Netherlands Institute for Radio Astronomy

LOFAR: Special Issues

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Preamble

http://www.astron.nl/~mckean/ERIS-2011-2.pdf

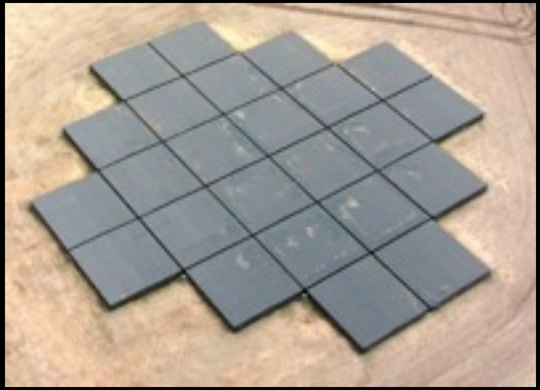
- **AIM:** This lecture aims to give a general introduction to LOFAR and point out the differences between LOFAR and other typical dish based instruments.

- **OUTLINE:**

  - The Low Frequency Array
  - Special Issues
  - Imaging of Cygnus A
  - Summary

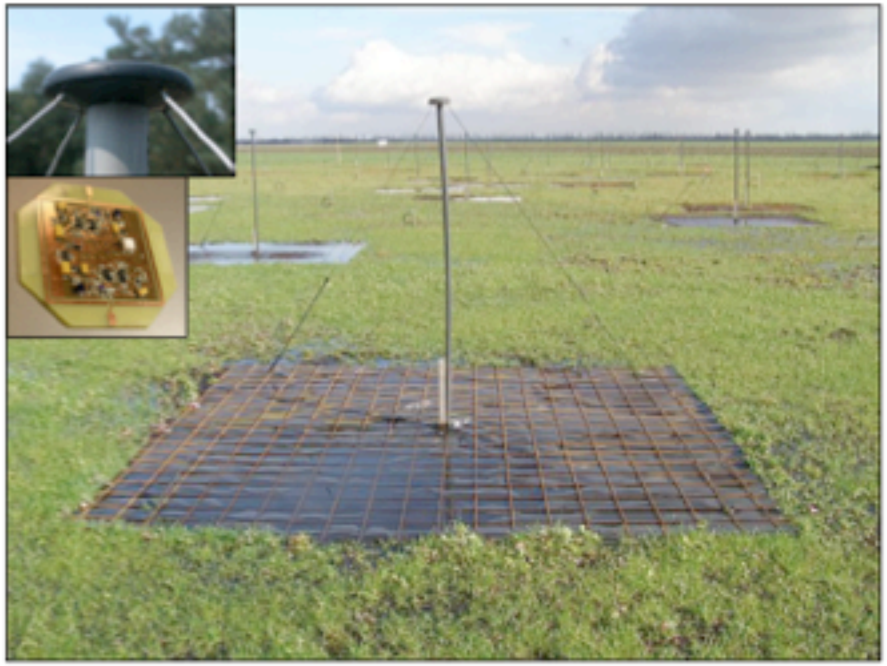
The Low Frequency Array - Key Facts

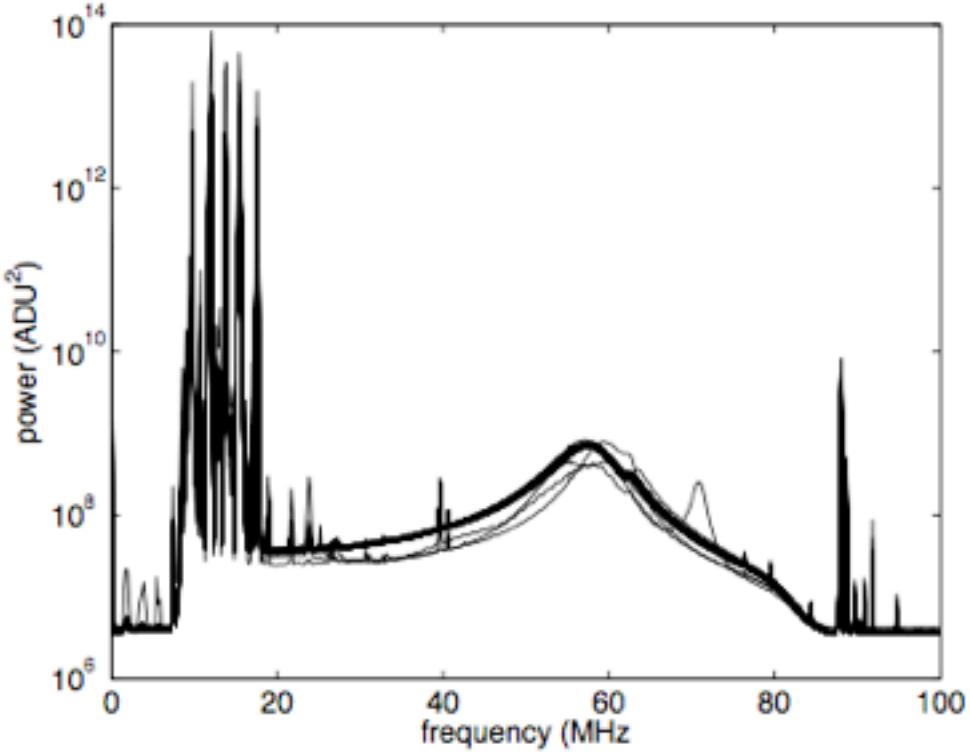
- The International LOFAR Telescope (ILT) is being built in the Netherlands, Germany, France, UK and Sweden (~€50M construction + running costs).
- Operating frequency is 10 -- 240 MHz.
- 1 beam with up to 48 MHz total bandwidth, split into 244 sub-bands with 256 Channels.
- <244 beams on the sky with ~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* polarizations, ground plate.
- Low cost, high durability (15 year operation), whole sky coverage.

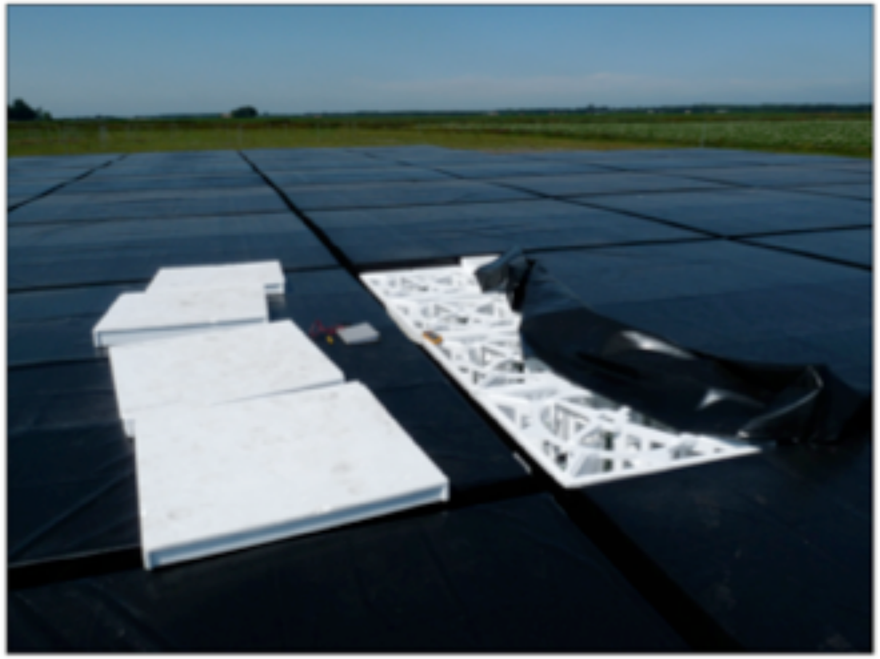


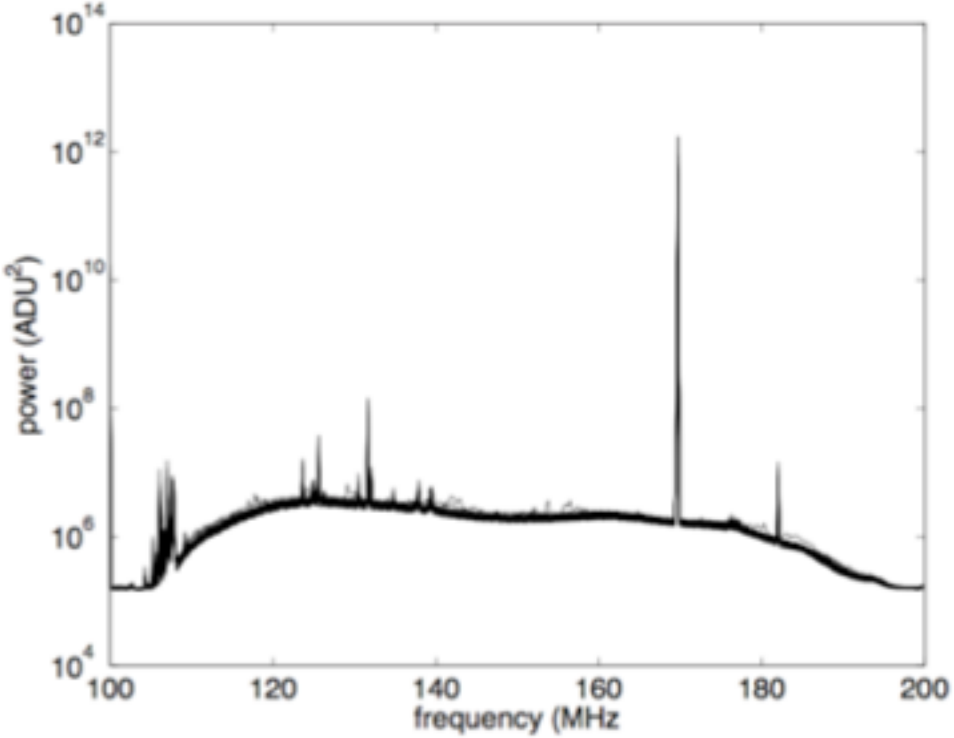


- **The response curve:** There is a peak close to the resonance frequency (52 MHz) - dipole arms are 1.38 m long.

High Band Antenna (HBA)

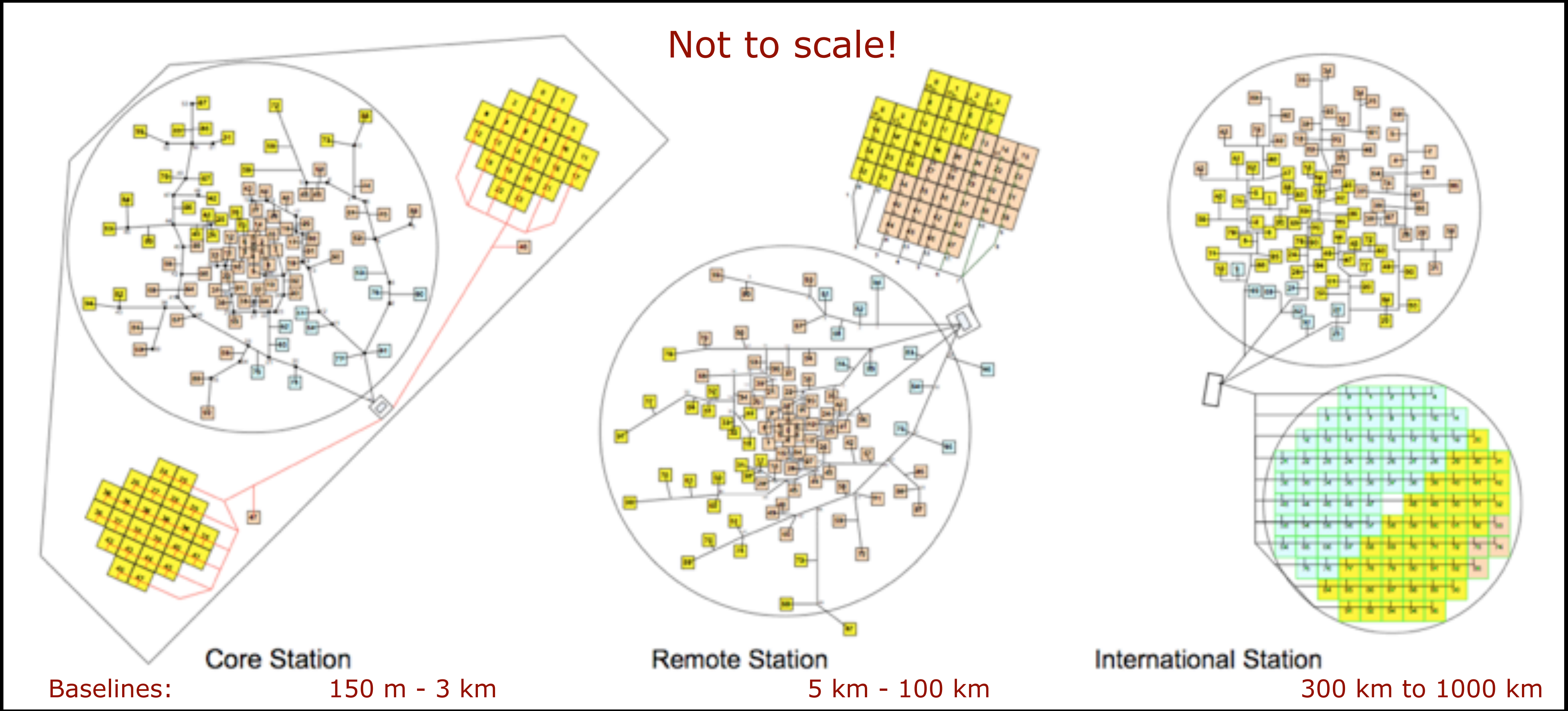
- **HBA antennas:** Each tile consists of 4 x 4 dual *linear* polarization aluminum dipoles, housed in a polystyrene structure, covered by polypropylene sheets.
- Dipoles are combined to form a single "tile beam".





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

Stations



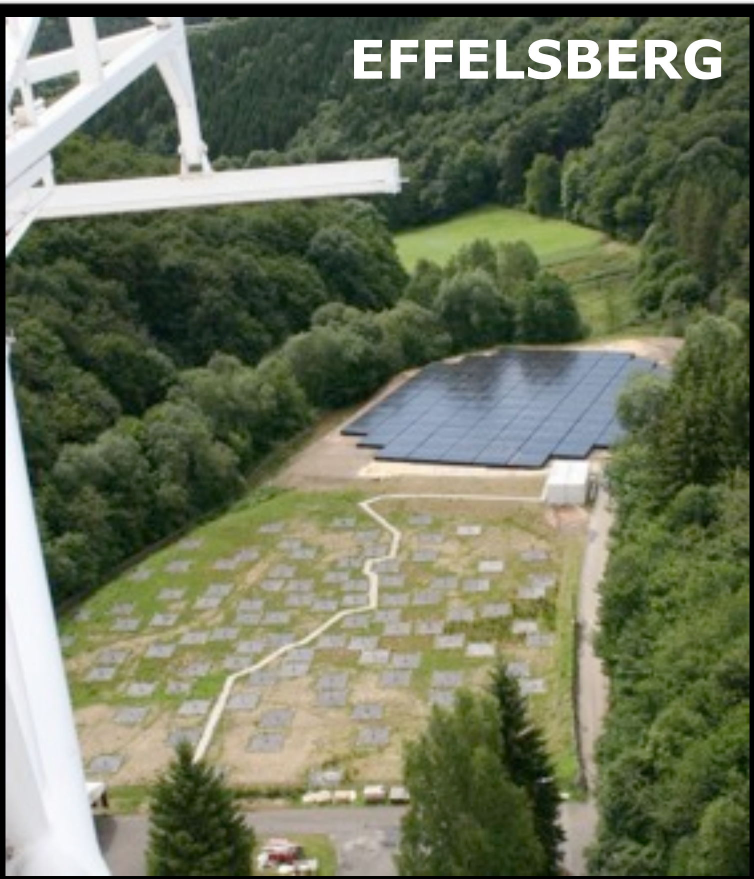
- **Three types:** Core (24), Remote (16) and International (8 so far).
- Different beam shapes
- Different sensitivities.

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

Core stations

6 Station Superterp

International Stations



Field-of-View (FWHM v Freq.)

ASTRON

- 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.

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

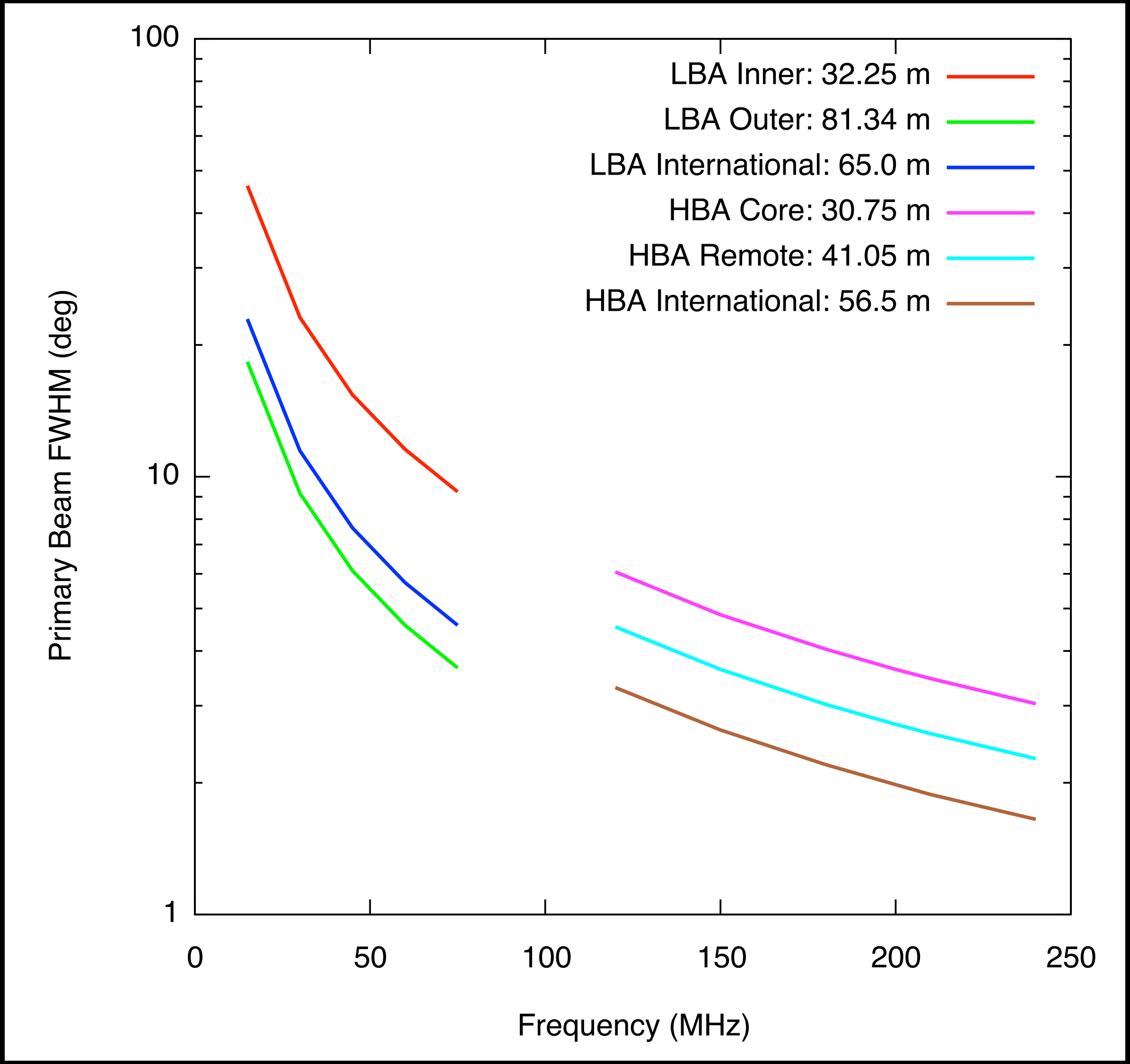
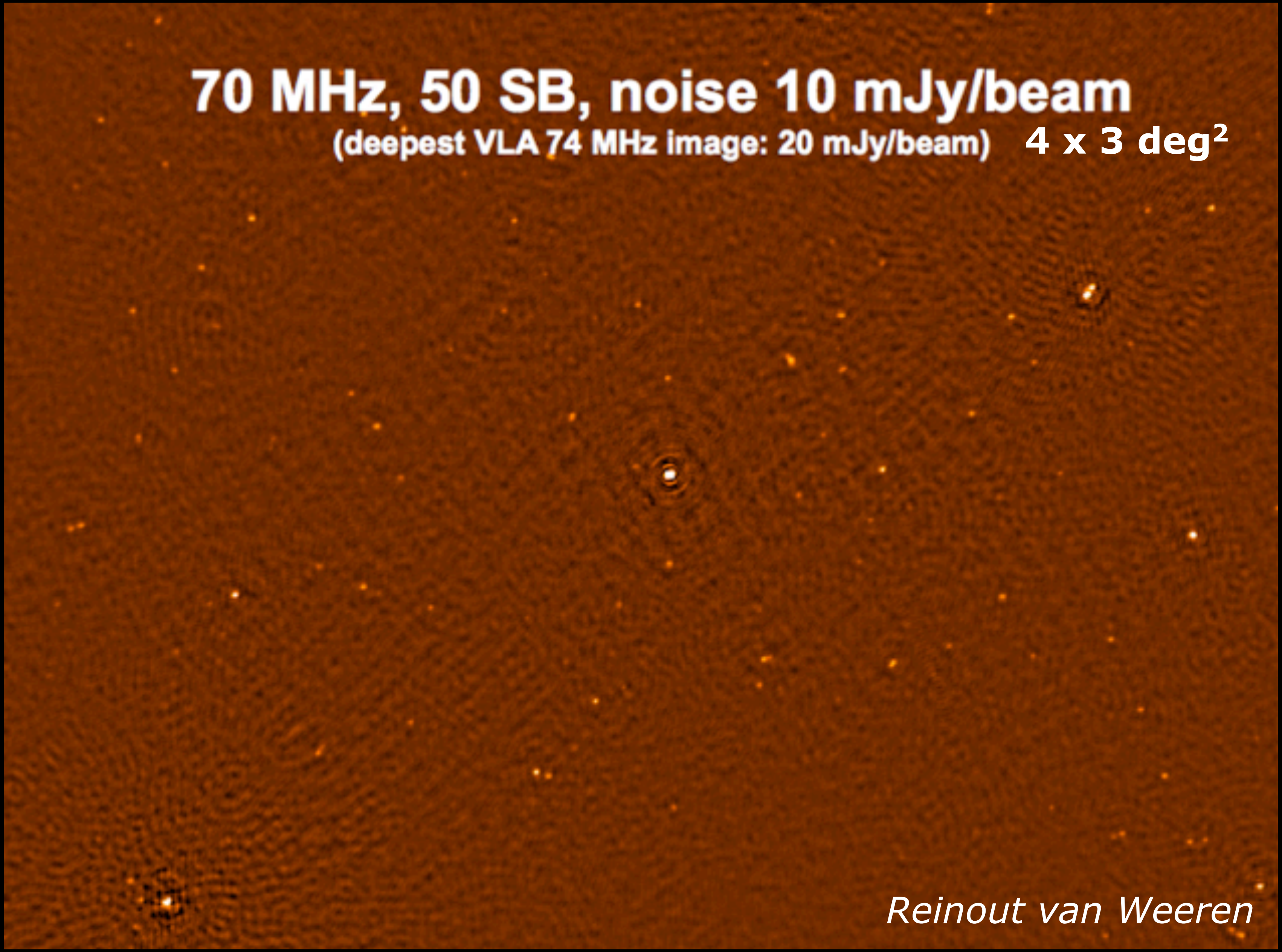


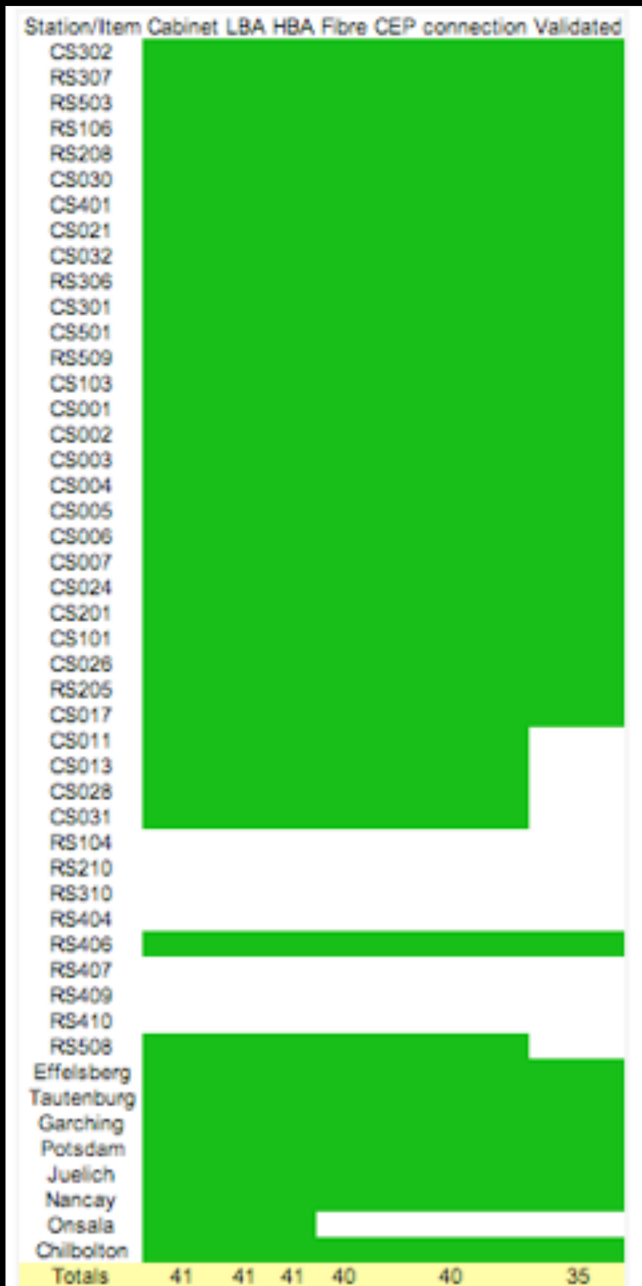
Image of field around 3C196



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.
- <244 beams can be formed, increasing survey speed, efficiency, calibration.

Current Status



- Station role-out started in Summer 2009.
- Core is basically complete
- RS508 and RS509 just connected.
- 35 stations validated (20 core, 8 remote and 7 International)
- Locations for the final 7 remote stations still to be decided.

http://www.astron.nl/radio-observatory/astronomers/current-status

A Pan-European Array (ILT)

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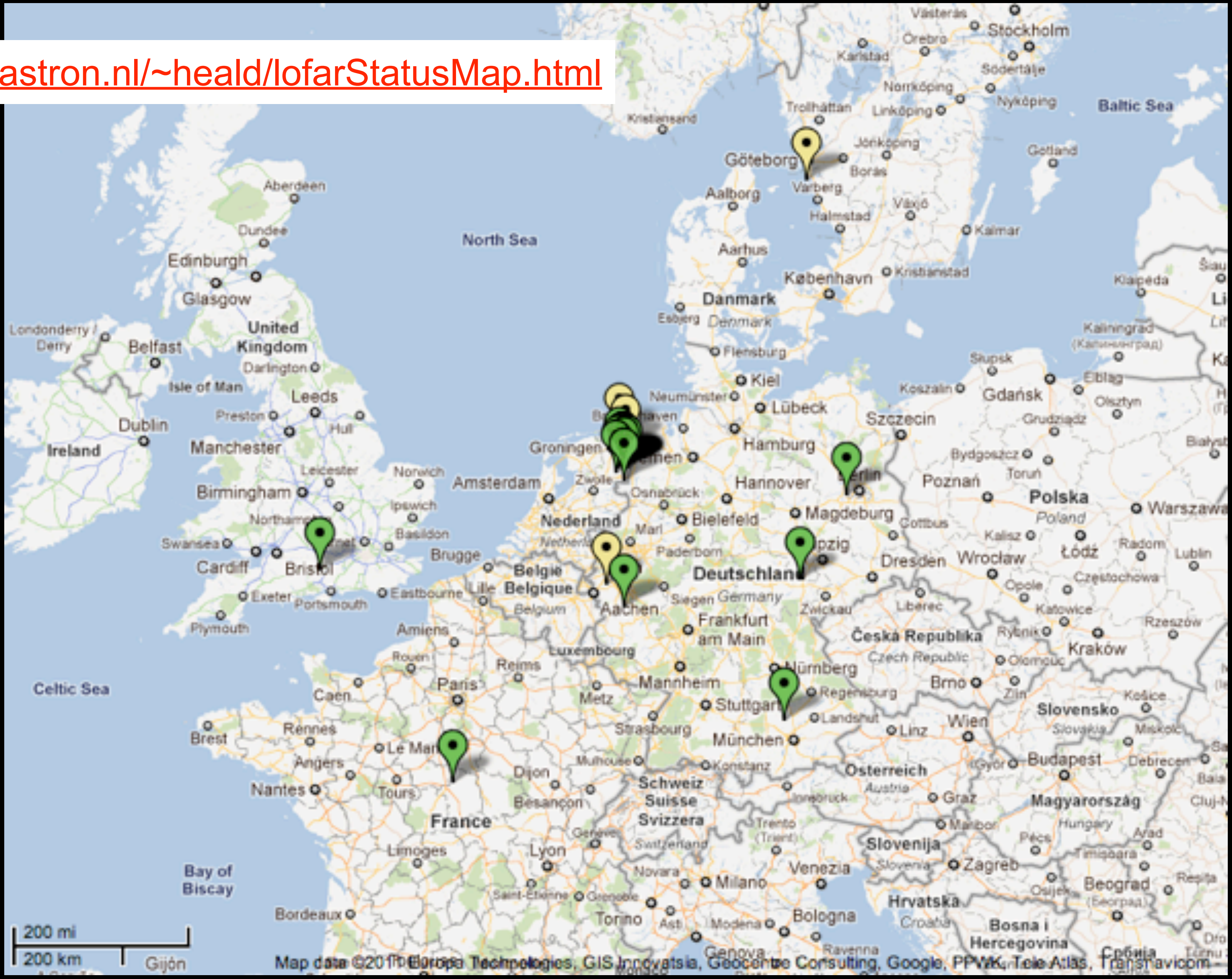
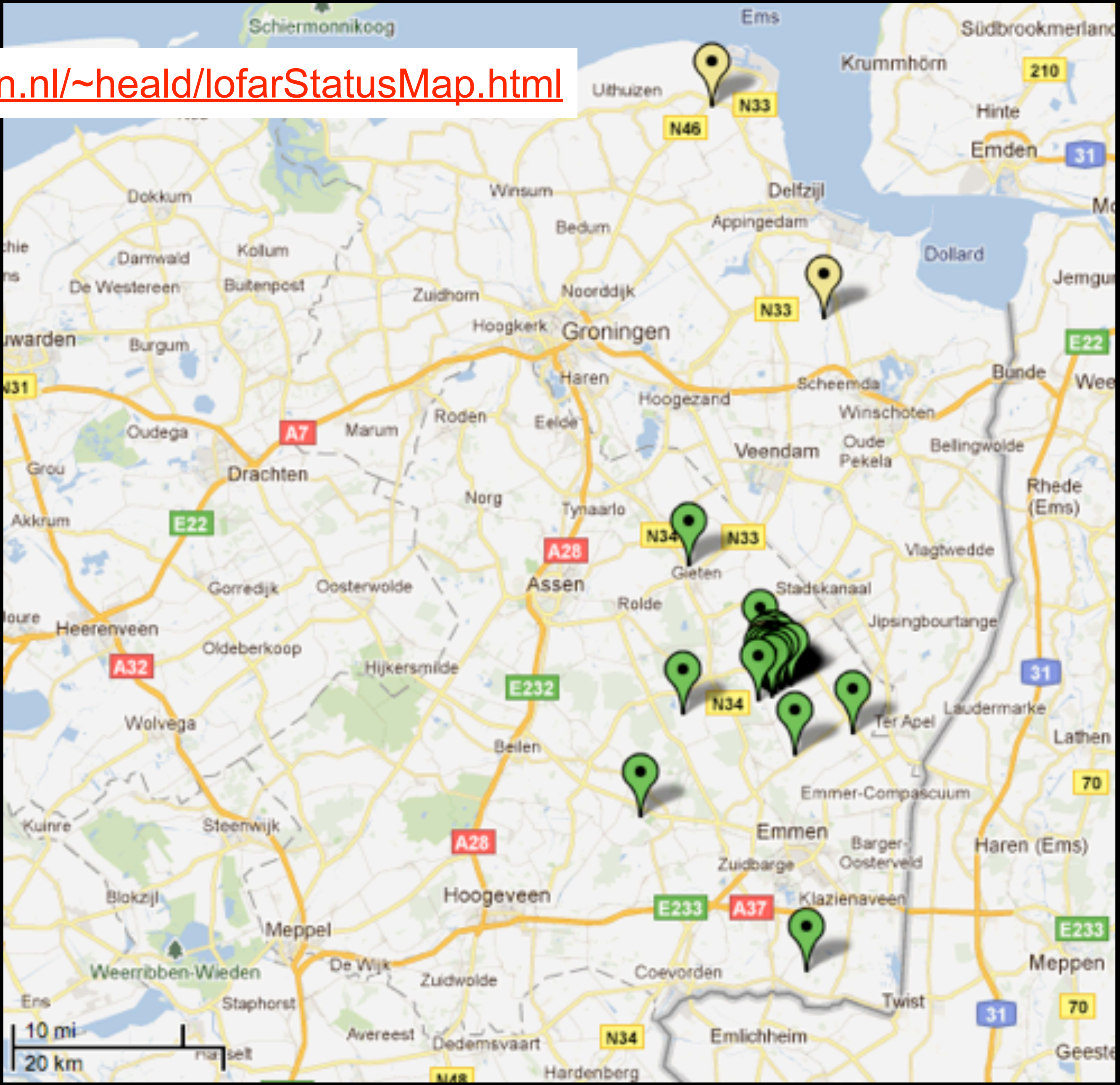
http://www.astron.nl/~heald/lofarStatusMap.html



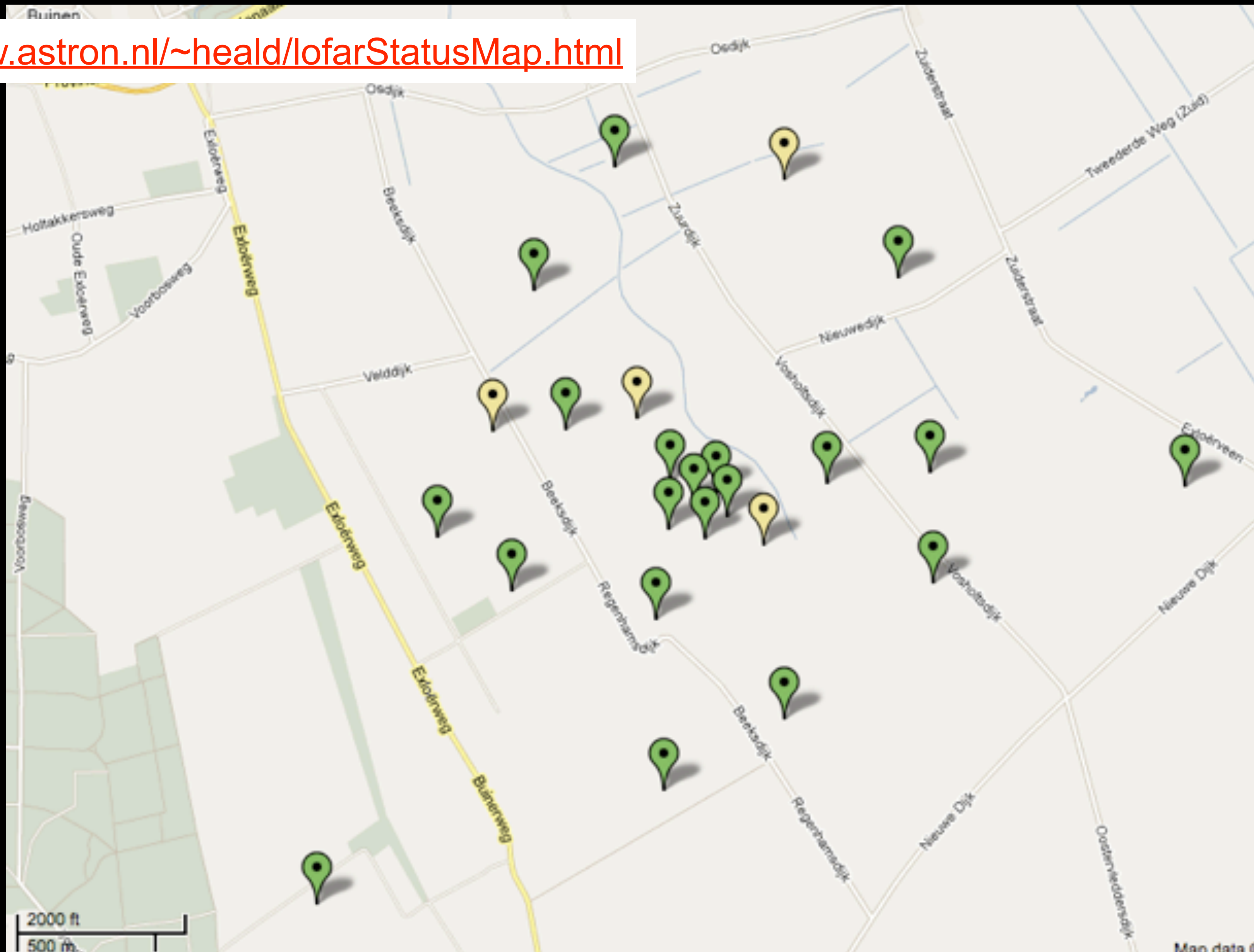
The Dutch Array (LOFAR-NL)

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

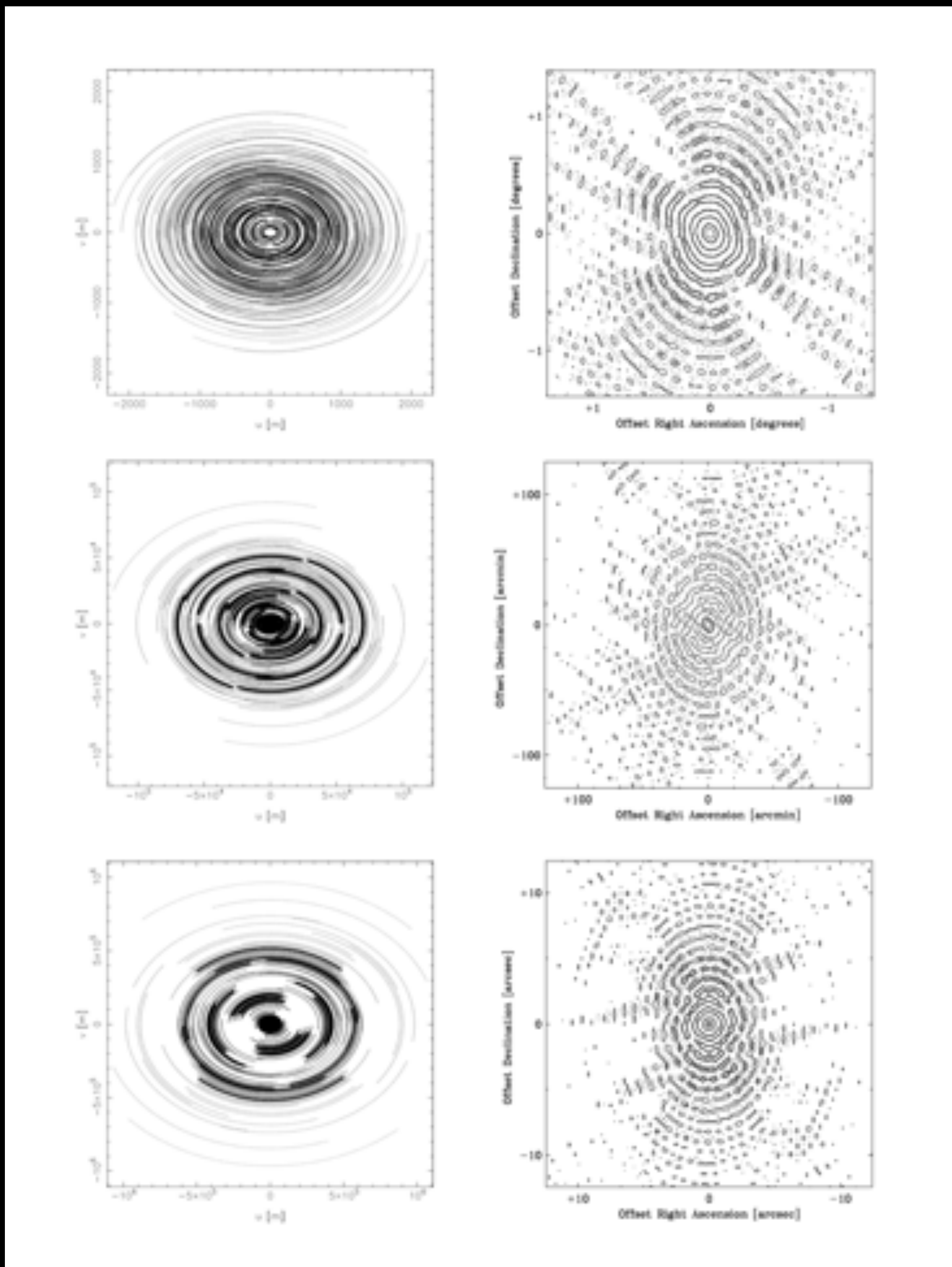


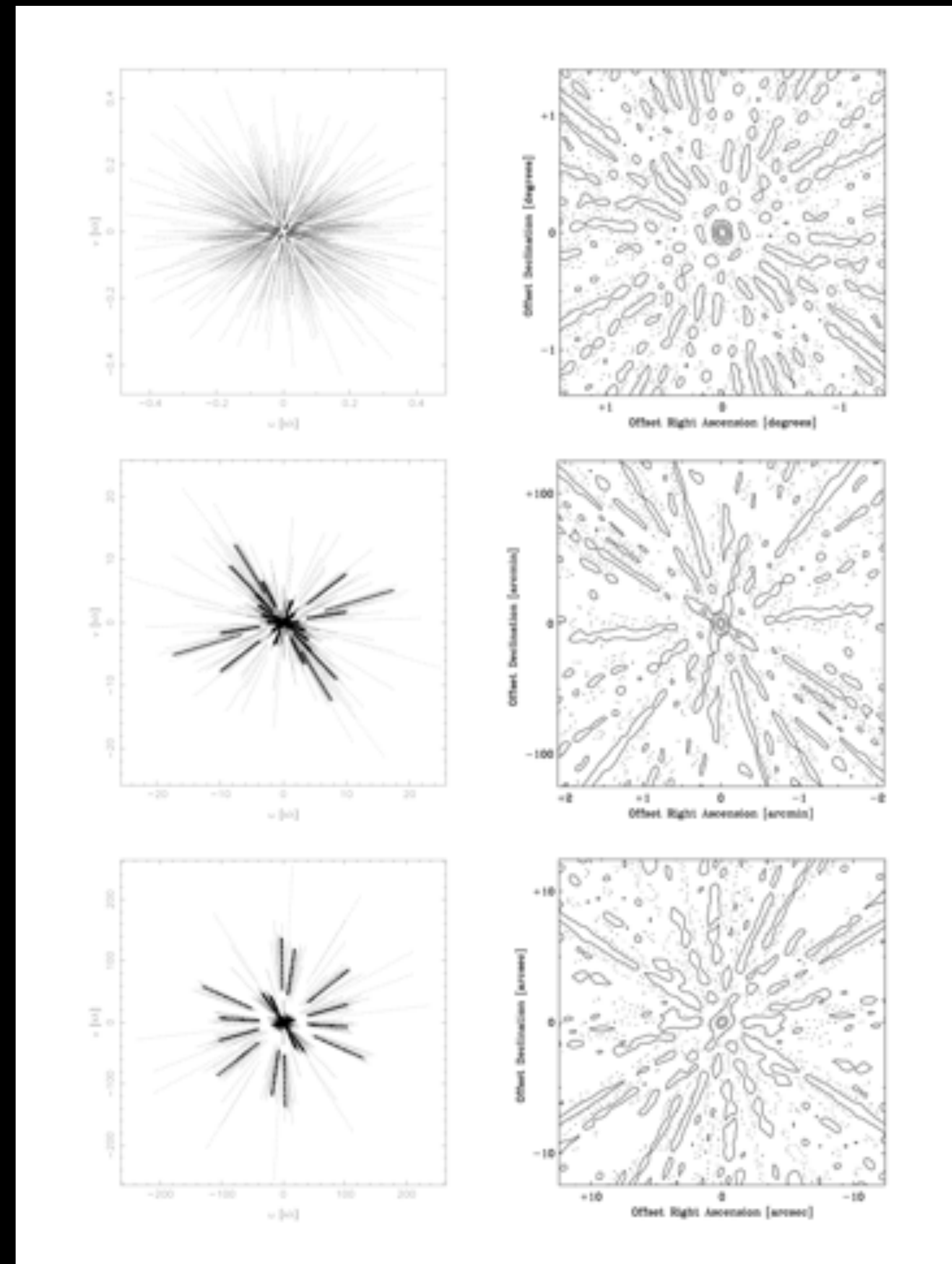
The Core Array

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



UV coverage



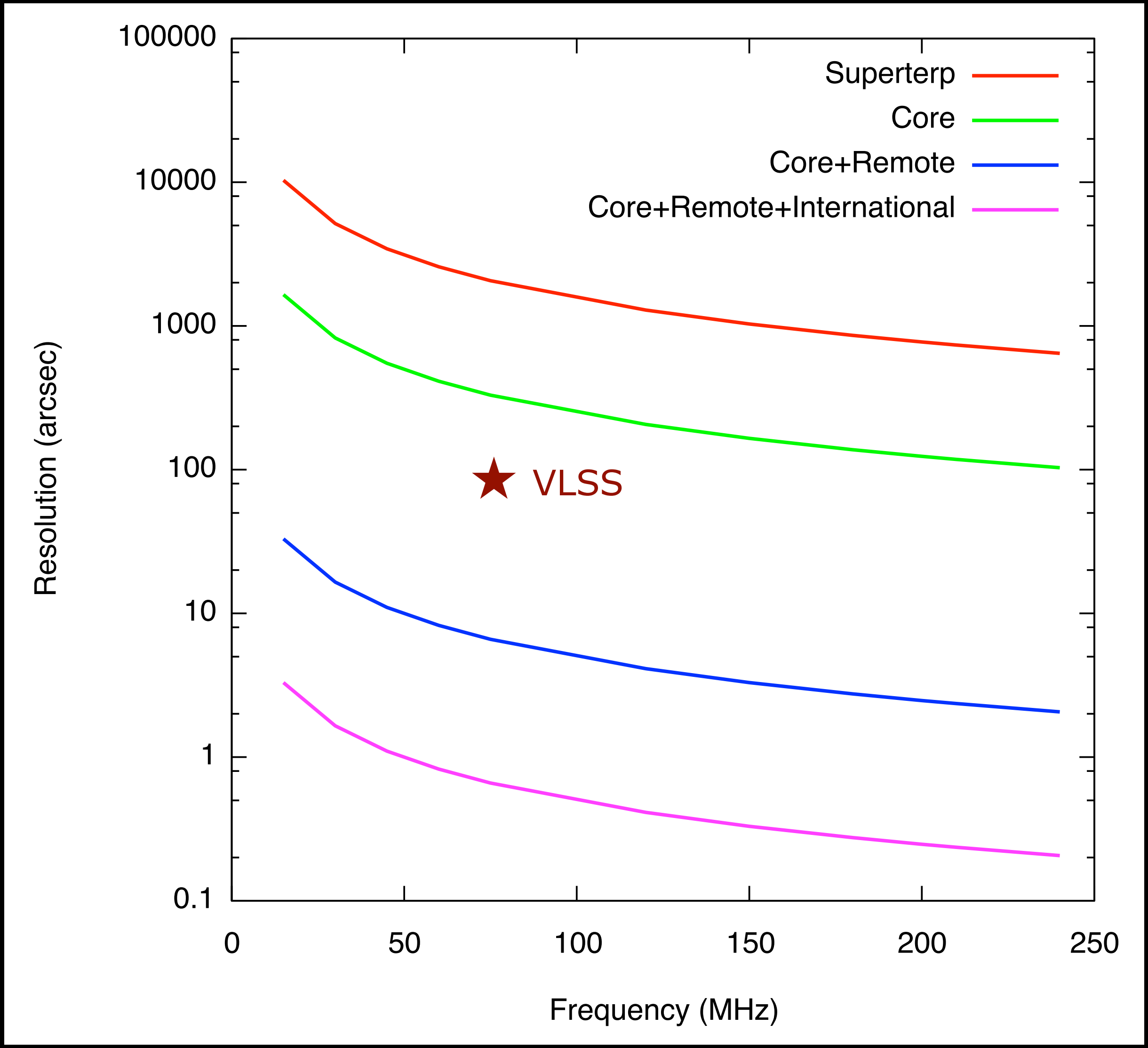


Angular Resolution

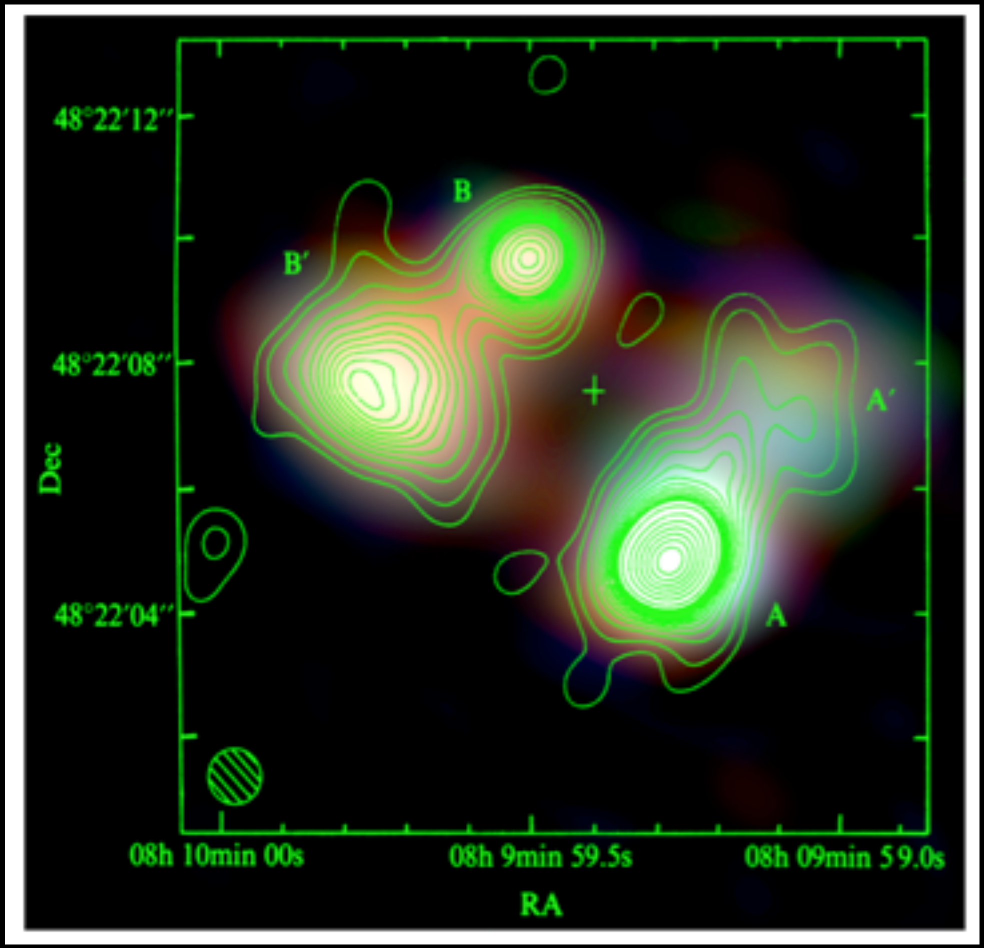
- LOFAR will have an unprecedented angular resolution at low frequencies.

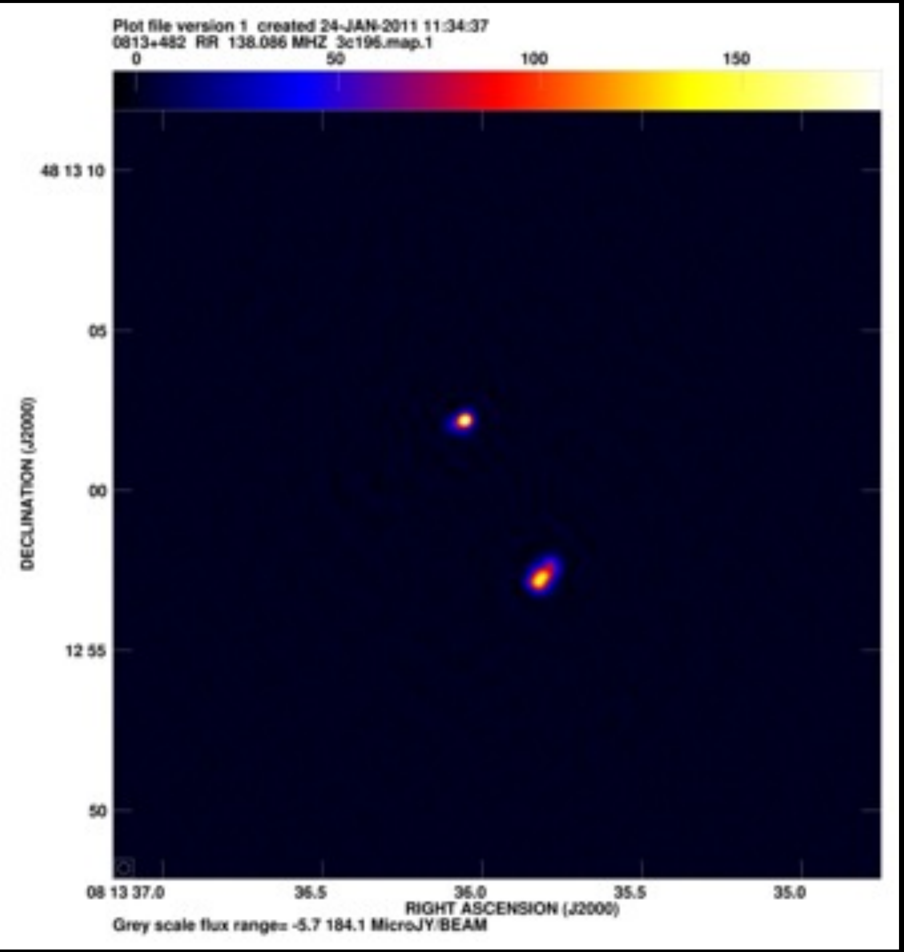
$$\mathrm{FWHM}\ [\mathrm{rad}] = \alpha\ \frac{\lambda}{D}$$

- 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,

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

- The system temperature is,

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

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

$$T_{\rm sky} = T_{s_0}\ \lambda^{2.55}$$

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

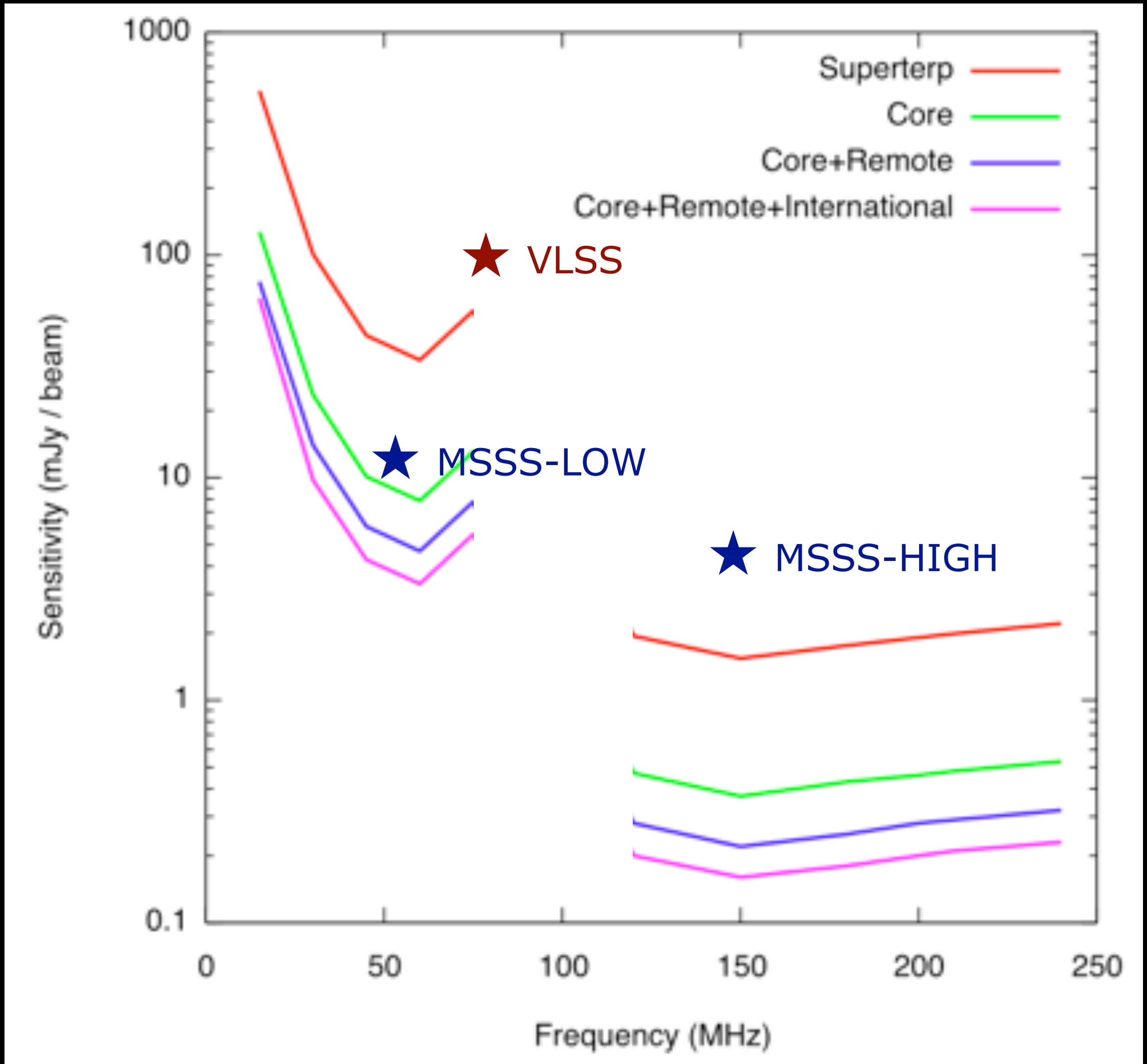
$$A_{\rm eff,dipole} = \min\left\{\frac{\lambda^2}{3}, \frac{\pi d^2}{4}\right\}, \qquad A_{\rm eff,dipole} = \min\left\{\frac{\lambda^2}{3}, \frac{25}{16}\right\}.$$

Array sensitivity

- Using the radiometer equation the sensitivity of the array (48/96 antennas per station) for dual polarization, 1 hour on source and a 4 MHz bandwidth is,

- Much more sensitive than VLSS survey at 74 MHz.

- LOFAR calibrator survey (Million Source Shallow Survey) will:
  - go much deeper than anything before.
  - Better angular resolution
  - Frequency coverage (30-78 MHz, 120-168 MHz).
  - Just the start.



Special issue 1: 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 = Polarizations = 4 (XX, YY, XL, LX).

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

C = Channels = 256

S = Subands = 244

Be = 1

bytes/Sa + overhead = 8 + 0.2

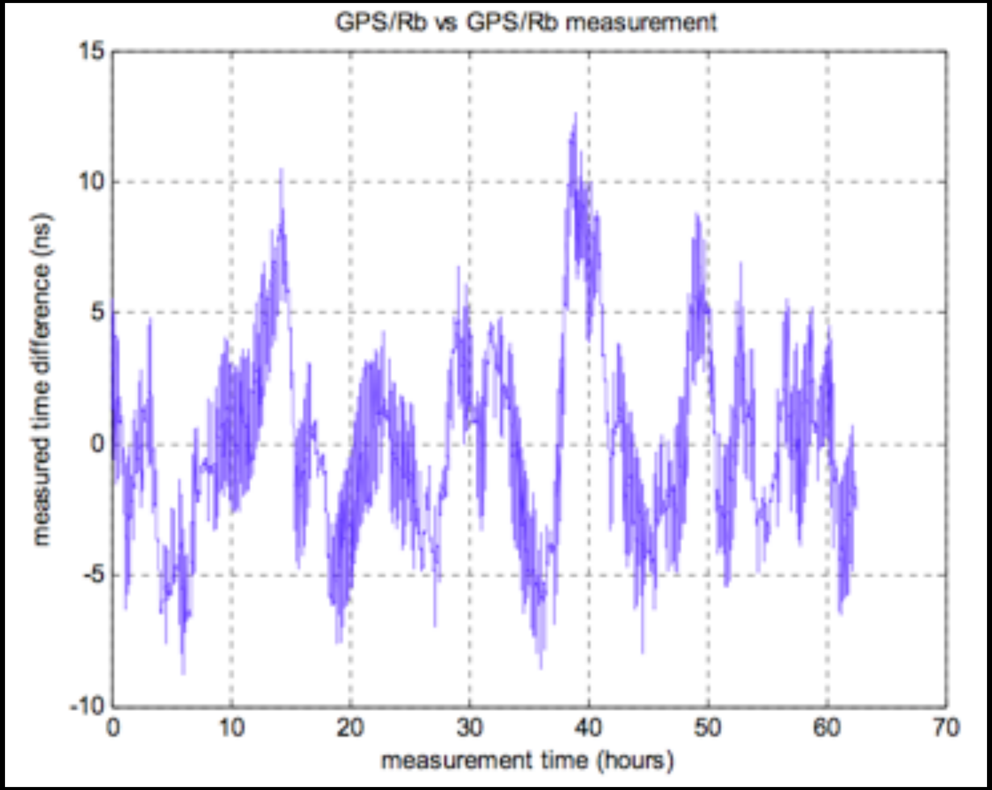
Data Vol = 113 Tb **Need data pipeline!**

Special issue 2: Station clocks / errors

- **A VLBI system:** Each LOFAR station has an independent clock system, except for the 6 Superterp stations, which use a single clock.
- A rubidium maser (short-term timing) that is controlled by a GPS clock (long term stability).

- Offset between two GPS/Rb clocks over a 2.5 day period.
- RMS is 3.5 ns, and the max offset is 10 ns.
- ~100 to 300 MHz

- Making a tied-array over the full a LOFAR array is difficult due to the loss of coherence.
- Fringe finding needed.



Special issue 2: Station clocks / errors

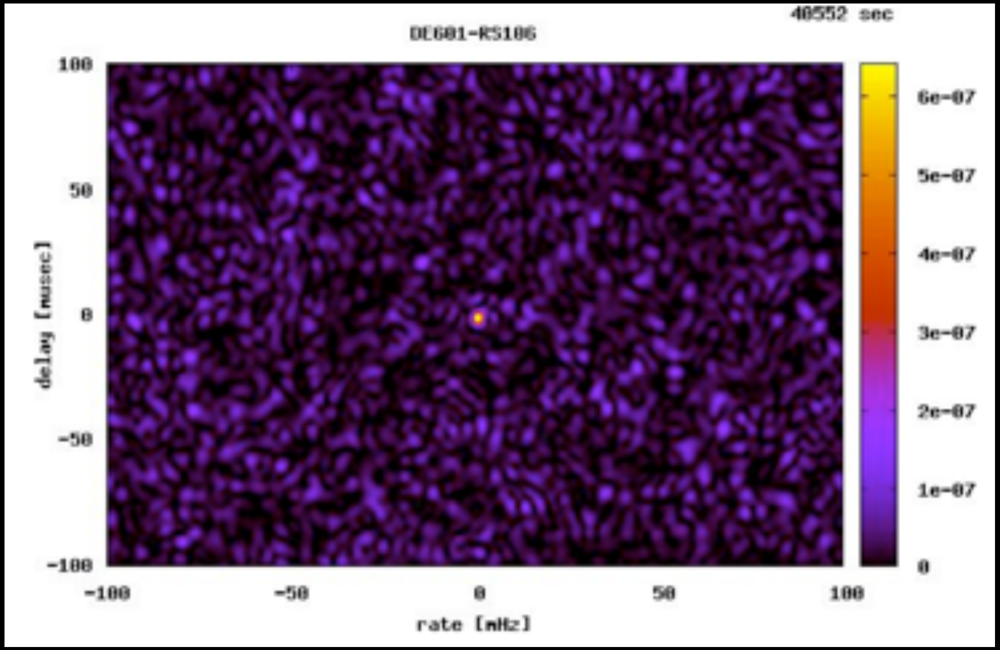
- Clock offsets and addition geometric delays caused by the ionosphere can lead to de-coherence.

- Major problem for long baselines where the fringe rate is highest (see VLBI lectures).

- No public analysis package for VLBI with LOFAR.

- Postdocs positions available at Portsmouth and Bonn for those who are interested.

- But, it can be done (see images of 3C196 from before).



Olaf Wucknitz

Special issue 3: Calibration

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

Baseline based, non closing errors

Gain amplitude and phase

Errors due to elevation

Opacity and path length variation

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

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

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

Bandpass response

Instrumental polarization

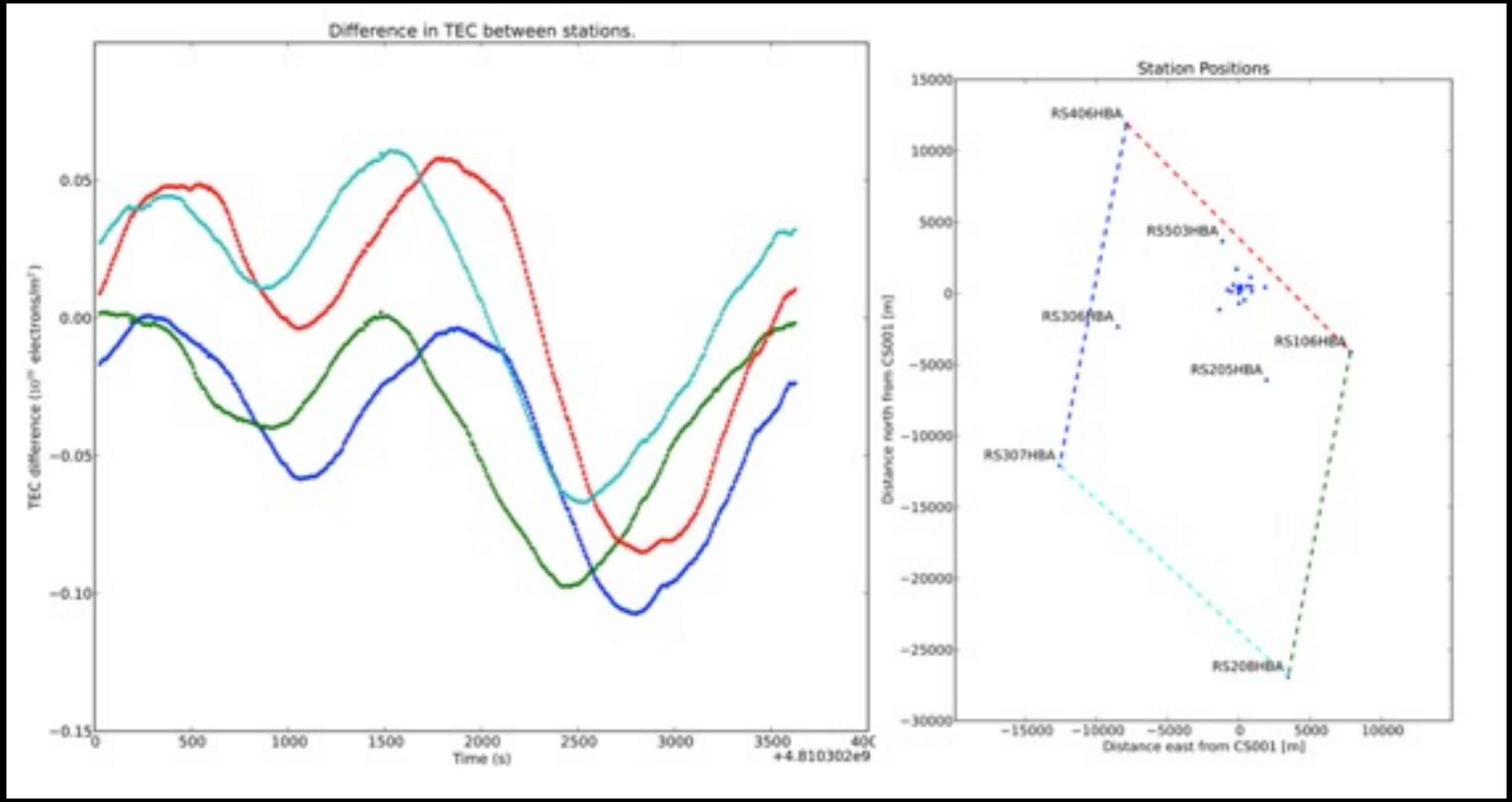
Change in paralactic angle

- Jones matrices only valid for solving in one direction - CASA does not give direction dependent calibration!
- *So what? LOFAR is still just an interferometer!*

Special issue 3a: Ionosphere

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

Mark Aartsen

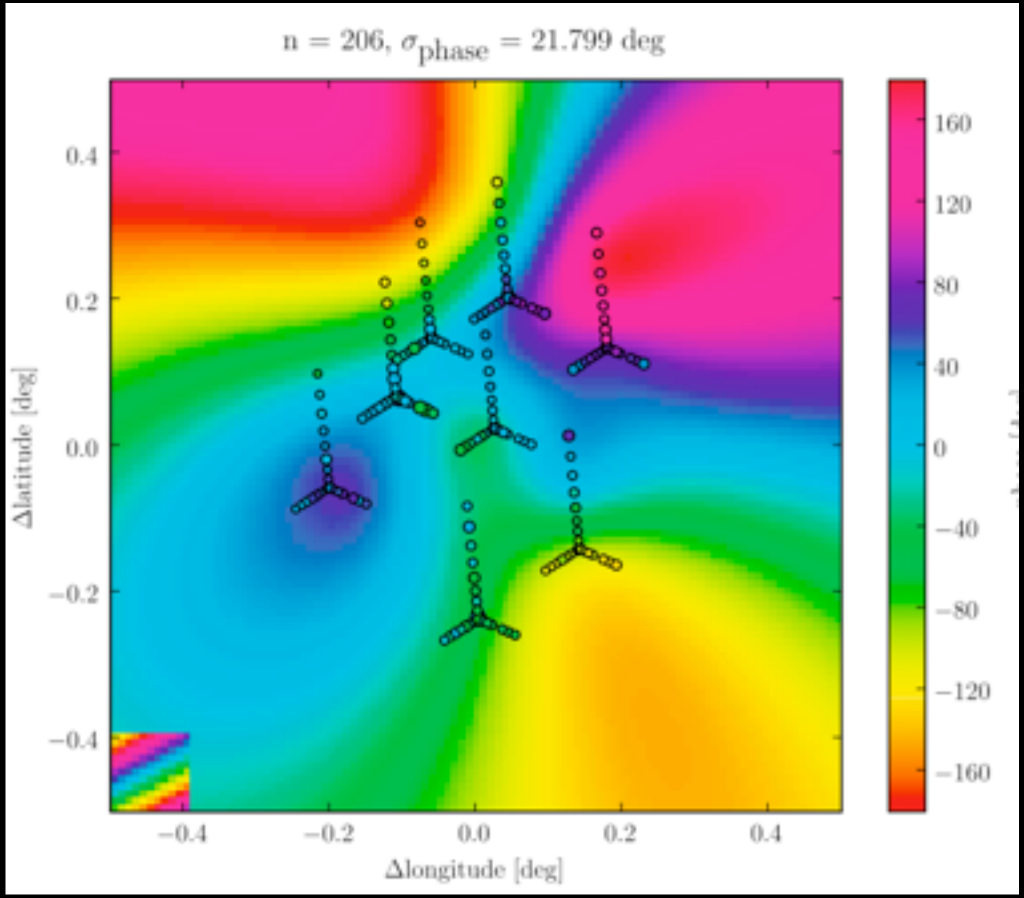


- The recent detection of the motion of an ionospheric wave over the LOFAR remote stations.
- *So what, the same is the case for other interferometers.*

Special issue 3a: 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)

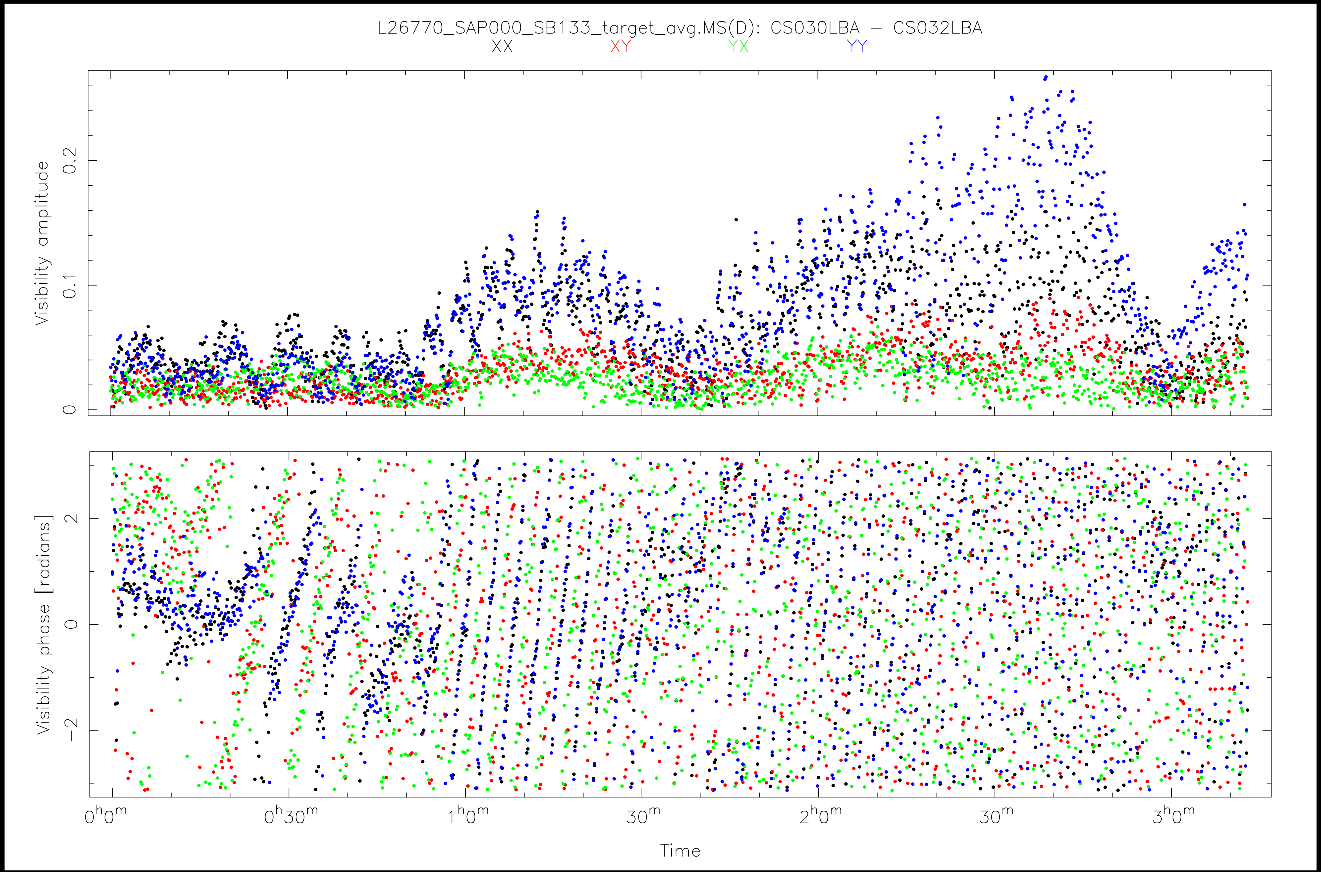


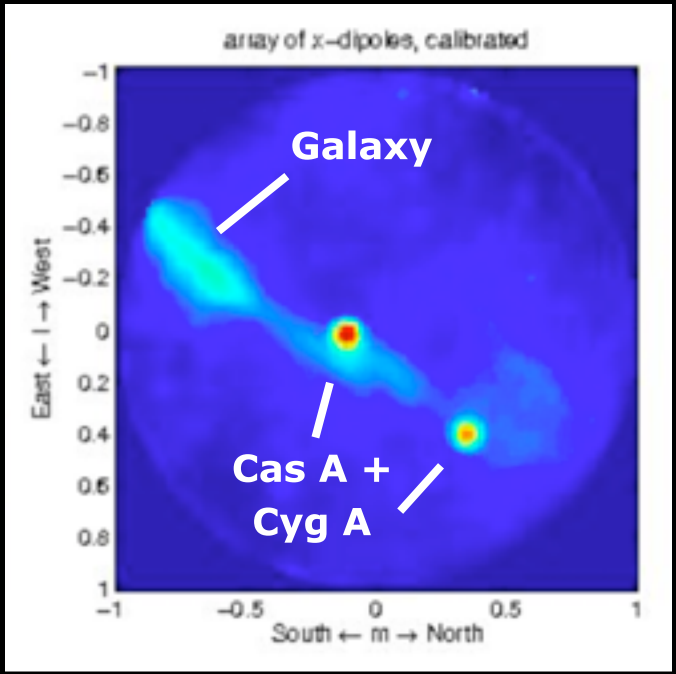
- Observations of 8 sources with the VLA at 74 MHz (10 degree FoV).
- The solutions for each antenna toward each source are used to create a phase screen.
- **Wide-field low frequency observations need Direction Dependent gain solutions (phase and amplitude).**

Huub Intema et al. (2009)

Special issue 3b: The wide-fields

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





- Bright sources are strong enough to cause ripples in the visibility function.
- DDE's are slowww.

Special issue 3b: De-mixing the A-team

- **De-mixing:** Removal of strong off-axis from the visibility data (van der Tol et al., 2007, IEEE TSP, 55, 4497).
- An alternative to direction-dependent gain solutions (faster!).
- Measured visibility (where $\mathbf{a}_n$ contains phase shift etc):

$$\hat{\mathbf{v}} = \mathbf{a}_1 v_1 + \mathbf{a}_2 v_2 + \mathbf{a}_3 v_3 = \begin{bmatrix} \mathbf{a}_1 & \mathbf{a}_2 & \mathbf{a}_3 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \mathbf{A}\mathbf{v}$$

- Average and solve

for each source,

$$\bar{v}_i = \frac{1}{N_t N_f} \sum_{j=1}^{N_t} \sum_{k=1}^{N_t} a^*_{ijk} \hat{v}_{jk}$$

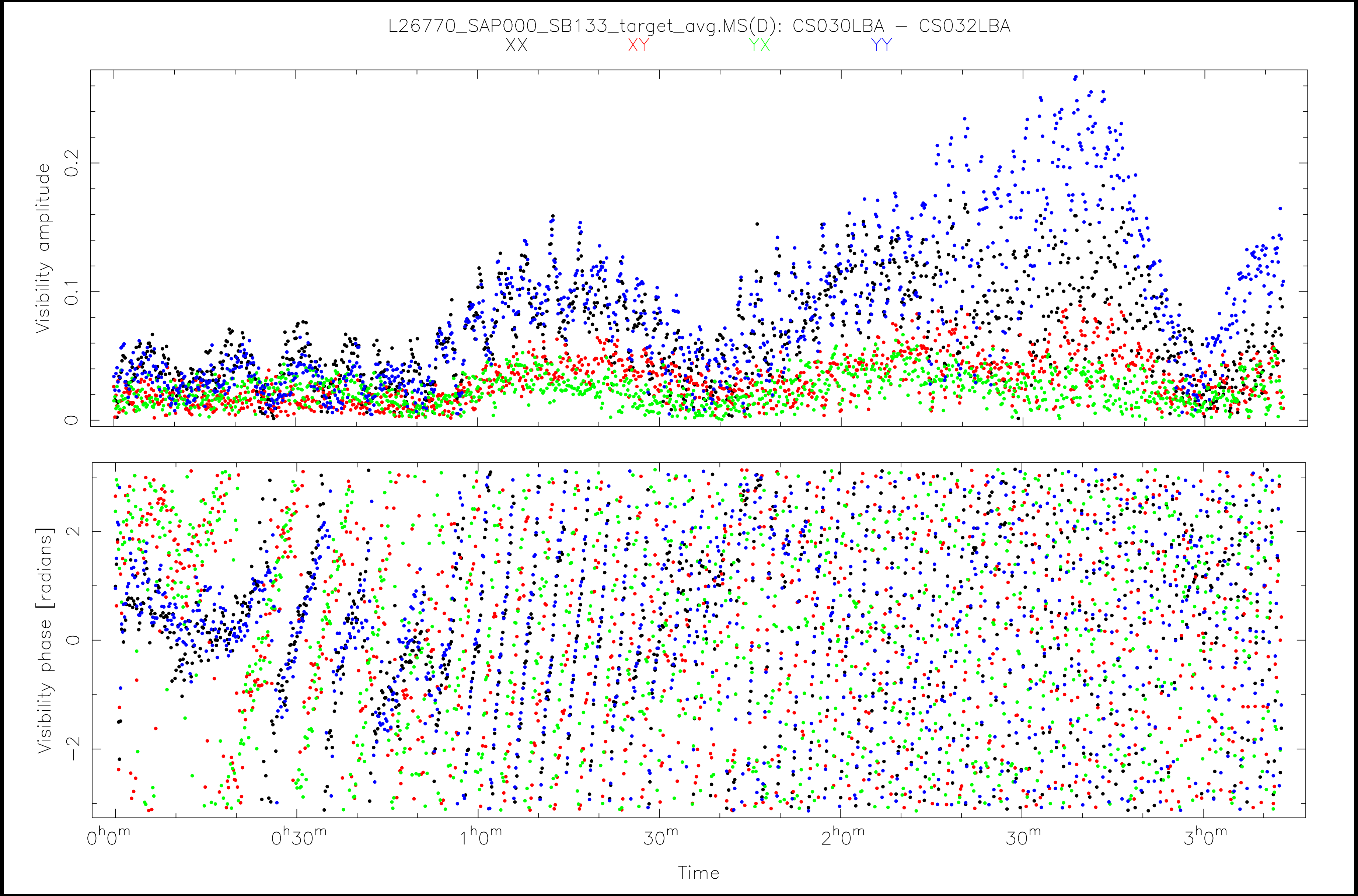
- The de-mixing matrix is,

$$\mathbf{M} = \left(\frac{1}{N_t N_f} \mathbf{A}^{\mathrm{H}} \mathbf{A} \right)^{-1}$$

- The visibility function becomes

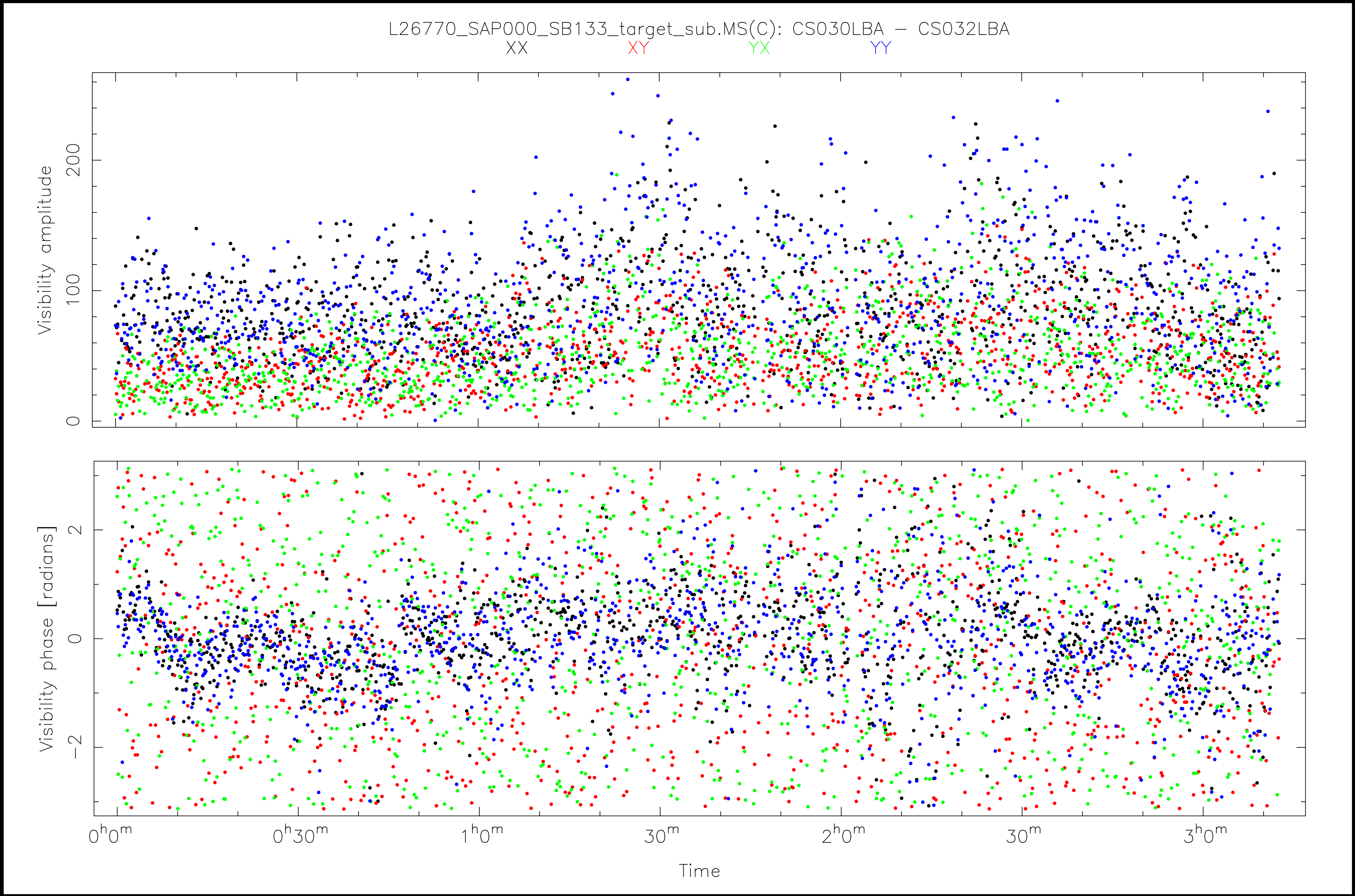
$$v_1 = \bar{v}_1 - M_{1,2} \tilde{v}_2 - M_{1,3} \tilde{v}_3$$

Special issue 3d: Off-axis sources



George Heald

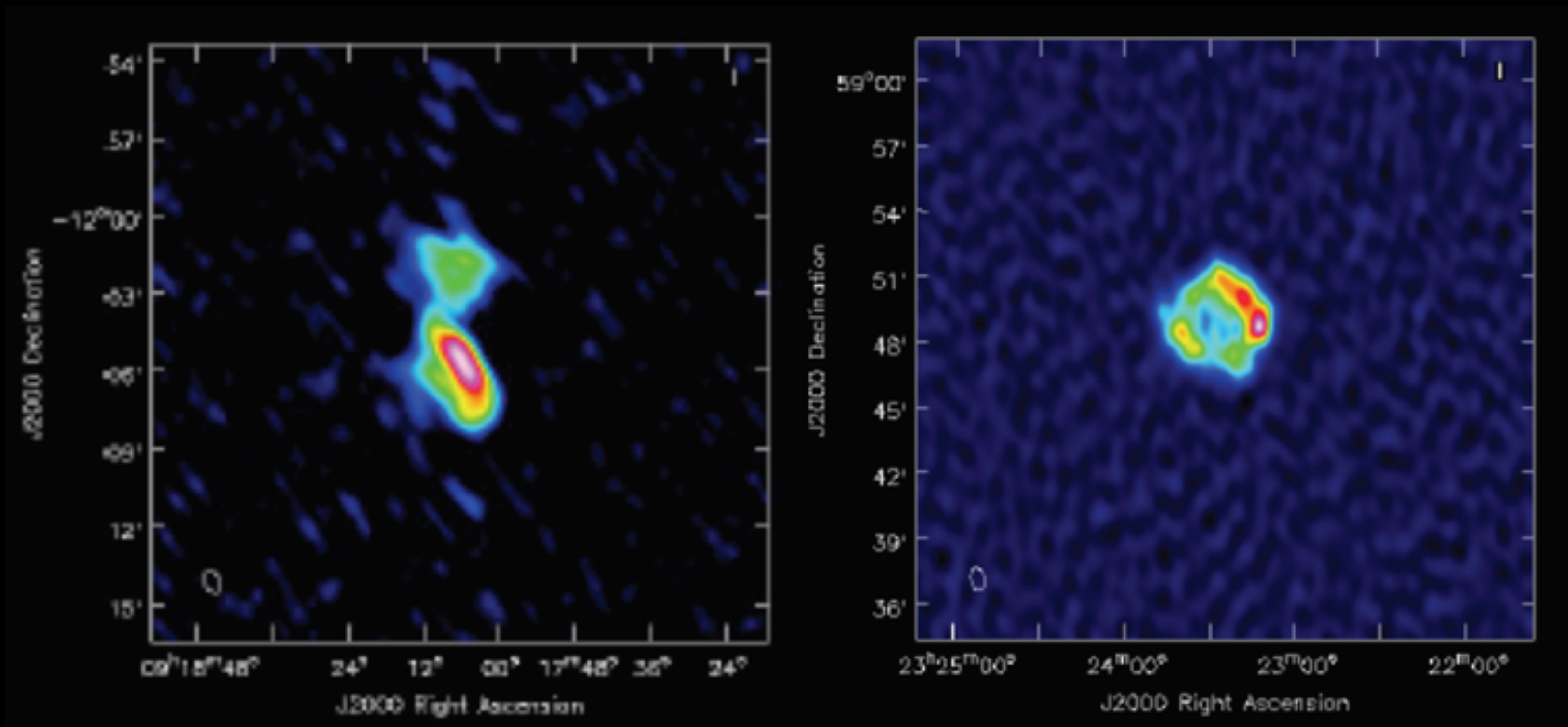
Special issue 3d: Off-axis sources



George Heald

Special issue 3d: Far-field sources

- Hydra A and Cassiopeia A de-mixing ~ 127 degrees separation on the sky

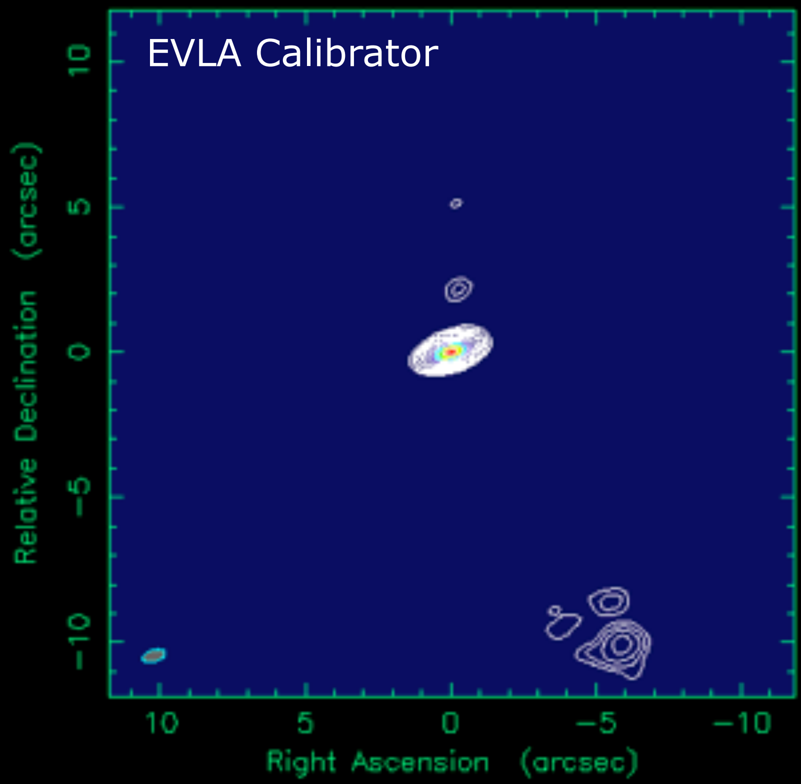


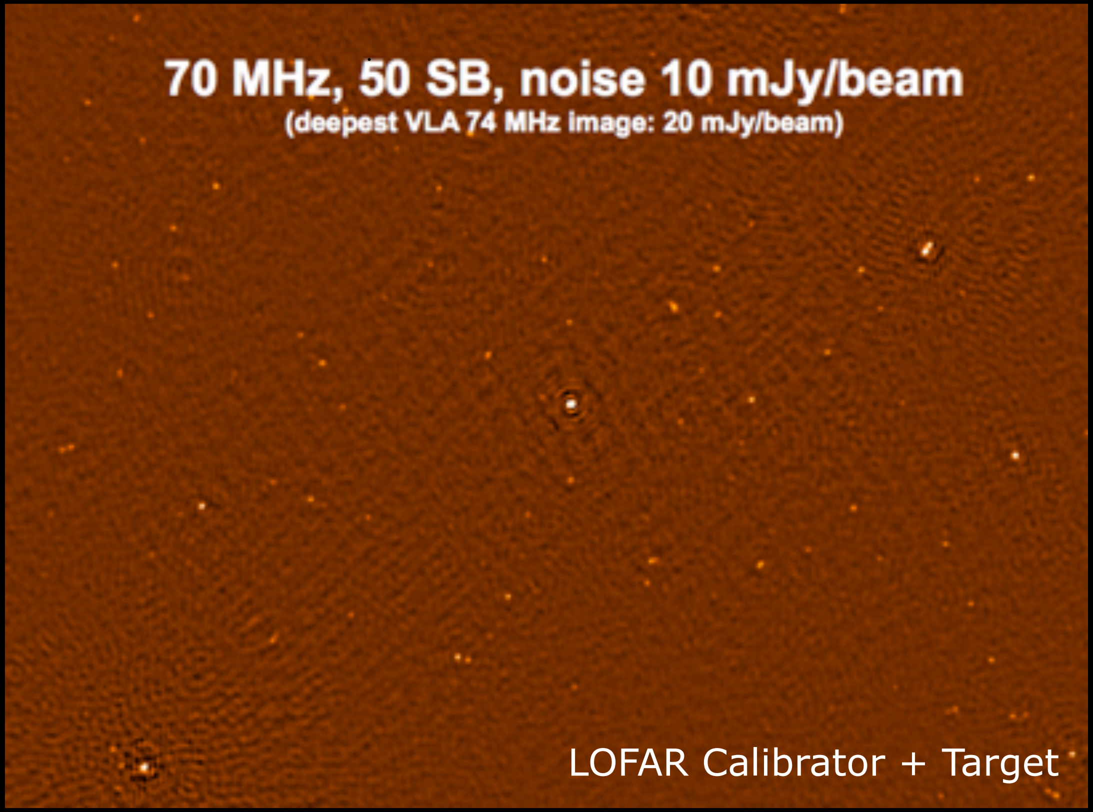
Reinout van Weeren

- De-mixing is faster than carrying out DDE’s (when number of sources is small), but only works when the trouble maker is well outside the primary beam.

Special issue 4: Sky models

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



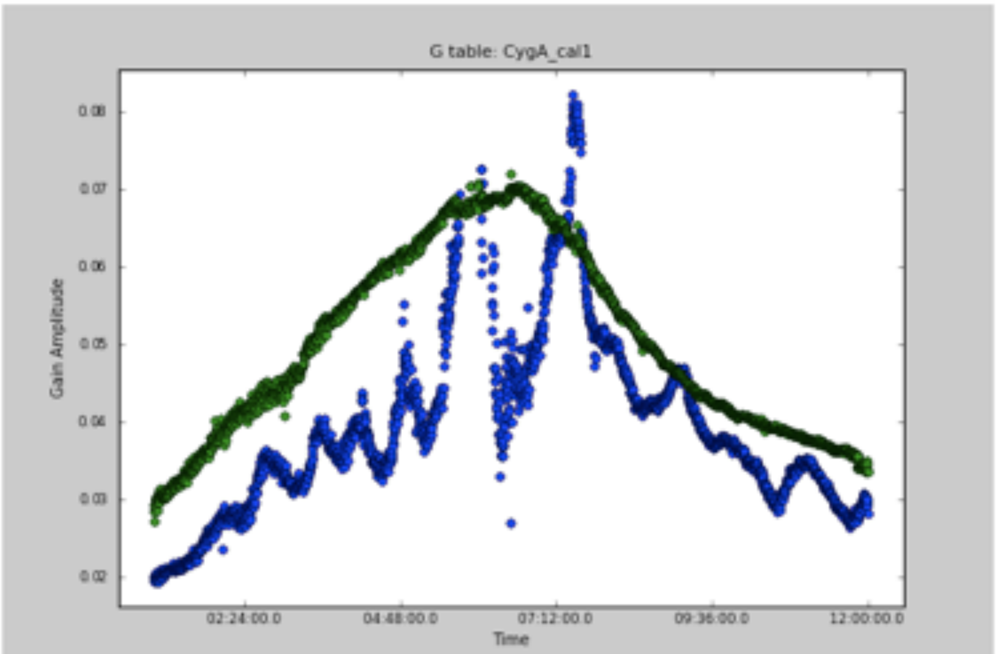


- In beam calibration with the dominant sources in the field is used.

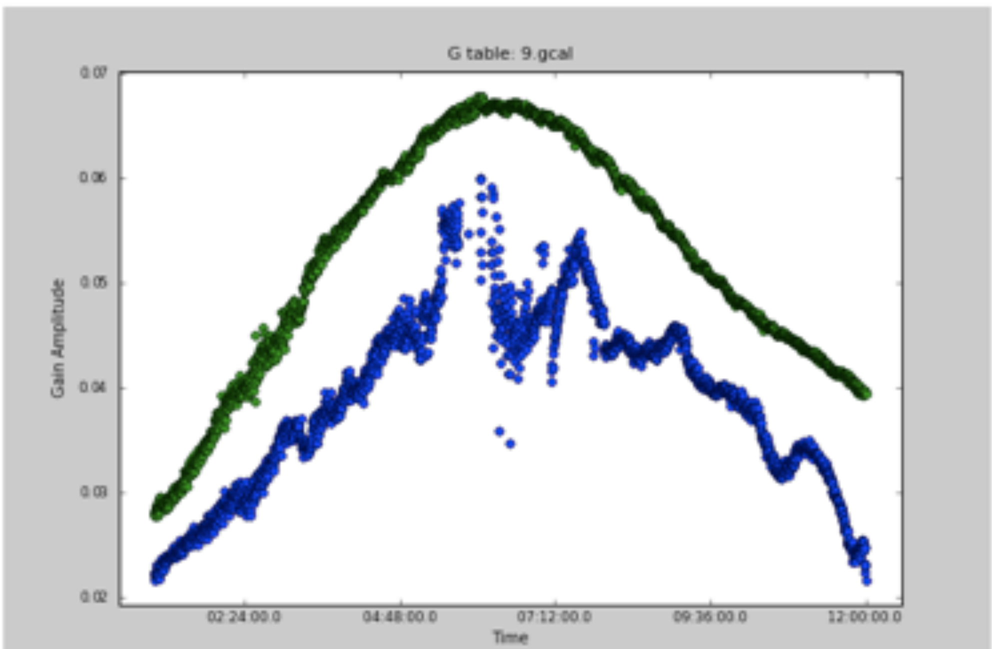
  Good since it gives the amplitude and phase for the target field as a continuous function of time.

Special issue 4: Sky models

- 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

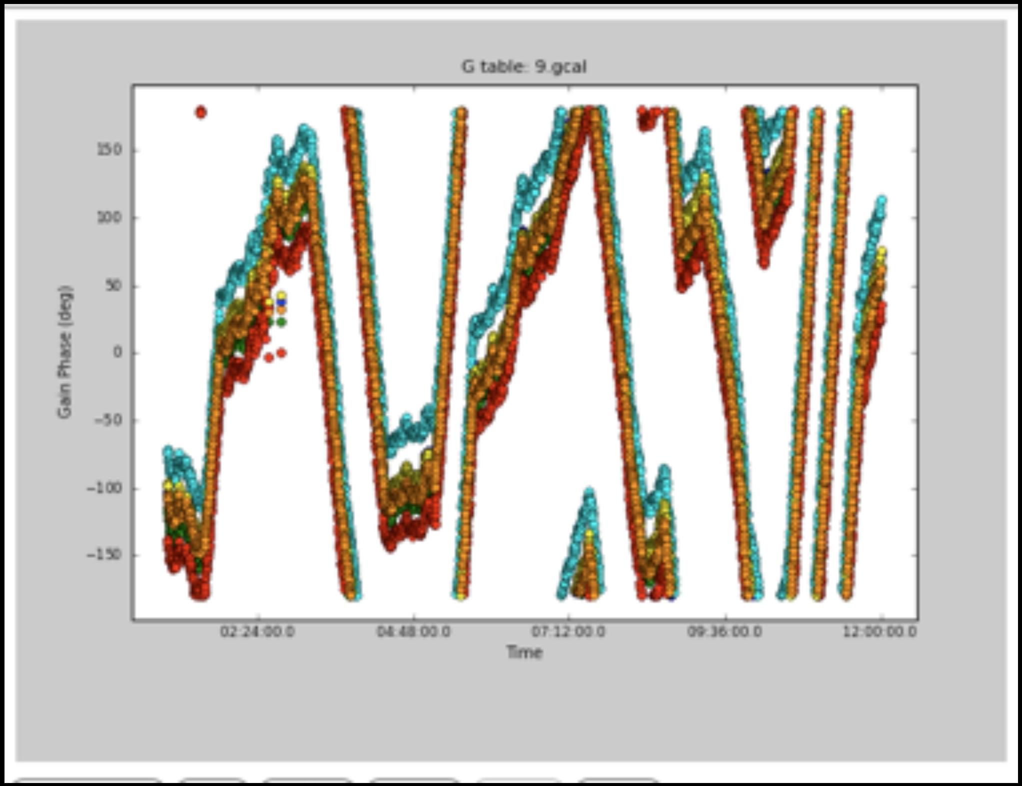


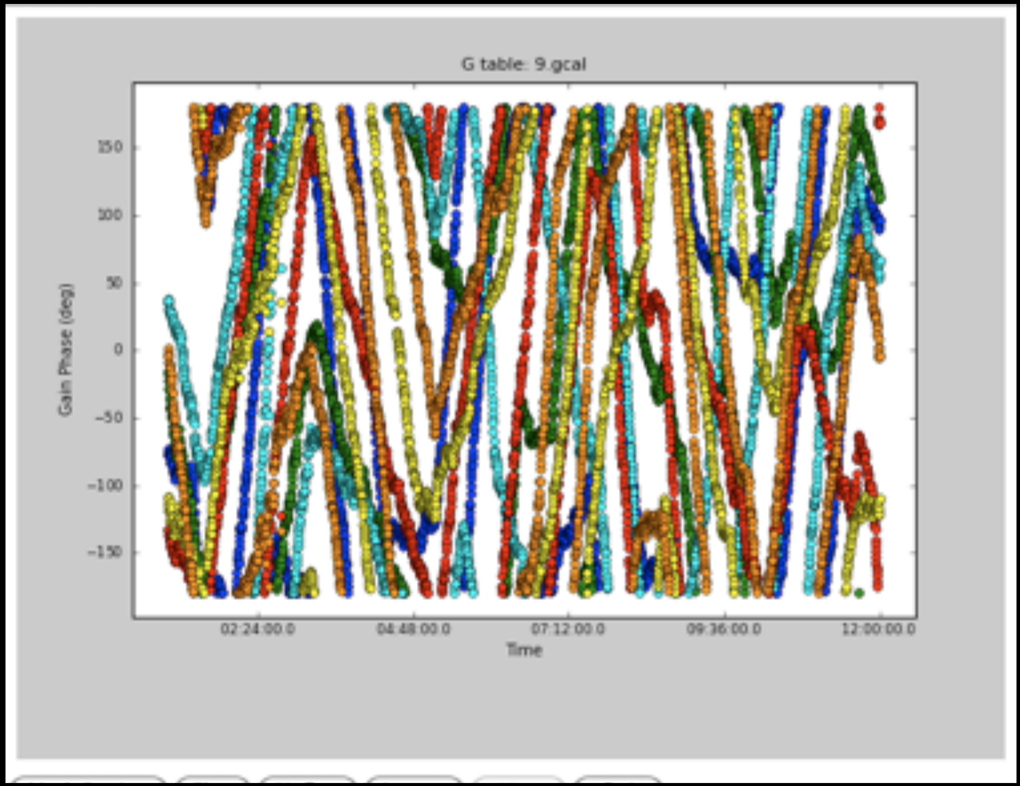
Better after self calibration

- 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).

Special issue 5: Phase Solutions

- The phase response of the 6 superterp stations is very similar - as expected.

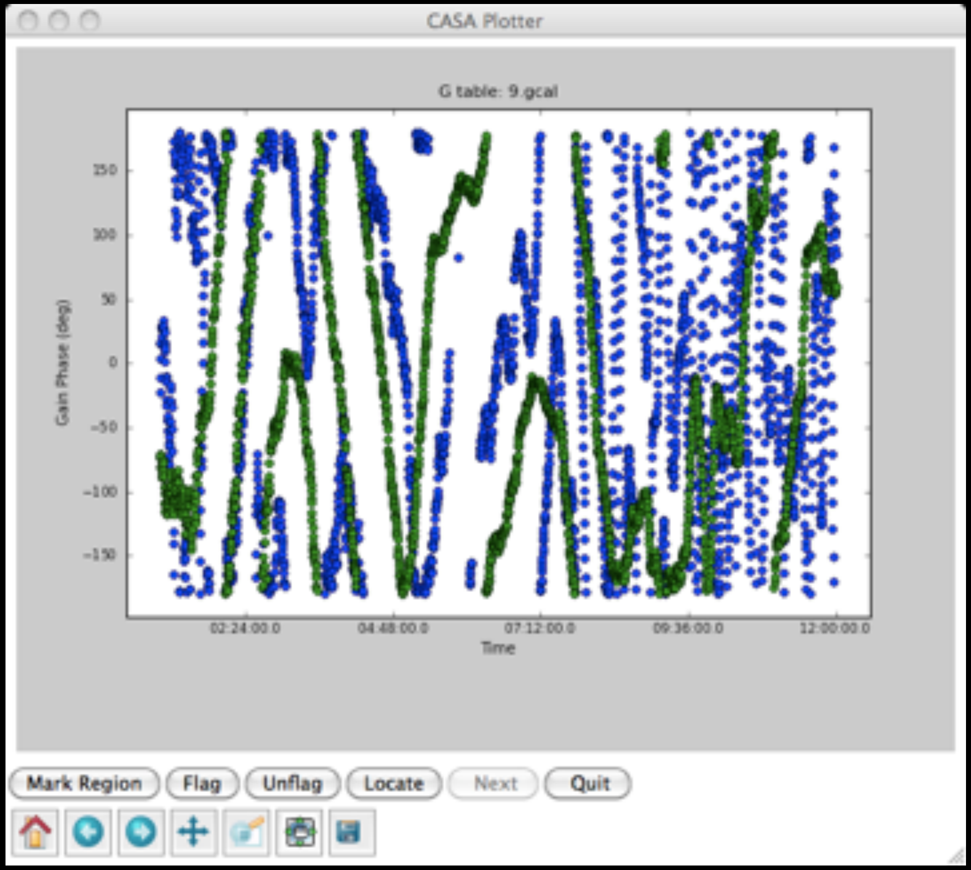


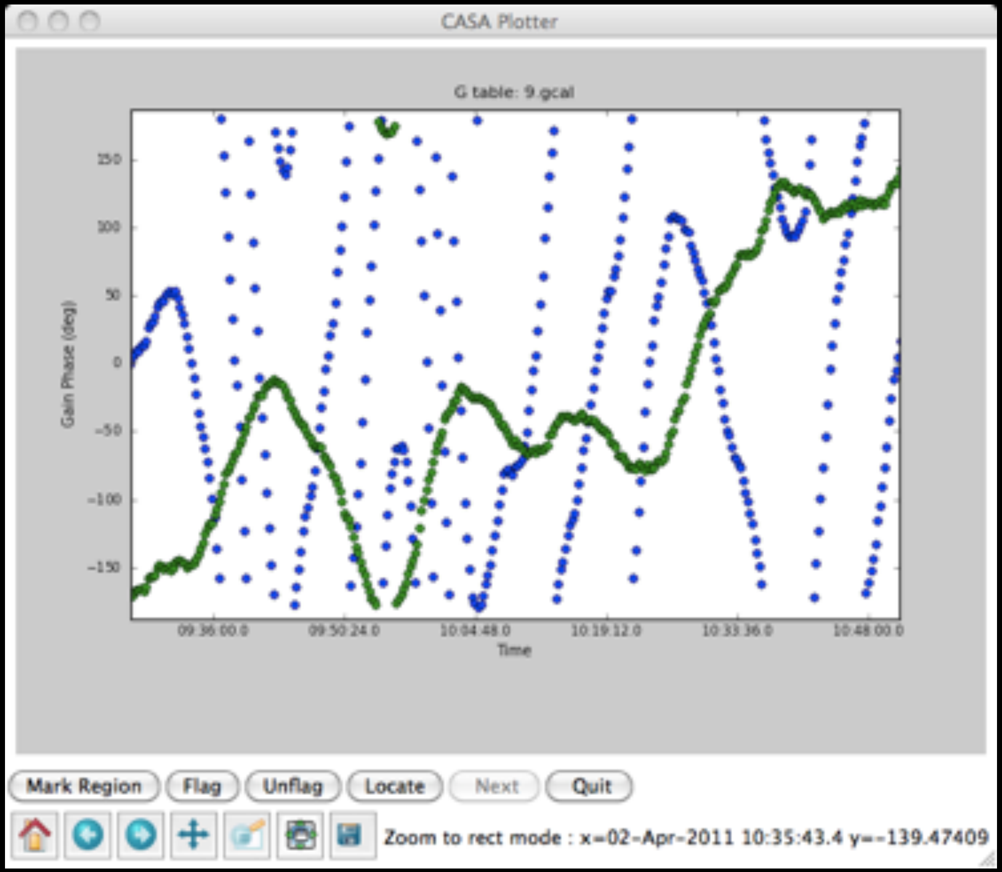


- The phases are almost identical - similar baseline lengths (< 300 m), same clocks.
- Longer baseline lengths <2 km, different clocks.

Special issue 5: Phase Solutions

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





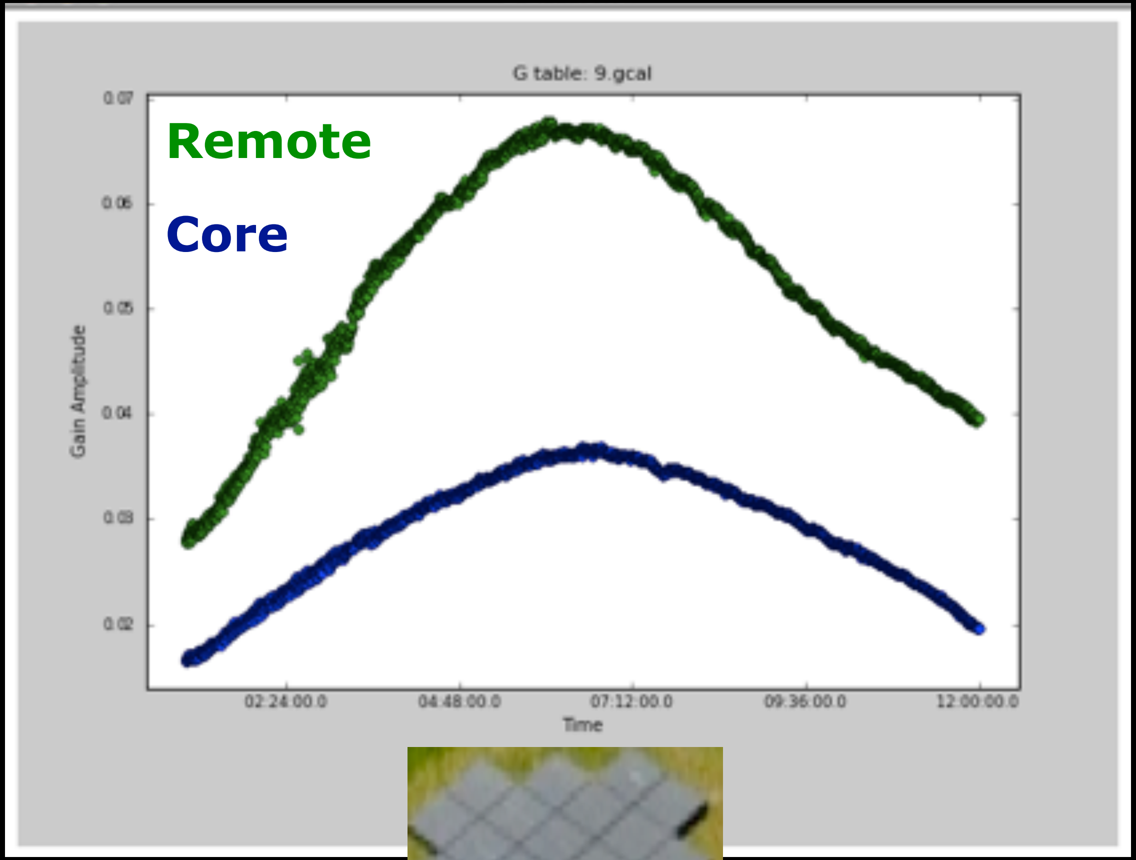
- Phases change faster for longer baselines.
- Still trace the changes for 15s visibility integration time.

Special issue 6: The station beam

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

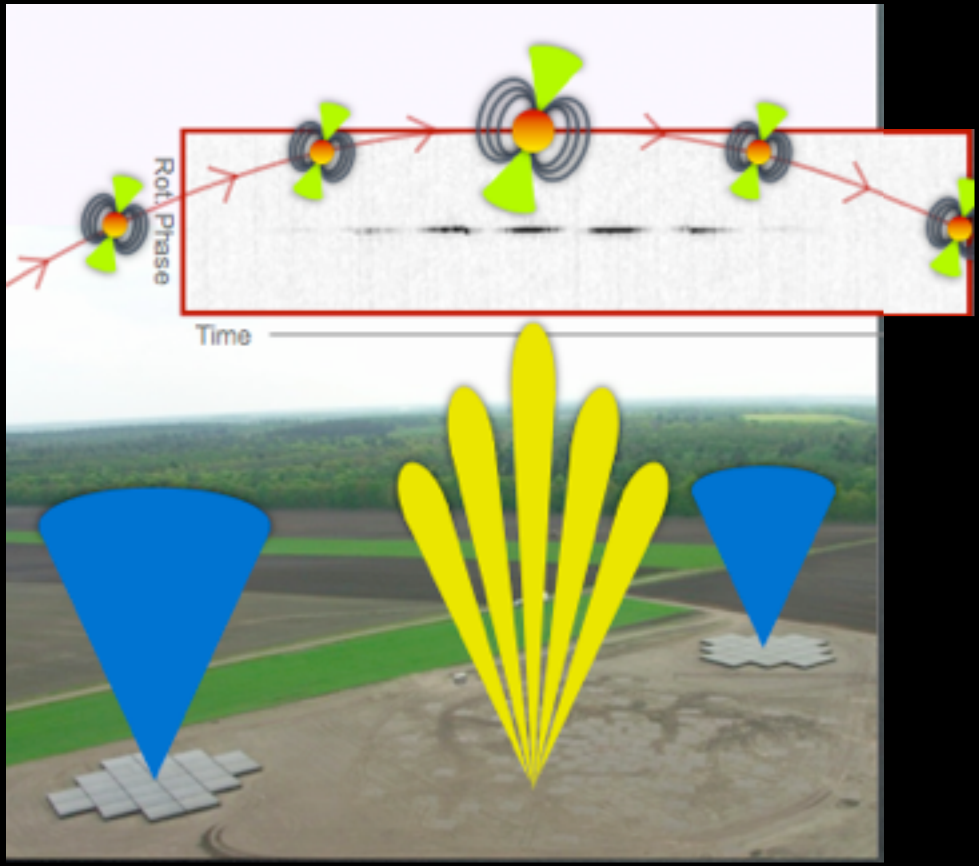
- For LOFAR, the gains change over time because the projected area of the station changes with respect to the source.

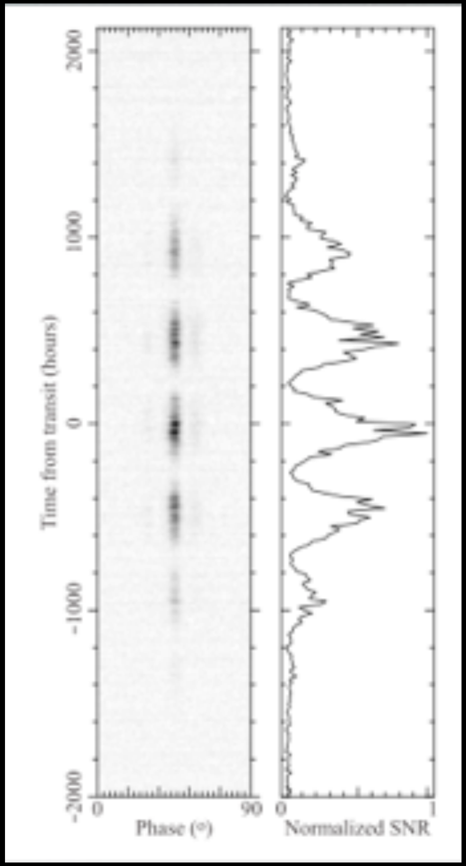
- Core, Remote and International stations have different areas, so the amplitude gain is also different.



Special issue 6: The beam response

- **The beamformer updates once a second:** Almost constantly re-determining the combination of dipoles (by adjusting the weights). This changes the response over time.

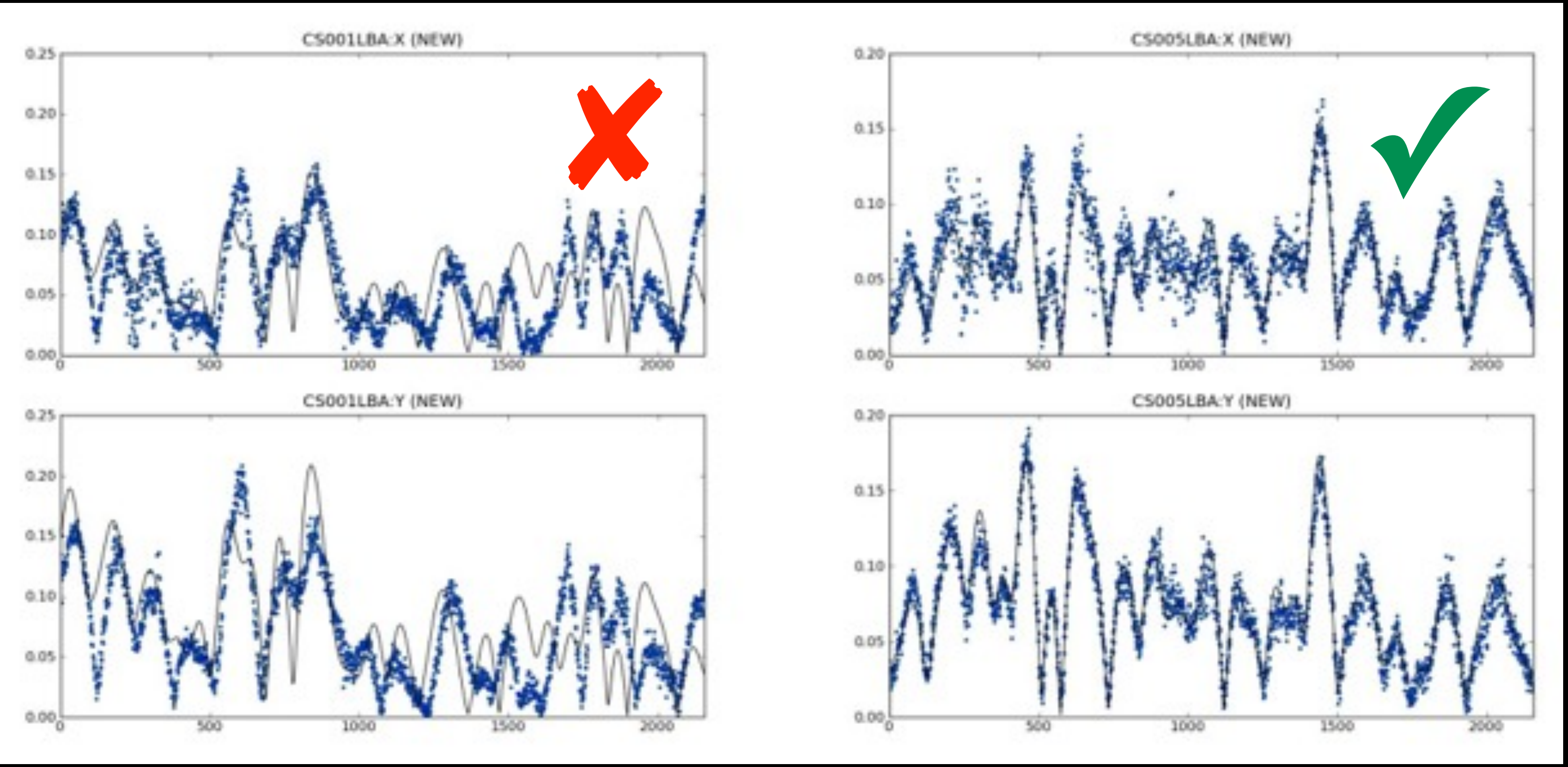




Jason Hessels

Special issue 6: The beam response

- **How well do we know the beam?**
  - Beam is a weighted combination of dipoles (LBA) and tiles (HBA).
  - How well do we know their response? Is is uniform? Does it change with time?
  - What if dipoles fail during the observation?



Special issue 7: Imaging

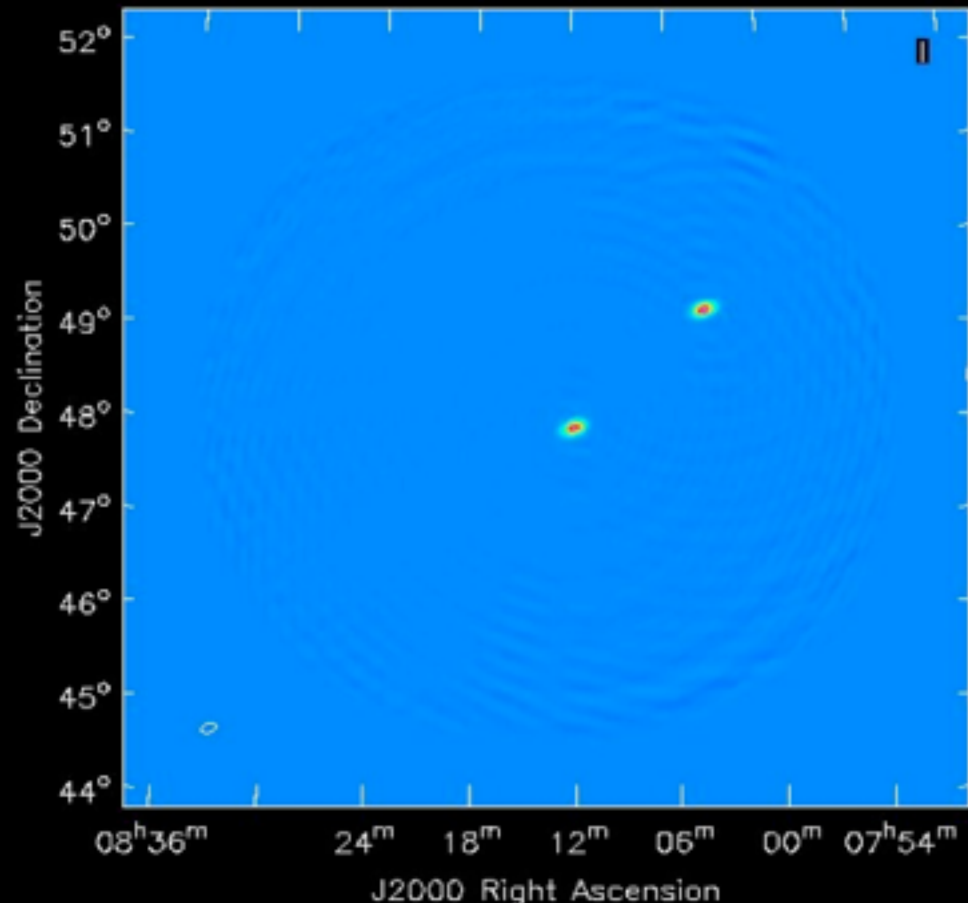
- The aim of imaging is determine an accurate surface brightness distribution (positions and flux-densities) of the sky.

- We need:

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

  ii) An accurate measurement and implementation of the LOFAR Beam in the imager.

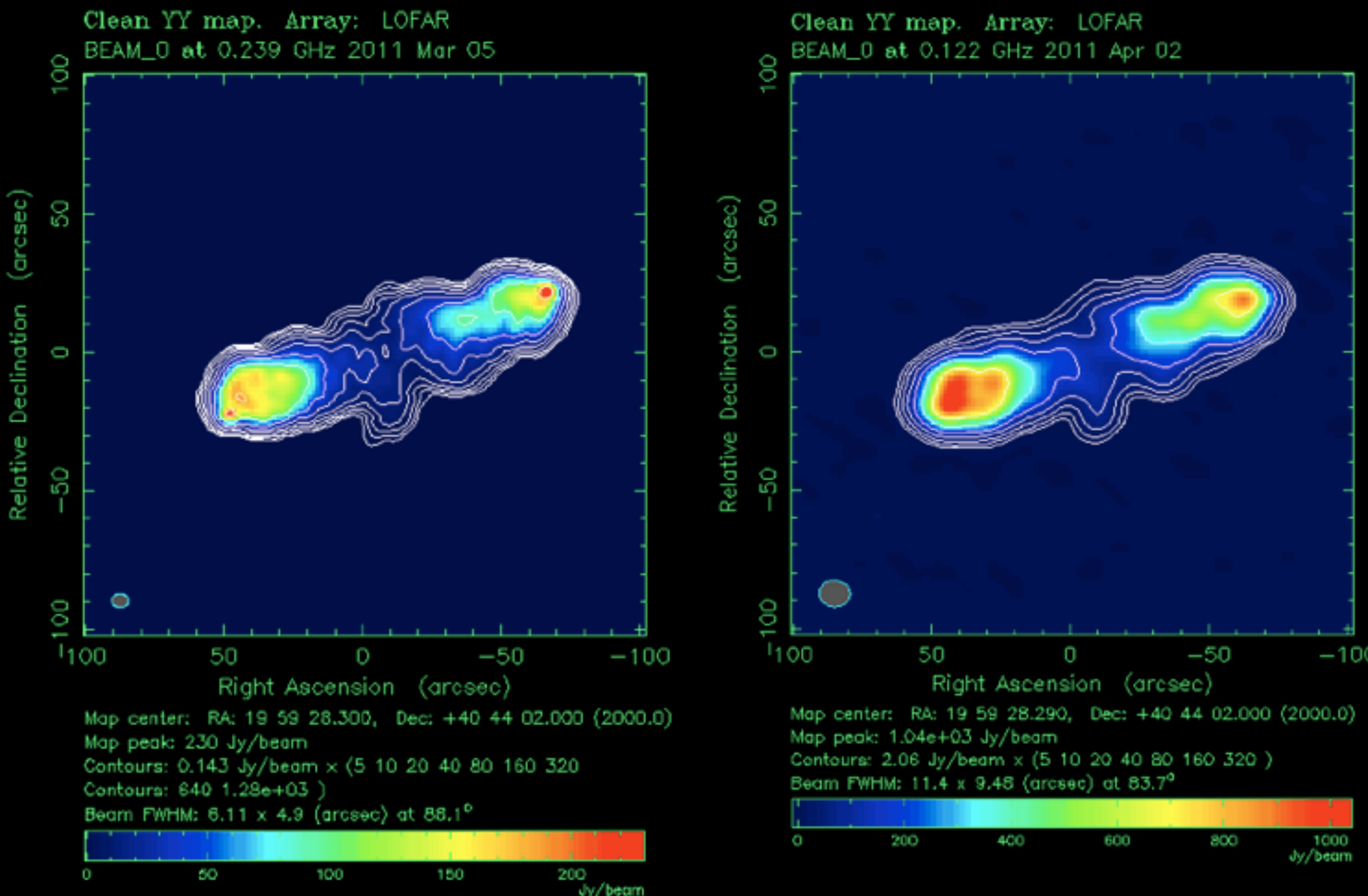
  iii) Speeeeed!



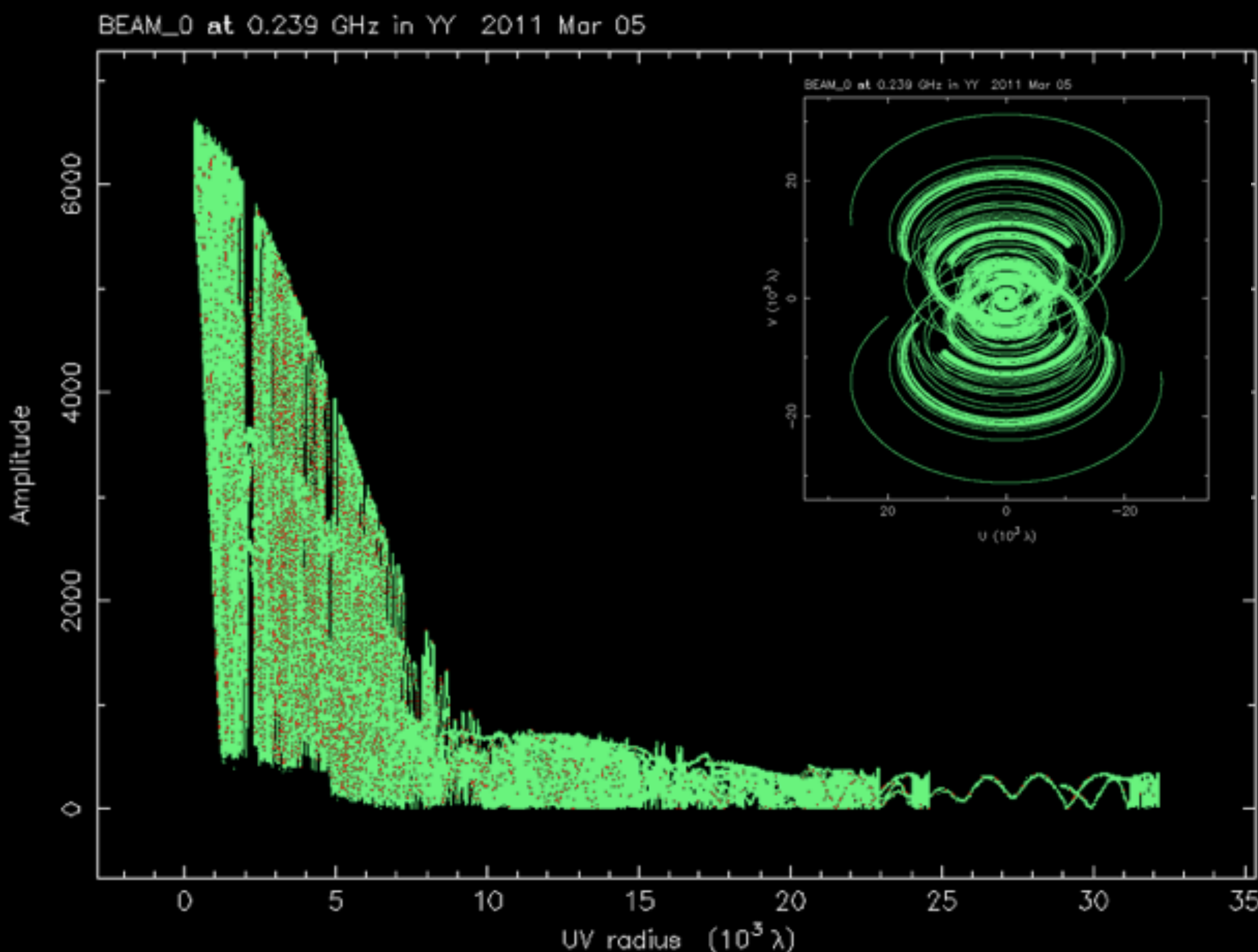
- Limits the dynamic range of images, and allows for self-calibration.

- Simulations show flux-densities recovered at the 1% level.

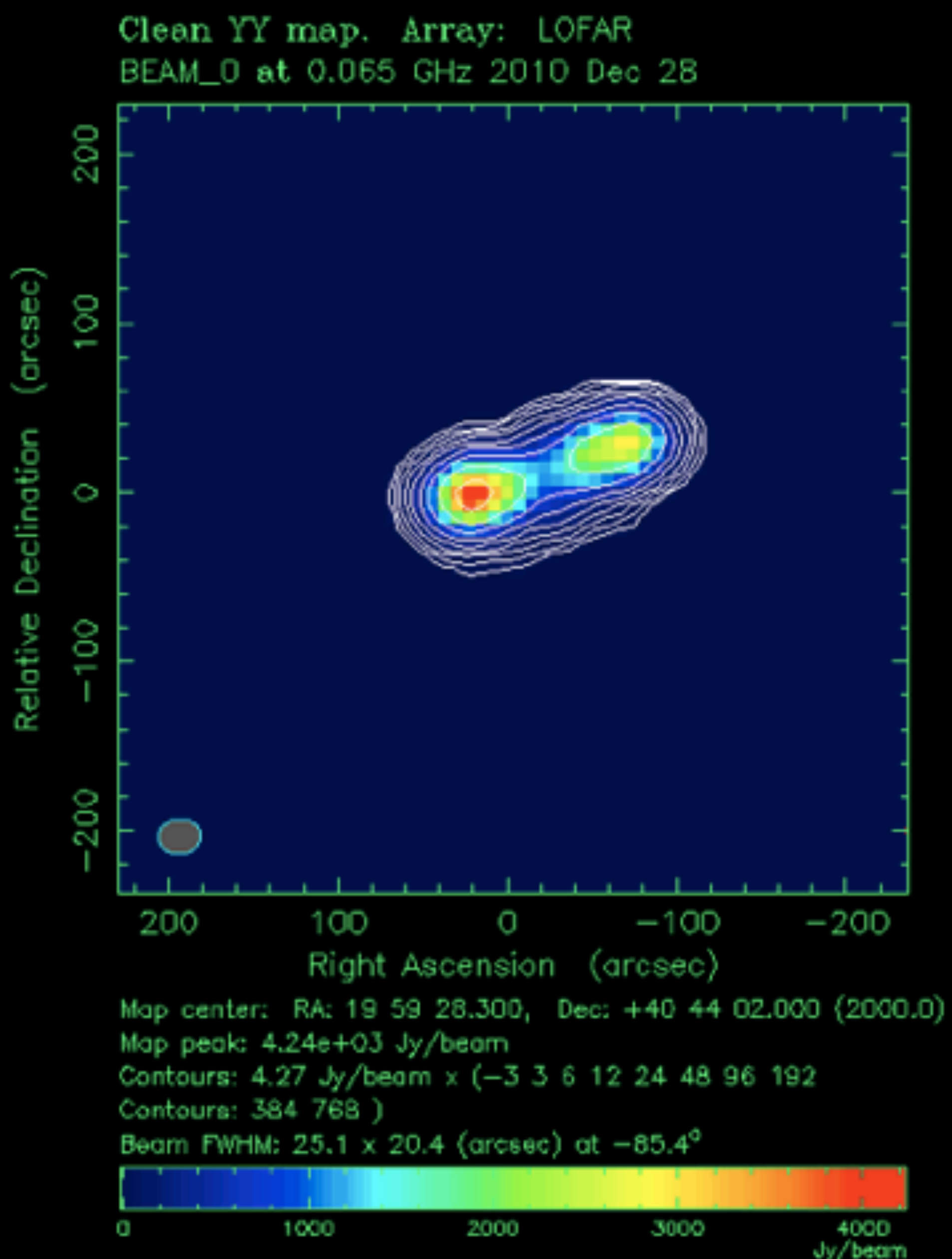
LOFAR imaging of Cygnus A (HBA)

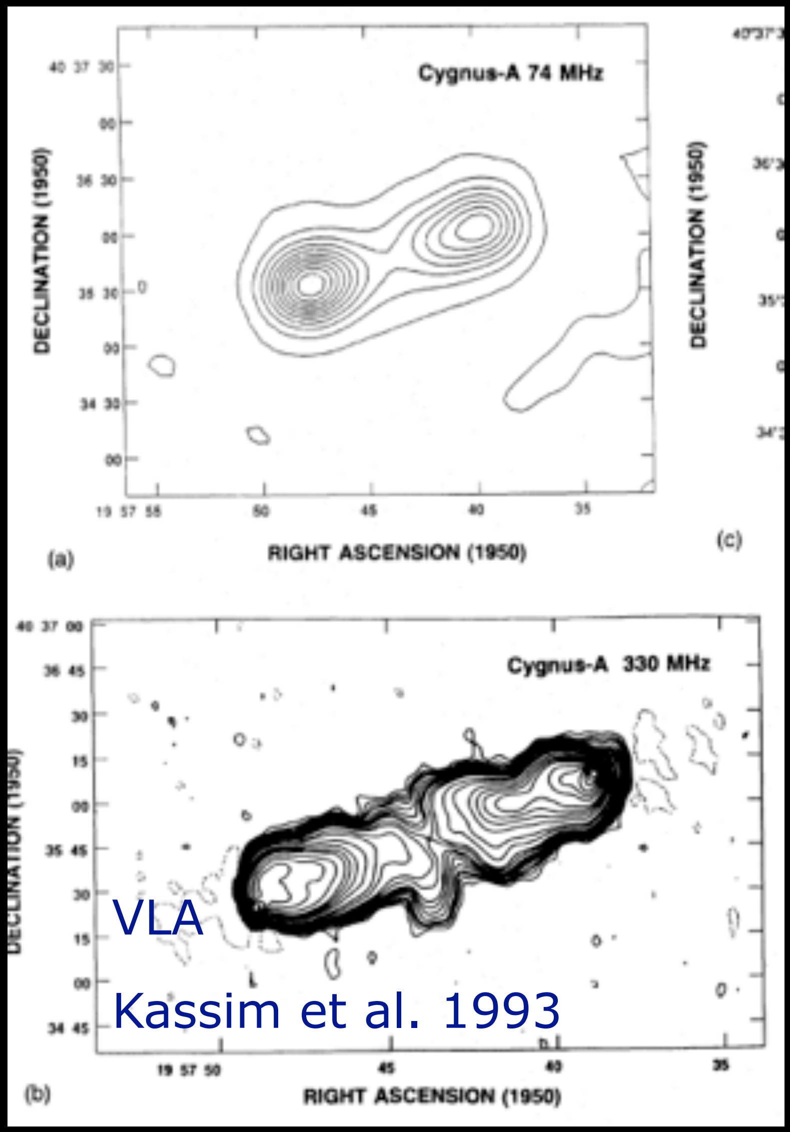


LOFAR imaging of Cygnus A (HBA)



LOFAR imaging of Cygnus A (LBA)





Summary

- LOFAR is almost fully constructed (7 remote stations to go!).
- Imaging data over the 10-240 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, but still a way to go!
- Special care needs to be taken in the analysis of LOFAR data due to
  - Data size.
  - Direction dependent effects.
  - The LOFAR beam shape.
  - Need for wide-field imaging (w-projection).
- Enjoy getting your hands on LOFAR data this afternoon.