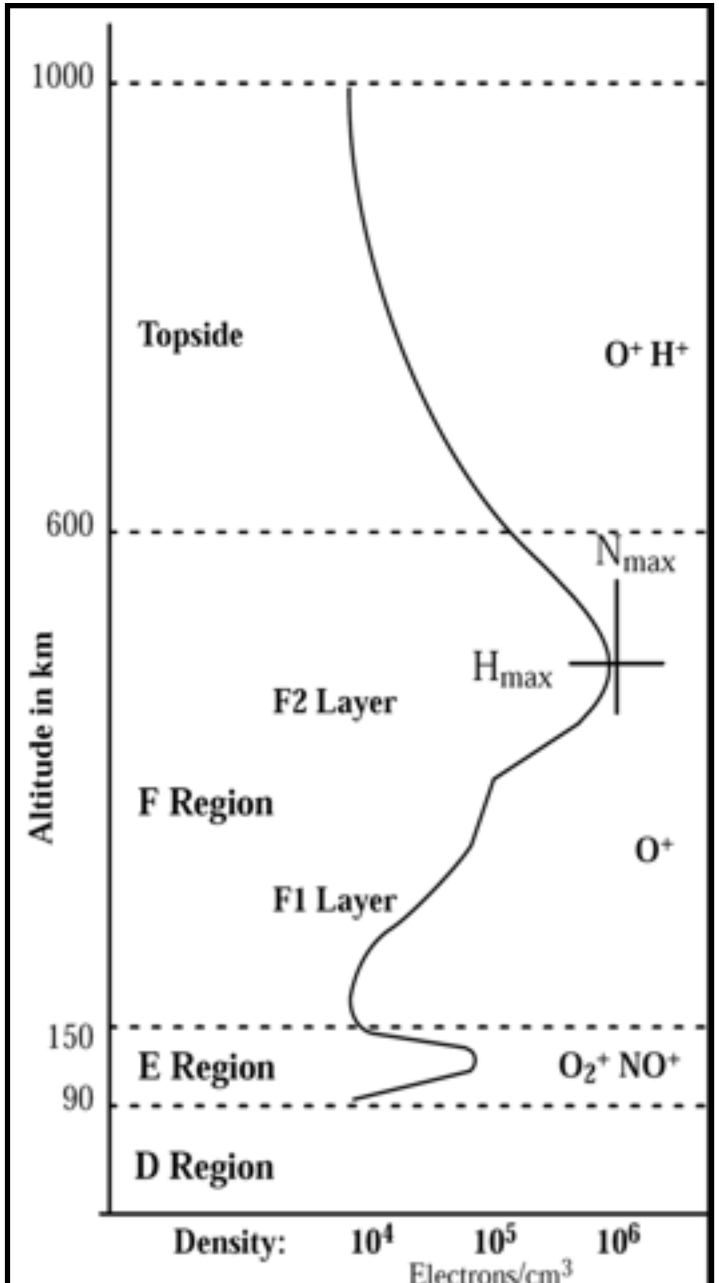
2) The beam changes as a function of frequency (FWHM ~ λ / D).

An error in your model can be absorbed in the calibration

$$\vec{V}_{ij} = J_{ij} \vec{V}_{ij}^{\mathrm{IDEAL}}$$

3. Direction dependent effects. II - The atmosphere

The ionosphere

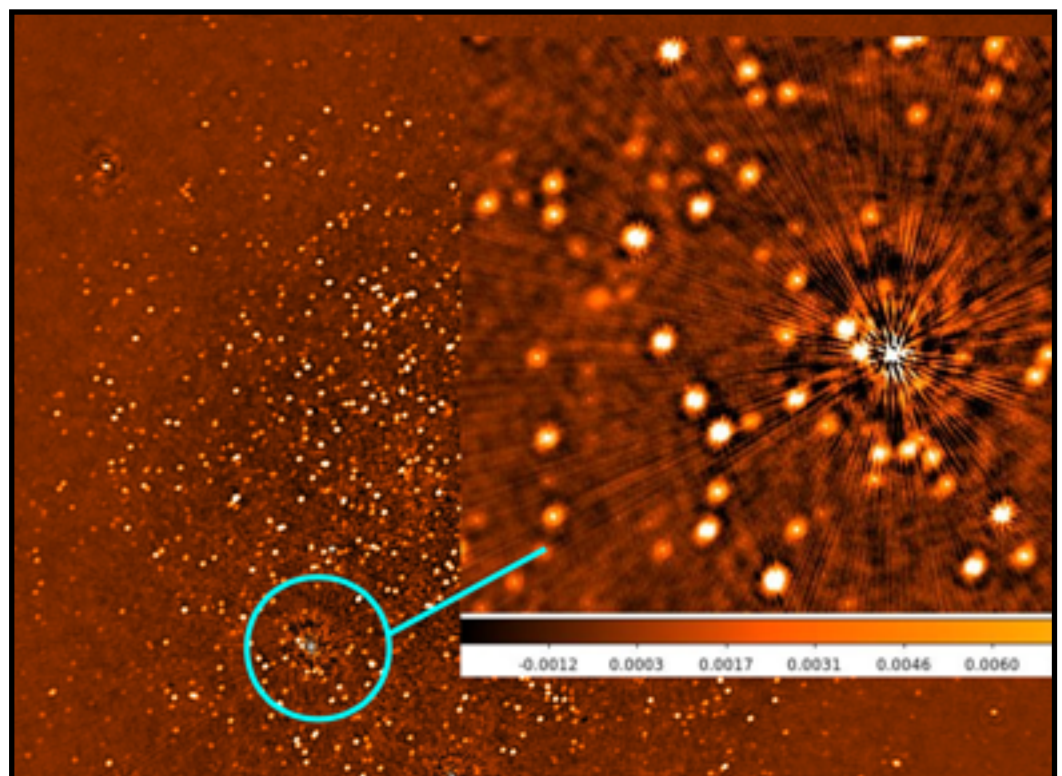


The ionosphere is a reflecting (to long wavelengths) layer of the atmosphere at ~ 125 km.

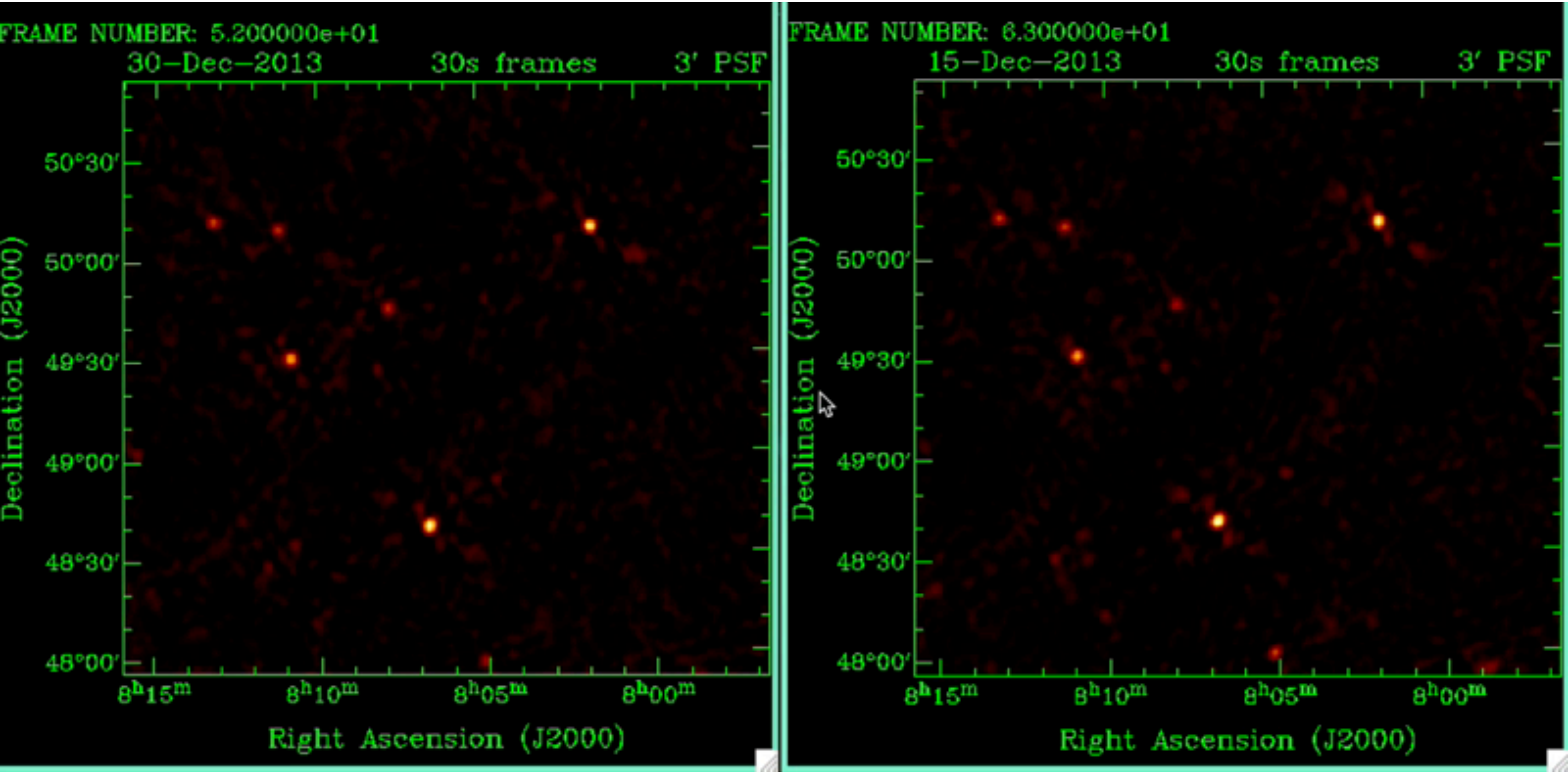
Structure and electron density changes with altitude.

Effects radio waves through:

1) Reflection (transparency)
2) Scintillation (continuum imaging)
3) Faraday rotation (polarisation)



The ionosphere



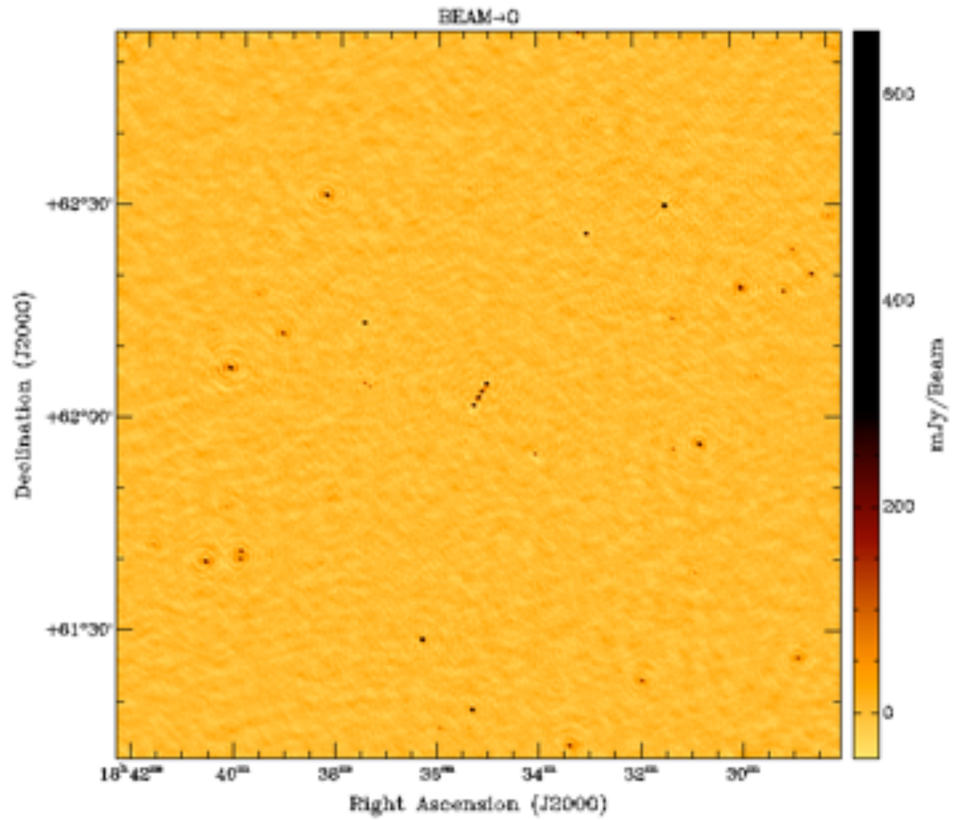
Ger de Bruyn

Direction dependent calibration

The solution to these issues is to calibrate the gains, not in a single position, but over several positions (10s to 100s) across the sky.

$$\vec{V}_{ij} = \sum_s J_{ij,s} \vec{V}_{ij}^{\mathrm{IDEAL}}$$

Sarod Yattawatta

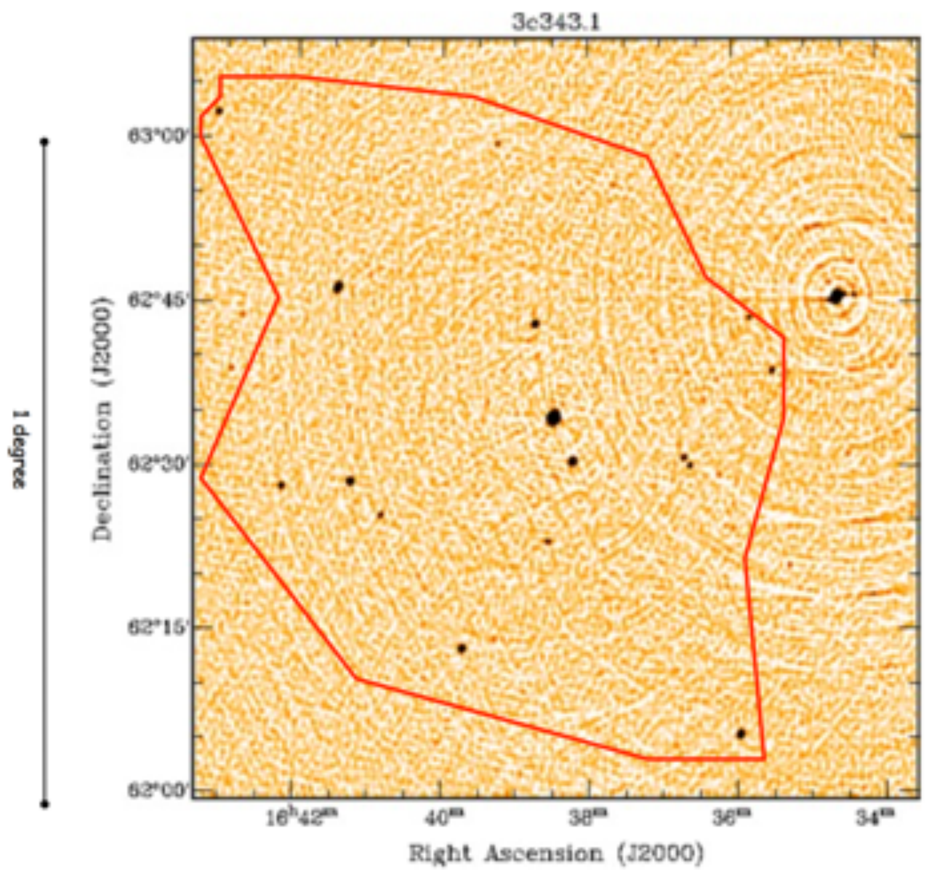


Computationally expensive and the robustness is a matter of (current) debate.

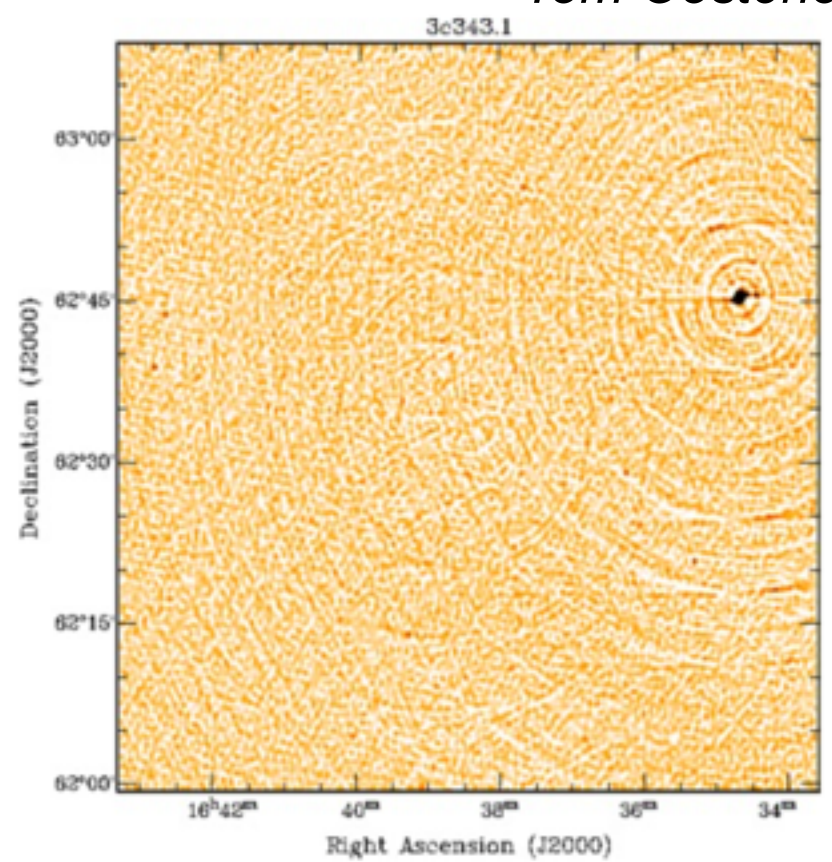
Direction dependent calibration

Alternatively, calibrate in one direction at a time and remove the troublesome sources (called peeling)

Tom Oosterloo



Full-field self-calibration

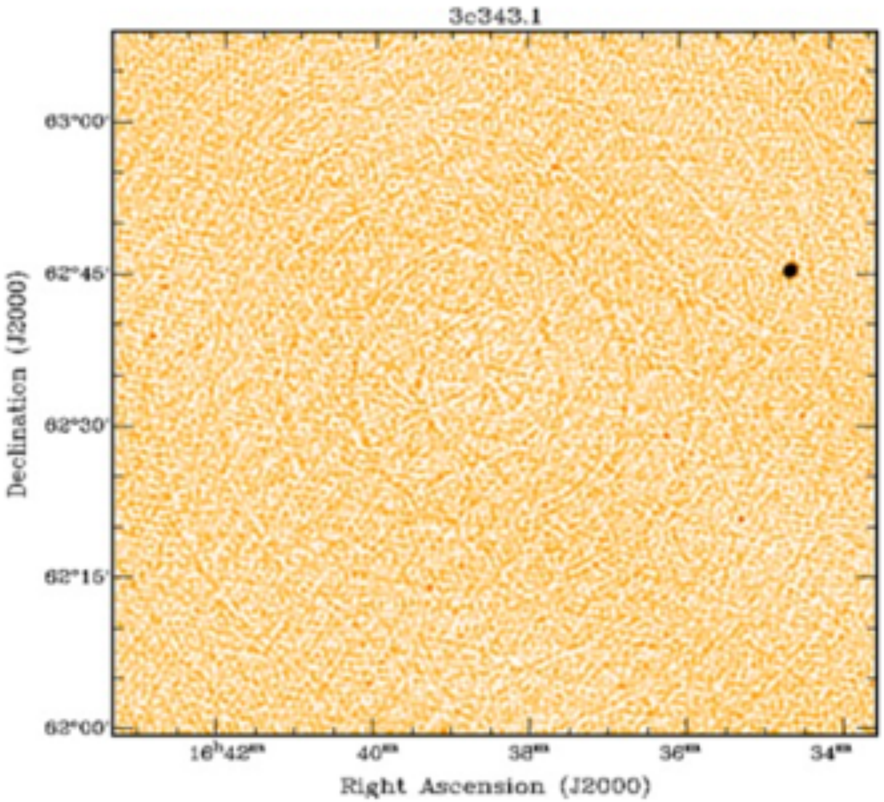


Subtract central sources only, leave off-axis source.

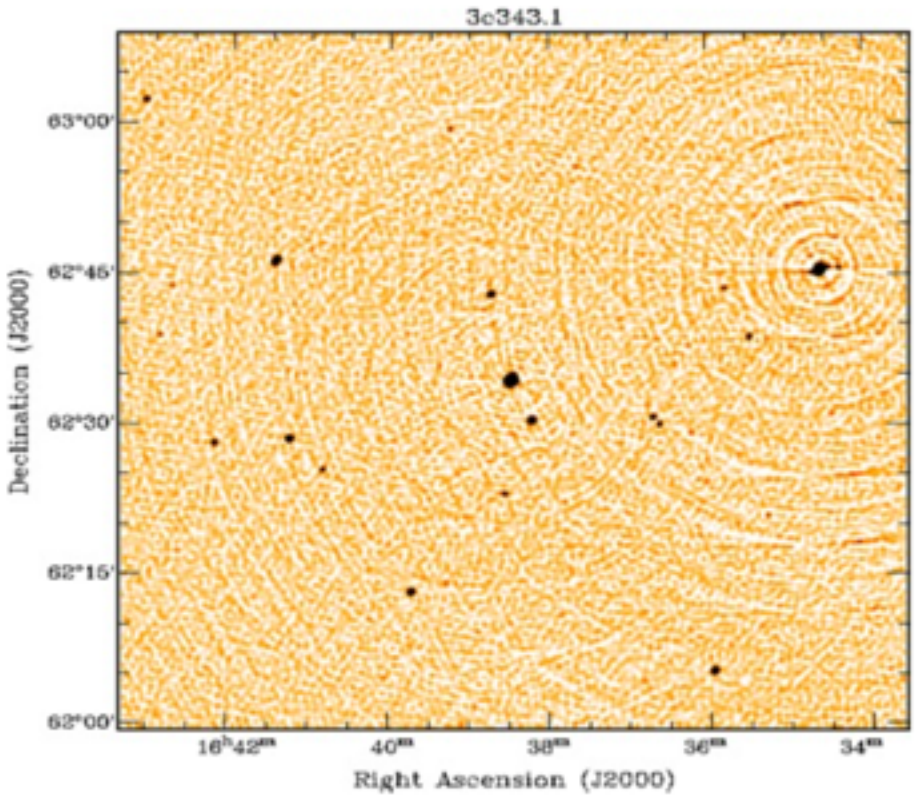
Direction dependent calibration

Alternatively, calibrate in one direction at a time and remove the troublesome sources (called peeling)

Tom Oosterloo



Self-Calibrate using model of off-axis source, apply calibrations and image

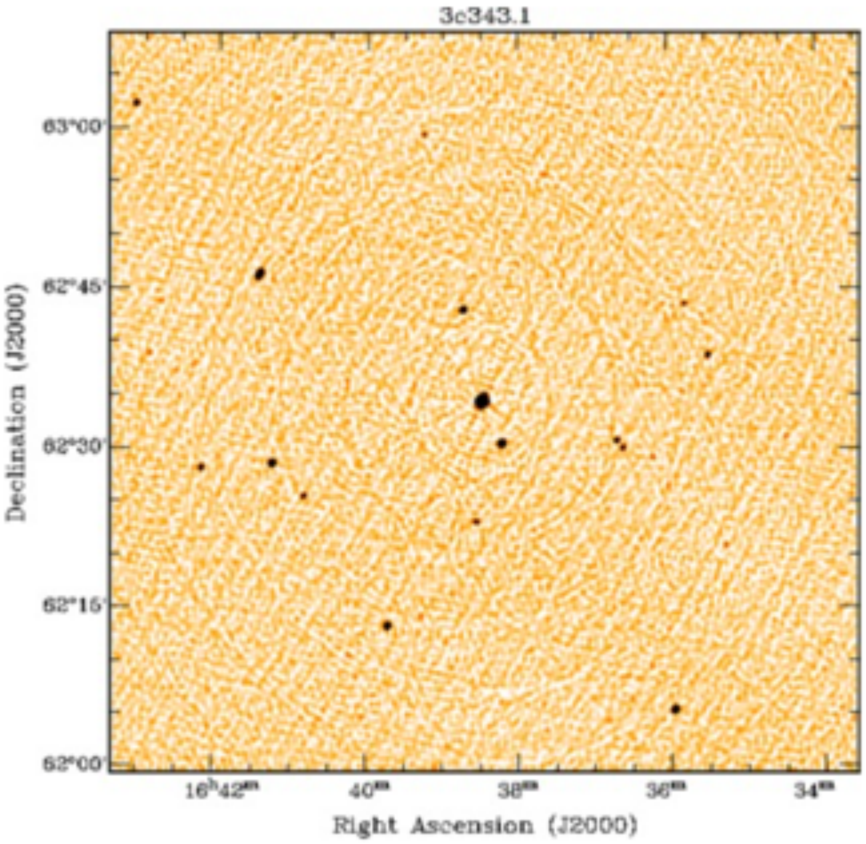


Apply-corrections to whole dataset and remove off-axis source. Remove any corrections.

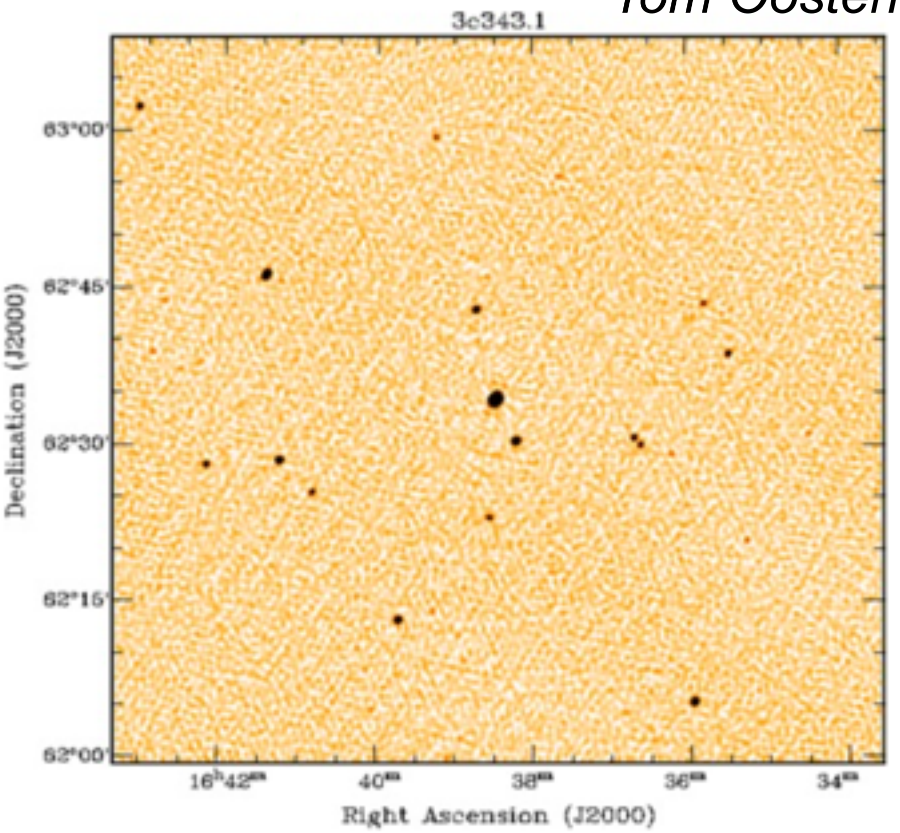
Direction dependent calibration

Alternatively, calibrate in one direction at a time and remove the troublesome sources (called peeling)

Tom Oosterloo



Make new image of the sky (without off-axis source).

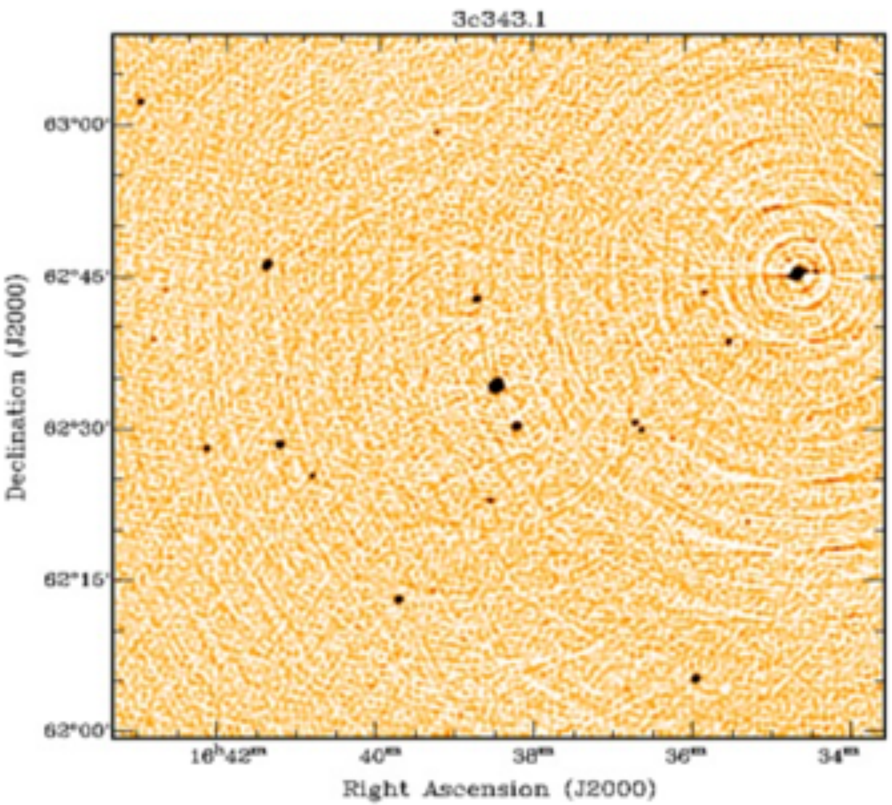


Use self-calibration, apply calibration and make new image.

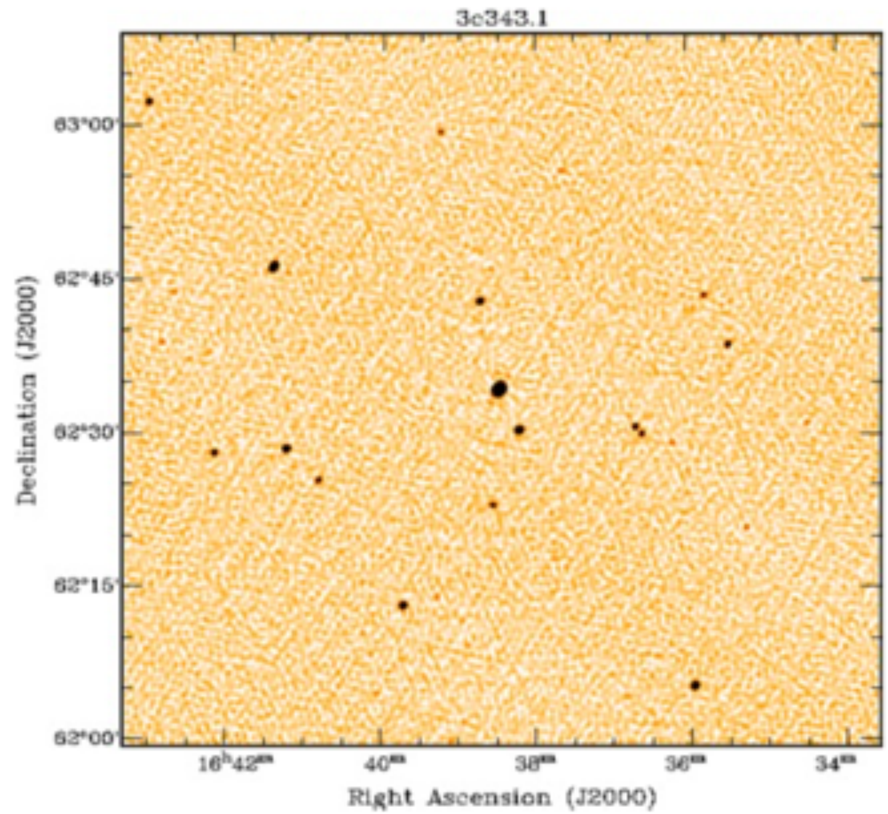
Direction dependent calibration

Alternatively, calibrate in one direction at a time and remove the troublesome sources (called peeling)

Tom Oosterloo



Before.

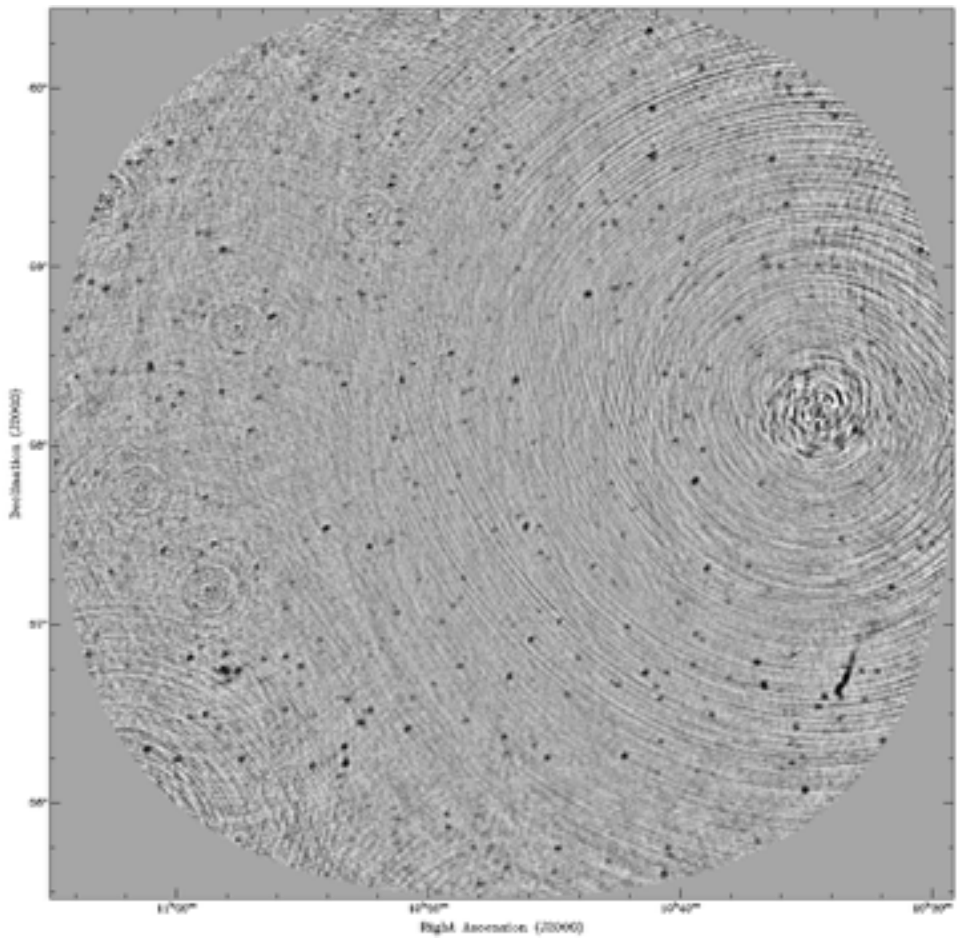


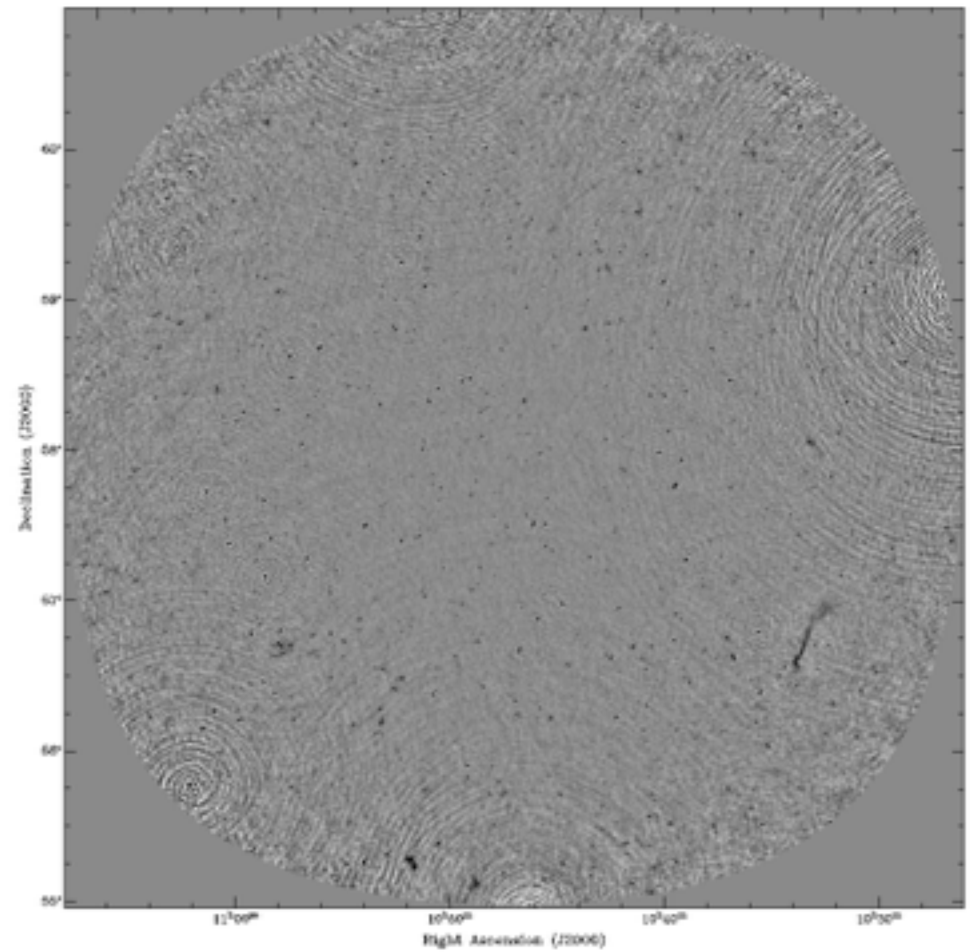
After peeling.

Direction dependent calibration

Alternatively, calibrate in one direction at a time and remove the troublesome sources (called peeling)

Elizabeth Mahony

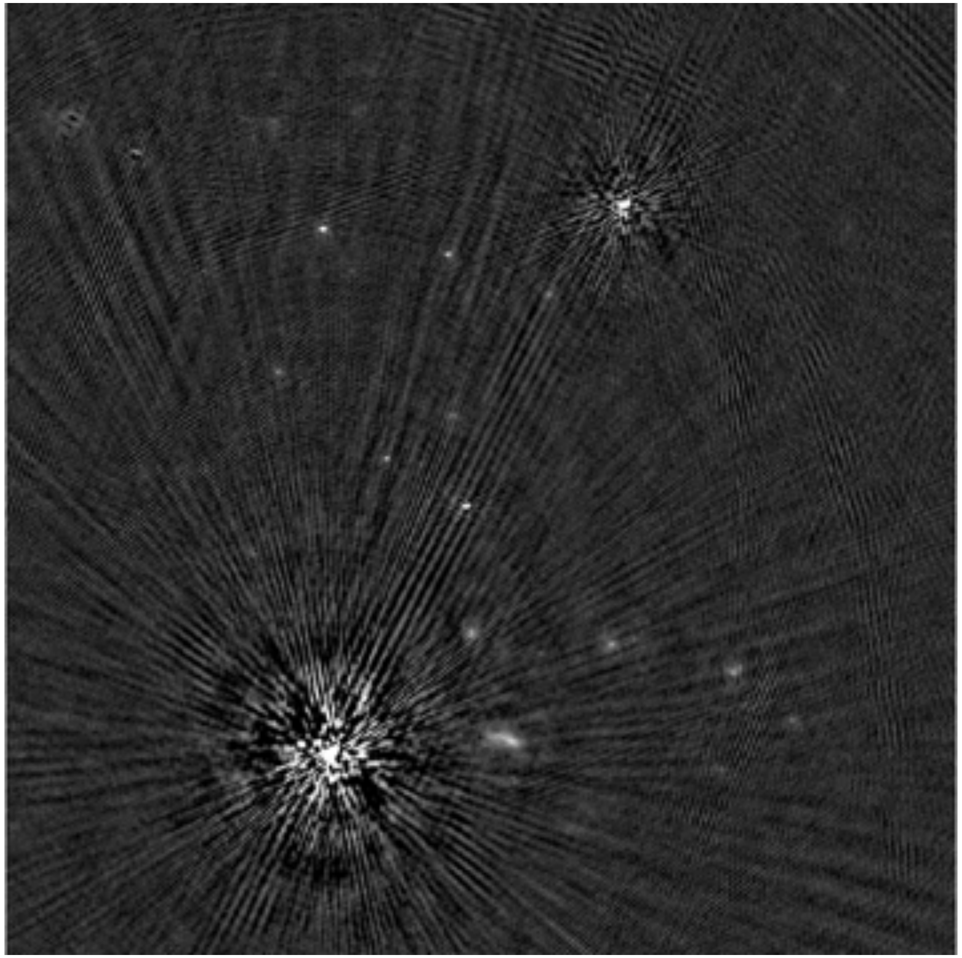


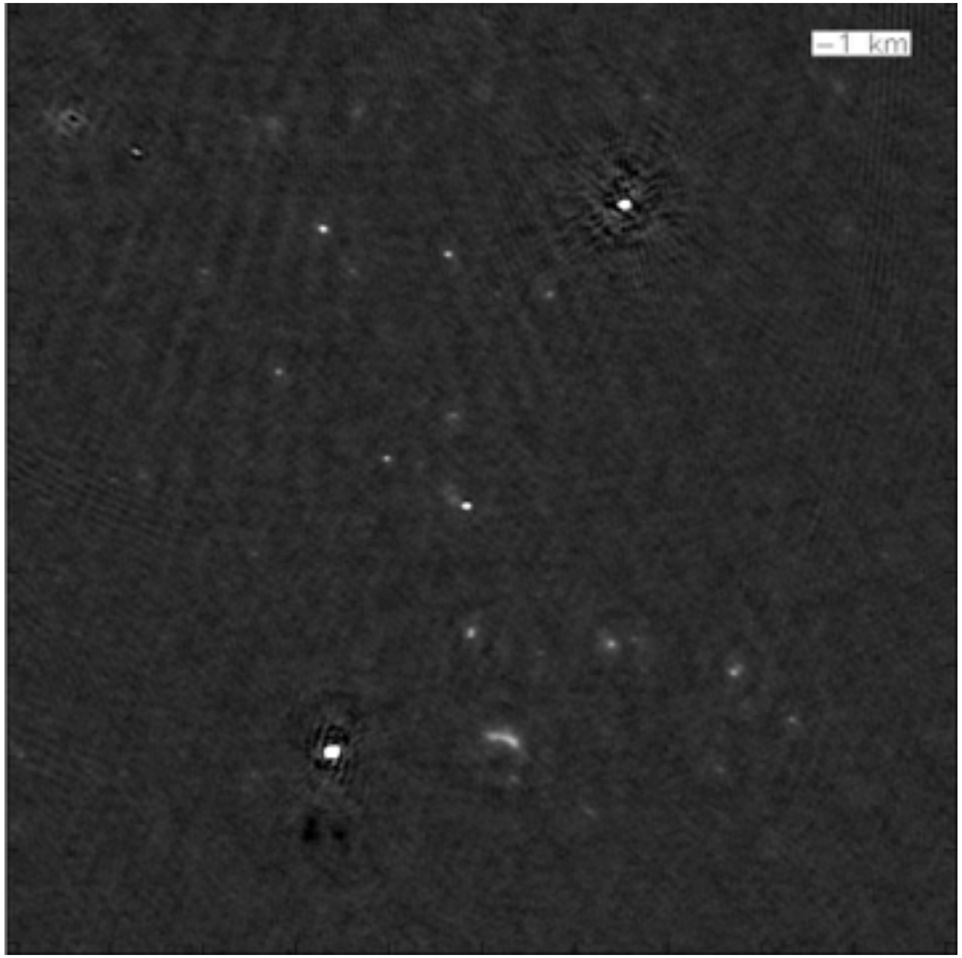


Direction dependent calibration

Alternatively, calibrate in one direction at a time and remove the troublesome sources (called peeling)

Wendy Williams





Direction dependent calibration

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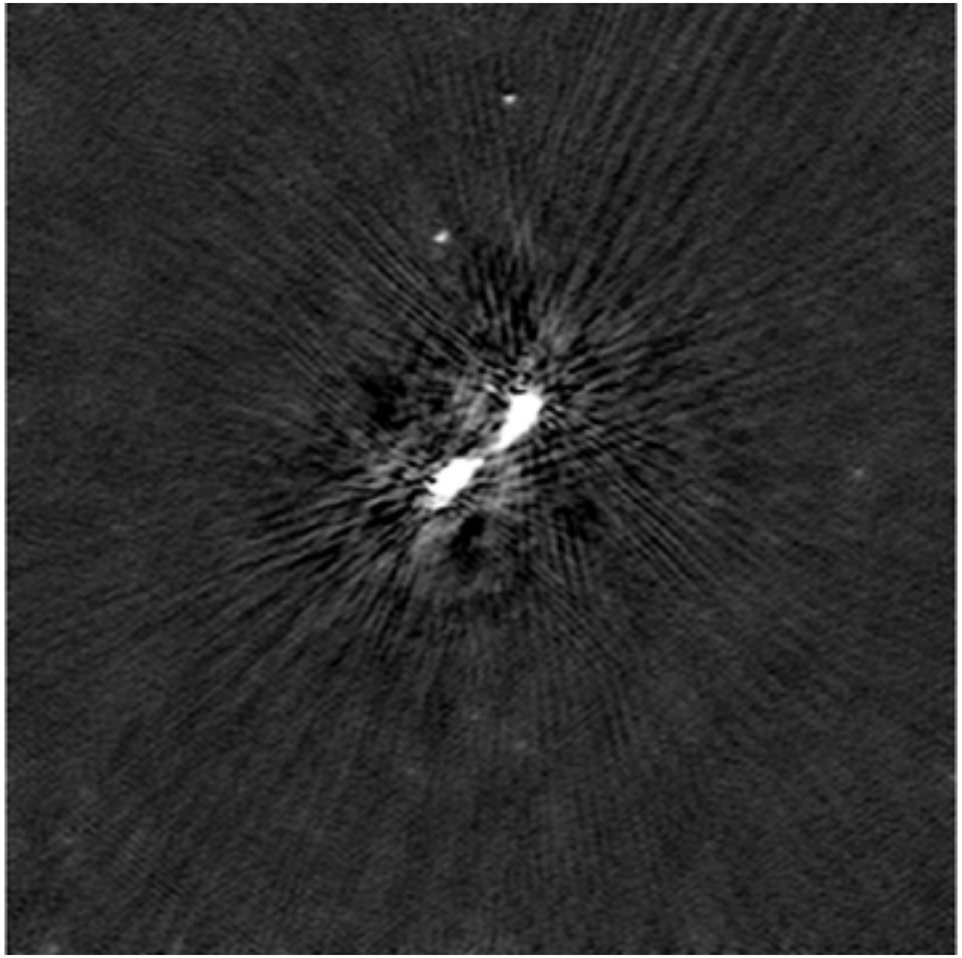


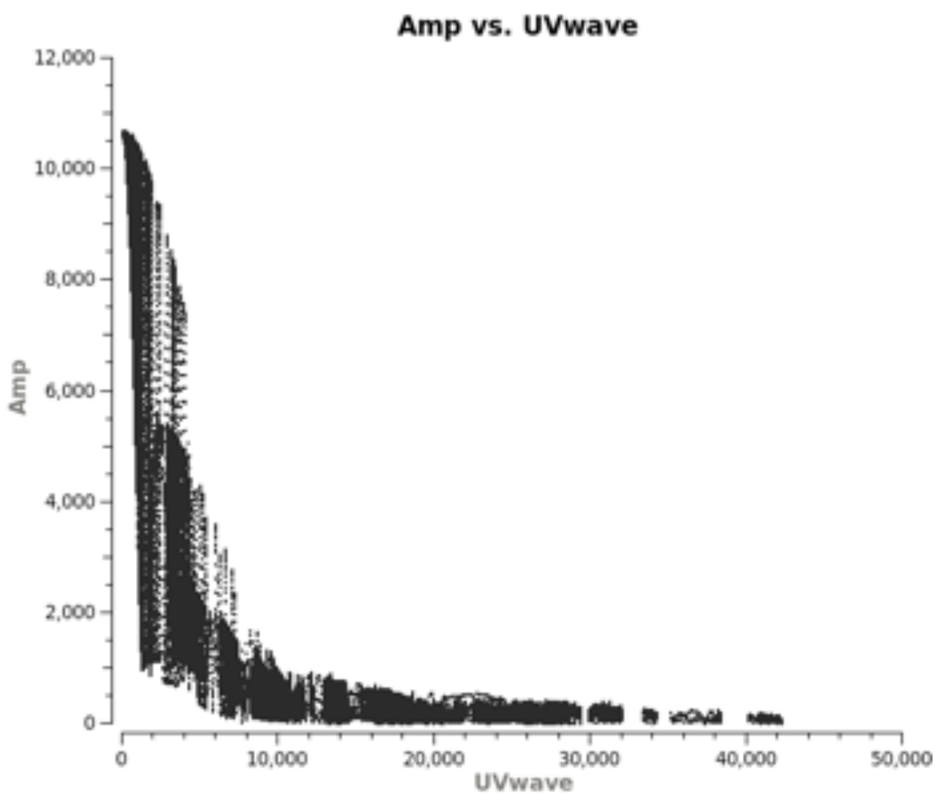
4. Spectral dependence of calibration

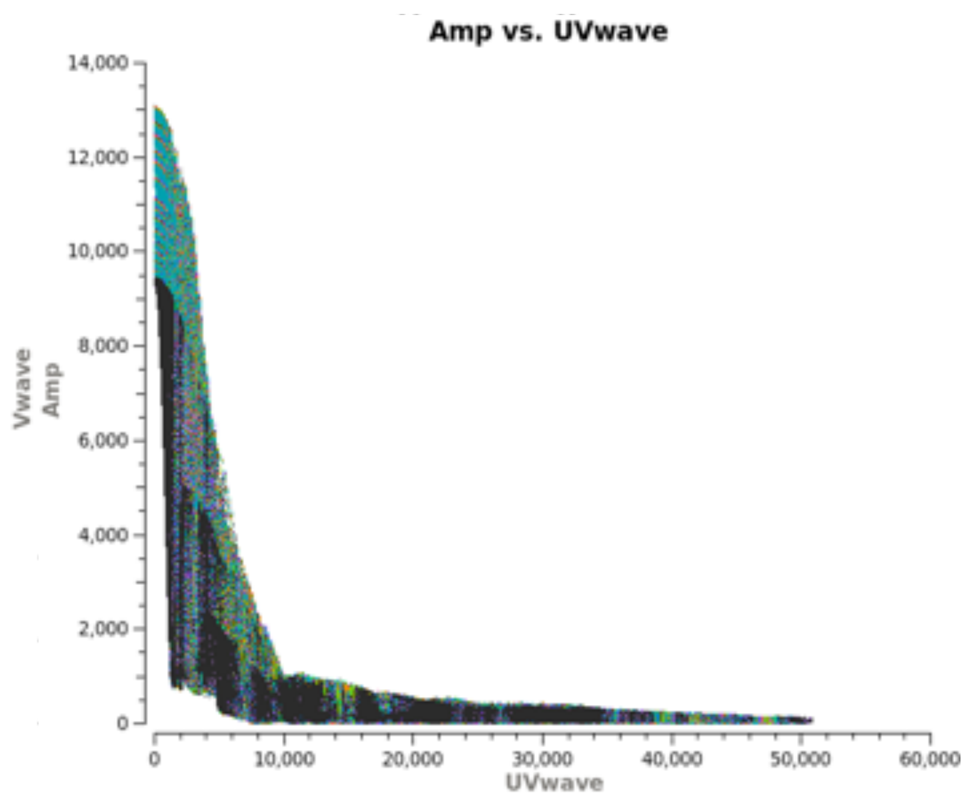
Dealing with large bandwidths

New interferometers have (fractional) large bandwidths.

- Good for sensitivity: $\sigma_T \sim (\Delta v)^{-0.5}$
- Better for image fidelity: good uv-coverage.

Must know the surface brightness distribution as a function of frequency.





Multi-Frequency Synthesis (MFS)

We can represent the sky in emission interms of a Taylor expansion about some reference frequency (see Rau & Cornwell 2011).

Taylor co-efficient images

MS model image

Build *I(v)* model:

$$\boldsymbol{I}_{\nu}^{\mathrm{m}} = \sum_{t=0}^{N_{\mathrm{t}}-1} w_{\nu}^{t} \boldsymbol{I}_{t}^{\mathrm{sky}} \quad \text{where} \quad w_{\nu}^{t} = \left(\frac{\nu - \nu_0}{\nu_0}\right)^{t}$$

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

Parameterise:

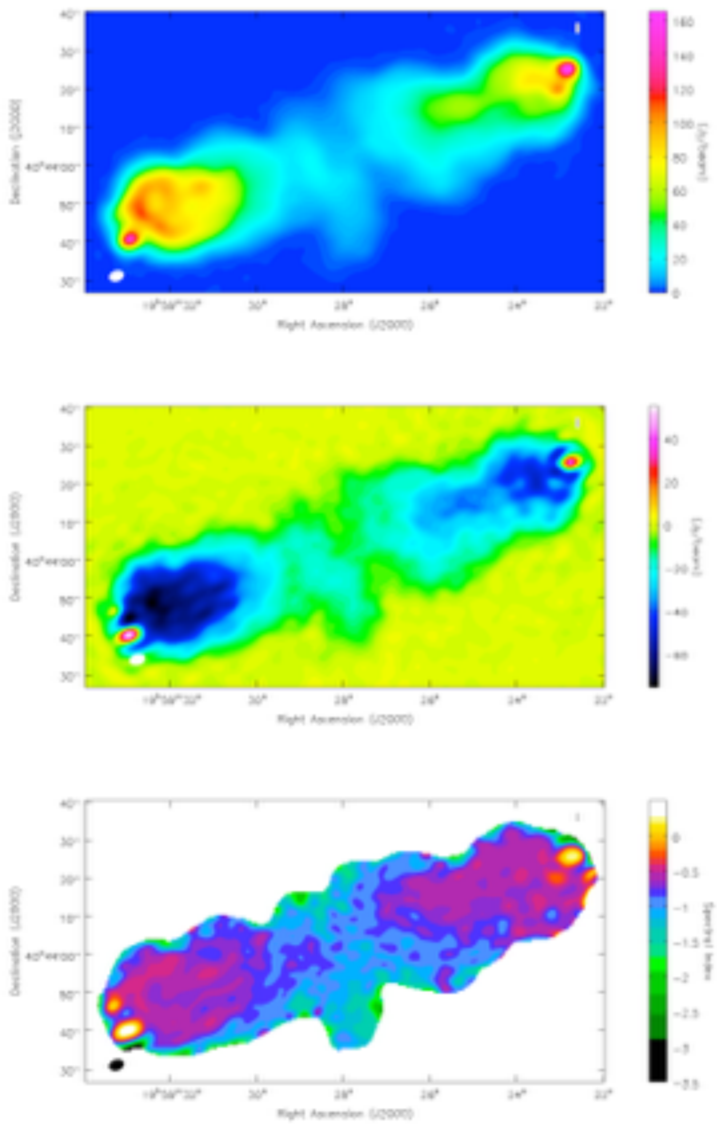
$$\boldsymbol{I}_{\nu}^{\mathrm{sky}} = \boldsymbol{I}_{\nu_0}^{\mathrm{sky}} \left(\frac{\nu}{\nu_0}\right)^{\boldsymbol{I}_{\alpha}^{\mathrm{sky}} + \boldsymbol{I}_{\beta}^{\mathrm{sky}} \log\left(\frac{\nu}{\nu_0}\right)}$$

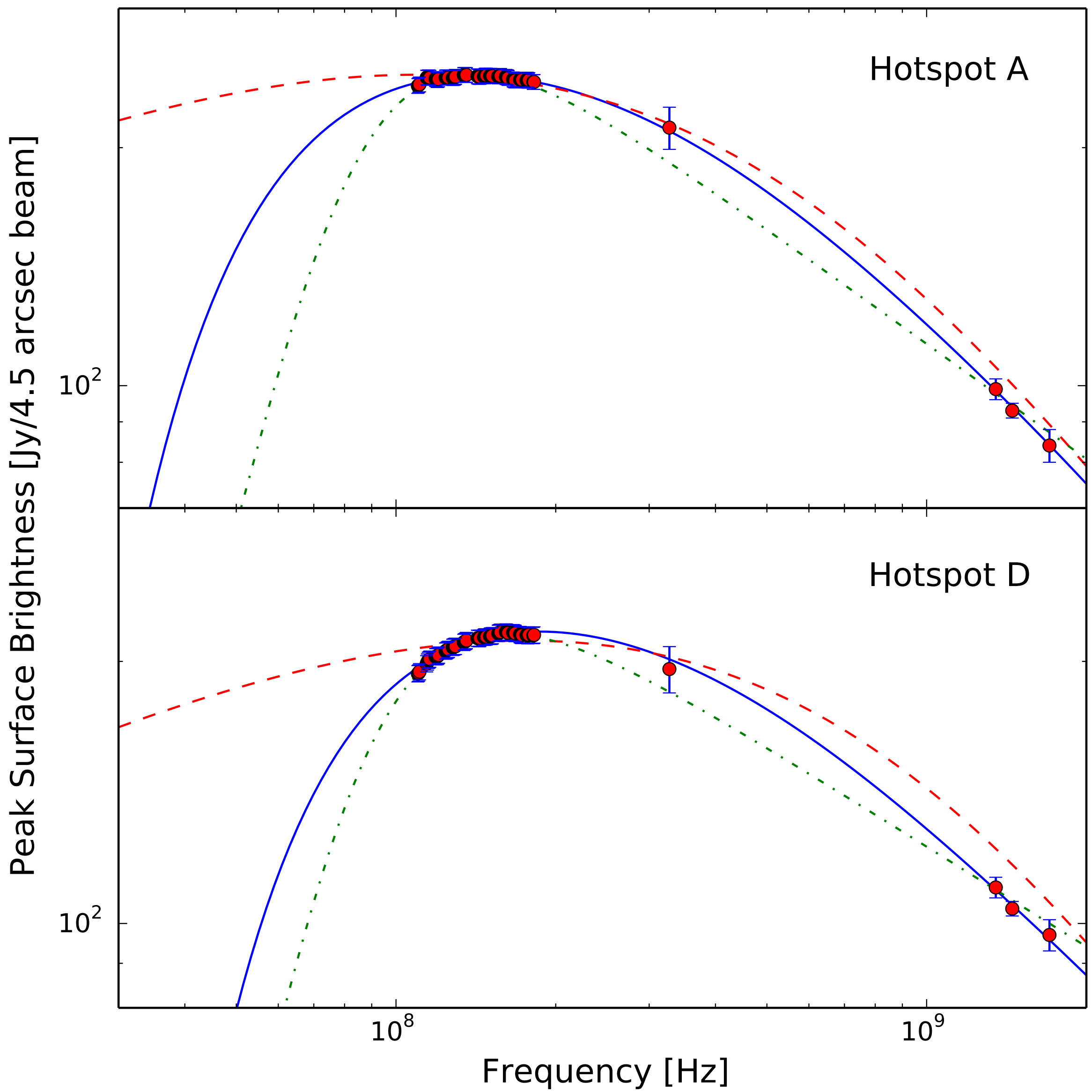
Sky images:

$$\boldsymbol{I}_{0}^{m} = \boldsymbol{I}_{\nu_0}^{\mathrm{sky}} \;;\; \boldsymbol{I}_{1}^{m} = \boldsymbol{I}_{\alpha}^{\mathrm{sky}} \boldsymbol{I}_{\nu_0}^{\mathrm{sky}} \;;\; \boldsymbol{I}_{2}^{m} = \left(\frac{\boldsymbol{I}_{\alpha}^{\mathrm{sky}}(\boldsymbol{I}_{\alpha}^{\mathrm{sky}} - 1)}{2} + \boldsymbol{I}_{\beta}^{\mathrm{sky}}\right) \boldsymbol{I}_{\nu_0}^{\mathrm{sky}}$$

Imaging example: Cygnus A

LOFAR imaging at 109 to 183 MHz for 8 h on source.





Summary

1. The Low Frequency Array will transform our view of the low frequency Universe (with a frequency coverage and resolution that surpasses even the SKA, as proposed).

2. Direction dependent effects will limit the quality of wide-field imaging due to time variable beam patterns, time variable ionosphere and our limited knowledge of the sky model.

3. New advanced calibration techniques are being tested and already show promise in reaching the thermal noise in the images, but careful study of the effects of direction dependent calibration need to be better understood.

4. Spectral variation in the sky model must also be taken into account due to the large bandwidths of the new telescope systems.