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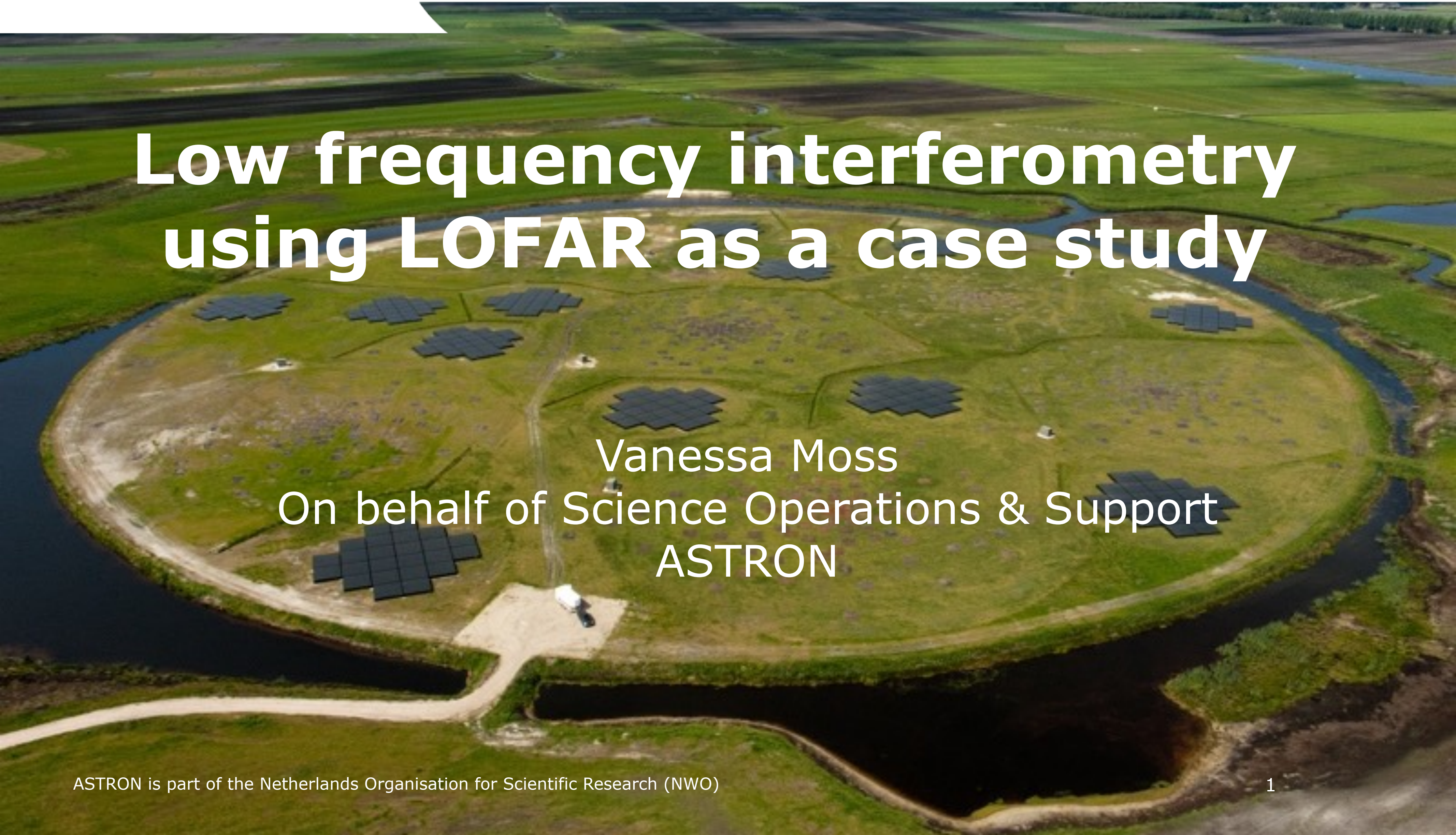
RadioNet

Netherlands Institute for Radio Astronomy



# Low frequency interferometry using LOFAR as a case study


Vanessa Moss
On behalf of Science Operations & Support
ASTRON

# 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

# 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.

- **KEY DIFFERENCES:**

  1. **Beam-forming** instead of tracking
  2. Effects of a wide **field-of-view**
  3. Not being able to ignore the **ionosphere**
  4. An array of thousands of elements **(cheaply)**

# Contents

## 1. The Low Frequency Array

# The Low Frequency Array - Key Facts

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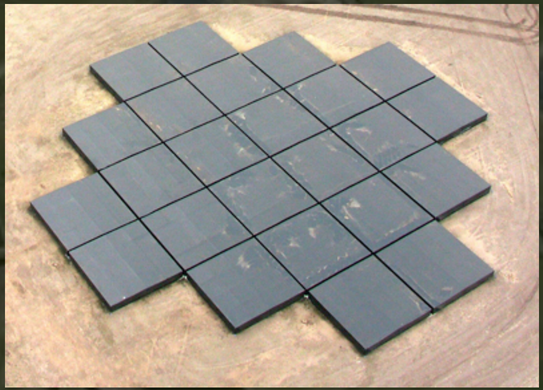
- The International LOFAR Telescope (ILT) has stations in the Netherlands, France, Germany, Ireland, Poland, Sweden and UK (~€50M construction + running costs)
- Operating frequency is 10 -- 250 MHz
- 1 beam with up to 96 MHz total bandwidth, split into 488 sub-bands with up to 256 Channels (8-bit mode)
- <488 beams on the sky with ~0.2 MHz bandwidth
- 1700 -- 7 deg$^2$ field-of-view (frequency-dependent)
- Low Band Antenna (LBA; Area ~ 75200 m$^2$;

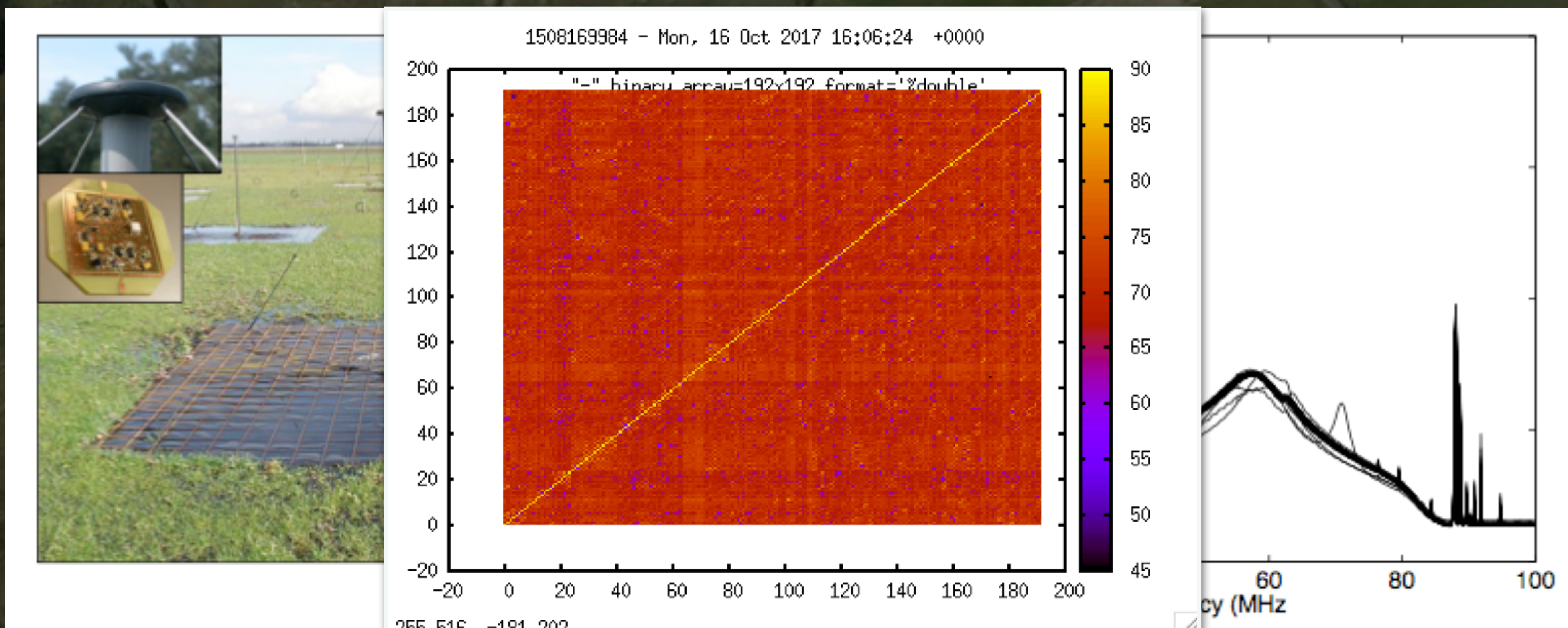
  $T_{rec}$ ~ 500 K; 10-90 MHz)
- High Band Antenna (HBA; Area ~ 57000 m$^2$;

  $T_{rec}$ ~ 160 K; 110-240 MHz)
- Correlated with COBALT, based in Groningen



# Low Band Antenna (LBA)

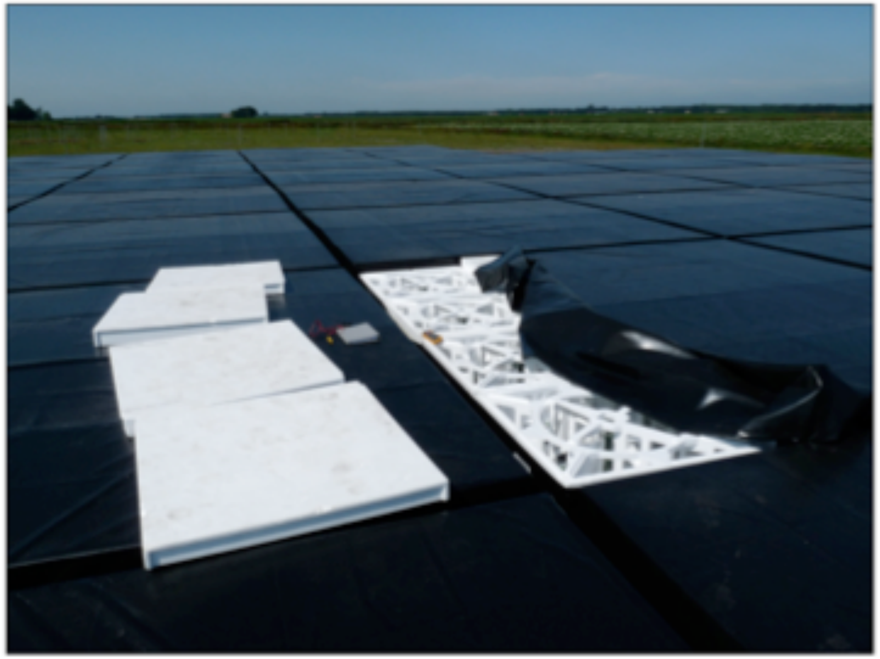
- **LBA antennas:** Cap containing the low noise amplifiers (LNAs), copper wires receive two orthogonal *linear* polarisations (XX and YY), ground plate
- Low cost, high durability (15 year operation), whole sky coverage

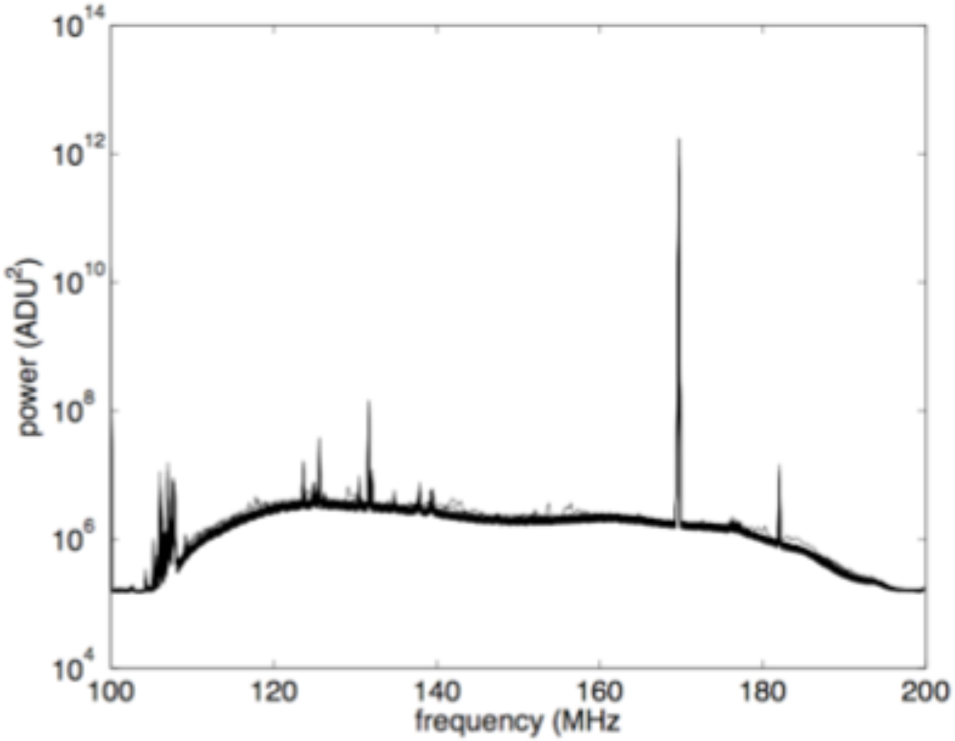



- **The response curve:** There is a peak close to the resonance frequency (58 MHz) - dipole arms are 1.38 m long

# High Band Antenna (HBA)

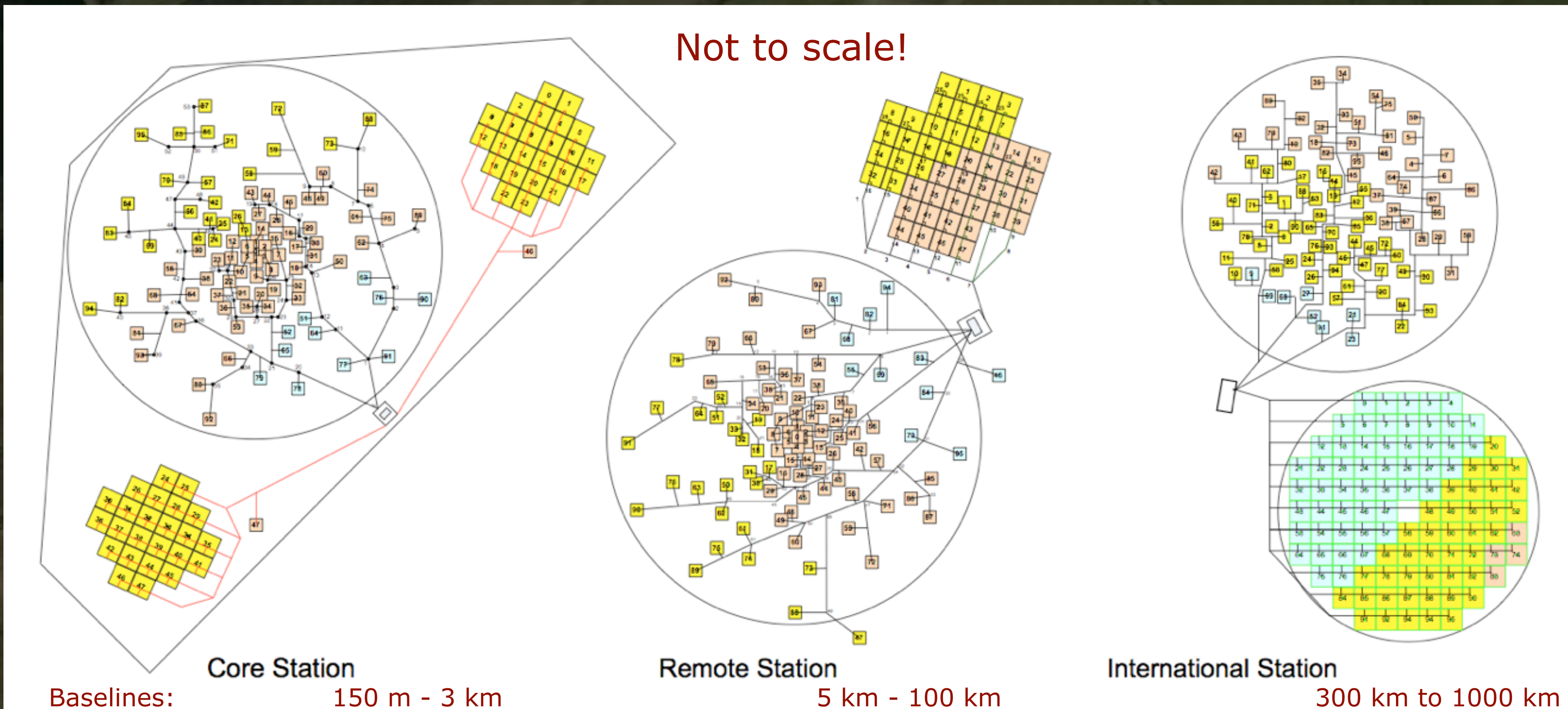
- **HBA antennas:** Each tile consists of 4 x 4 dual *linear* polarisation aluminium dipoles, housed in a polystyrene structure, covered by polypropylene sheets
- Dipoles are combined to form a single "tile beam"






- **The response curve:** There is a smoother response over the main HBA observing band, compared with the LBA response curve

# Stations




- **Three types:** Core (24), Remote (14) and International (13 so far)
- Different beam shapes
- Different sensitivities

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

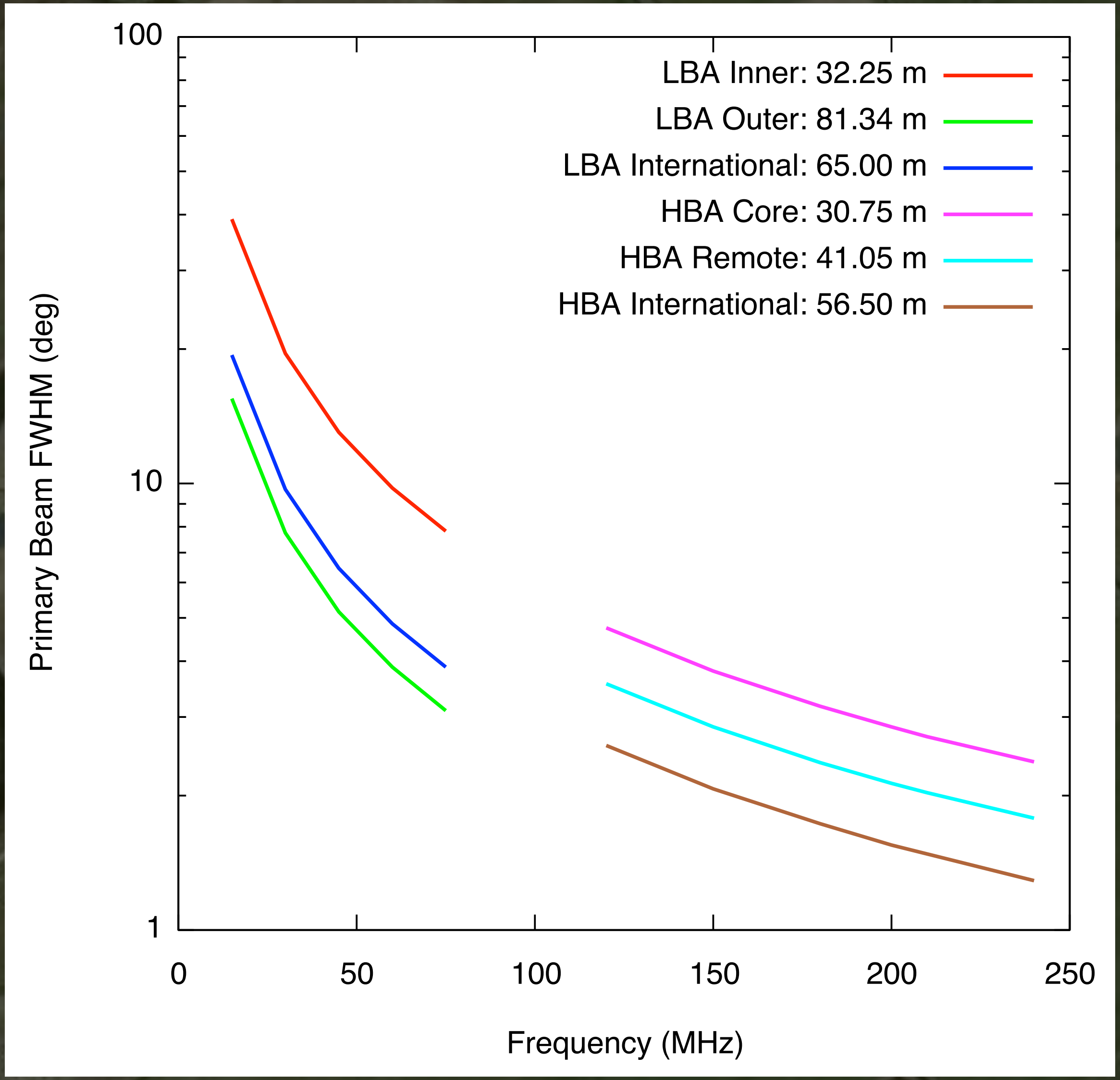
# Field-of-View (FWHM vs. frequency)

- LOFAR features an unprecedented field-of-view:

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

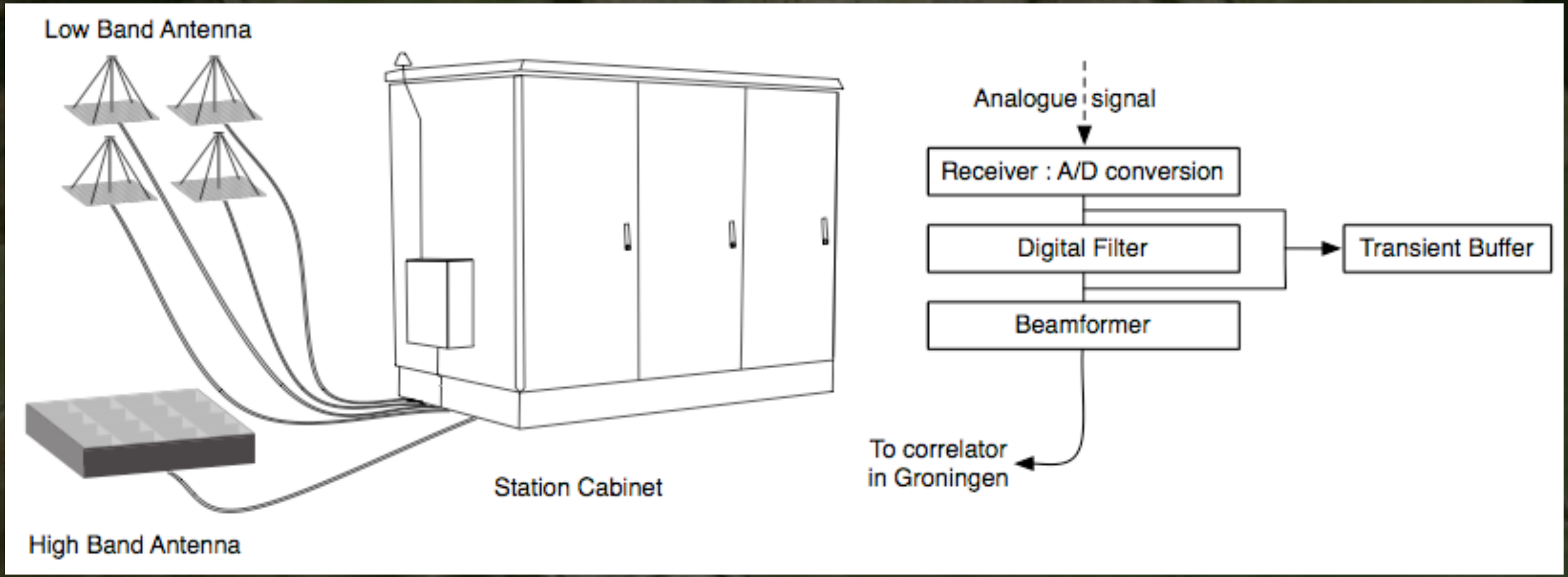
- Where α depends on the tapering used at the station level:

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



# Central cabinets

- **Receiver Control Units (RCU):** Input antenna voltages are converted to base-band frequencies, amplified, filtered and digitised
- Receive signals linearly across 40 dB range - 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



# Central cabinets

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# Beam-forming

- Unlike standard telescopes, phased arrays like LOFAR 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
- **LOFAR:** <488 beams can be formed, increasing survey speed, efficiency, calibration.

# 6 station superterp (300 m)

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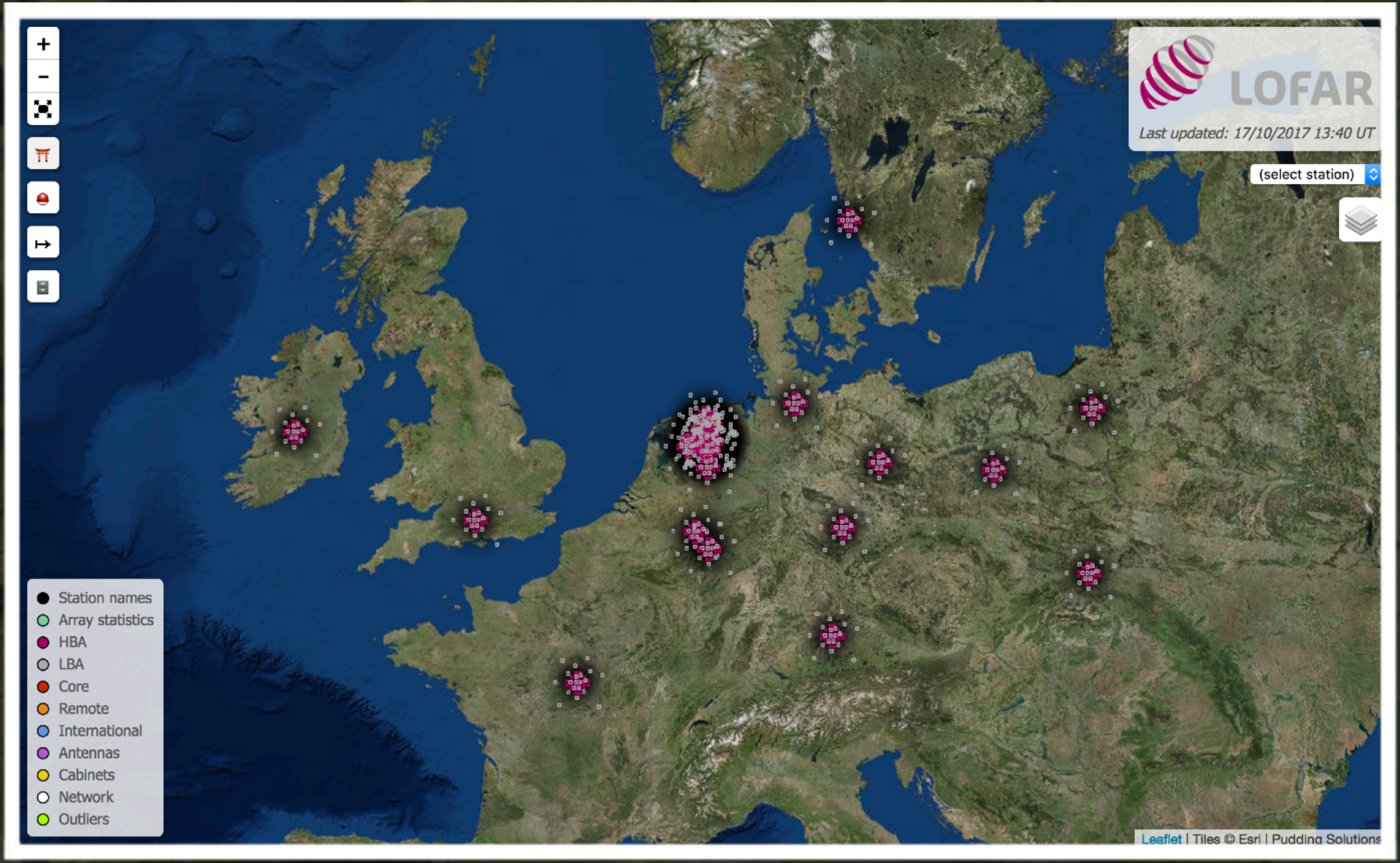
# Interactive LOFAR map




http://astron.nl/lofartools/lofarmap.html

# The Superterp (6 stations)

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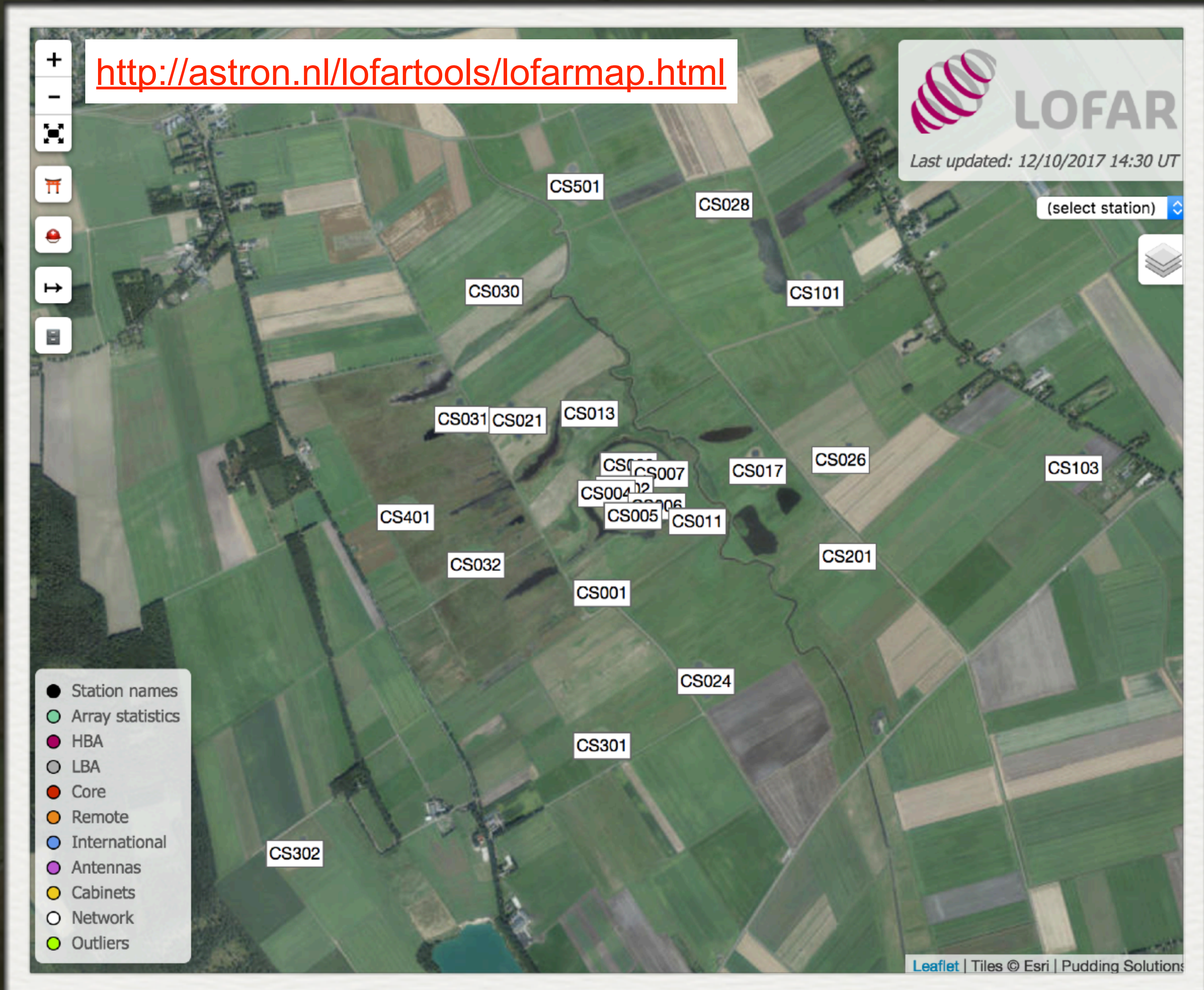
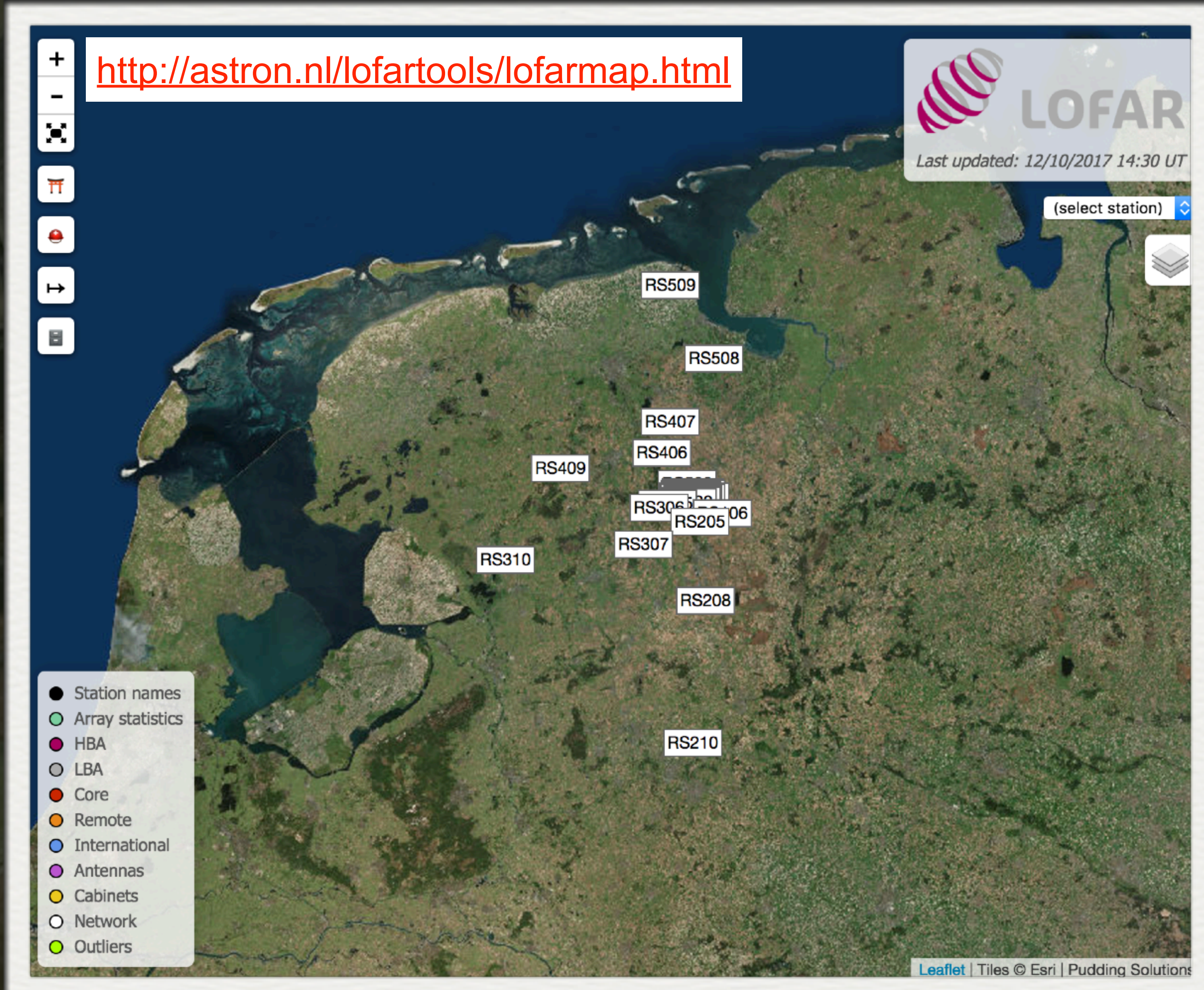
# Core stations (24)

# The Core Array (24 stations)

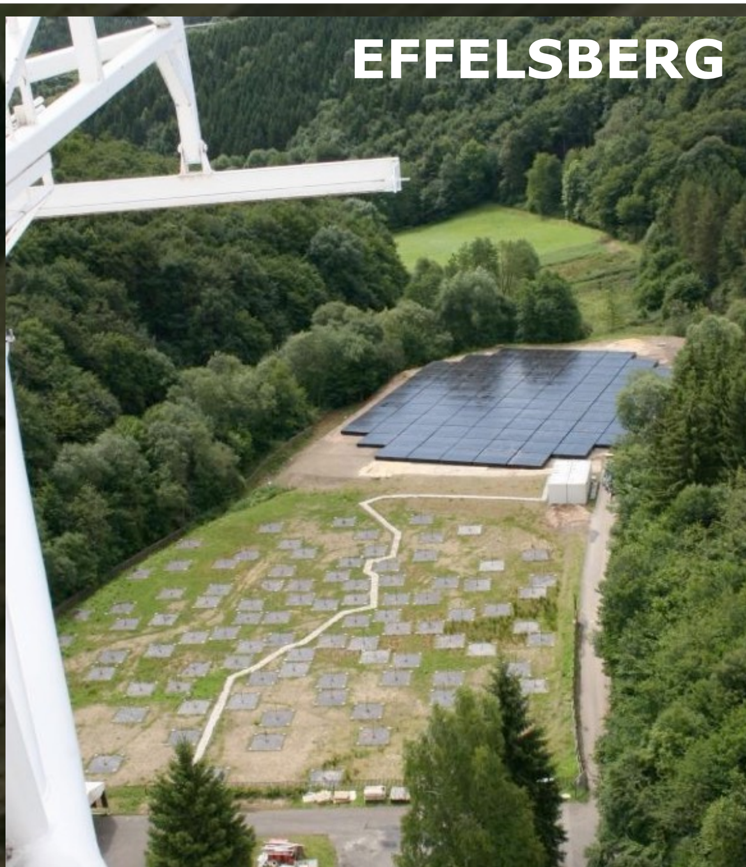


# Remote stations (14)

# The Dutch Array (LOFAR-NL 38)



# International Stations (13!)





# A Pan-European Array (ILT 51)

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# A Pan-European Array (ILT 51)

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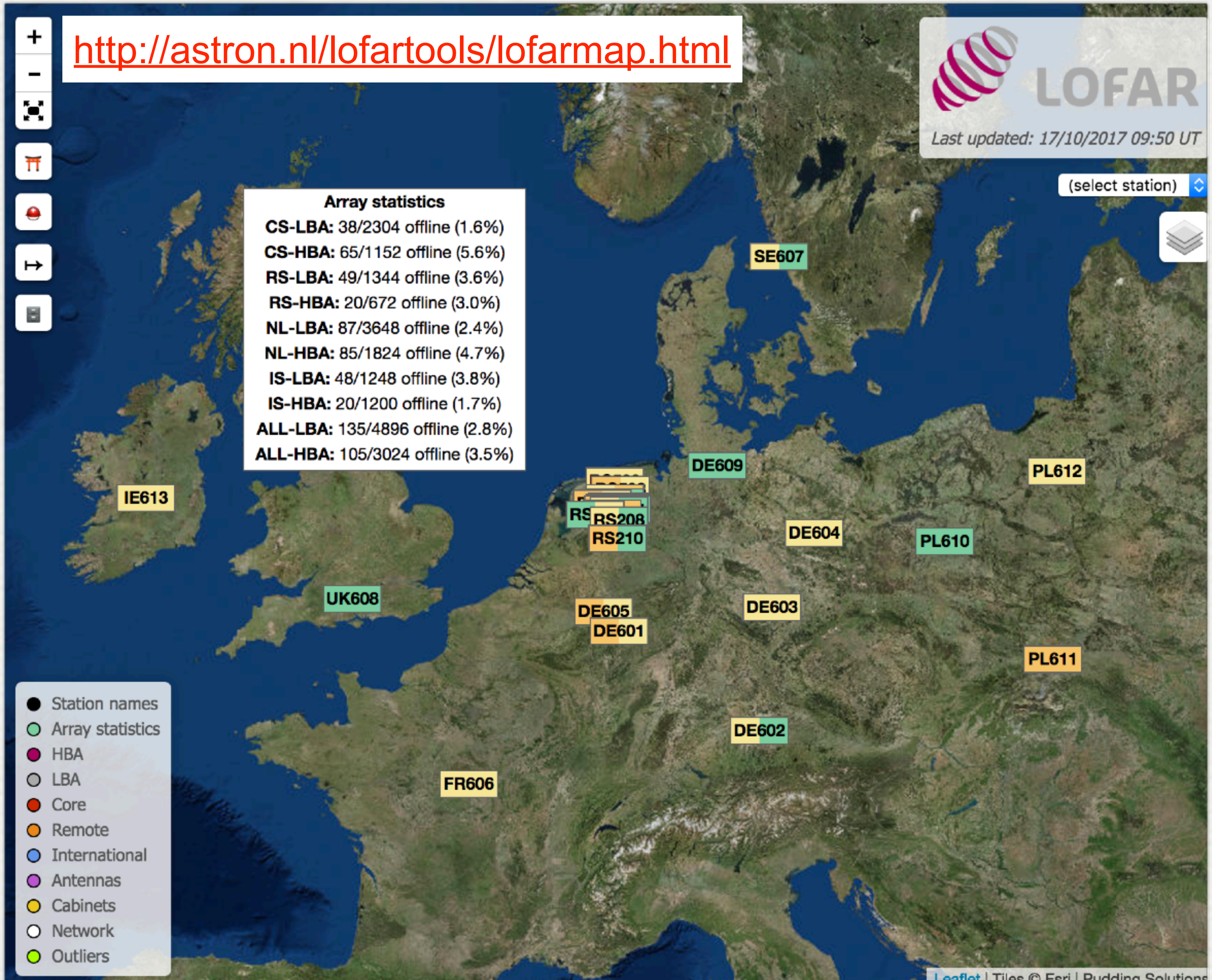
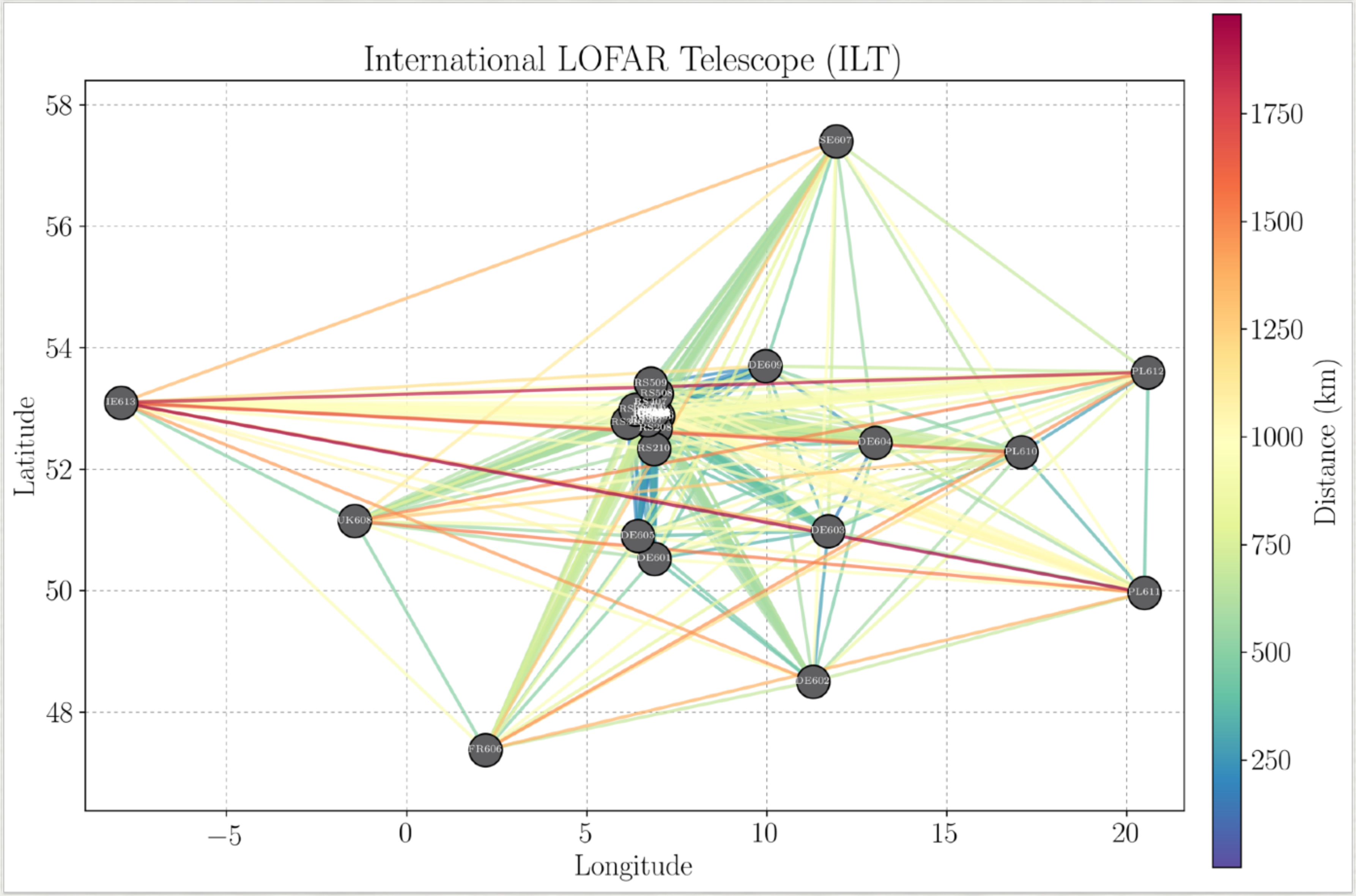
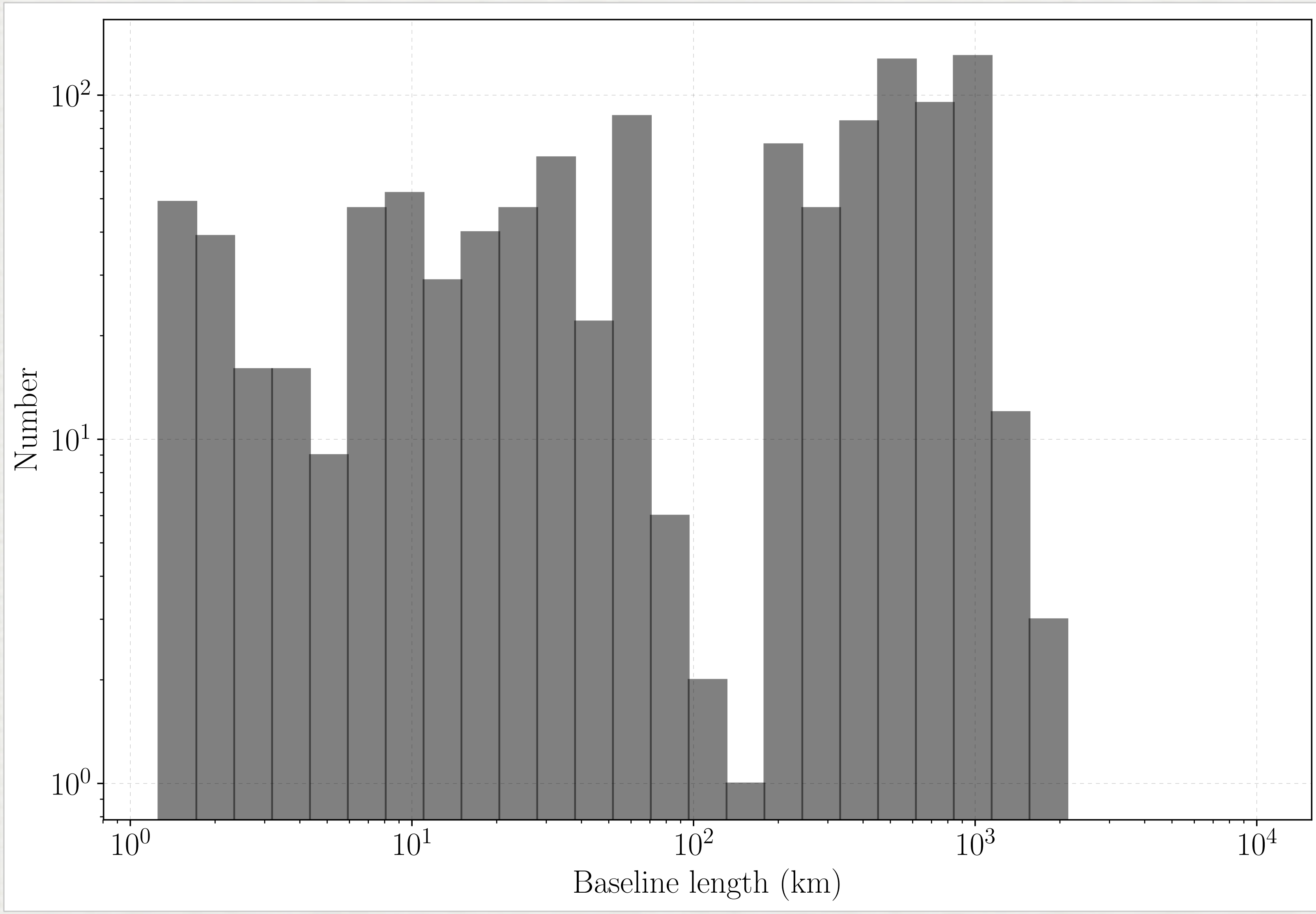


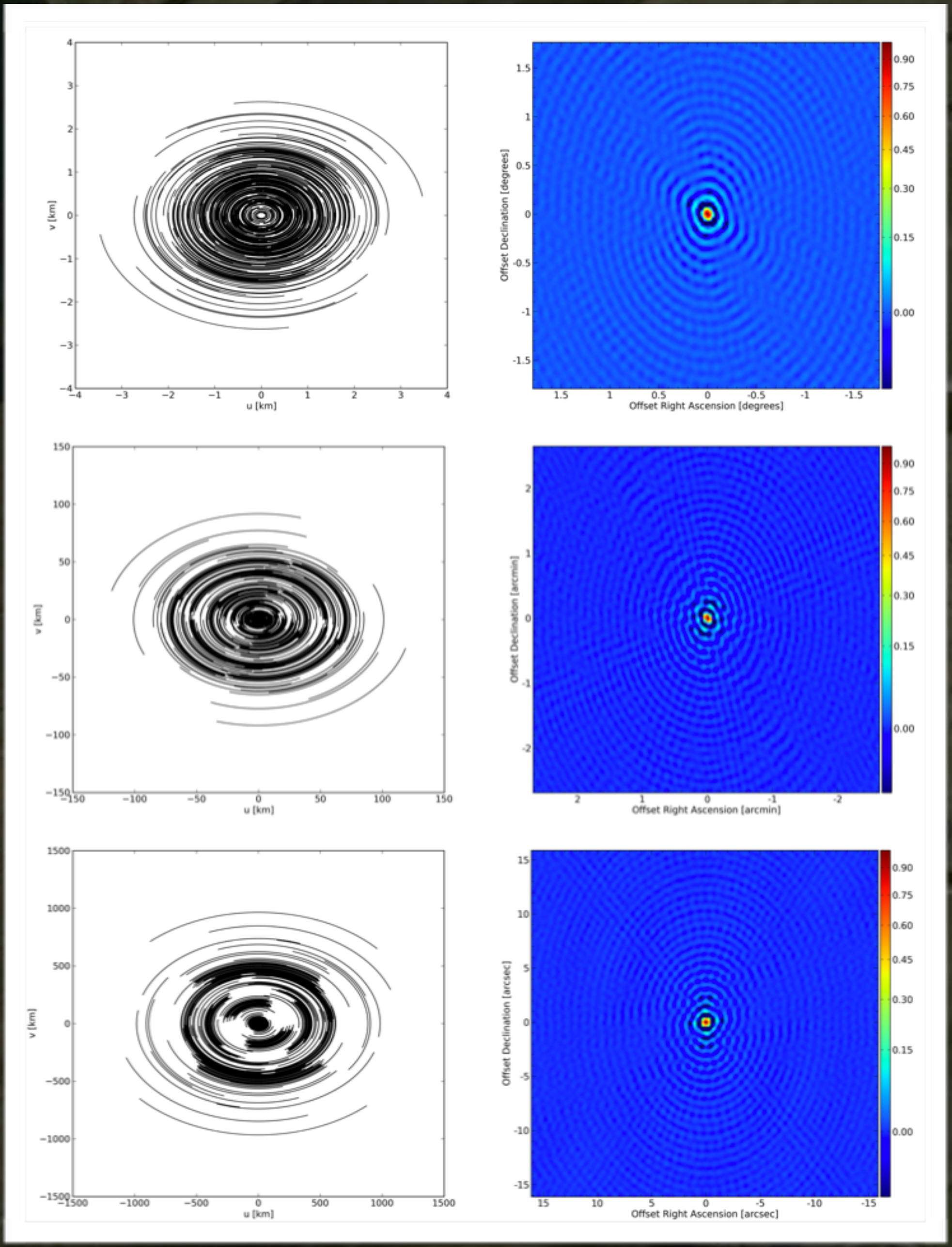
# Baseline lengths

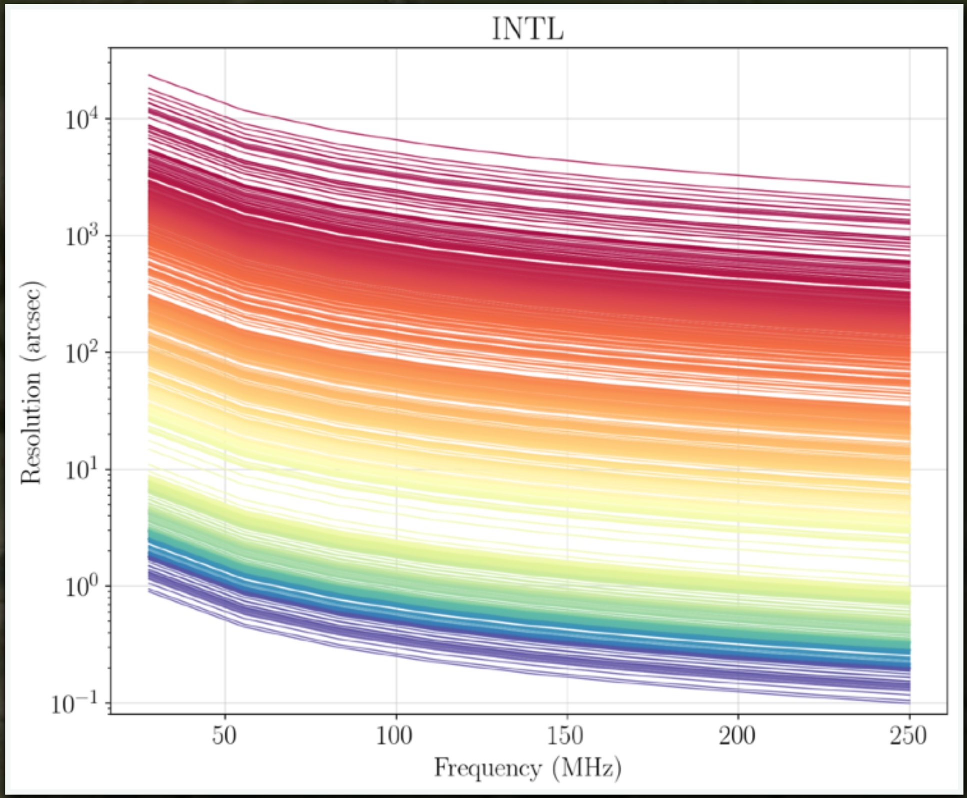


# Baseline lengths



# UV coverage and angular resolution

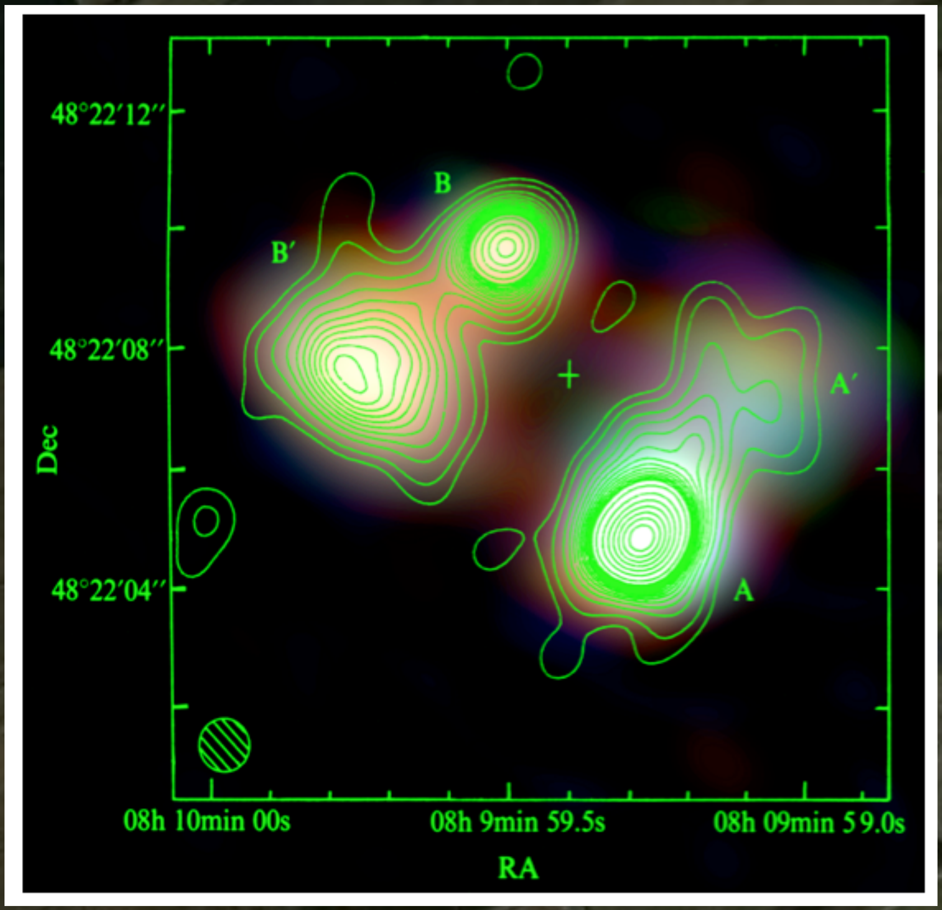


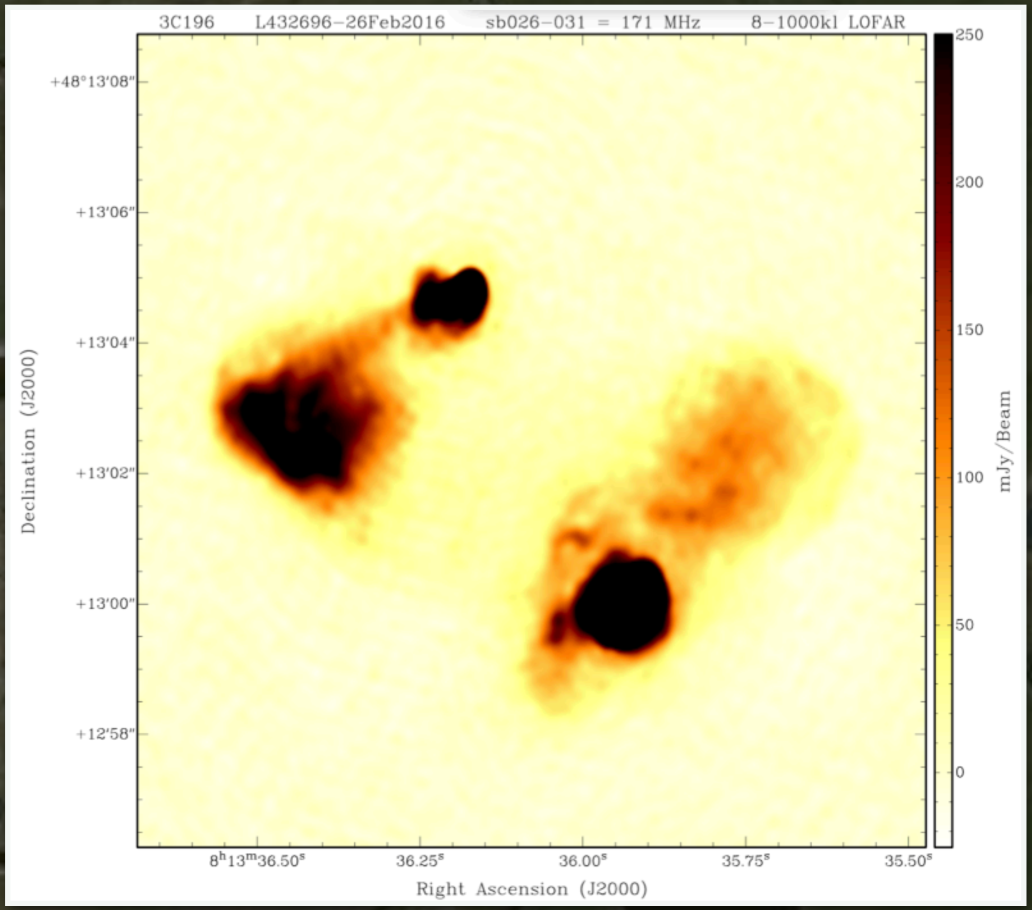




$$\mathrm{FWHM}\ [\mathrm{rad}] = \alpha\ \frac{\lambda}{D}$$

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
- **1.5 arcsec beam** *Olaf Wucknitz*

- HBA image of 3C196 resolves double structure at 171 MHz
- **0.25 arcsec beam**

*Ger de Bruyn*

# Radio frequency interference

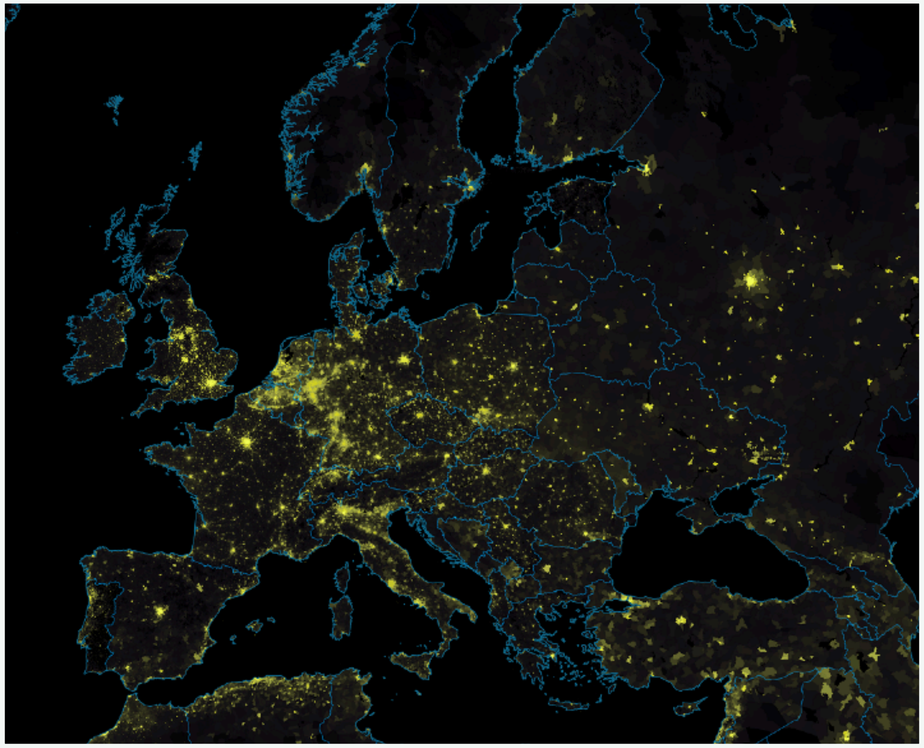
- Europe is a highly populated area - lots of radio frequency interference!
- Most LOFAR stations are very much surrounded by inhabited areas
- LOFAR mitigates RFI by

  i) having a small time and frequency resolution (1s; 3 kHz)

  ii) having 40 dB range in receiver units to stop saturation to other channels

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

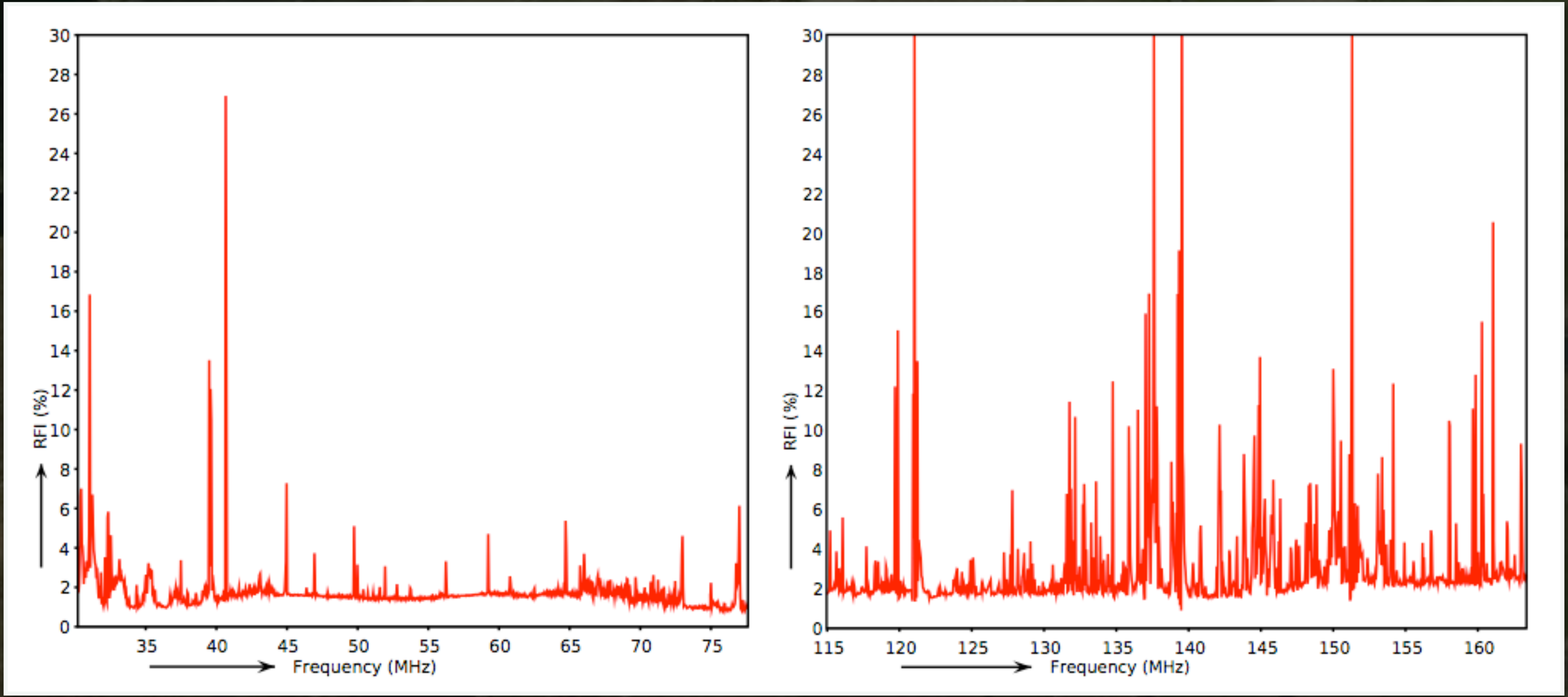
  iv) antennas close to the ground (nearby radio horizon)



Robert Szucs / Elijah Meeks

# Radio frequency interference

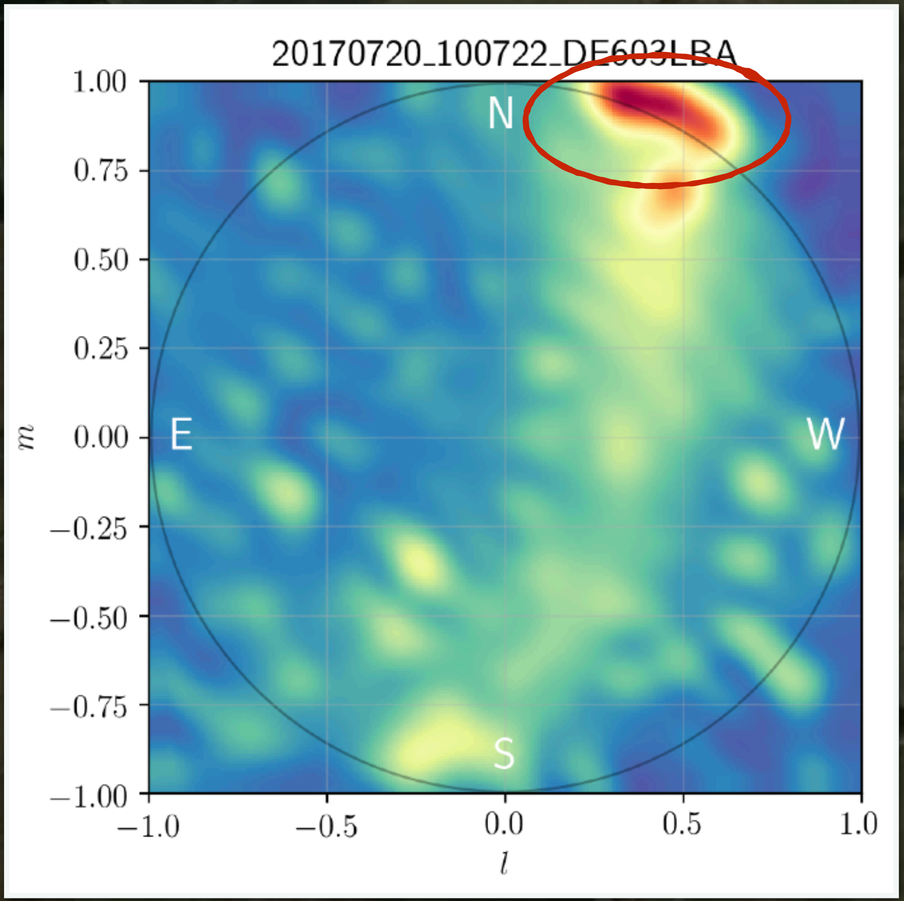
(Offringa et al. 2012, 2013)




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

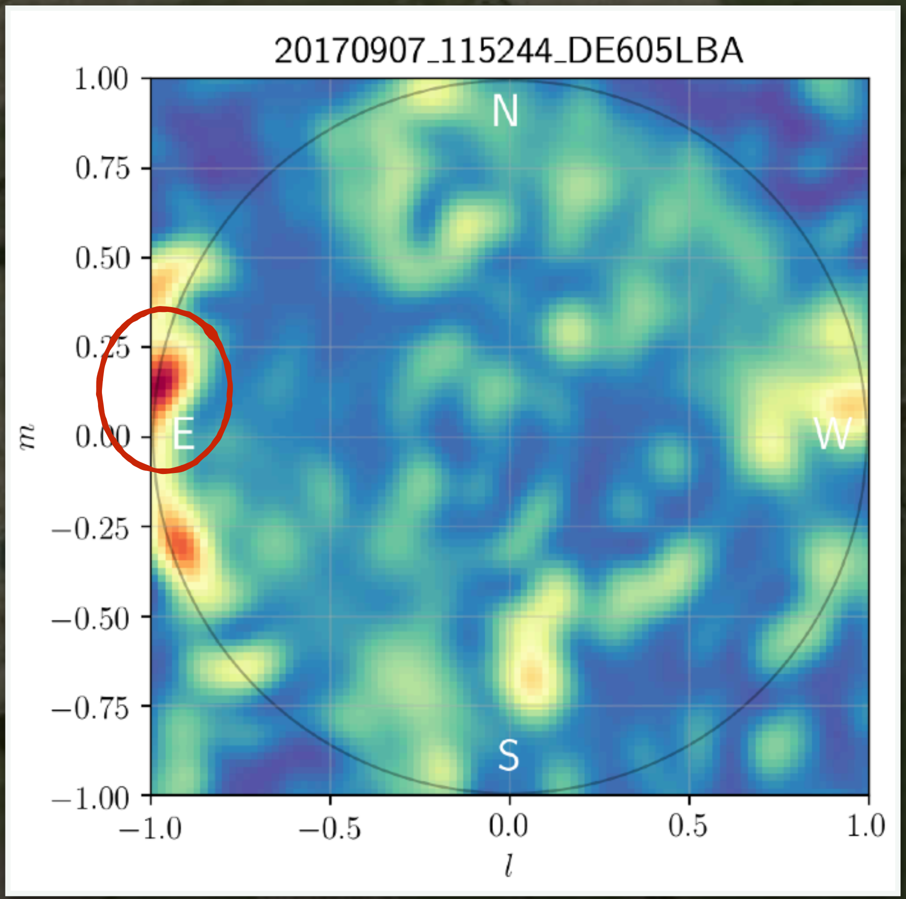
# All-sky imaging with the LBA

DE603: 20th July 2017



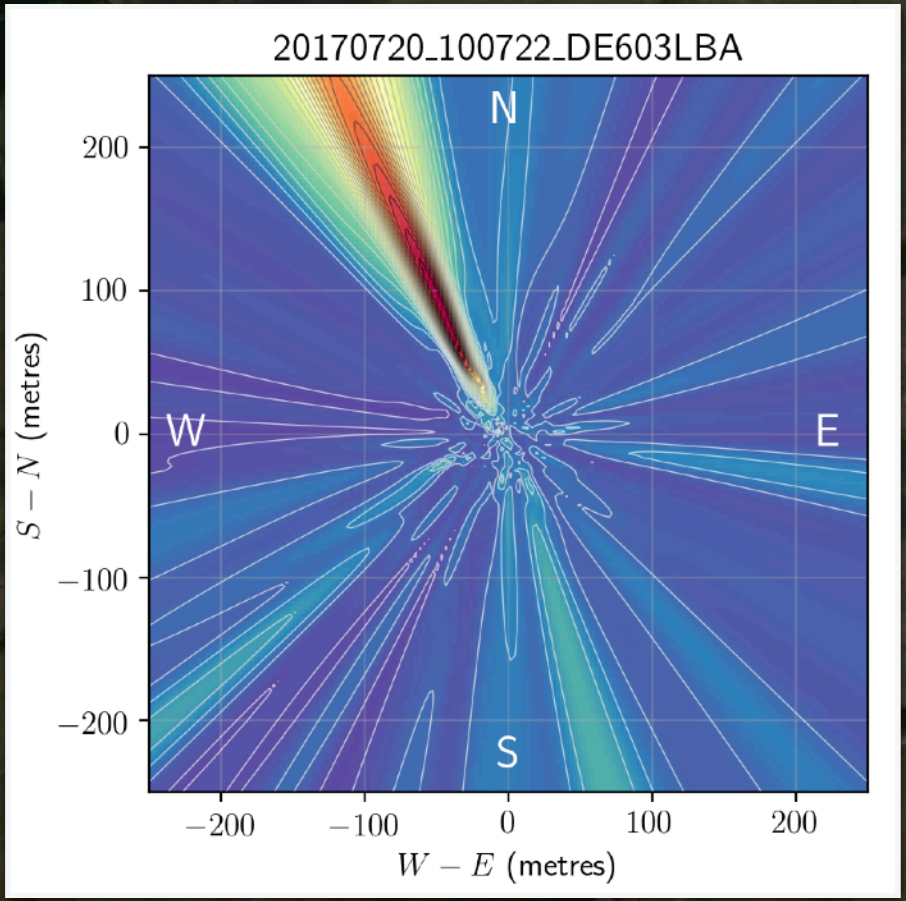

RFI visible in north-west

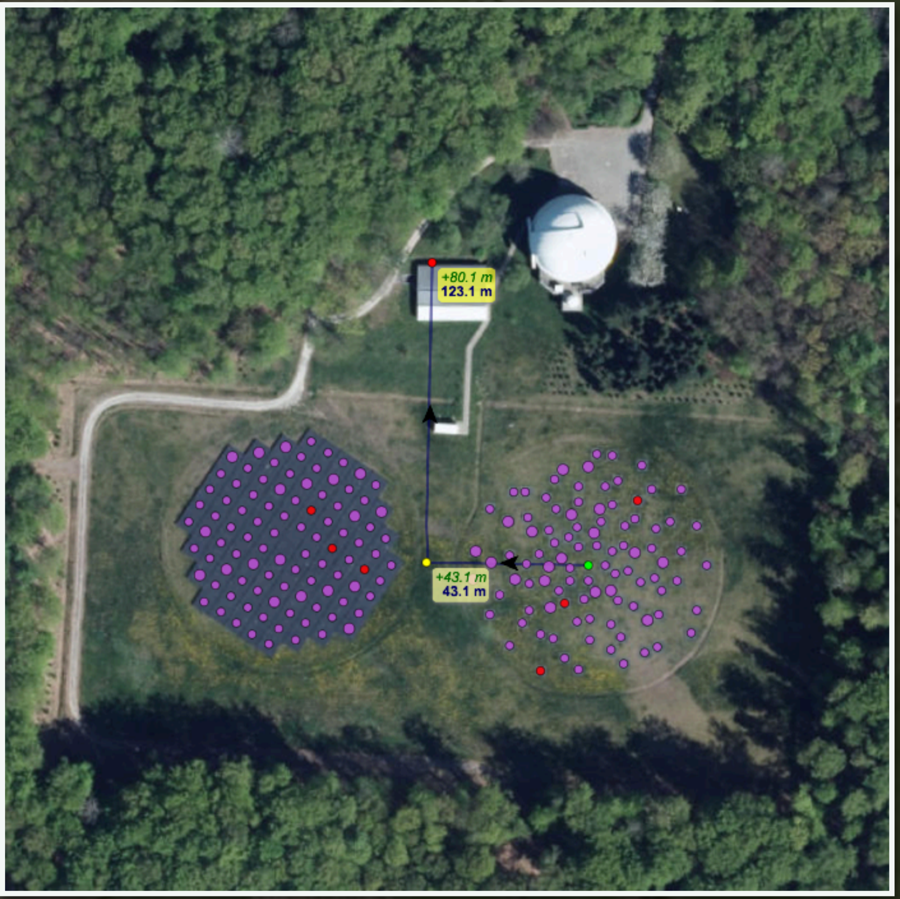
DE605: 7th September 2017



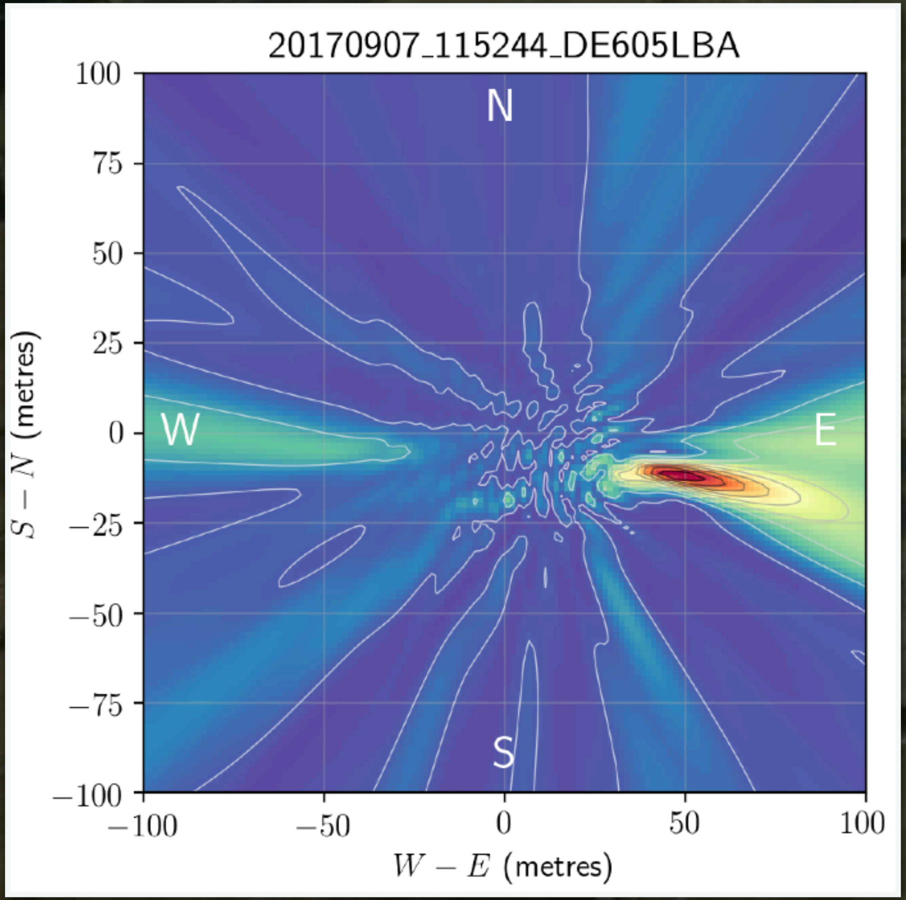

RFI visible in east

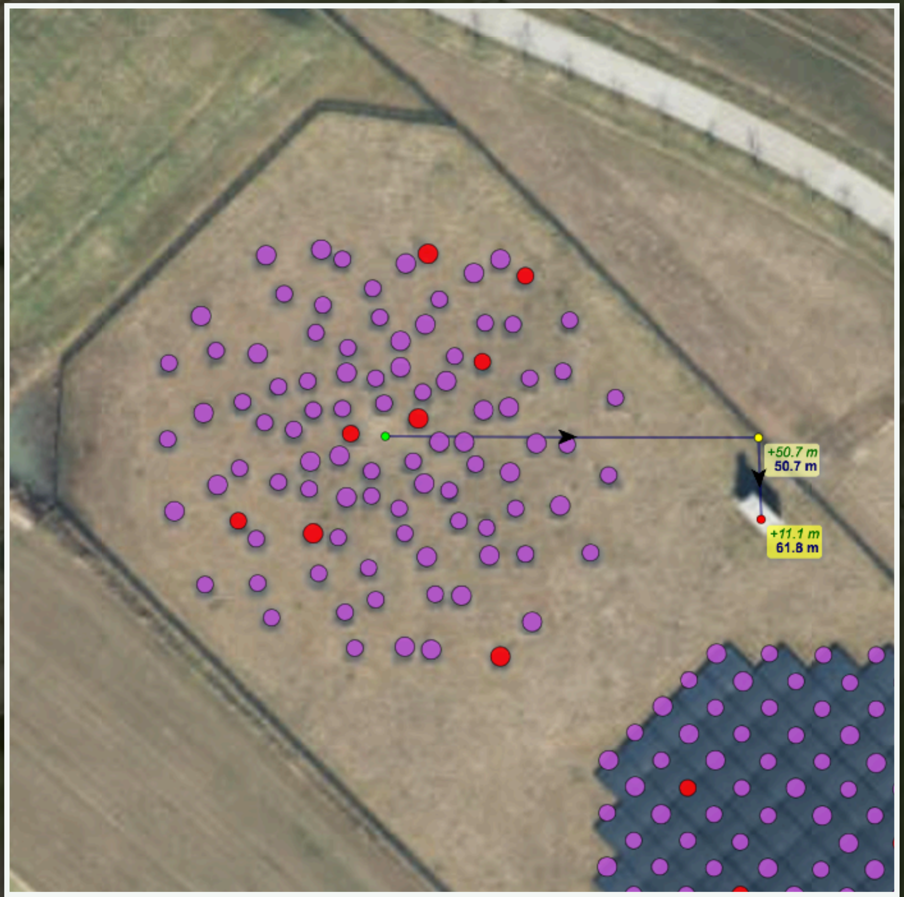
# Near-field imaging of RFI: DE603



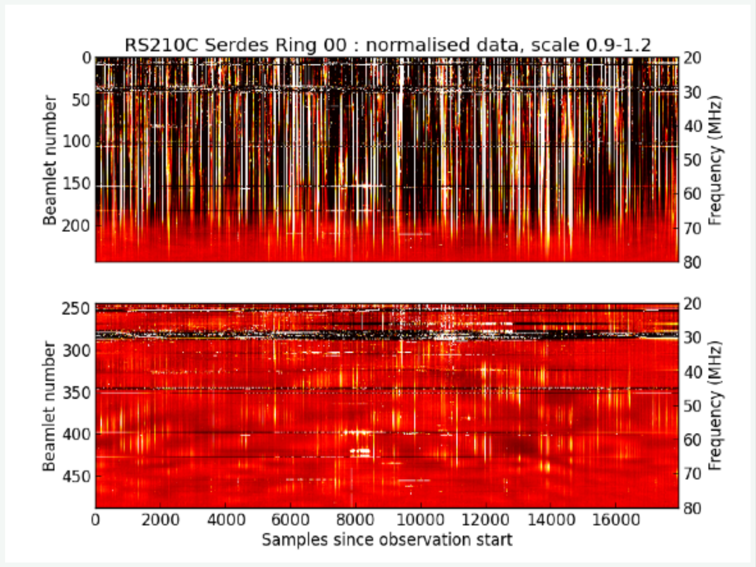
# Near-field imaging of RFI: DE605

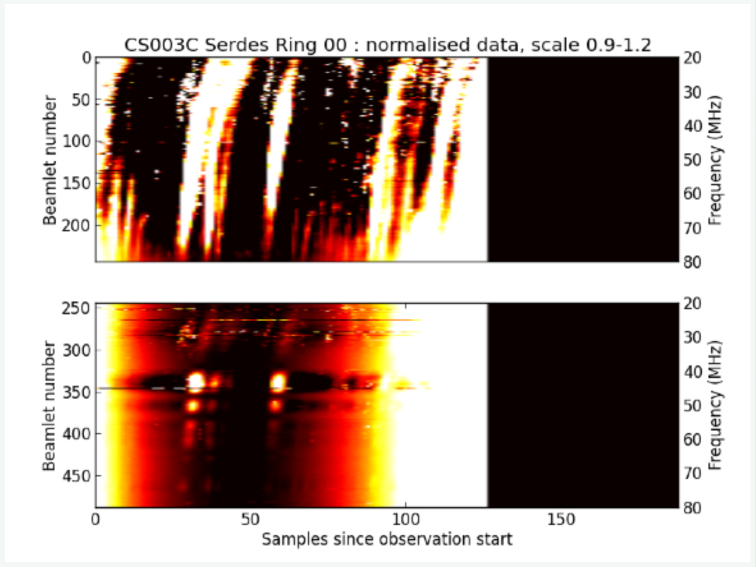


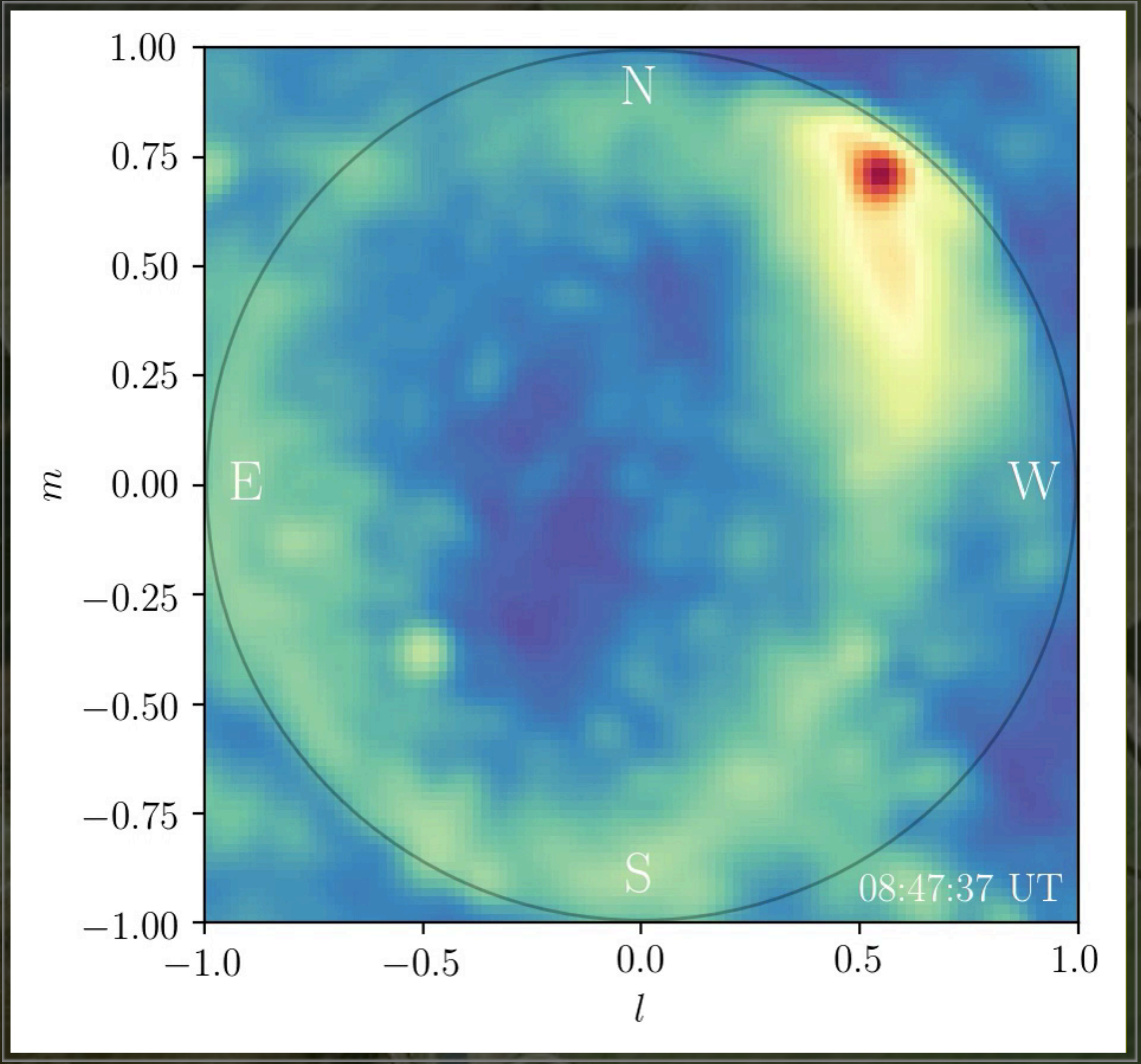
# Solar interference

- The Sun is one of the key contributors to radio frequency interference, if it happens to be in an active phase
- Very bright, low-frequency solar RFI is seen alongside Type II/III solar bursts, at varying levels of intensity
- The wide-field nature of LOFAR observing means that an active Sun can have strong effects on the data



# Solar interference: PL611, 17/08/17



# 2. Direction dependent effects
# I - The beam

# Wide field imaging is fun!

Imaging wide-fields is useful for,

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

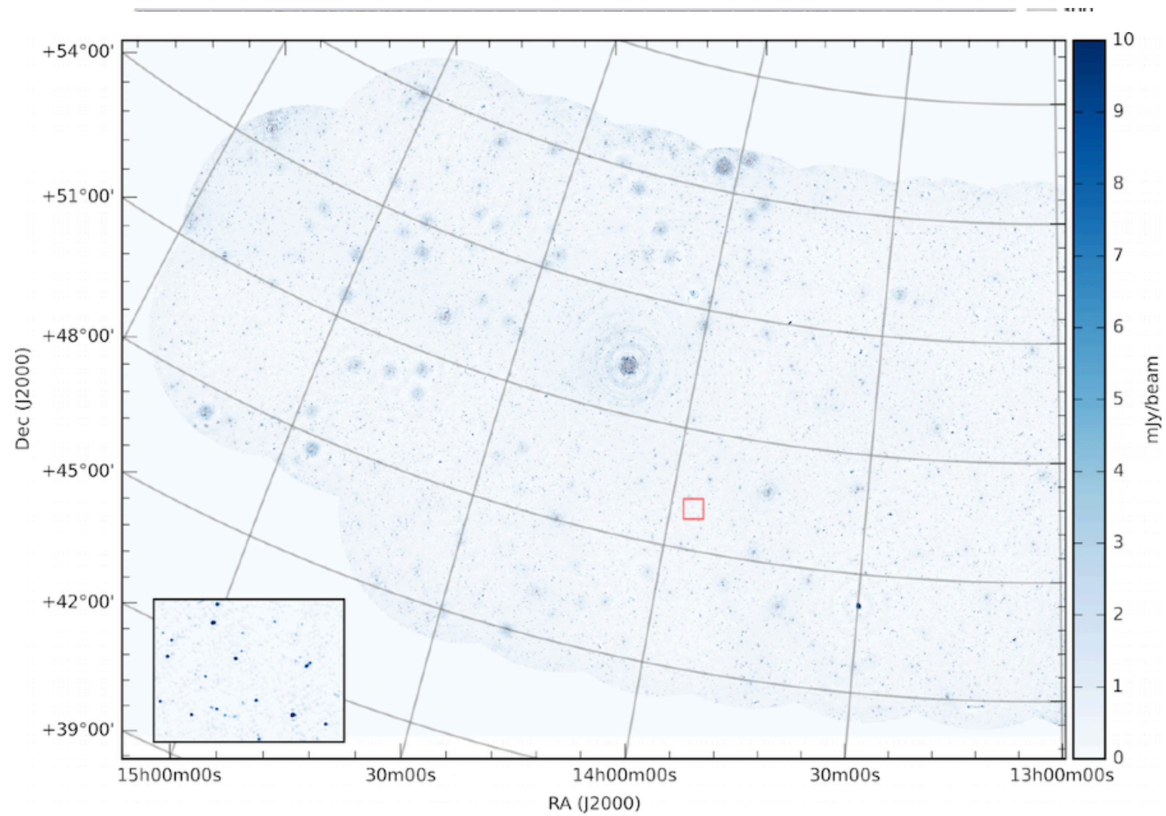
Wide-fields introduce many issues for a good calibration:

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, *George Heald* / LOTSS DR1, *Tim Shimwell*

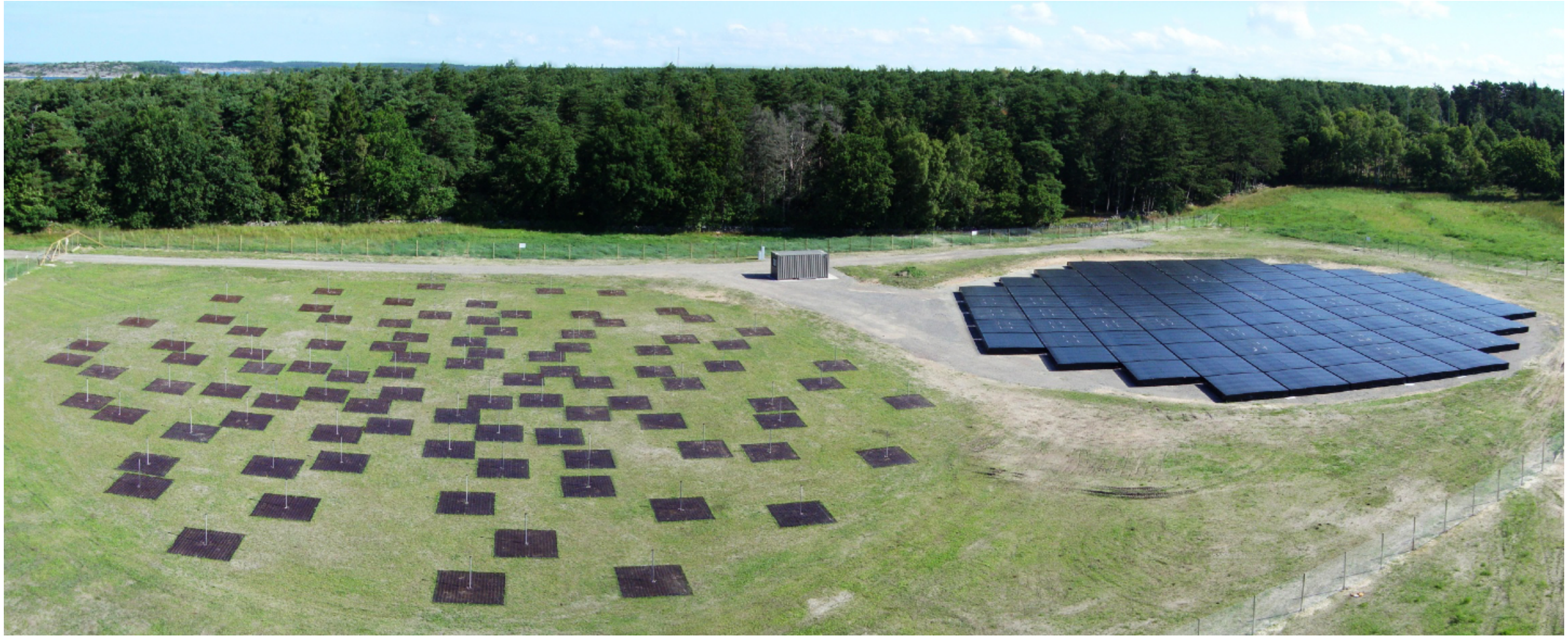


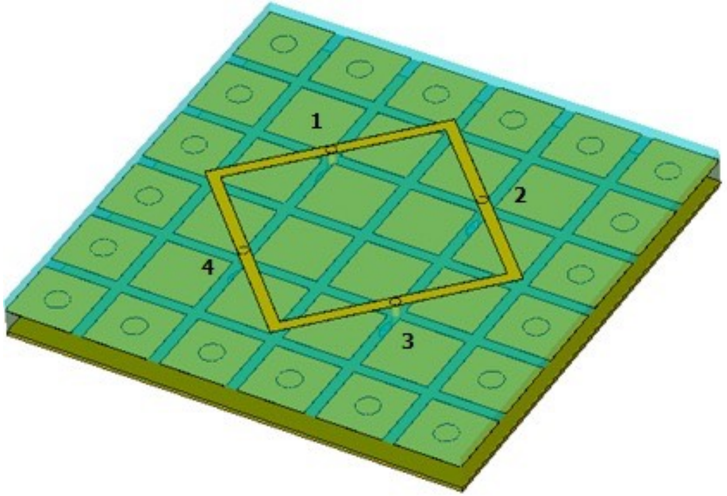

350 square degree

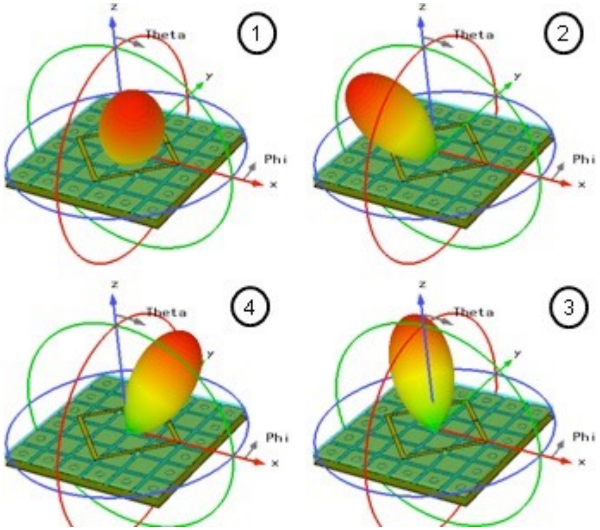
~0.5 mJy /beam

[25″ resolution]

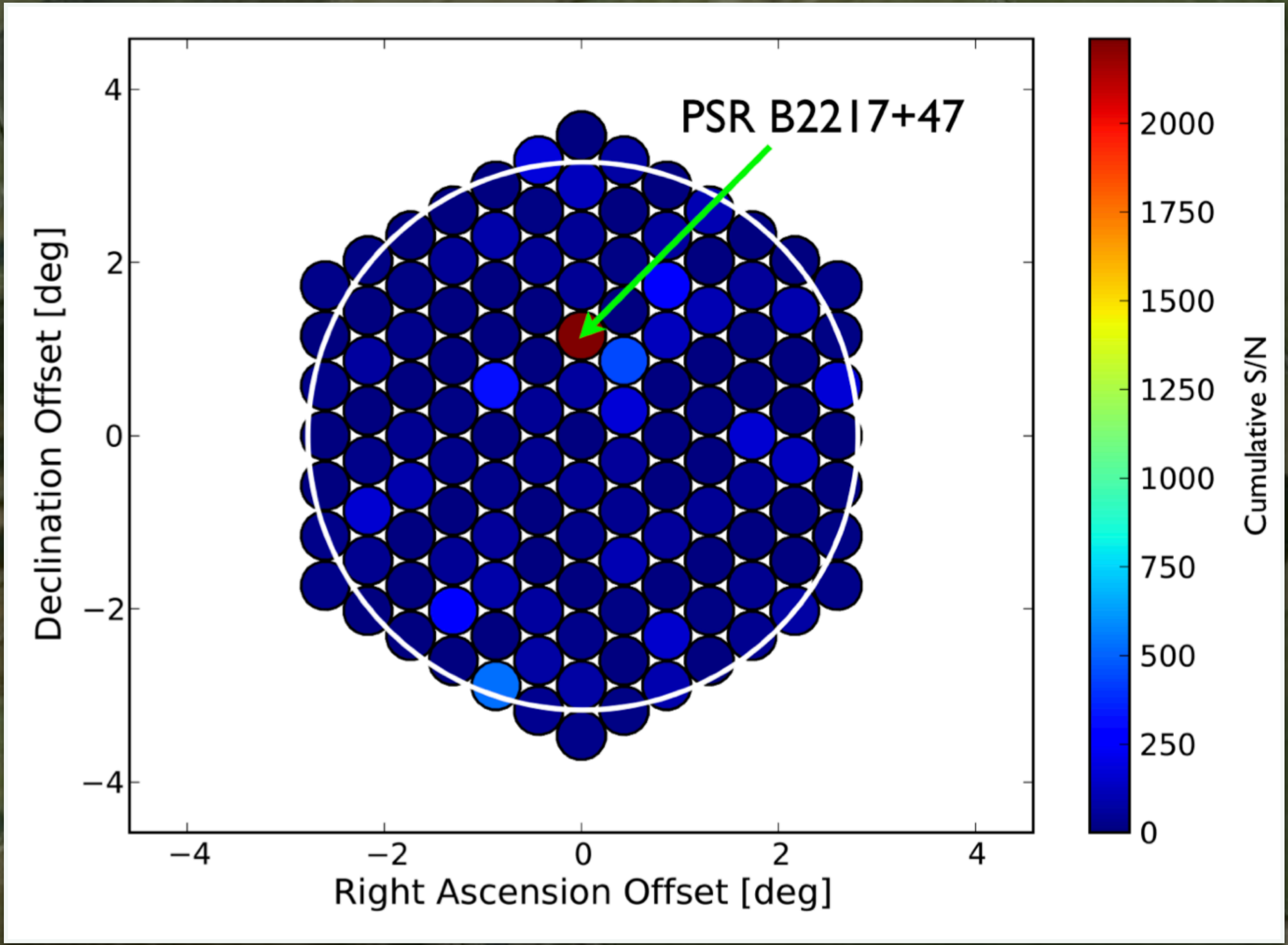
# Beam-forming



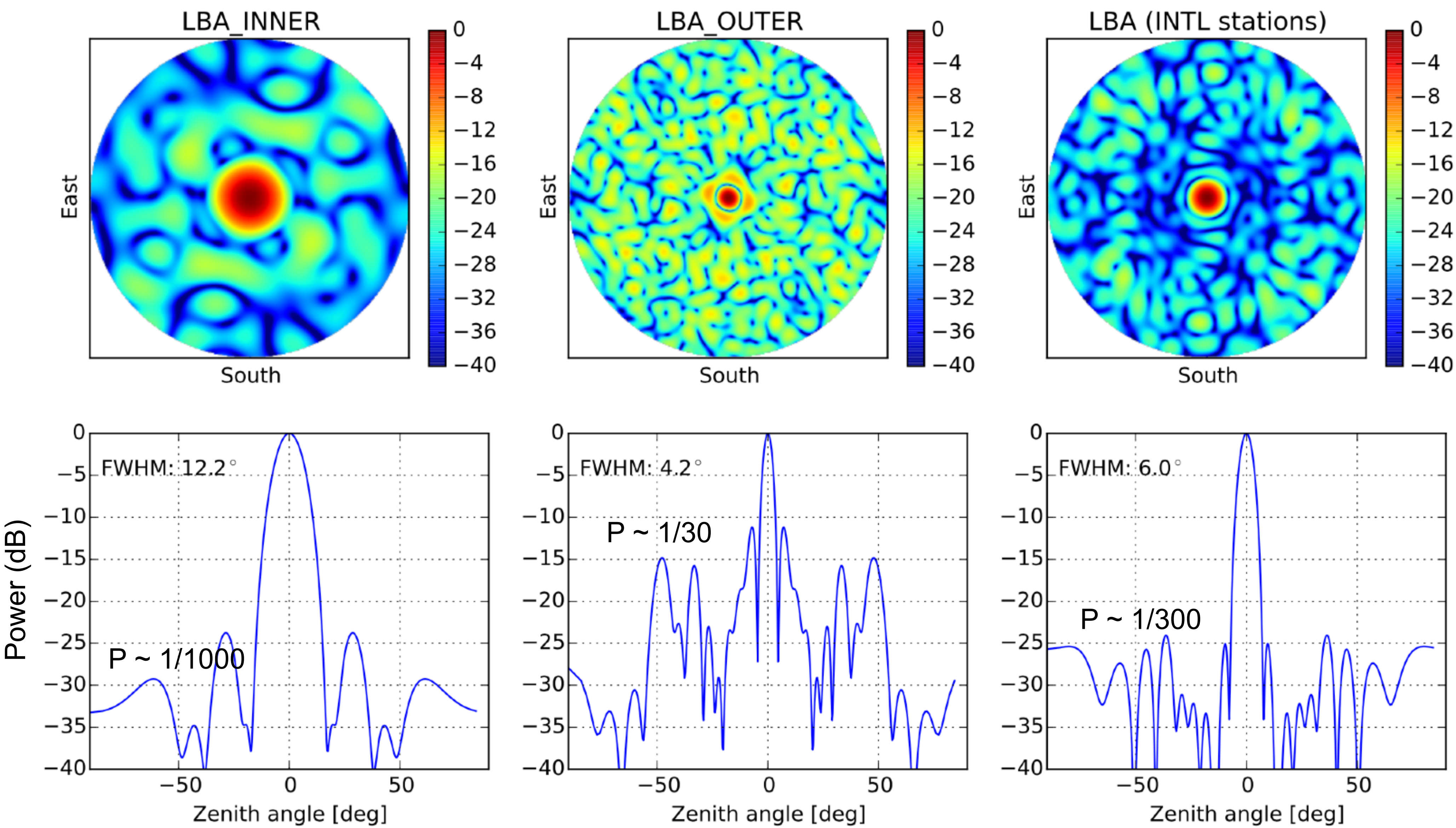


# Beam-forming: pulsar example

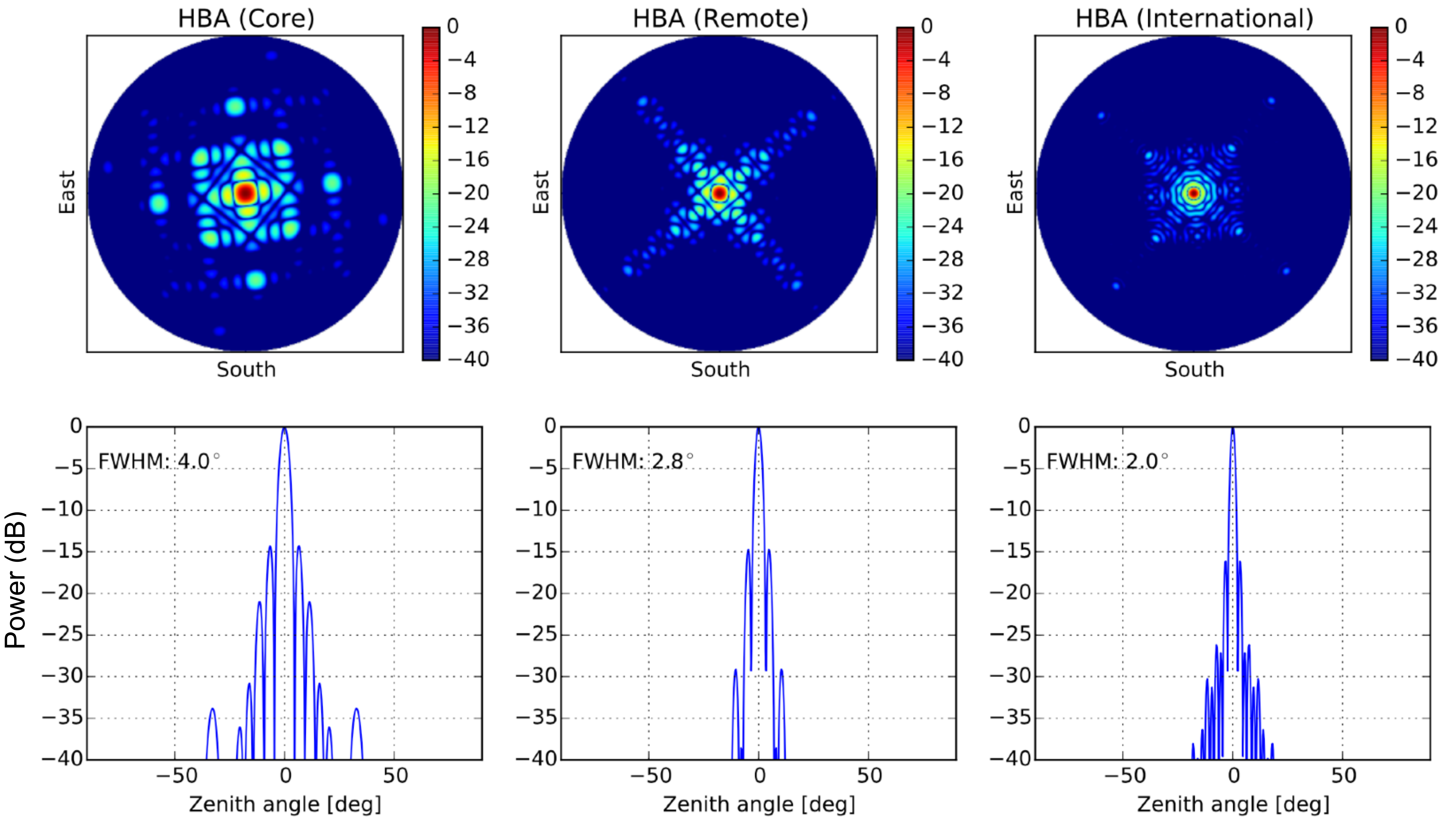


# Example of the LOFAR LBA beam



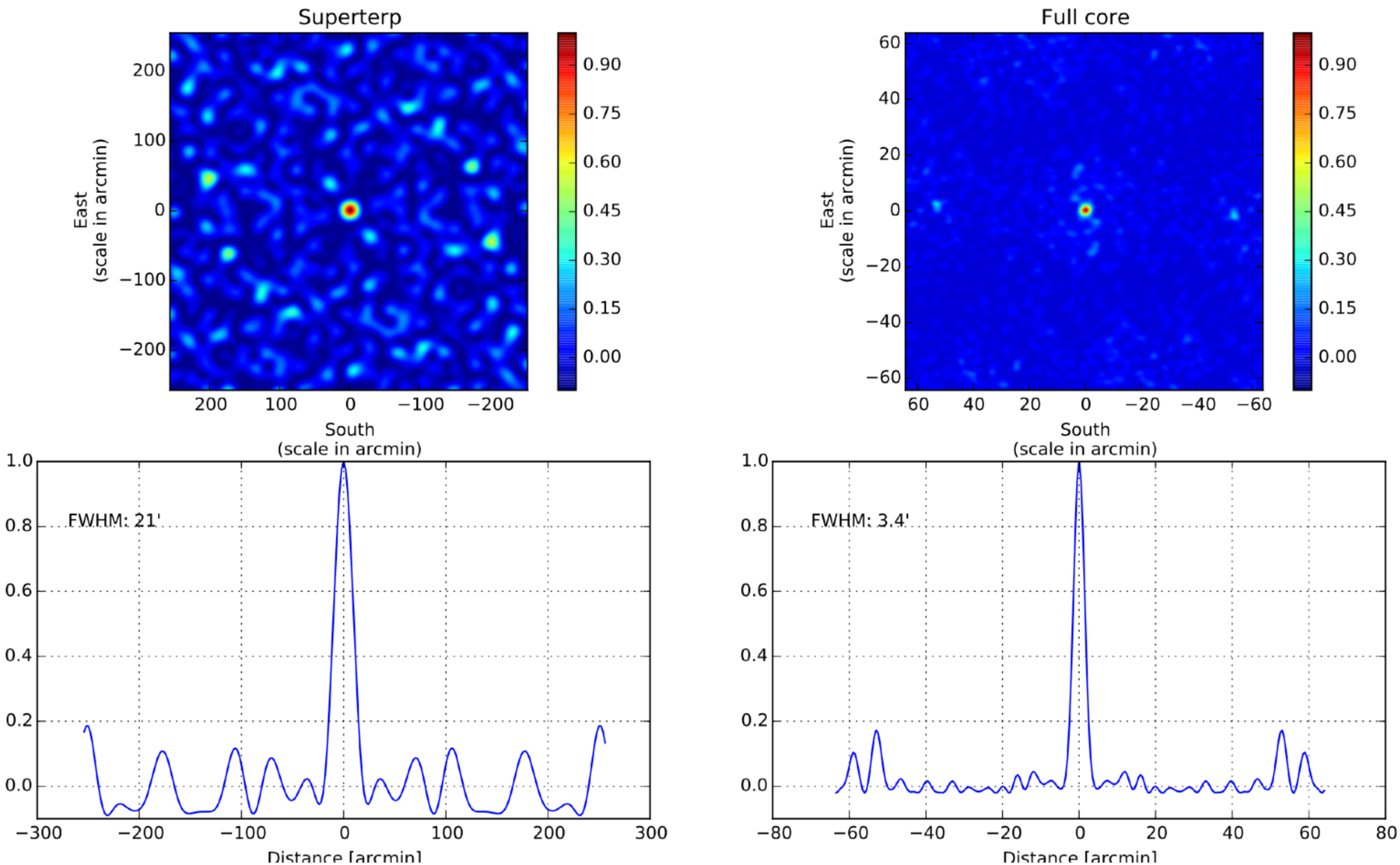

*Michiel Brentjens*

# Example of the LOFAR HBA beam




*Michiel Brentjens*

# Example of LOFAR beam combined




*Michiel Brentjens*

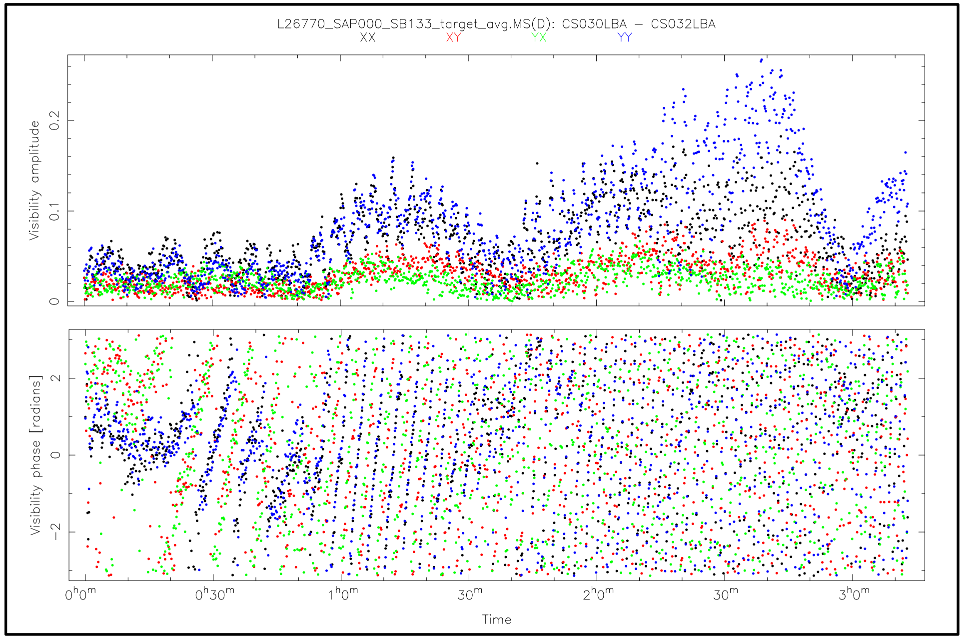
# Bright off-axis sources

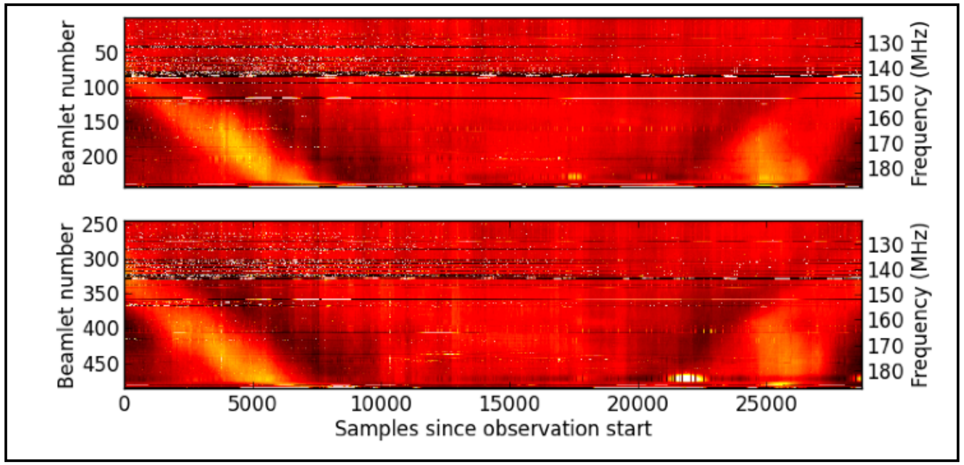
Cygnus A and Cas A are ~20000 Jy at 60 MHz.

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

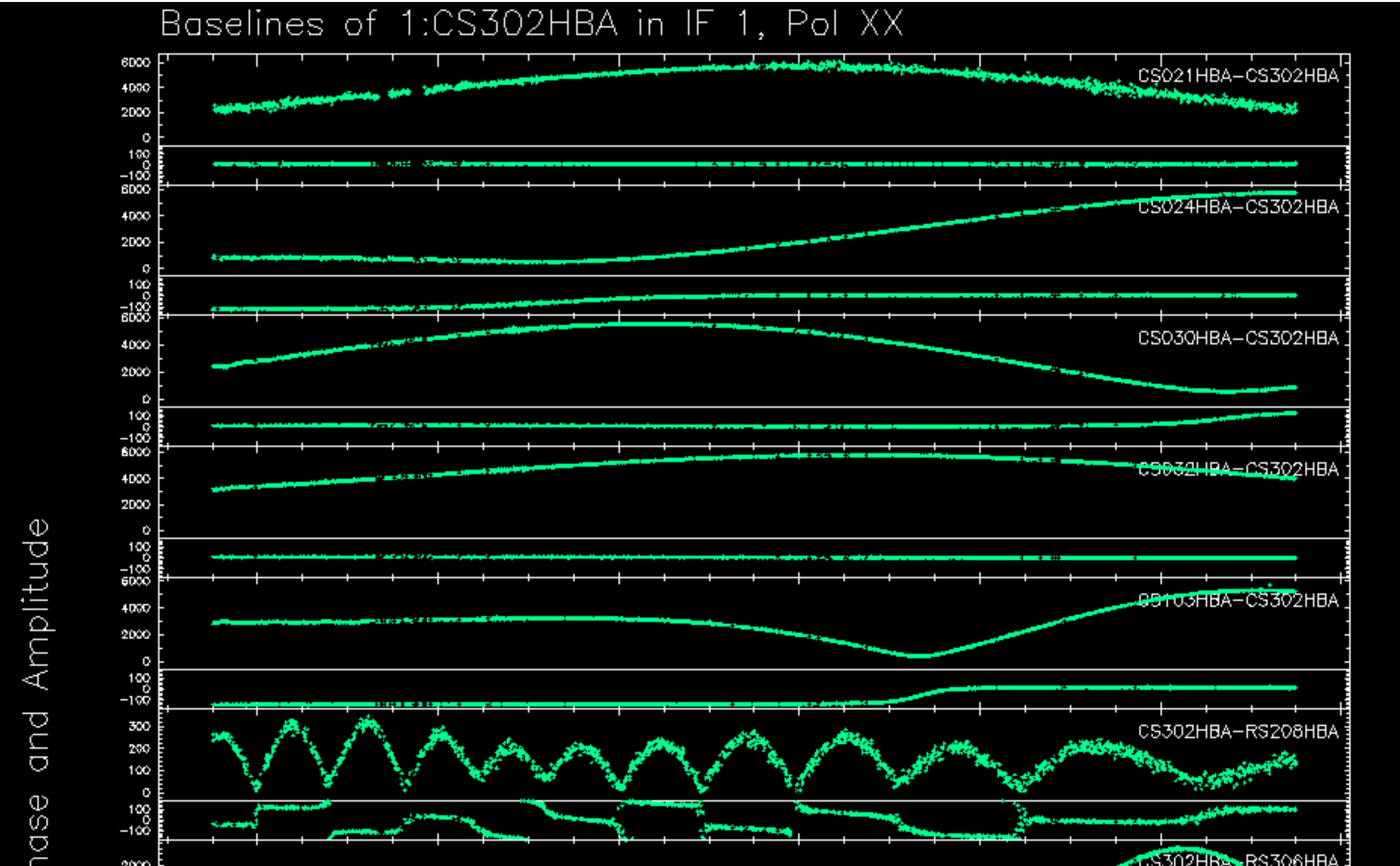
Solution, phase-shift to the their locations, self-calibrate using good models and subtract them from the target visibility data

This is called “demixing” in LOFAR



# The beam is not constant with time



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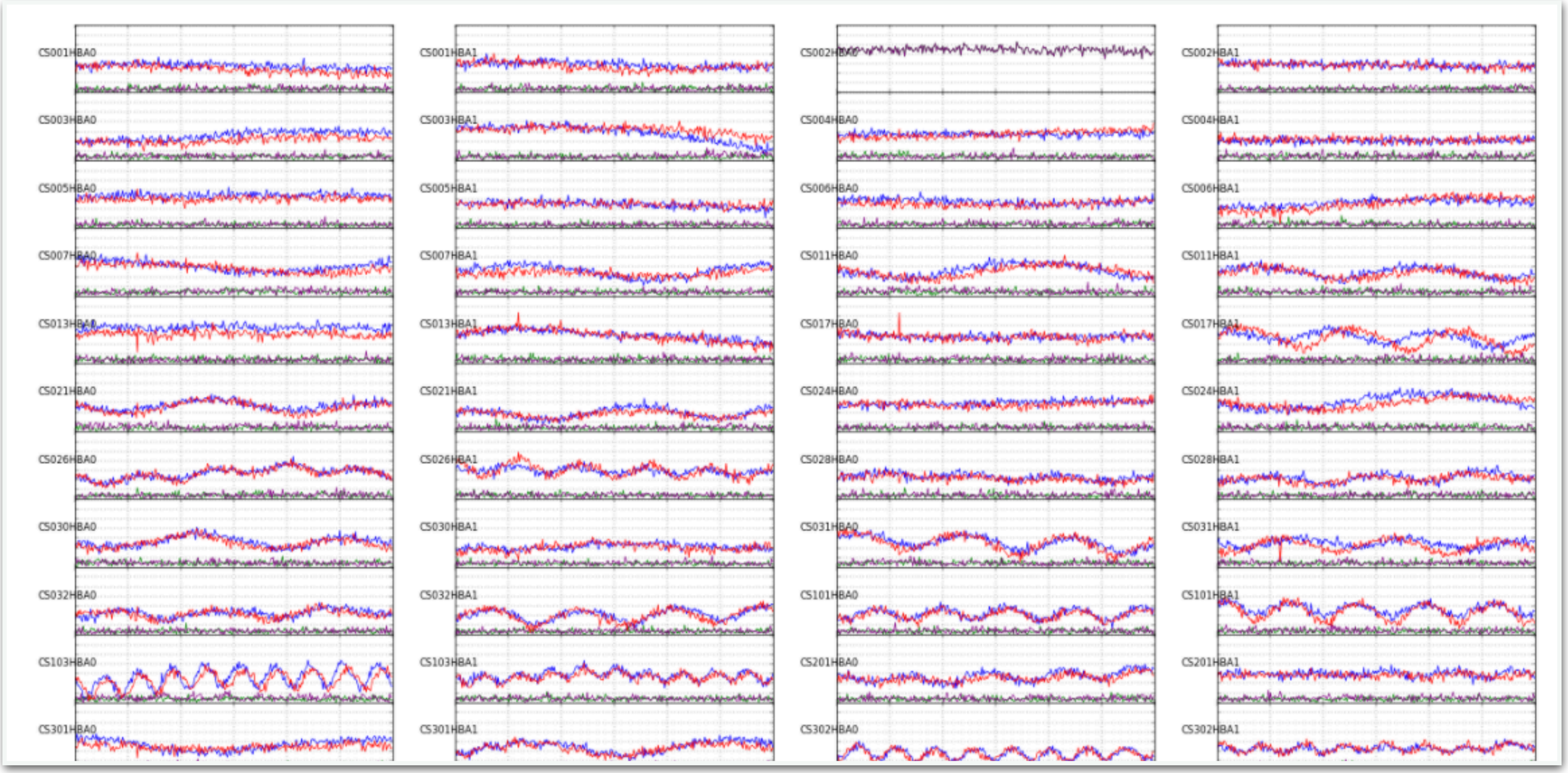
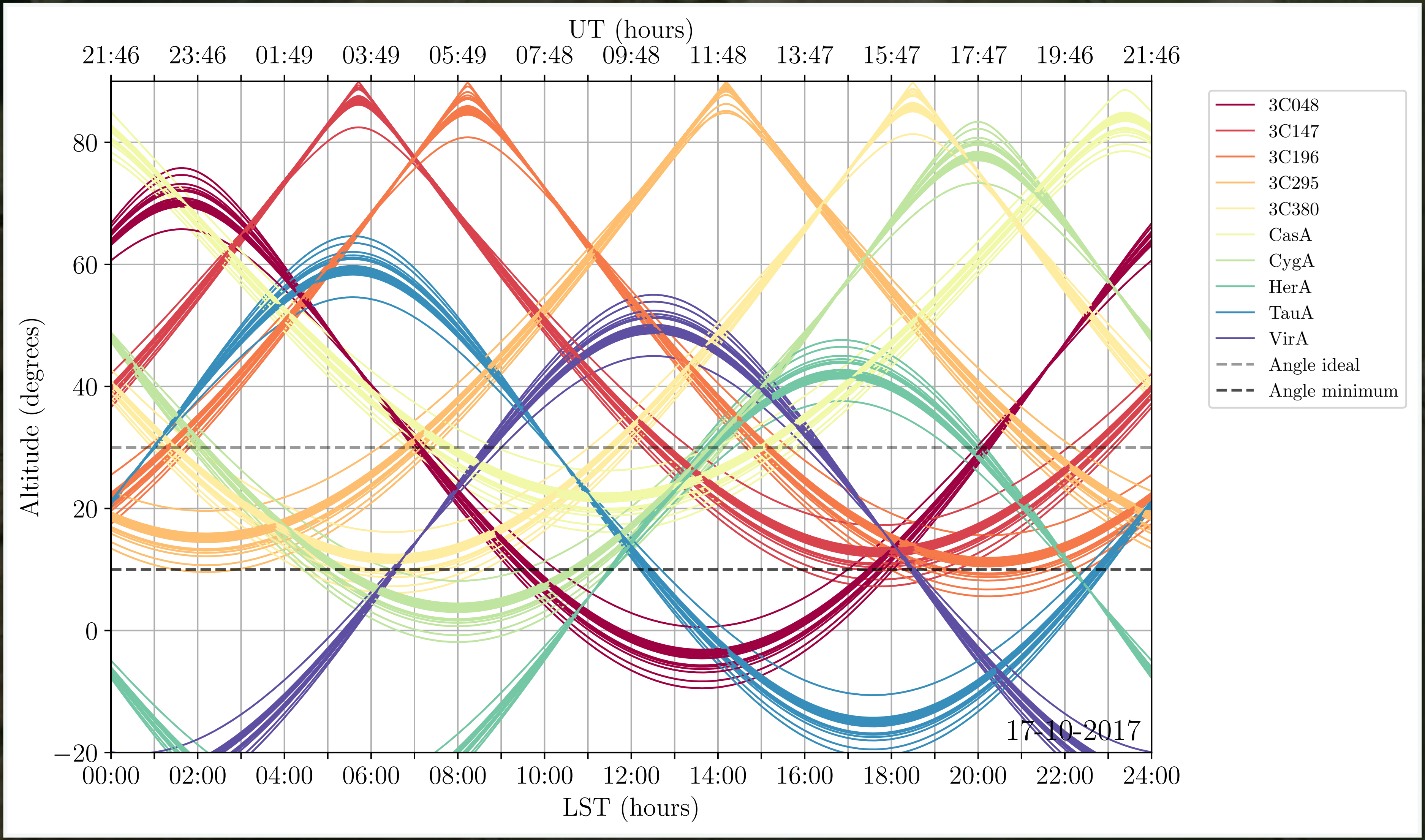
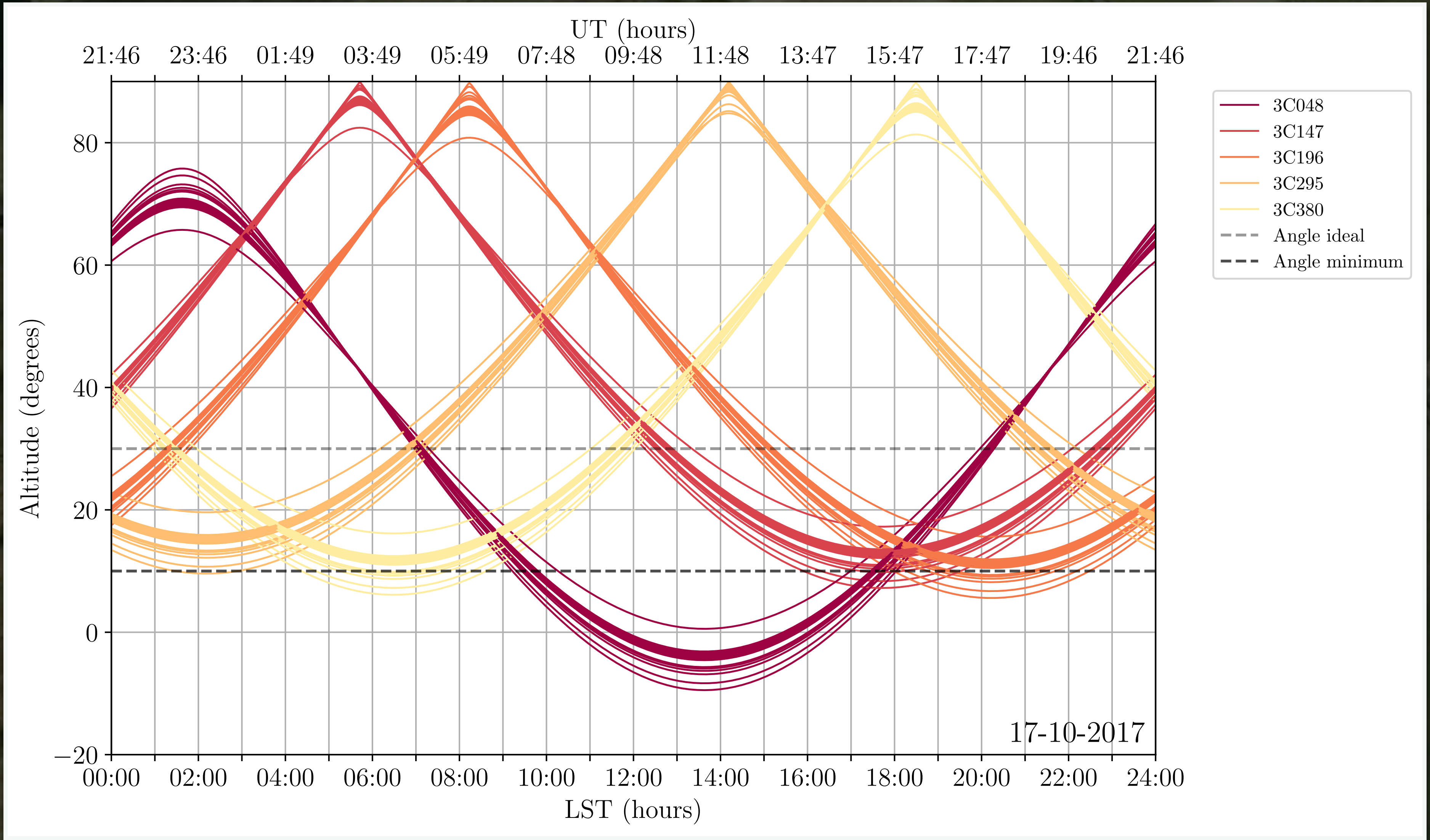



**Above**: visibilities over time to CS002HBA0 at 120 MHz, showing the drift in amplitude over time (even here for a relatively short calibrator observation)

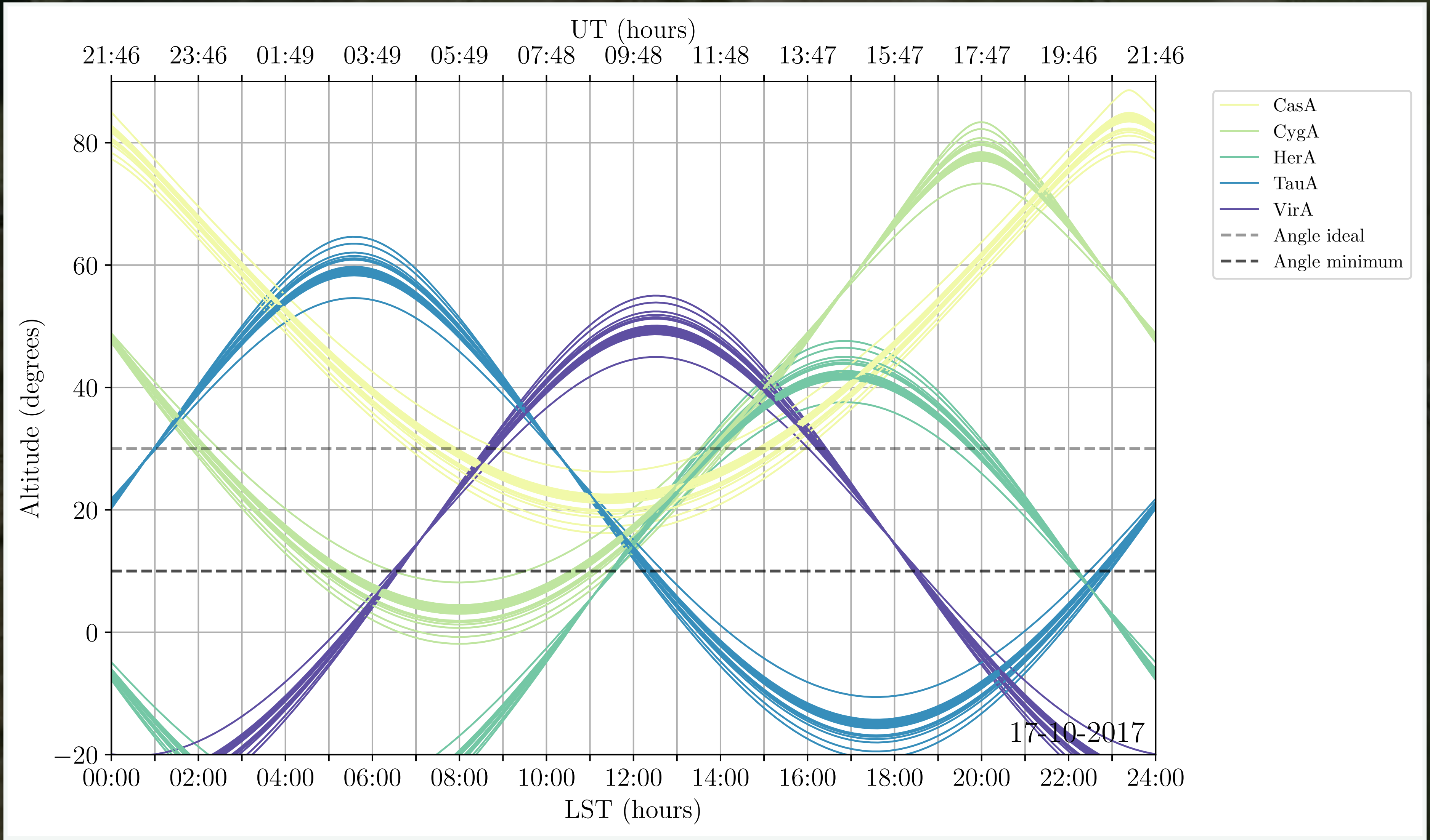
# Key LOFAR sources



# Key LOFAR sources: Calibrators

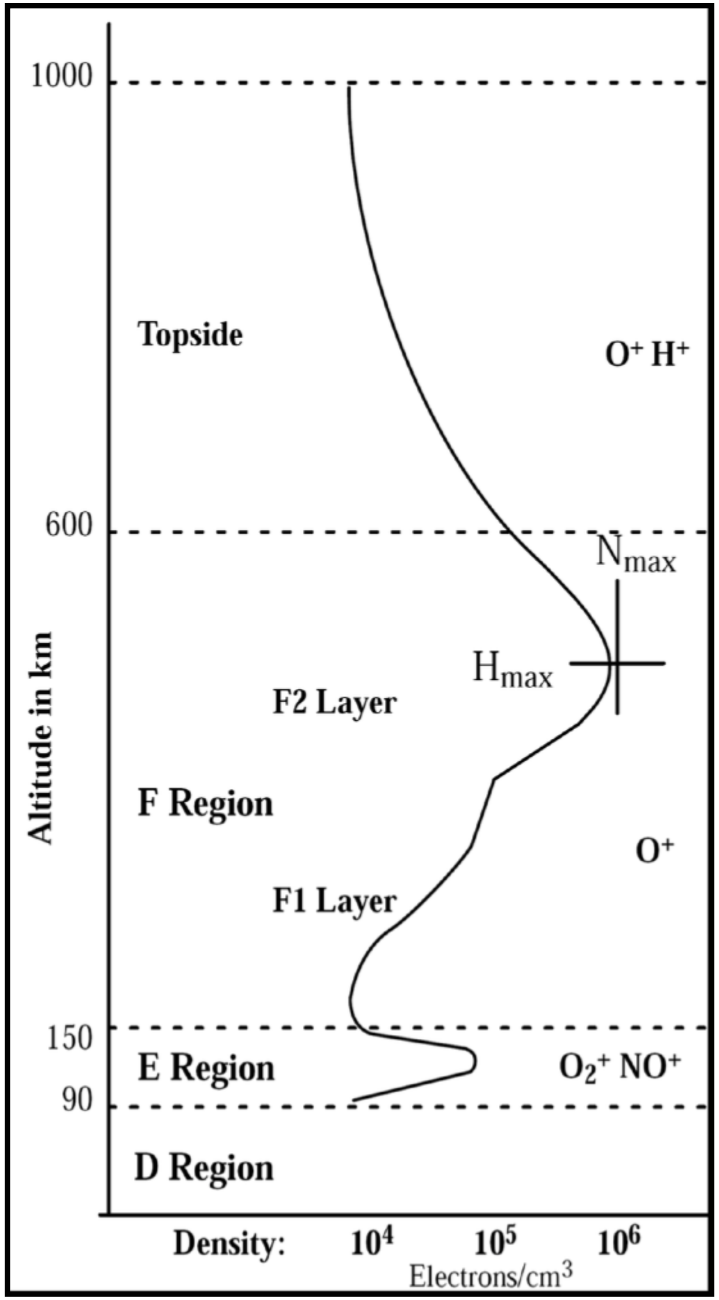


# Key LOFAR sources: A-Team



# 3. Direction dependent effects II - The atmosphere

# The ionosphere

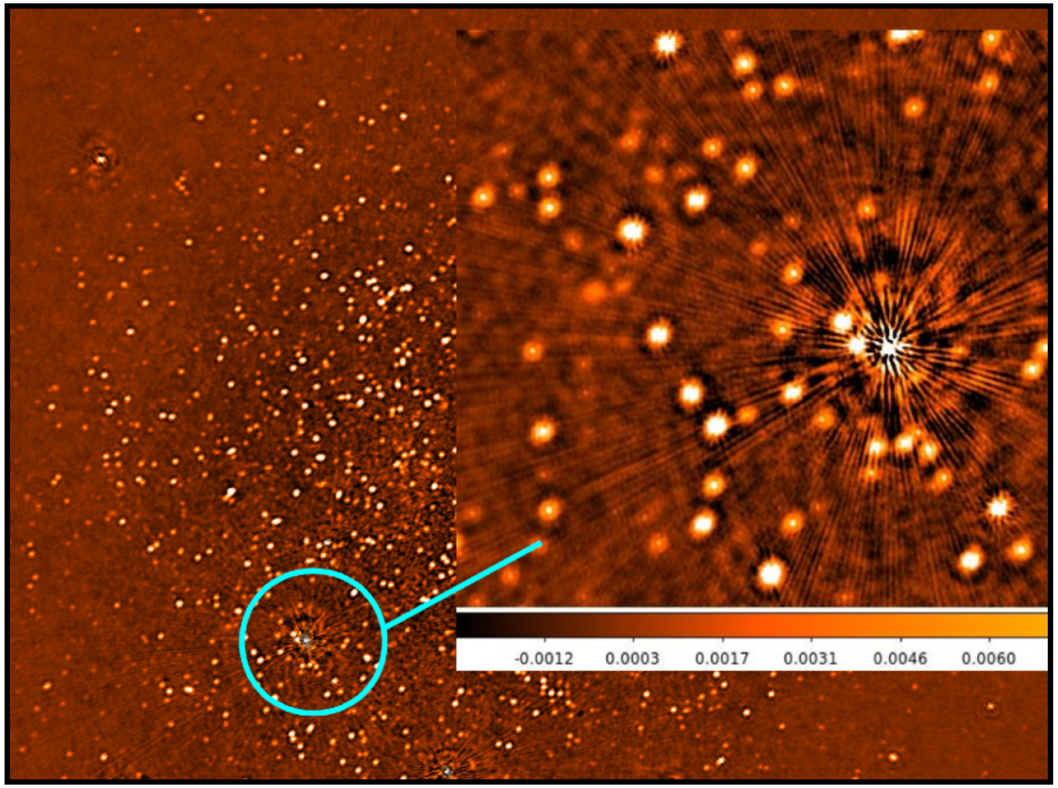



The ionosphere is a reflecting (to long wavelengths) layer of the atmosphere at ~ 125 km

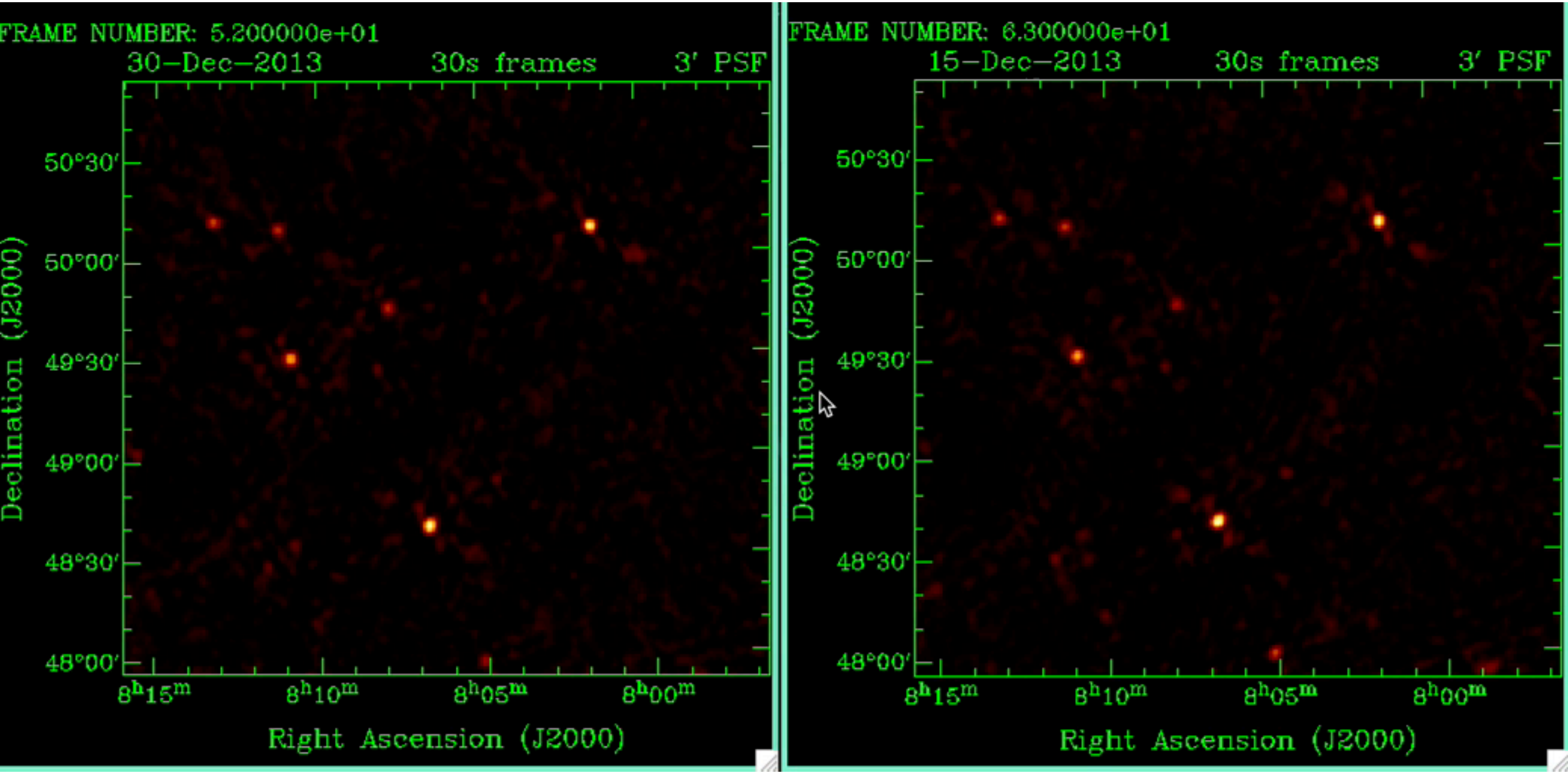
Structure and electron density changes with altitude

Affects propagation of radio waves through:

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



# The ionosphere

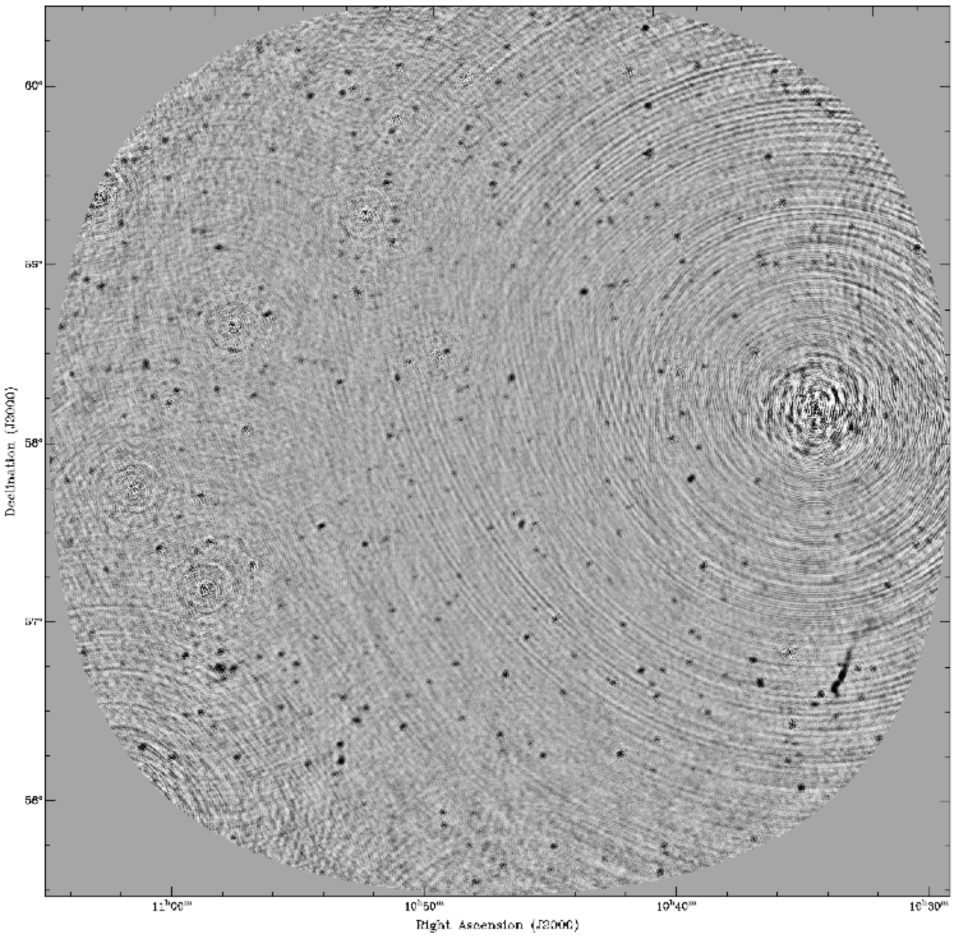


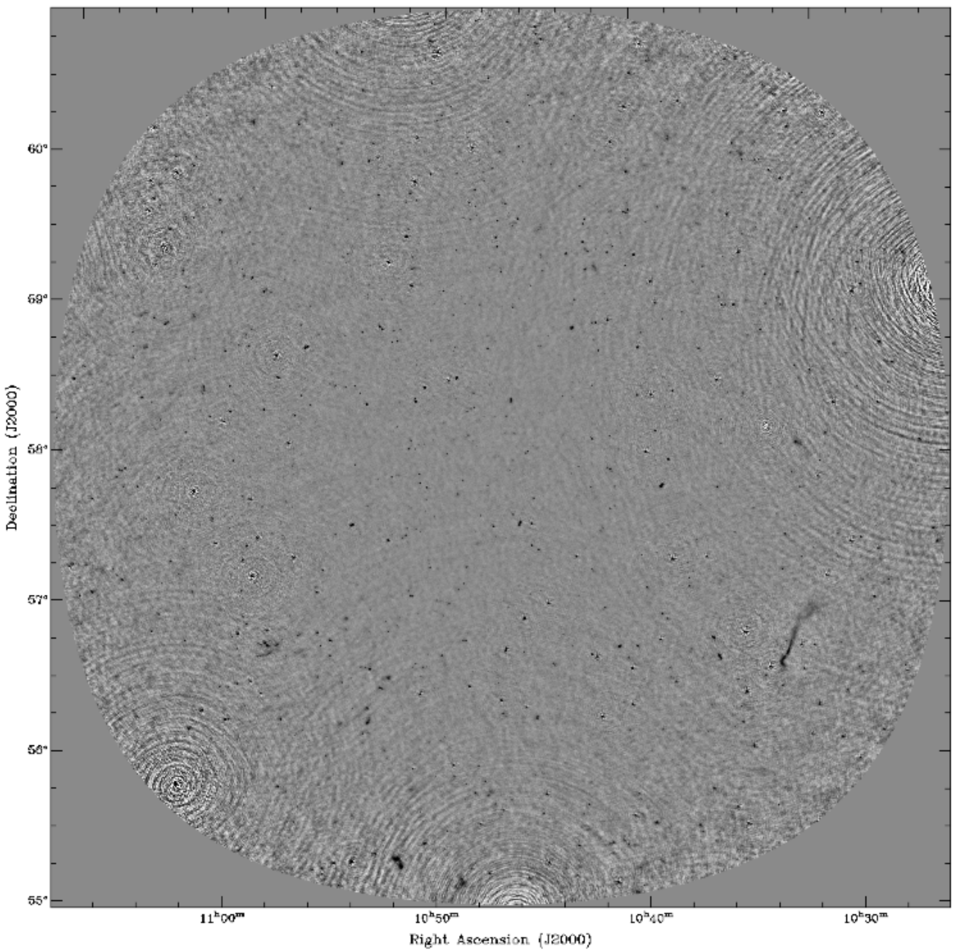

*Ger de Bruyn*

# Direction dependent calibration

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

*Elizabeth Mahony*



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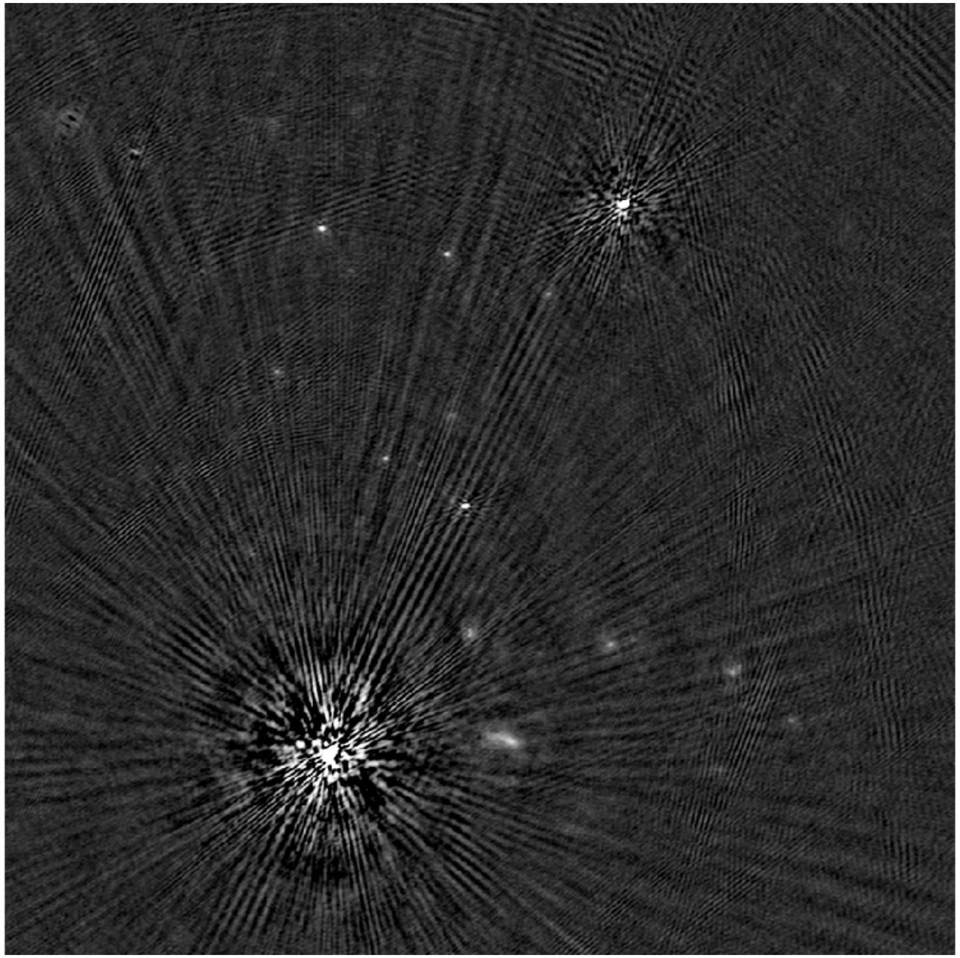
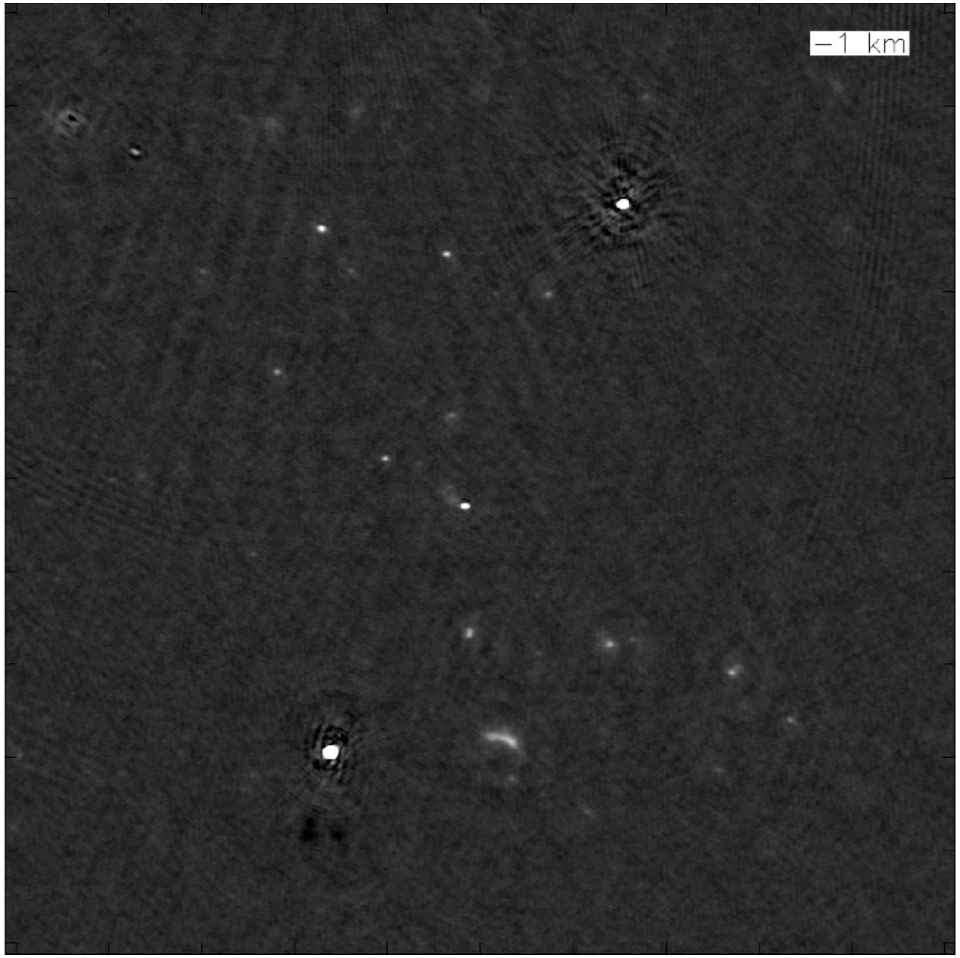
*Wendy Williams*





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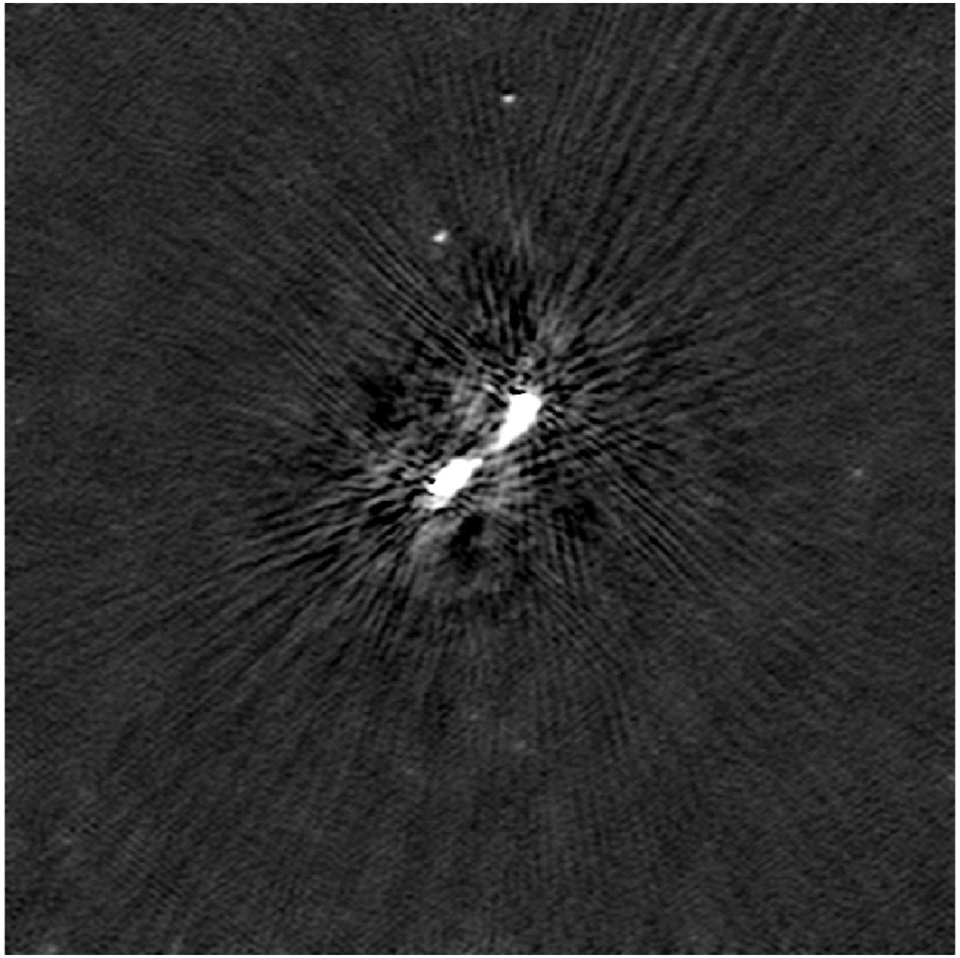
*Wendy Williams*



## Telescope Scientists - Science Operations & Support (SOS)

| | Roberto Pizzo | Richard Fallows | Marco Iacobelli | Vanessa Moss | Emanuela Orru' | Aleksandar Shulevski | Sander ter Veen | Matthijs van der Wiel | Pietro Zucca |
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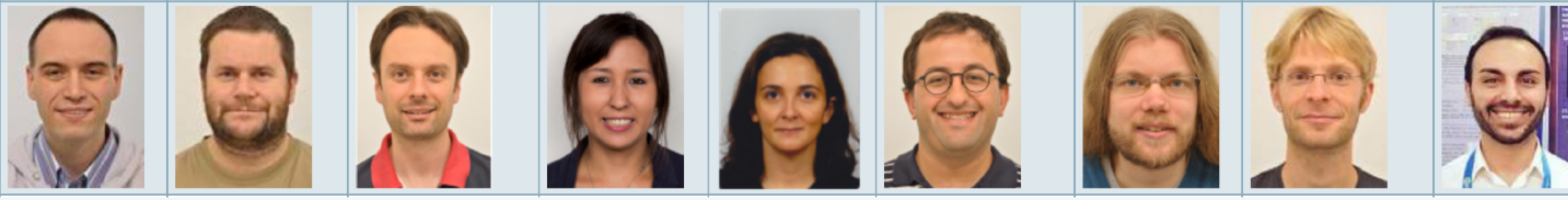

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LOFAR

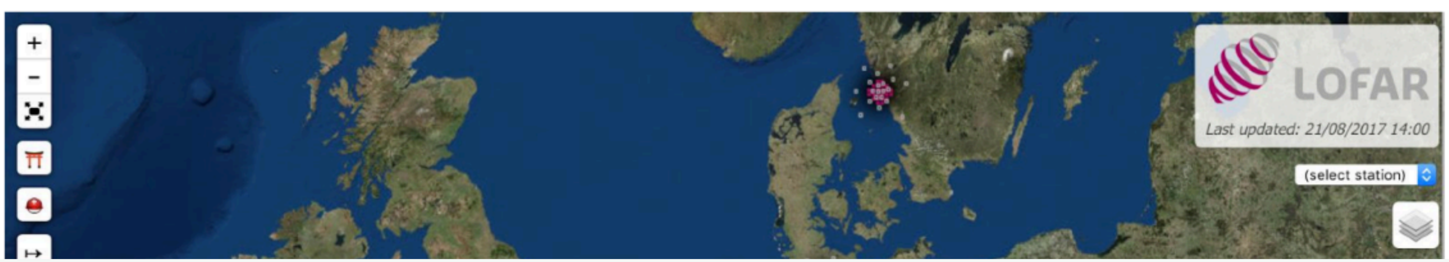
# LOFAR: Quick Start Guide

|| v1.1 || 16th October 2017 ||

*This document aims to provide a succinct overview of various aspects of LOFAR, supplemented by links to external, more detailed information. It is specifically aimed at new users, but contains information relevant for all users of LOFAR. Any suggestions, improvements or comments can be sent to sos@astron.nl.*

**What is LOFAR?**

LOFAR (LOw Frequency ARray) is an international telescope operated by ASTRON spanning several countries, including the Netherlands, France, Germany, Ireland, Poland, Sweden and the UK, currently comprising 51 individual stations. There are two types of antennas at each station: the High Band Antennas (HBA, 110-240 MHz) and Low Band Antennas (LBA, 10-90 MHz). In total there are around 8,000 antennas spread across the continent.




http://astron.nl/~moss/lofar/LOFARQuickStartGuide-v1.1.pdf

# Summary

ASTRON

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 (c.f. John/Andre's talk!)

# Acknowledgments

ASTRON

John McKean, for making available his 2015 ERIS lecture on LOFAR
Michiel Brentjens, for LBA sky/near-field imaging and LOFAR technical details
Science Operations & Support, for explanation of various details of LOFAR