“(My) Life, the Universe and everything”

Calibration, large FOV (beams), science and other topics

a radio astronomer’s perspective

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Outline

— Preliminary remarks

— Important aspects of calibration

— Dynamic range in all its facets

— Some astrophysical projects with extreme DR requirements

— The 3 major unknowns in calibration: sky, atmosphere & instrument

— Properties of, and (science) results from, WSRT

— A very different array: LOFAR

— Ionospheric issues (?)

Preliminaries

Main purpose of talk:

- Results from WSRT (30+ years) and LOFAR (7+ years)

- Wide assortment of issues, not all related to beams

- Mix of science and technical issues

- Thermal noise vs dynamic range: what is more important ?

Acknowledgements:

Jan Noordam, Wim Brouw, Jaap Bregman, Michiel Brentjens, Roberto Pizzo,
Gianni Bernardi, Sarod Yatawatta, Oleg Smirnov,…

Standard calibration

Calibration is needed for:

1) astrometry → accurate (absolute or relative) positions
2) photometry → (absolute or relative) flux scale, spectral shape
3) image/PSF quality and image fidelity/DR

Traditional methods used:

Determine Gain/Phases (frequency) on Stable (pointlike) external calibrator:

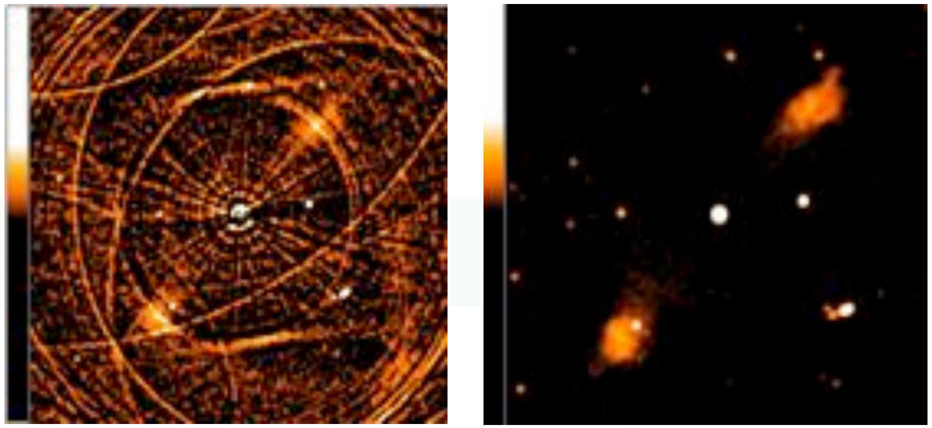
→ good for 1) and 2)

Apply selfcalibration → needed for 3)

Selfcal + deconvolution gets rid of:

- sidelobes /grating lobes,
- phase/gain drifts,
- troposphere/ionosphere

WSRT 21cm: giant radio galaxy B1245+67



de Bruyn, 1991, unpublished)

Astrometry (the oldest astronomical discipline)

Absolute astrometry is difficult because of the refraction due to trophopshere and ionosphere. So we often do only relative astrometry.

Realtive astrometry requires a dense network of (stable) position calibrators.
We need source centroids which may be frequency dependent.

Two important applications for (relative) astrometry:

- accurate sub-arcsec positions for cross-identification (with optical/infrared/X-ray images)
- proper motions (e.g. in relativistically moving blobs)

At low frequencies (i.e. LOFAR) the task is very challenging because of the wide FOV and large ionospheric refraction angle. But also in VLBI with a relatively small FOV, the problem remains , because the PSF is much smaller and stations are far apart.

In the absence of a global ionospheric phase screen model in LOFAR we have to do relative astrometry within the isoplanatic patch, an angle which can be rather small (0.1 -1^{o}) .

How well can we measure positions ?   This depends on size of the PSF and the S/N !

rule of thumb : $\Delta pos \sim PSF / 2*(S/N)$ → LOFAR in principle can work at 0.01” level

Absolute flux scale: going beyond the A-team

Flux scale currently known to ~2 %. Based on CasA + CygA (Baars et al, 1977)

All arrays WSRT/VLA/ATCA/GMRT,.... have derived relative scales to <1% at high frequencies (325 MHz and up). 3C196 may become primary calibrator (Perley, 2011).

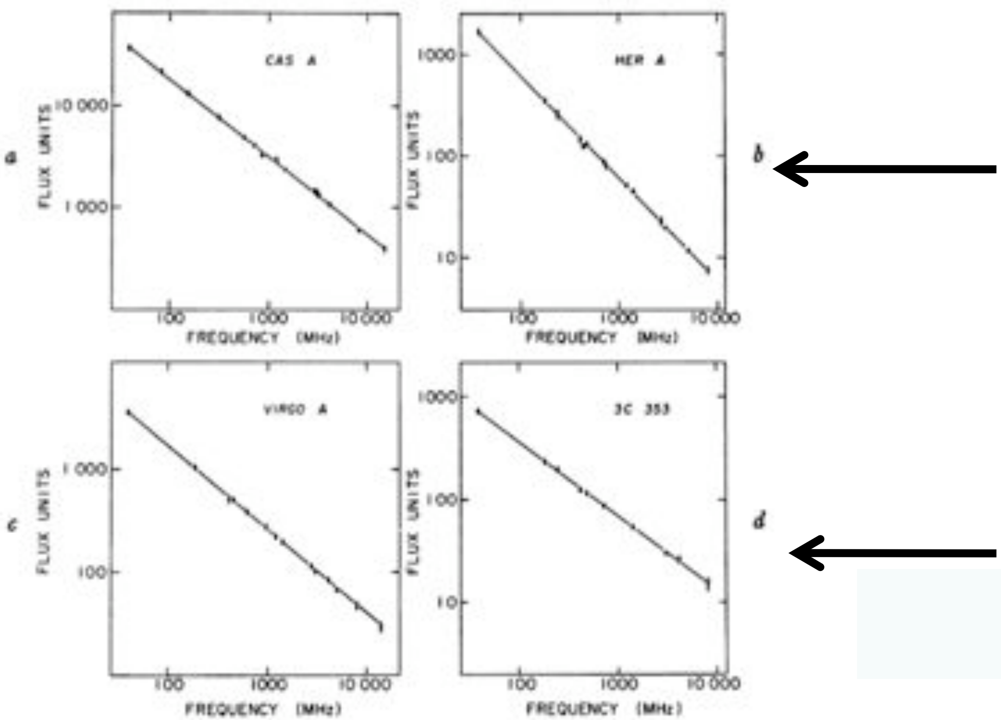


FIG. 1.—Spectra of calibration sources: (a) Cas A (3C 461) based on absolute flux densities corrected to the epoch 1964.4; (b) Her A (3C 348) based on ratios to Cas A; (c) Vir A (3C 274) based on ratios to Cas A; (d) 3C 353 based on ratios to Cas A.

Bright secondary calibrators

HerA = 3C348

2' double

(to be tied to 3C196 via WSRT flux scale)

3C353

5' double

Image Dynamic Range

Image DR: peak / off-source rms.

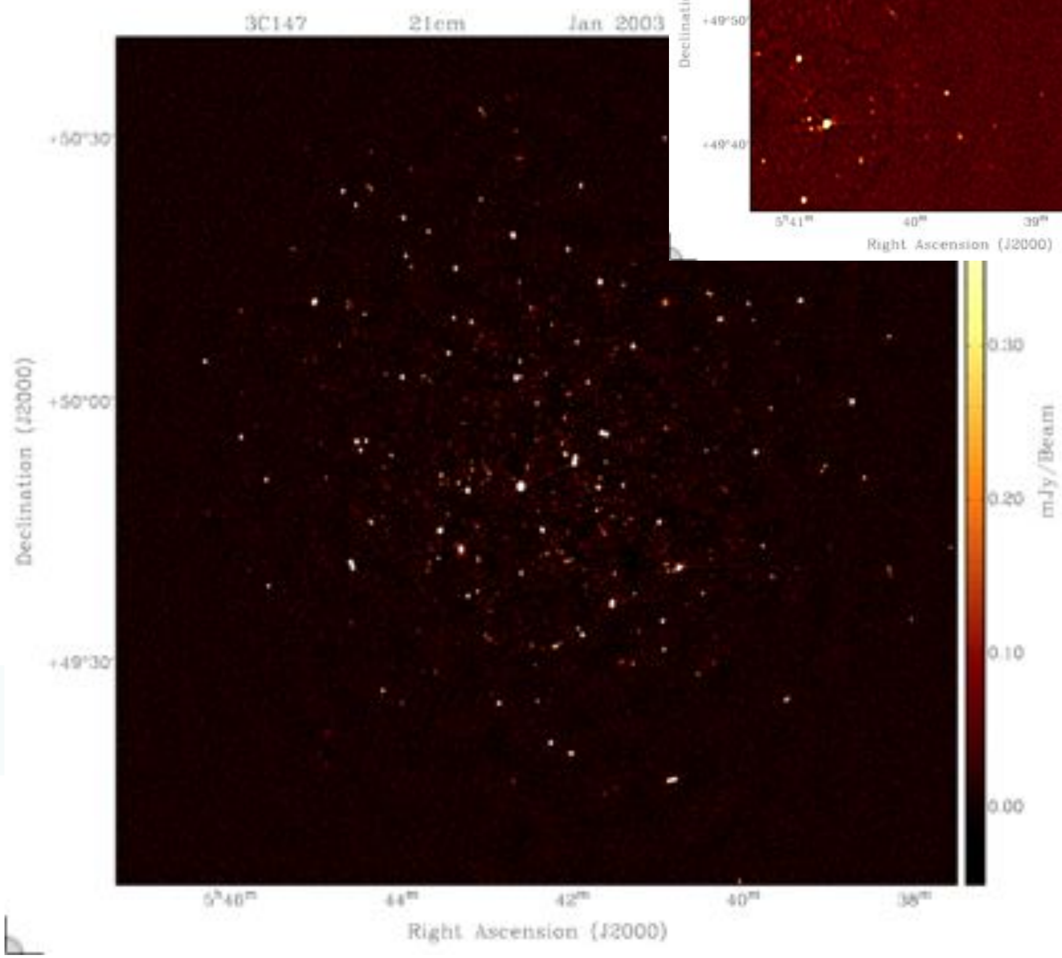
DR is position dependent !

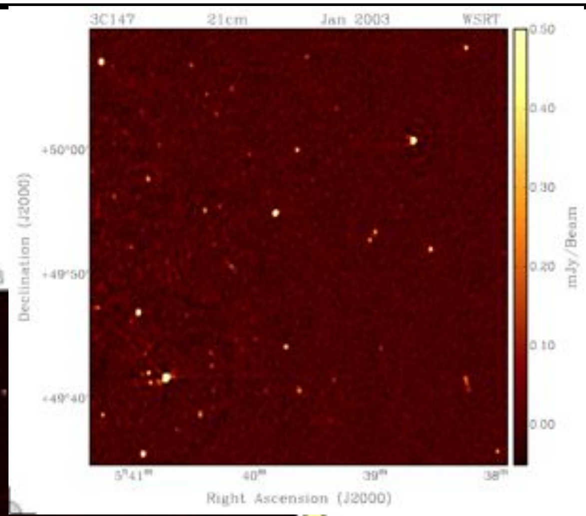
WSRT
3C147
21cm

22 Jy /15 μJy

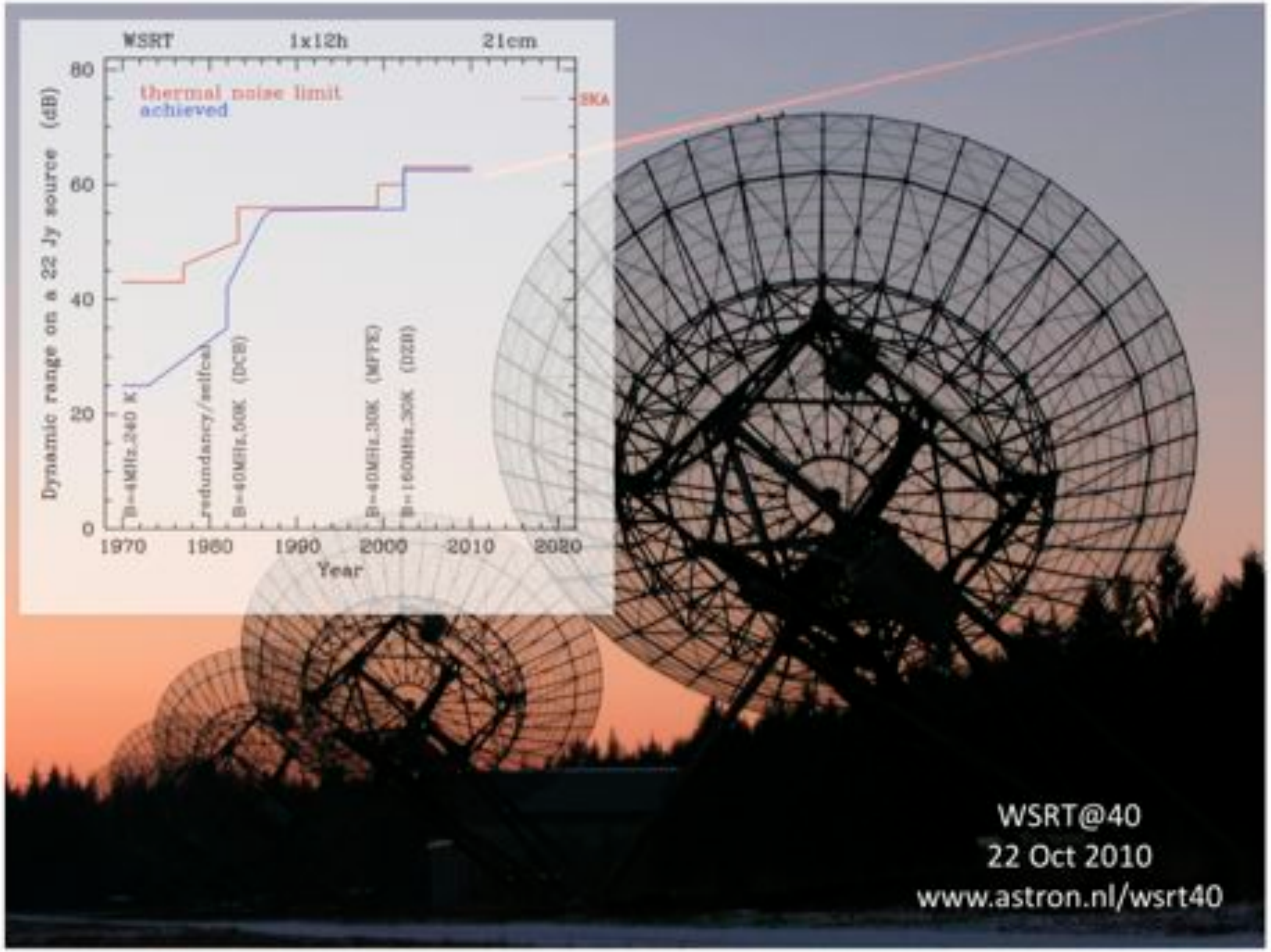
DR=1,500,000:1

On-axis versus
off-axis makes a
major difference !

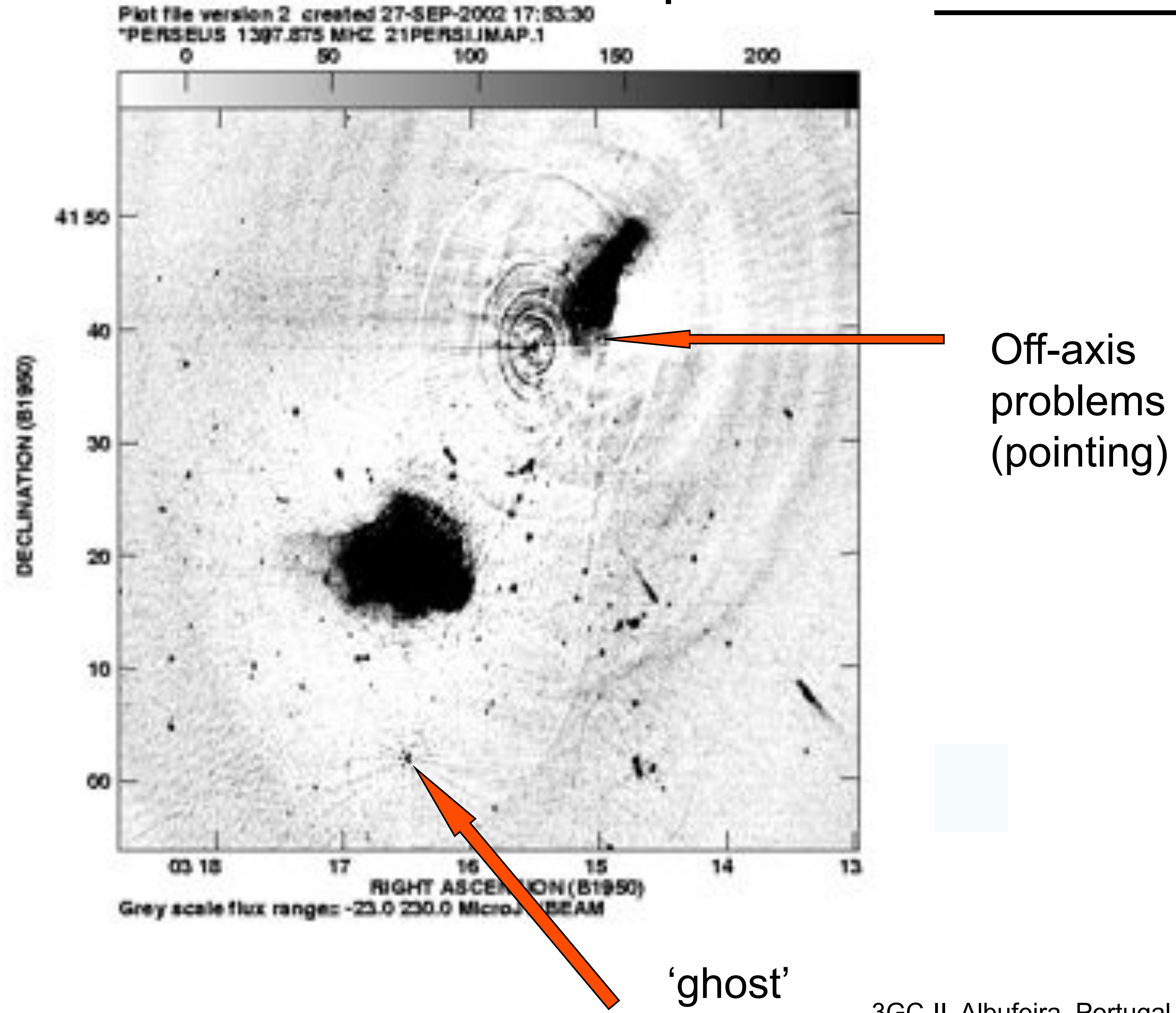




History of Dynamic Range in WSRT imaging



WSRT 21cm Perseus cluster: 6 powers of 10



Attempt to make very different beams: WHAT

Oct 2005:

4 tiles (3.3x3.3m)

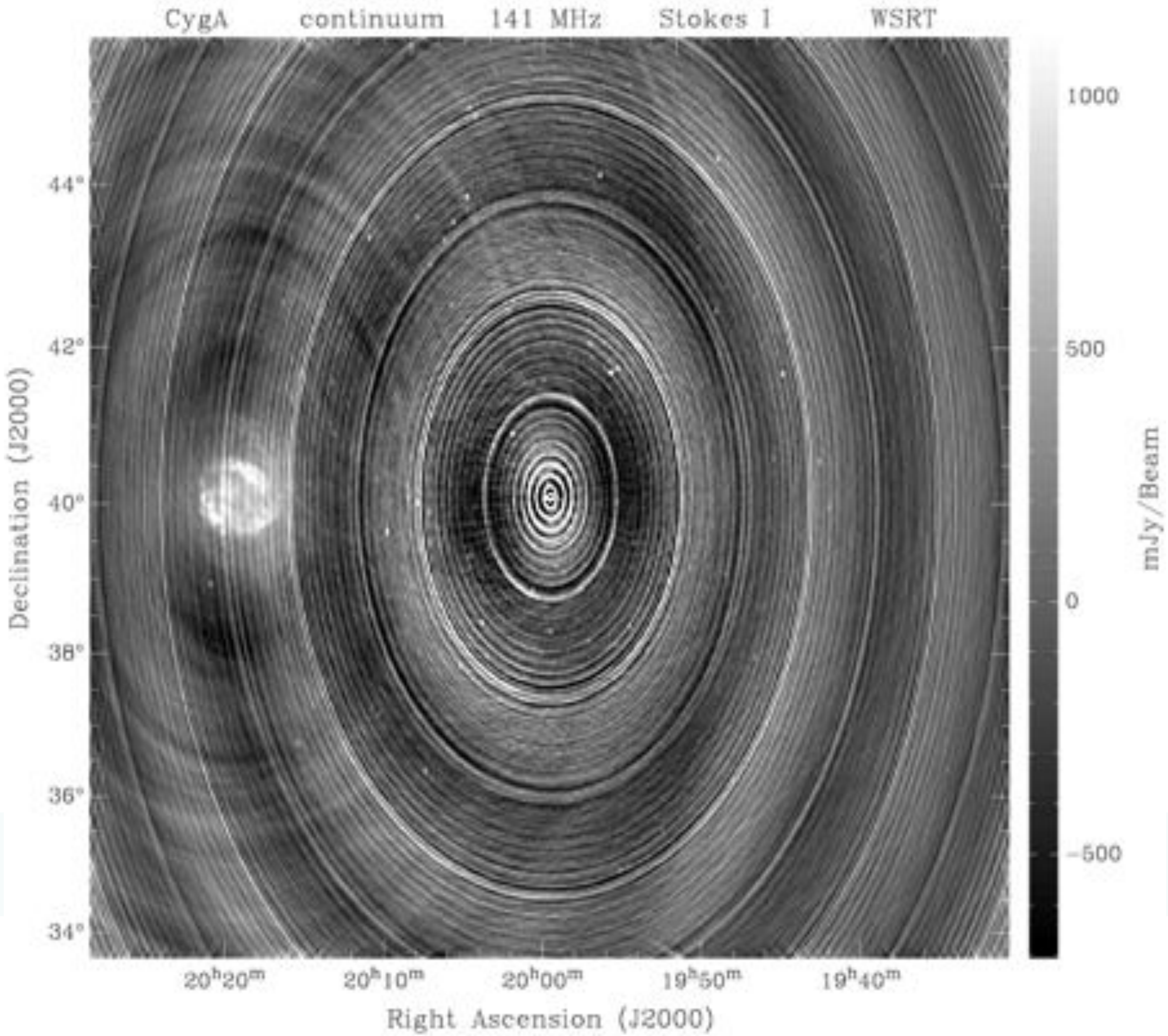
4x4 dual pol / tile

near WSRT RT8

Westerbork Highband AntennaTeststation

Unfortunately the software was not yet ready to handle this → fewer lessons were learned than could have been !

The ultimate in Dynamic Range ? → observe CygA !



CygA Oct 2005

WSRT + WHAT

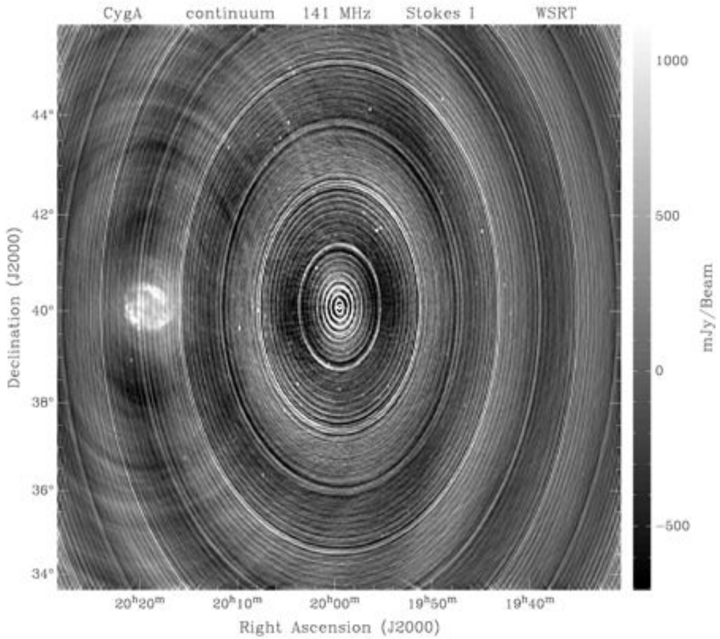
S_{Cyg}~ 11,000 Jy

141 MHz image with only WSRT baselines

Lots of background sources visible but obvious CygA deconvolution problems !

Bright extended sources: deconvolution limited DR

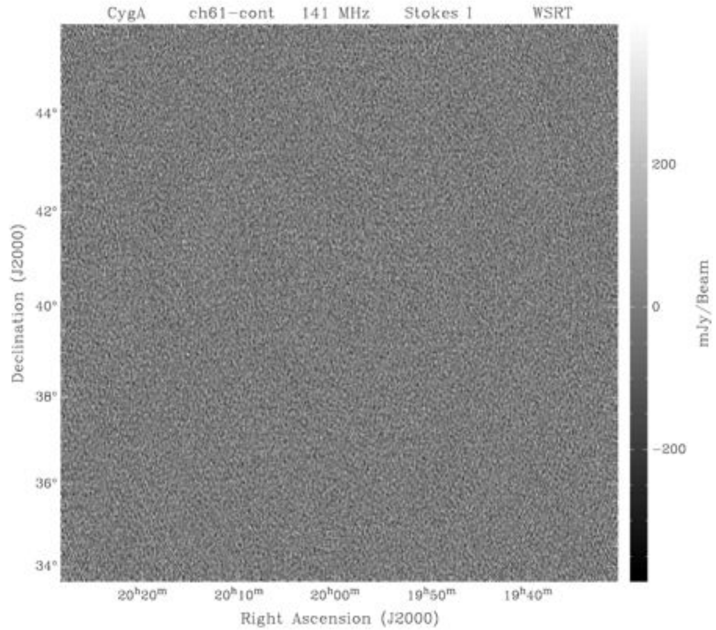
'CONTINUUM' (B=0.5 MHz)



(Original) peak: 11000 Jy

Dynamic Range ~ 5000:1

'LINE' CHANNEL (10 kHz) - CONT



noise 70 mJy

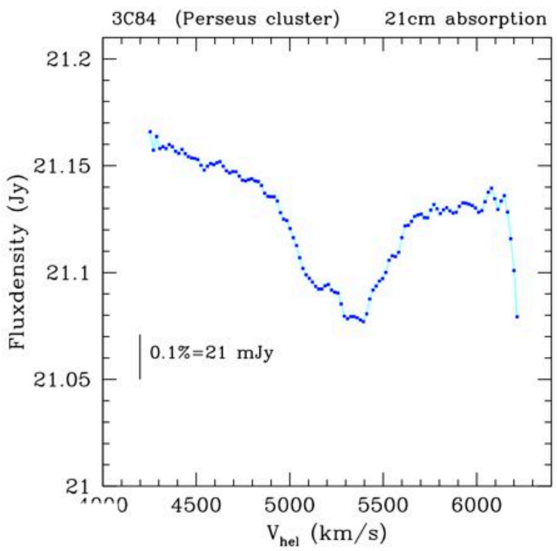
vs ~150,000 : 1 !!

Lesson: your data may be better than you think !

Spectral Dynamic Range

Spectral dynamic range: a measure of the quality of the spectral baseline

5,000:1 is very good !



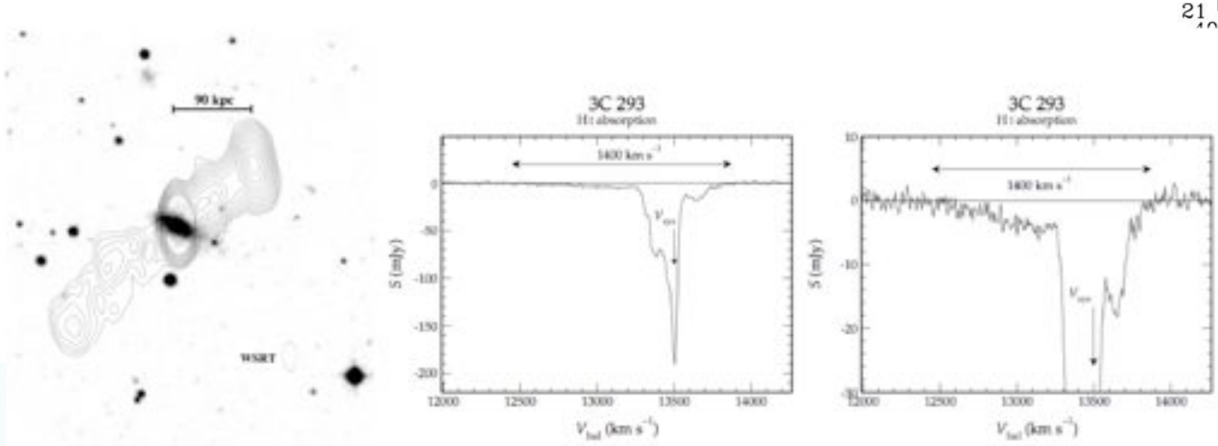


Fig. 1.— *(Left)* Continuum image of 3C 293 at the resolution of WSRT 21-cm observations (Emonts et al. in prep). *(Middle)* The H I absorption spectra with a zoom-in (*Right*) to better show the new detected broad H I absorption. The spectra are plotted in flux (mJy) against optical heliocentric velocity in $km\,s^{-1}$.

Morganti et al,

Science themes with high DR requirements

Spectral dynamic range:

- faint or very broad absorption
- faint emission

Imaging dynamic range: haloes around bright radio sources:

- Evidence for past activity in (double) radio sources
- Contrast issues: superluminal motion and relativistic boosting
- Thomson scattering (haloes) of radio sources in clusters

Detecting the Epoch of Reionization:

- Requires a spectral and Imaging dynamic range of $\sim 10^6$:1
- Very large areal coverage

Calibration issues: a conceptual overview:

Calibrating dipole-station arrays like LOFAR at low frequency conceptually involves 3 major unknowns:

— the Sky or the Global Sky Model (= GSM)

— the station beampattern: (position/time, frequency, polarization) dependent

— the Ionospheric phase screen (2-D or 3-D)

Calibration is the process that solves for all stable and, more important, time varying parameters

Qualitatively our knowledge will steadily increase because

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

But quantitatively we still always have to worry about whether :

1. there are enough constraints to fit for all ionosphere/beam parameters (the unknowns)?
2. it can be done in the available processing time (> 0.5 x real time) ?
3. the dynamic range will be sufficient to allow thermal noise limited performance ?

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++/Casa : WSRT, VLA, GMRT,..

For LOFAR, with all its novel and complicated aspects, we need to do much better.

Two calibration packages have been, and continue to be, developed:

— MeqTrees is being used to develop/simulate our understanding, as well as calibrate

— BBS / SAGEcal will be implementing efficiently what we have learned

— and we use CASA/CImager for imaging

If you are not satisfied with the result: (i) blame the hardware/firmware, (ii) check the software/pipeline, or (iii) (most likely) reconsider your understanding of the problem !
If still no improvement: consult an expert.

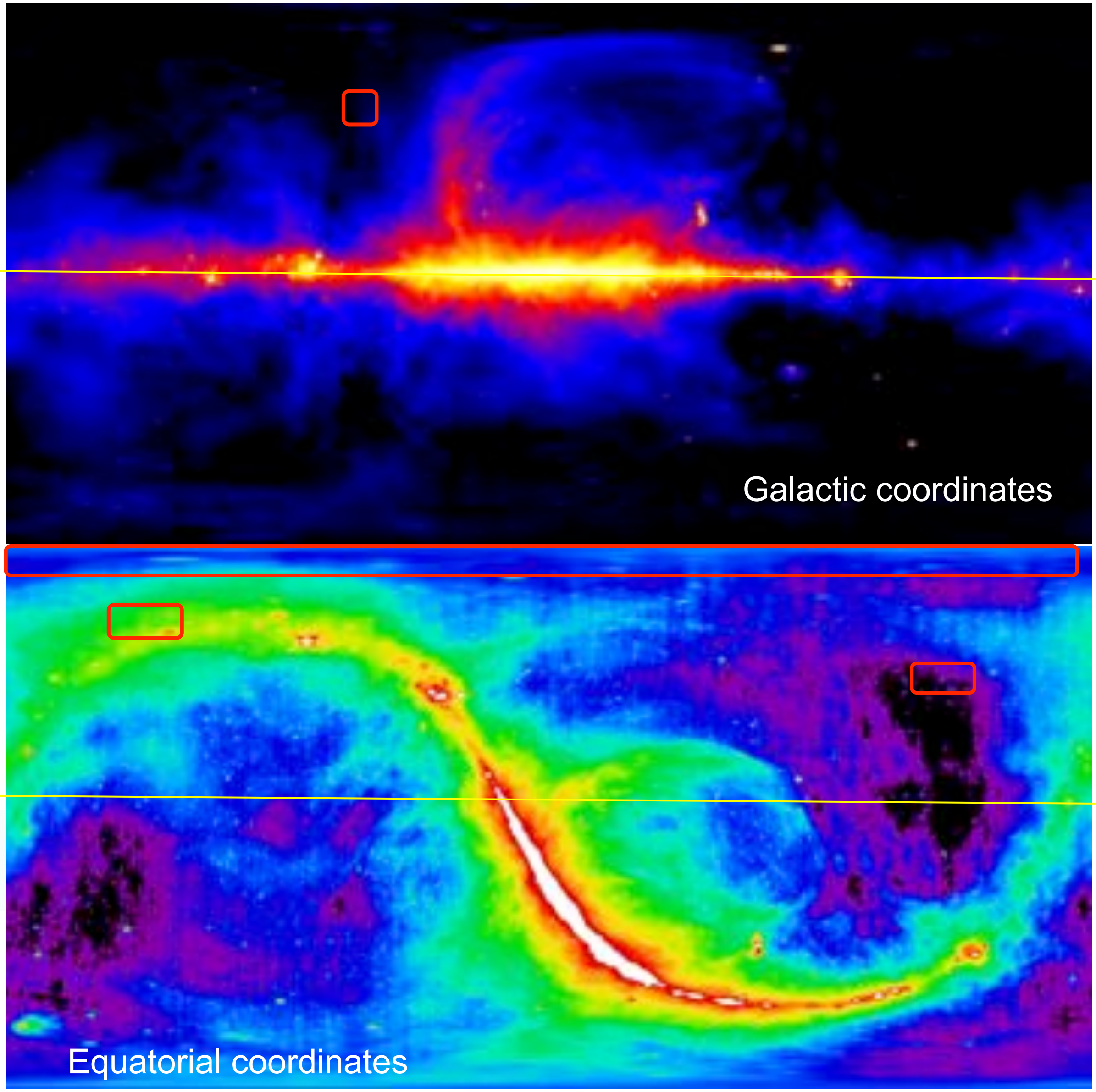
Imaging our Galaxy

Our Galaxy is major source of ‘noise’ at low freq !

Haslam et al (1981)

408 MHz

All-sky (0.85^o PSF)



Location of 3 WSRT LFFE-fields (Nov07)

From left-to-right

— ‘FAN’

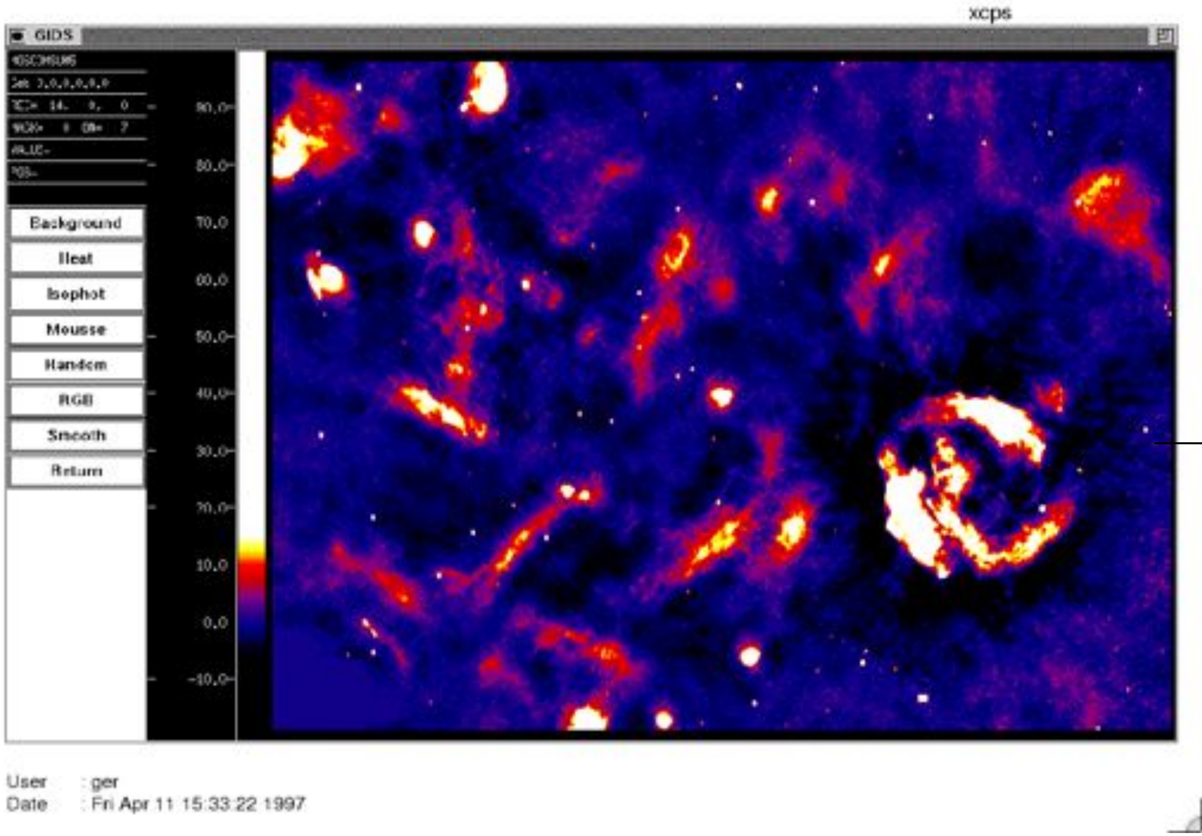
— NCP

— 3C196

(red box=12^{o}x12^o but station HPBW ~5^o-7^o and ‘tile’ beam ~ 22^o)

…and can be very complex   (CygX region, l= 80°, b=0°)

WSRT   350 MHz   6x12h synthesis   mozaic   6° x 5°



→ 5° to CygA

Emission (SNR, HII regions, stars) is everywhere !

WSRT deep wide field images

- beams
- sidelobe levels
- ionospheric effects

Results from some WSRT projects

Several successes but also problems:

- '21cm band' 1175 - 1460 MHz

  Perseus cluster 6x12h (1994 - 2003)
  3C147 1x12h (2003 - 2006)
  3C343 / 3C343.1 1x12h (2000)

- '1 meter band' 310 - 390 MHz

  Perseus cluster (2002)
  Abell 2255 cluster (2006)

- '2 meter band ' 115 - 175 MHz

  3C147 (2004 - 2006)
  Cygnus A (2004 - 2006)

WSRT-backend:

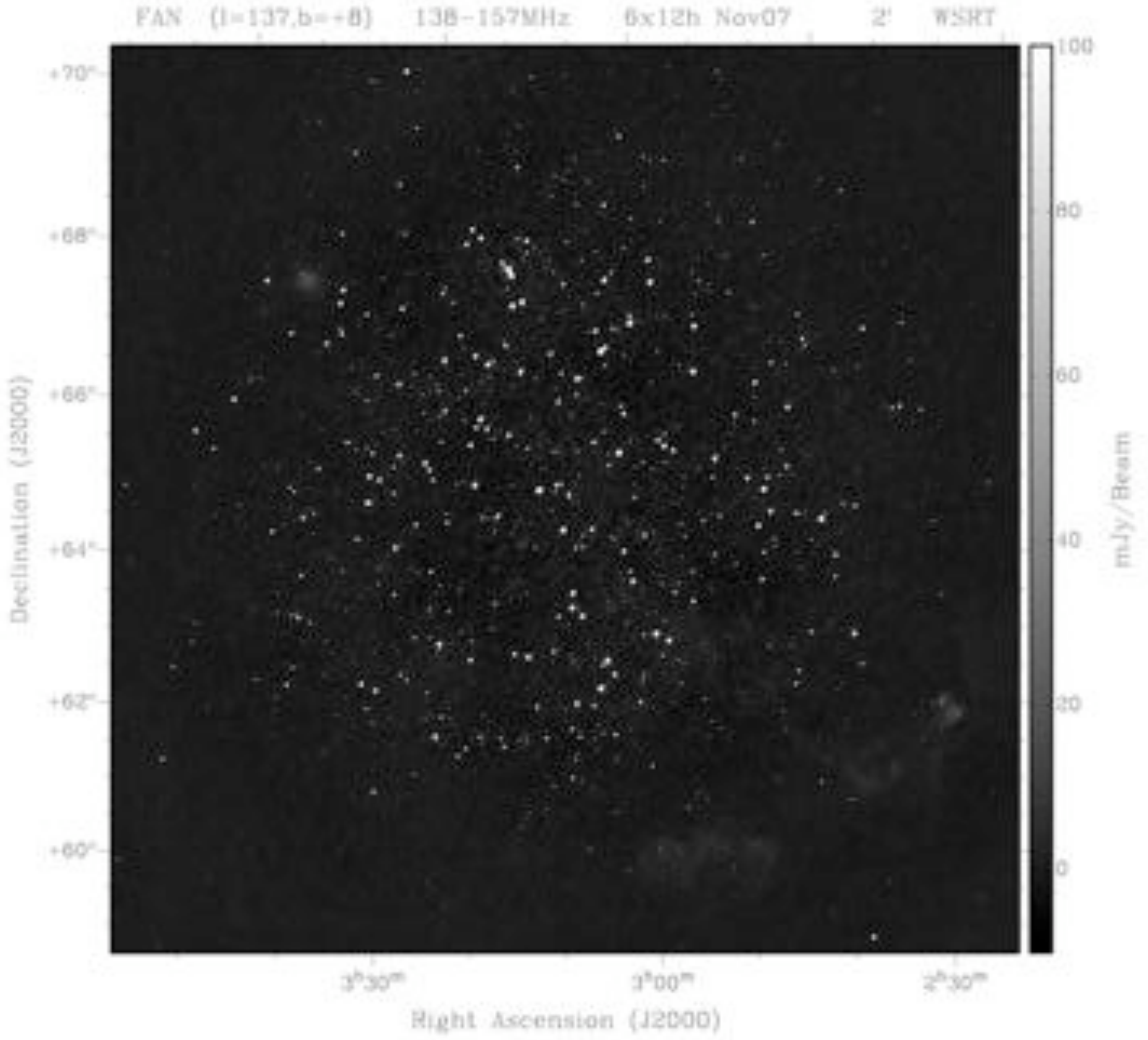
8 x 20 MHz, each 64ch x 4pol

8 x 10 MHz, each 128ch x 4pol

8 x 2.5 MHz, each 512ch x 4pol

de Bruyn, SKA-calibration meeting, Capetown, Dec 2006

Deep WSRT 150 MHz imaging (FAN, l=137, b=+8)



range

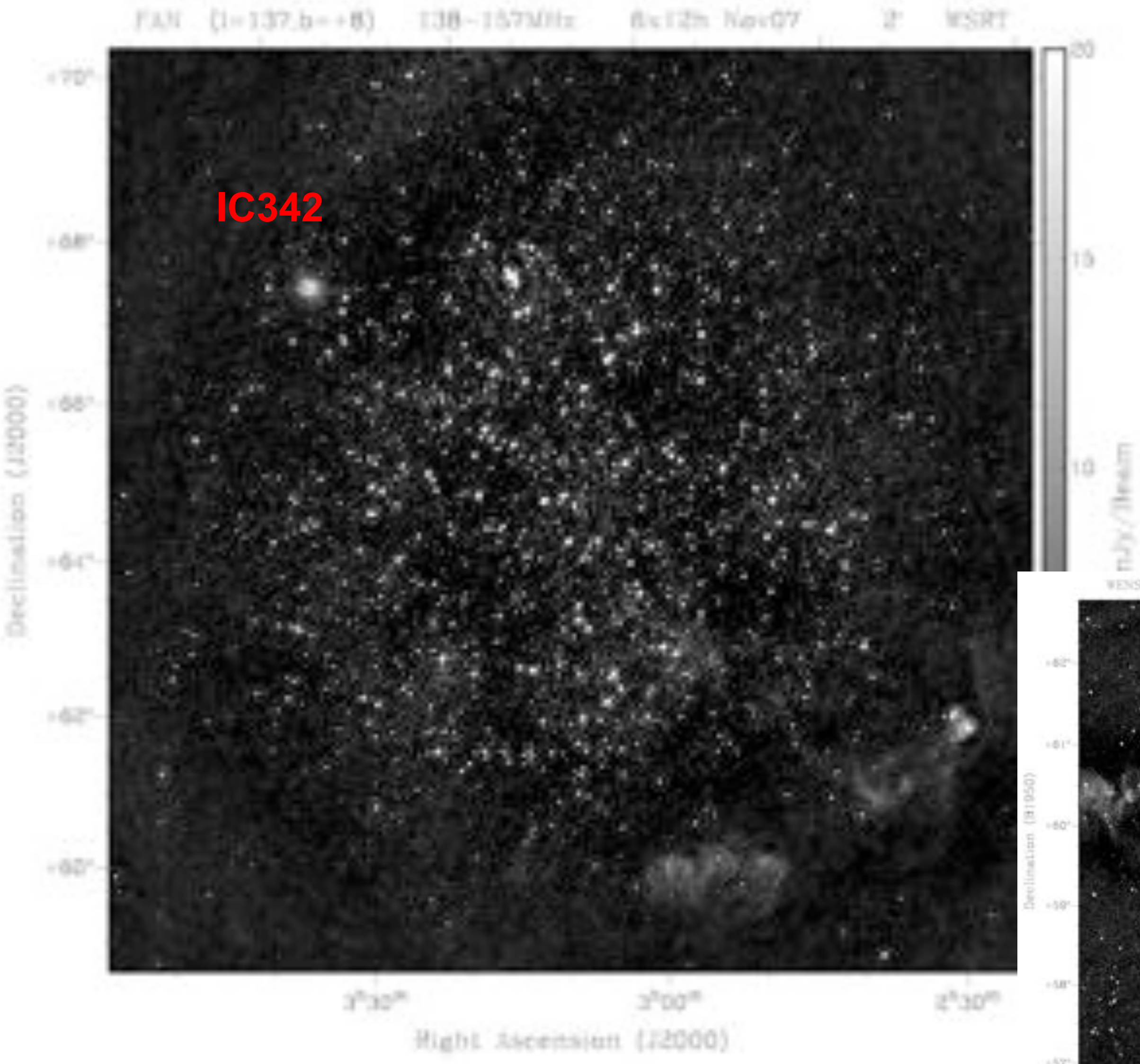
-10,100 mJy

Peak ~ 3 Jy ,

Noise ~ 0.6 mJy

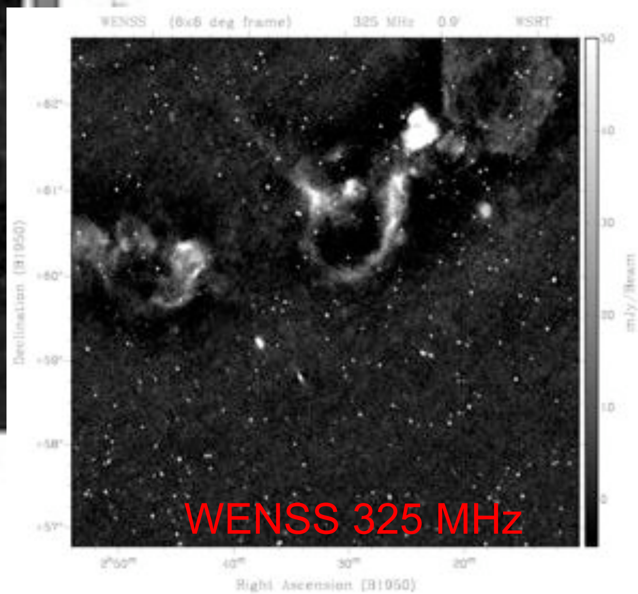
DR ~ 5,000: 1

Bernardi et al (2009)

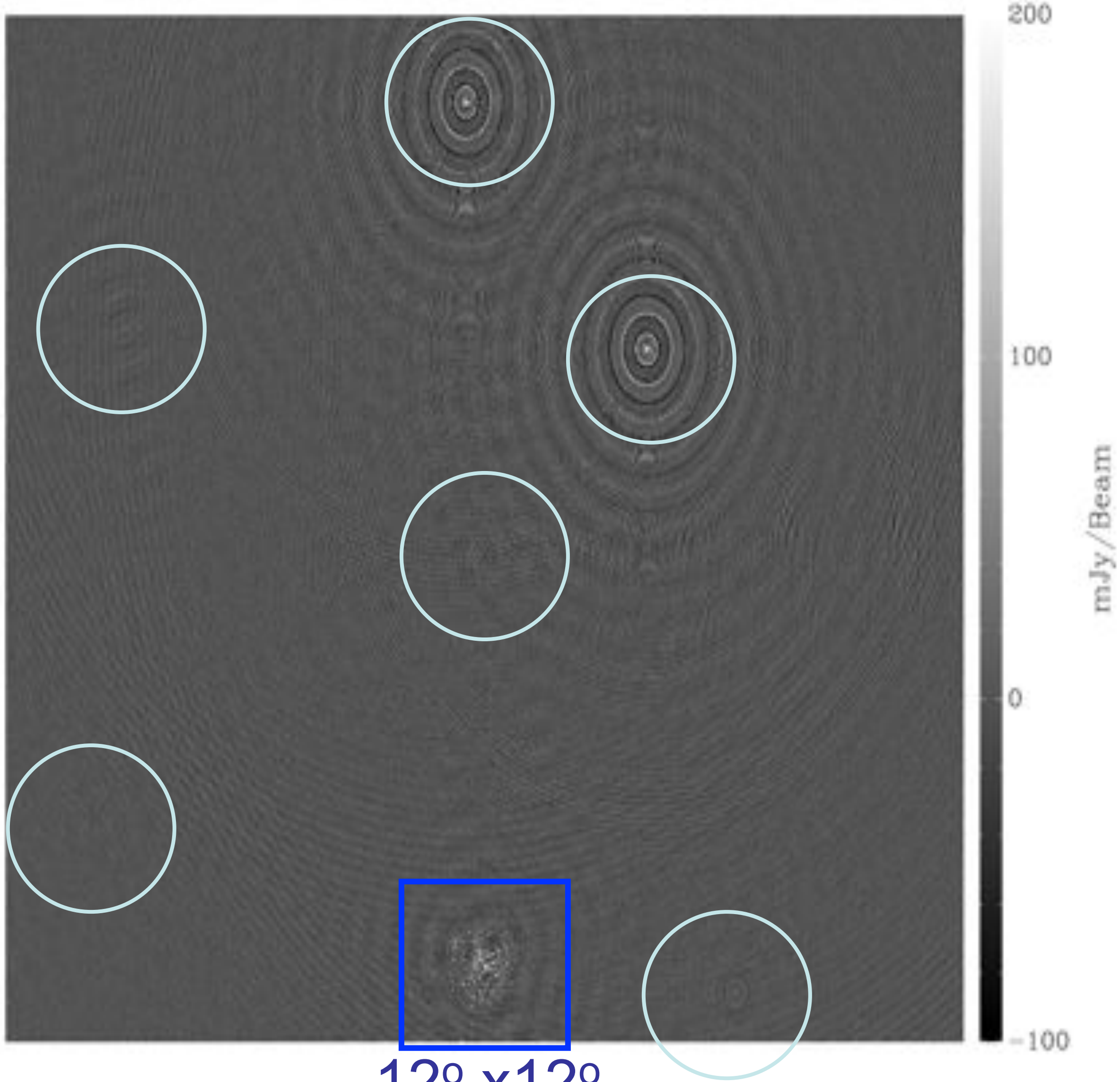


Confusion noise ~3 mJy

~ 10^{o} from Galactic plane



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



CygA

Sun

CasA

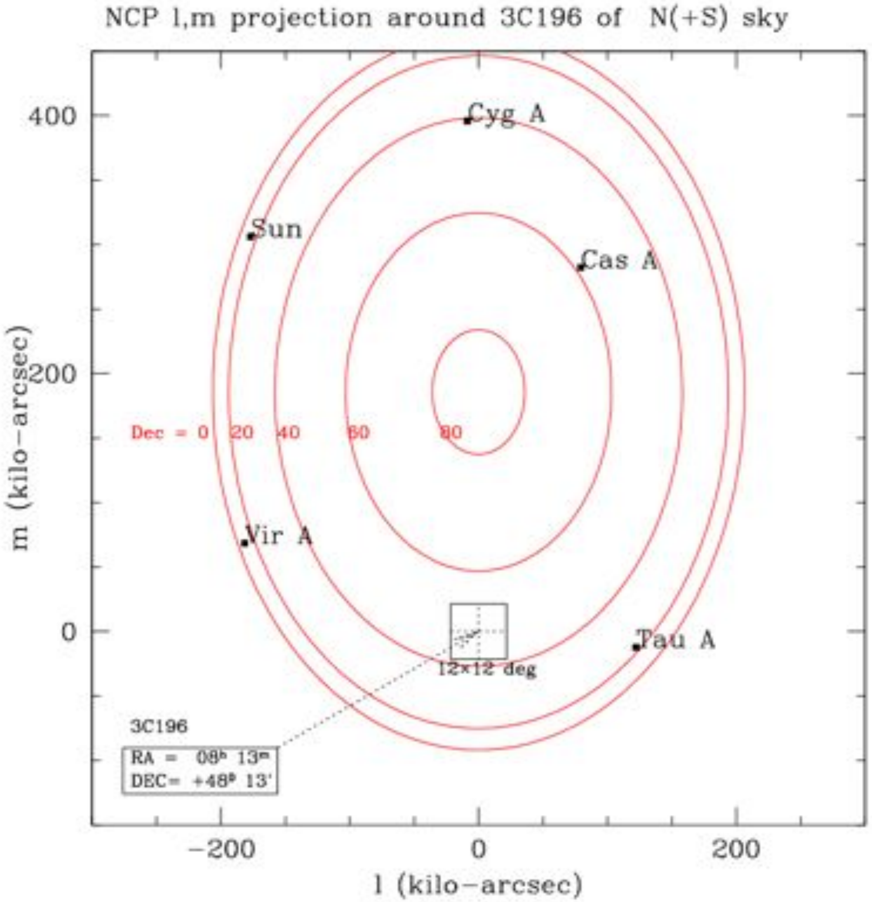
NCP

VirA

TauA

12^o x12^o

WSRT all-sky imaging



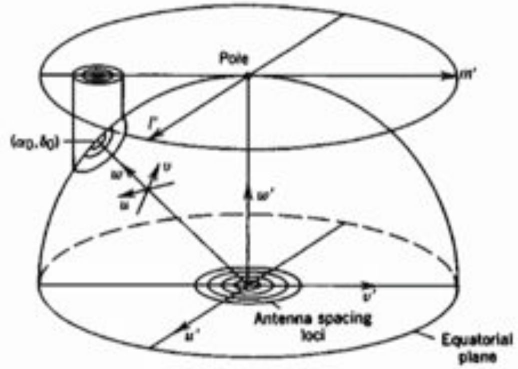
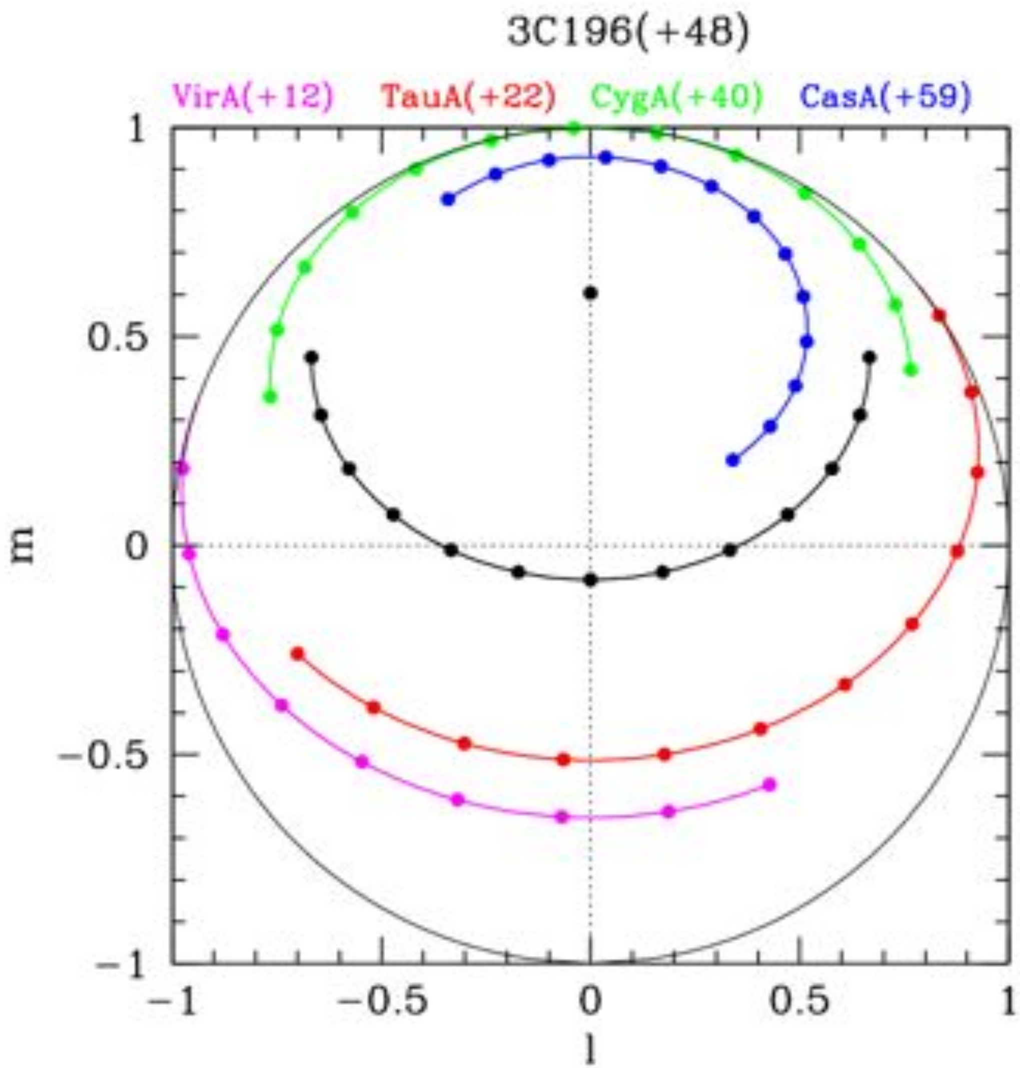


Figure 3.5 The (u′, v′, w′) coordinate system for an east–west array. The (u′, v′) plane is the

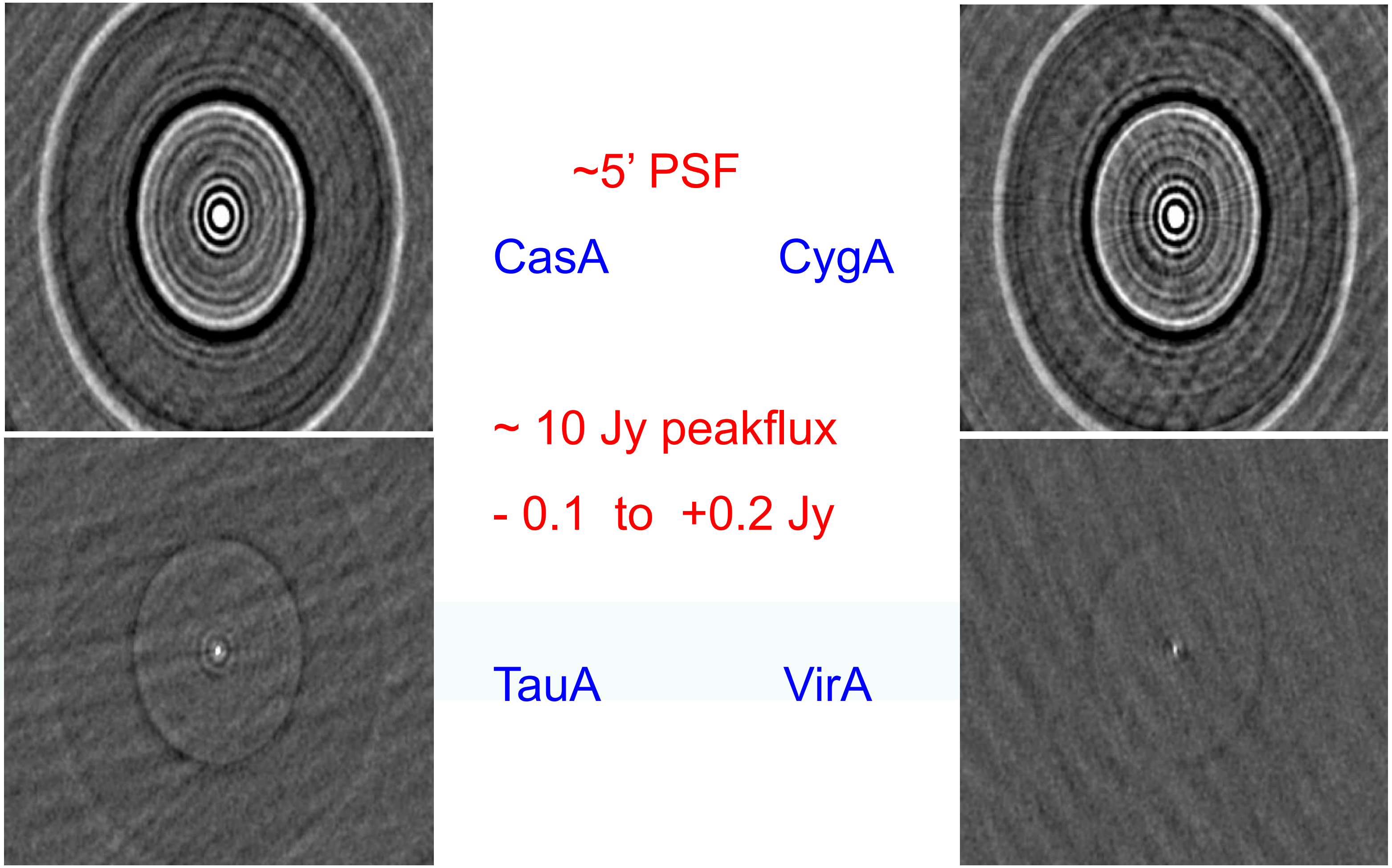
The A-team locations during a 12h WSRT 3C196 synthesis



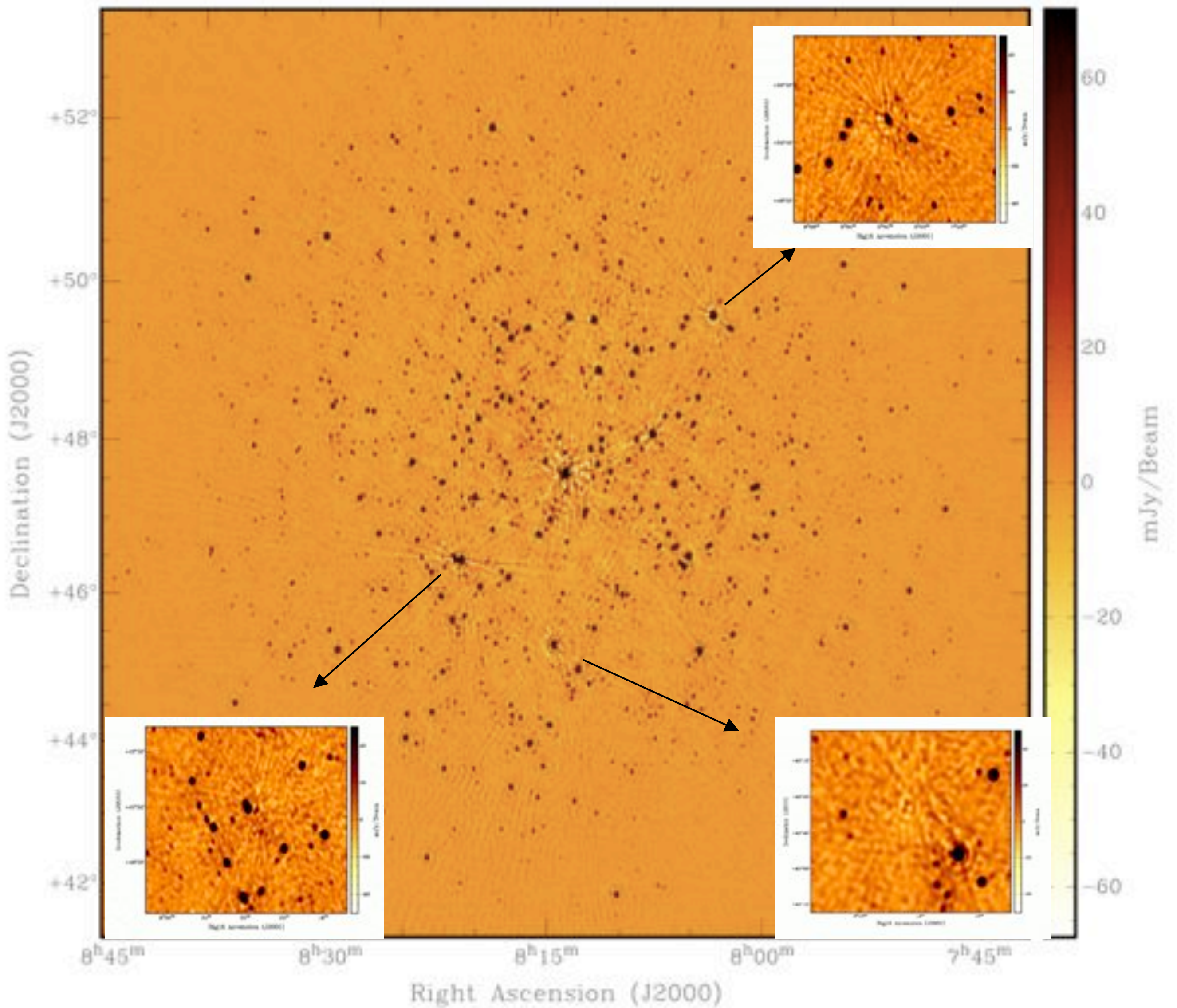
Note that the l,m here are a zenith "'l,m" projection

The A-team in WSRT observations of 3C196

The A-team is about 30dB attenuated yet looks remarkably stable in both flux and position. This is great, but called for a detailed investigation….



3C196: going deeper → non-isoplanaticity & peeling



3C196

80 Jy peak

~ 0.6 mJy noise

(classic confusion 3mJy)

2000+ sources

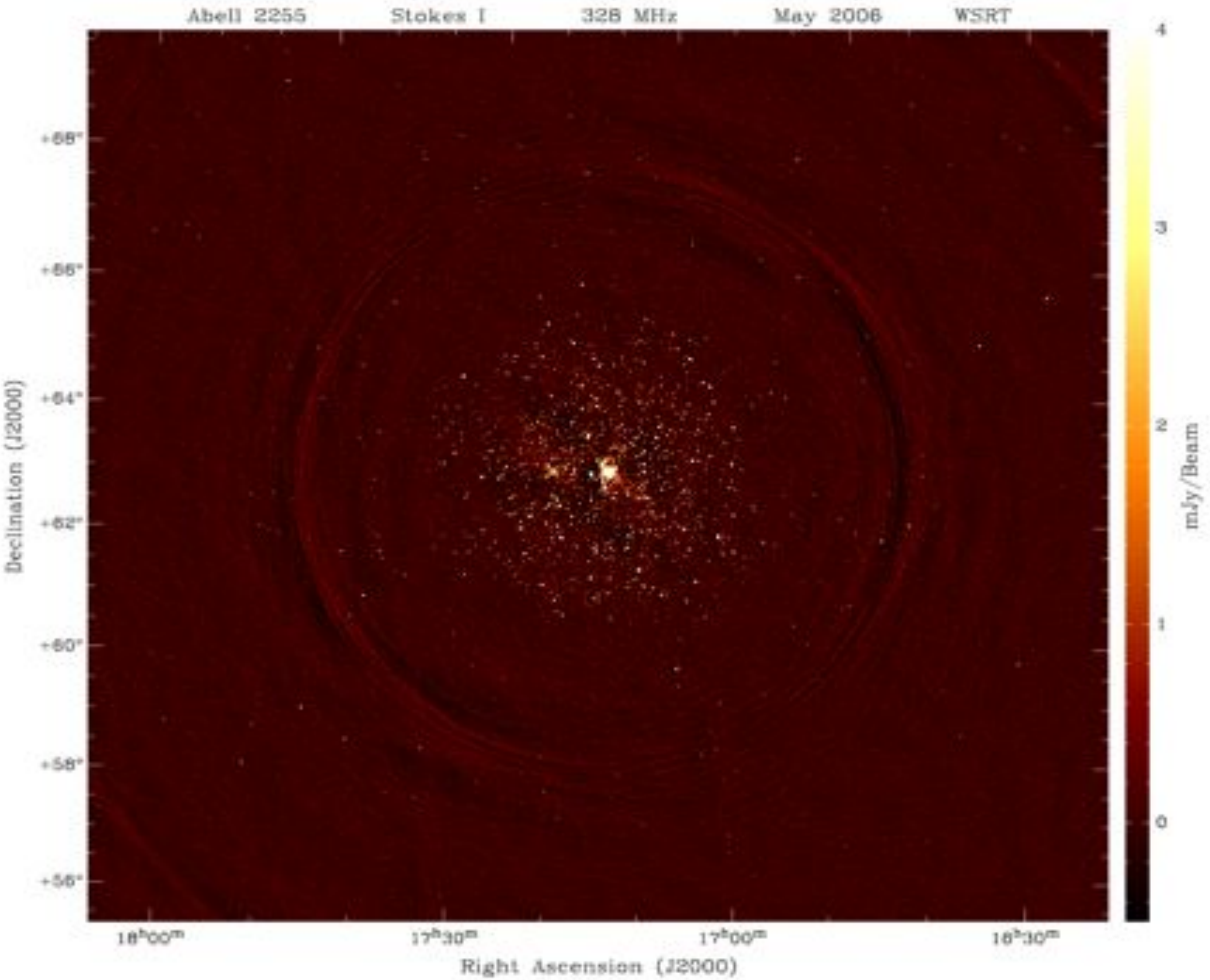
Separately peeled

DD-solutions

Bernardi etal, 2010

WSRT study of the cluster Abell 2255

Pizzo & de Bruyn



Note:

Beam size

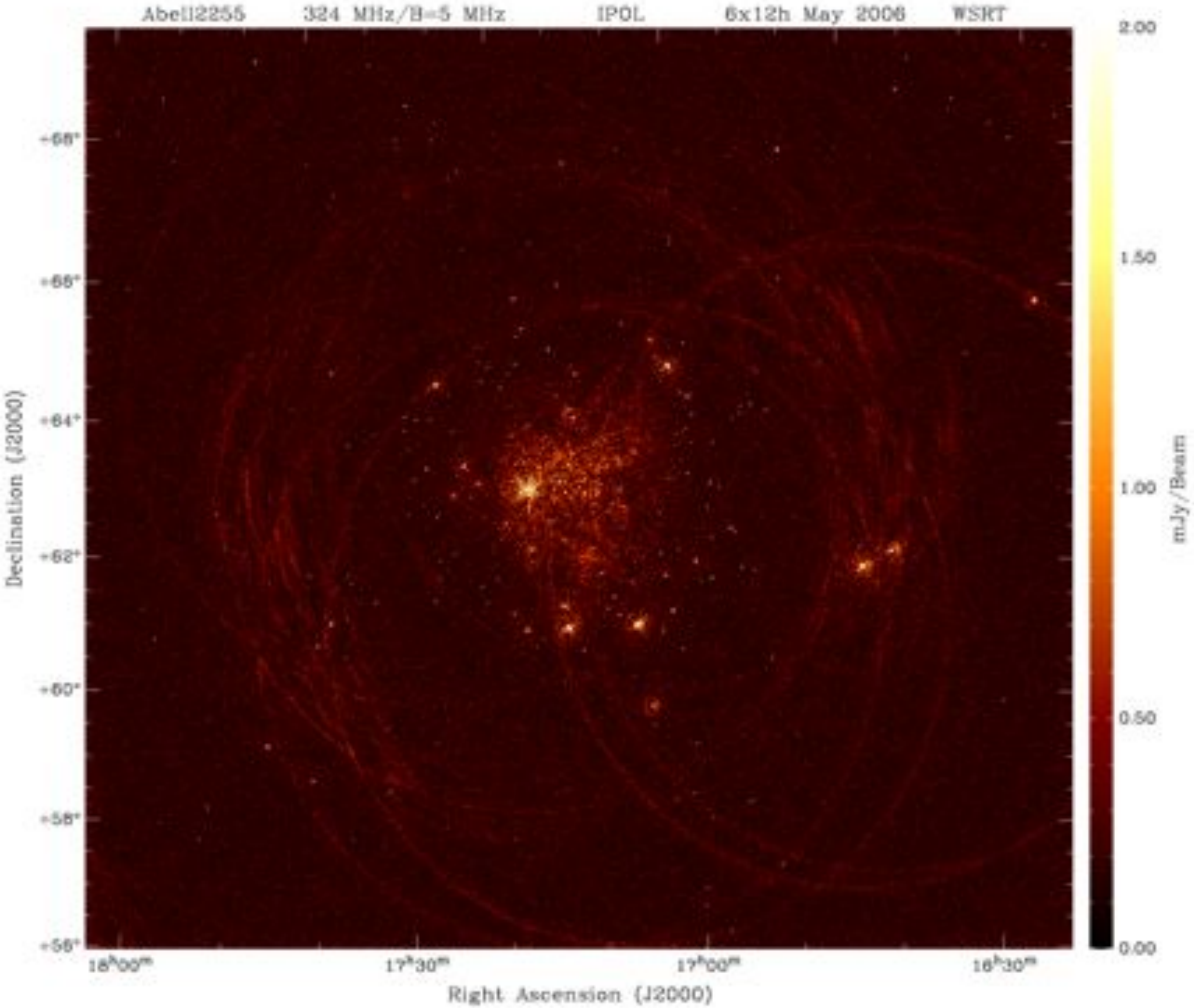
Grating lobe

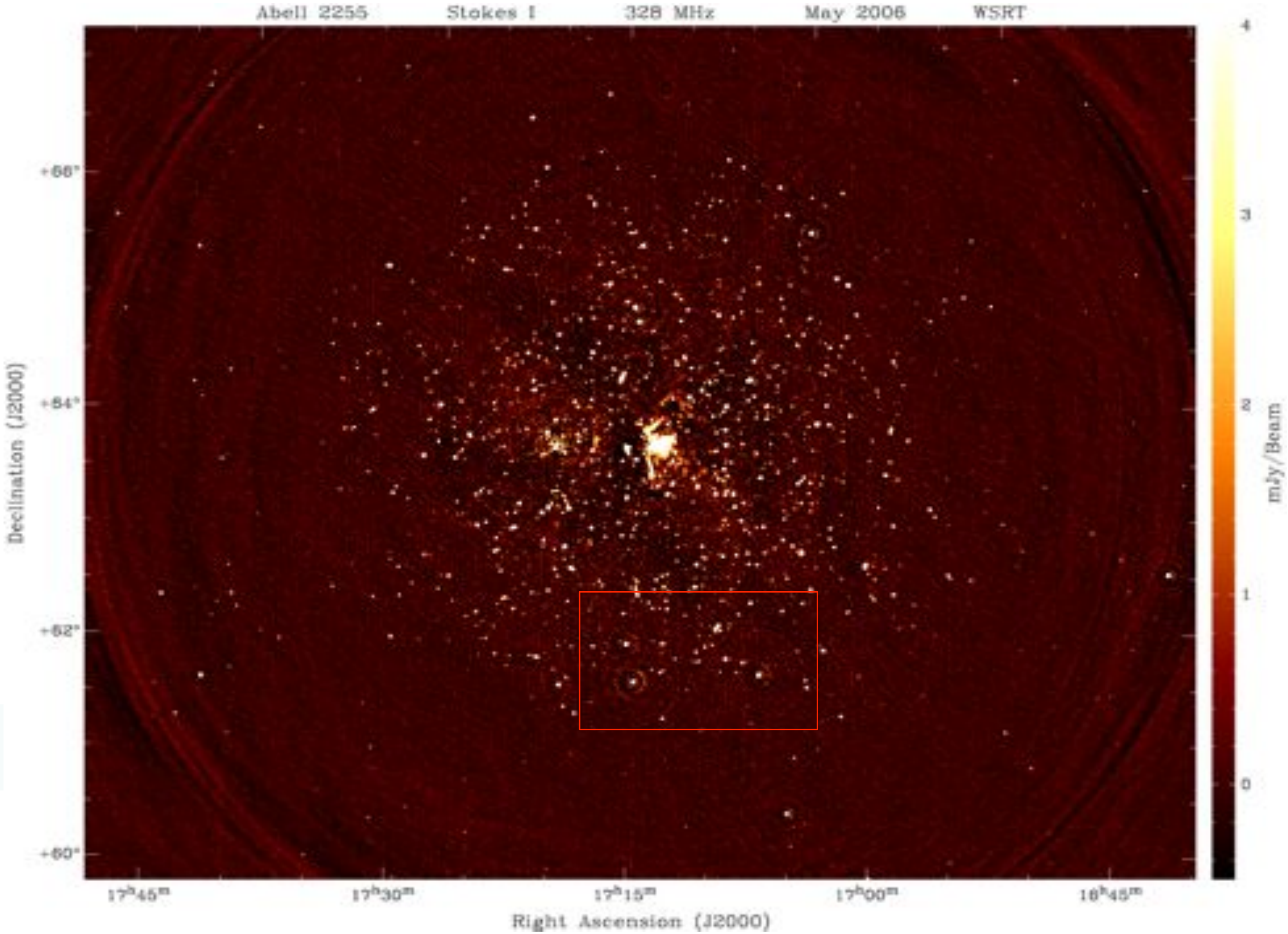
Source density

Even larger image (14^o x 14^o) in polarized emission

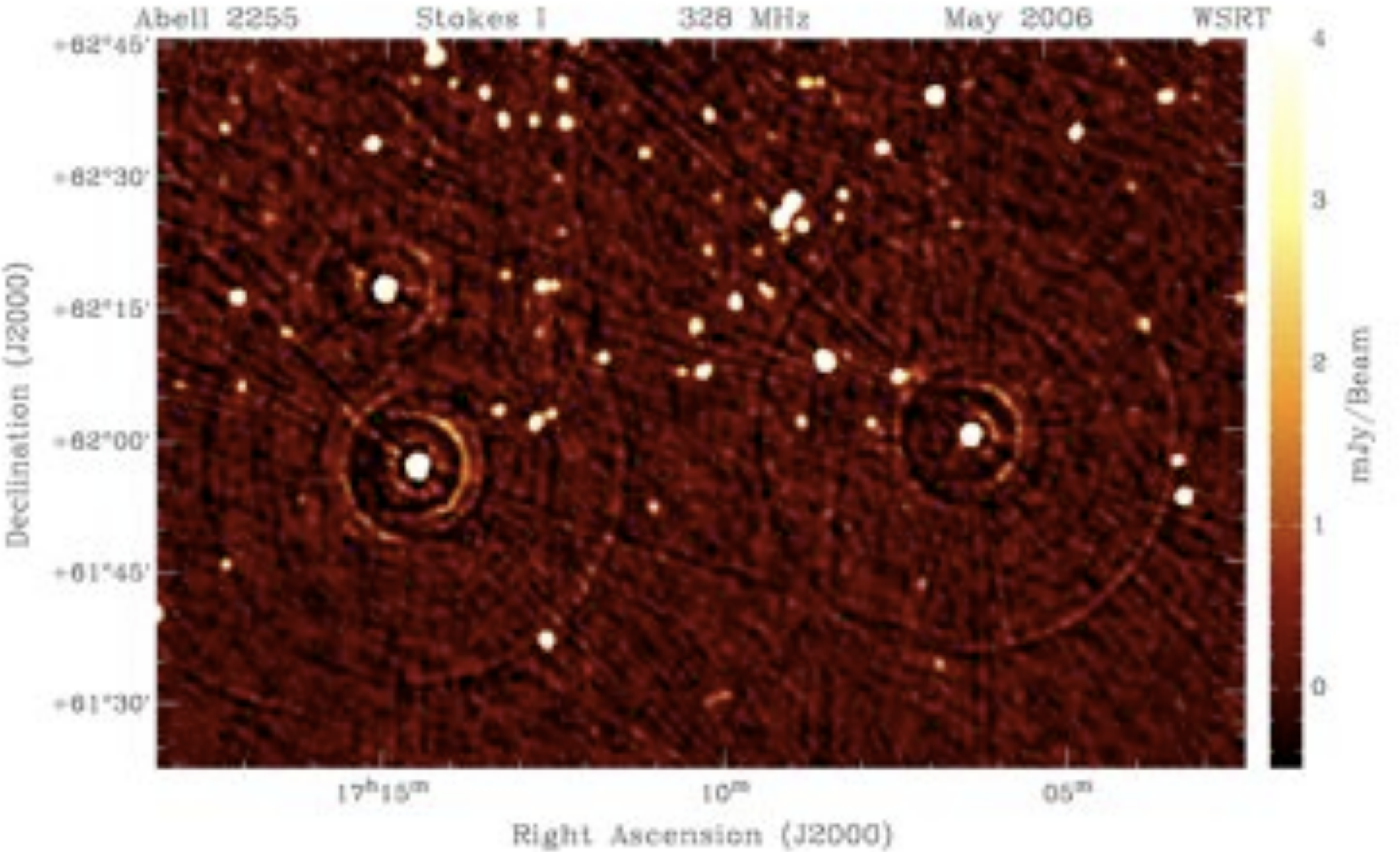
Image dominated by Galactic foreground + cluster polarization (in centre of the field)

Bright off-axis sources show complicated position dependent polarized error patterns

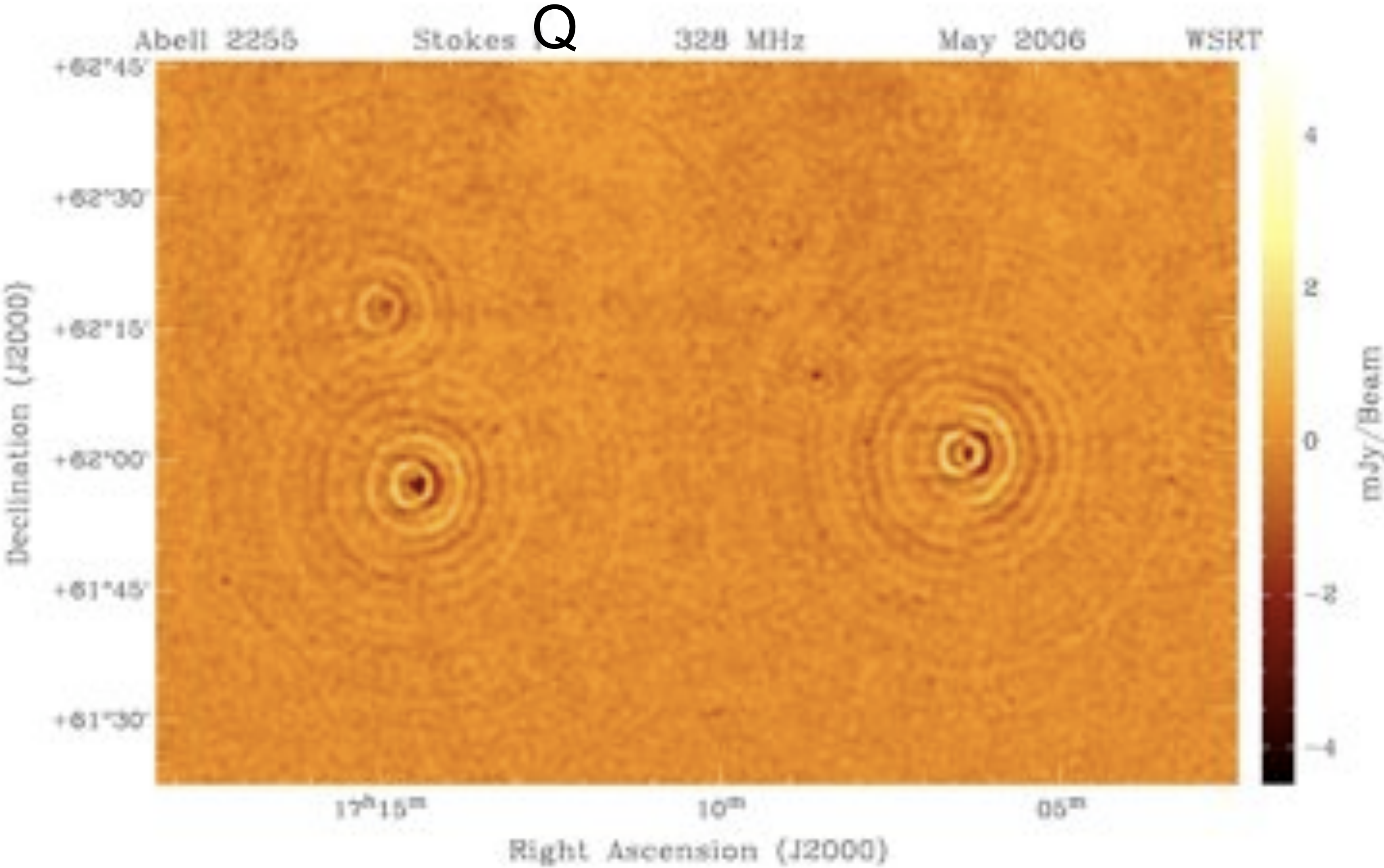



Abell 2255 Stokes I 328 MHz May 2006 WSRT
Declination (J2000)
Right Ascension (J2000)
mJy/Beam

Stokes I image of two bright off-axis sources

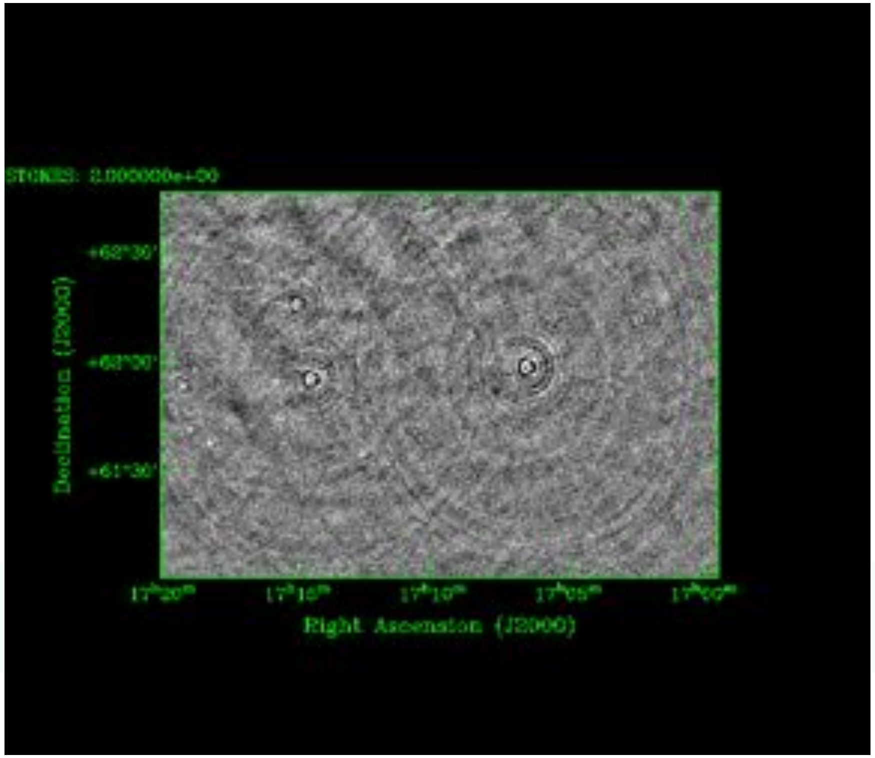


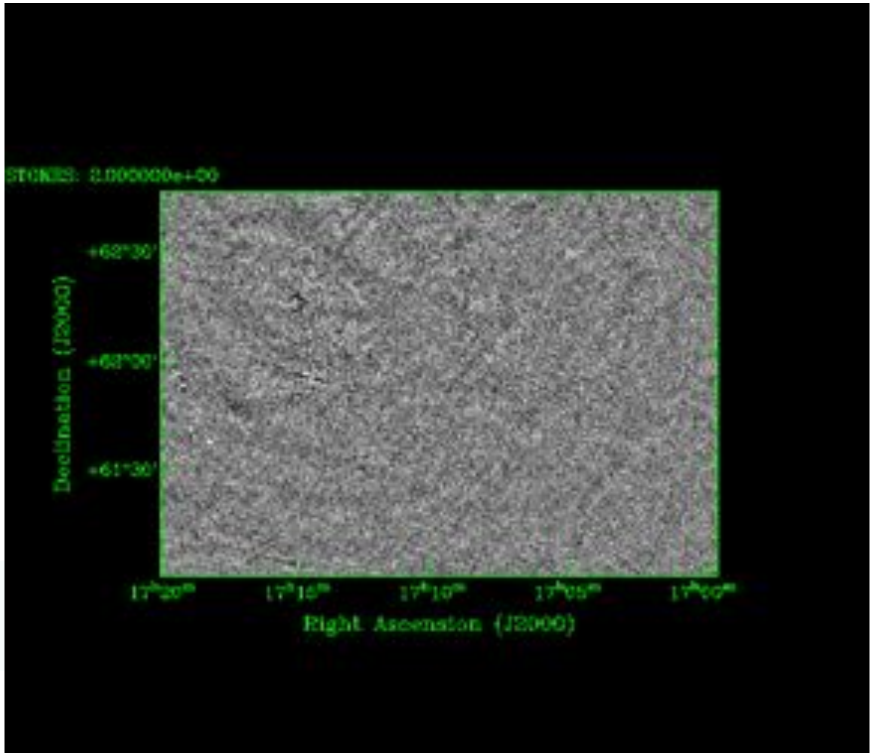
Stokes Q image of the same two sources



MeqTrees calibration on the two southern sources

Sarod Yatawatta: nov 2006
It would be interesting to study the solutions….





3C343 / 3C343.1 a suitable pair to test peeling

3C343.1 5 Jy

3C343 1.5 Jy (apparent, 3x attenuated)

Thermal noise ~ 30 μJy (~ 100,000 : 1)

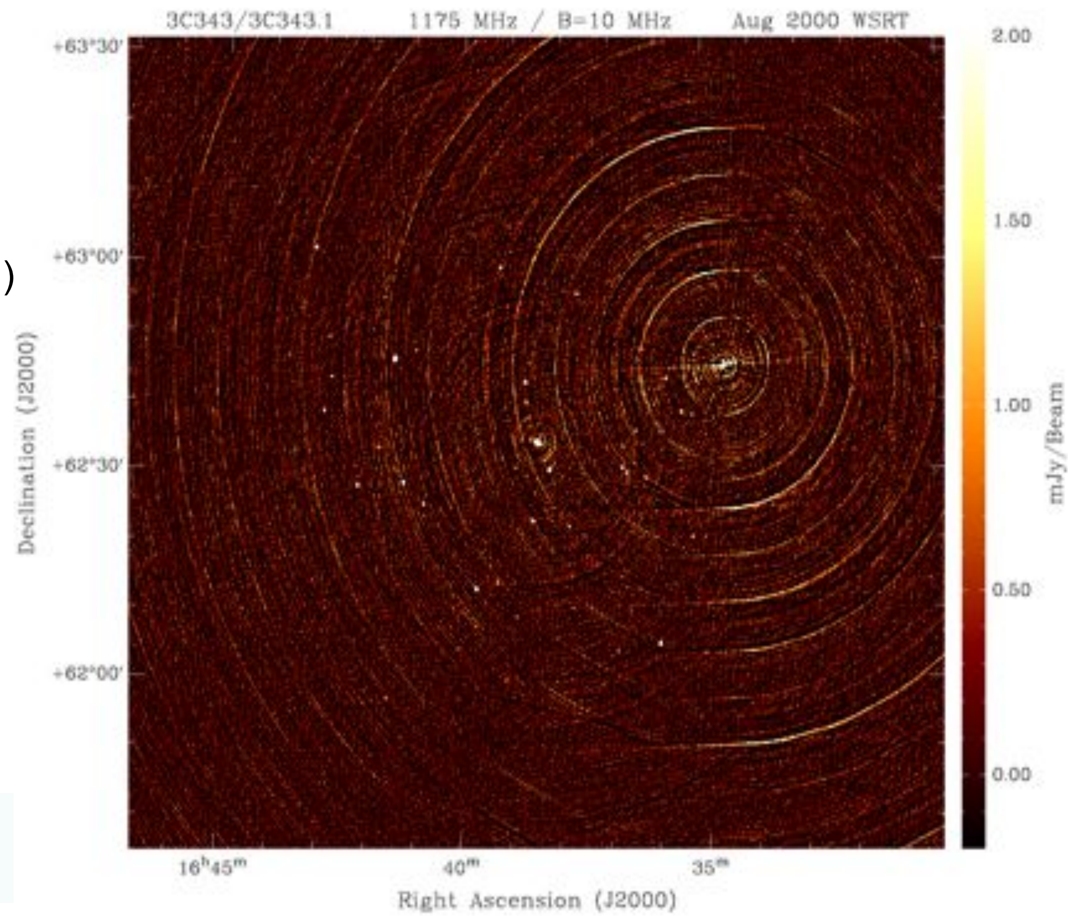
1x12h 4 Aug 2000

1175 MHz B=10 MHz (64 channels)

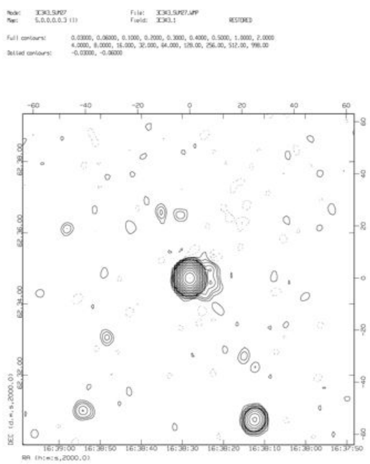
NEWSTAR processing:

(~40 job script using programs NCALIB, NMODEL, NMAP, NFLAG, NCOPY, NCLEAN)

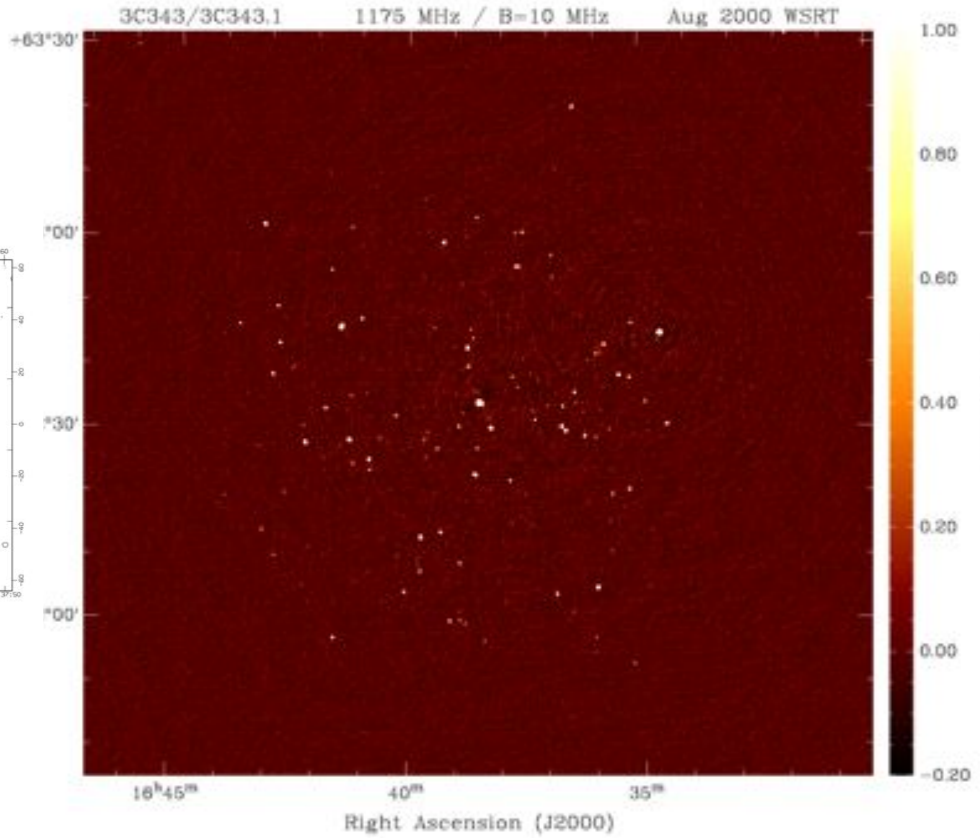
Small closure errors at each source location.

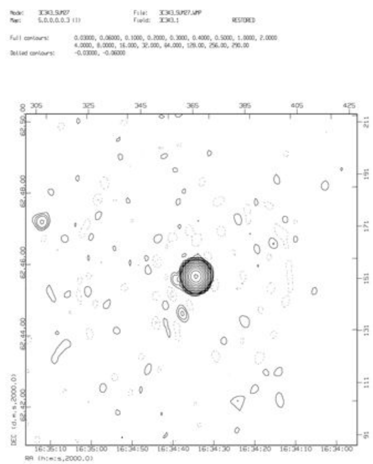


after ~1h and three selfcals....



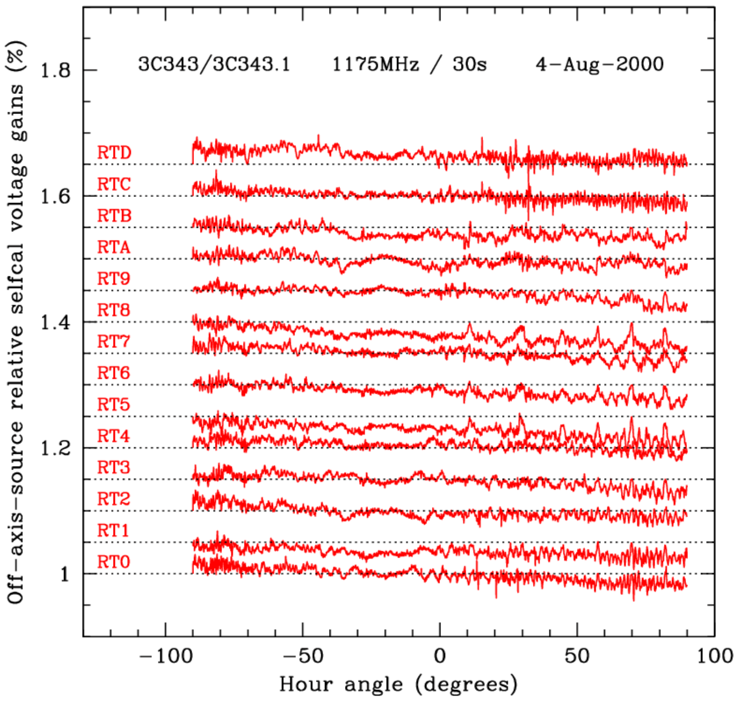
3C343.1

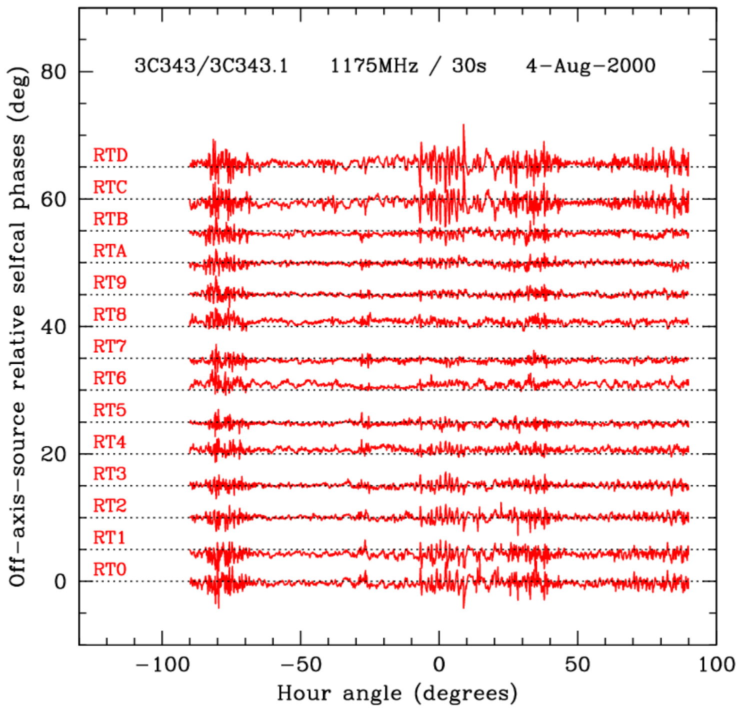




3C343

Off-axis (=differential) gain + phase solutions on 3C343



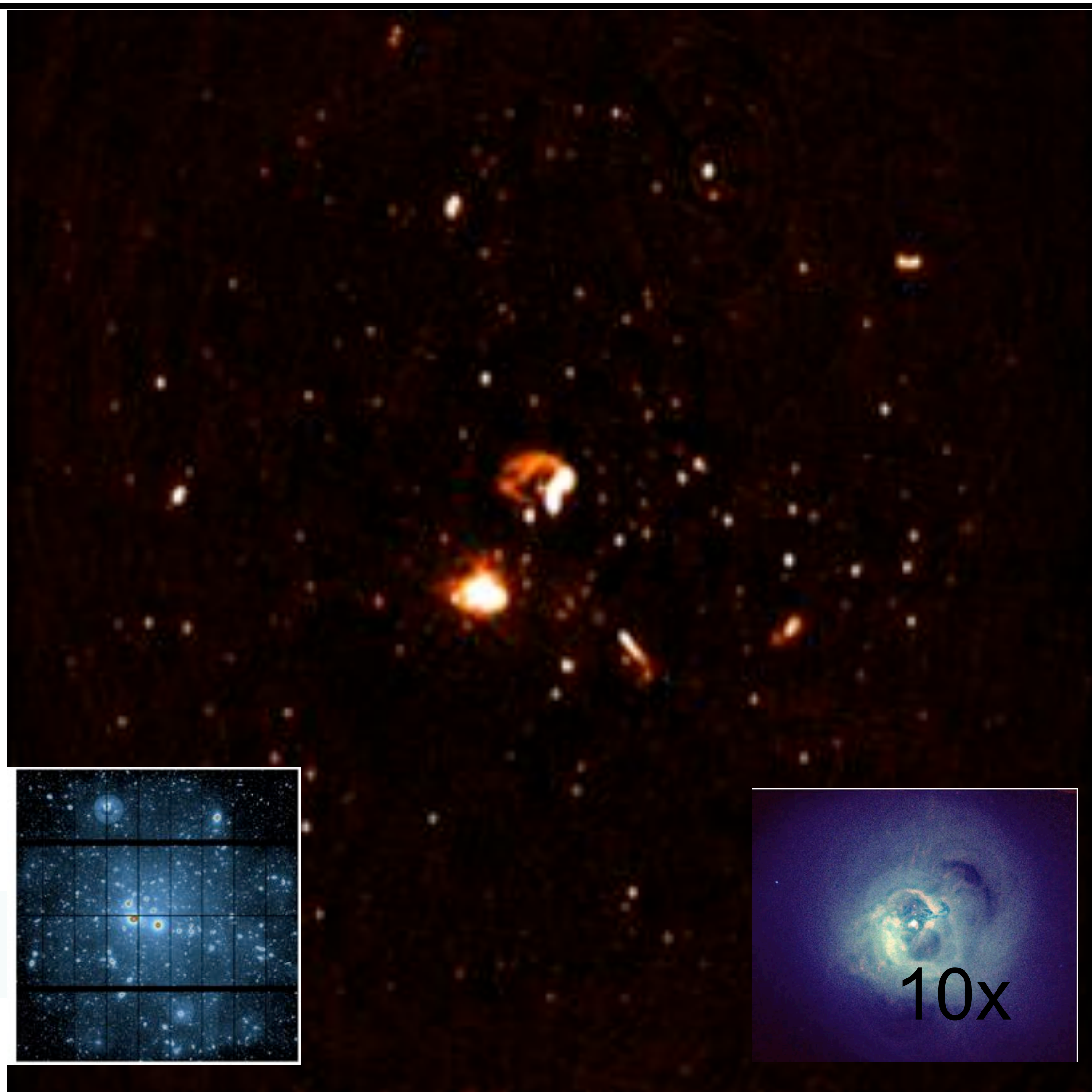


The average gain slope of 3% (range 2-4%) in (voltage) gains corresponds to (e.g.) a systematic pointing drift of ~ 42" during 12h

My favourite field: The Perseus cluster

$4^o \times 4^o$

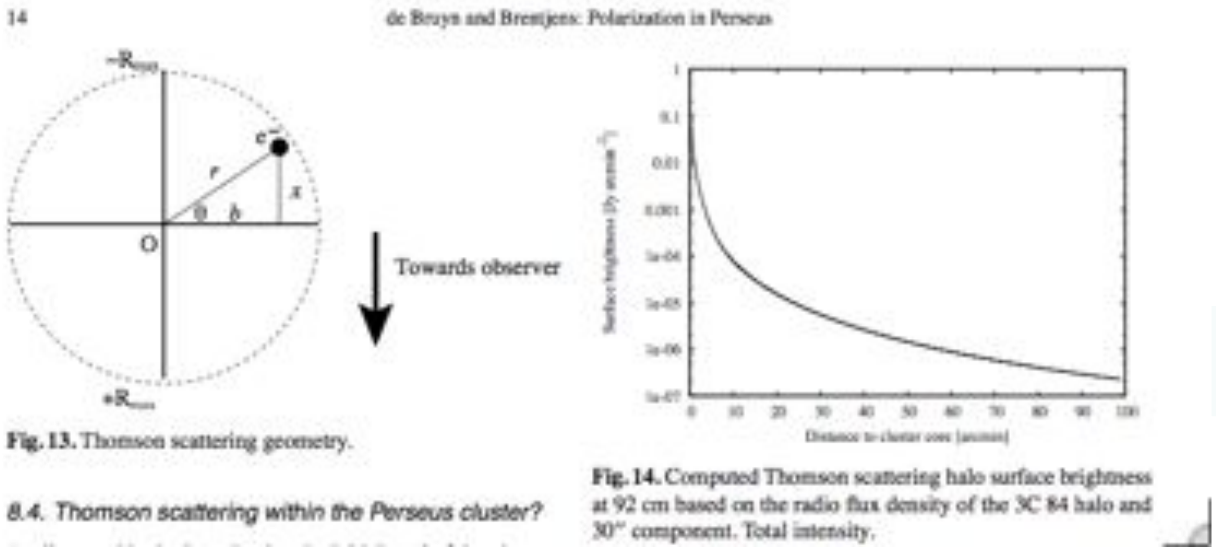
92cm
WSRT 1984



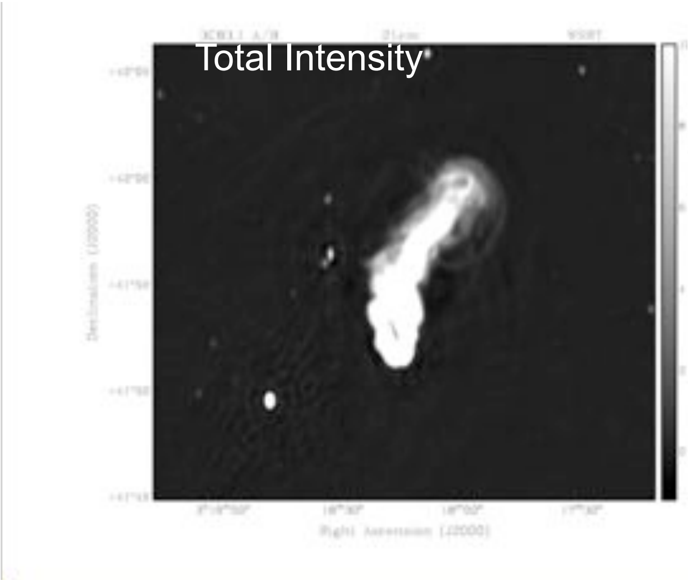
Optical X-ray

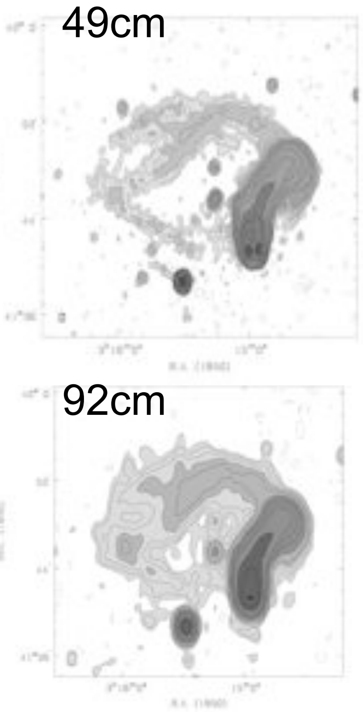
Science projects in the Perseus cluster

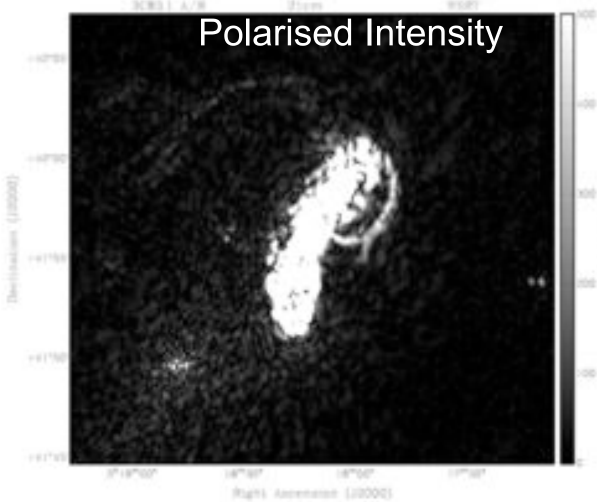
- Diffuse emission and polarization in the cluster
- HI emission and absorption
- RM of background radio sources
- Head tail source spectra (see next slide)
- Thomson scattering of internally generated radio photons by cluster electrons



Perseus-NORTH (north of tailed source)







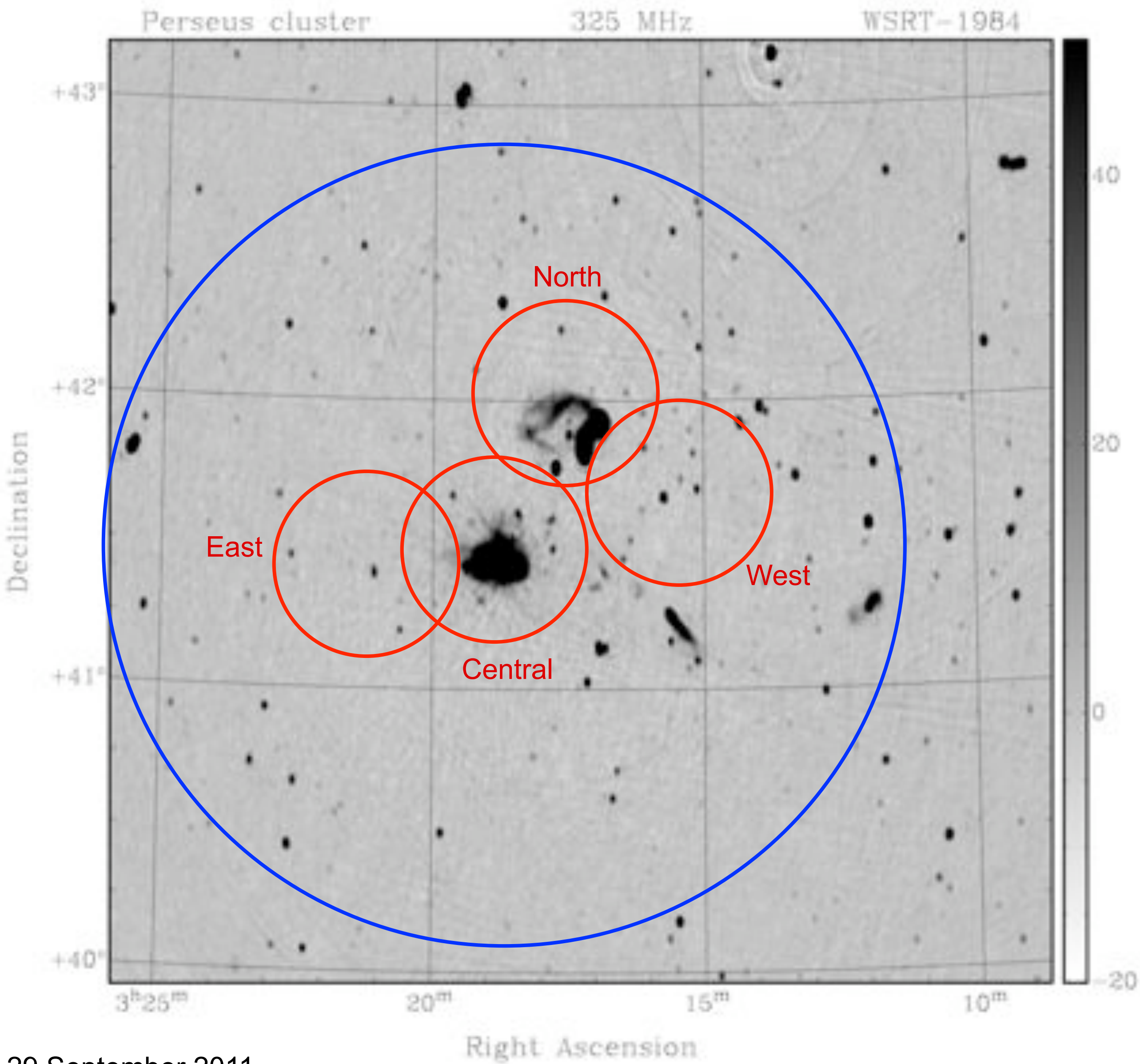
(Sijbring & de Bruyn, 1998)

Very complex field to process (NGC1265 polarization, 3C83.1A, 3C84)

A giant 'magnetic loop' ~ 60% polarized (!) with RM ~ 50 - 100 rad/m^2

Very thin and highly polarized ridges in OLD tail of NGC1265 !

New 21cm pointings



3x12h & 6 x 12h

8 x 20 MHz

64ch x 4 pol

Nov ’03 (C & W)

Oct ‘07 (E & N)

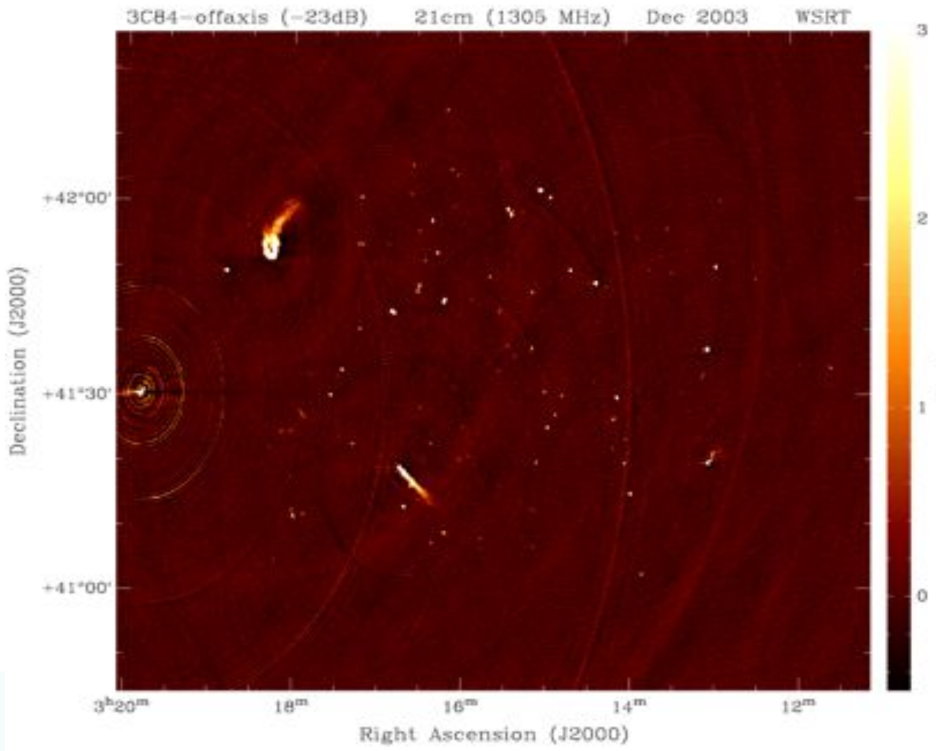
The West, East and North field had a 22 Jy source (3C84) at the 6-23dB point of the primary beam !

⇒ apparent flux of 5 Jy, 0.5 and 0.15 Jy

Perseus - WEST

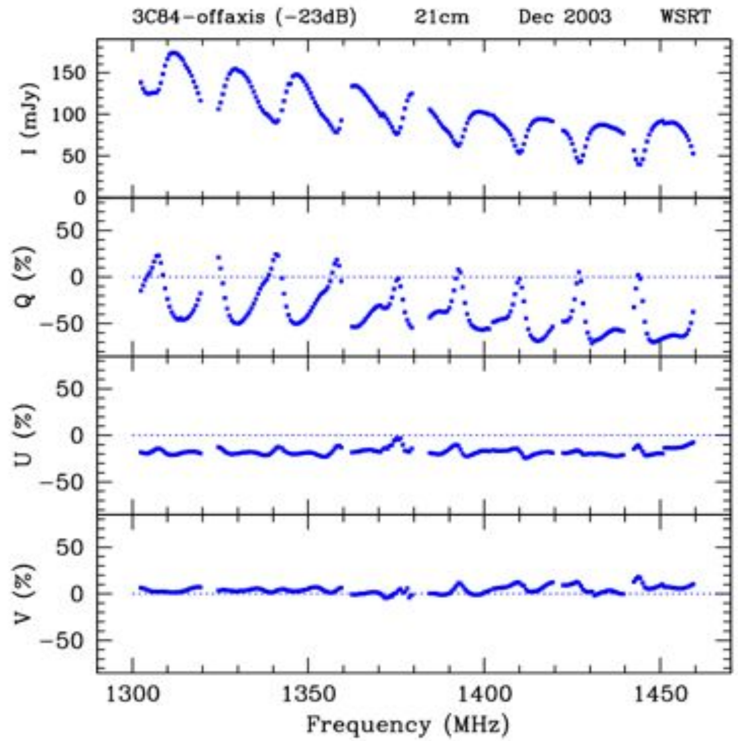
Raw image

Stokes I



Spectral passband

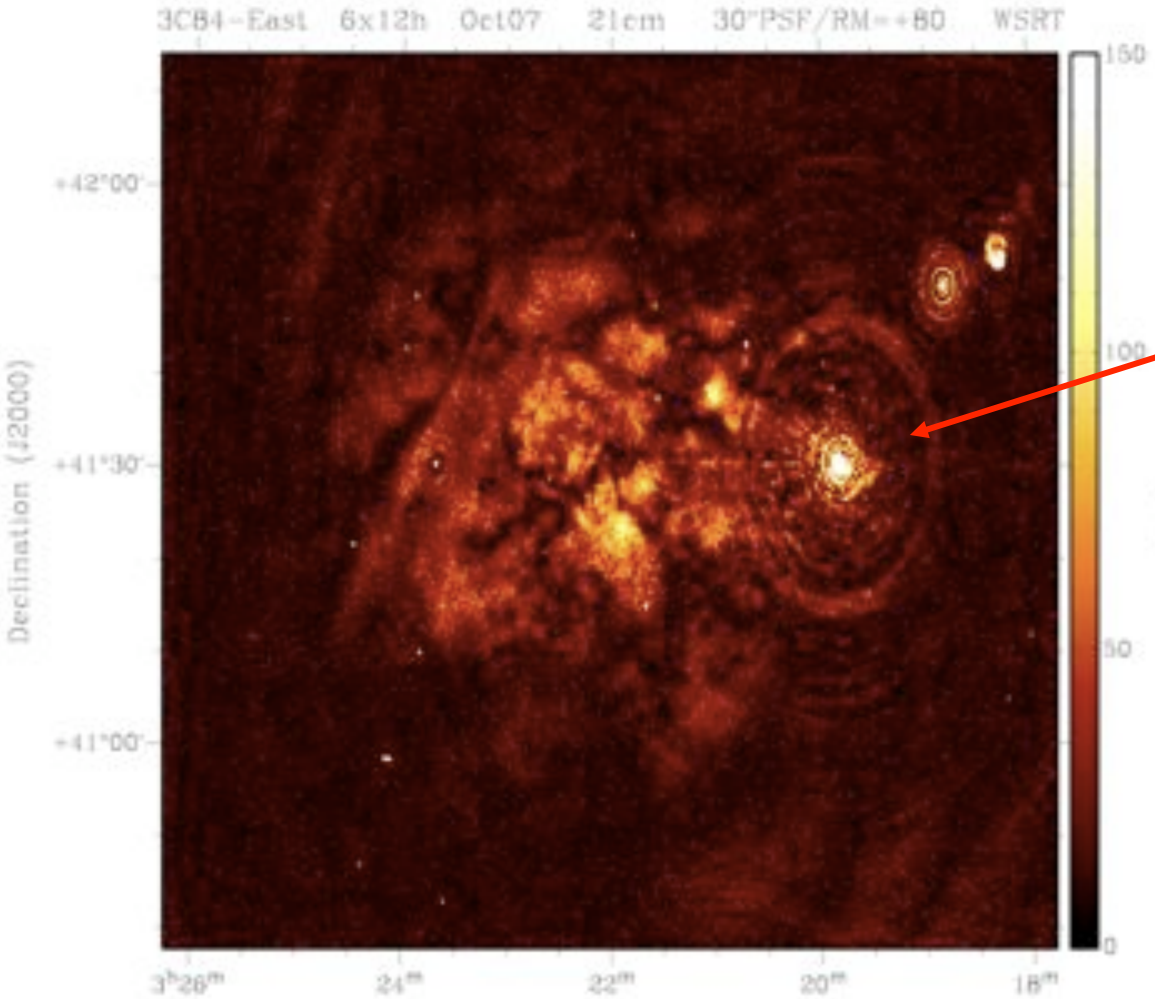
I,Q,U,V (frequency)



(see also Popping & Braun, 2008)

High DR requires **selfcal per 0.5 MHz channel !!**

Perseus - EAST



30”x45” smoothed image

6x12h (12m sampling of uv-plane !)

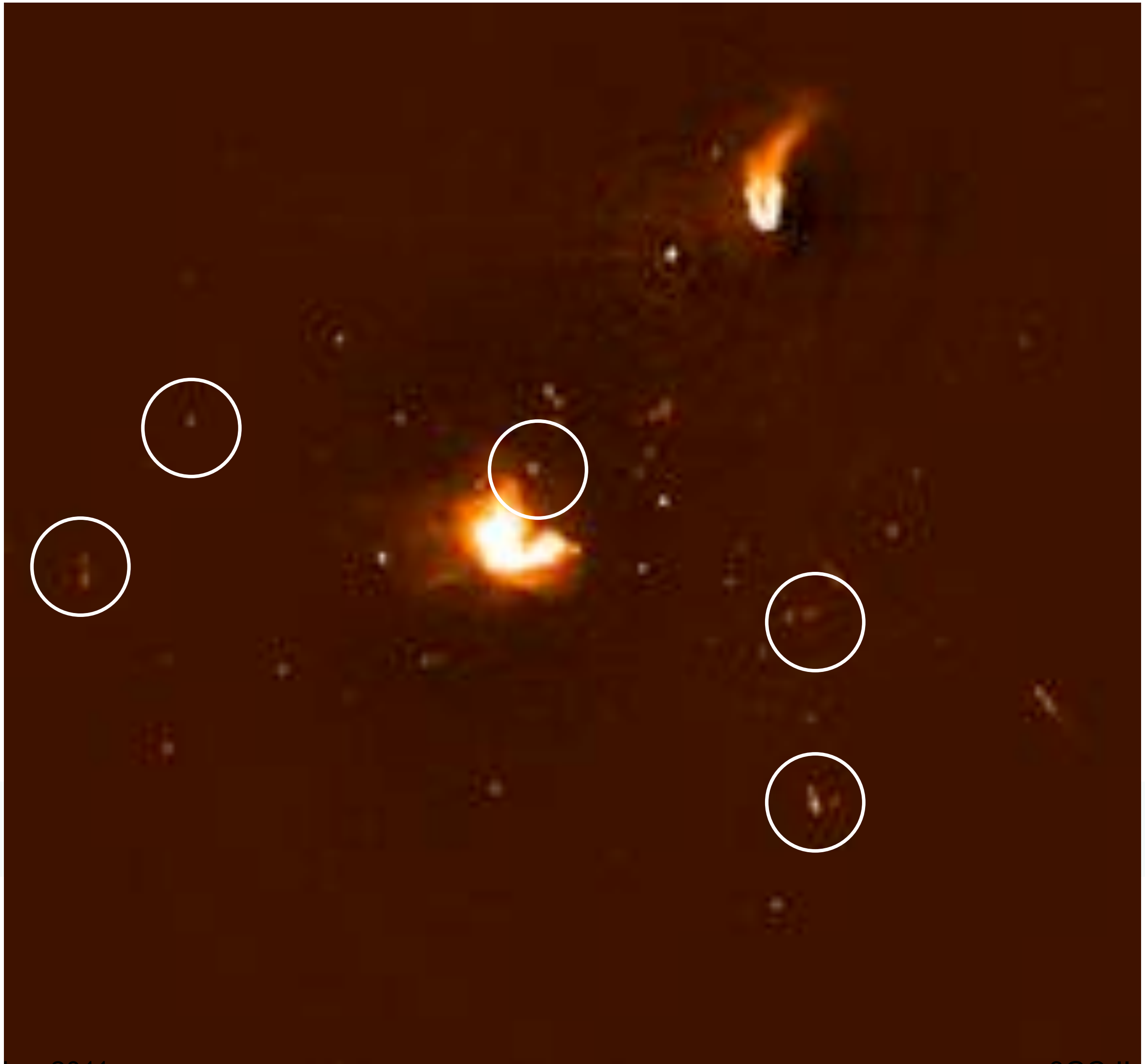
I-peak ~ 5 Jy (3C84)

Pol-noise ~ 5-7 μJy/PSF

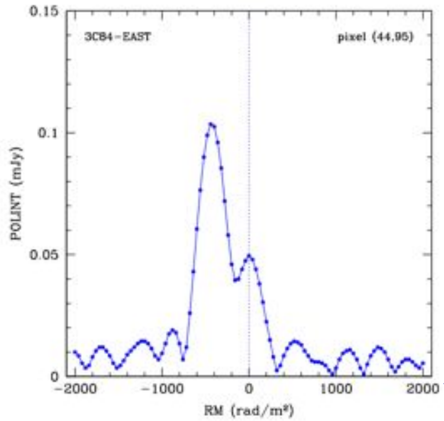
⇒ DR ~ 10^6 : 1

The emission is obviously not due to Thomson scattering but originates in our Galactic foreground !

RM's of sources behind Perseus cluster



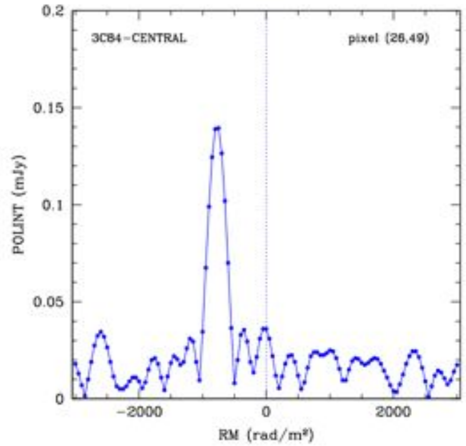
‘RM spectra’ of sources behind Perseus cluster



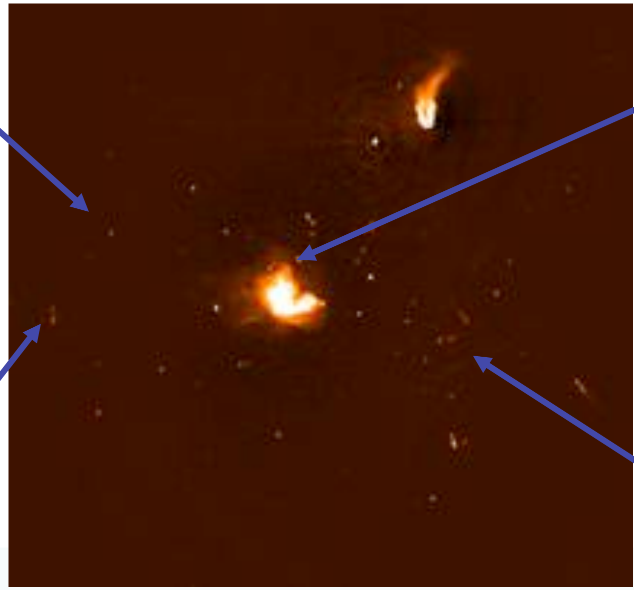
RM= - 440 rad/m^2

Raw Faraday spectra produced using RM-synthesis (Brentjens & de Bruyn, 2005).

Width of RMSF ~ 300 rad/m^2

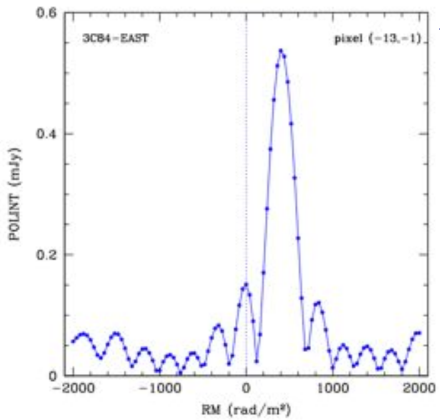


RM= - 780 rad/m^2

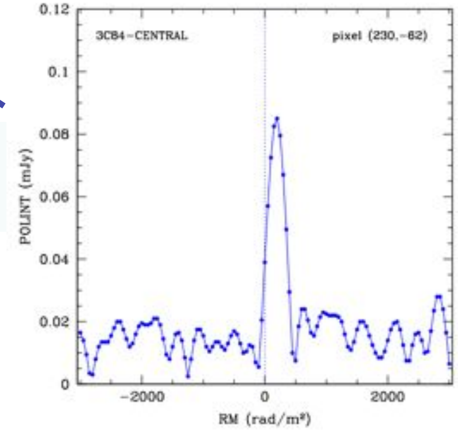


RM= + 400-500 rad/m^2

RM= + 200 rad/m^2



noise levels in RM spectra at ~ 5-10 microJy/beam



LOFAR: the ultimate SKA pathfinder

The LOFAR observatory

LBA (10) 30 - 90 MHz
isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)

Core	2 km	24 (24) stations
NL	80 km	16 (9) stations
Europe	>1000 km	9 (8) stations

A station will have 24 - 48 – 96 antennas/tiles

Principle of **Aperture Synthesis**
Array resolution: sub-arcsec to degrees

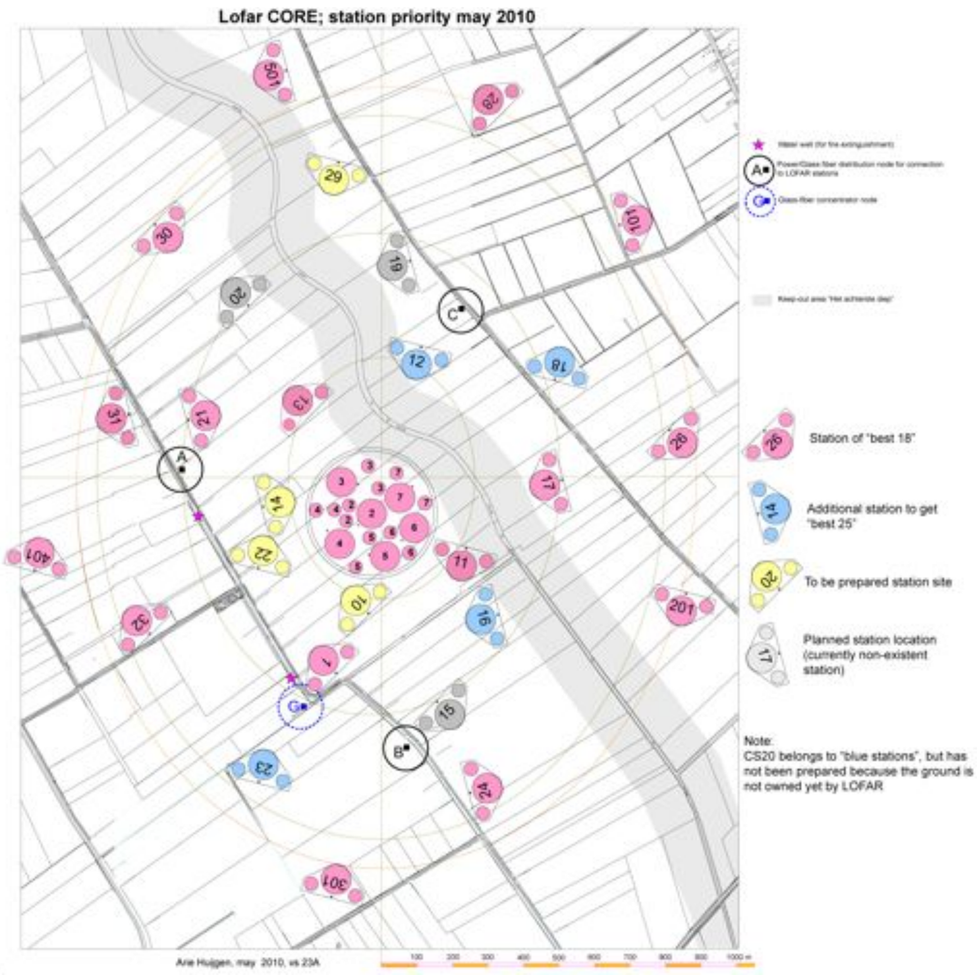
Pulsars: tied-array(s), (in)coherent sums

Sensitivity (after 6 h, 40 MHz, ~ 50 stations)
@ 60 MHz ~ 3 mJy
@ 150 MHz ~ 0.1 mJy

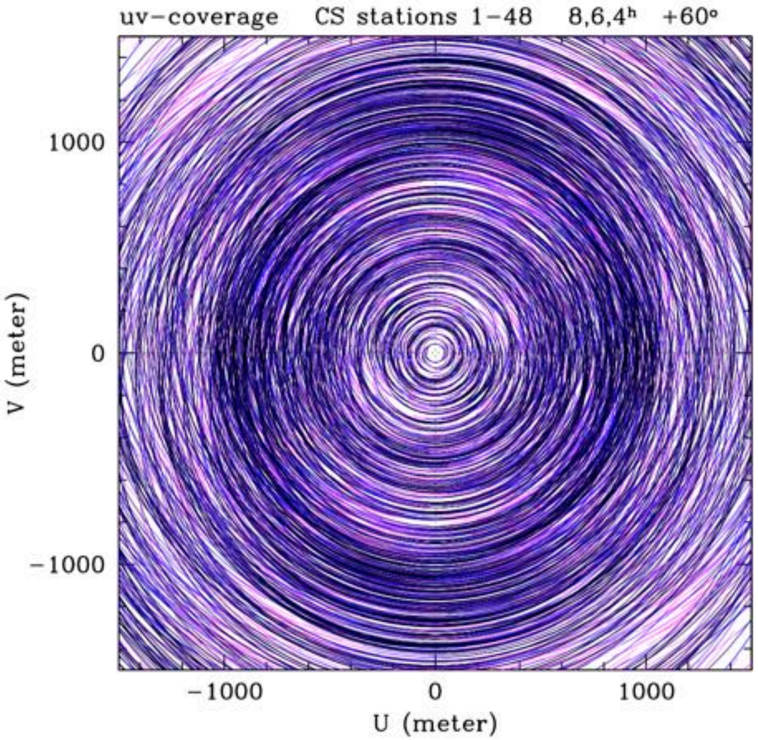
LOFAR core array (Sep 2011)

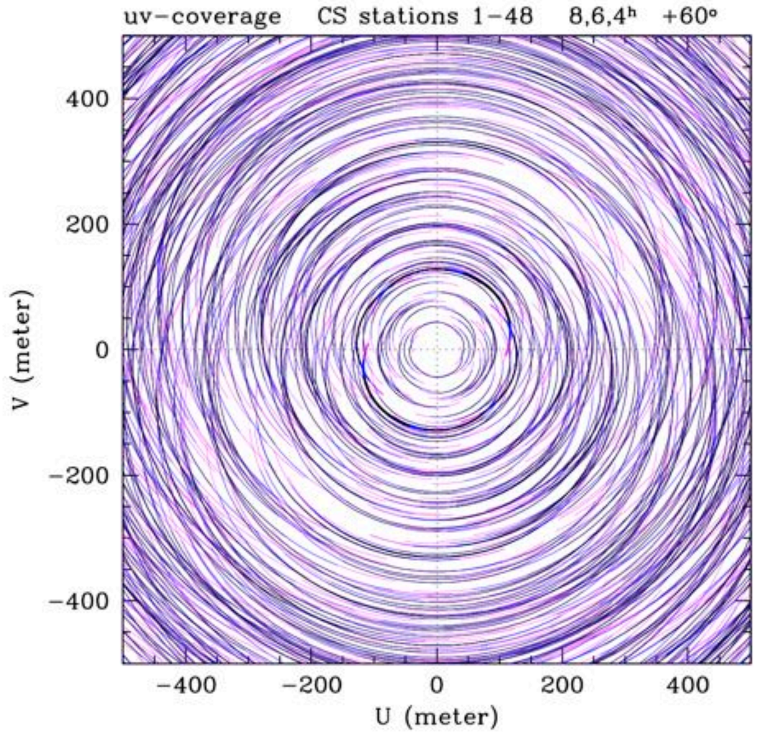
LBA: 24 stations

HBA: 24x2 stations

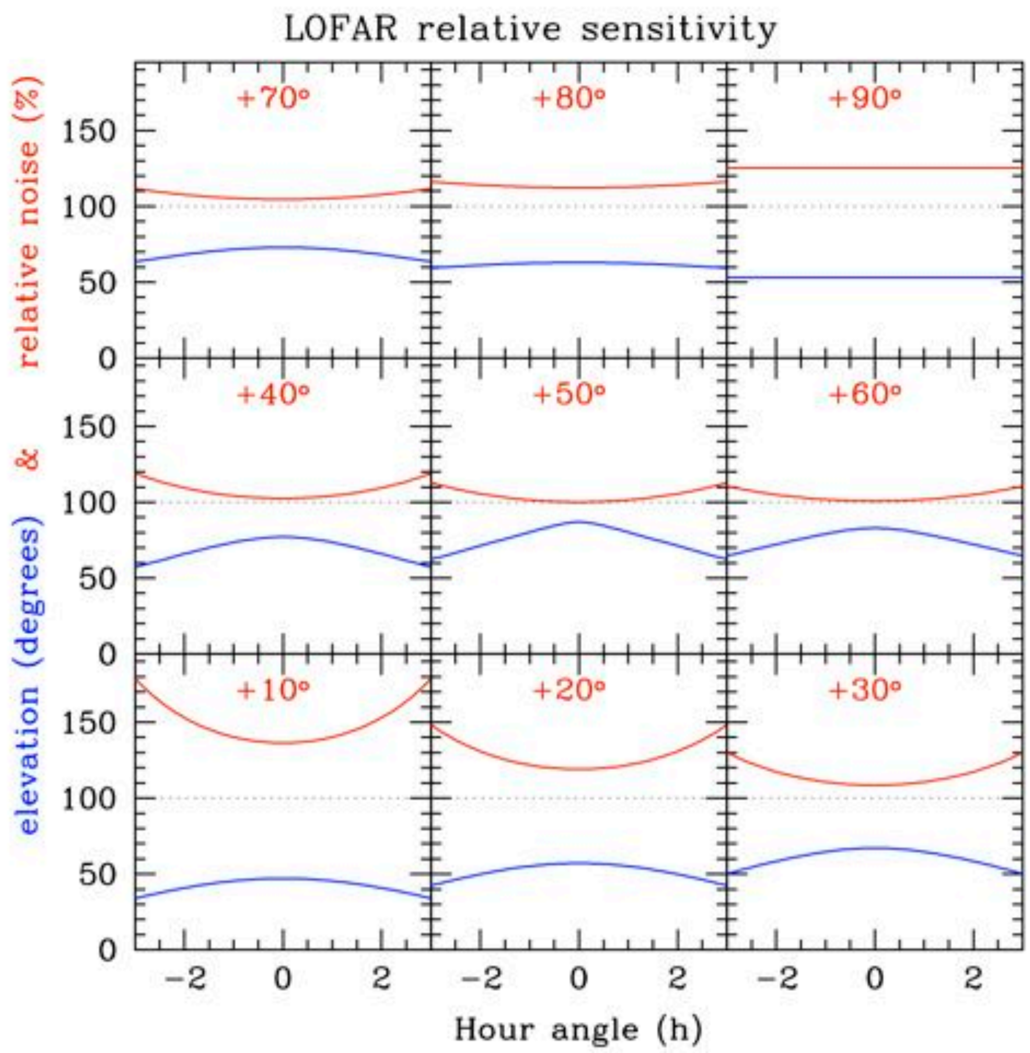


Full synthesis HBA uv-coverages in the core





Elevation and sensitivity as function of (Dec,HA)

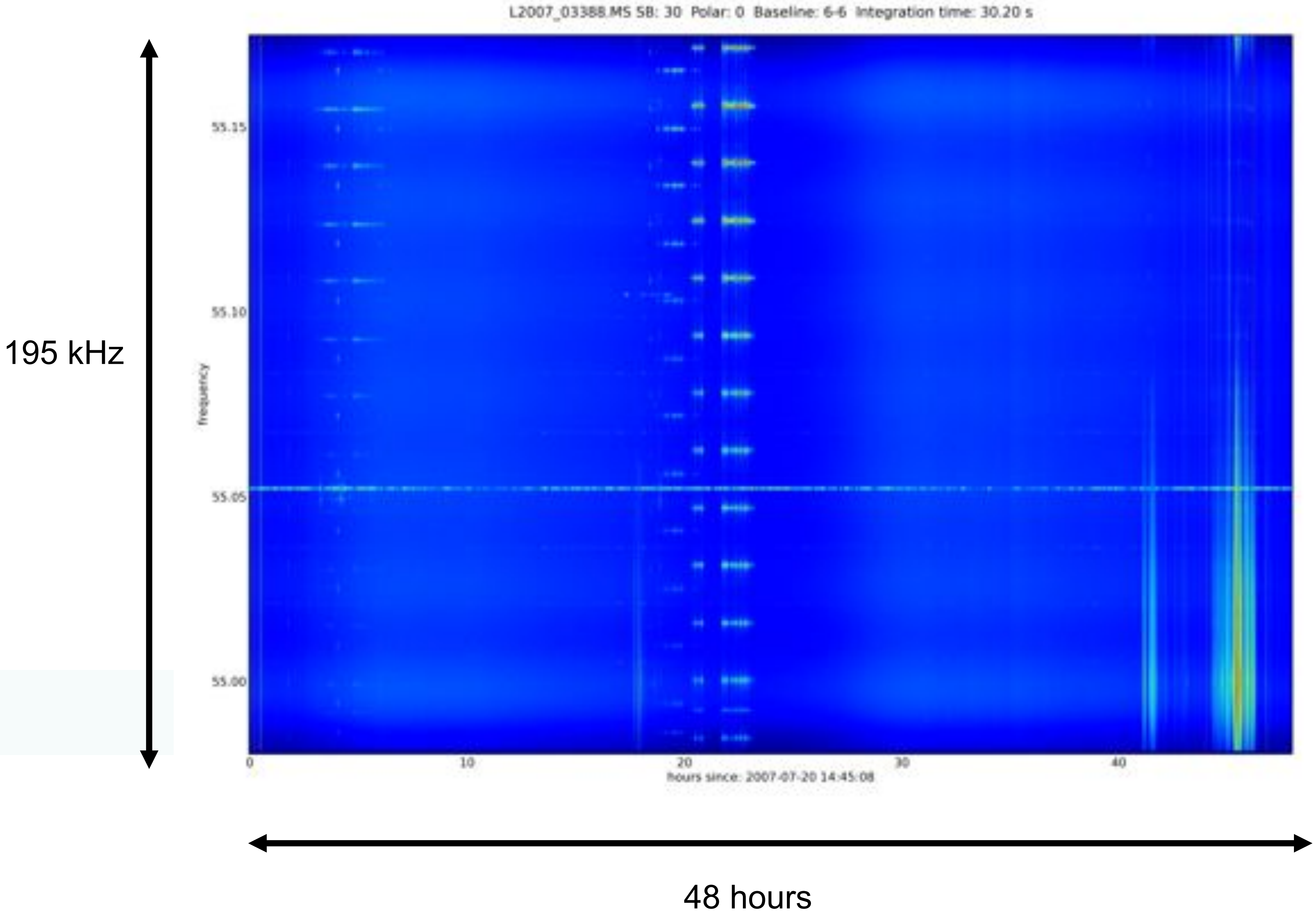


Two well studied fields:

NCP
Dec=+90°

3C196
Dec=+48°

LOFAR tracking airplanes (or meteorites)



Airplane movie with LOFAR CS010 (25 Feb 2008)

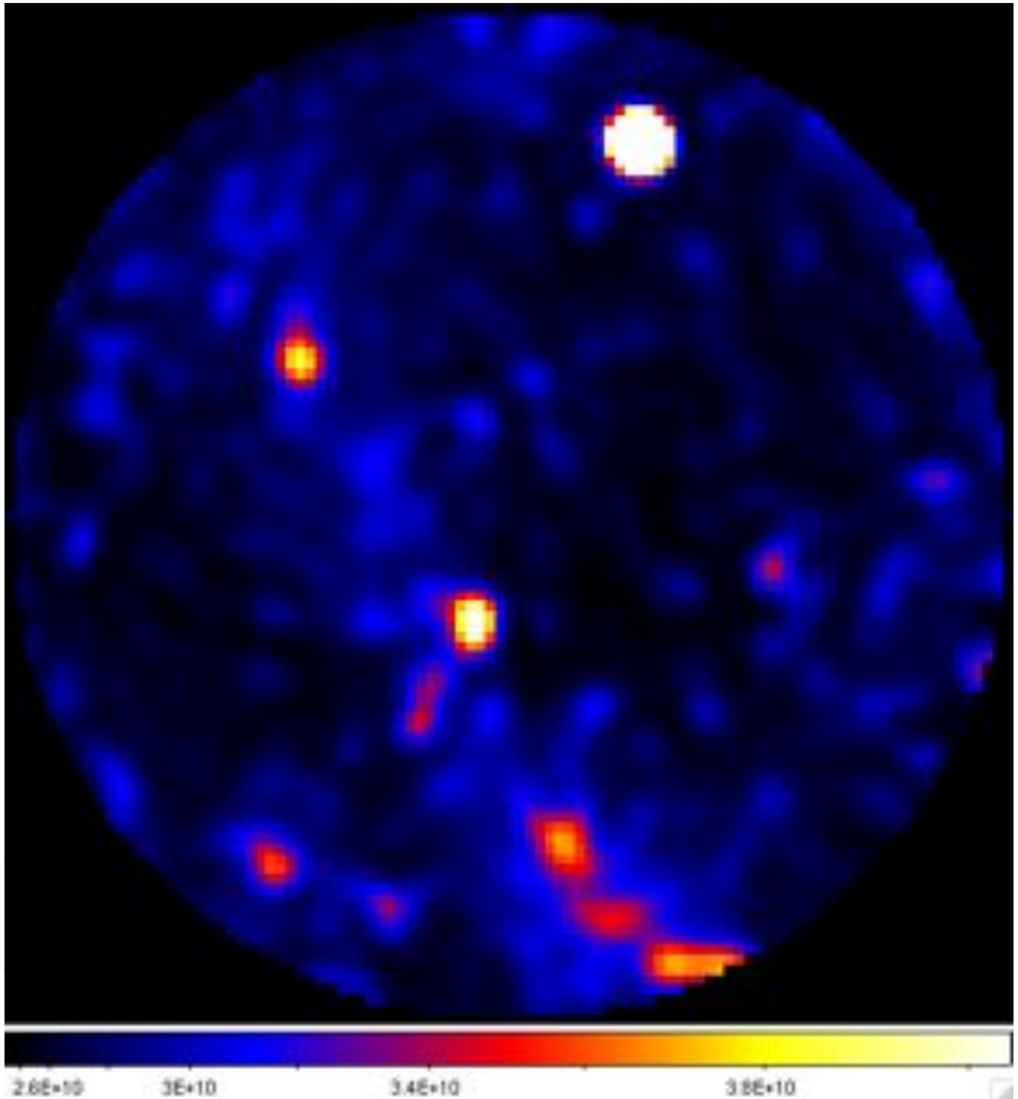
Movie using 60 x 1s snapshot all-sky images using the LOFAR CS10 stationcorrelator at a frequency of 55.05 MHz (0.8 kHz channel)

It contains the emission from the Milky Way, CasA and CygA, as well as a moving airplane illuminated by reflected emission from a Danish TV transmitter (~ 400km NE from Exloo)

Note drifting intensity-scaled sidelobe patterns (uncalibrated data) of the airplane reflected signal !

Another airplane, as well as a meteorite show up briefly at the end of the movie

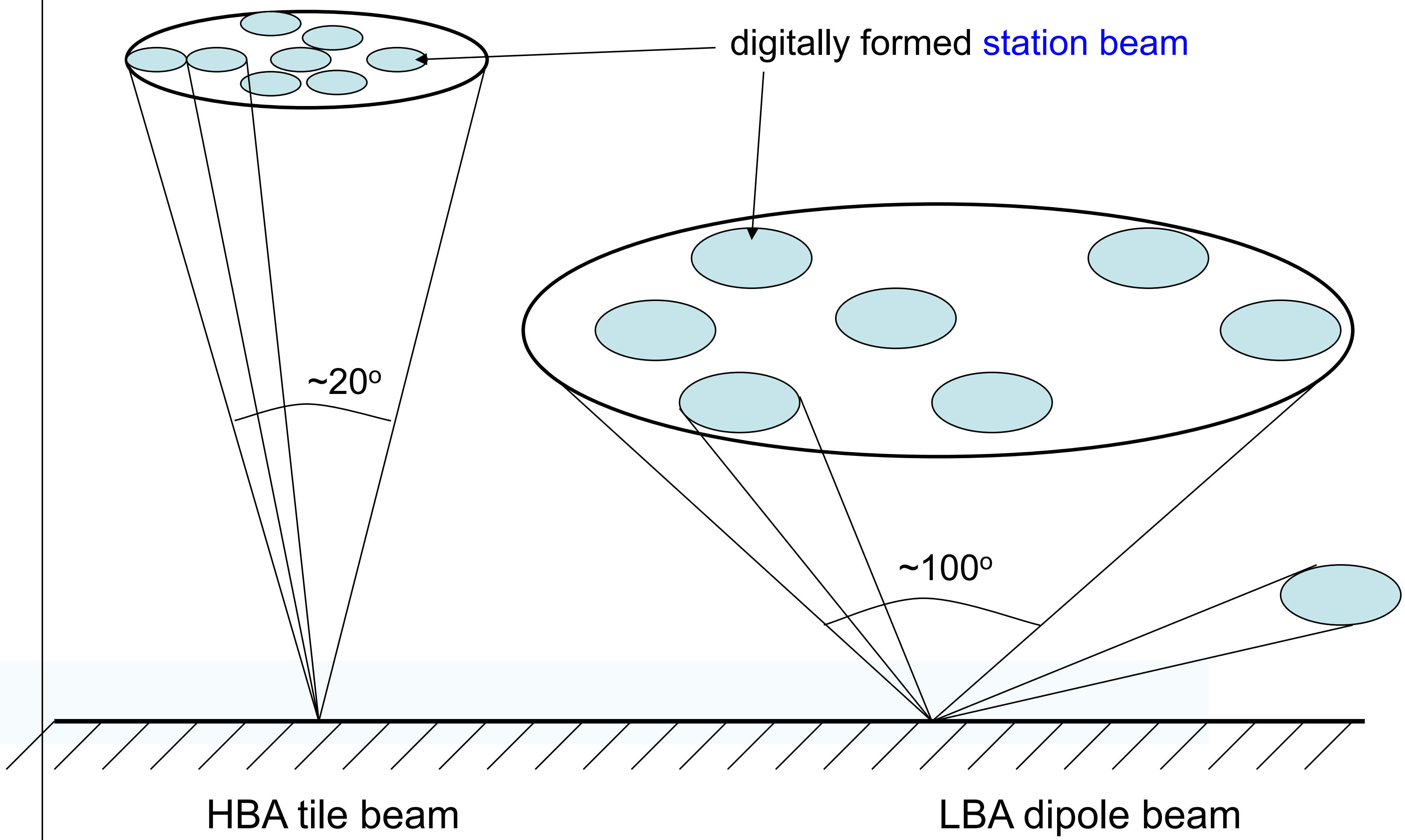
(Michiel Brentjens)



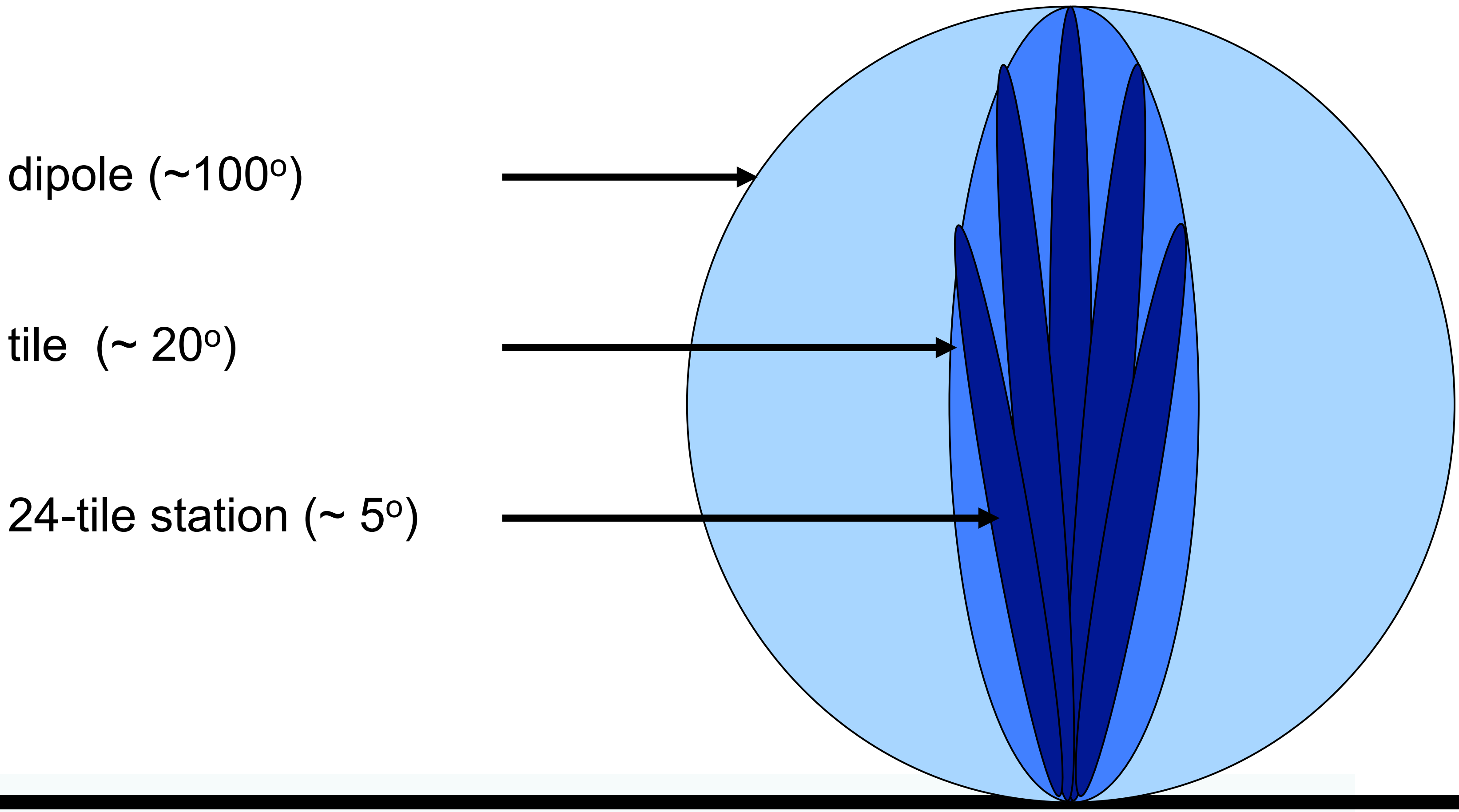
LOFAR = all-sky imaging

(John Baldwin, Jaap Bregman)

LOFARs very wide FOV (good & bad !)



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



Ways to look at LOFAR calibration parameter space

Primary tools/issues:

uv-coverage: snapshots vs long syntheses

- varying primary beam shape/size

baseline length: 3 km, 75 km, 1000 km

- Galactic diffuse emission
- source structure
- ionospheric effects ('seeing')
- data volume / image size/ processing time

frequency space: < 30, 40-80, 120-180, 190-230 MHz

- primary beam size
- source spectra

CS-1 (‘mini’-LOFAR) : our ‘learning’ array

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

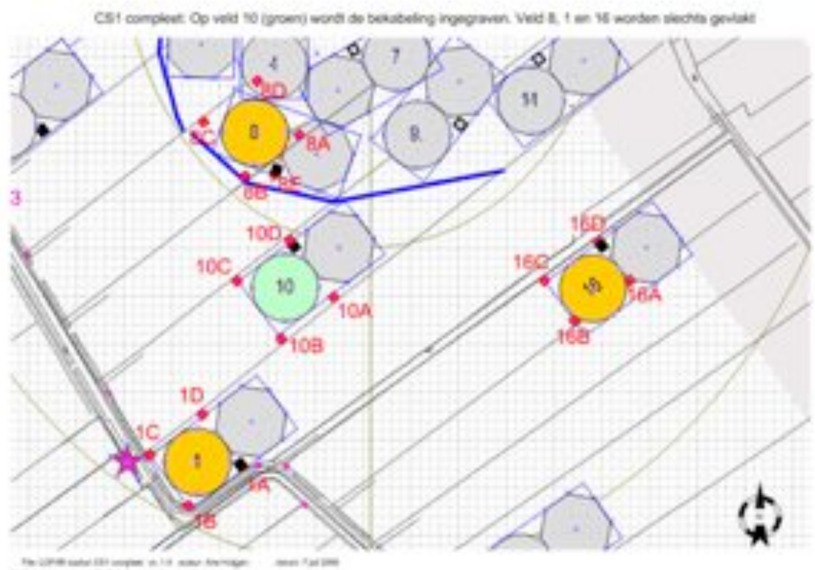


Figure 1: CS1 station locations.

400 m

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

16 dipoles (~70 baselines)

3 x 24h

38 - 59 MHz
Bandwidth ~ 6 MHz

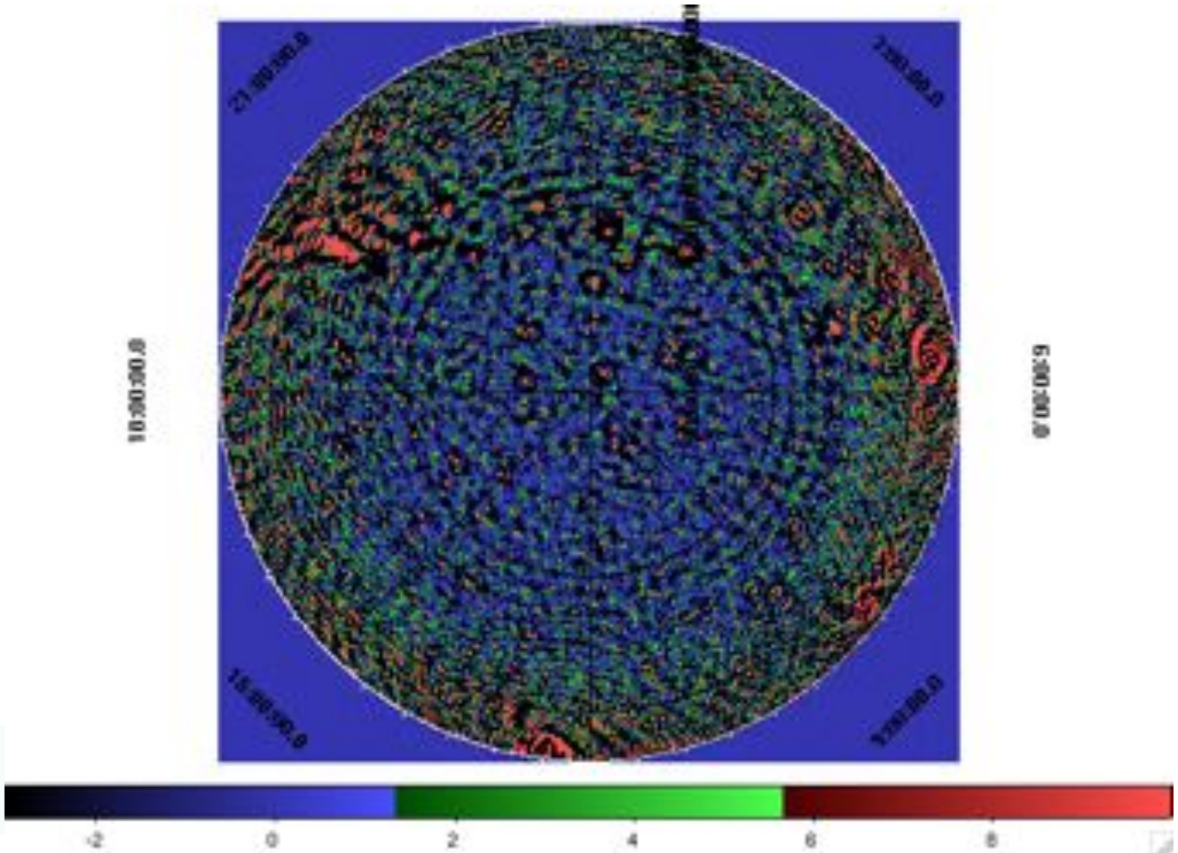
~ 800 sources !

PSF ~ 0.5°

noise ~ 1 Jy

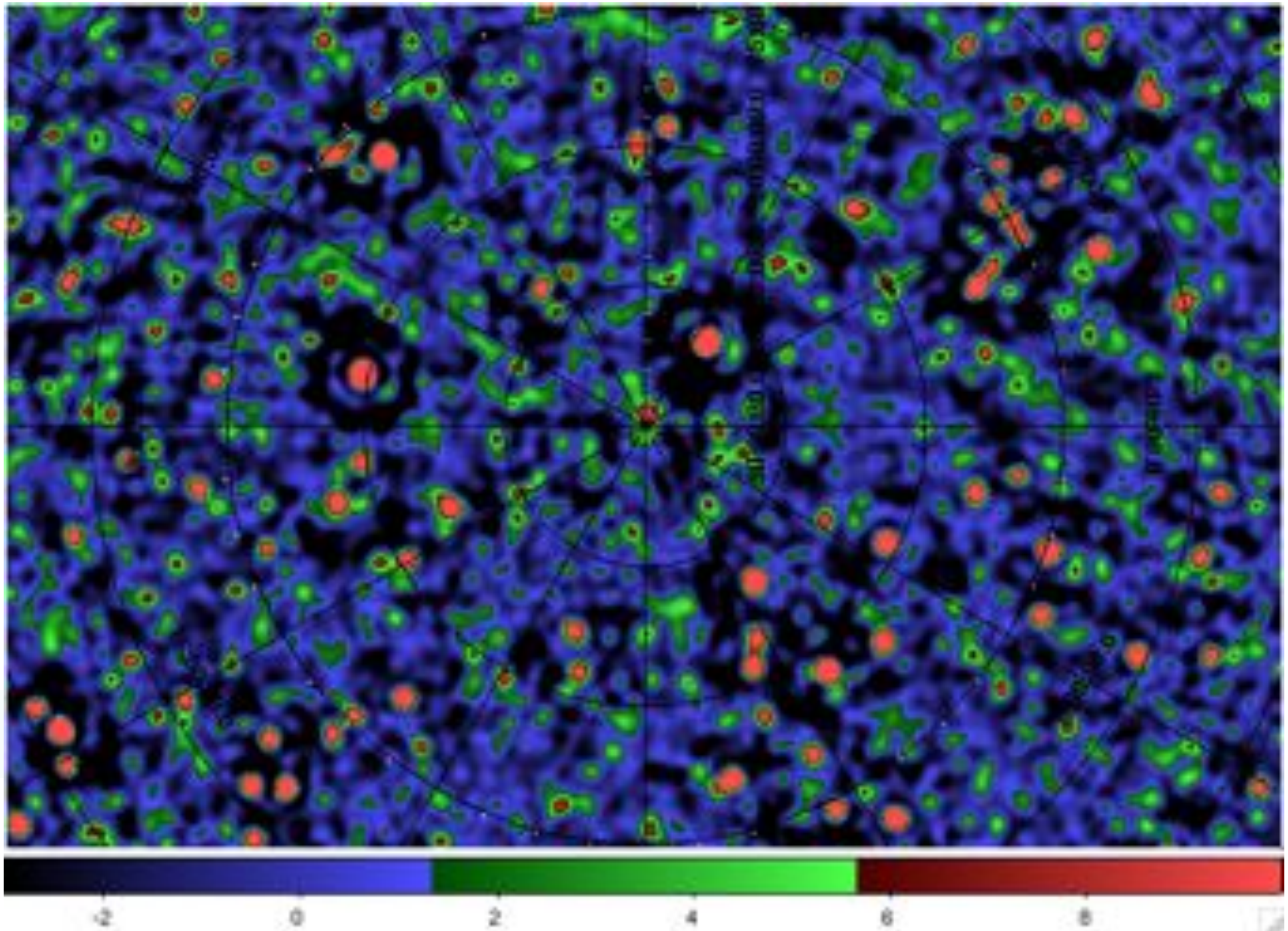
CasA/CygA (20,000 Jy)
subtracted

- beam corrected -
- no deconvolution as yet



Yatawatta, 2007

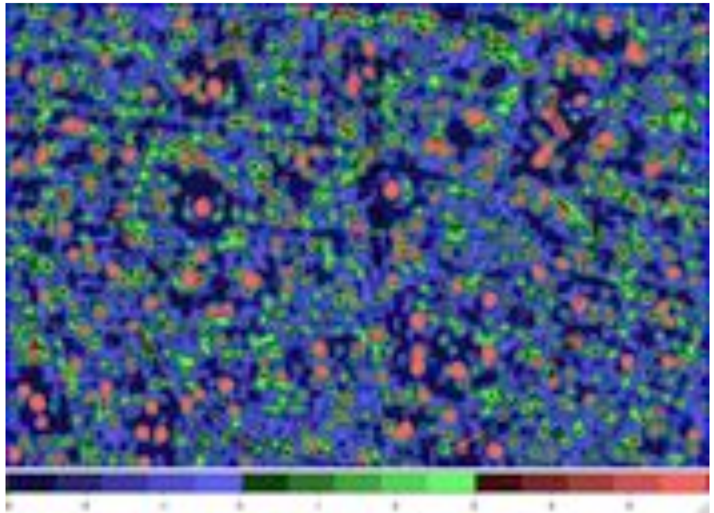
Zooming in at the NCP: confusion limited !

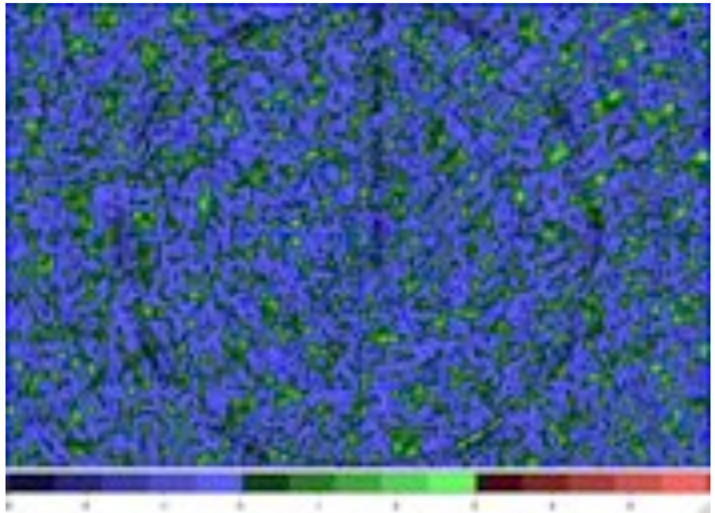


Some lessons from CS-1

- MeqTrees / BBS all-sky imaging at LBA and HBA
- with ~10-arcsec accuracy all over the sky !
- classical confusion limited imaging achieved
- DR >1000:1
- difference noise <0.5Jy (LBA) and <0.2 Jy (HBA)
- dipole-beam behaviour as expected
- mostly very benign ionosphere in 2007

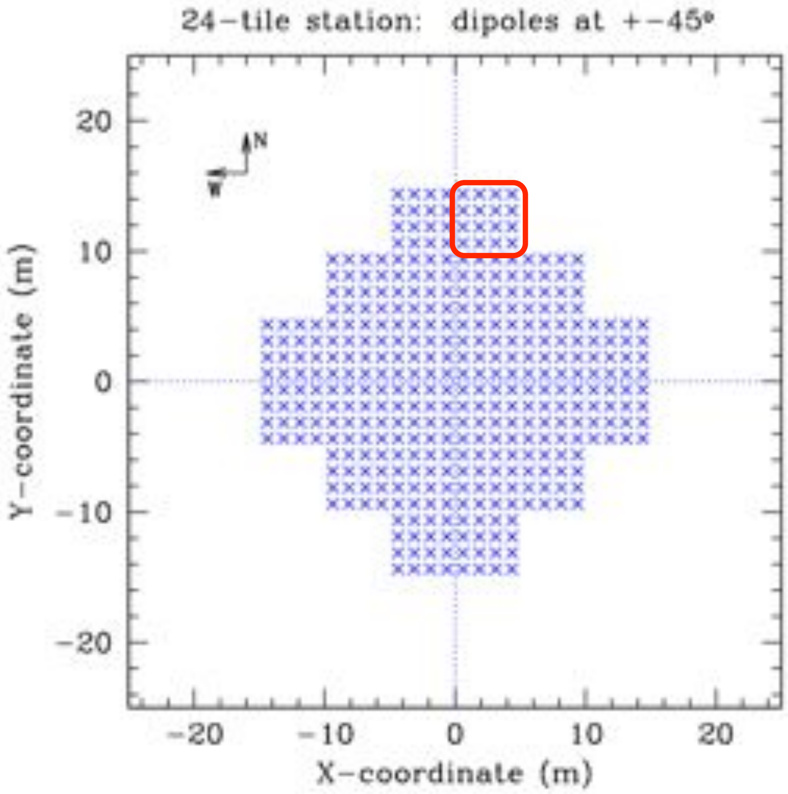
3x24h averaged (LBA)

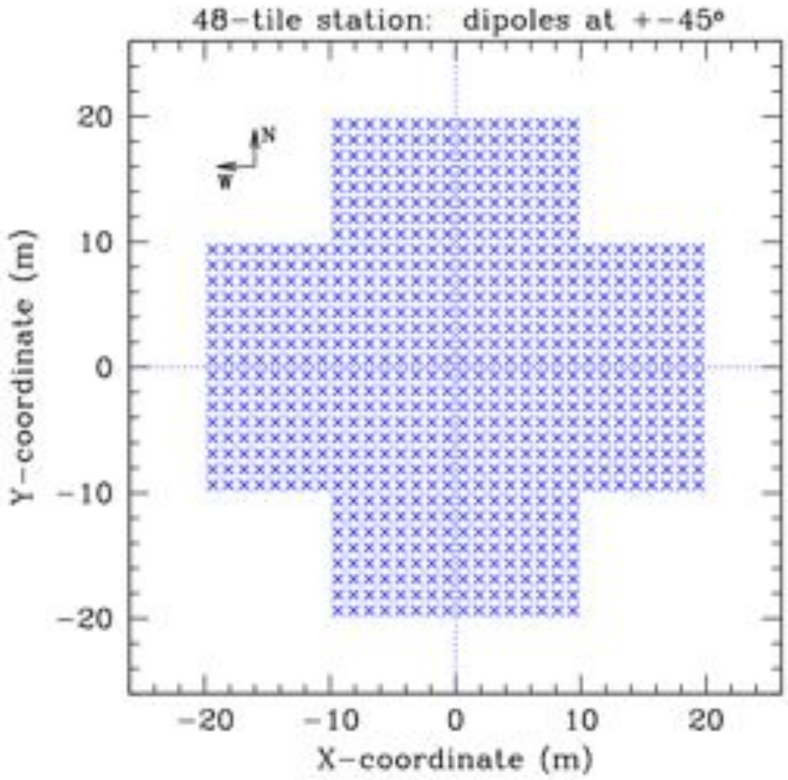




24h-24h difference (LBA)

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





Physical area: 600 m^2

SEFD (150 MHz, zenith) ~ 2600 Jy

Physical area: 1200 m^2

SEFD (150 MHz, zenith) ~ 1300 Jy

Grating lobes (due to 5x5-m tiles) !

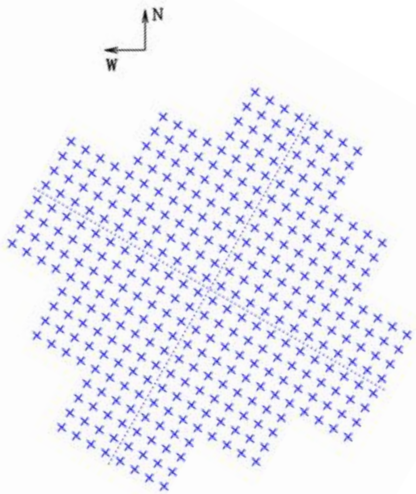
At frequencies > 120 MHz LOFAR tiles produce high-sensitivity grating lobes (on the other side of the sky). This depends on both elevation and observing frequency. The 'beam' then has multiple widely separated areas. This then causes serious contamination of the visibility data. (much like the A-team (CasA, CygA,…) corrupts all LOFAR data)

To combat these we have rotated the stations, and back-rotated the antennas within the tiles ⇒ **all dipoles remain parallel (X)**

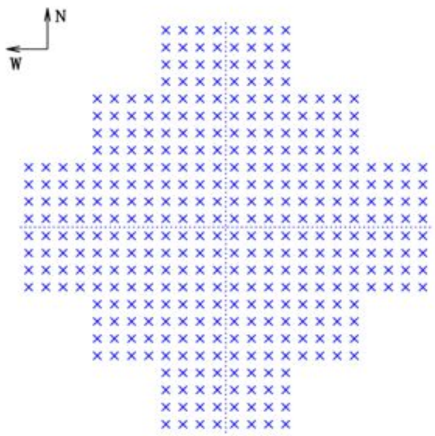
Each station has a unique rotation. The result is that the voltage beam of each station is different and every interferometer has a different view of the sky.

GOOD because interferometric power beam levels at large distance are reduced

BAD because all stations have different beams.

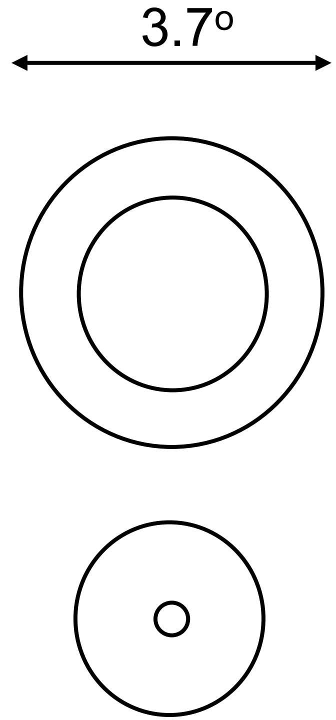


30^{o} rotation



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 - ST288 (65m - 300m)	0.03	2.3x0.5



LOFAR interferometers may have 4 different beam sizes

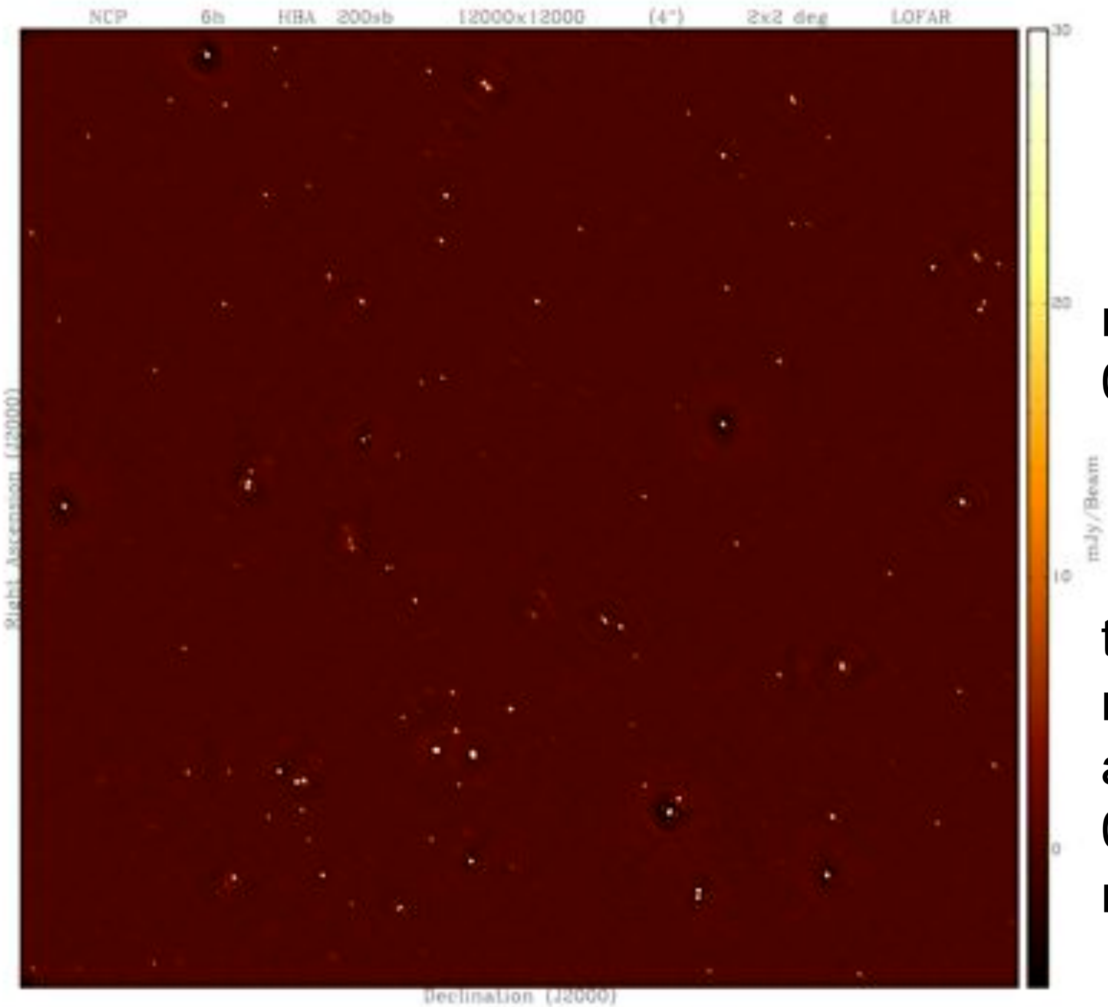
LOFAR: deep NCP imaging (1)

$2^o \times 2^o$

1 x 6h

200 subbands
115-163 MHz

18CS + 7RS

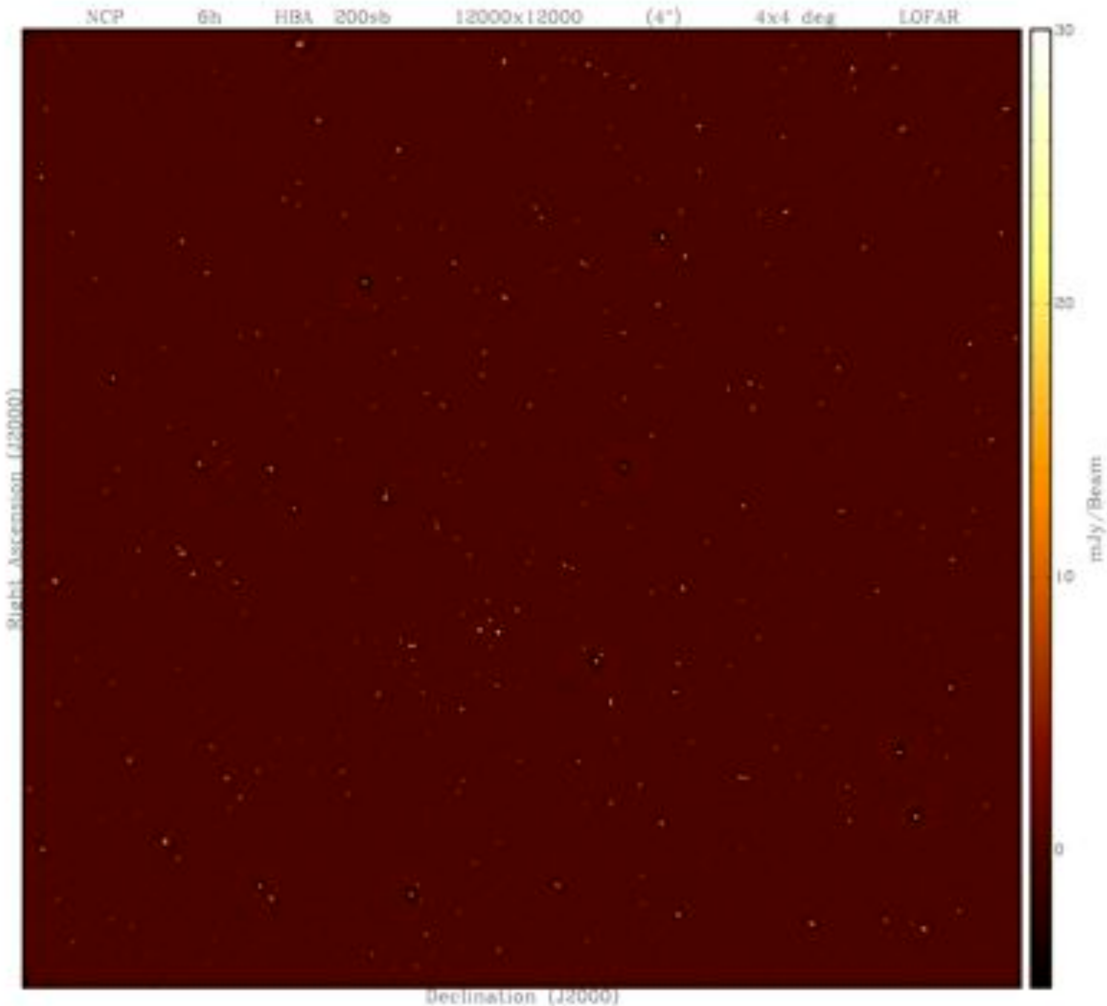


noise level
0.22 mJy

thermal
noise is
about
0.1-0.2
mJy.

LOFAR: deep NCP imaging (2)

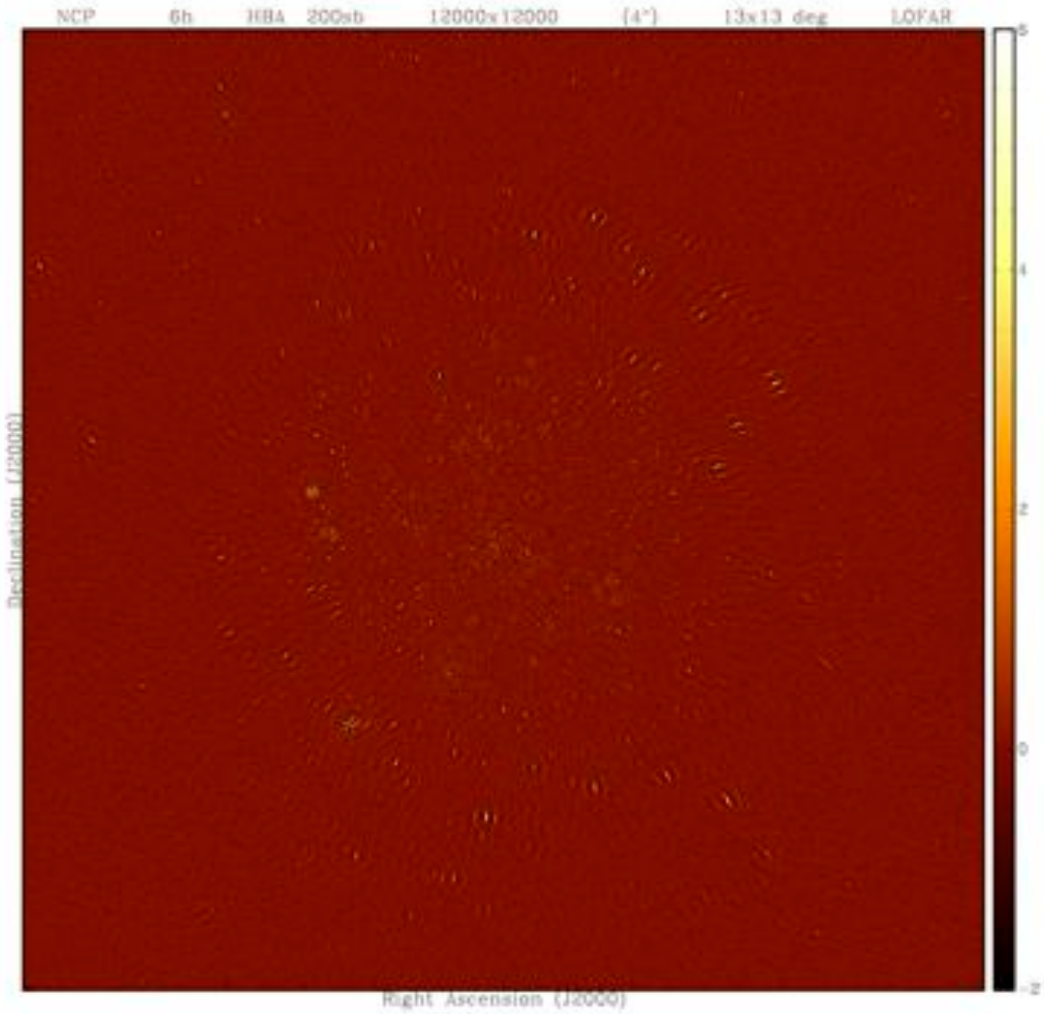
4° x 4°



LOFAR: deep NCP imaging (3)

13^o x 13^o

12k x 12k pixels !



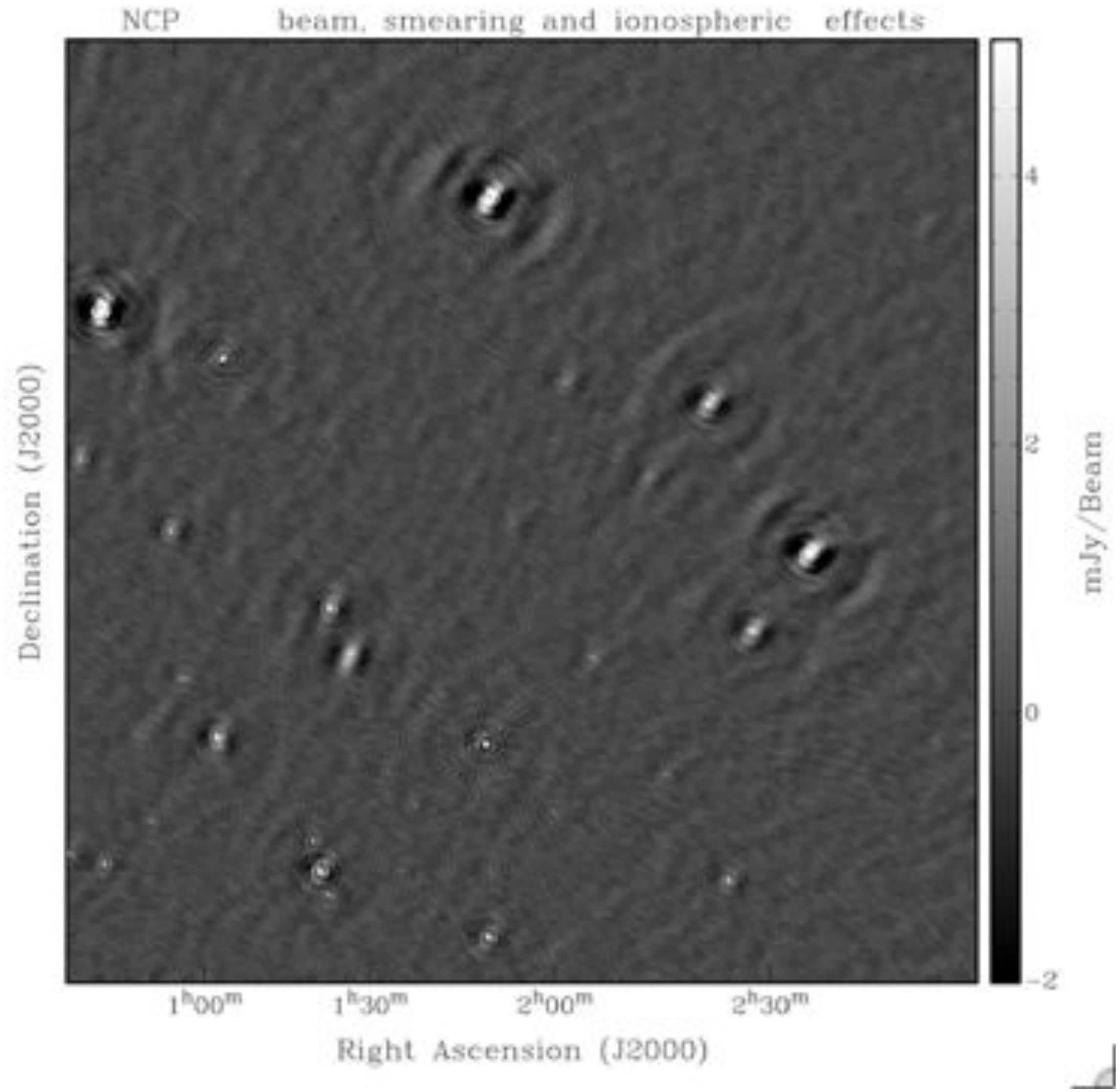
LOFAR: deep NCP imaging (4)

Edge effects:

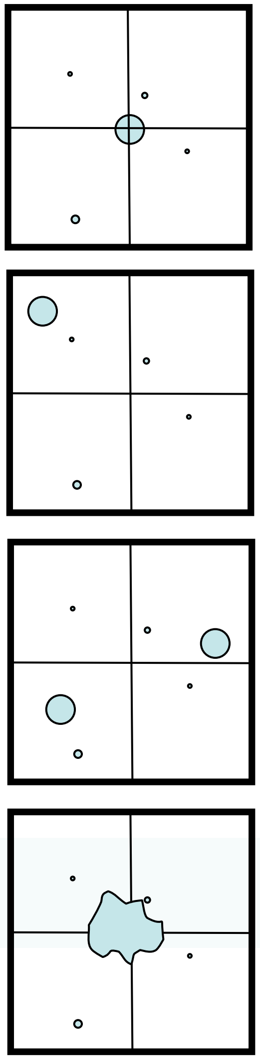
Bandwidth/
delay
smearing

Differential
ionosphere

Beam
variations



Overview of dynamic range issues



(1) on-axis point source

(2) off-axis point source

(3) ≥ two off-axis point sources

(4) extended source

Dynamic Range: DR = peak flux / rms noise

source configurations and causes

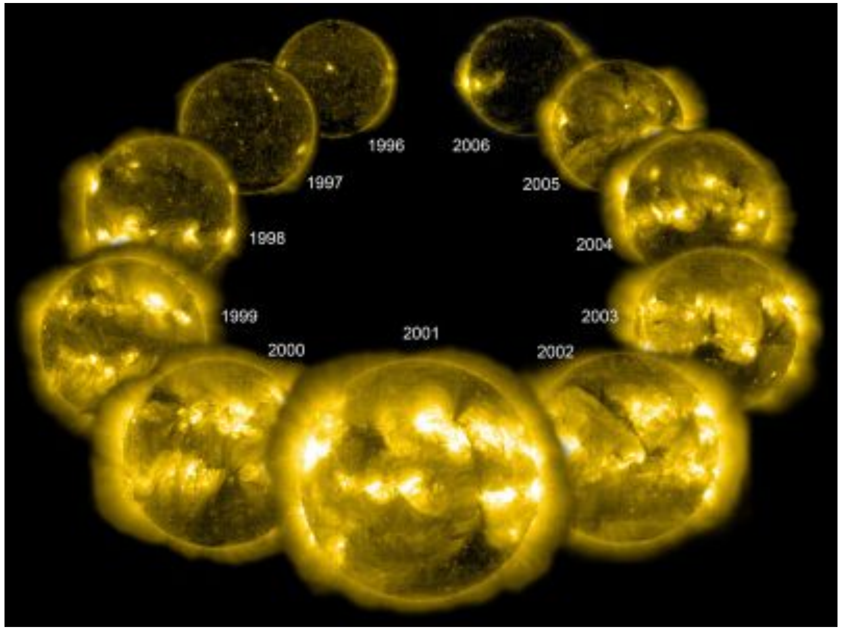
	1	2	3	4
✓ (mechanical) pointing	-	X	X	-
✓ non - isoplanatism (ionosphere)	-	-	X	-
✓ decorrelation (troposphere/ionosphere)	X	X	X	X
✓ closure errors (cross-talk, ...)	X	X	X	X
✓ non-linearity (RFI, ...)	X	X	X	X
✓ ghosts (Gibbs, image rejection..)	-	X	X	X
✓ polarization leakage instability	-	X	X	X
✓ deconvolution limitations	-	-	-	X
✓ variable sources	X	X	X	X
✓ software errors/deficiencies	X	X	X	X

de Bruyn, SKA Calibration meeting, Cape-Town, Dec 2006

The end

LOFAR and the ionosphere

Ionospheric issues



Soho-solarcycle,

APOD 5 dec07

Non-isoplanaticity (low freq, large FOV)

Solar cycle (next maximum ~2012/2013)

Array scale > refractive/diffractive scale

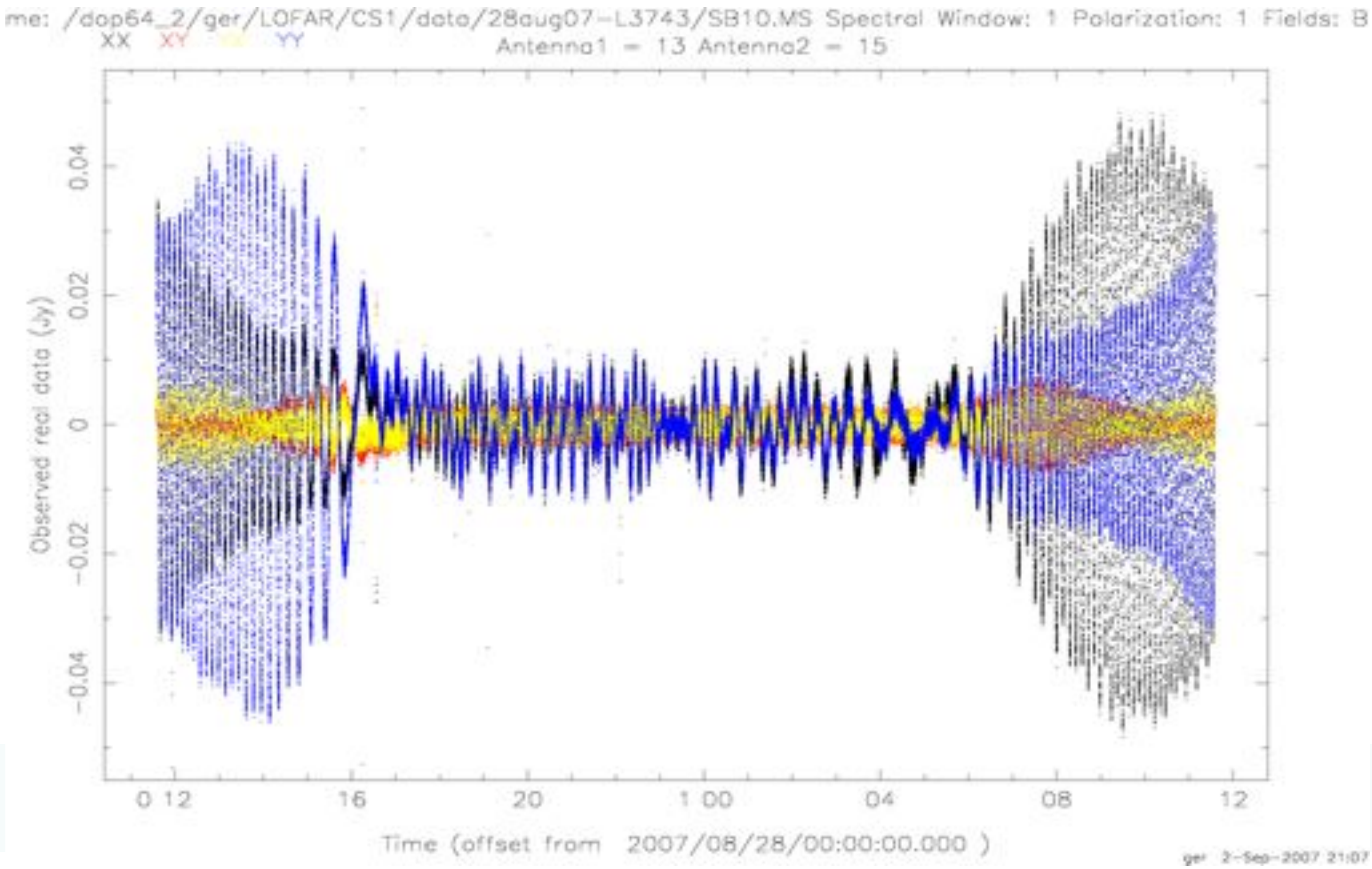
TID's, (Kolmogorov) turbulence

Tools/approaches:

- Bandwidth synthesis (sensitivity, freq-dependence,..)
- Peeling individual sources and screen modelling
- Large scale screen modelling
- GPS-TEC starting model
- Utilize 2-D frozen flow approximation (?)
- 3-D tomography solutions (multiple screens/layers)

The difference between night and day (220 MHz)

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

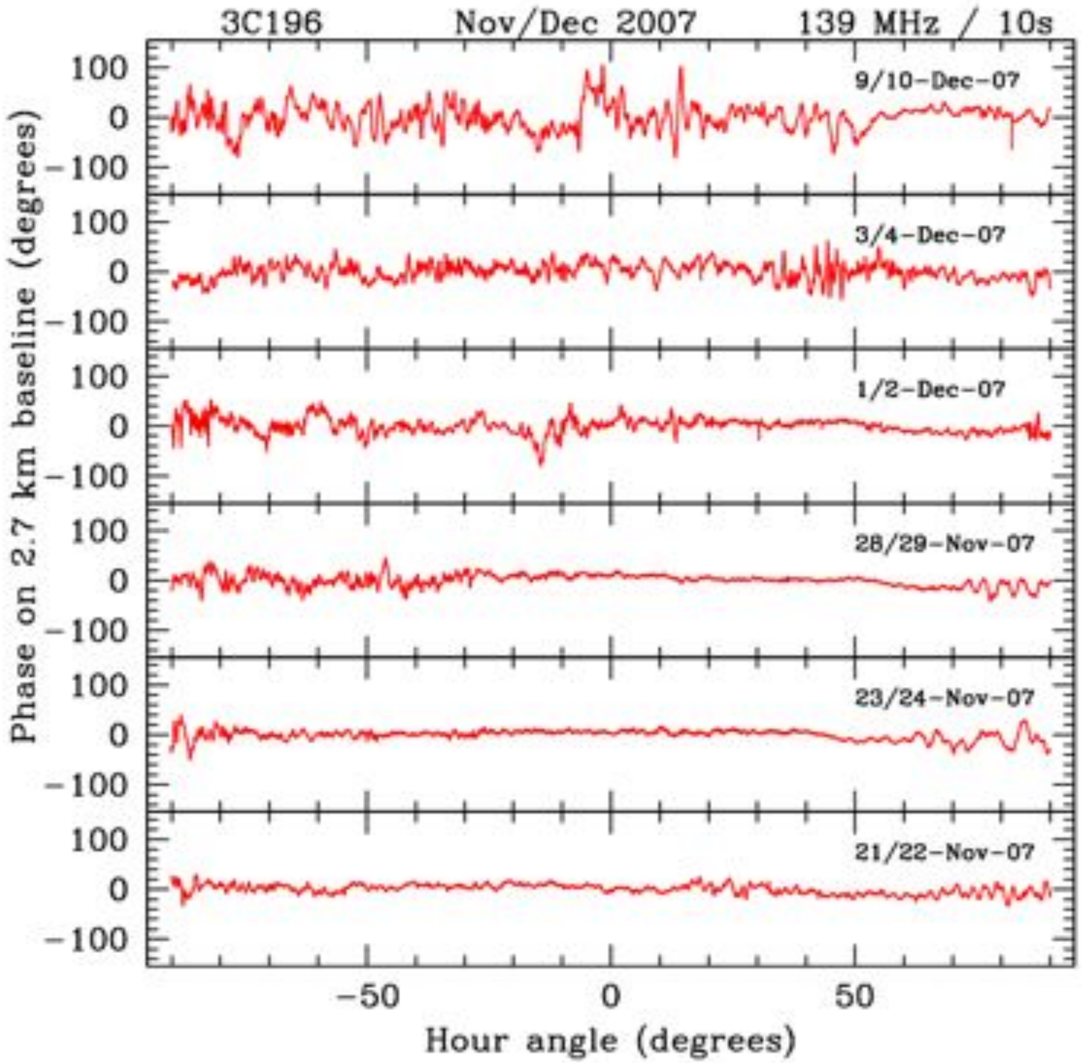


Single dipole
(August 2007)

CS-1

XX XY YX YY

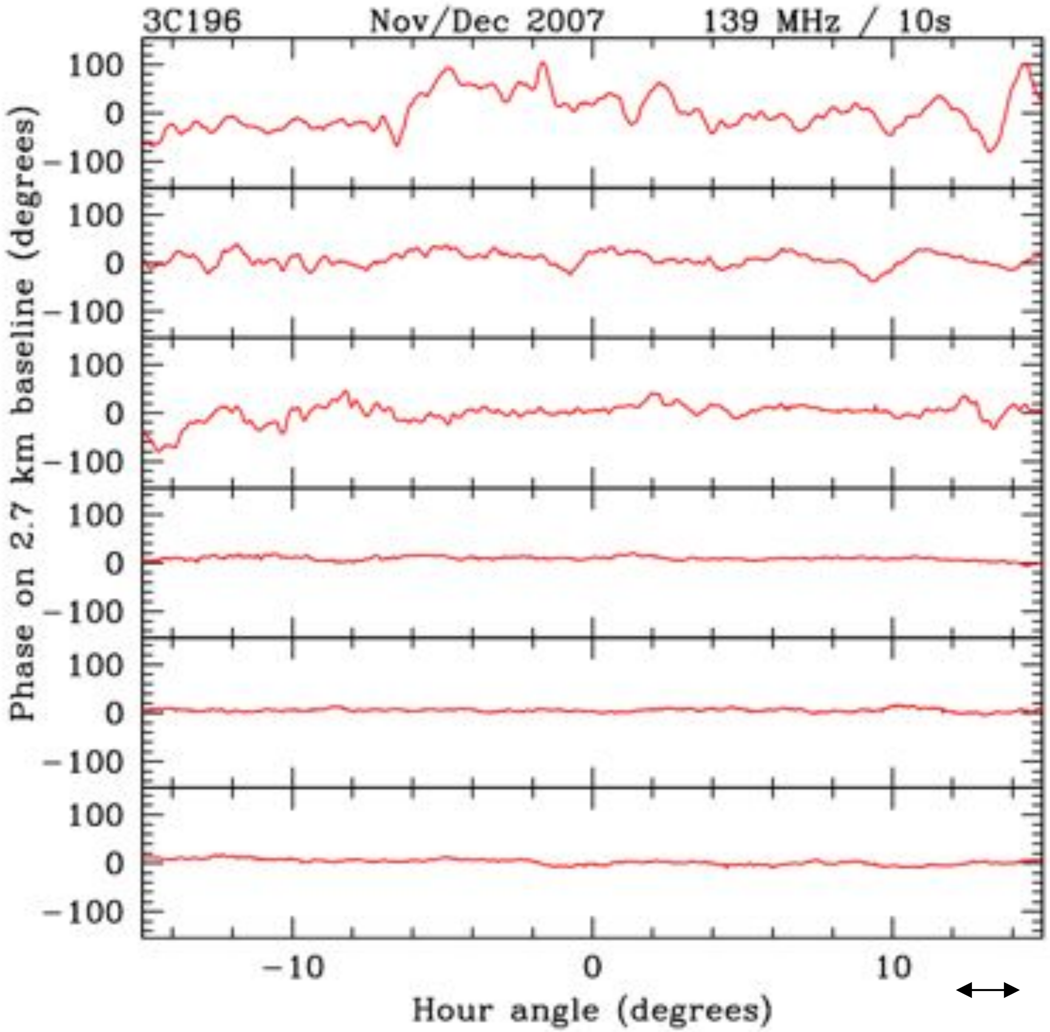
3C196 - selfcal phase solutions



6 x12h in a
3 week period

Note the very
different
ionospheres !

3C196 selfcal phase solutions: zooming in



Note ‘well-resolved’ turbulence/waves

(noise

= line thickness)

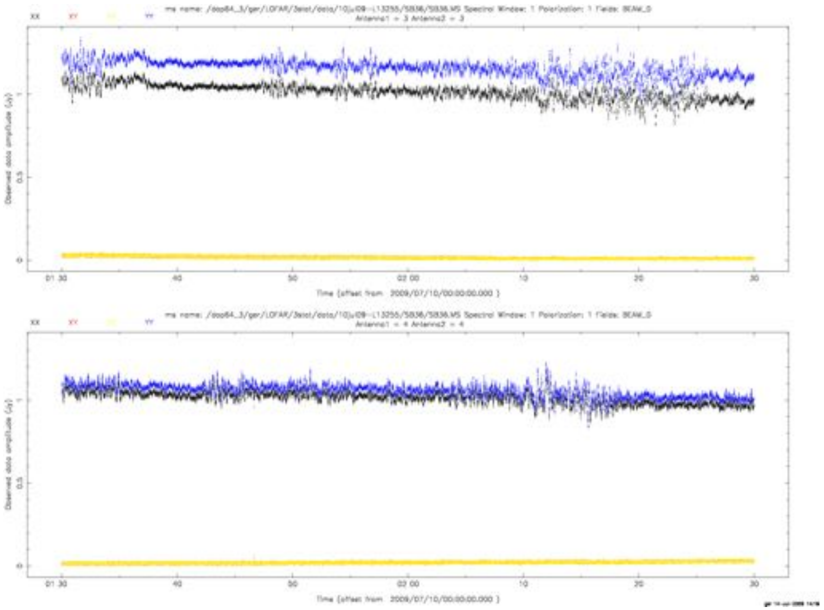
2^o = 8min = 48 samples

Fast total power variations in EoR band: scintillation !

RS307

127 MHz

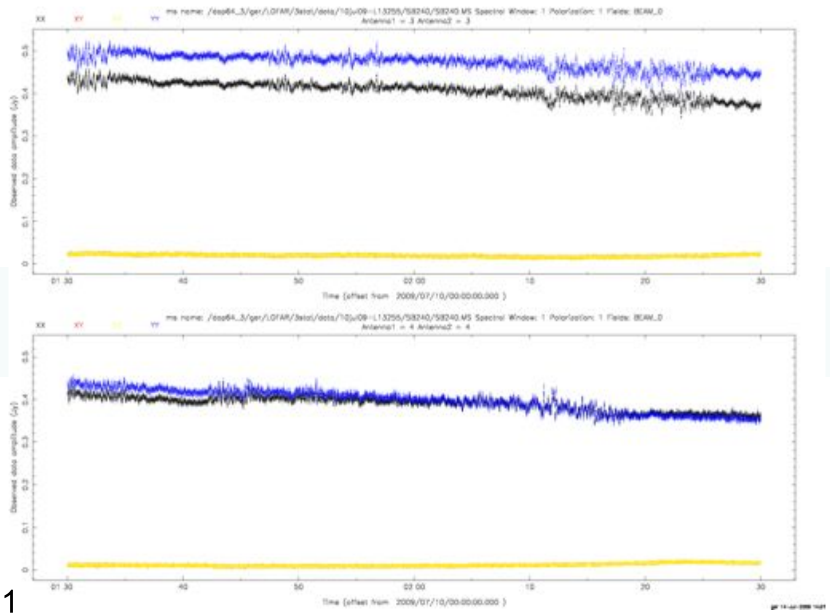
RS503



RS307

168 MHz

RS503



1h of data on CygA

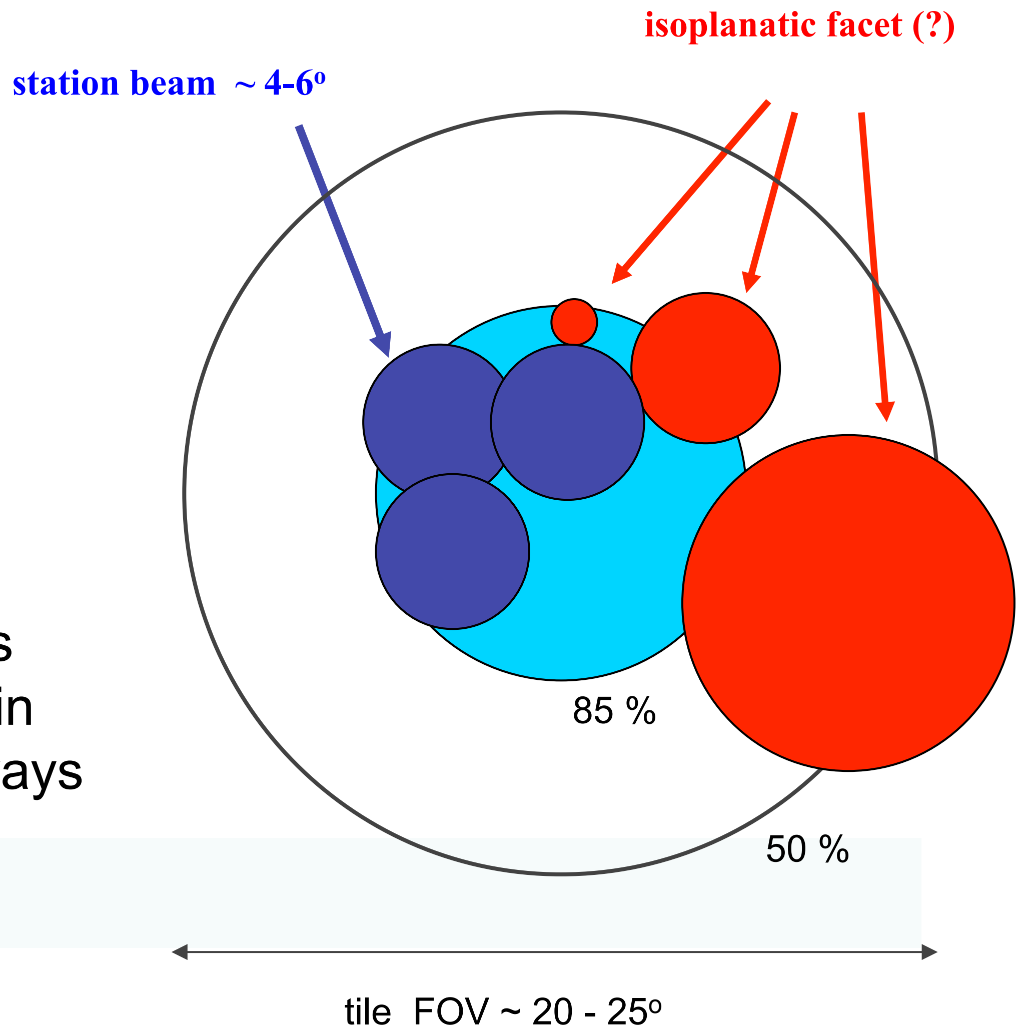
frequent periods of ~10m with +-10% p-p amplitude variations

uncorrelated over 15 km

correlated in frequency, polar.
(stronger at low frequencies)

==> ionospheric scintillation
((de-)focusing)

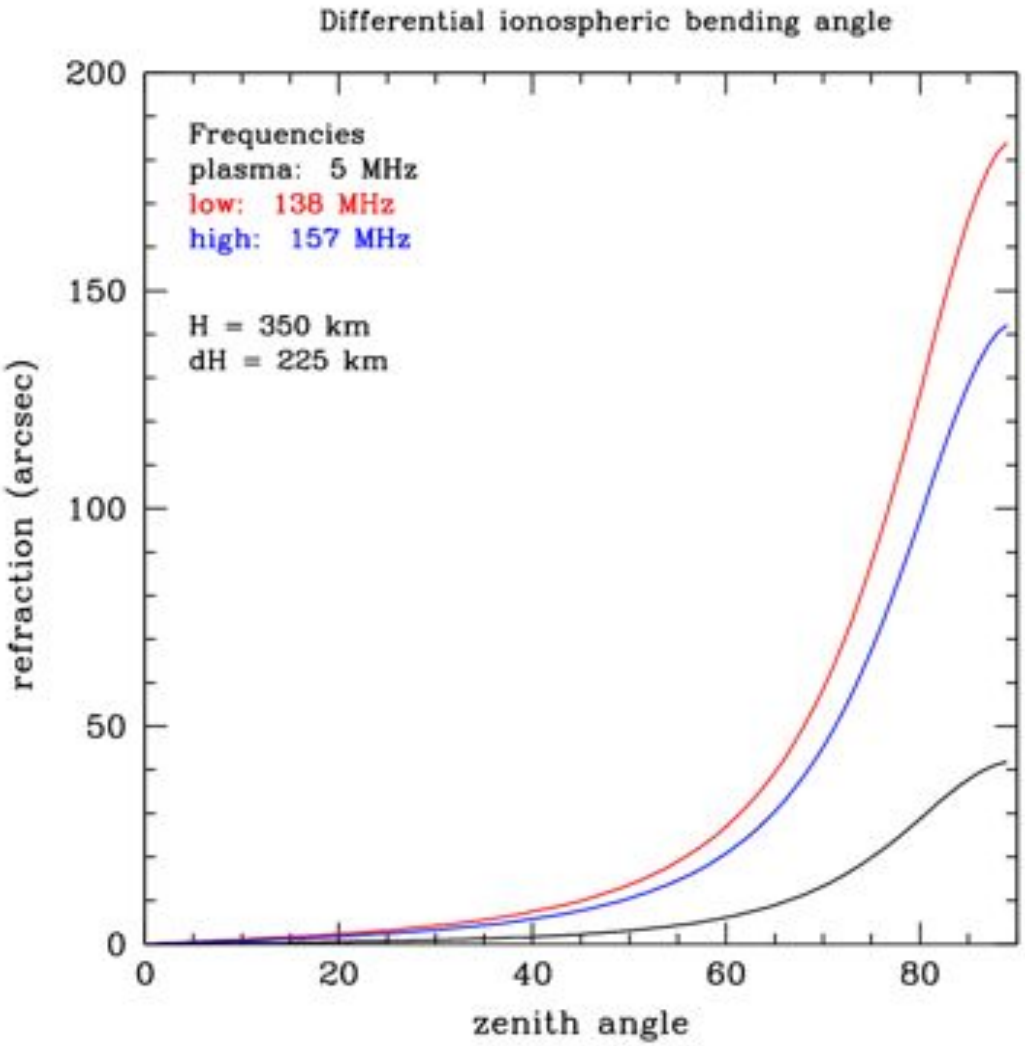
HBA angular scales (24 tiles/station)



Note:

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

Frequency-dependent ionospheric refraction



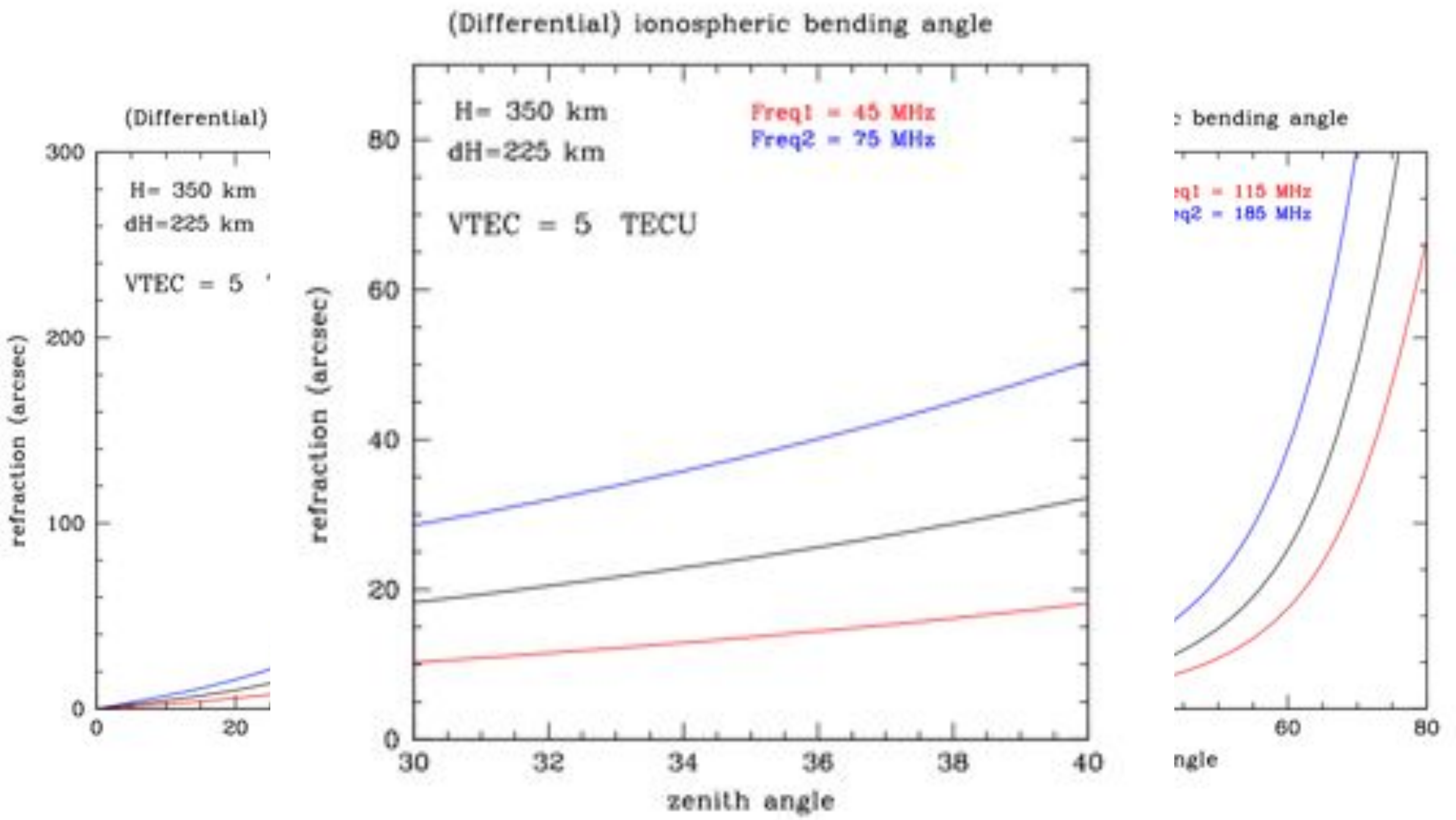
'Linear or quadratic' ?

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

Differential Ionospheric Refraction Monitoring



LOFAR resolution (PSF) at 60 MHz ~ 16” (50km / L)