LOFAR calibration

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Outline

— Traditional calibration

— New calibration software

— Overview of the LOFAR calibration problem

— LOFAR beams and FOVs

— LOFAR and the Sun

— Dynamic range

— The learning phase: WSRT-LFFEs and CS1

— LOFAR and the ionosphere

— BBS-MIM modelling of WSRT data

—(list of issues not covered at the end)

Standard calibration

Calibration is needed for:

1) astrometry --> accurate positions

2) photometry --> (absolute) flux scale, spectral shape

3) image/PSF quality and image fidelity/DR

Method used:

Determine Gain/Phases (frequency) on

Stable (pointlike) external calibrators: --> 1) and 2)

Apply selfcalibration --> 3)

Calibration/imaging software …

Aperture synthesis array (users) use many different reduction packages

— AIPS : VLA, WSRT, GMRT, ATCA, VLBI,…

— Miriad : VLA, ATCA, WSRT,…

— NEWSTAR: WSRT

— AIPS++ : WSRT, VLA, …

For LOFAR, with all it novel /complicated aspects, we need to do much better.
Two packages have been, and continue to be, developed:

— MeqTrees is being used to develop/simulate our understanding (Smirnov)

— BBS will be implementing efficiently what we have learned (van Zwieten)

— and we use AIPS++/CASA for imaging

If you are not satisfied with the results blame the hardware/firmware, the software, or reconsider your understanding of the problem !

LOFAR calibration framework *(e.g. Noordam, 2006)*

Developed largely in house: Bregman, Hamaker, Noordam, Brouw, Wijnholds, Yatawatta, Brentjens, Nijboer, …

Several new aspects compared to 'standard' selfcal:

- Major direction dependent corrections
  - Phase => 'non-isoplanaticity' of the ionosphere (low freq, wide FOV)
  - Gain => elevation/azimuth dependent beamshape

  ⇒ image-plane vs uv-plane correction solving/treatment

- All-sky calibration, very wideband synthesis and imaging
  - Global Sky Model needed (spectral index, structural parameters, polarization)
  - w-term always very important (w-projection, speed issue)

- Full-polarization Measurement Equation (Hamaker, Bregman, Sault 1996)

  (Jones matrix description: B, G, E, I, F : 2x2 matrices, both complex and scalar)

  Bandpass, electronic Gain, Beam, Ionosphere refraction, Faraday rotation

Calibration issues and overview:

Calibrating dipole-station arrays at low frequency conceptually involves

3 major unknowns:

- Sky or Global Sky Model (= GSM)
- Station beampattern: (position, frequency, polar) dependent
- Ionospheric phase screen

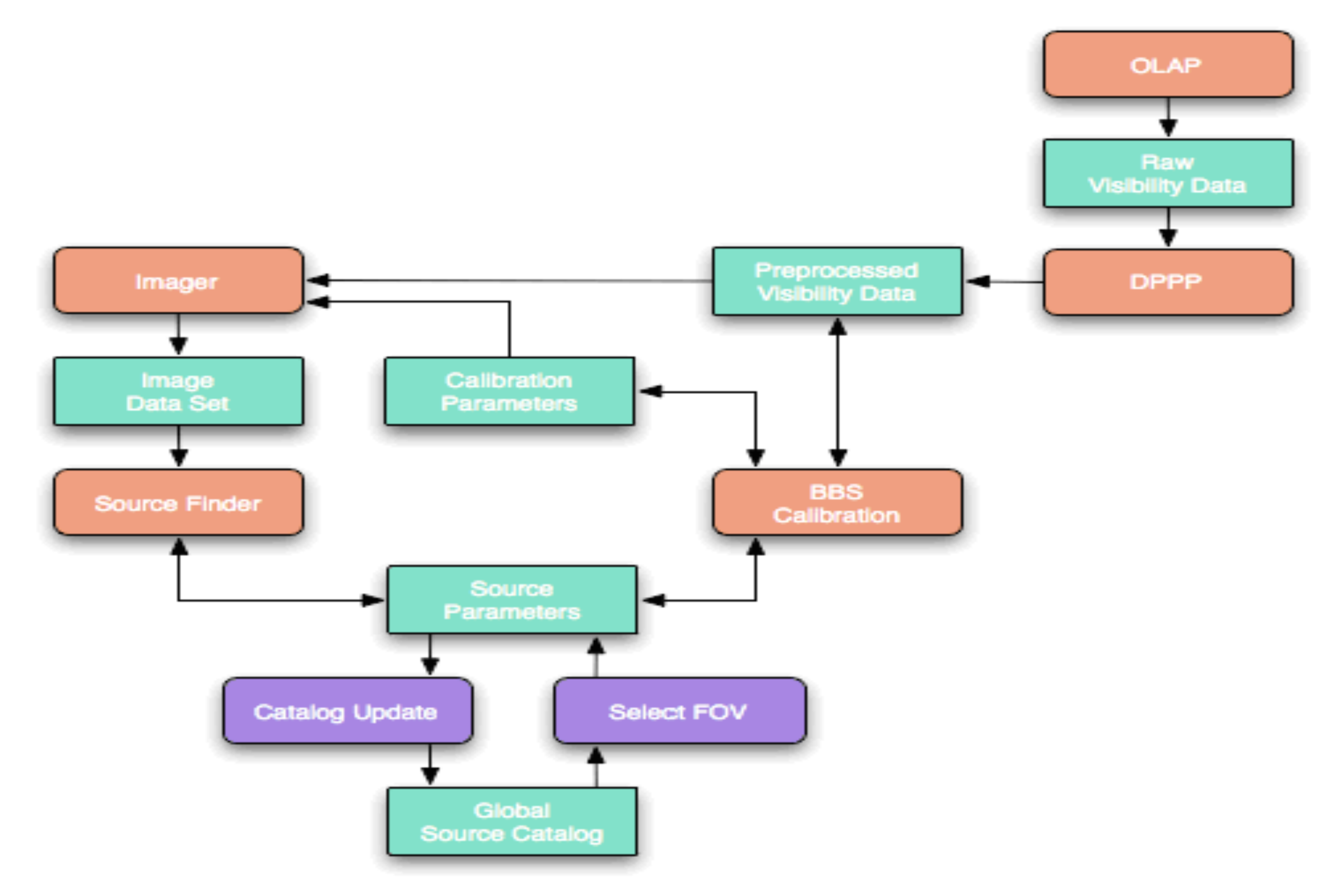
Qualitatively our knowledge will steadily increase stepwise

1. After some time (= MSSS !) we will know the GSM: I,Q,U,V (RA,Dec, freq, (time))
2. Improved modeling of beampatterns (expect/hope to be stable = predictable)
3. Remaining challenge (every 10s) is solving for phase-screen

Quantitatively we still worry whether :

1. there are enough constraints to fit for all ionosphere/beam parameters?
2. it can be done in the available processing time (~ real time) ?
3. the dynamic range will allow thermal noise limited performance ?

Calibration+Imaging pipeline (Nijboer)



LOFAR and its field of view

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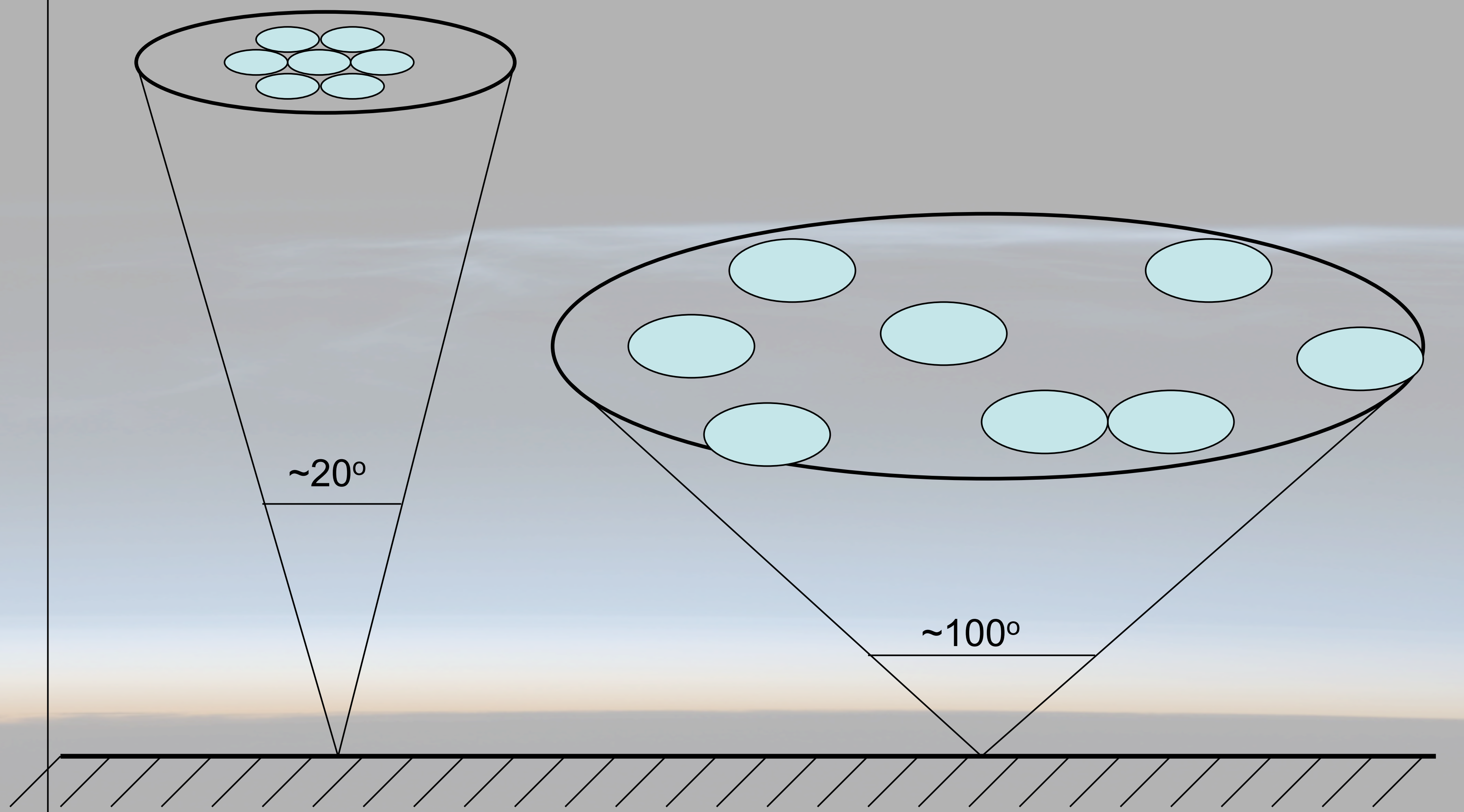
HBA tile/station FOV & LBA dipole/station FOV



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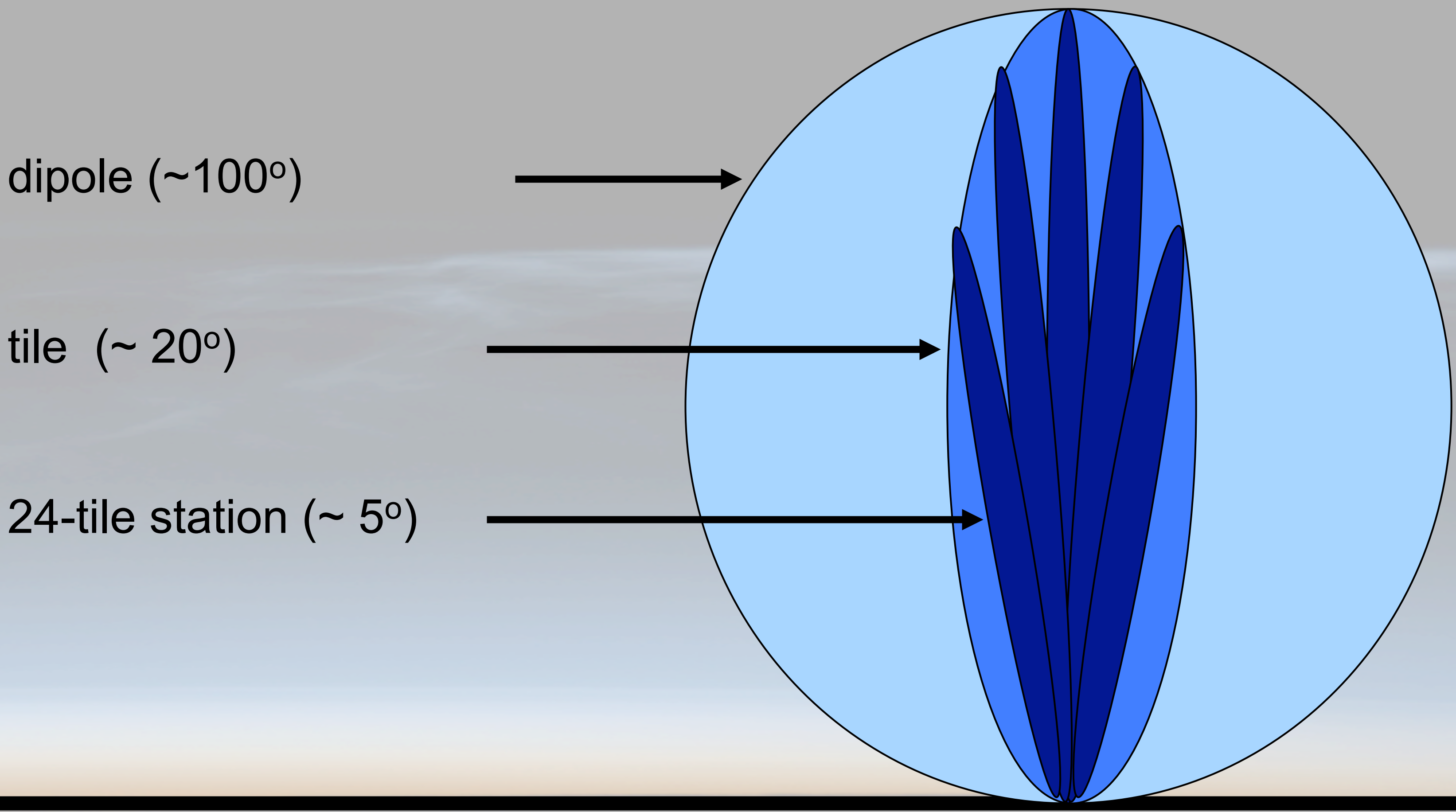
Fields-of-view in core (HBA at ~ 150 MHz)



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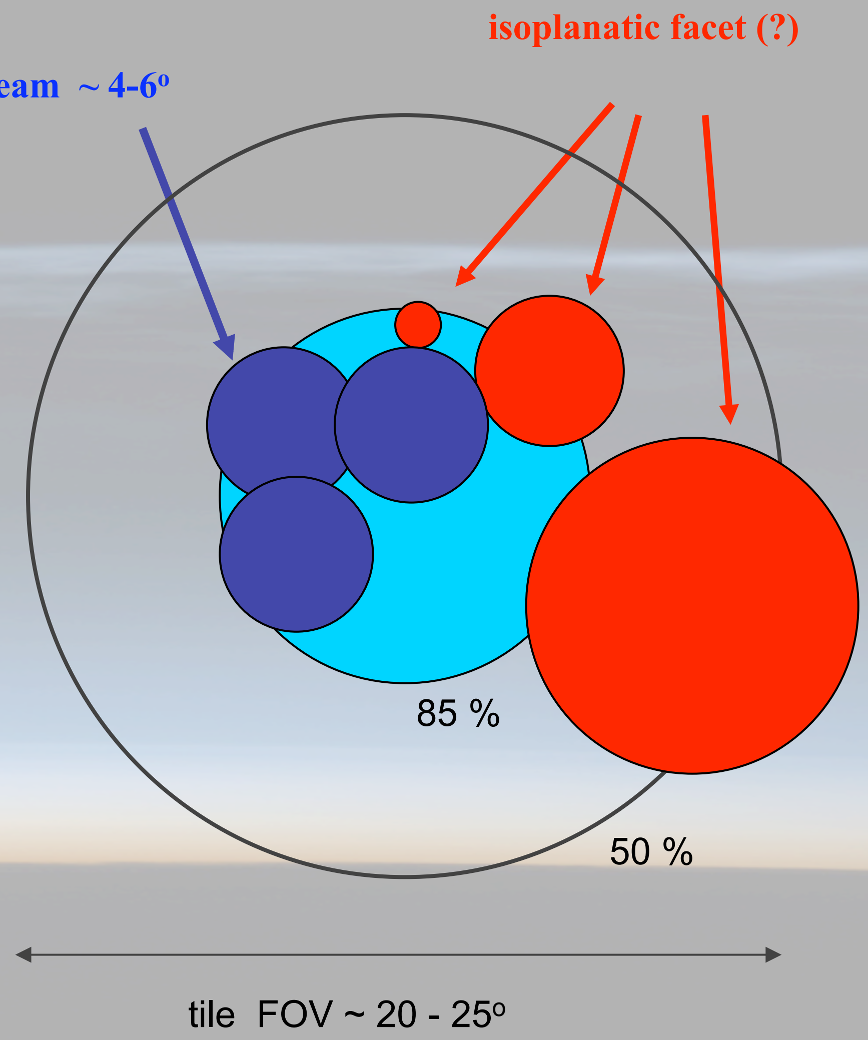
HBA angular scales (24 tiles/station)



Note:

All scales are more or less frequency dependent but in different - timevariable - ways

LOFAR and the Sun

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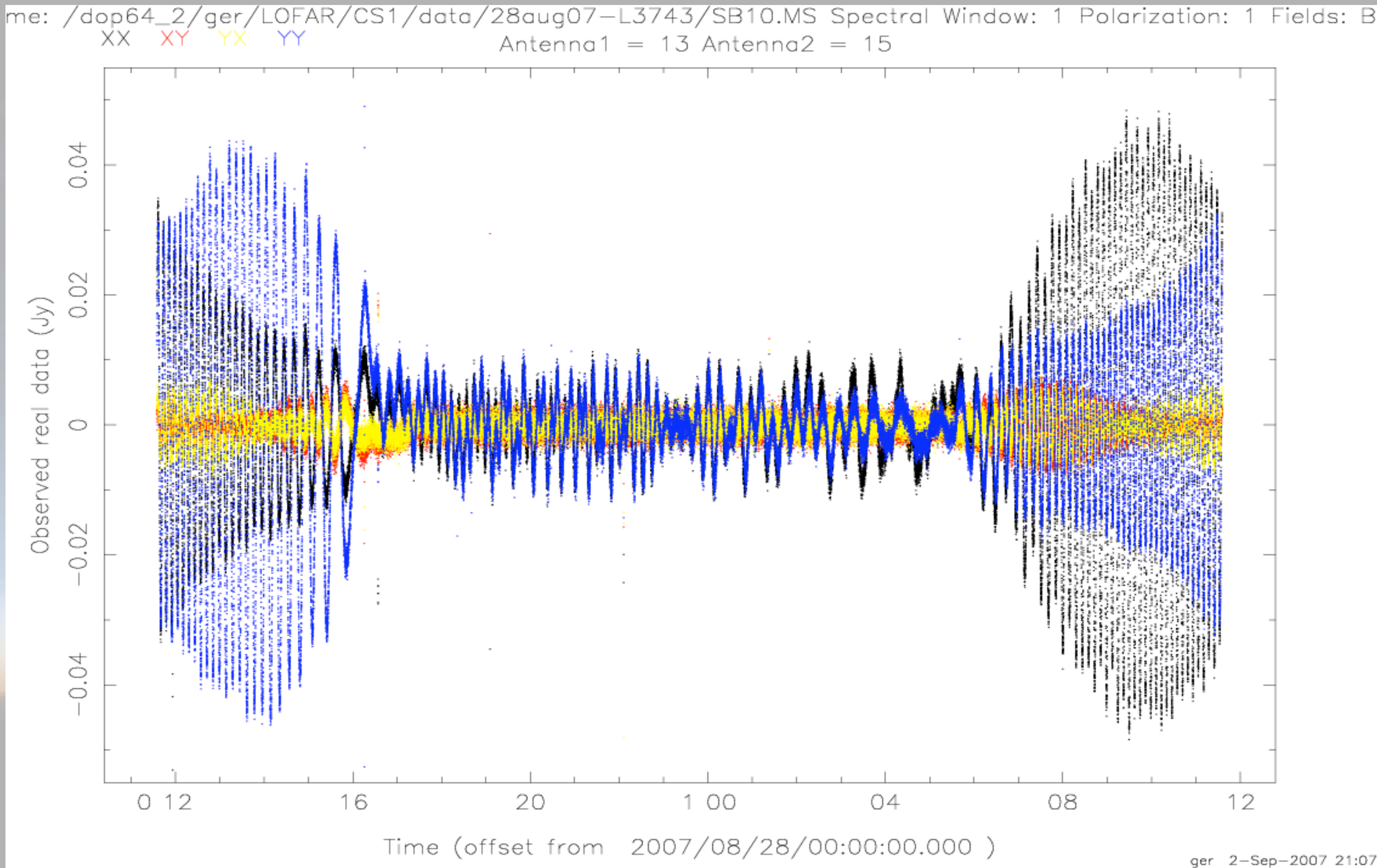
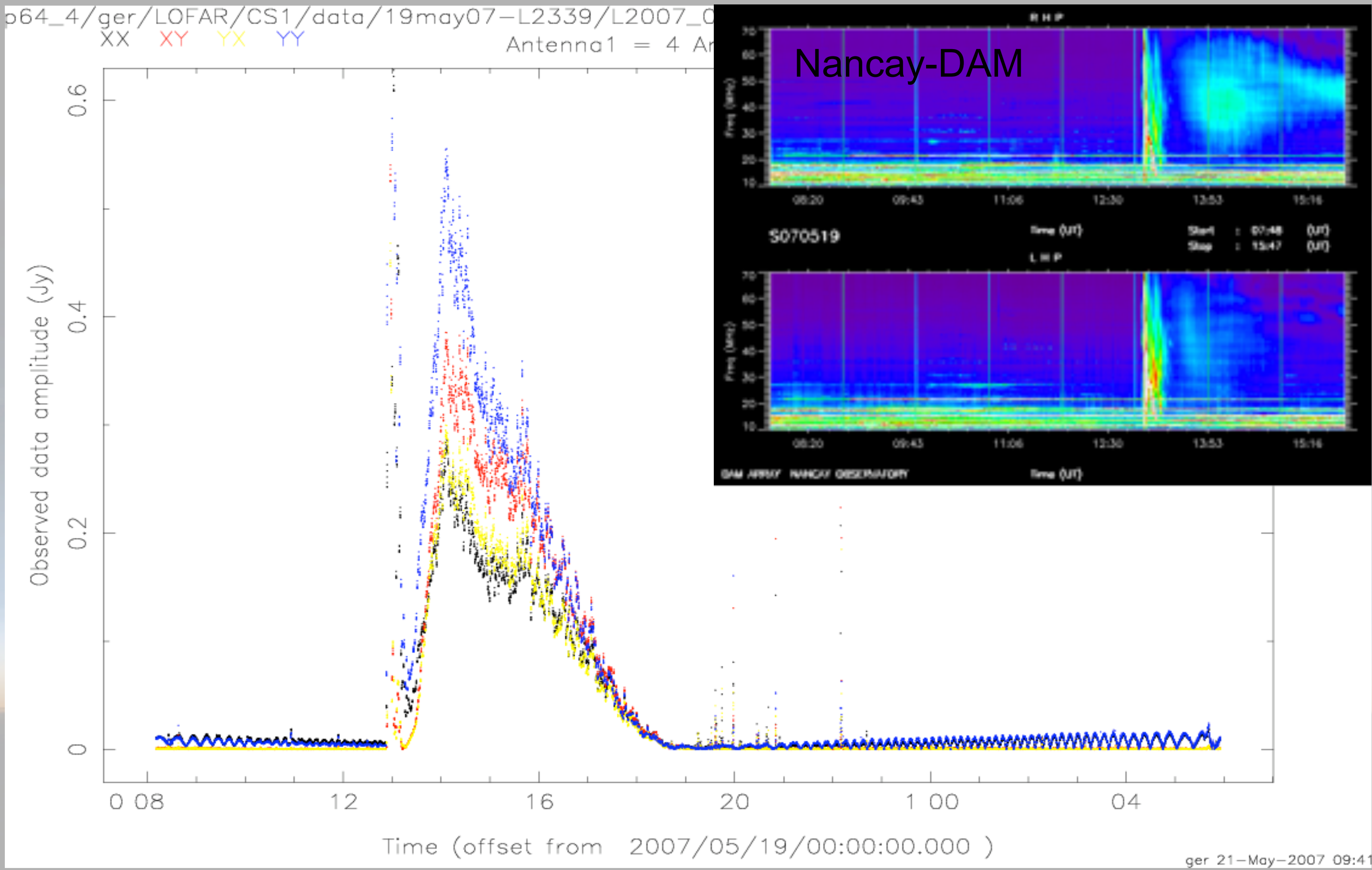
The difference between night and day (220 MHz)

(quiet) Sun, CasA and CygA   (freq $^{+2}$ or freq $^{-1}$)



XX XY YX YY

The disturbed Sun ~50 MHz 19May07



LOFAR and high DR imaging

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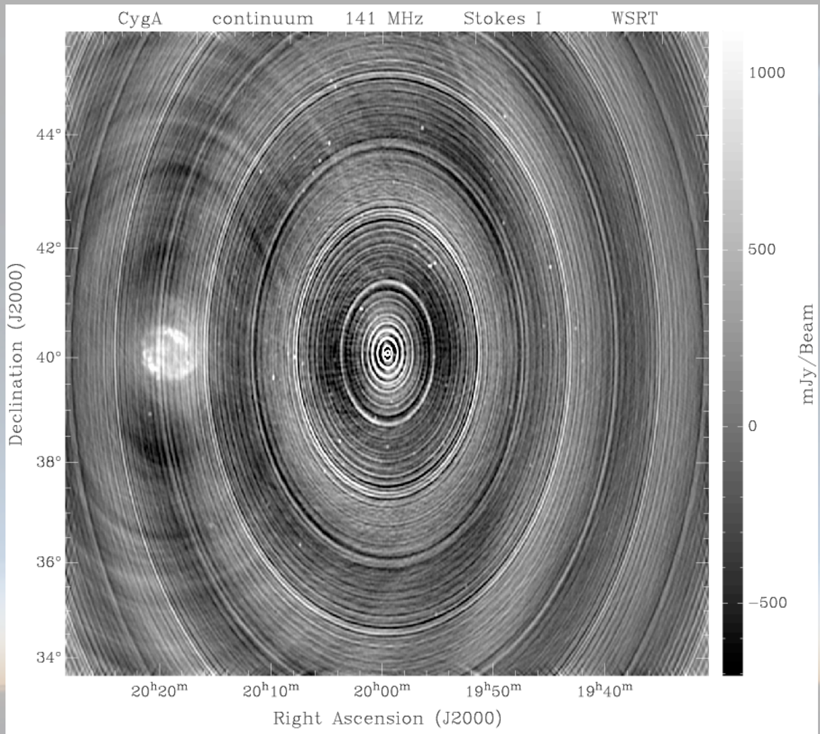
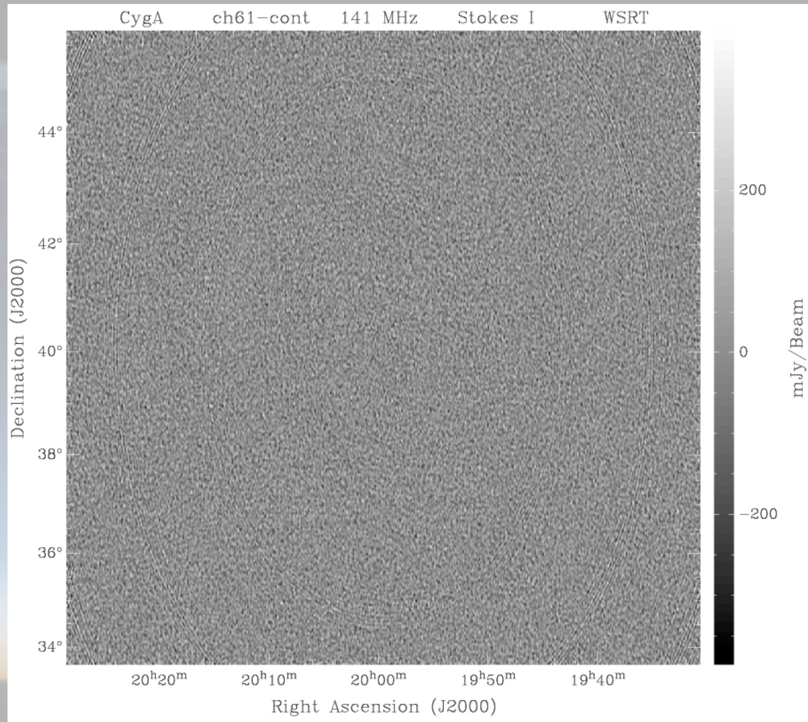
Very bright sources, DR and deconvolution issues

WSRT imaging of Cygnus A, HB20 and environment

‘CONTINUUM’ (B=0.5 MHz) ‘LINE’ CHANNEL (10 kHz) - CONT



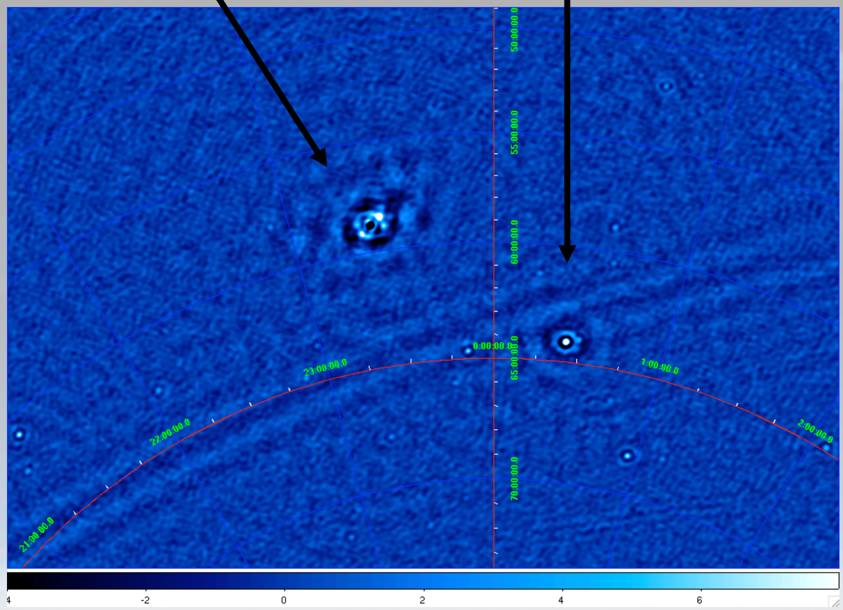


(Original) peak: 11000 Jy noise 70 mJy

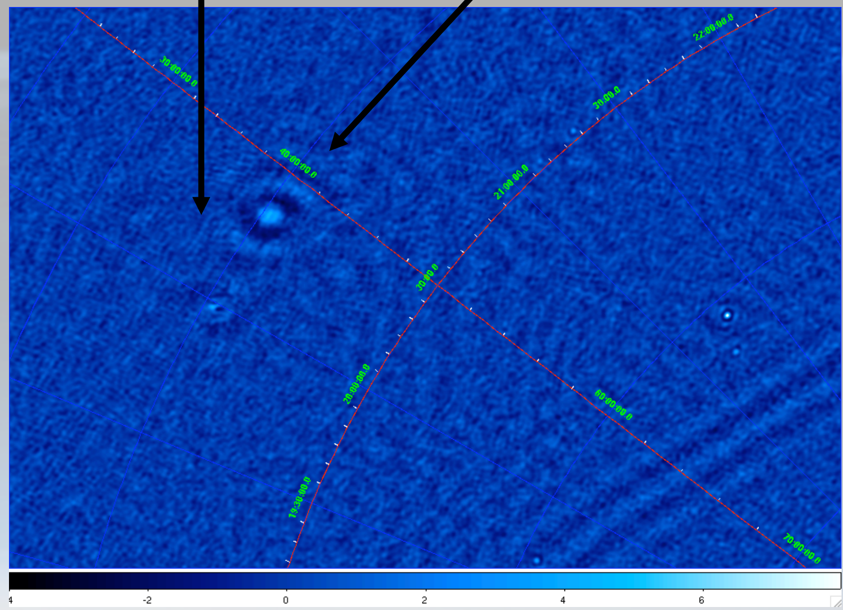
Dynamic Range ~ 5000:1 vs ~150,000 : 1 !!

Zooming in on LOFAR-CS1 150 MHz images

CasA & Tycho's SNR



CygA & HB20



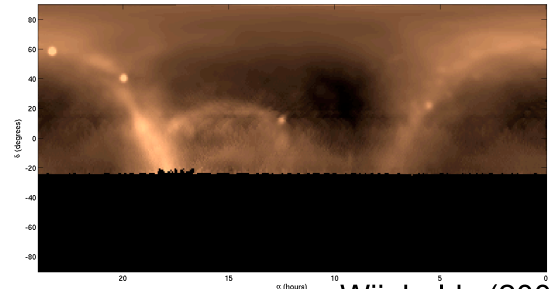
Dynamic range >1000: 1

- CasA resolved (still deconvolution issues)

LOFAR and all-sky imaging

(+ WSRT lessons)

LOFAR pilot facilities/experiments


Wijnholds (2005)

2004-05 ITS 20 - 40 MHz 80x6.7s

2004-08 WSRT LFFE 115 - 175 MHz

- several deep 6x12=72h syntheses, all-sky imaging !
- 2m - polarimetry

2006-07 WSRT ‘WHAT’ 115 - 175 MHz (4 tiles)

- ⇒ array beampatterns/polarization

2007-08 CS-1 10 - 80 MHz & 110 - 240 MHz > 72h syntheses

- station calibration, analog/digital beamforming,
- datatransport, tracking, correlation,
- calibration, imaging, …

CS-1 configuration ('mini'-LOFAR)

Dec 06 --> Mar 09

- hardware distributed across 4 stations:
  - LBA: 96 dipoles (48 + 3x16)
  - HBA: 32 dipoles + 6 tiles
- per station: 4 -12 'micro'stations
- digital beamforming (with 4 - 48 dipoles)
- baselines from ~ 10 - 450 meter
- 16 'micro'stations
  ⇒ 120 (~ 70) interferometers
- 24 microstations
  ⇒ 276 (~ 180) interferometers

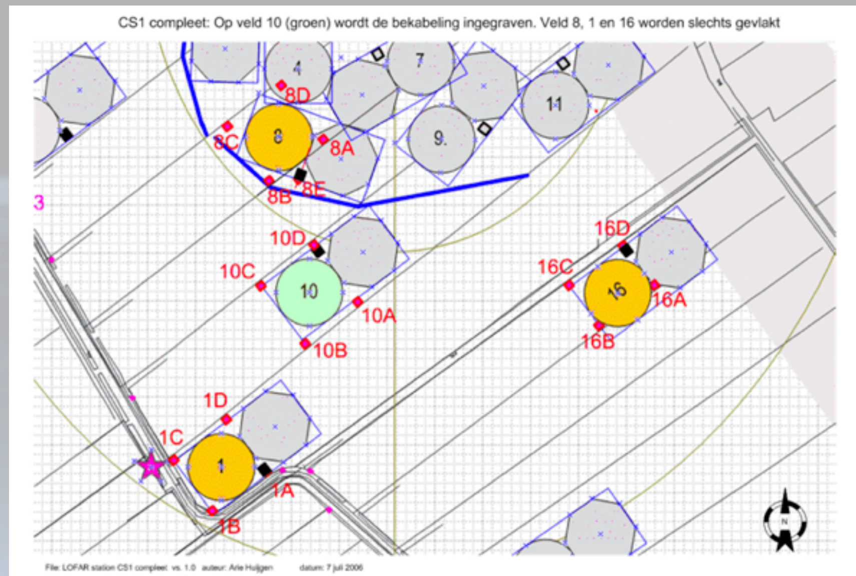


Figure 1: CS1 station locations.

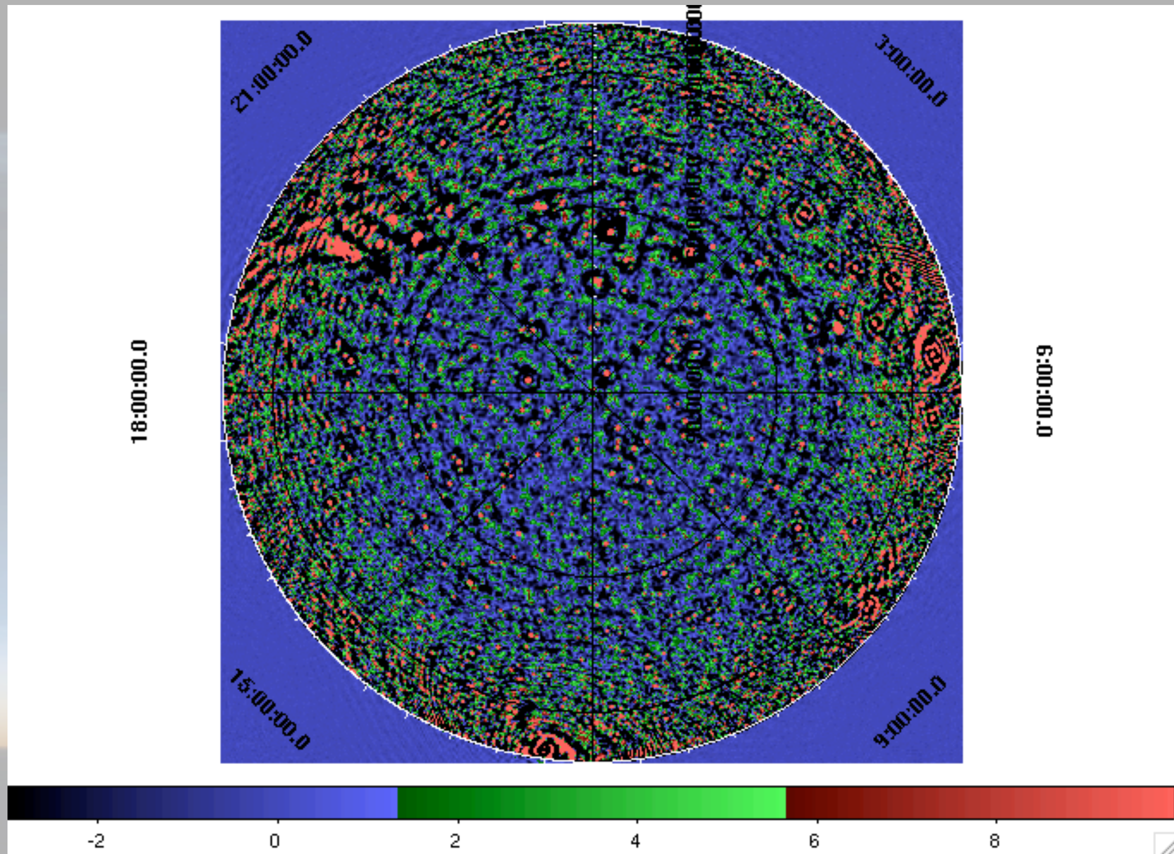
400 m

All-sky LOFAR CS-1 image at ~ 50 MHz

16 dipoles (~70 baselines)

3 x 24h

38 - 59 MHz
Bandwidth ~ 6 MHz



~ 800 sources !

PSF ~ 0.5°

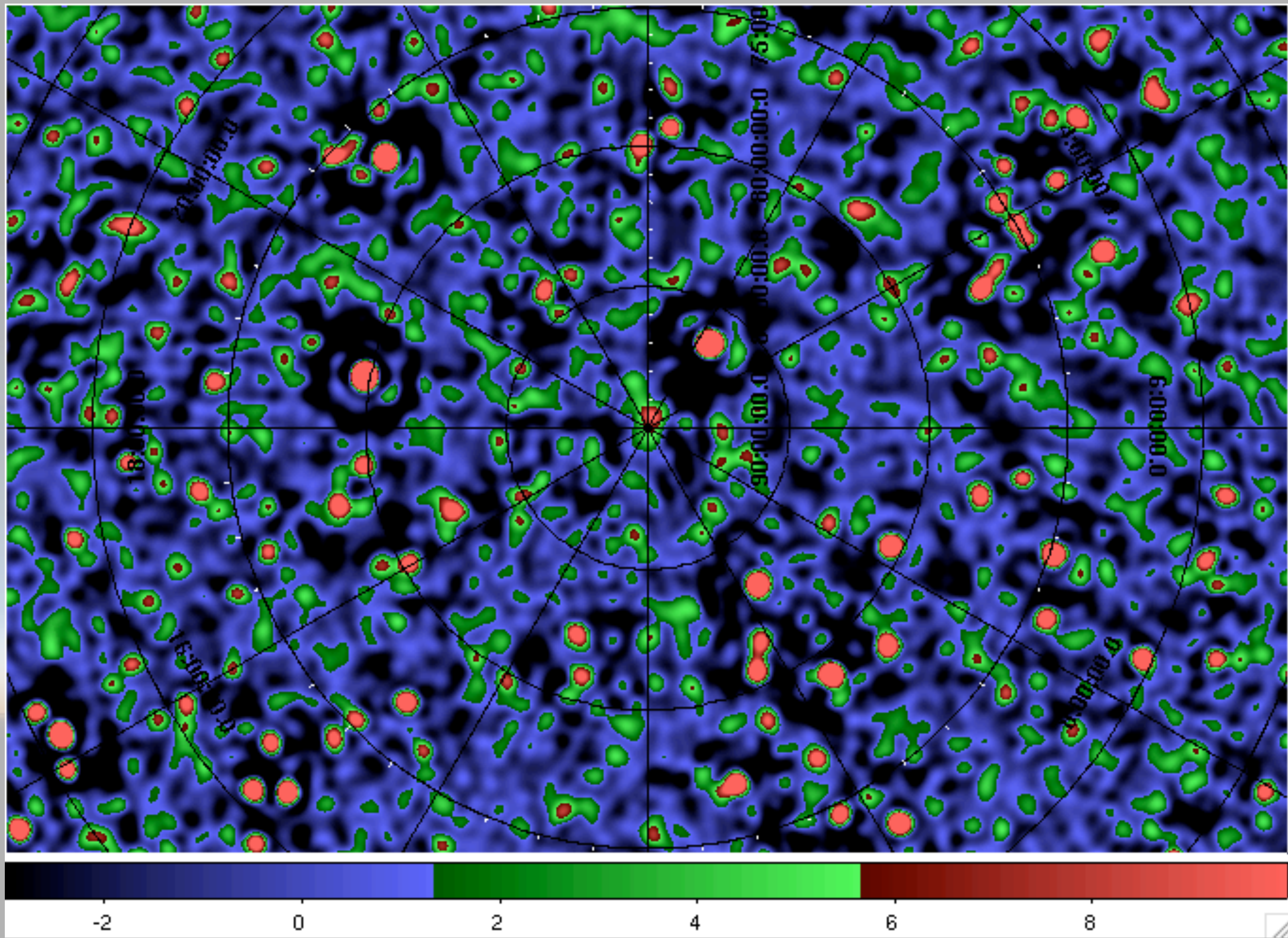
noise ~ 1 Jy

CasA/CygA (20,000 Jy)
subtracted

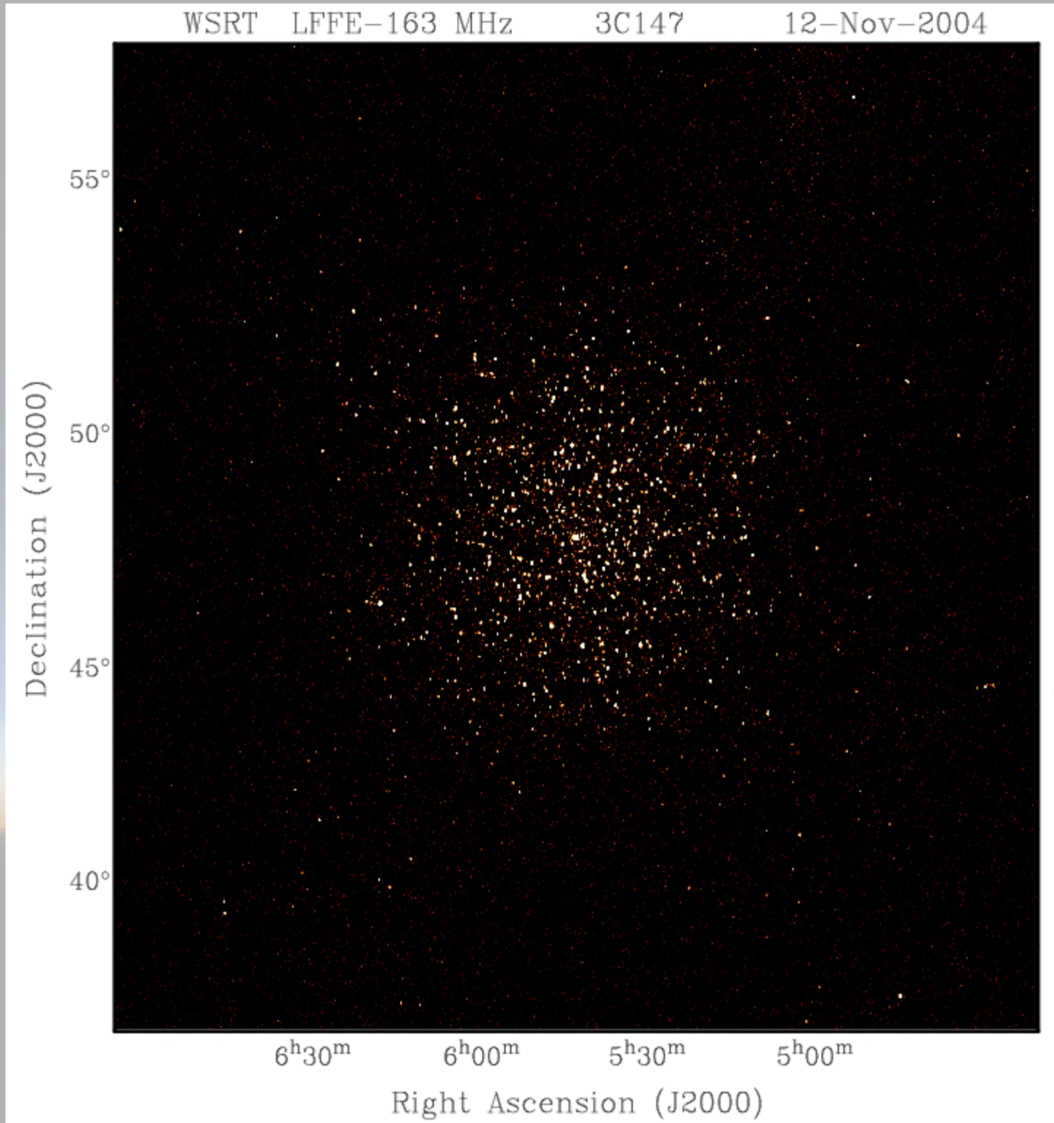
- beam corrected -
- no deconvolution as yet

Yatawatta, 2007

Zooming in: confusion limited !



The first WSRT LFFE image (in nov 2004)



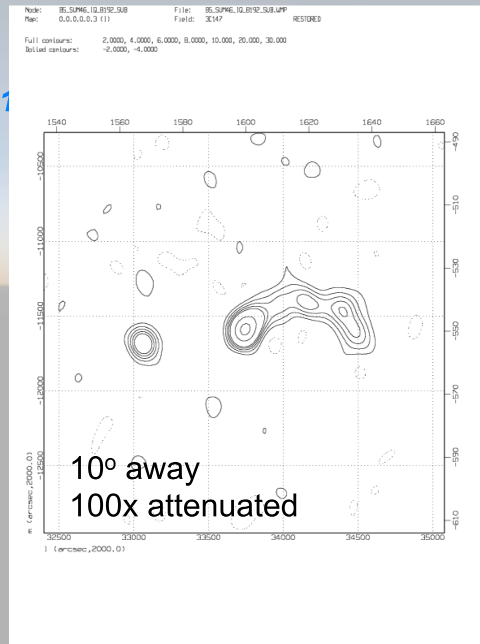
3C147 60 Jy pointsource

rms noise 3-4 mJy

VERY quiet ionosphere

Isoplanatic scale > 20° !!

3C129/129.1



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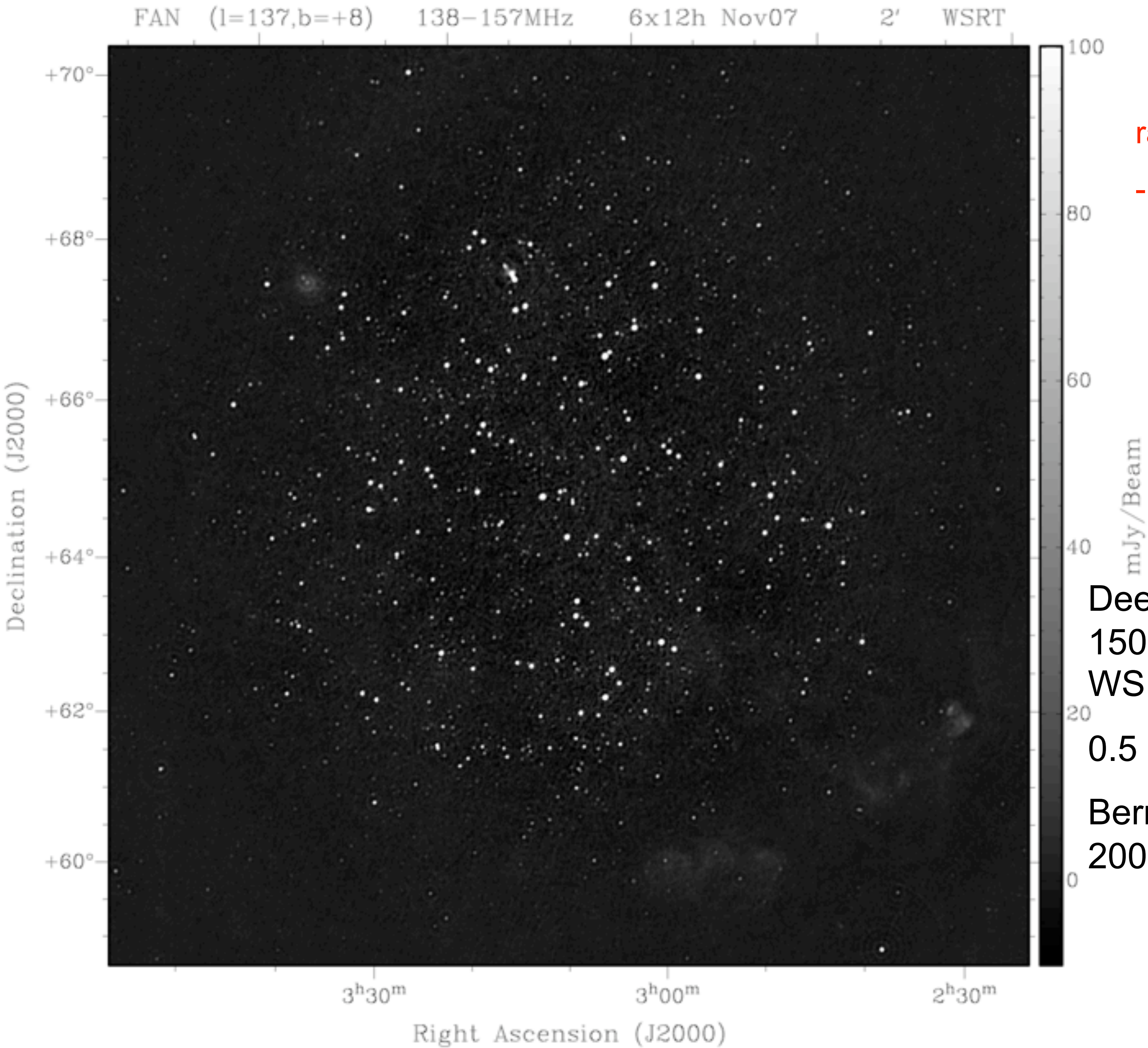


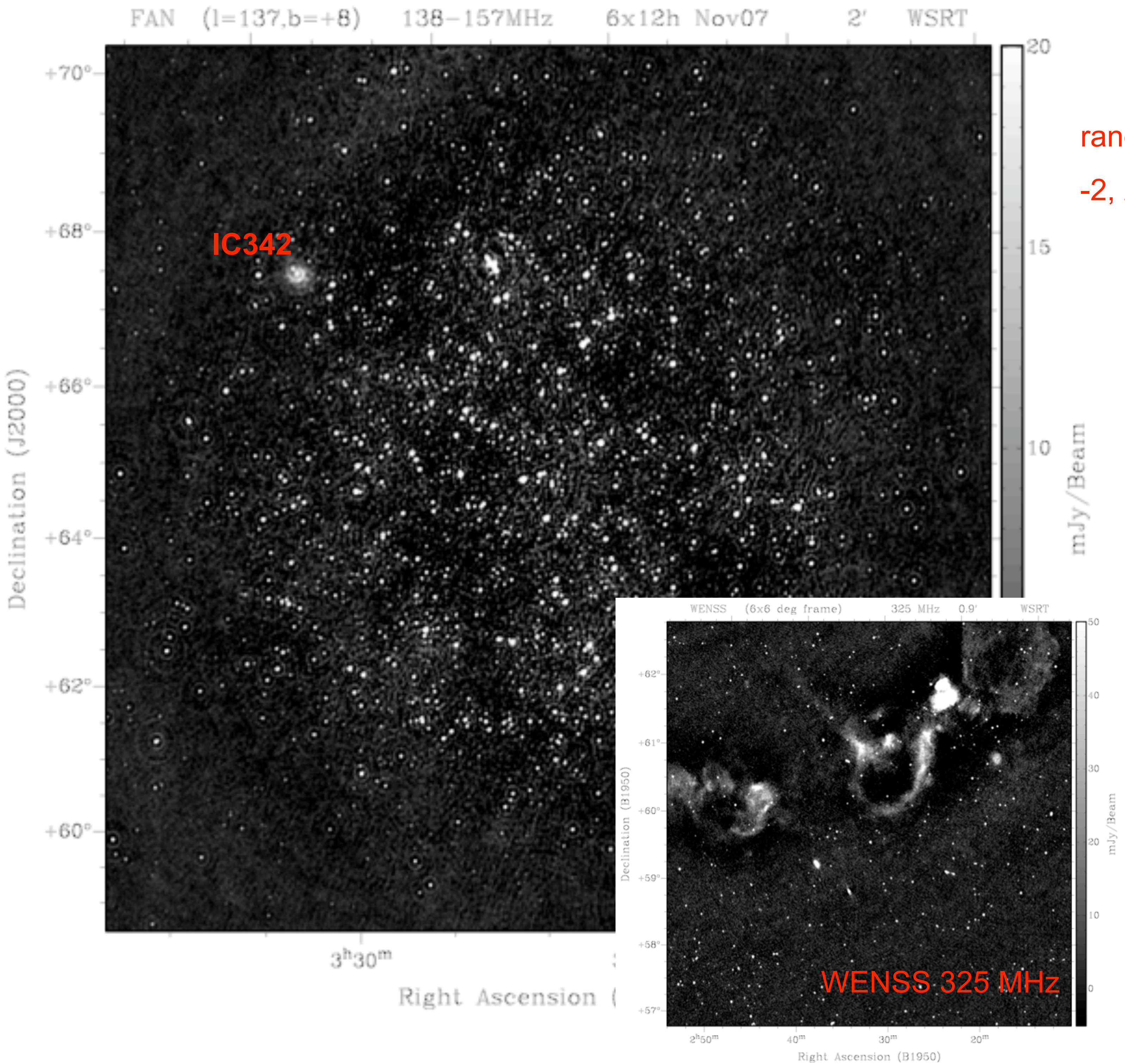
range

-10,100 mJy

Deepest ever 150 MHz WSRT image

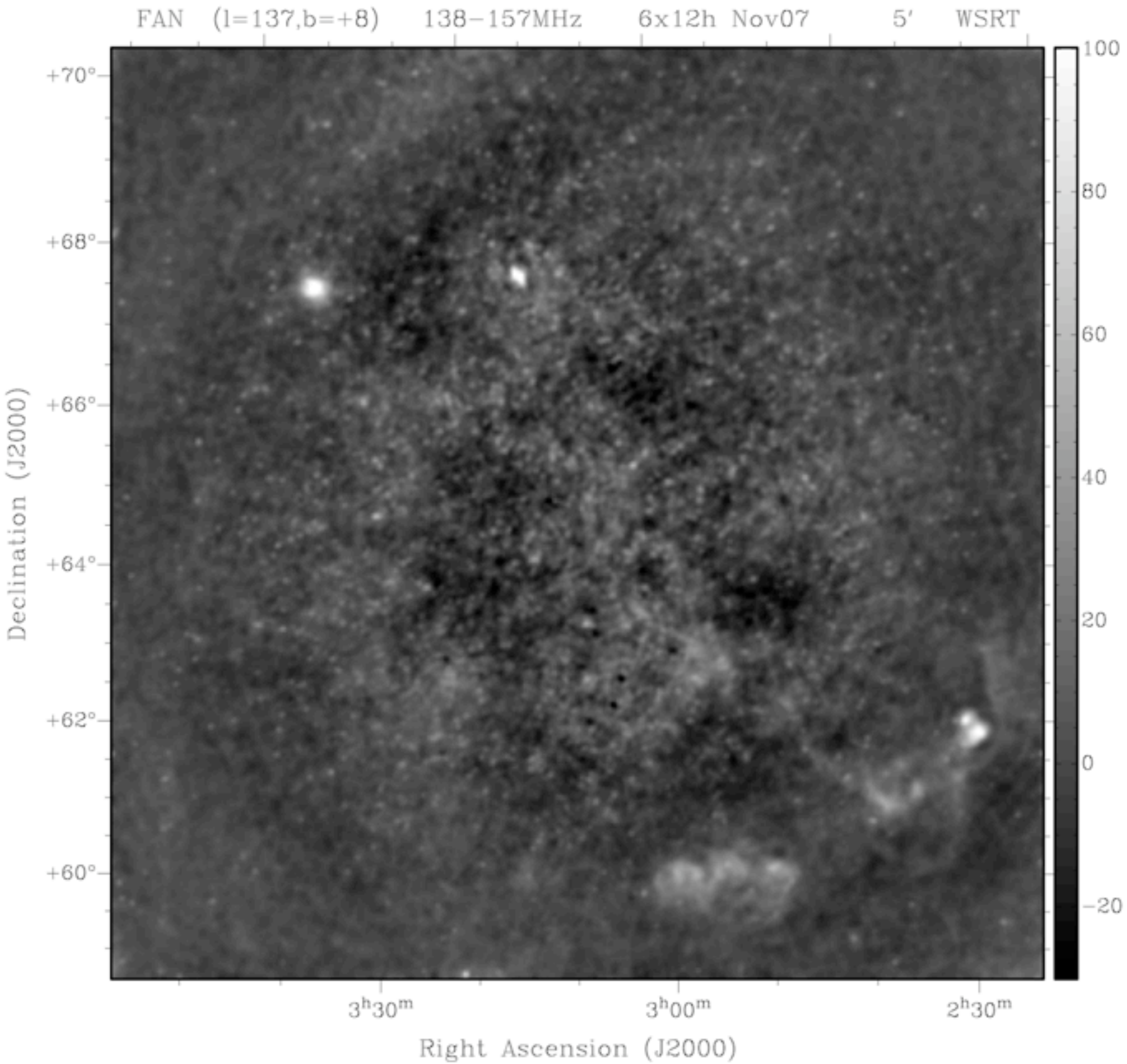
0.5 mJy noise

Bernardi et al, 2009)



range

-2, 20 mJy



Residual image after subtracting sources to 20 mJy and smoothed to 5'

range

-30,100 mJy

Diffuse Galactic foreground visible !

LOFAR and the ionosphere

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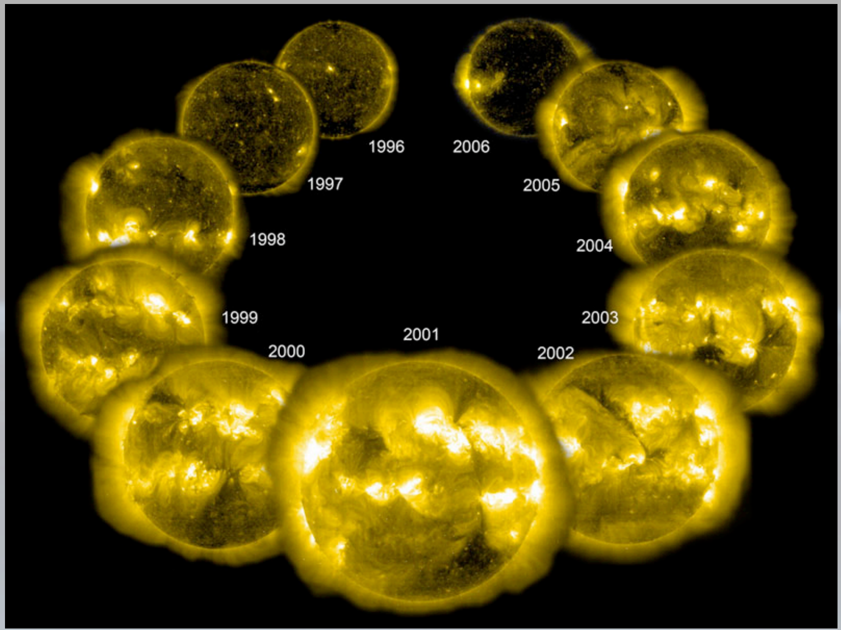
Ionospheric issues

Non-isoplanaticity (low freq, large FOV)

Solar cycle (next maximum ~2012)

Array scale > refractive/diffractive scale

TID's, (Kolmogorov) turbulence



Soho-solarcycle,

APOD 5 dec07

Tools/approaches:

- Bandwidth synthesis (sensitivity, freq-dependence,..)
- Peeling individual sources and screen modelling (SPAM, Intema)
- Large scale screen modelling (MIM, Noordam; LIONS, van Bemmel et al))
- GPS-TEC starting model (Anderson, Mevius)
- Utilize 2-D frozen flow approximation (?)
- 3-D tomography solutions (multiple screens/layers: => EoR KSP needs)

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Ionospheric TEC modeling

1) Both refraction and Faraday rotation depend on absolute TEC which changes relatively slowly with time and position

2) Selfcalibration/imaging depend on relative TEC which varies rapidly (1-10s) --> selfcal/peeling takes (partly) care of this

3) Ways to measure absolute TEC:

— differential angles in large FOV images (26-Nov-08 - LSM)

— Faraday rotation (29-Oct-08 - LSM)

— GPS data (not accurate enough ??)

— snapshot all-sky observation sequences (e.g. 10s every 120s) and combining absolute+relative delays

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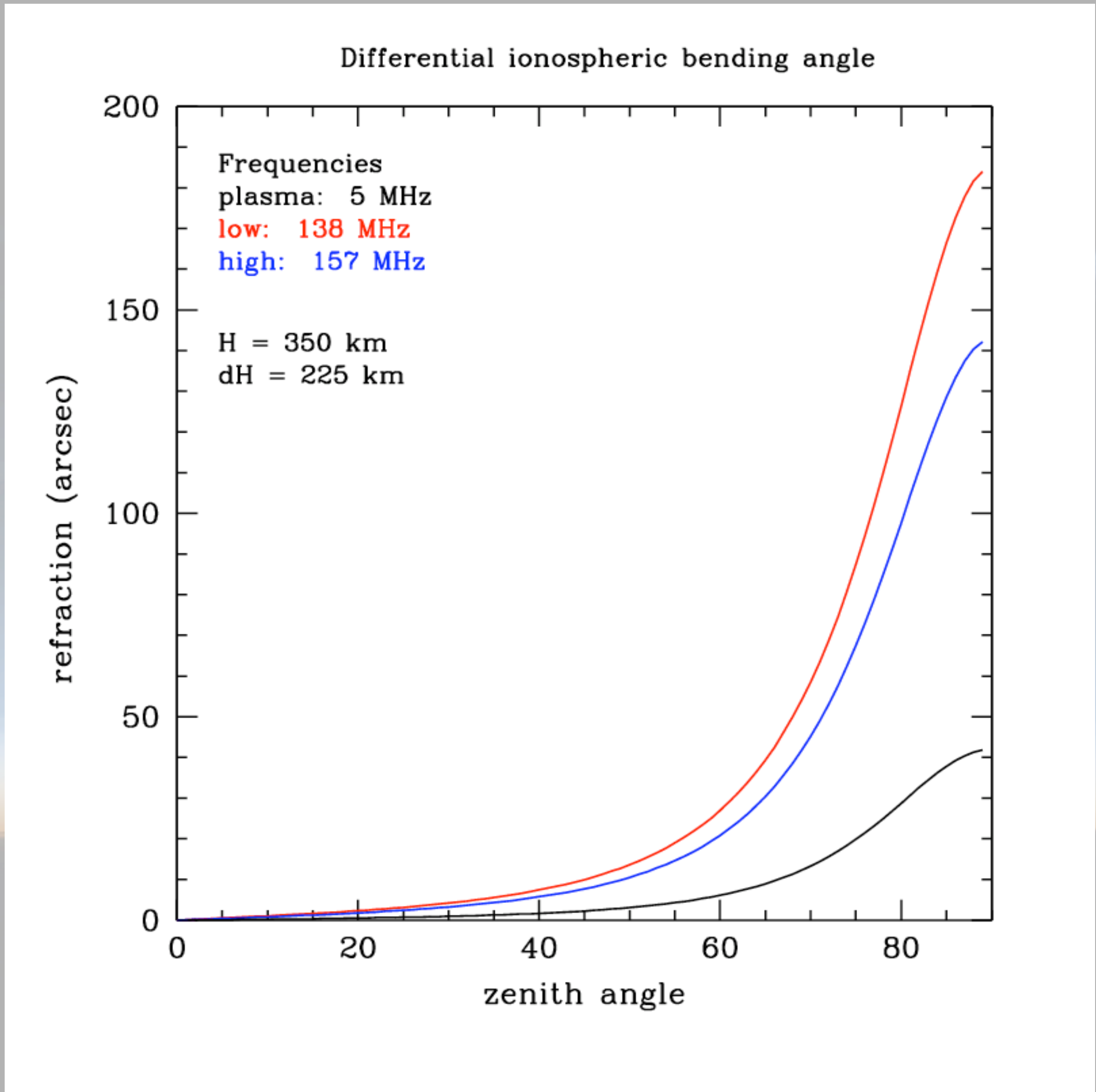
Frequency-dependent ionospheric refraction



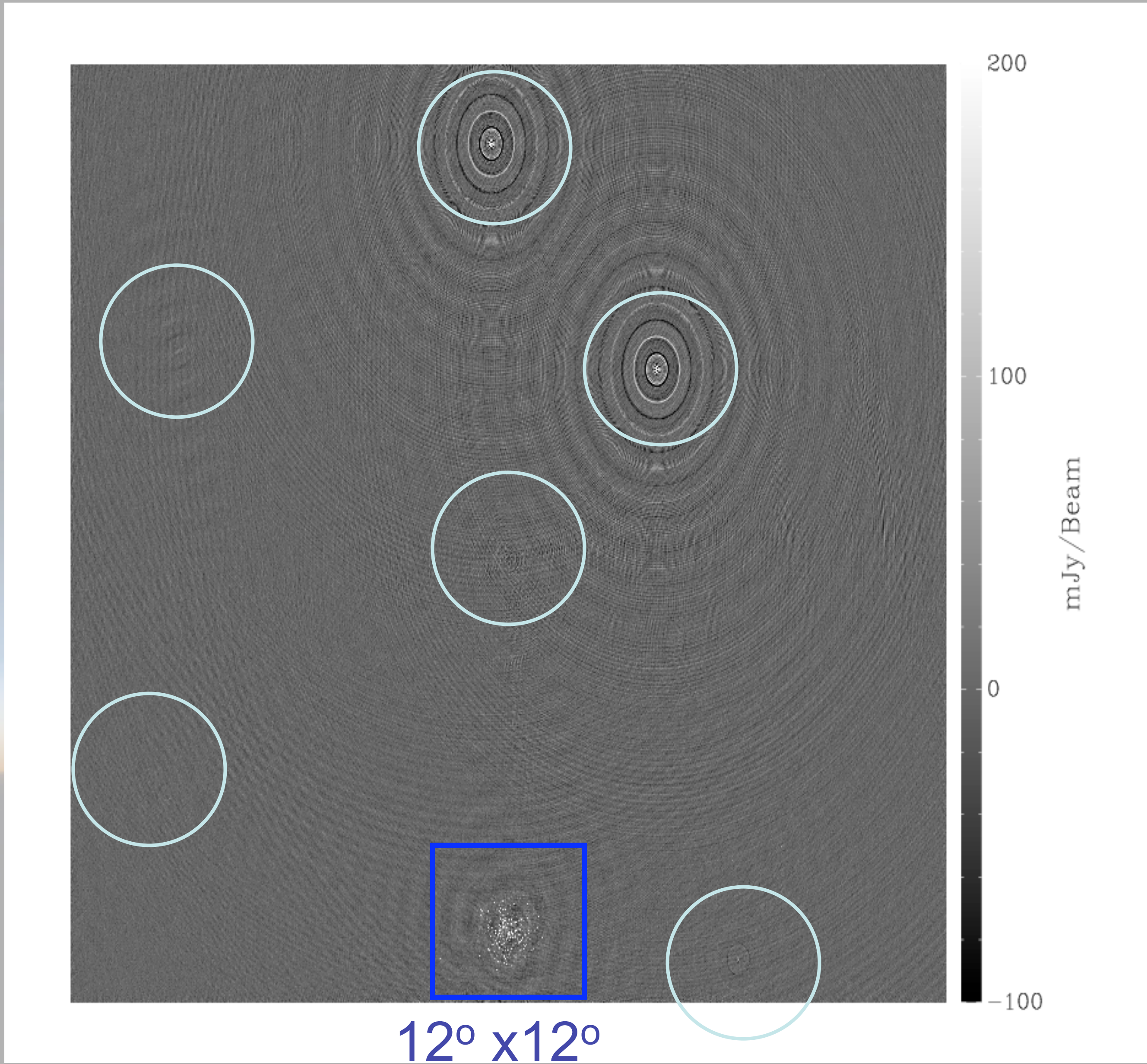
'Linear or quadratic'

Refraction scales linearly with TEC and quadratically with the plasma frequency

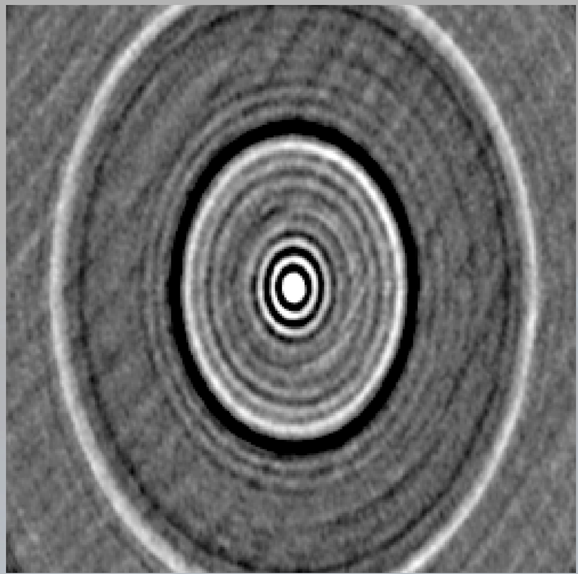
Refraction also scales quadratically with observing wavelength

but our ability to measure this angle scales again linearly with wavelength

WSRT 150 MHz image of 3C196: 'all-sky imaging needed !'

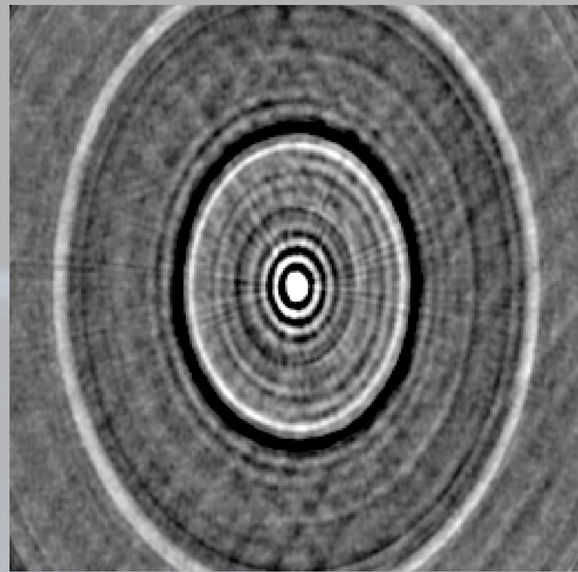


The A-team in WSRT 138-157 MHz observations of 3C196



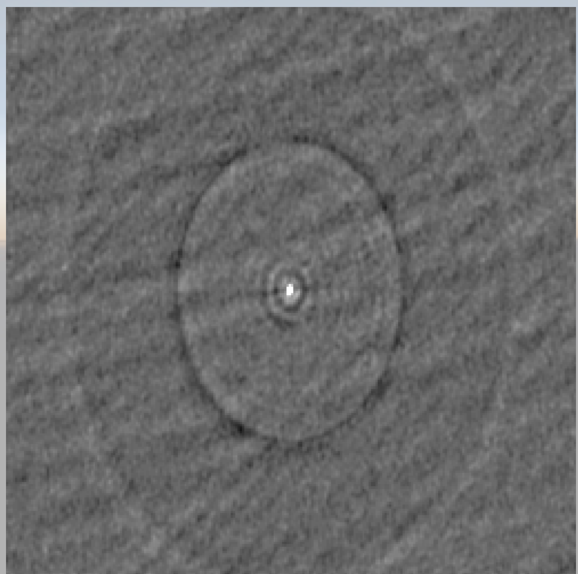
5' PSF

CasA CygA

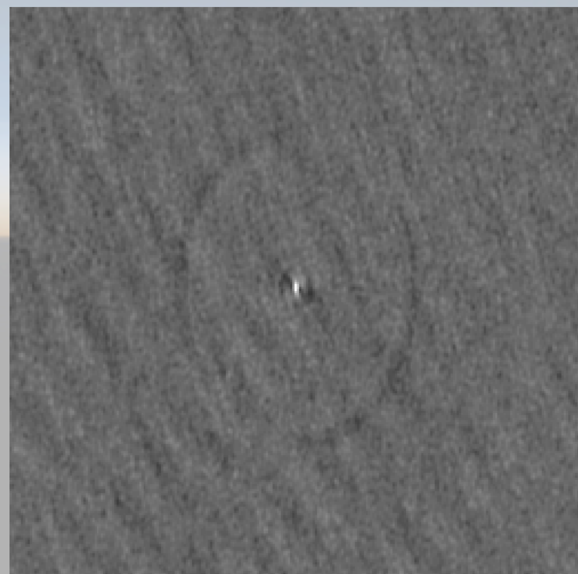


~ 10 Jy peakflux

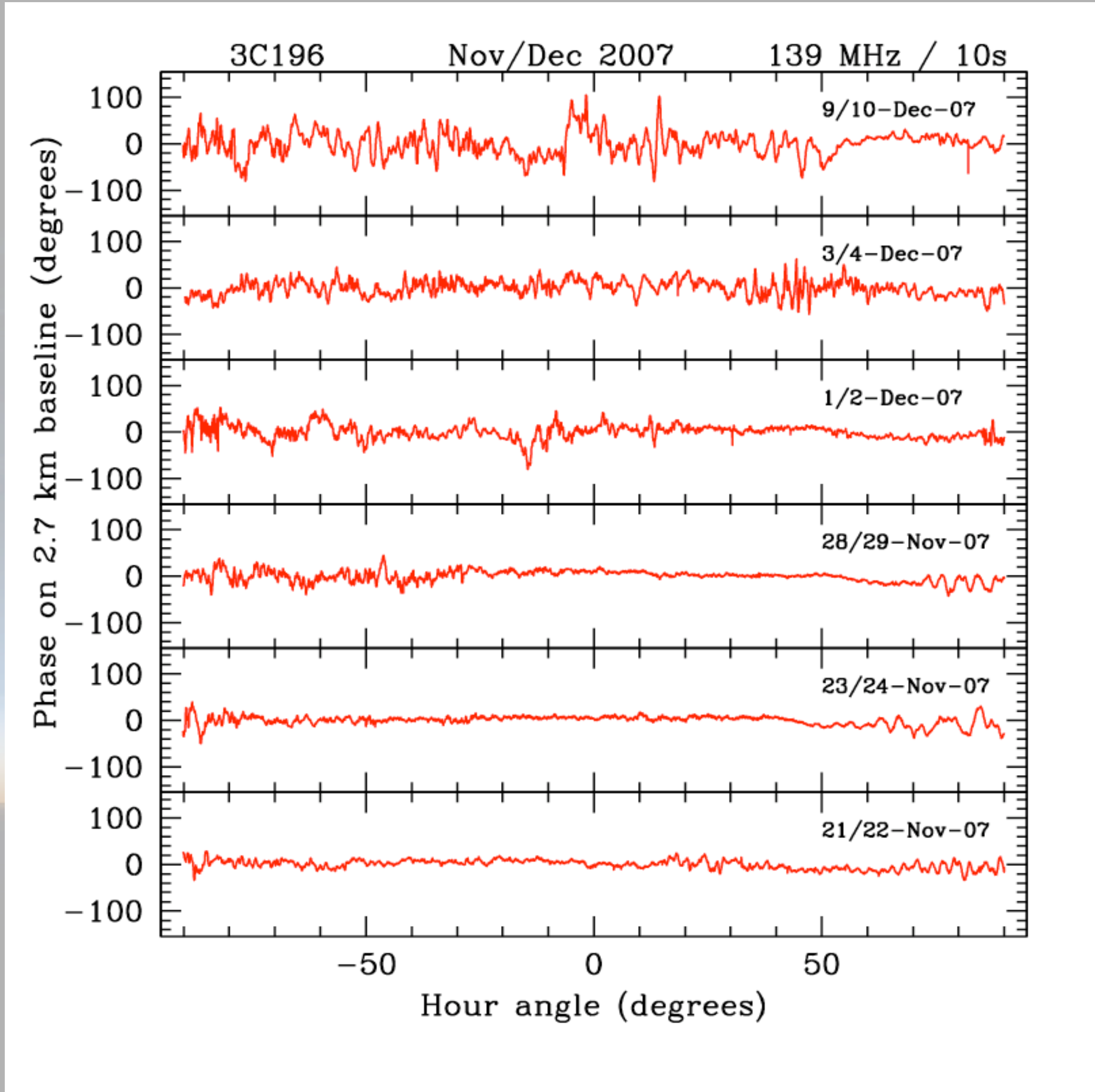
- 0.1 to +0.2 Jy



TauA VirA



3C196 - selfcal phase solutions

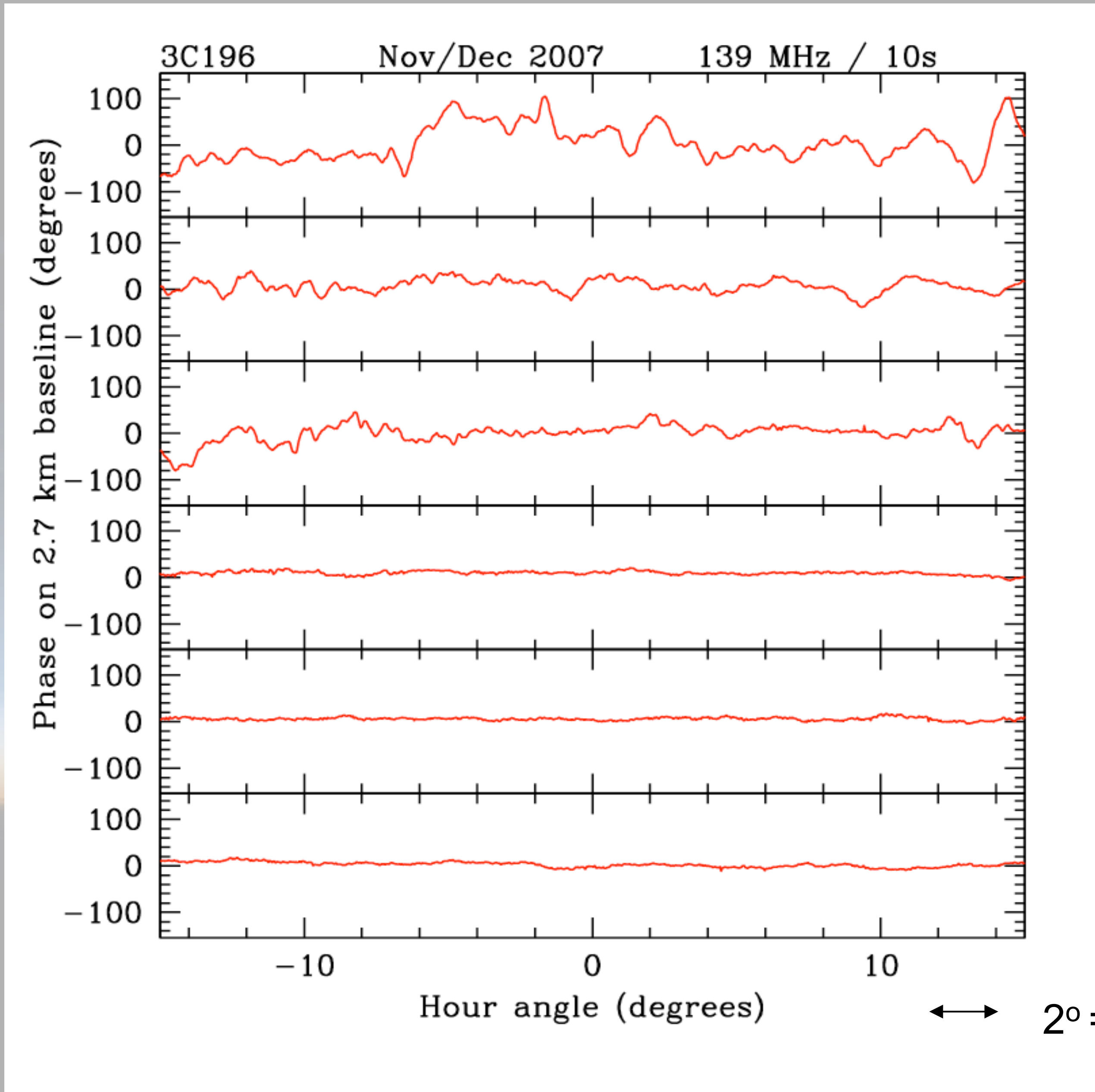


6 x12h

Note the very different ionospheres !

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

3C196 selfcal phase solutions: zooming in



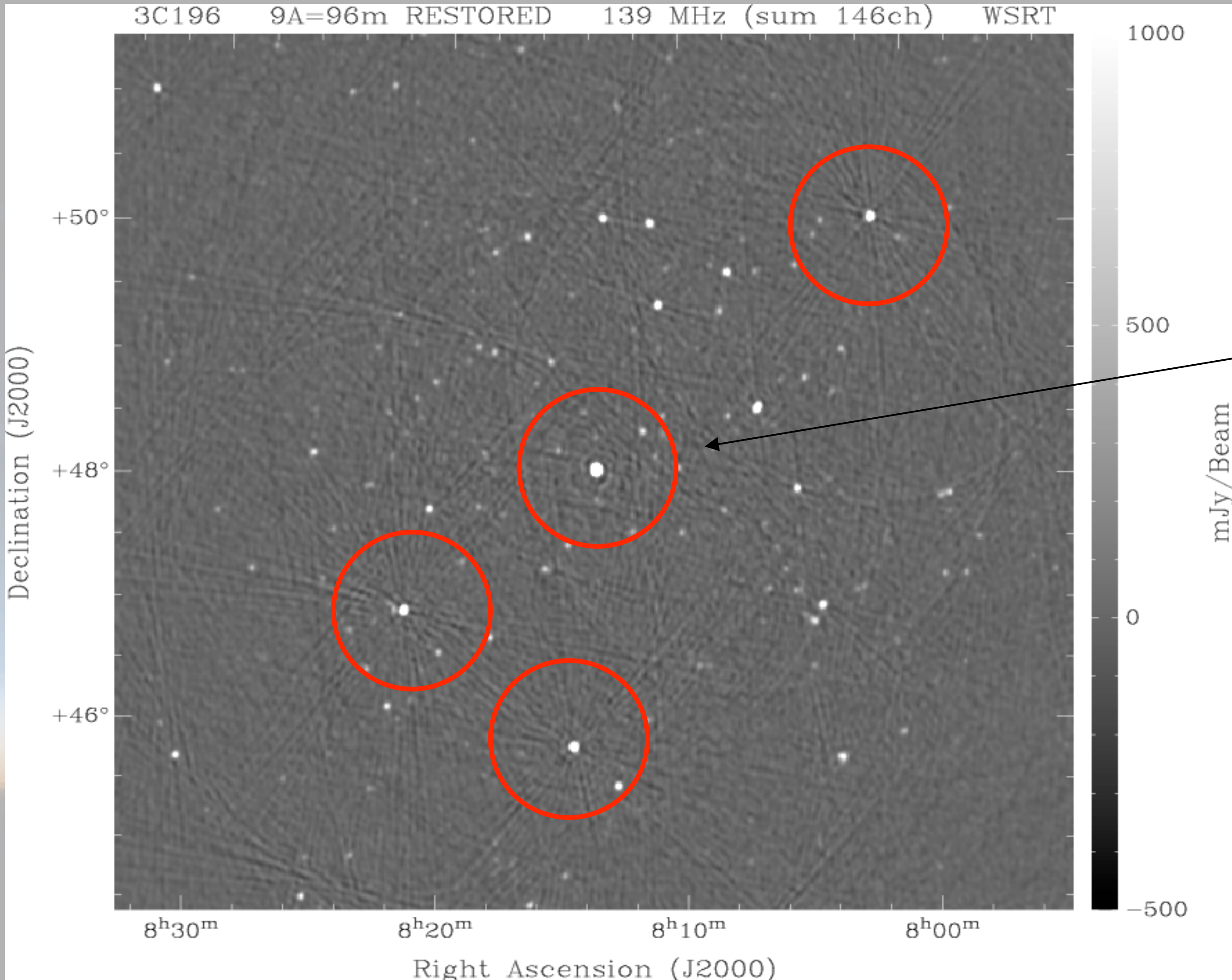
Note ‘well-resolved’ turbulence/waves

(noise

= line thickness)

↔ 2^o = 8min = 48 samples

3C196 in last night: serious nonisoplanaticity !!



3C196

80 Jy

3 other sources

6-8 Jy

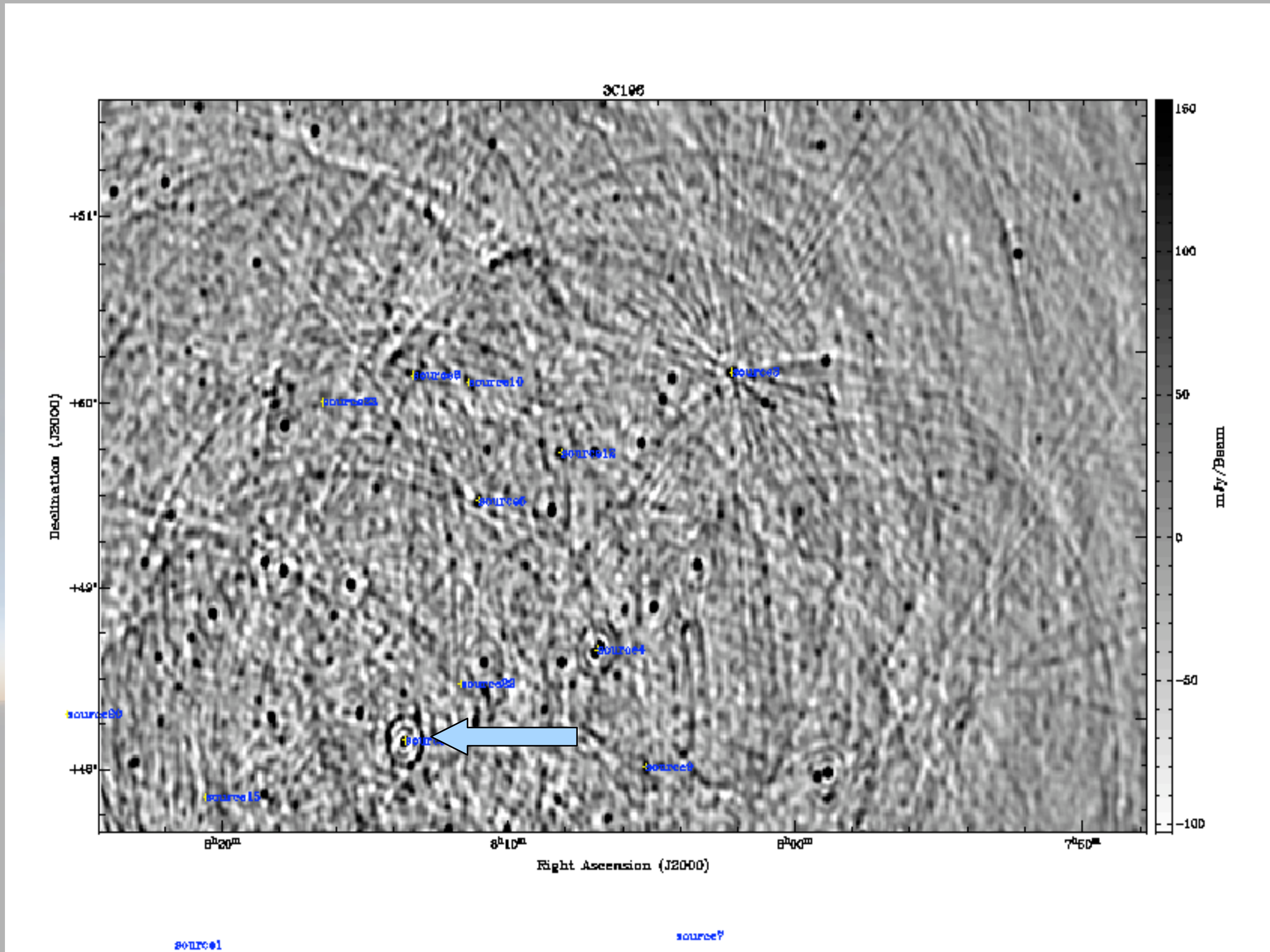
BBS and MIM-modeling on 3C196 WSRT data

Work in progress by Maaijke Mevius, Gianni Bernardi, Joris van Zwieten

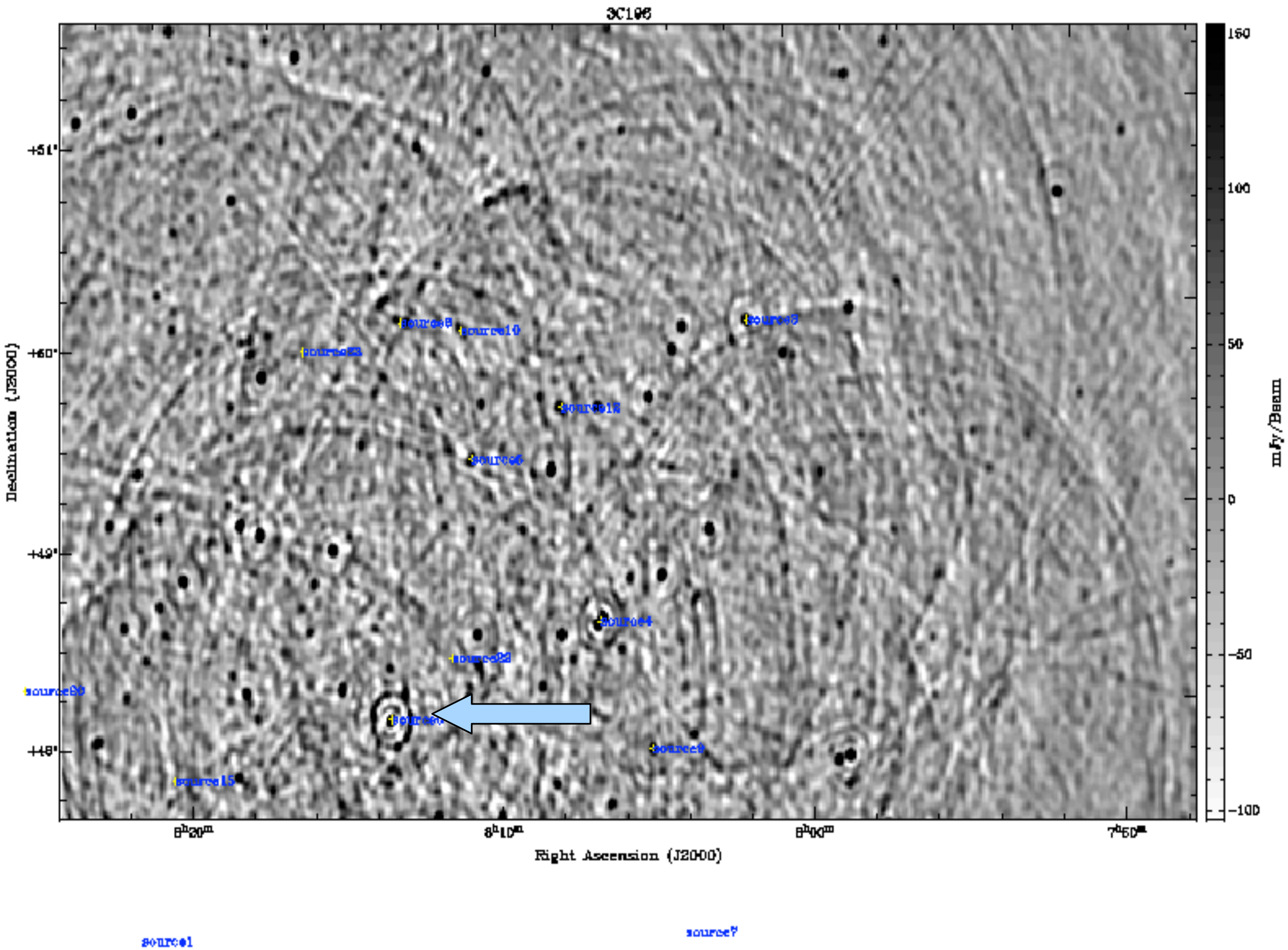
Fitting 2-dimensional phase screen at altitude of 300 km

- Solving directly on UV-data (using known positions)
- 2 parameters : plane
- 5 parameters : 2nd order
- 8 parameters : 3rd order

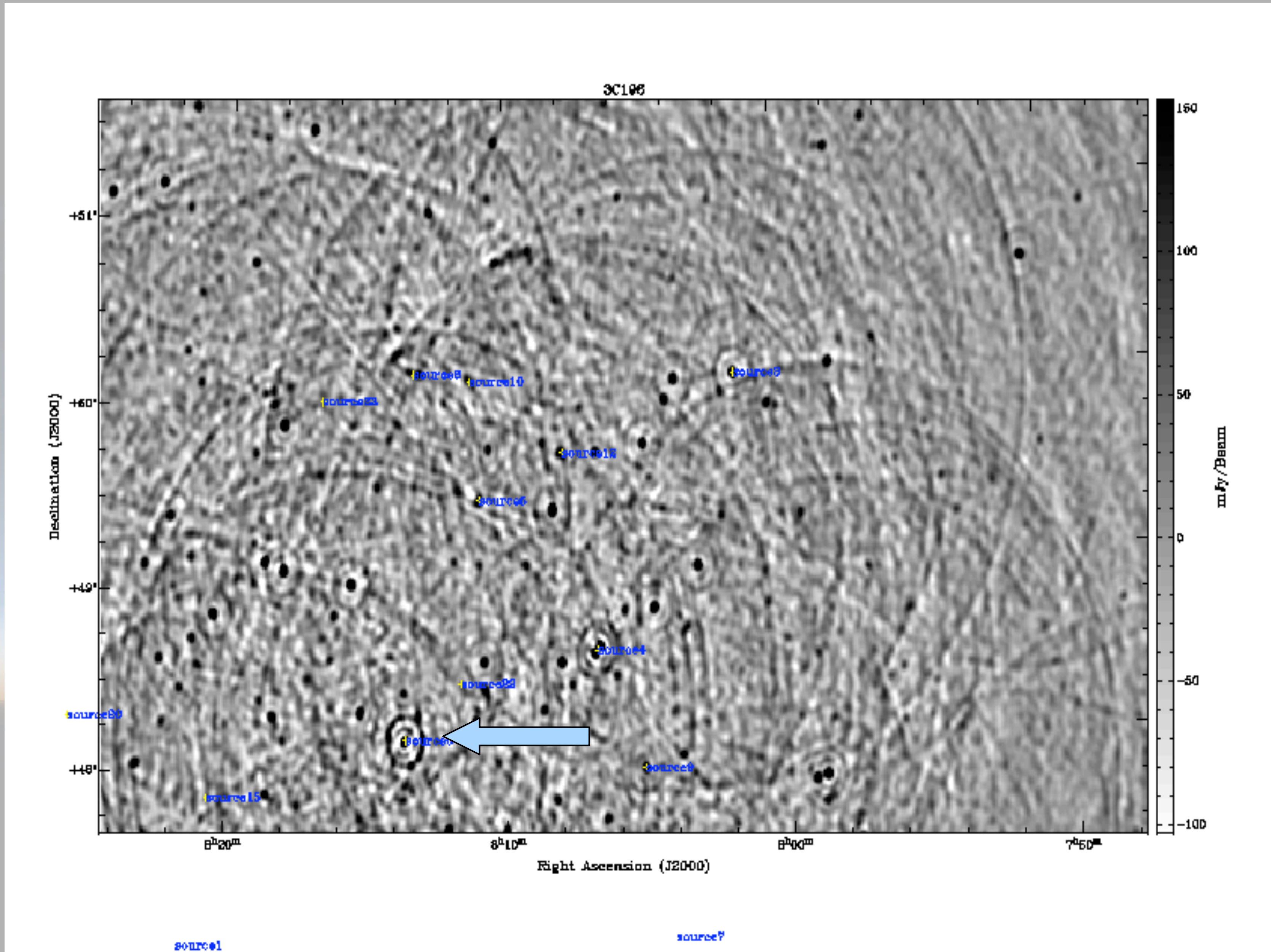
2 parameters



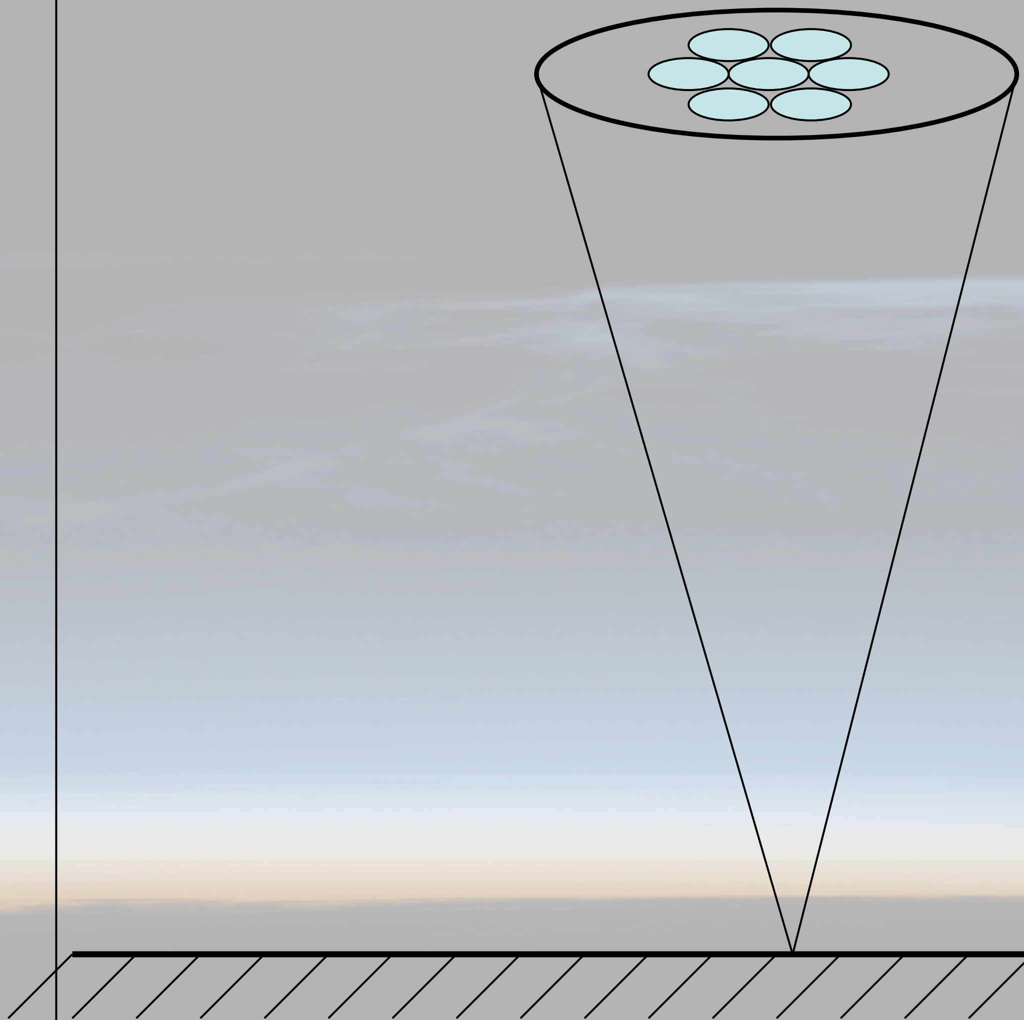
5 parameters



8 parameters



HBA tile and station FOV and the ionosphere



Hexagonal grid of 3.5° beams project, at 300km height, to circles of ~ 20 km diameter

It takes 'frozen turbulence' about 2-4 minutes to cross 20 km (assuming 300-600 km/h = 5-10 km/minute)

(Minimum speed ~ 100 km/h)

If indeed screen is 'frozen' for that long we can track it and use it to predict or interpolate the phase-errors at any location.

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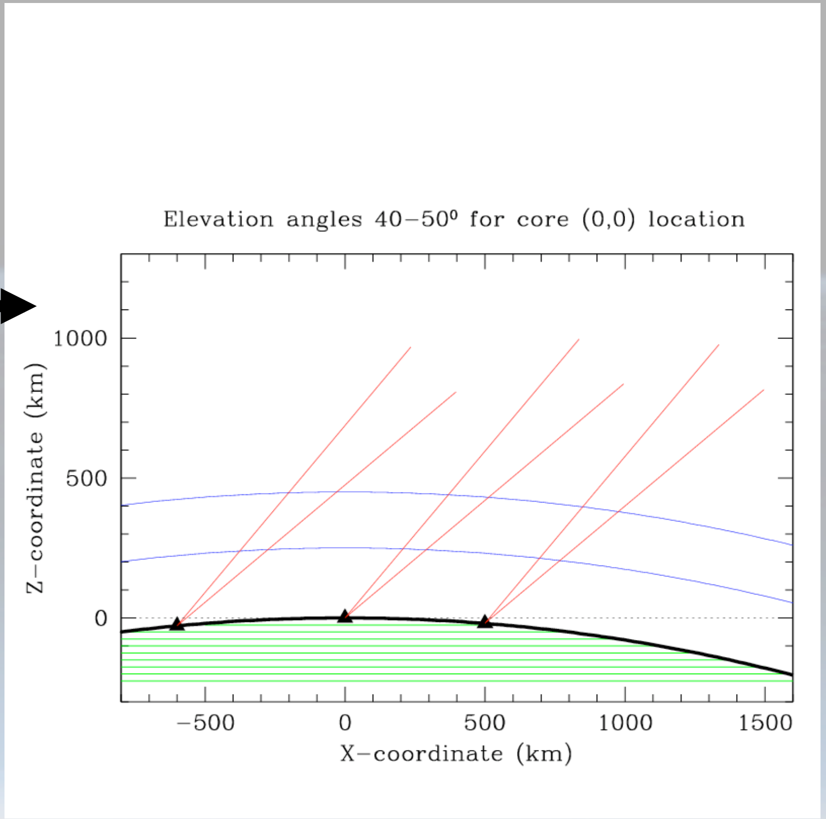
European baselines: non-overlapping screens !

Basic problems of European LOFAR:

1) isoplanatic patch small (~ 3-15' ?)
2) ~10x fewer calibrator sources
3) non-overlapping screens →
4) large datavolumes (0.2s, 1 kHz?)



A possible solution (for HBA)

1) solve for NL screen in NL-LOFAR
2) correlate ~ 10-20 superstation tiedarray beams with each Eu-station (sensitivity ~ 10x better)
3) dynamically track the screen motion using > 20 probes ←
4) 1m x 600 km/h ~ 10 km ~ 2° at 300 km height

'default' mode for EoR KSP on much smaller scales ('rapid' all-sky calibration mode)

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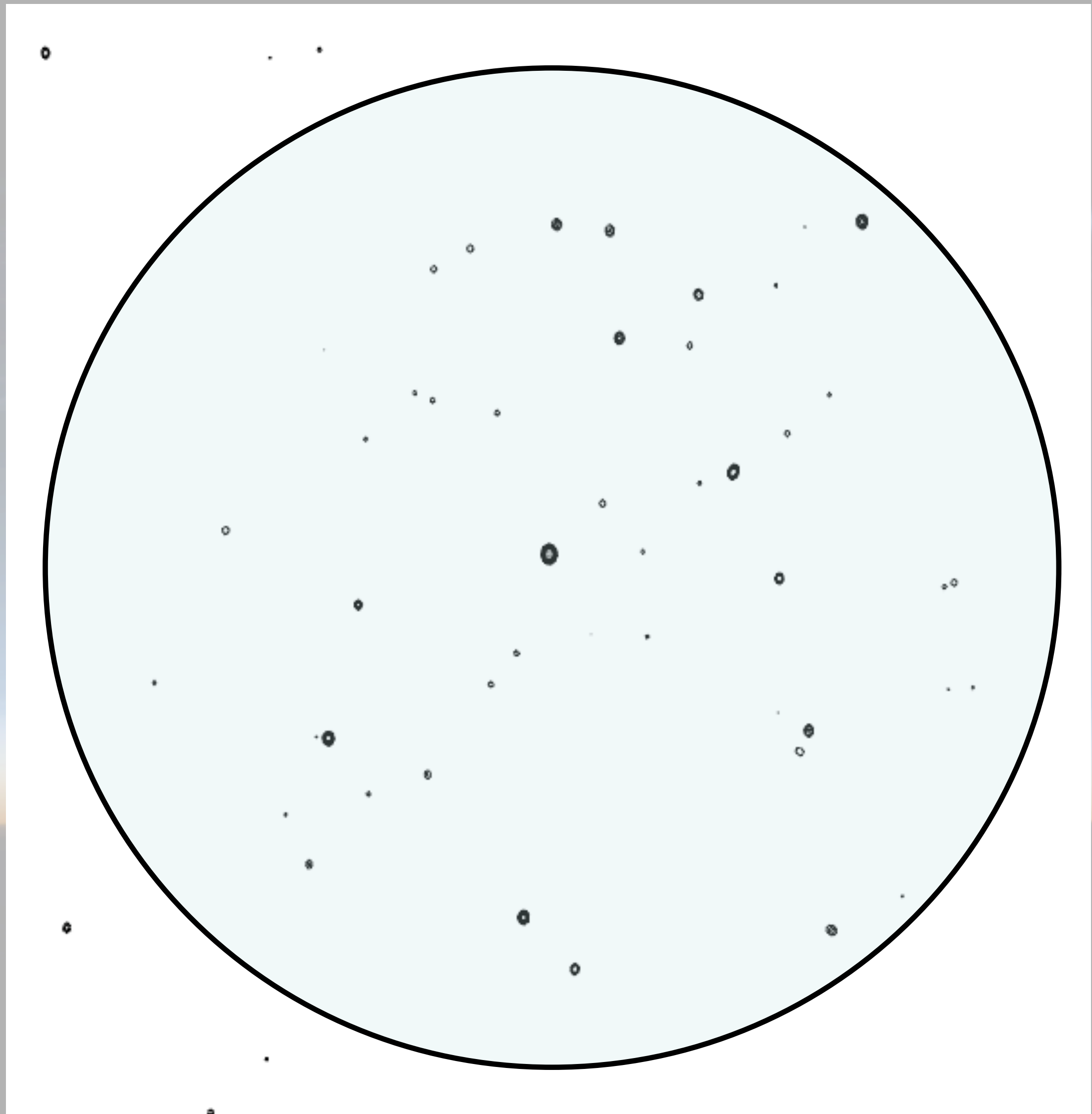
3C196 field: ~45 sources with apparent flux S_{139MHz}> 0.5 Jy

⇒ a 2-D (3-D?) reconstruction of the phase screen may become possible

6.5°



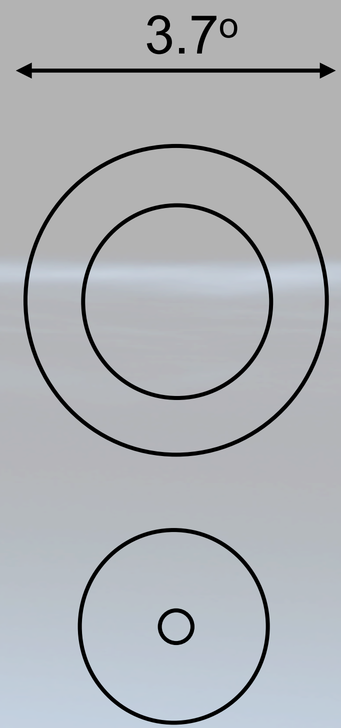
d ~ 35 km

at

h_{ion} = 300km

European calibration issues (HBA 150 MHz)

#antennas	noise (Jy) (10s,15 MHz, 2pol)	FOV (HPBW,deg)
Eu96 - NL48 (65m - 40m)	0.07	2.3x3.7
Eu96 - SS288 (65m - 300m)	0.03	2.3x0.5



Required on line:

- known positions to attempt correlation, or coherent addition of complex 0.2s visibilities, using SS6 ionospheric screen)

- global TEC model to predict refraction

Many calibration issues still under investigation…

— 3 types of effective primary beams (core, NL, Europe)

— extreme non-isoplanaticy (> 20 facets)

— what to do when the ionosphere scintillates

— very wide frequency range MFS (>factor 1.5 -2, different beams !)

— day/night effects (thermal/flaring Sun)

— absolute flux scale

— always working with intrinsic sky fluxes (snapshots)

— deconvolution with spatially varying beams

— deconvolution at >> 10000:1 DR

— Galactic plane imaging and very short spacings

— intrinsic polarization calibration (Faraday rotation, RM synthesis)

— calibrating European baselines over wide FOV

This will be a major commissioning task:

Debugging/understanding all these issues when they hit you all at once !