LOFAR: history, lessons, status & results

Ger de Bruyn ++

++ LOFAR team, EoR project team

Kapteyn Institute, Groningen &
ASTRON, Dwingeloo

LOFAR: some array design and data processing issues

- A bit of history, descope and upgrades
- Configuration , stations, uv-coverage, maximum baseline
- Frequency range, resolution and RFI mitigation issues
- FOV stations, (multi-) beaming
- Data processing and data products
- Foregrounds (total intensity, polarization)
- Ionospheric effects and calibration
- Some LOFAR and EoR results

LOFAR rescope and upgrades

LOFAR changes/evolution in configuration/specs

Important changes: for good or bad

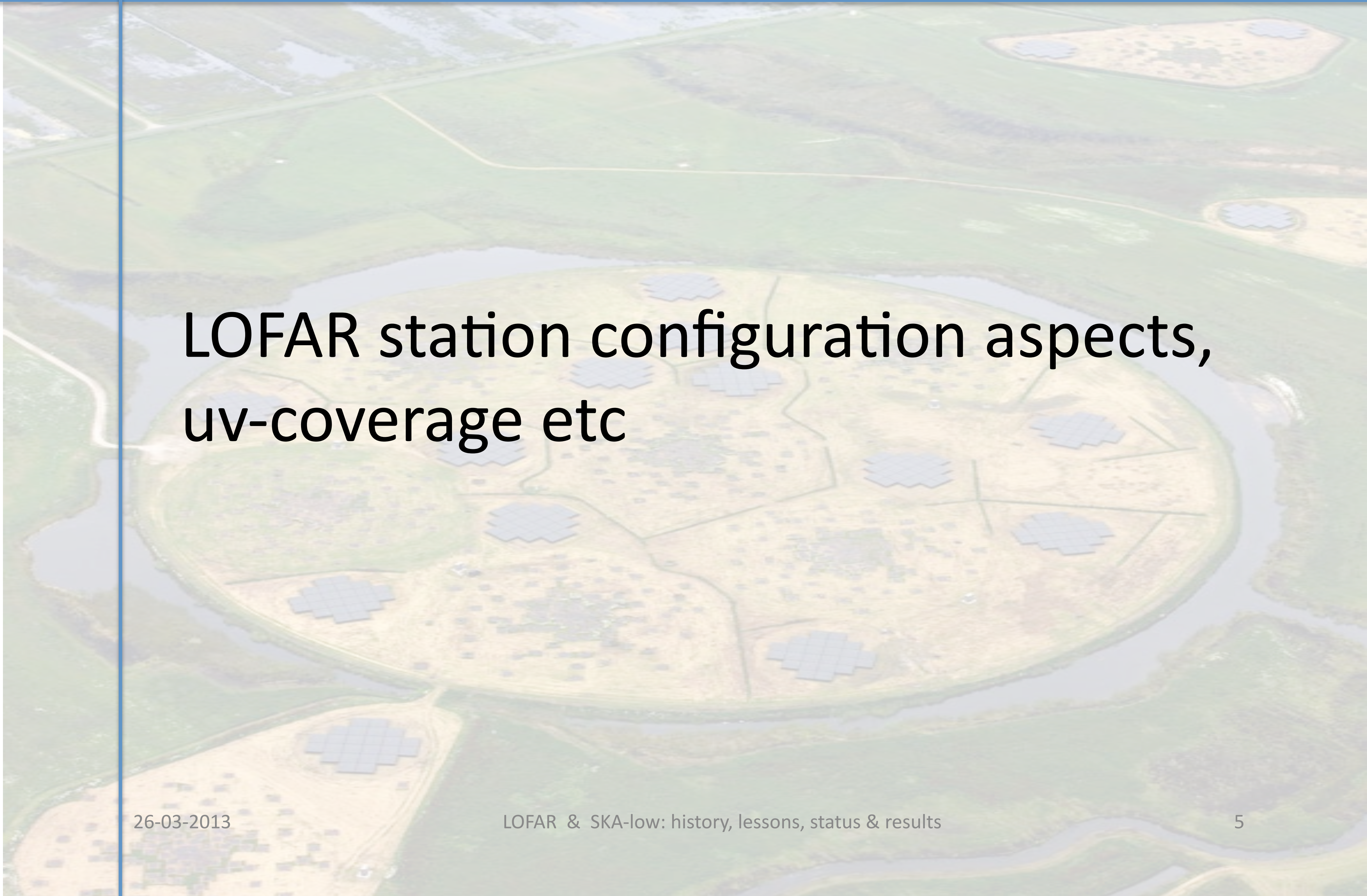
Sep 2007: rescope from 32 CS + 45 RS → 18x2 CS + 18 RS array
NL stations from 96 tiles/RCUs → 48 tiles/RCU's
→ barely complete uv-coverage (worries for EoR)
→ loss in sensitivity factor 3.5 !!

Losses for EoR / surveys somewhat compensated by larger FOV

2009 BlueGene correlation bandwidth: 32 MHz → 48 MHz
2 RS → 2 split CS

2010 4 additional CoreStations **24x2 CS + 16 RS**

Oct 2012: 16-bit → 8-bit data transport : 48 → 96 MHz bandwidth !!
Oct 2012: all core stations time-aligned on a single clock



LOFAR station configuration aspects, uv-coverage etc

The LOFAR observatory : brief overview

LBA (10) 30 - 90 MHz
isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)

Core	2 km	24 stations
NL	80 km	14(16) stations
Europe	> 1000 km	8+ stations

A station has 24 - 48 - 96 antennas / tiles

Principle of **Aperture Synthesis**

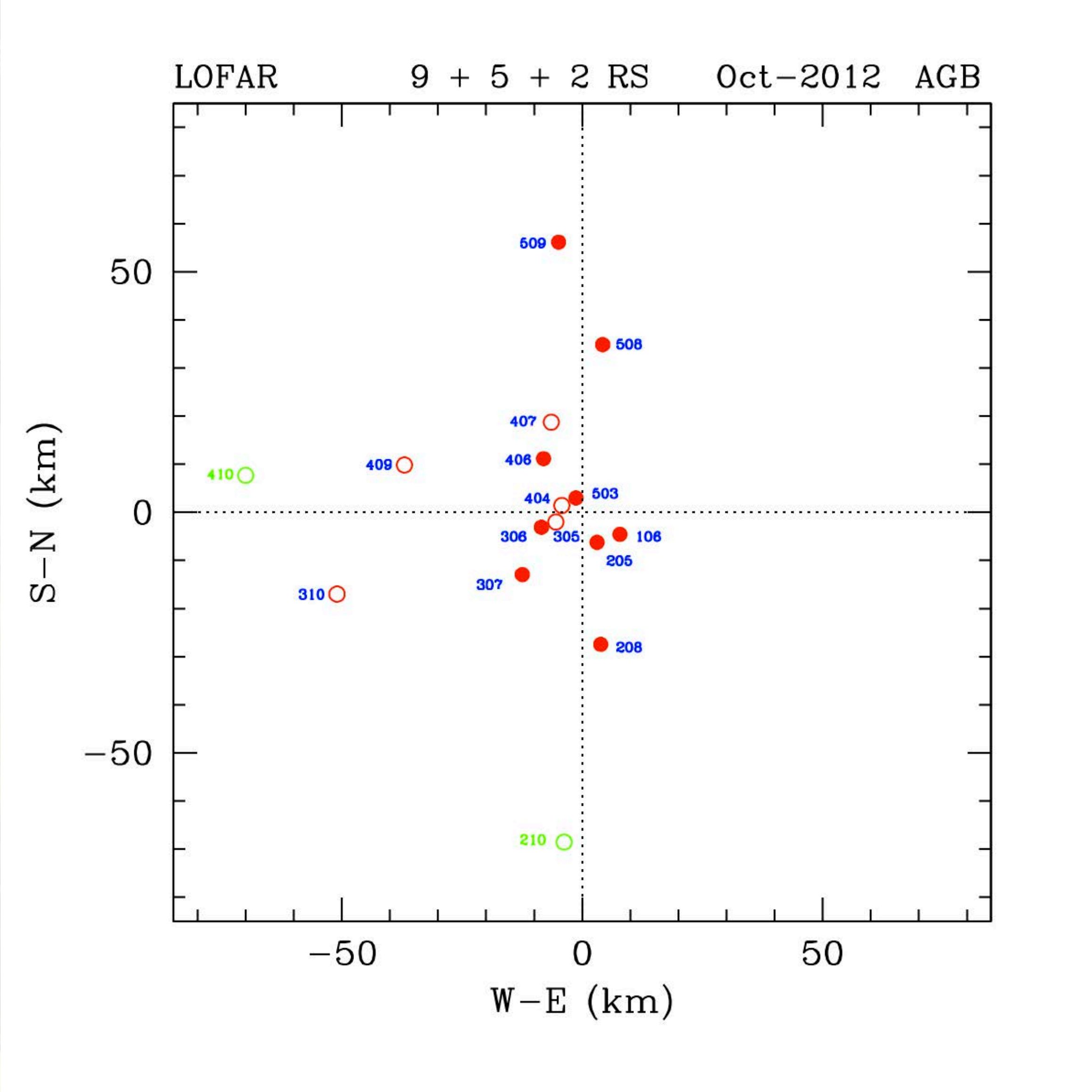
Array resolution: sub-arcsec to degrees

Pulsars: 128 coherent tied-array(s), (in)coherent sums

Bandwidth (8-bit mode): 96 MHz !!

Sensitivity (after 8 h, 60 MHz, ~ 60 stations) @ 150 MHz ~ 100 μJy (achieved!)

Locations of 16 Remote Stations (13 operational 2013.2)



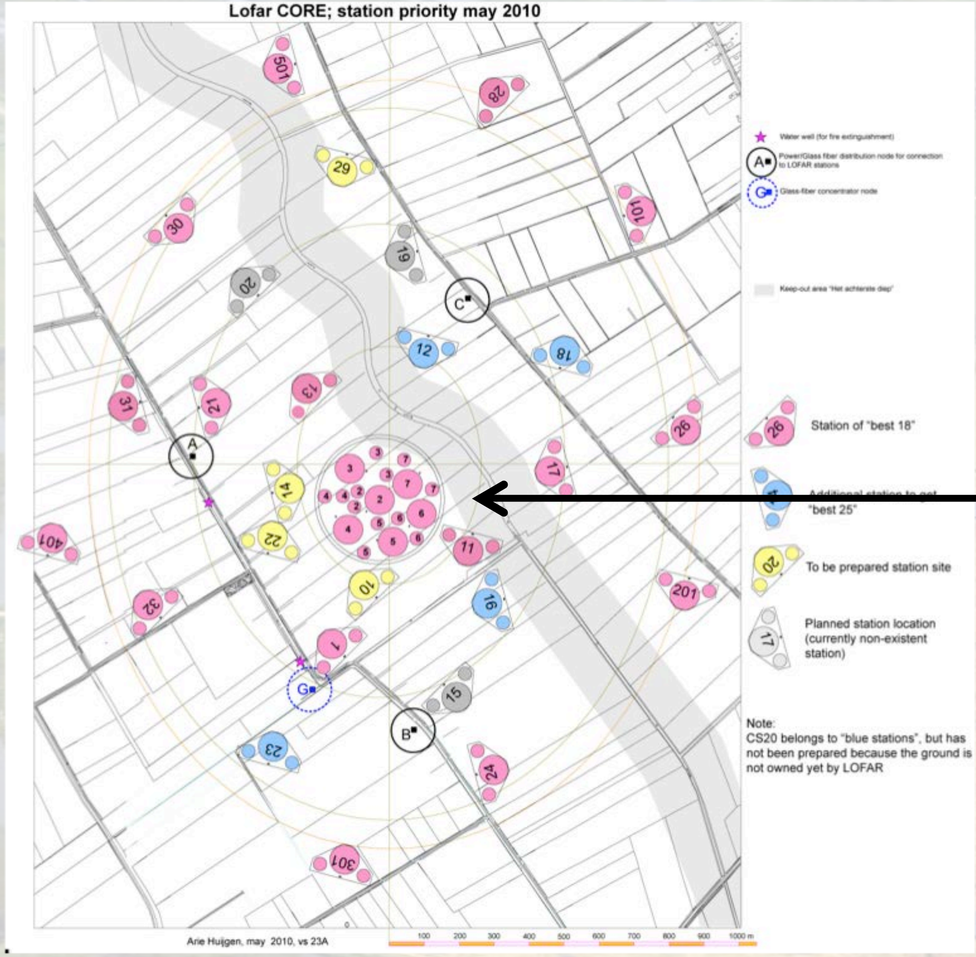
Latest additions

RS305 Nov 2012
RS407 Dec 1
RS409 Dec 20
RS310 Dec 20

RS210 May 2013

RS404 2013/2014
RS410 2013/2014

LOFAR core configuration - ‘tailored’ to EoR project



1000 m

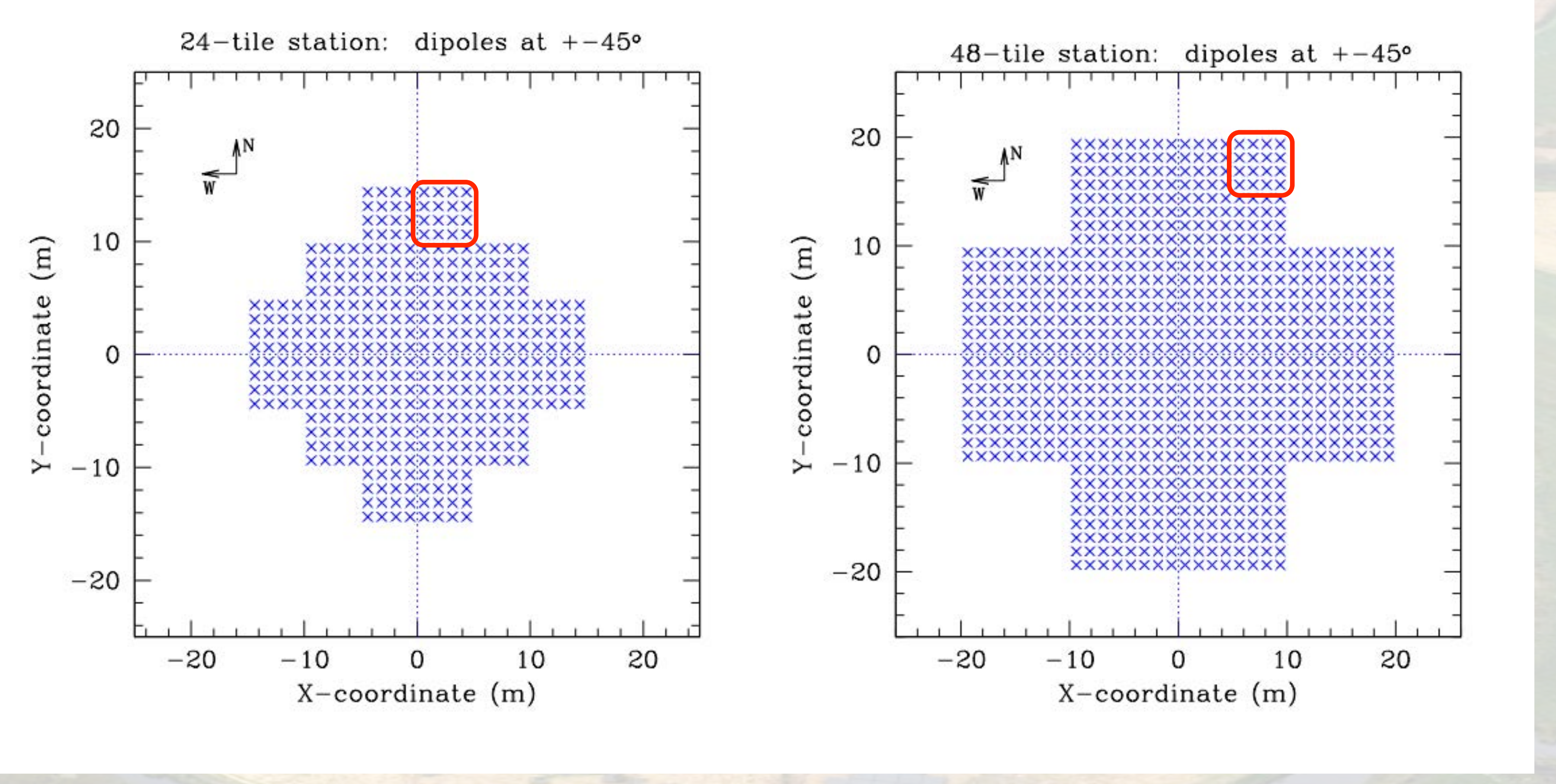
Core dimension
 2 x 2.5 km

the ‘superterp’
diameter ~ 350 m
6 stations
(more are possible !)

1st LOFAR station (May 2009)   48 HBA tiles → 2x24

Layout of 24-tile and 48-tile HBA-stations

All CS and RS have a unique rotation ….. to lower interferometric sidelobes



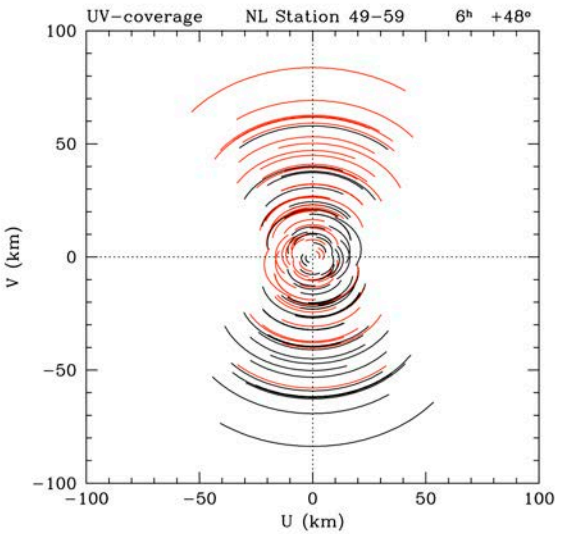
Physical area: 600 m²

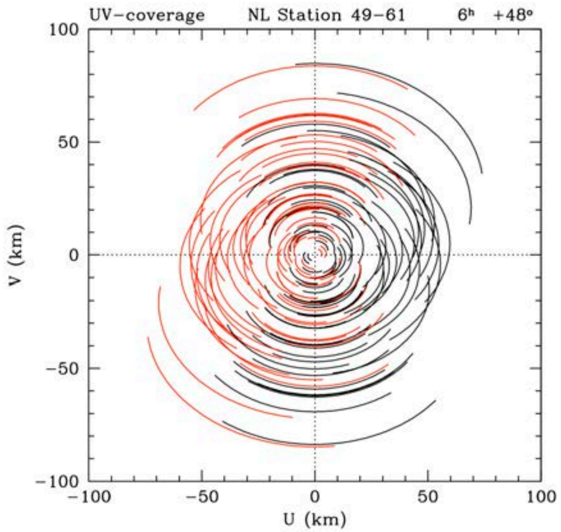
SEFD (150 MHz, zenith) ~ 2600 Jy

Physical area: 1200 m²

SEFD (150 MHz, zenith) ~ 1300 Jy

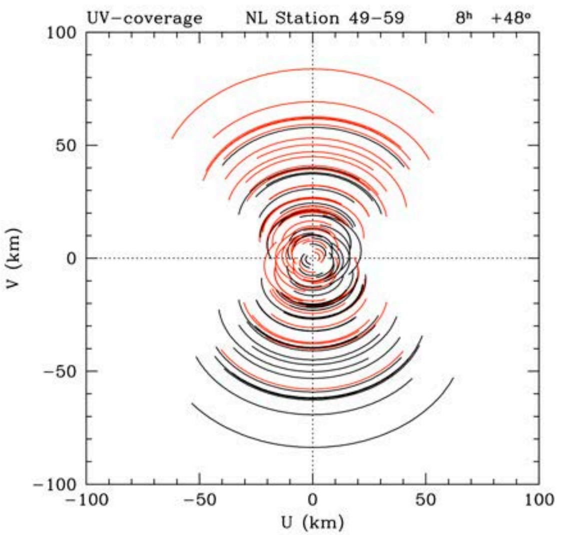
3C196: 11 or 13 Remote Stations 6h vs 8h synthesis

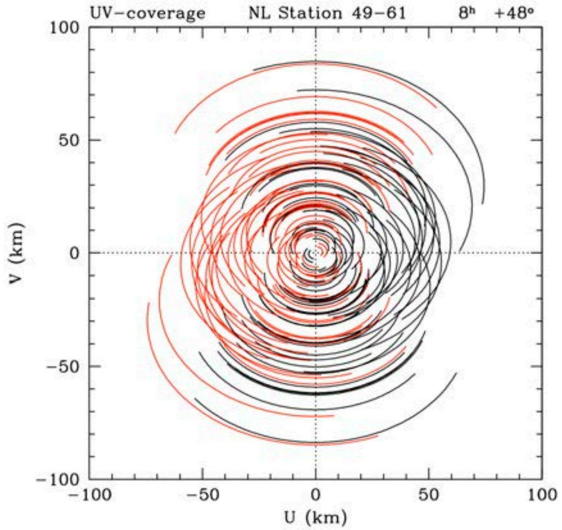




← 6h →

11 Stations 13

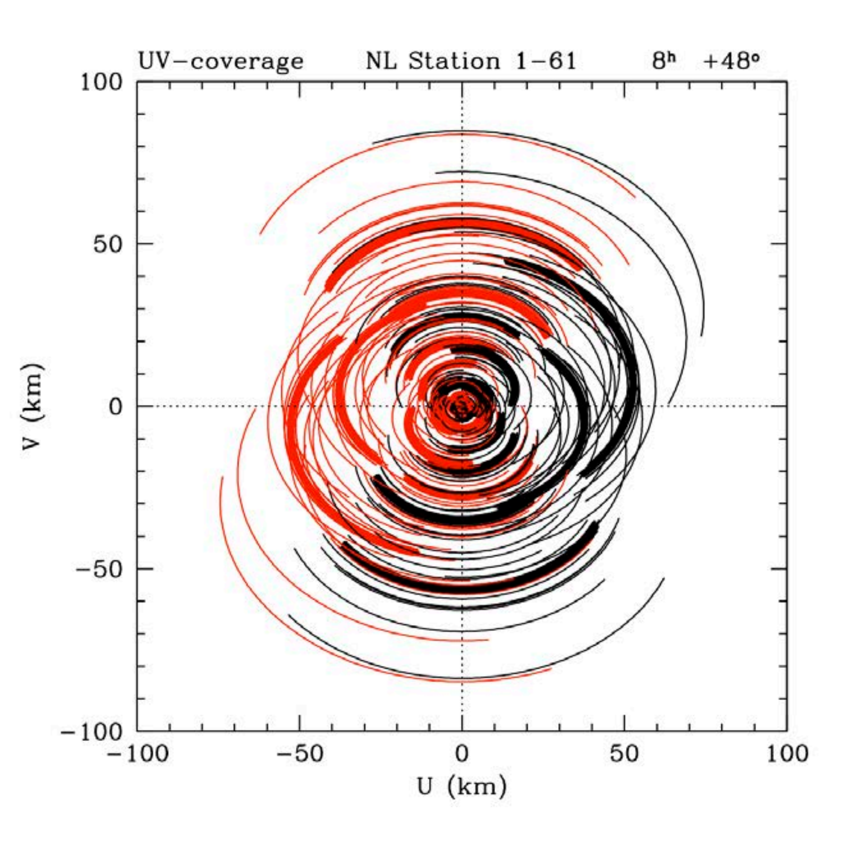


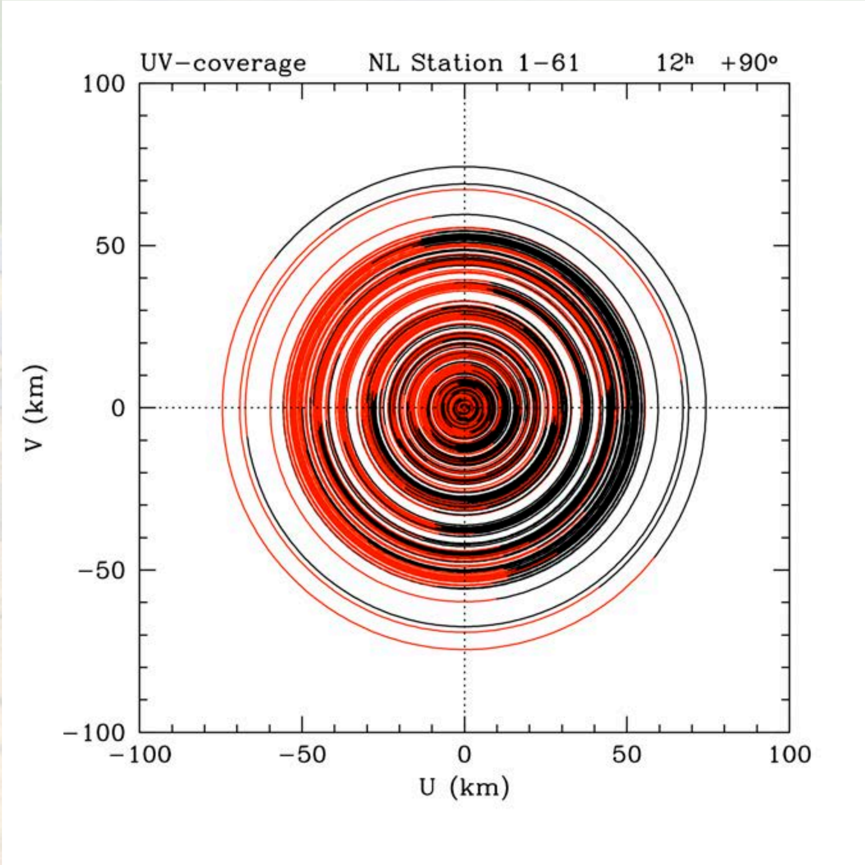


← 8h →

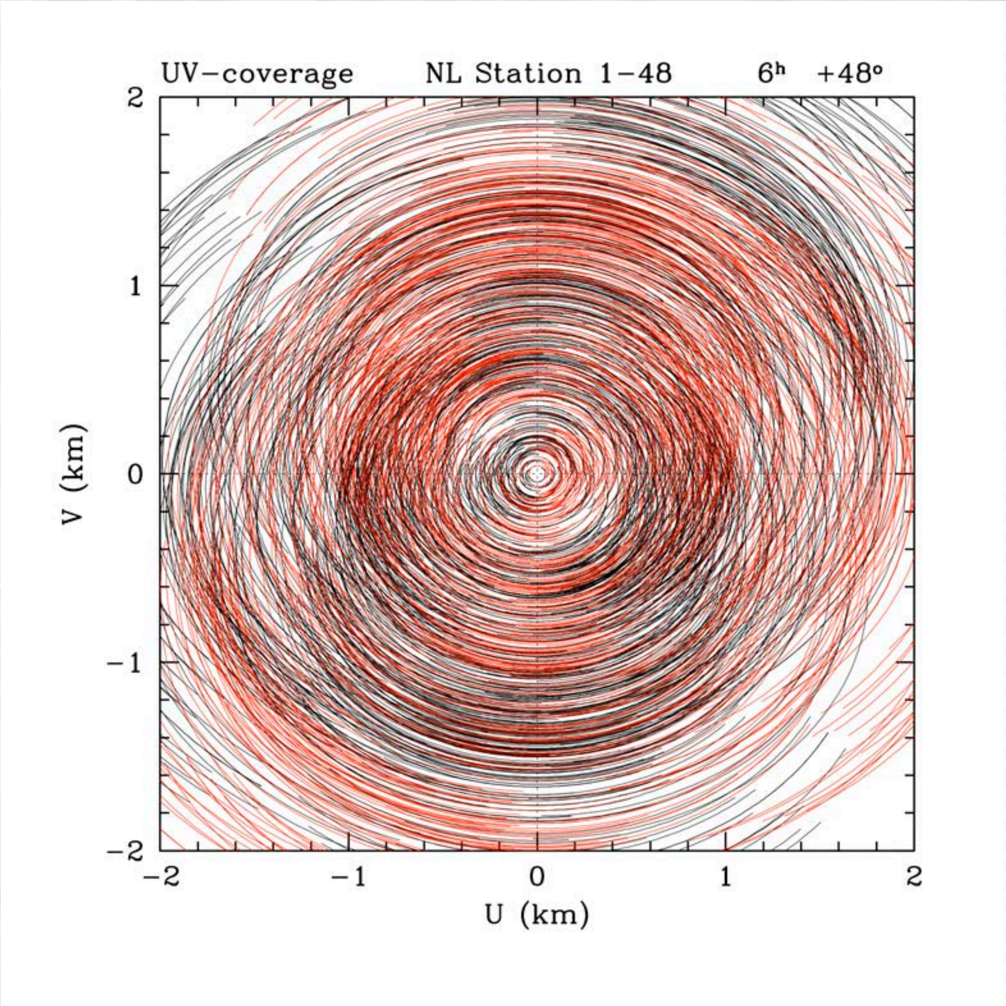
LOFAR uv-coverage with 48 CS + 13 RS

3C196 8h 'EoR-windows' NCP 12h





LOFAR core uv-coverage at Dec +48^o after 6^h



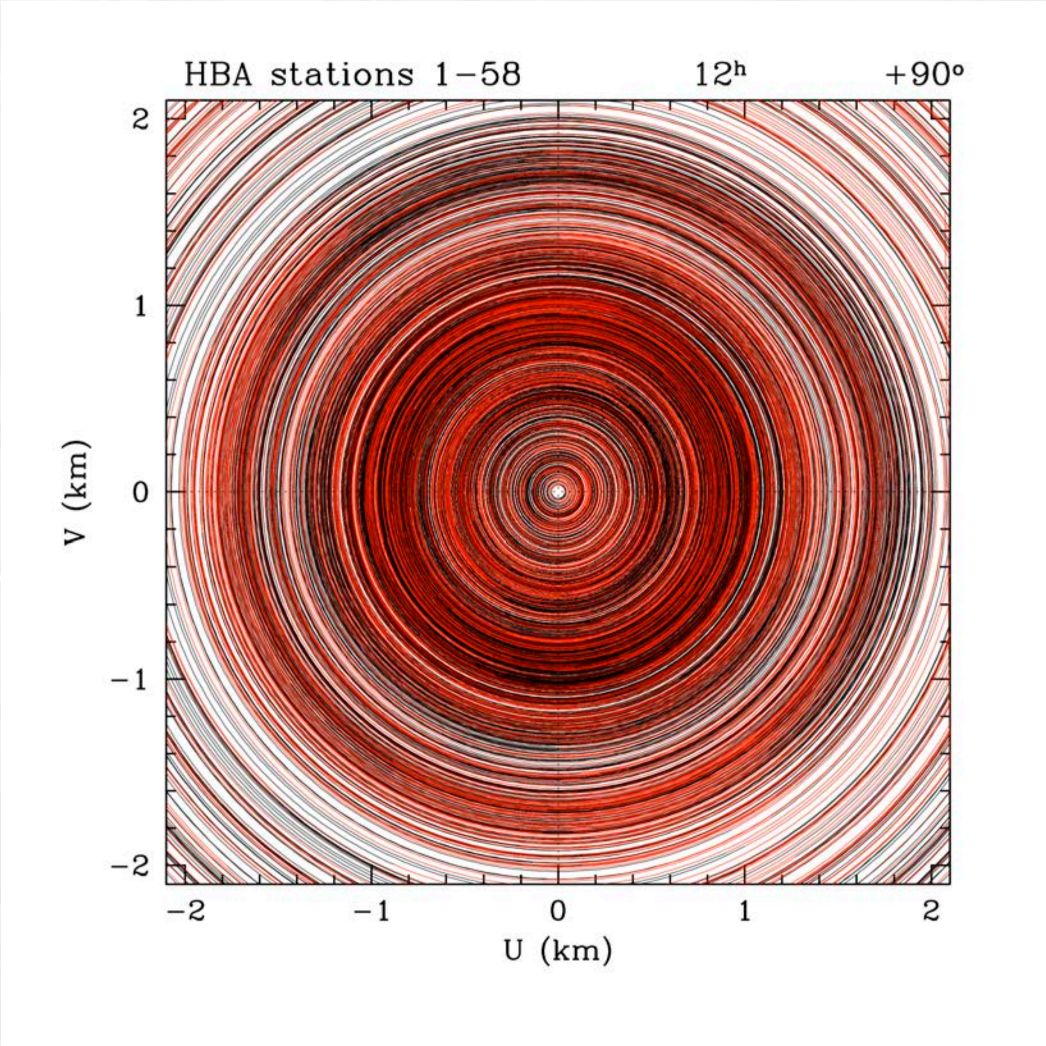
Complete uv-coverage is essential for the EoR

EoR signals are detectable on short baselines only (less than (say) 2 km)

→ resolution (PSF) 3- 5 ’

Long LOFAR baselines (10-60 km) are used for modeling, station calibration, confusion removal, and ionospheric calibration.

Inner uv-coverage at dec +90°

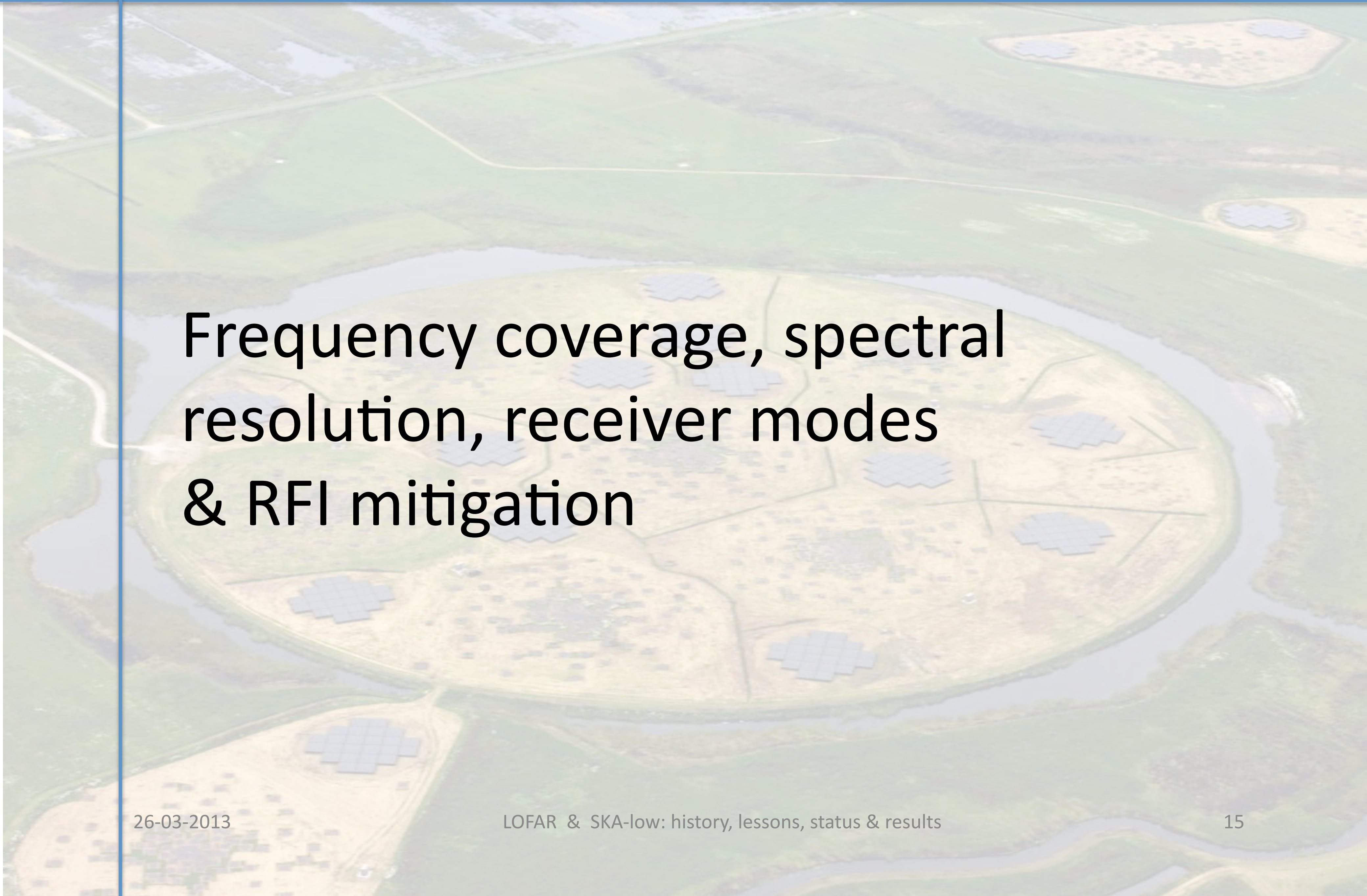


NCP +90°

Elevation 53° !!

Great field !
Alas, not at SKA sites

12h synthesis



Frequency coverage, spectral resolution, receiver modes & RFI mitigation

LOFAR frequency coverage and resolution

Two 12-bit ADC sampling modes: 200 MHz and 160 MHz clock

RFI & wide-field VLBI

(+ 21cm & rec lines)

Frequency filtering done in two digital (Poly-Phase-Filter) stages:
- at station ⇒ 512 subbands (either 156 or 195 kHz)
- at CEP (BG/P) ⇒ 256 channels for each of 488 subbands split over N beams

Oct 2012: 96 MHz total bandwidth → **124,928** channels of 0.76 kHz !

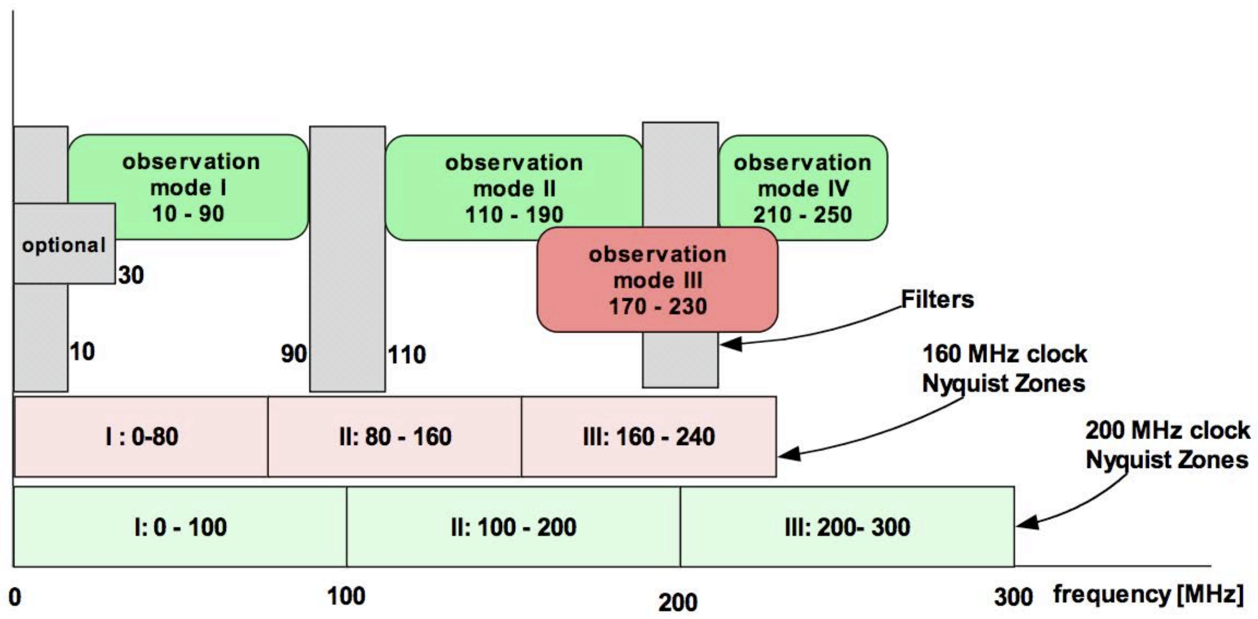


Figure 10 *Selection of Nyquist zones is used to select the observed band in the station.*

RFI mitigation, algorithms and research

Work by Andre Offringa:

Thesis defense: 22 Jun 2012
University of Groningen

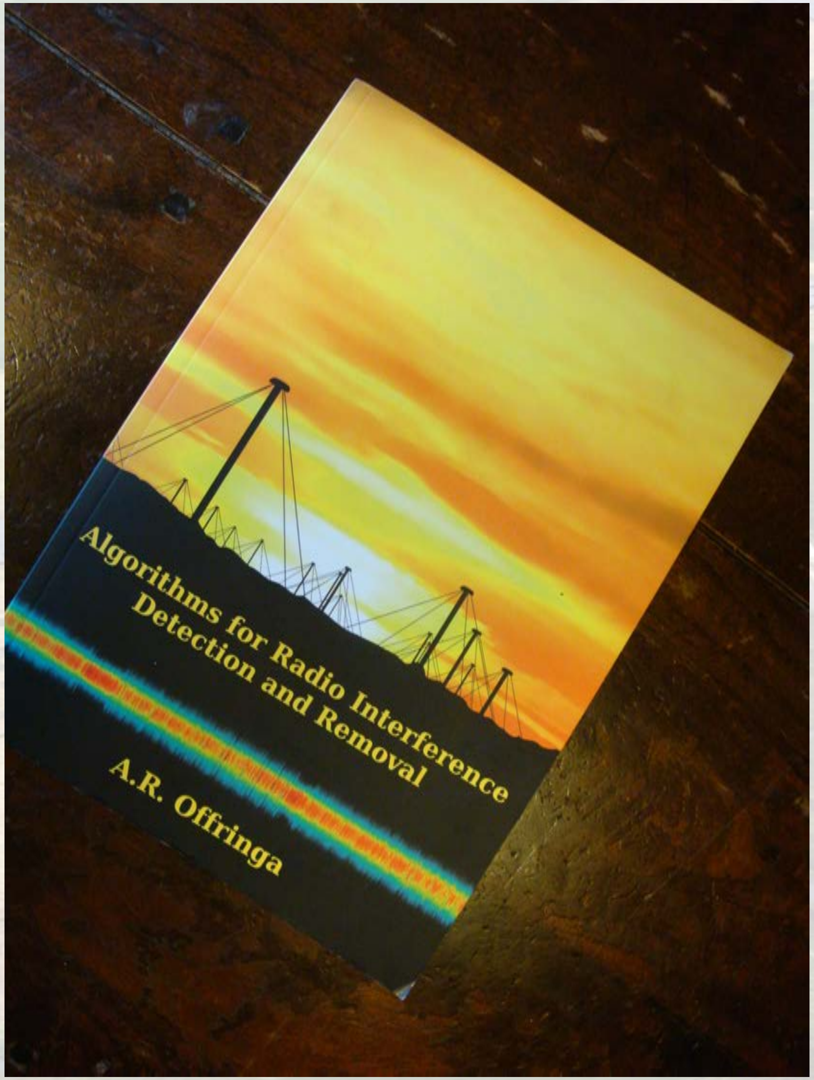
Products:

- AO-flagger

- Low-pass filtering approaches

- The LOFAR radio environment

- Spatial distribution of RFI sources



LOFAR radio RFI environment

Offringa, de Bruyn et al A&A, 549, A11, 2013

LBA 24h (1s, 0.76 kHz)
Only   1.8% RFI

33 stations   9 Oct 2011

HBA 24h   (1s, 0.76 kHz)
Only   3.2 % RFI

13 stations   27 Dec 2010

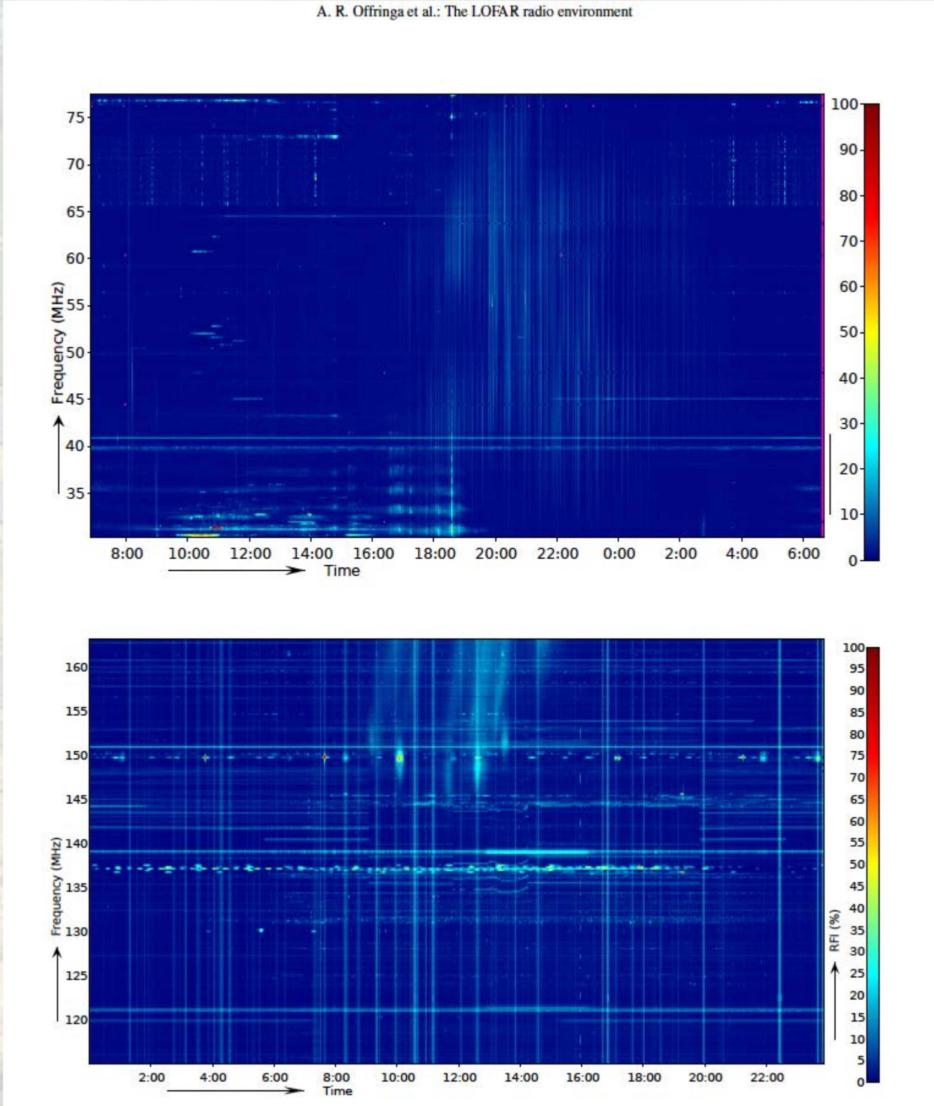


Fig. 10: The dynamic spectra of RFI occupancy during the surveys. Top: LBA, bottom: HBA.

A day in the life of LOFAR: HBA RFI-occupancy

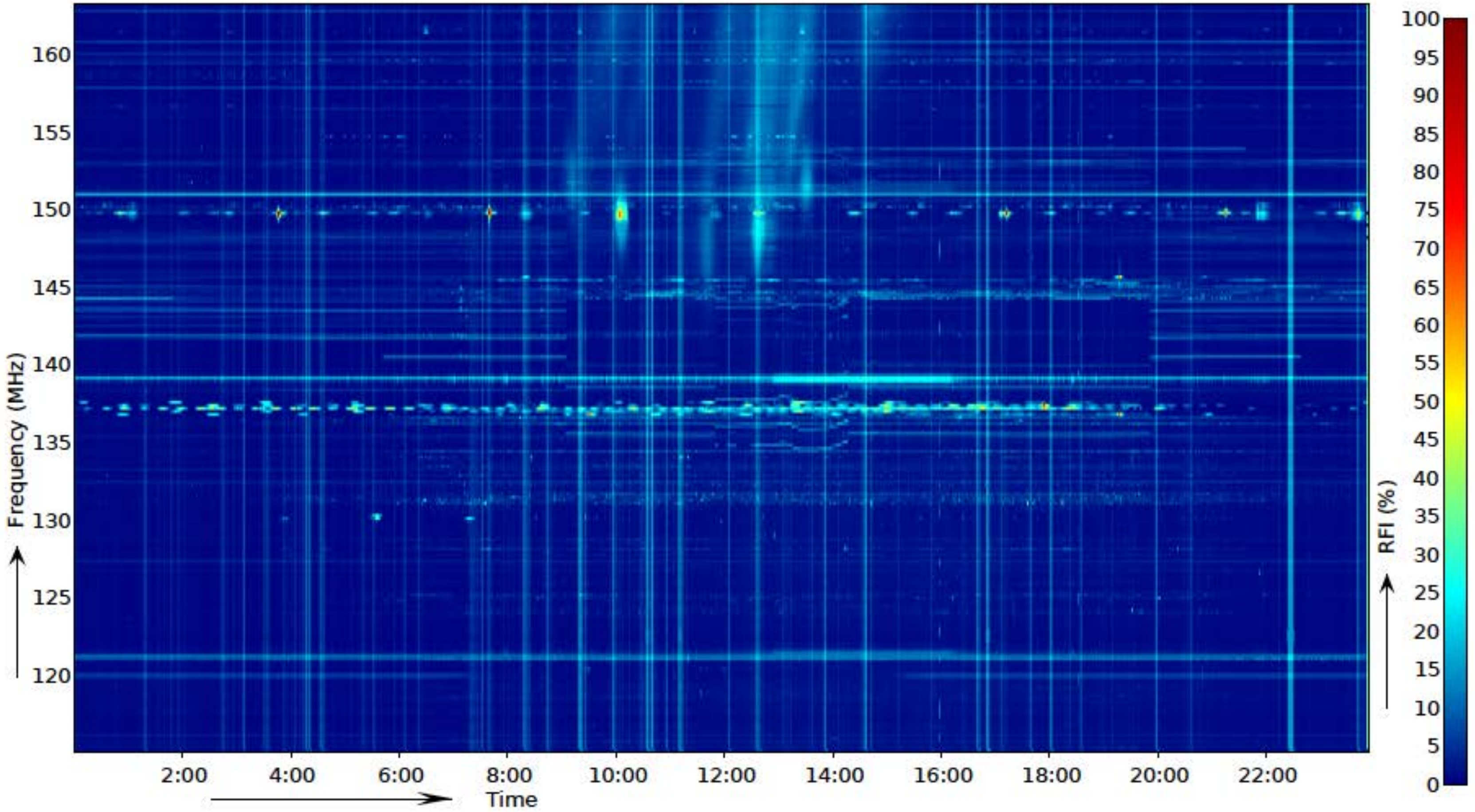
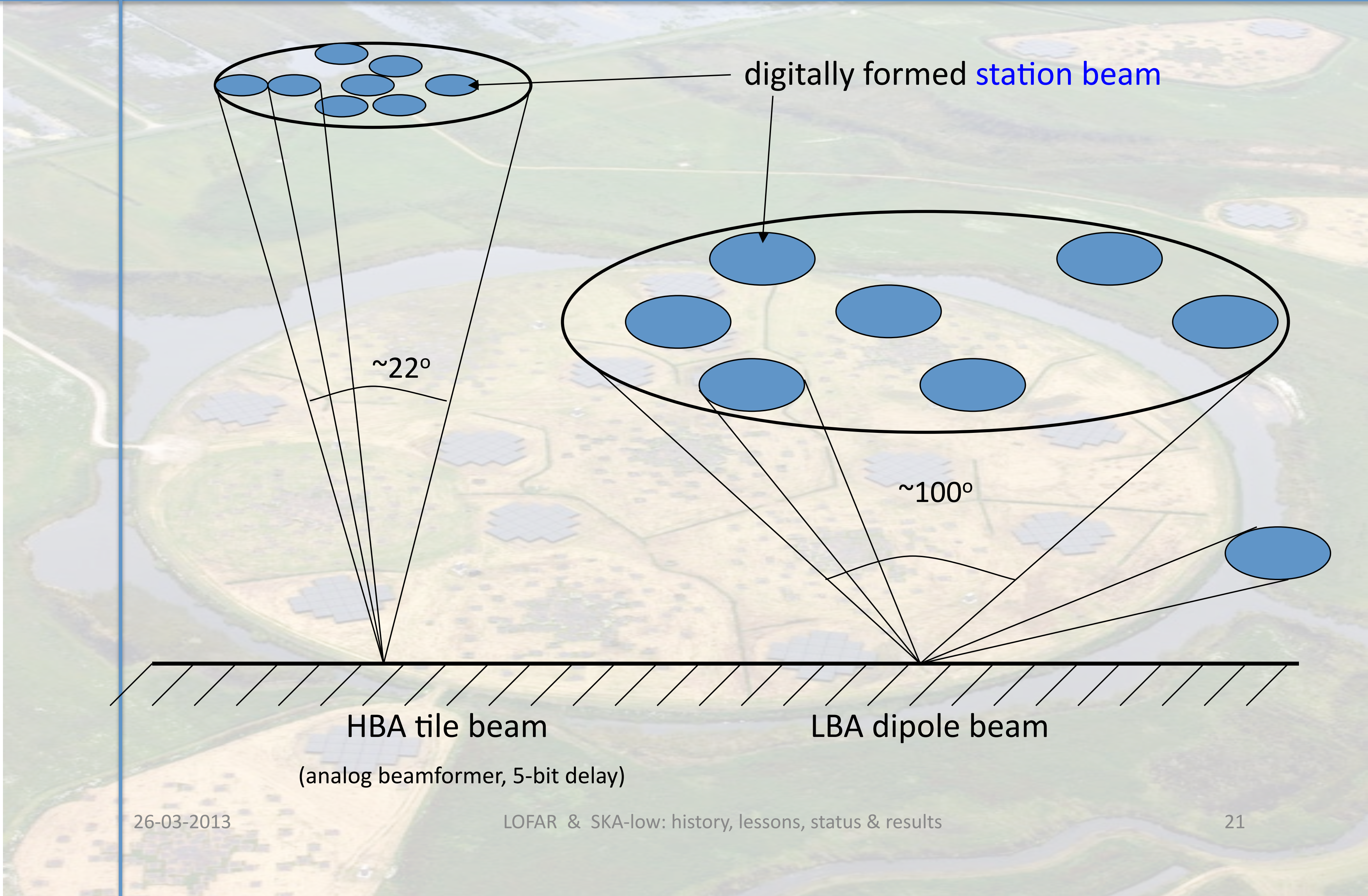


Figure 9. The dynamic spectrum of RFI occupancy during the HBA survey

Offringa et al, 2013

Multi-beaming aspects in LOFAR

LOFAR has a very wide Field-of-View



The future of radio astronomy: multi-beaming !

For imaging LOFAR has up to 8 digital beams (currently)
also expressed as 488 beamlets   (beam - subbands)

This has many, many advantages:

- great flexibility (e.g. EoR observations have 1x72 MHz + 6x4 MHz)
- survey speed
- imaging large areas (limited by LOFAR analog tile beam , 20-25^{o} HPBW)
- inside-beam calibration transfer
- ionospheric calibration (tomography, with extended ground array)
- simultaneous programs (timing pulsars, TOO,… multiple users)

Expandable in the future when processing cheaper
(# digital beams   ≈   # dipoles in station)

SKA AA-low must have multi-beaming !?

Dataprocessing & data products

LOFAR EoR data volume, products and formats

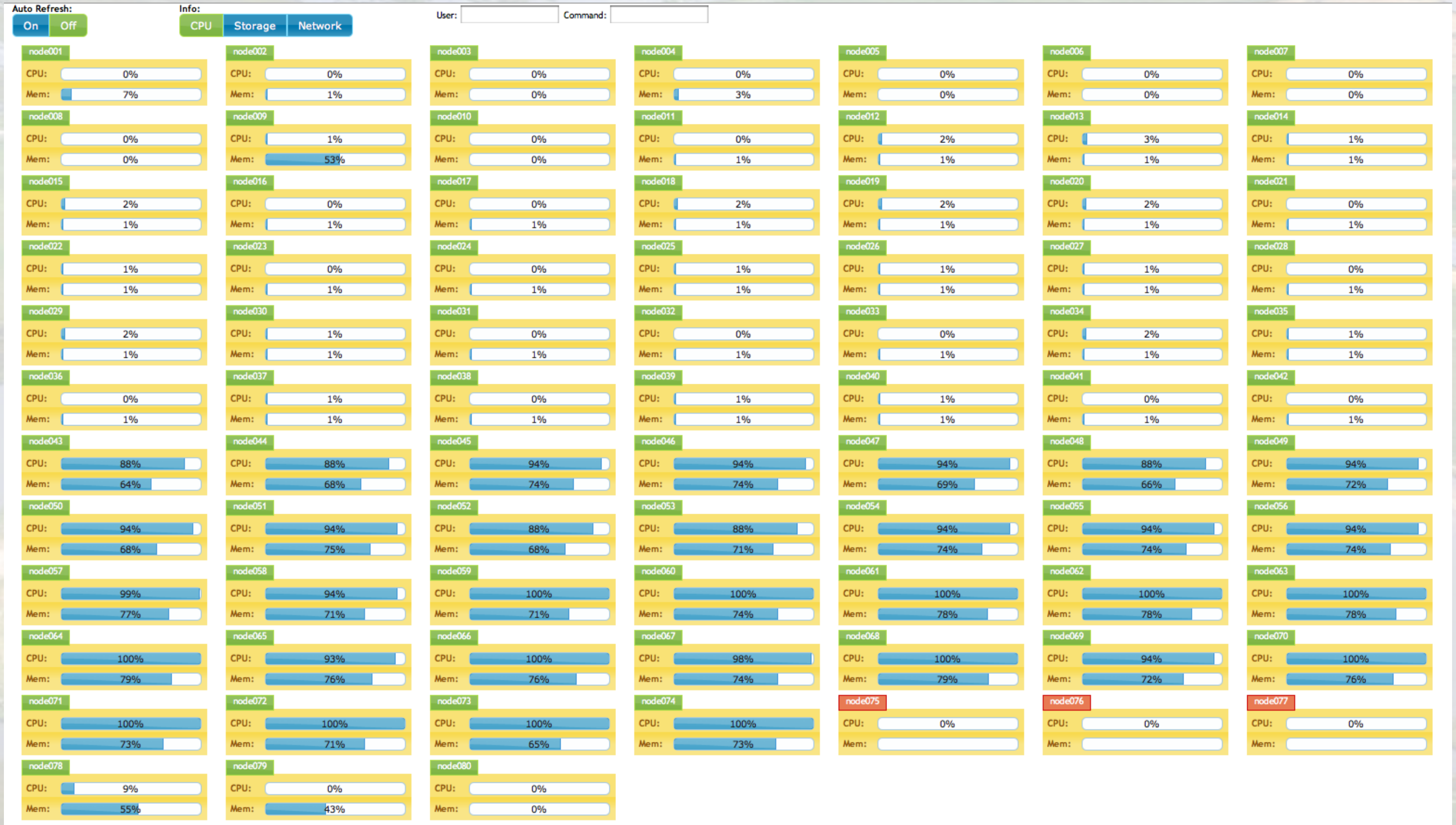
- Measurement Sets: raw, data format 64ch-2s **45 TB/night**

- Processed data sets/formats: **now accumulated ~ 0.5 PB**
  15ch - 2s (NB: 12kHz = 24 km/s velocity resolution at 150 MHz)
  3ch - 2s
  1ch - 10s

- Imagecubes: small, large,
  20x20 deg, 2” pixels, 6” PSF 36k x 36k x 370 (488)→ ~ 1 TB total (Stokes I)
  restored, apparent flux → science analysis
  6x6 deg, 40” pixels, 3’ PSF 512 x 512 x 370) (488) → ~ 1 GB (IQUV)

- Residual visibilities in ‘stripped’ format (gridded?)
  to use in ML inversion
  to use in Foreground Fitting
  to use in PS estimation

Screenshot EoR-cluster: 80-nodes (x 16 CPU + 2 GPU)

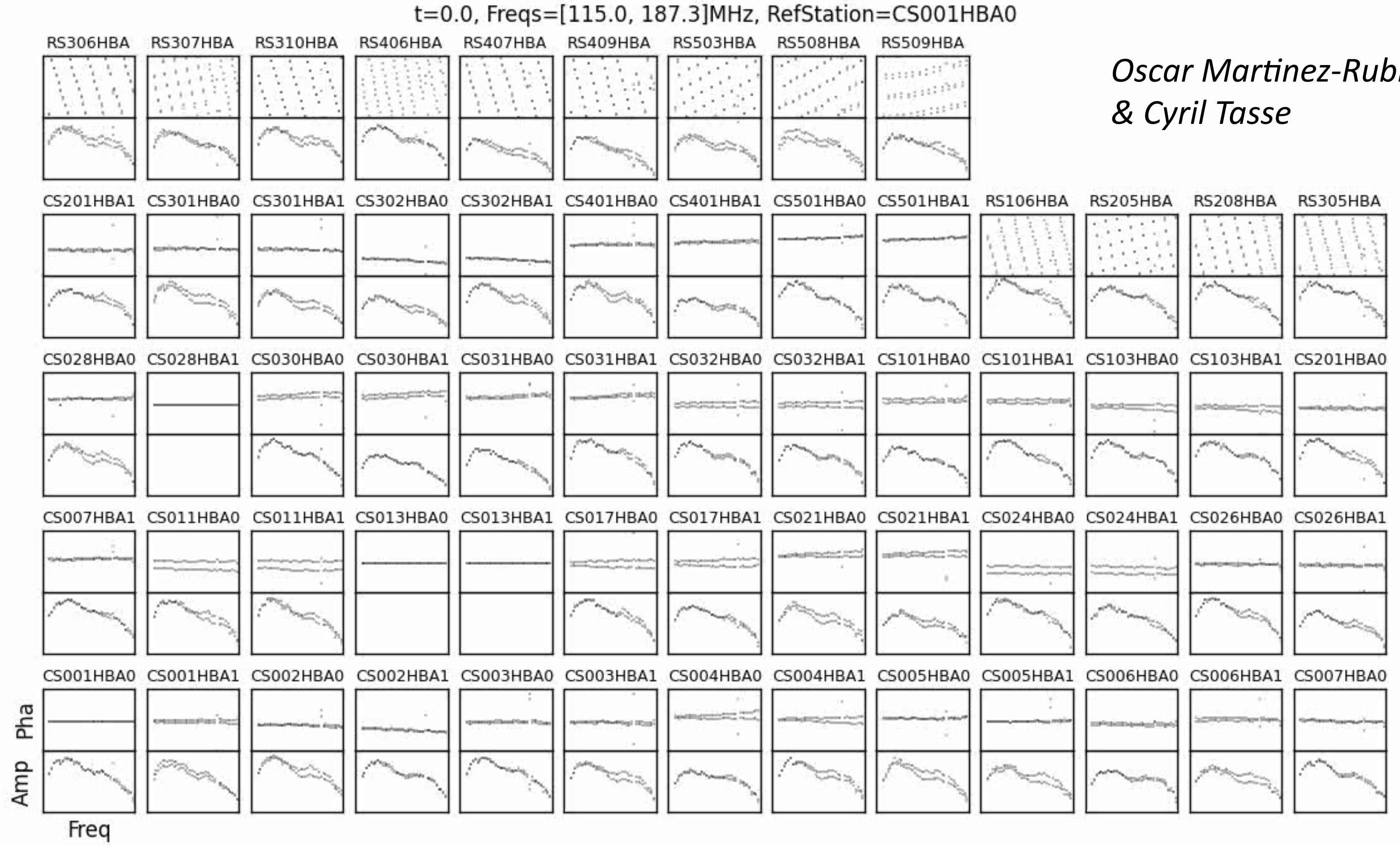


Lofar Eor Diagnostic DataBase *Martinez-Rubi etal, ADASS,2012 , arXiv*

dedicated 32 nodes for 3C196 and 32 nodes for NCP

Visualizing instrumental complex gains: 3C196

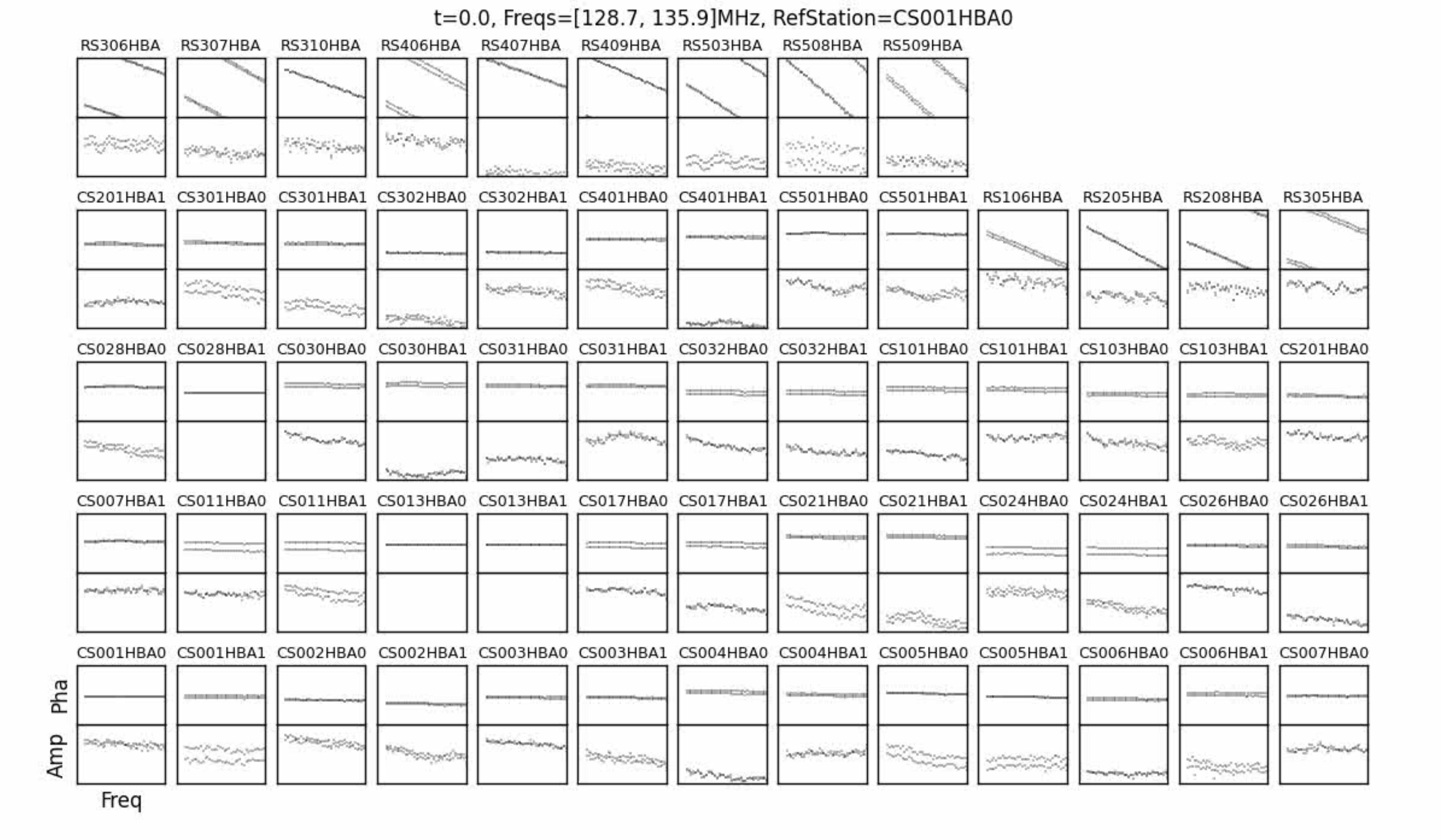
9/10 Jan ‘13 48 CS + 13 RS 8h at 10s 38/370 subbands



Oscar Martinez-Rubi & Cyril Tasse

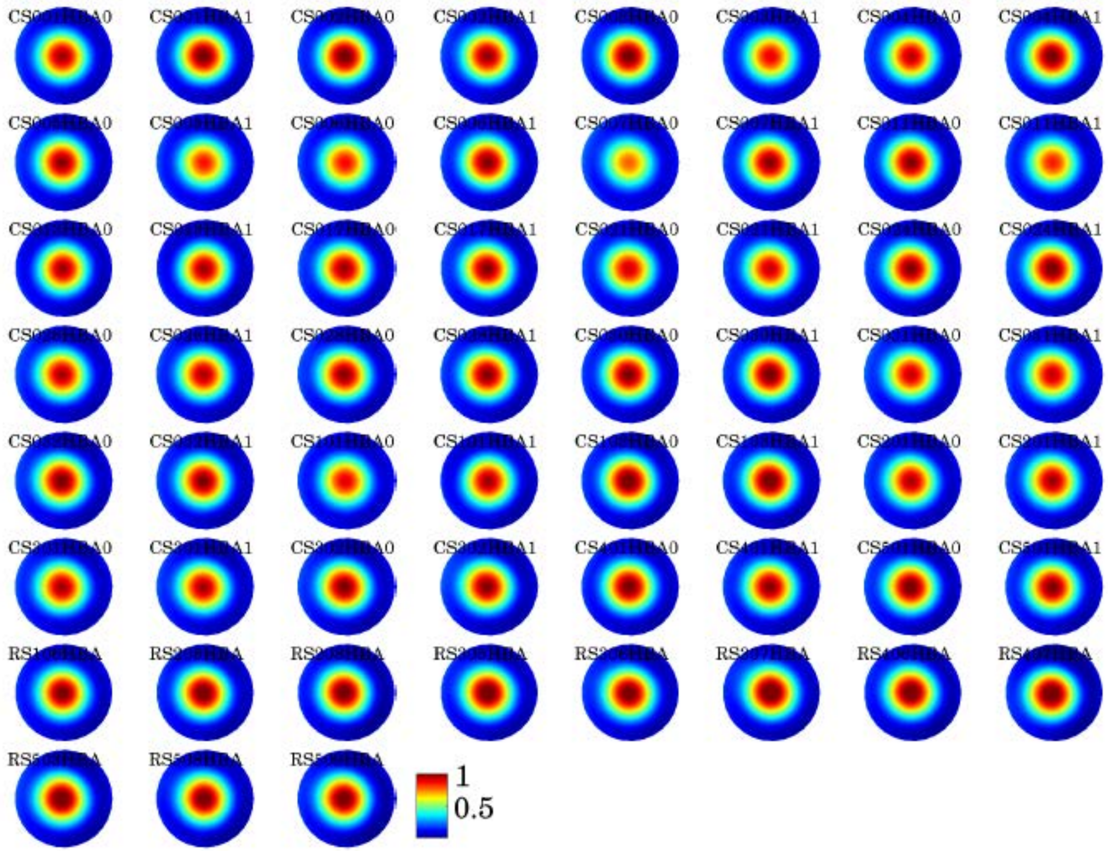
Visualizing instrumental complex gains: 3C196

9/10 Jan '13 48 CS + 13 RS 8h at 10s zoom 129-136 MHz



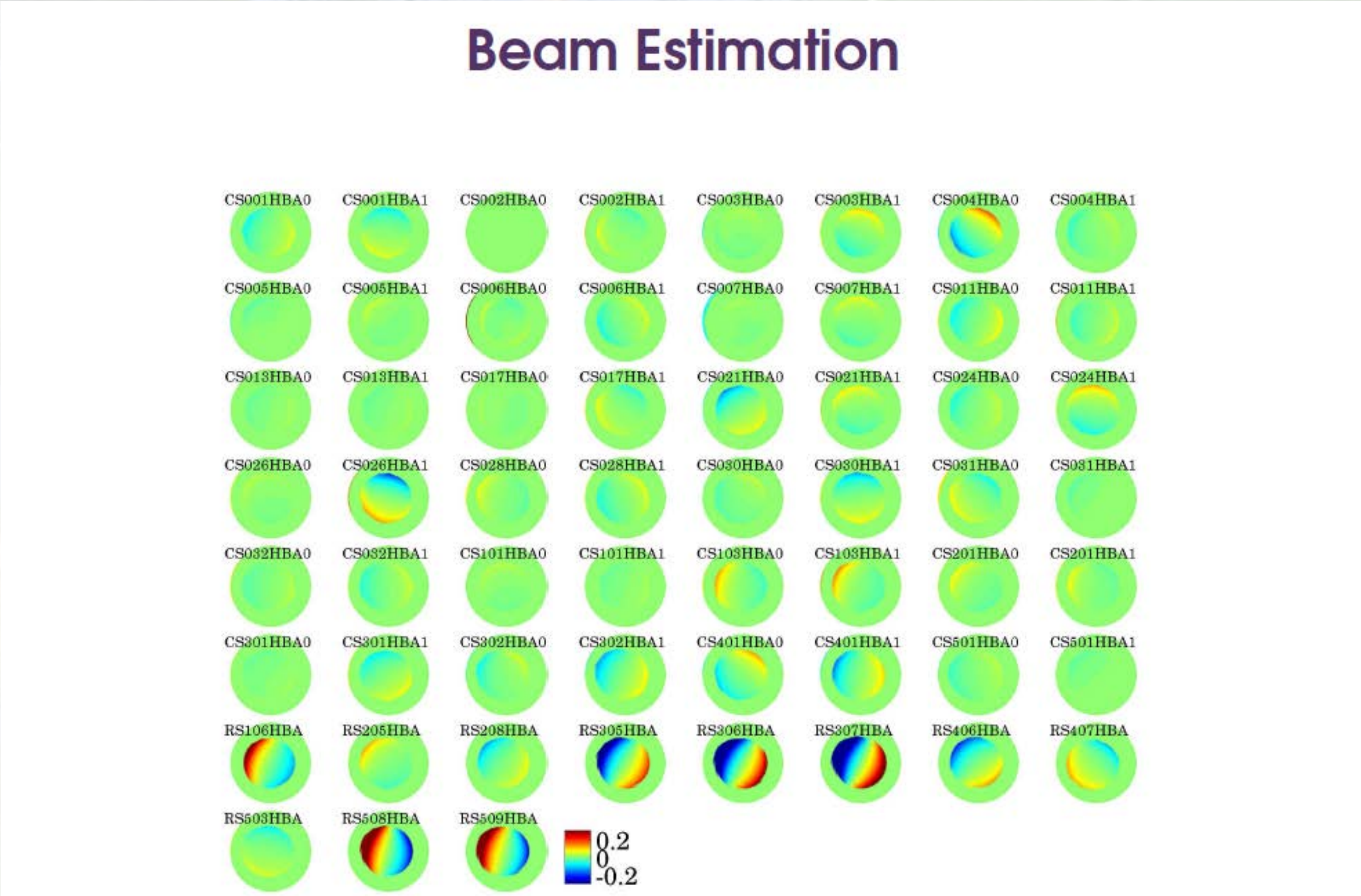
SAGEcal: NCP beam amplitude solutions (20m snapshot)

Beam Estimation

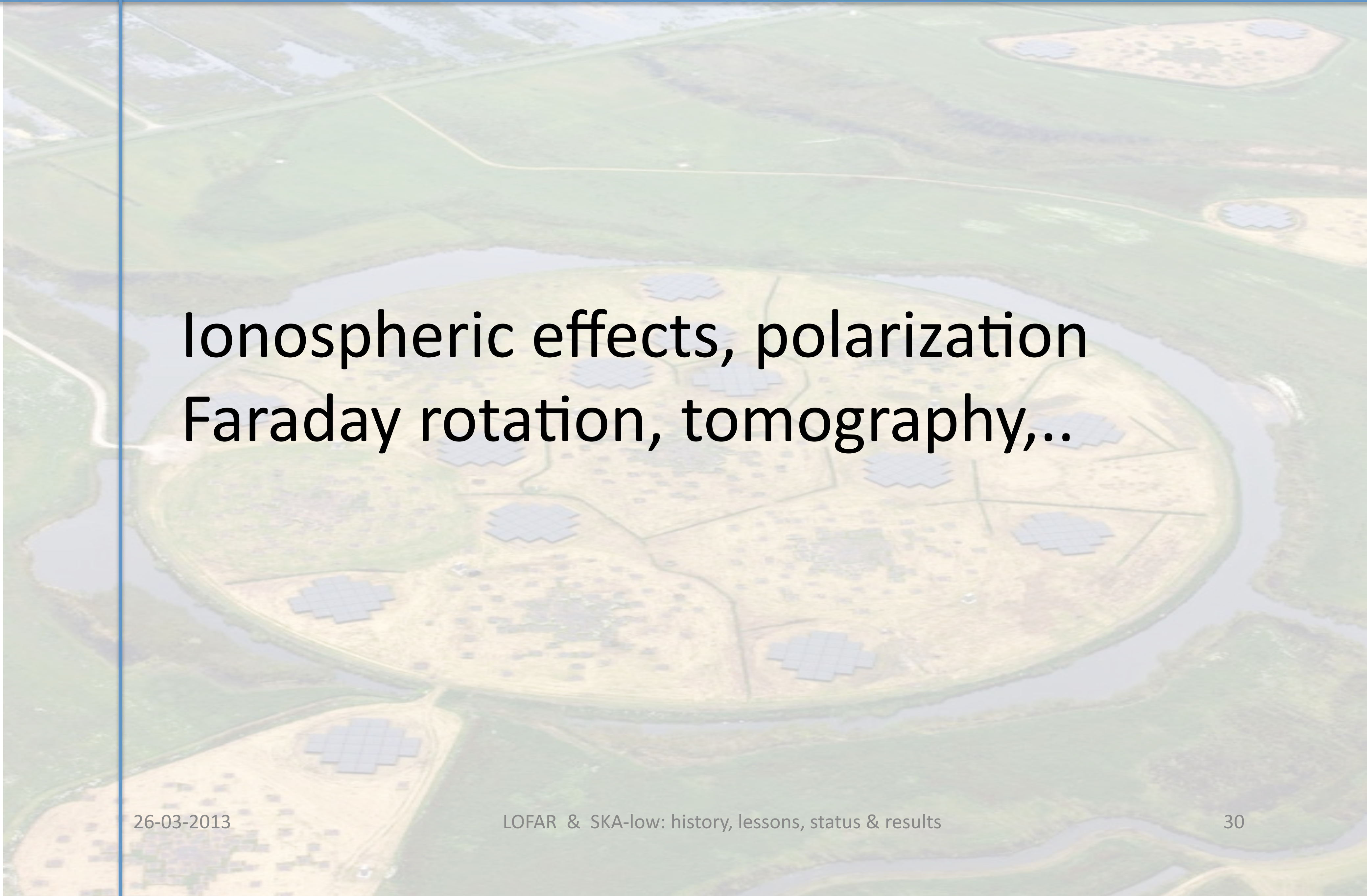


Data from 2012 December: beam amplitude 145 MHz 10 deg. FOV

SAGEcal: NCP beam phase solutions (20m snapshot)

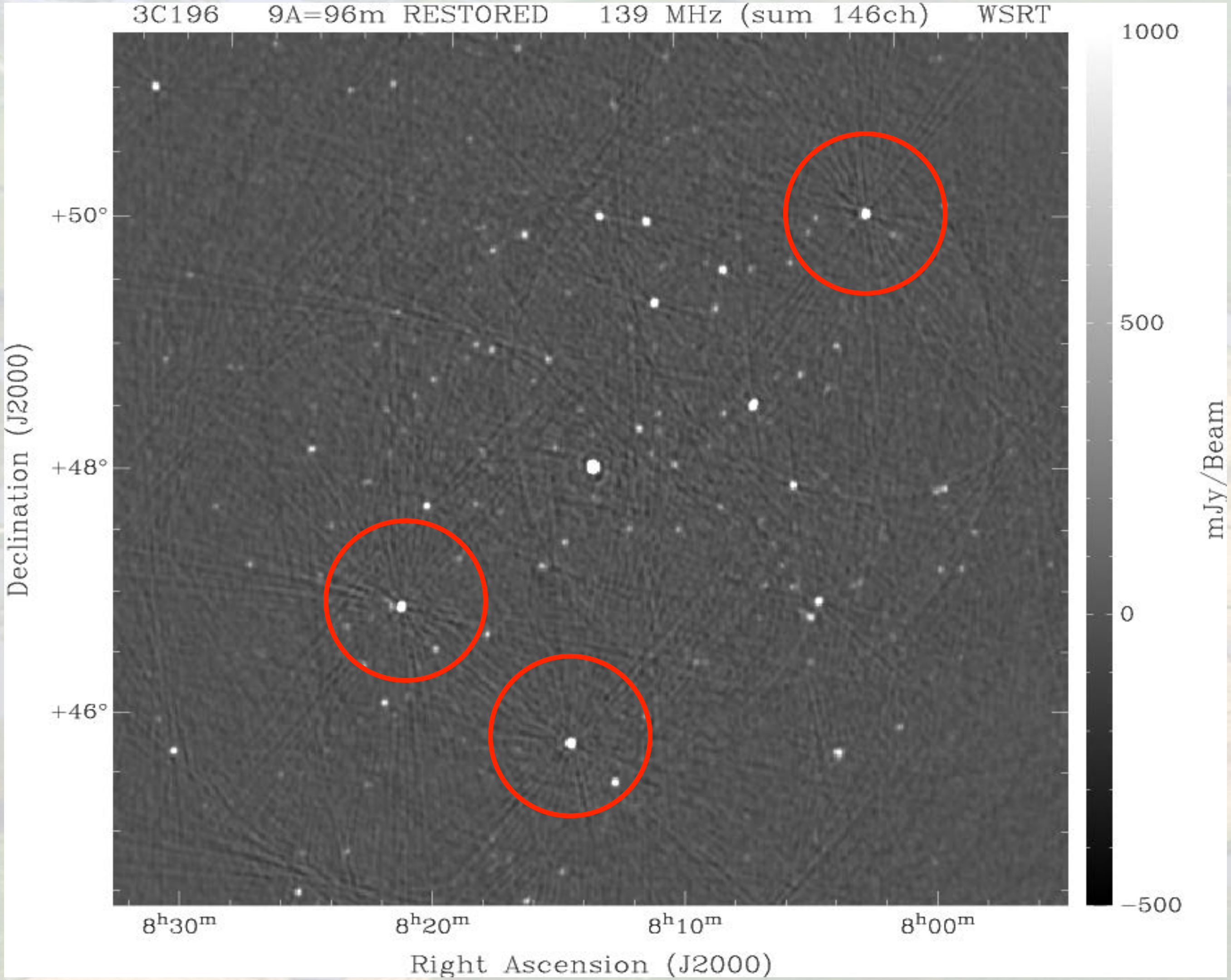


Data from 2012 December: beam phase (rad) 145 MHz 10 deg. FOV



Ionospheric effects, polarization
Faraday rotation, tomography,..

3C196 WSRT 139 MHz nonisoplanaticity in 3 km array!



3C196

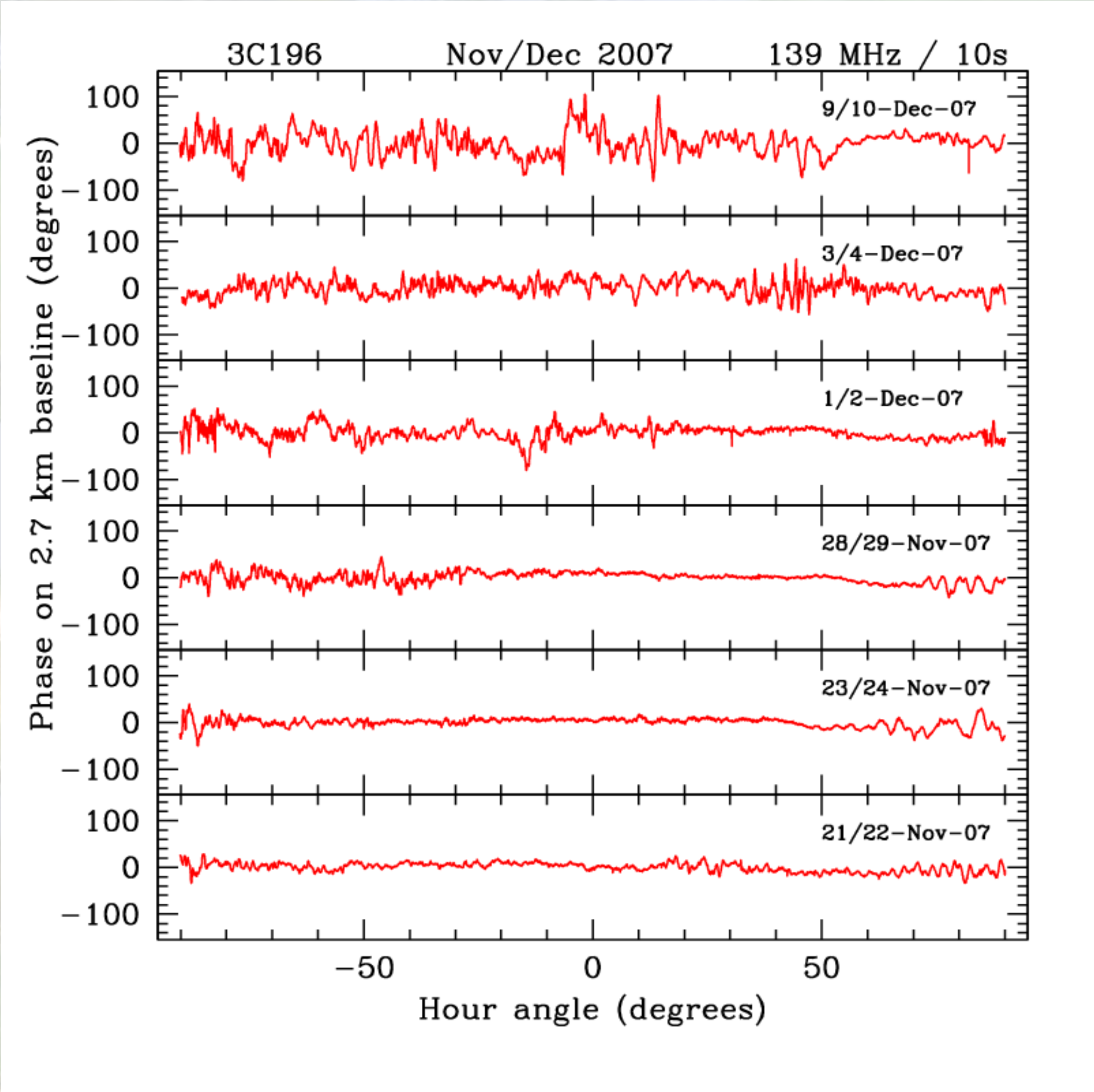
80 Jy

3 sources 6 - 8 Jy

Sources need to be ‘peeled’ for DDE’s

de Bruyn etal, 2009
Bernardi etal, 2010

3C196 WSRT selfcal phase solutions for 6x12h nights



6 x12h

Note the very different ionospheres !

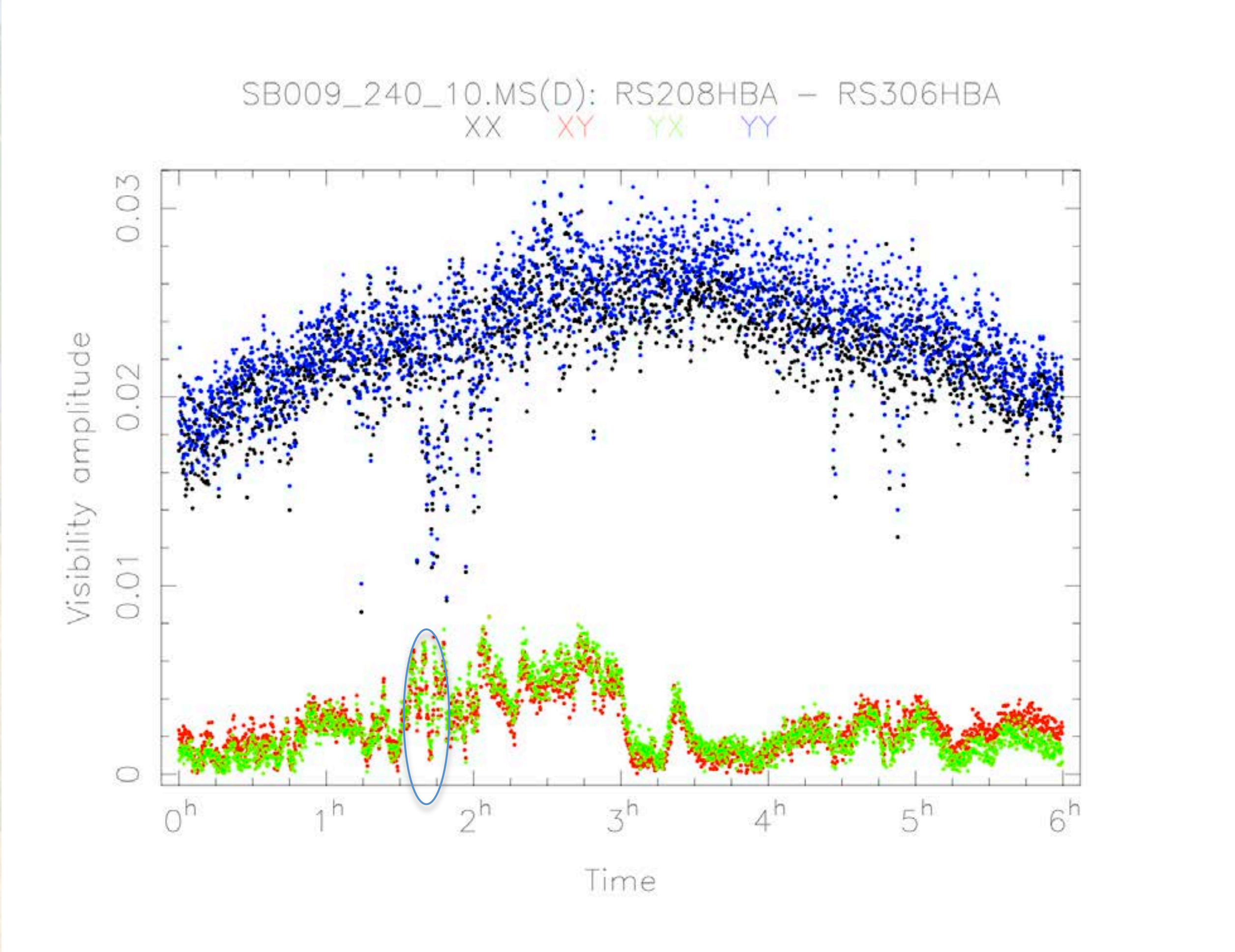
However, these hardly affect the quality of the Q,U images

3C196 117 MHz 4 Feb 2011

Observation with strong variable Differential Faraday rotation (DFR)

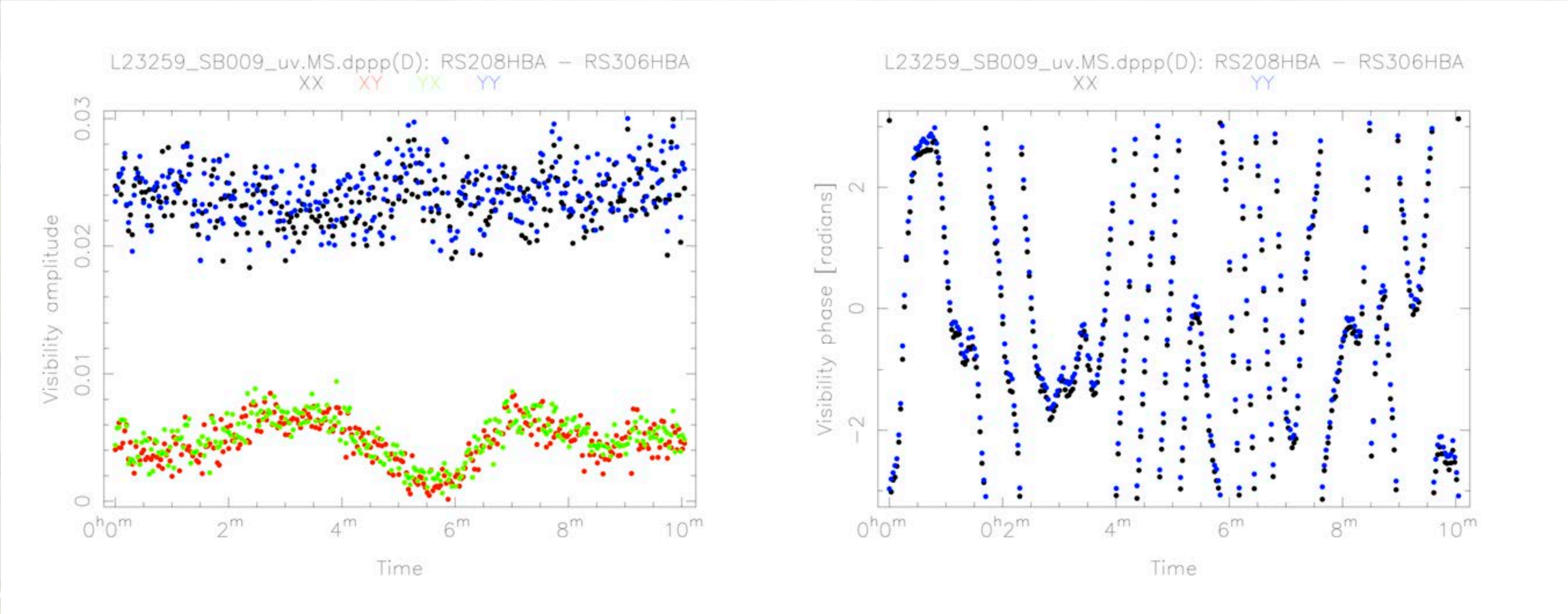
20 km baseline

and strong associated amplitude decorrelation



6h at 10s resolution

3C196 117 MHz 4 Feb 2011



Amplitude

10m at 2s resolution

Phase

10m at 2s resolution

DFR ~ 0.2 rad in 100s → DPD ~ 20 radians phase

Quantitative understanding of the effects of DFR

DFR converts (unpolarized) signals into circularly polarized signals visible in XY and YX.
DFR arises when we encounter large TEC gradients. Let us look at this quantitatively.

(Absolute) Ionospheric Phase Delay:

$\Delta\phi = -50\ \mathrm{TEC}\ (\lambda/2\mathrm{m})$ radians — where TEC is in TECU ($=1\times10^{12}$ el/cm^2)

(Absolute) Faraday Rotation of polarisation angle:

$\Delta\theta = \mathrm{RM}.\ \lambda^2 = 0.81\ 10^6\ B_{//}\ n_e.dl\ \lambda^2$ radians — where $B_{//}$ in Gauss and dl in pc

Differential Phase Delay (DPD) between two stations i and j :

$\Delta_{ij}(\Delta\phi) = -50\ \Delta_{ij}(\mathrm{TEC})\ (\lambda/2\mathrm{m})$ radians

Differential Faraday Rotation (DFR) between two stations i and j

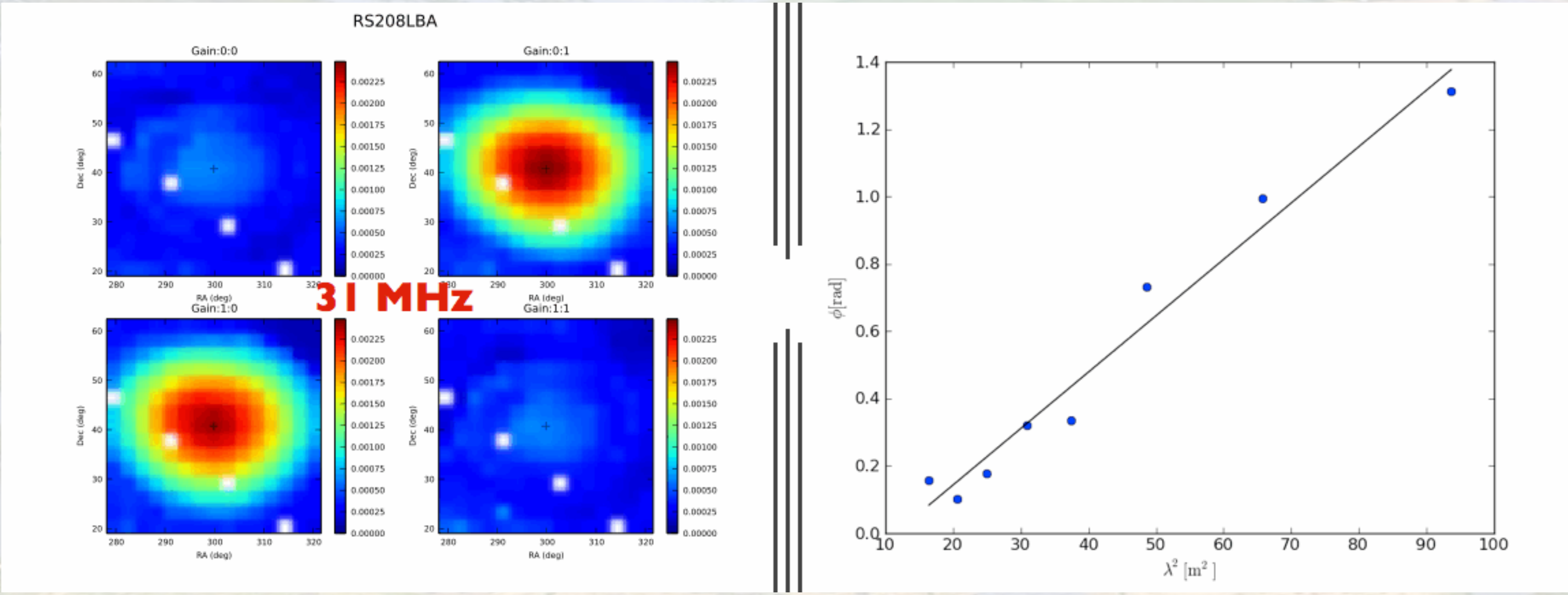
$\Delta_{ij}(\Delta\theta) \sim 1.04\ B_{//}\ \Delta_{ij}(\mathrm{TEC})\ (\lambda/2\mathrm{m})^2$

Hence: **$\mathrm{DPD/DFR} \sim 48\ (B_{//}.\ \lambda/2\mathrm{m})^{-1}$** — independent of the Δ(TEC) !

For a typical $B_{//} \sim 0.4$ Gauss and a frequency of 122 MHz ➔ **DPD/DFR ~ 100**

A DFR of 0.1 radian (as observed on ~ 25 km baselines) therefore also implies large ionospheric phase differences (~ 10 radians or ΔTEC ~ 0.2 TECU) !! On the previous slides one can see that this occurs quite often ! If ionospheric phase rates are very fast (say within 10s) they also cause **amplitude decorrelation** !

DFR effects on beam $(J_{00}, J_{01}, J_{10}, J_{11})$



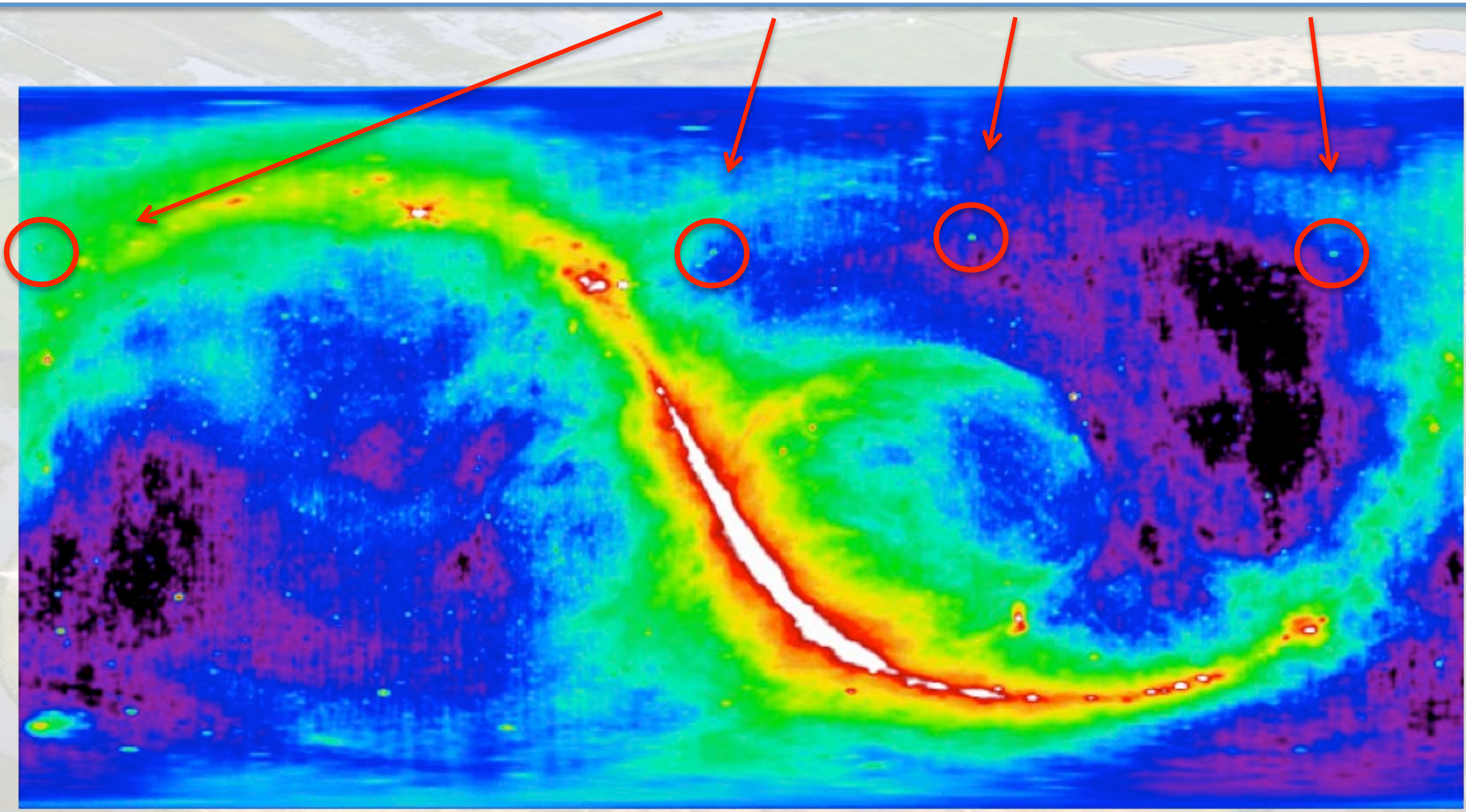
Differential Faraday rotation between two stations (28 km apart) rotates the signal from the parallel-hand (XX , YY) to the cross-hand (XY,YX) correlations.

This scales as λ^2

At 31 MHz ~ 90^{o} rotation !

(Galactic) foregrounds

Locations of calibrators: 3C147, 3C380, 3C295 and 3C196



Haslam et al, 1981

Full-sky high-frequency polarized images of our Galaxy

22.8 GHz   WMAP image

The FAN region

1.4 GHz   Reich et al

(more sensitive, but depolarization effects visible)

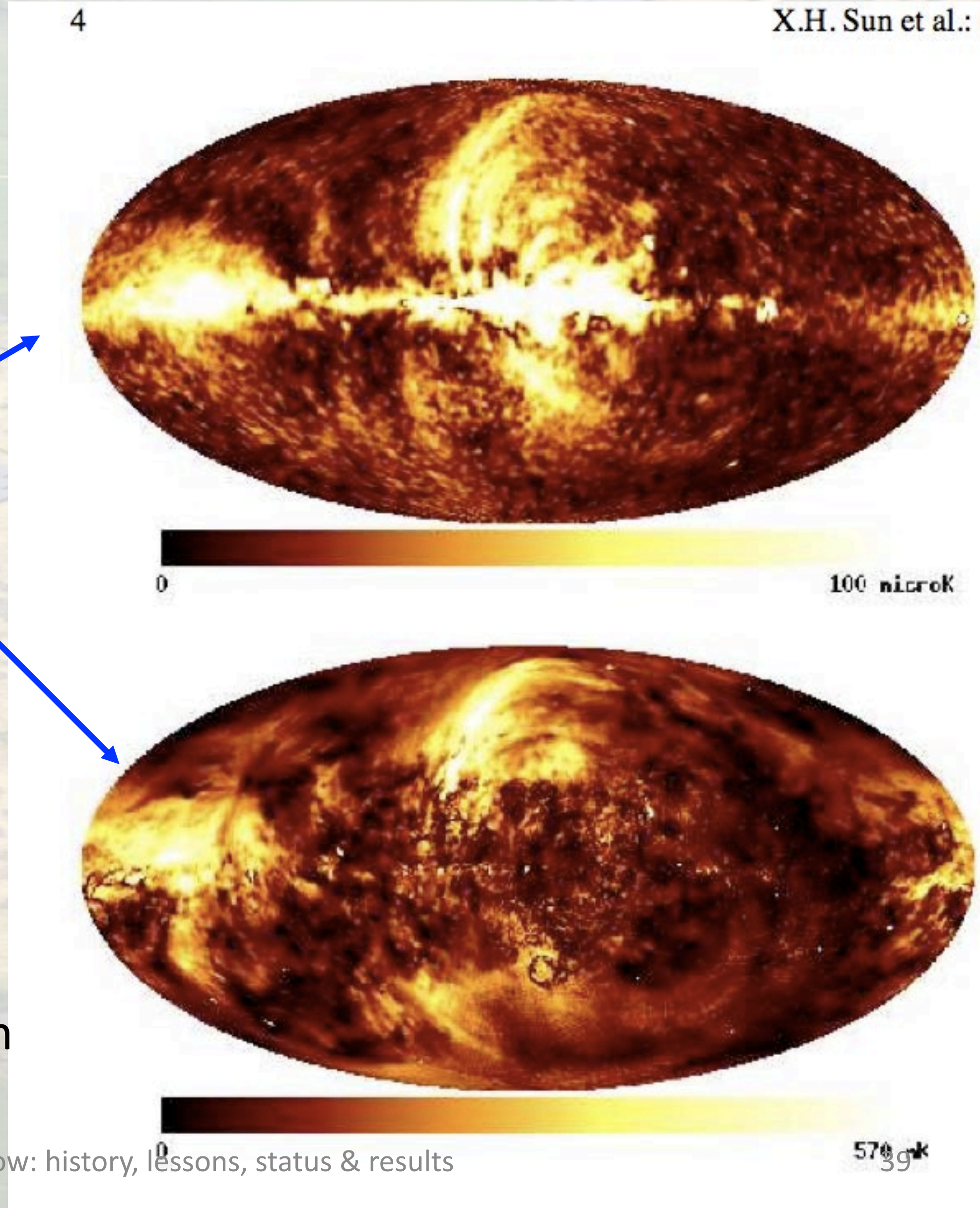
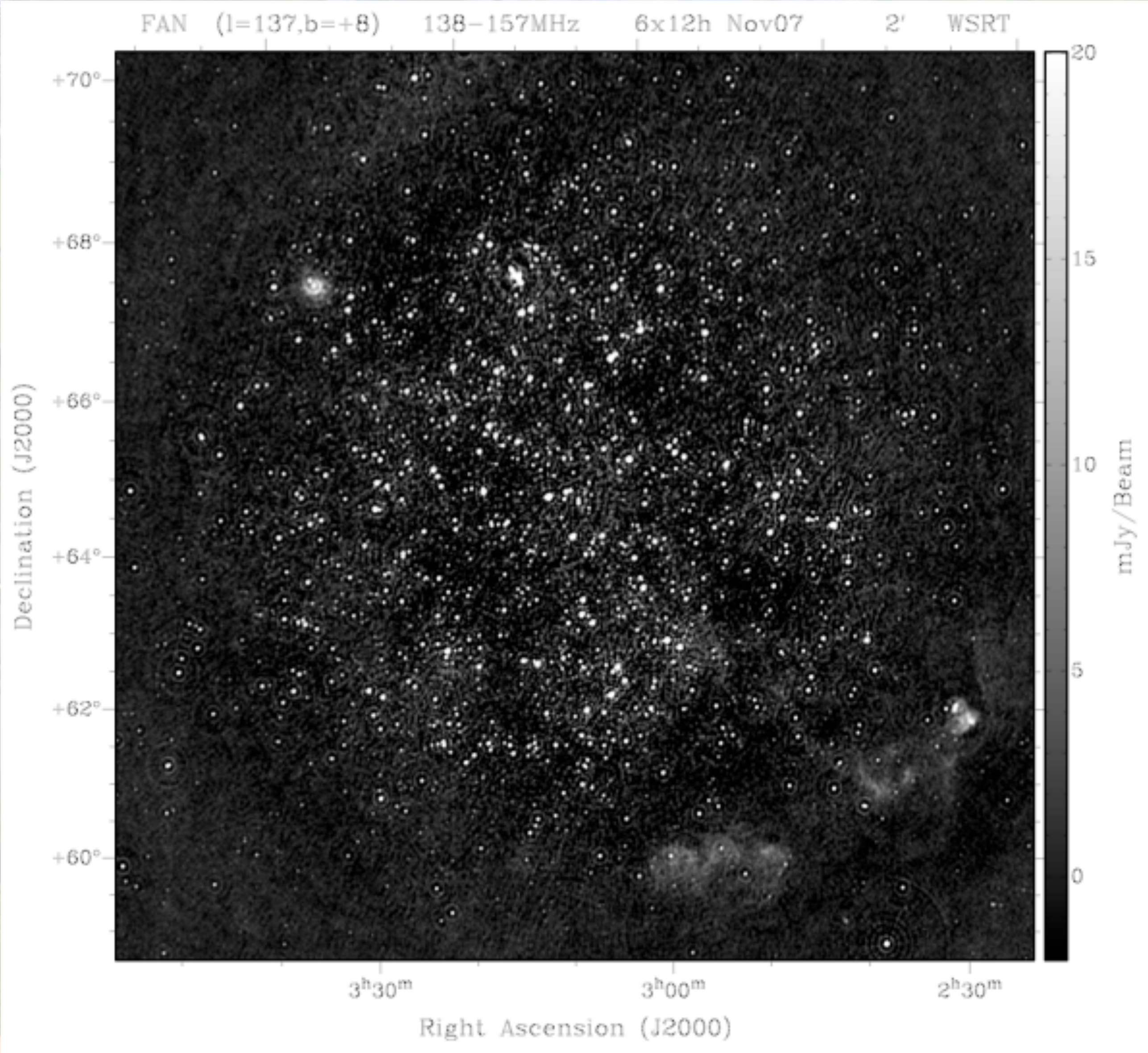


Fig. 2. The WMAP 22.8 GHz all-sky polarized intensity map (upper panel) and the 1.4 GHz all-sky polarized intensity map

WSRT 138-157 MHz FAN

Bernardi et al 2009

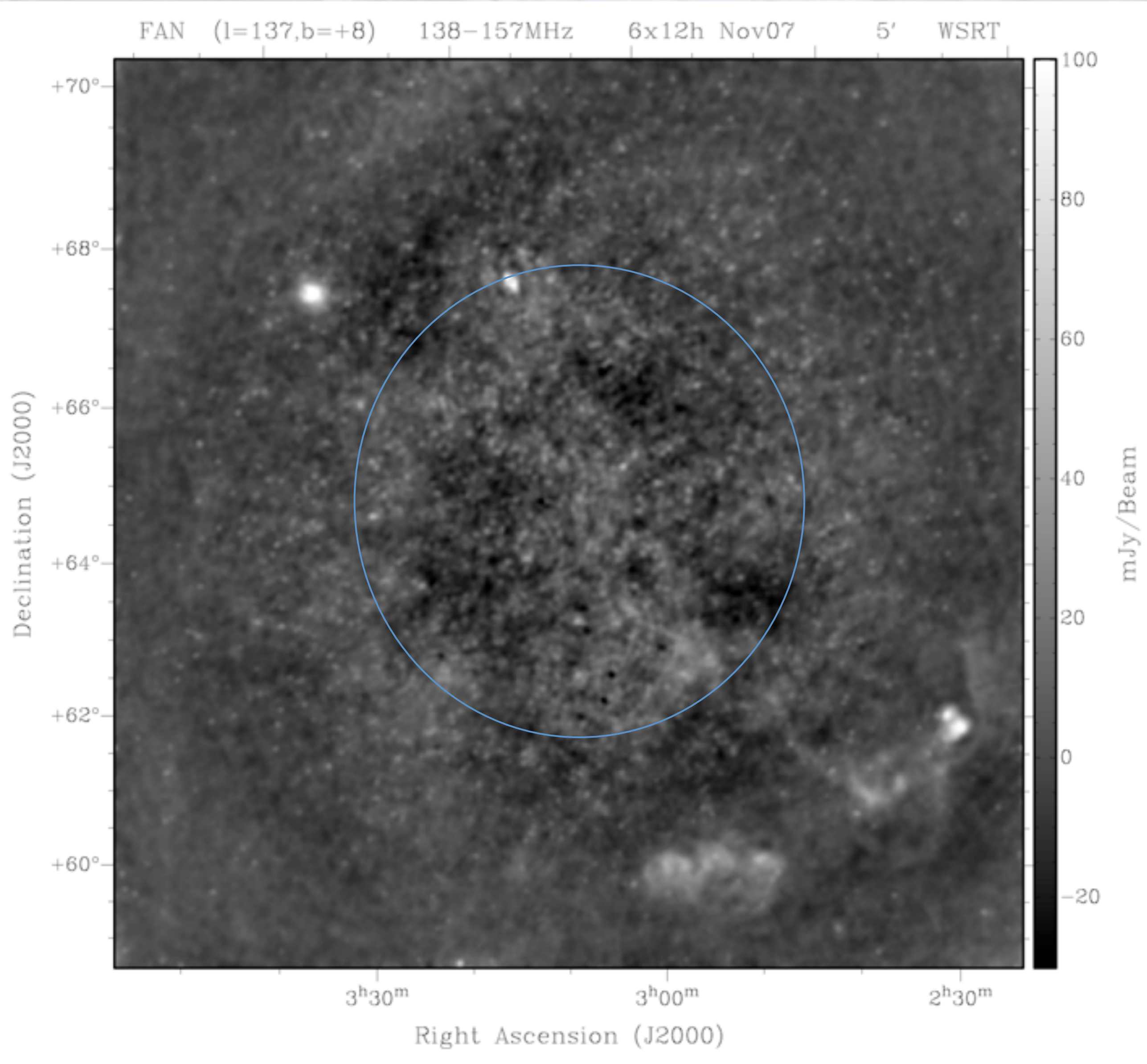


Range

-2, 20 mJy

WSRT 138-157 MHz FAN

Bernardi et al 2009

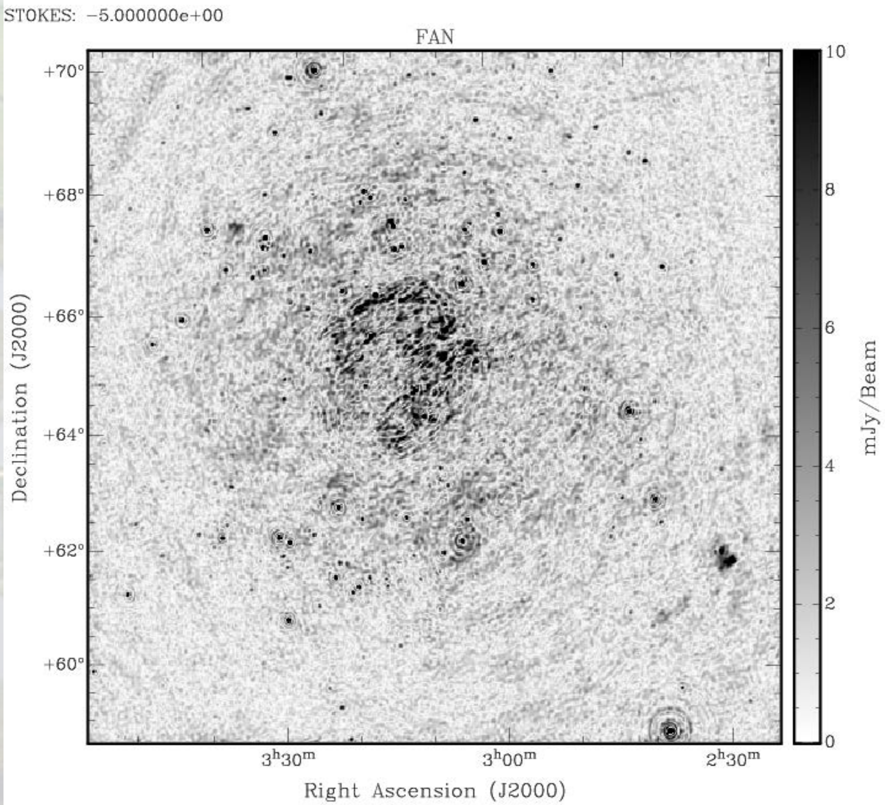


Residual image after subtracting sources down to 20 mJy

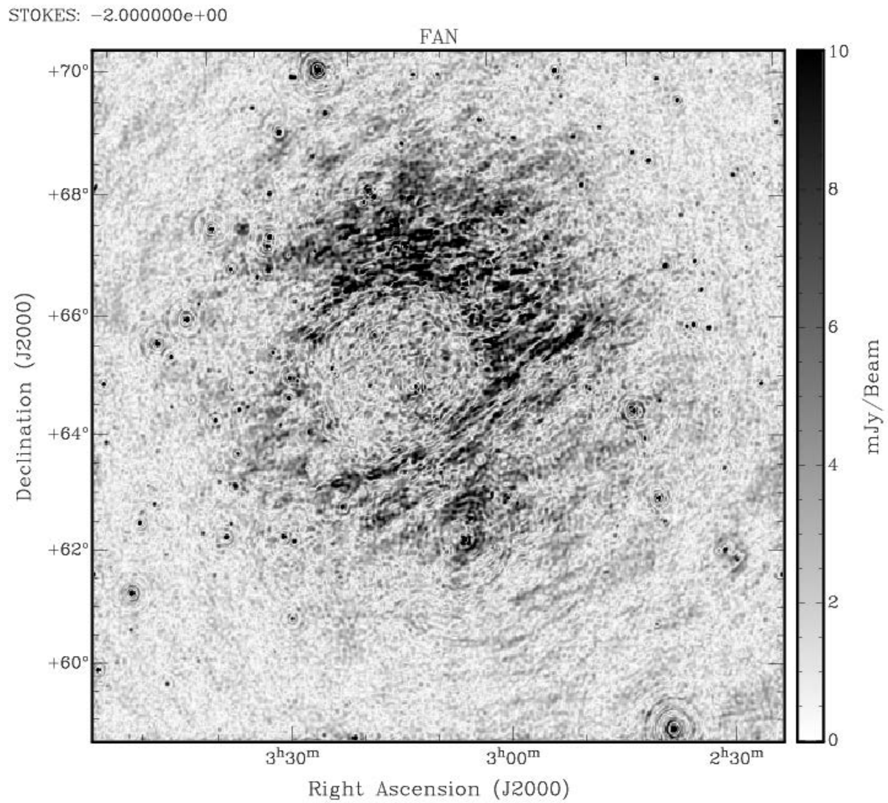
and smoothed to 5’

Polarized intensity distributions of the FAN

RM = - 5 rad/m^2



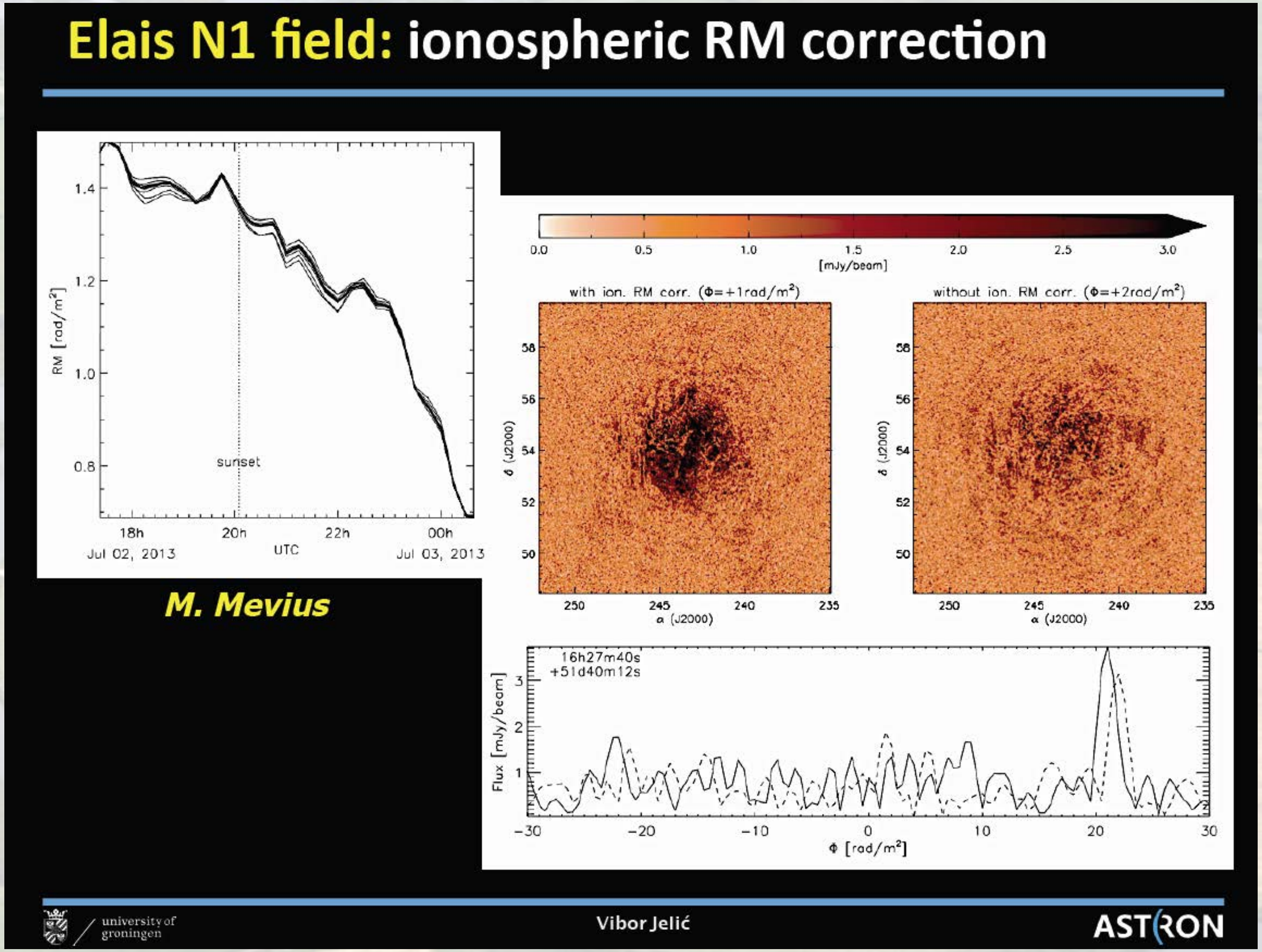
RM = - 2 rad/m^2



Variable polarized intensity at Faraday depths from - 6 to + 2 rad/m^2

Integrated about 10 K peak brightness !

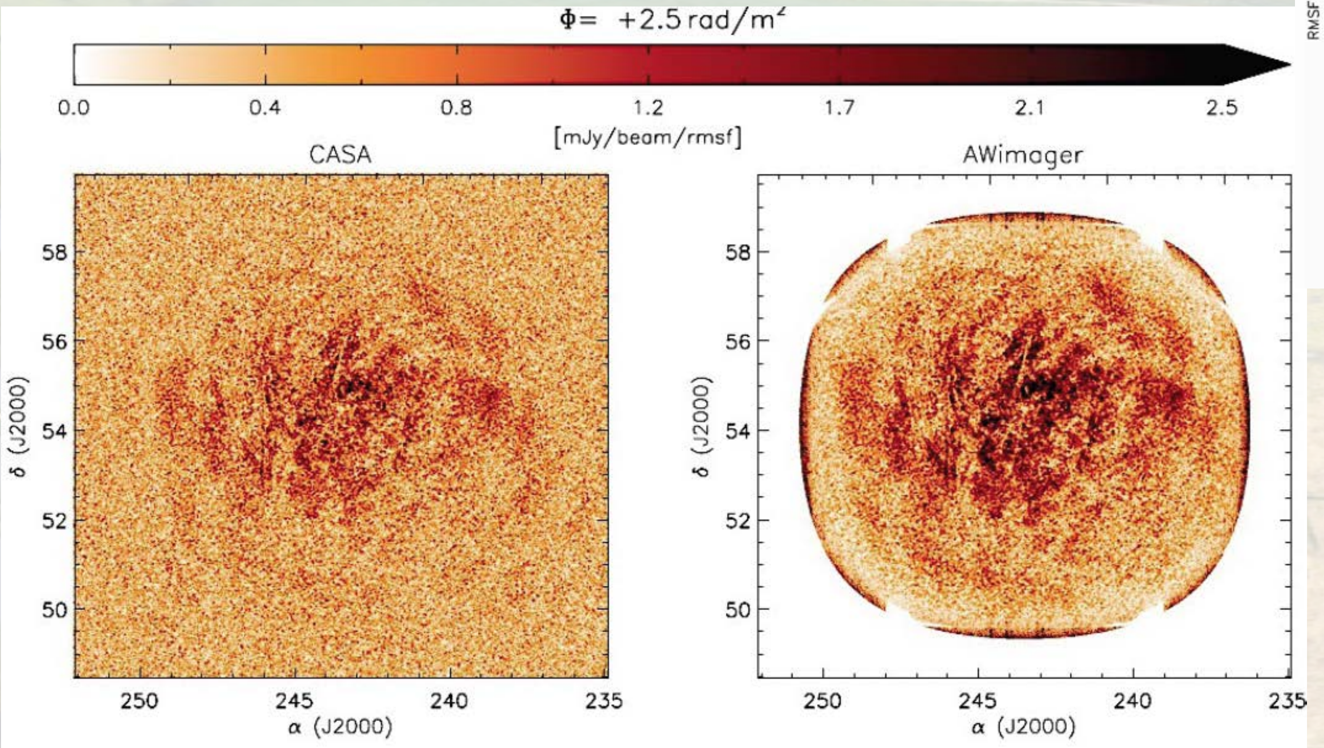
Correcting for time-variable Faraday rotation

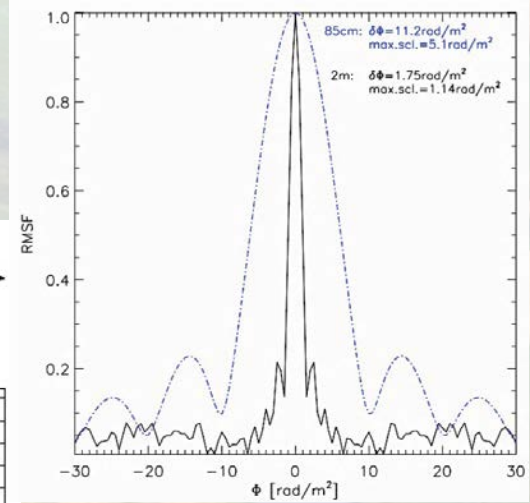


See also Sotomayor et al 2013 (arXiv)

Correcting for time-variable station beams: AW-imager

One frame from RM-cube of Elais-N1 field





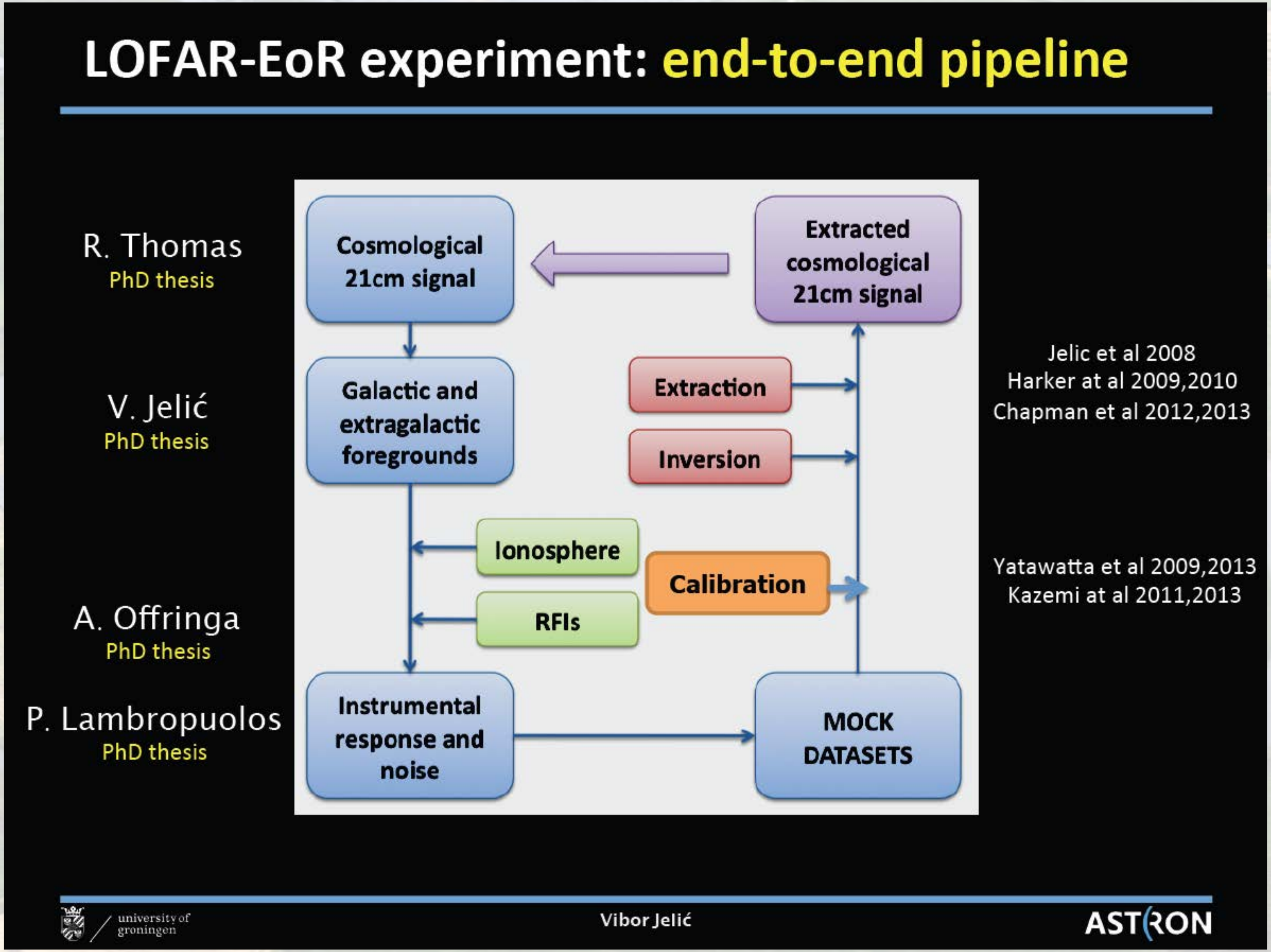
few K signals !

Jelic et al, 2013 *Tasse et al, 2013*

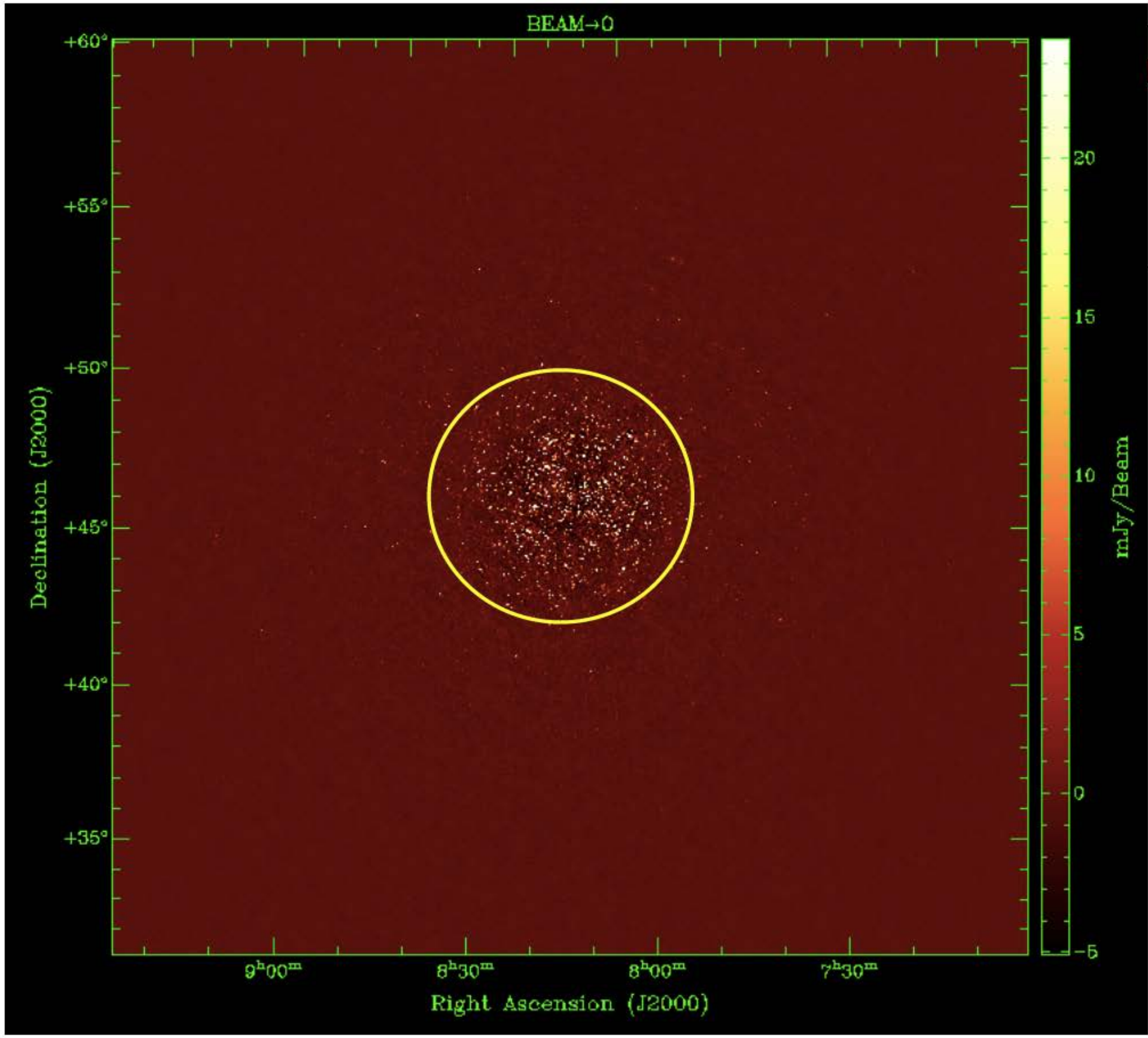
Some LOFAR and EoR-KSP results

Oct 2012 celebrating start of NCP observing

Preparing for the LOFAR EoR project : overview   '05-'12



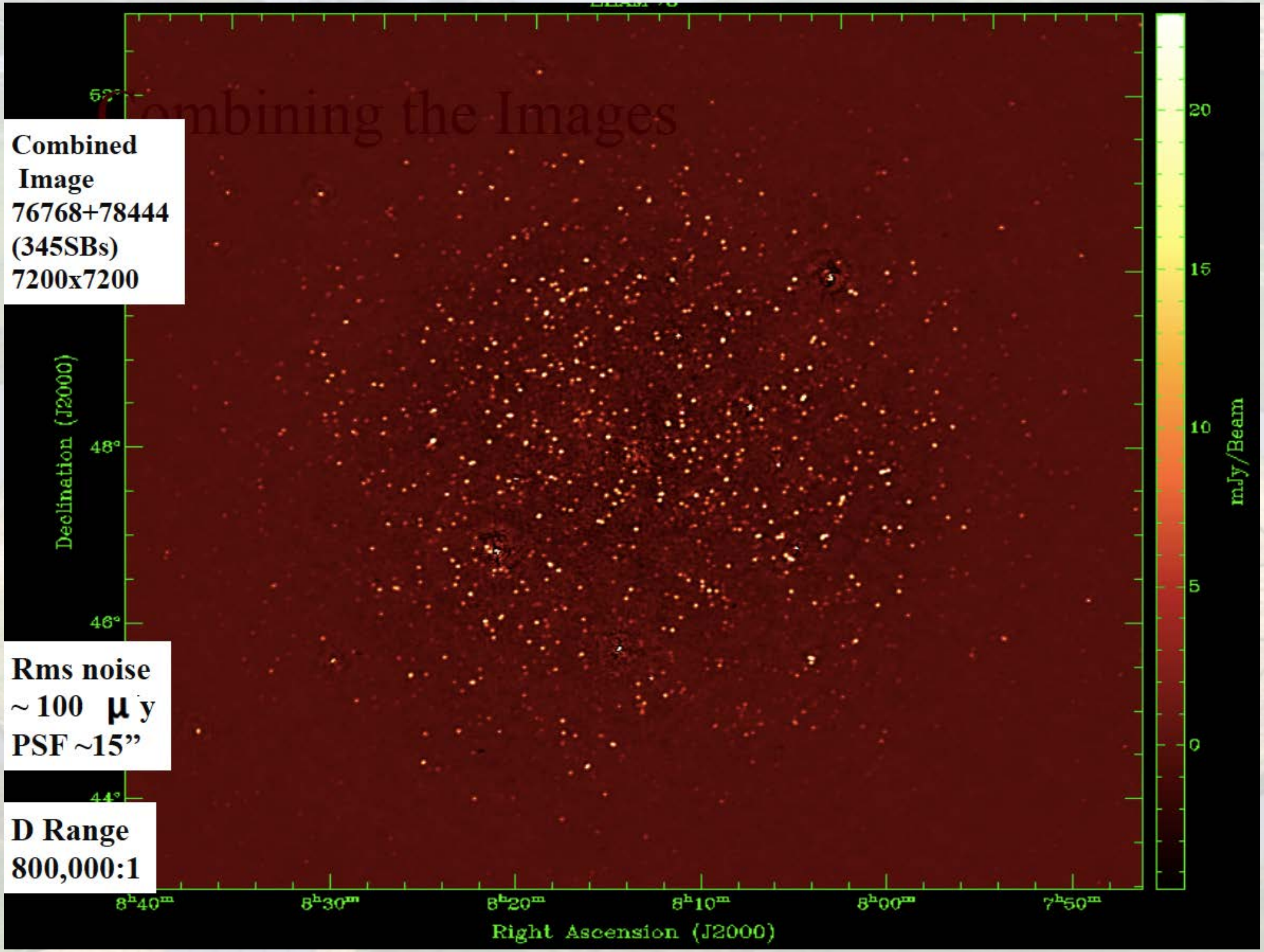
3C196 window: the full picture 45” PSF *Pandey etal*



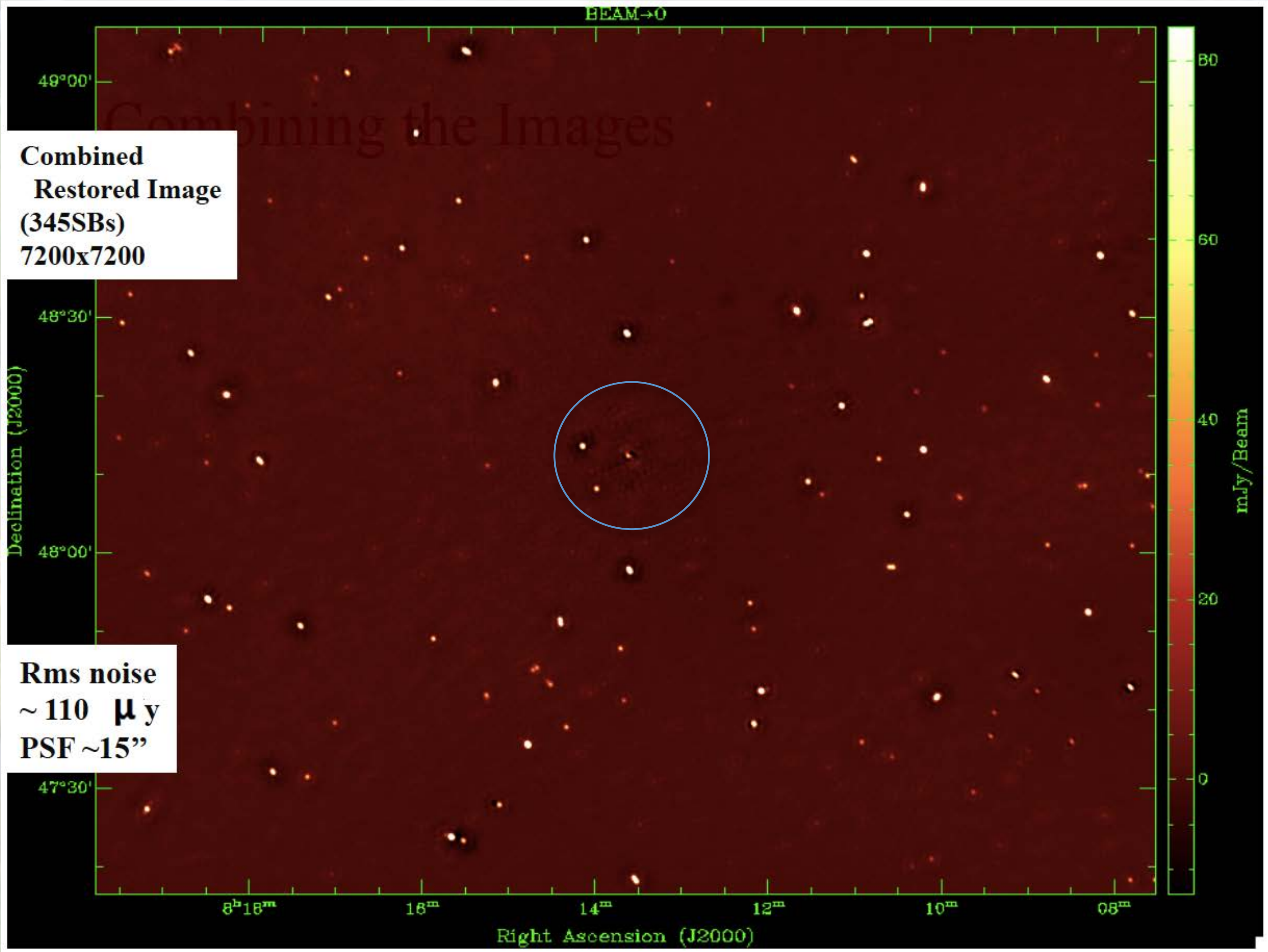
L79344
105microJy
45”x45”

No effect of Casa/Cyg.. A Team

3C196 average of 2x8h 15” PSF



3C196: zoom-view with 15” PSF (30 km taper)

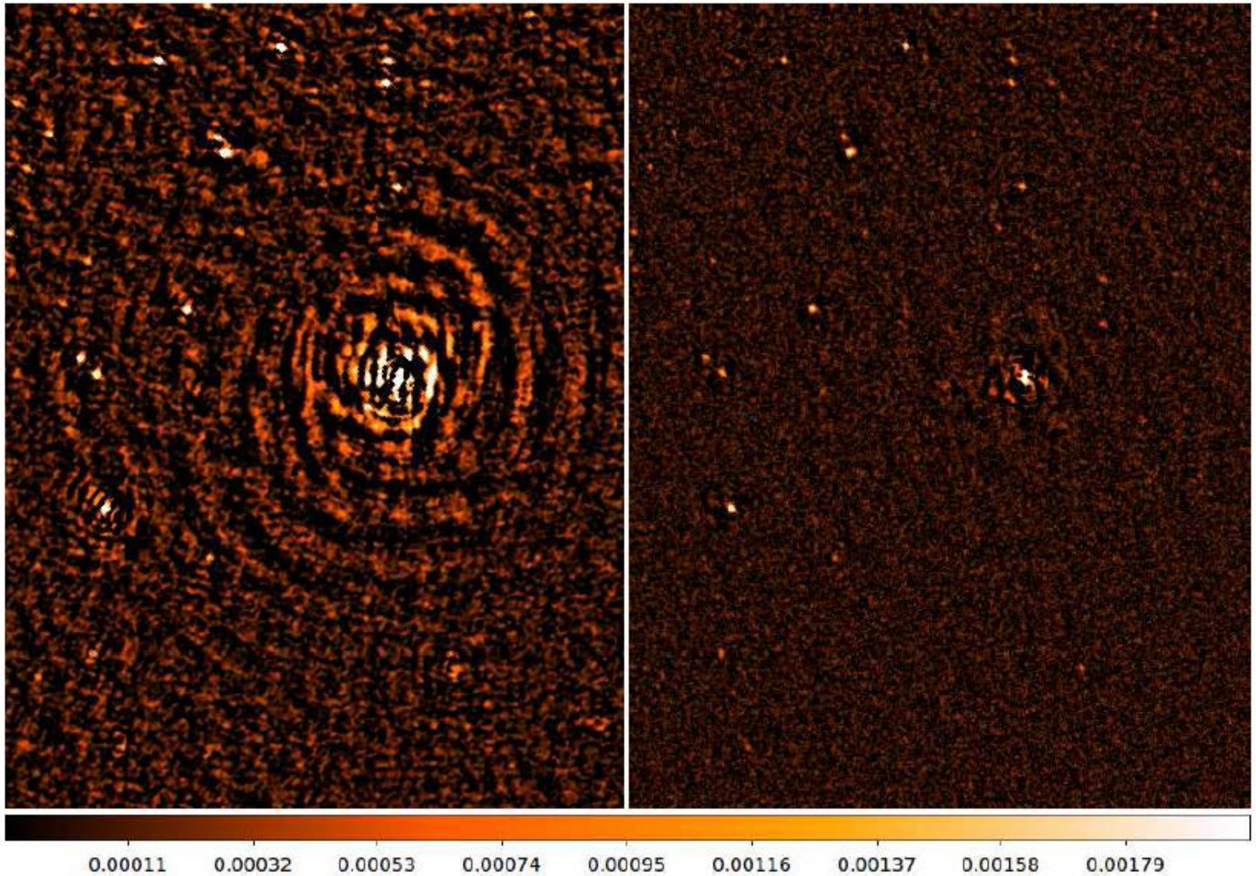


3C196 removed almost perfectly

Still awaiting 1000 km baseline data

Ultra-deep imaging on the NCP

Effect of Far Away Sources

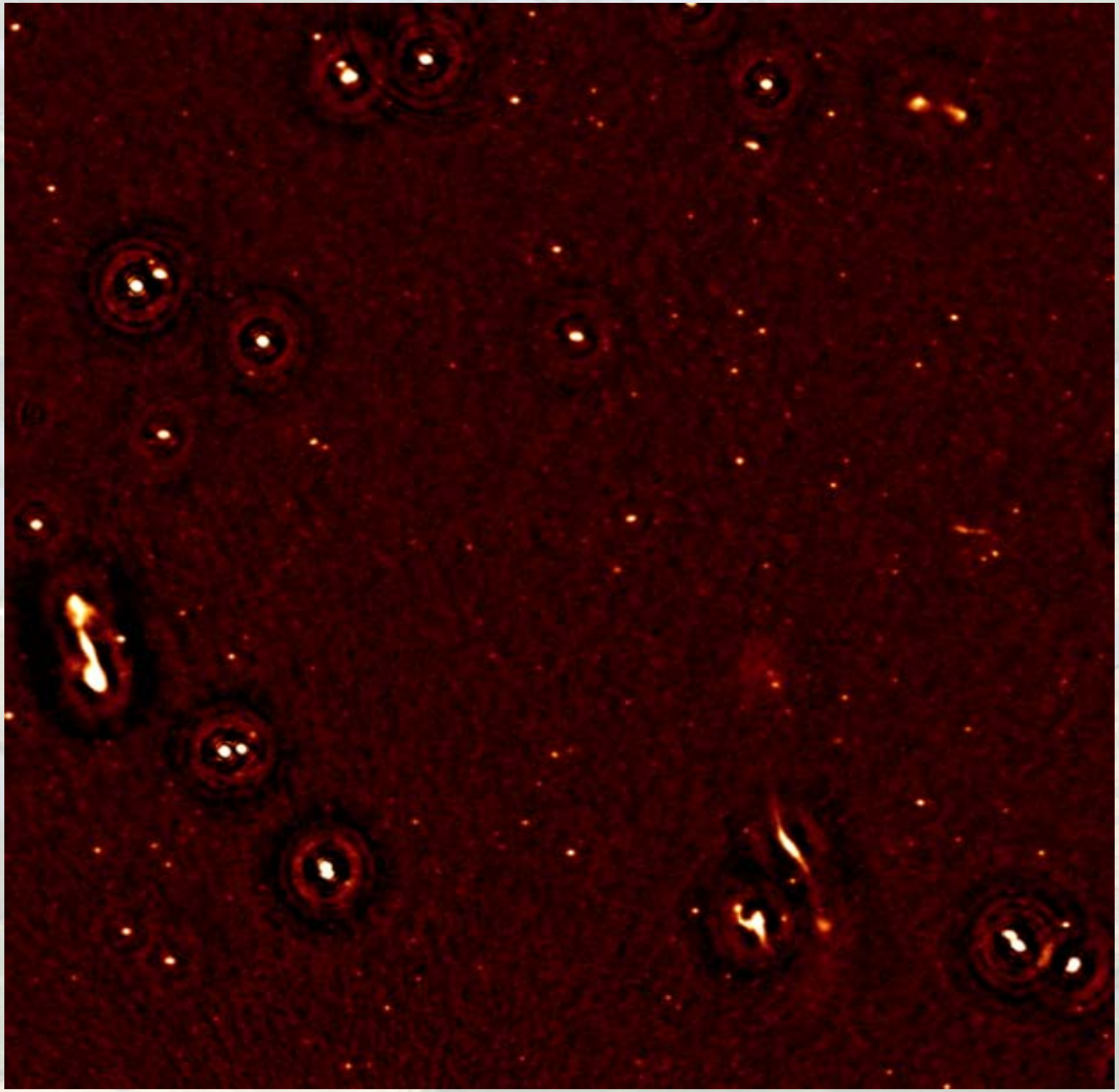


3C390.3, 11 degrees away from the NCP, before and after SAGECal

Sarod Yatawatta

Ultra-deep imaging on the NCP

Sarod Yatawatta

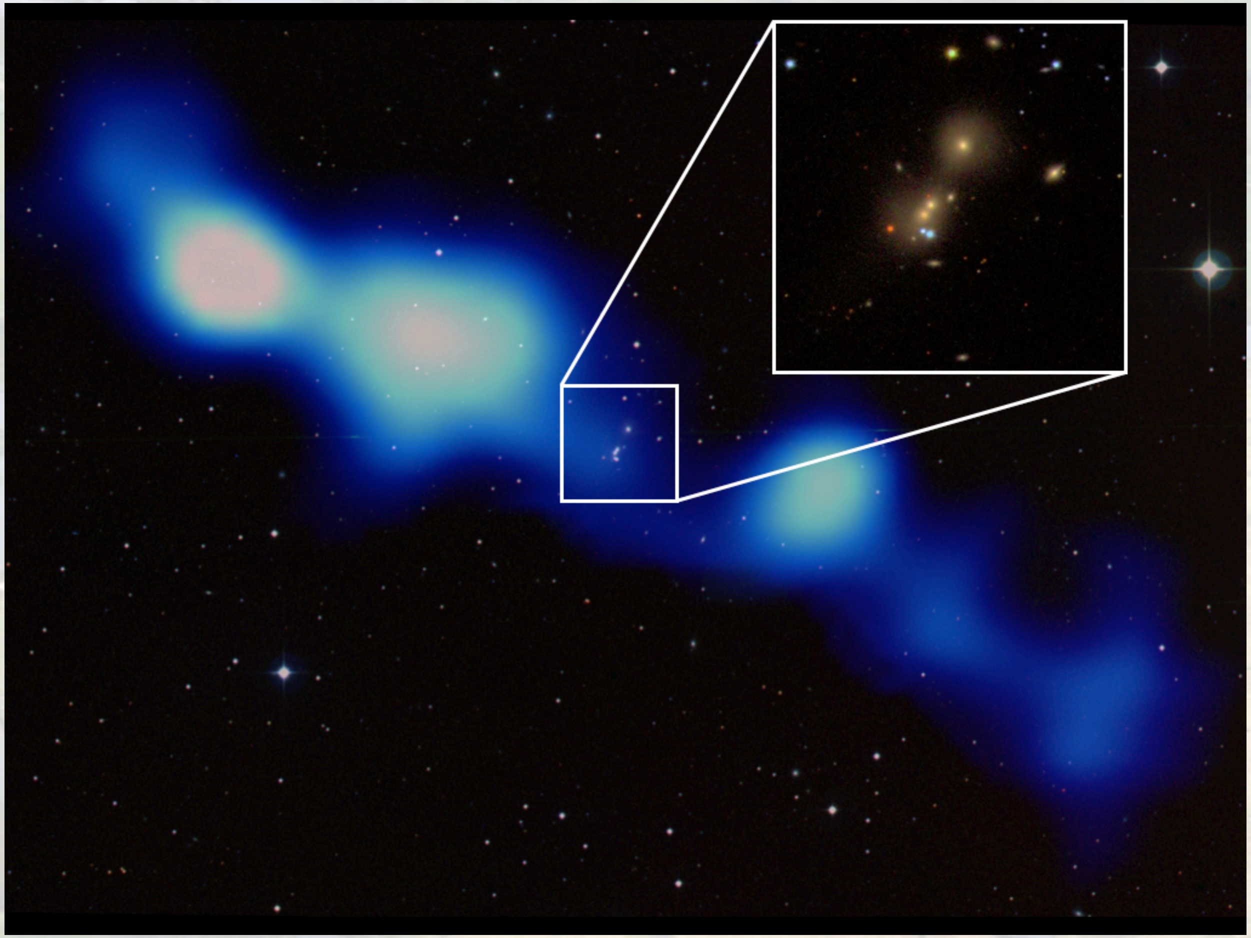


80 h on NCP
(5 x 15-16h)

Centered on NCP
0.7° x 0.7°
(1% of image)

PSF 6”x6”
rms 30 μJy

Giant radio galaxy MSSS → LOFAR Global Sky Model



Presented by George Heald at Dalfsen LOFAR meeting (19-20 March 2013)

See also Heald

AJDI , 20 March 2013

Conclusions

LOFAR works very well, once station beams were calibrated

RFI not an issue (30-80 and 115-200 MHz)

New developments in (fast) calibration and imaging were needed

Direction dependent calibration essential (100+ directions)

6” PSF widefield imaging: very large images needed 36k x36k pixels (2”)

Very high DR (>60 dB) $\rightarrow$ requires ~ 500 km baselines (3C196, 3C295) !

Image noise scales as $1/(B\ t)^{1/2}$ (up to B=60 MHz and t=100h !!)

Multi-beaming great asset

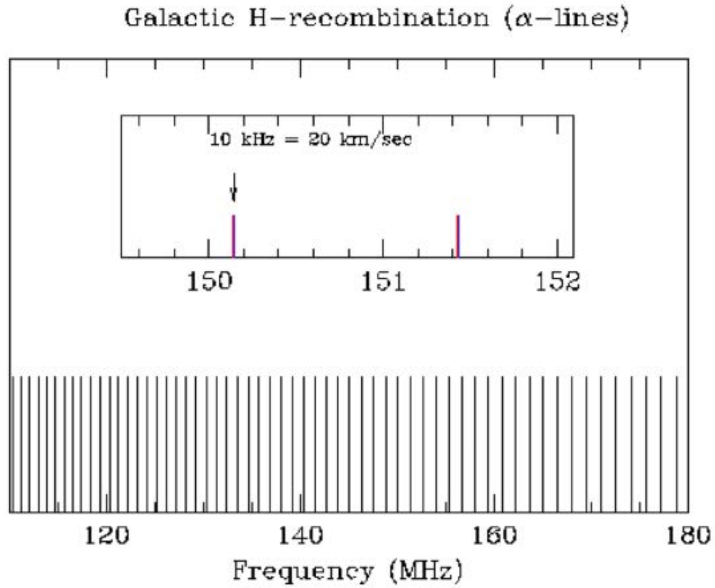
EoR and recombination line contamination

EoR and Galactic hydrogen recombination lines:

- In Galactic plane: ~ 100 - 500 mK (at 325 MHz, e.g. Roshi et al, 2001)
- Out of plane: probably less than 50 mK

Fluctuations on 3-10' scale probably an order of magnitude smaller still
Lines around 150 MHz probably weaker

NB: IF recomb lines are detected they will be helpful for fidelity checks.
Lines can easily be excised:
(~20 kHz / ~1 MHz or ~ 2% of spectrum)



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