An introduction to (the) calibration (of LOFAR)

Ger de Bruyn

ASTRON & Kapteyn Institute

The LOFAR observatory

LBA (10) 30 - 90 MHz
isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)

Core	2 km	18+ stations
NL	80 km	18+ stations
Europe	>1000 km	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 4 h, 4 MHz, ~ 50 stations)
@ 60 MHz ~ 3 mJy
@ 150 MHz ~ 0.1 mJy

Outline

— Traditional calibration

— Astrometry, flux scale and dynamic range

— Some lessons from the WSRT, including ionospheric effects

— Calibration at low vs high frequencies: the LOFAR problem

— Software and the Measurement Equation

— LOFAR beams and FOVs

— LOFAR and the Galaxy, day/night - Sun

— LOFAR and the ionosphere

— LOFAR and polarization

— Conclusions + (all the things I did not talk about)

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:

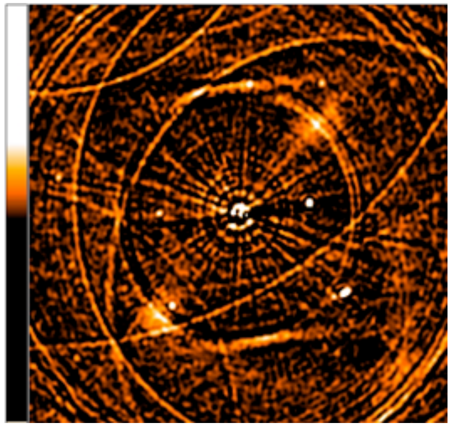
→ good for 1) and 2)

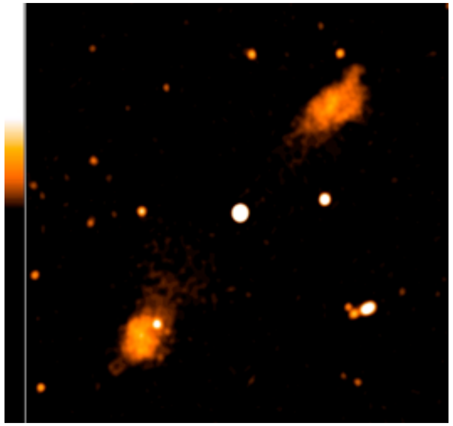
Apply selfcalibration → needed for 3)

Selfcal + deconvolution gets rid of:

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

WSRT 21cm: giant radio galaxy B1245+67





Absolute flux scale: going beyond the A-team

Absolute scale known to a few % .   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).

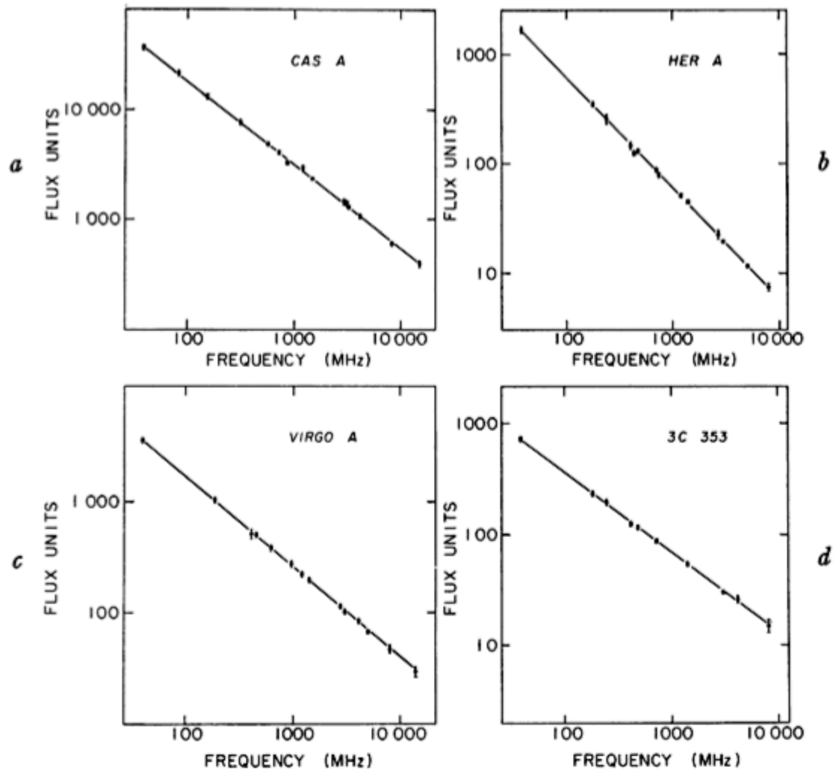


FIG. 1.—Spectra of calibration sources: (a) Cas A (3C 461) based on absolute flux densities corrected to the epoch 1964.4; (b) Her A (3C 348) based on ratios to Cas A; (c) Vir A (3C 274) based on ratios to Cas A; (d) 3C 353 based on ratios to Cas A.

Bright secondary calibrators

HerA = 3C348

2' double

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

3C353

5' double

Astrometry

Absolute astrometry is very hard at low frequencies because of the refraction due to the ionosphere. So we will most likely do only relative astrometry with LOFAR.

In the absence of a global ionospheric phase screen model we have to do that within the isoplanatic patch, an angle which can be rather small (0.1 -1°)

Two applications for relative astrometry:

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

Both require a very dense network of stable position calibrators.
We need to know source centroids. Need not be the same at all frequencies !
Important commissioning task for (European–scale) LOFAR !

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

Dynamic Range

Image DR: peak / off-source rms.

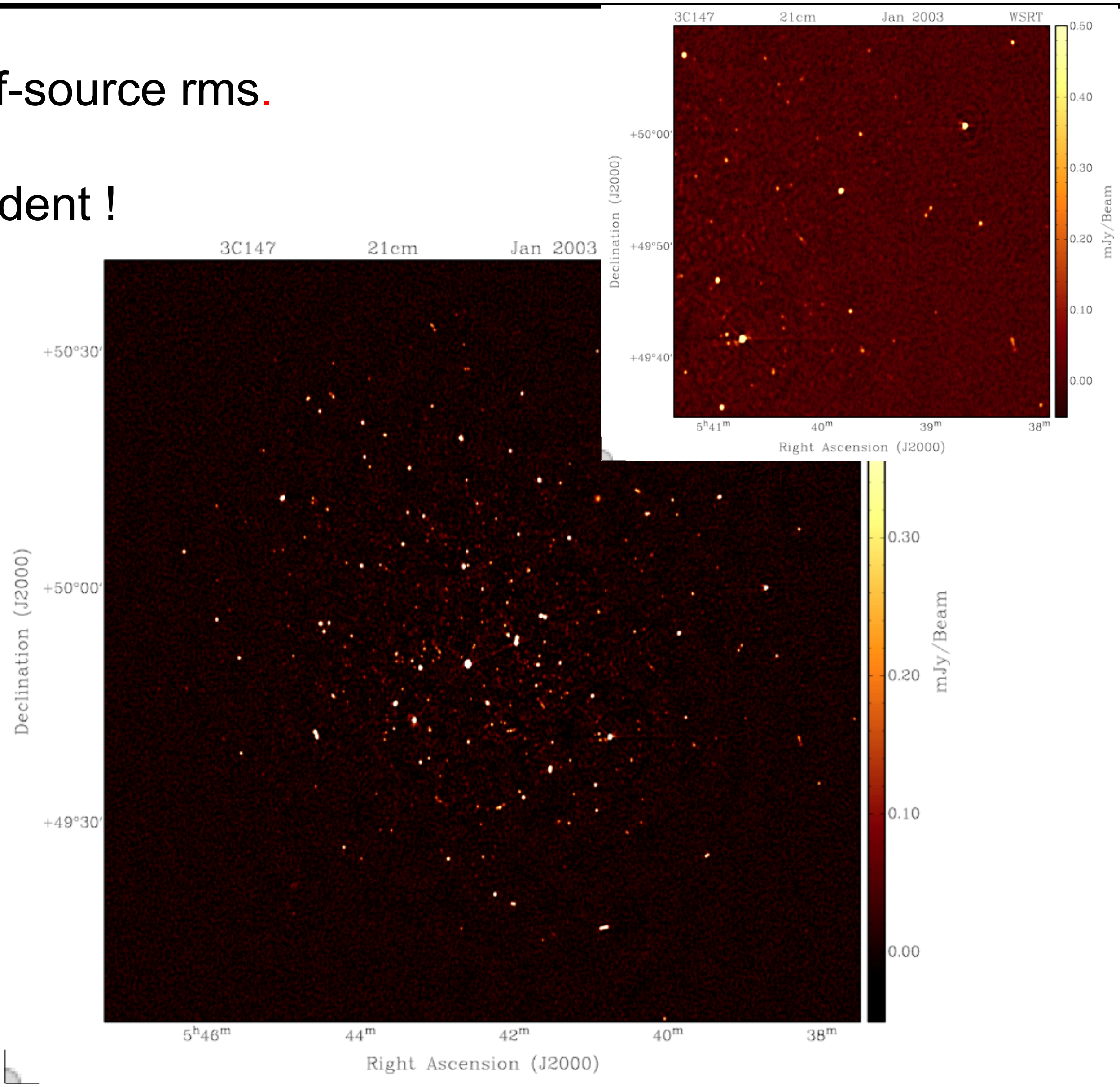
DR is position dependent !

WSRT
3C147
21cm

22 Jy /15 µJy

DR=1,500,000:1

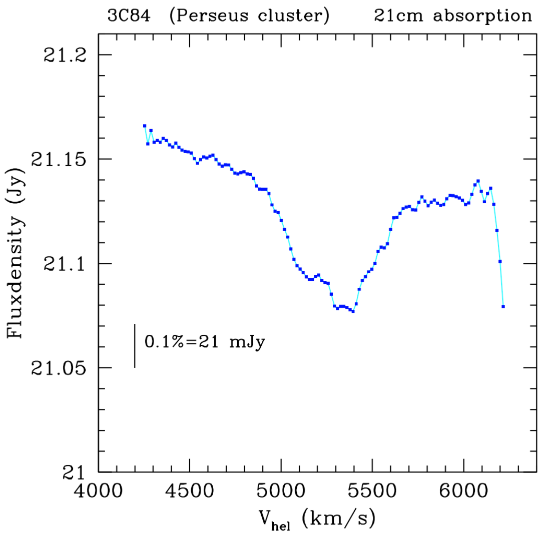
On-axis versus
off-axis makes a
major difference !



Dynamic Range

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

5,000:1 is very good !



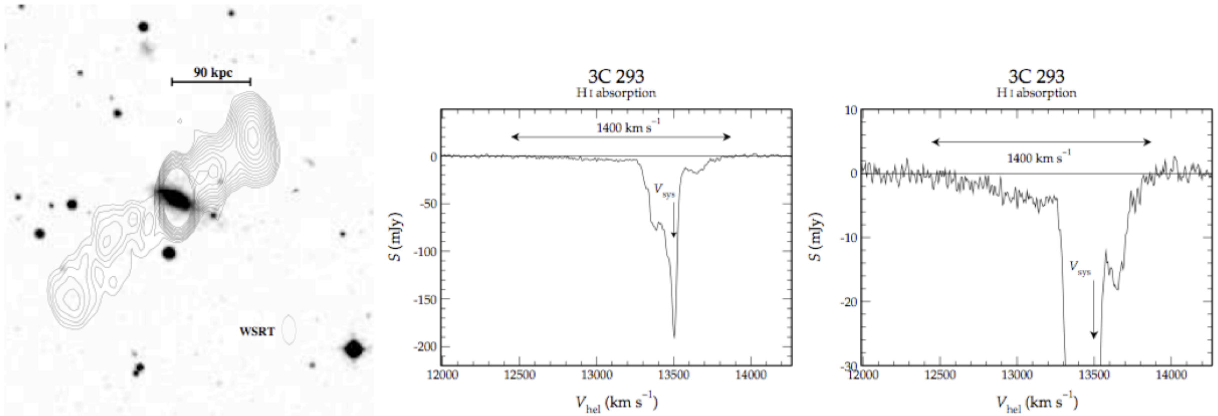


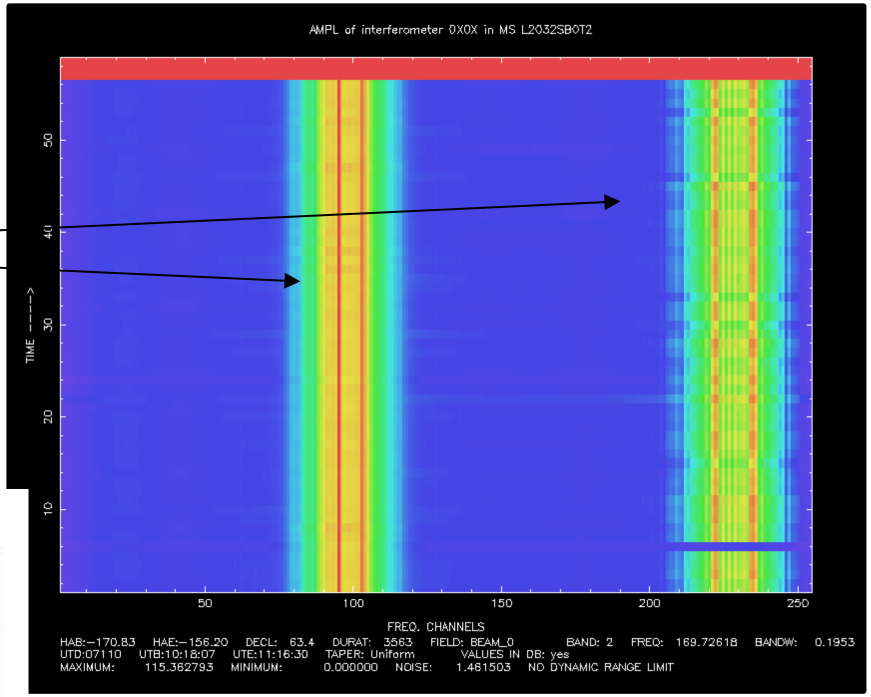
Fig. 1.— *(Left)* Continuum image of 3C 293 at the resolution of WSRT 21-cm observations (Emonts et al. in prep). *(Middle)* The H I absorption spectra with a zoom-in (*Right*) to better show the new detected broad H I absorption. The spectra are plotted in flux (mJy) against optical heliocentric velocity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

Very strong RFI in HBA (requires 12 bit ADC!)

Another important instrumental ‘dynamic range’

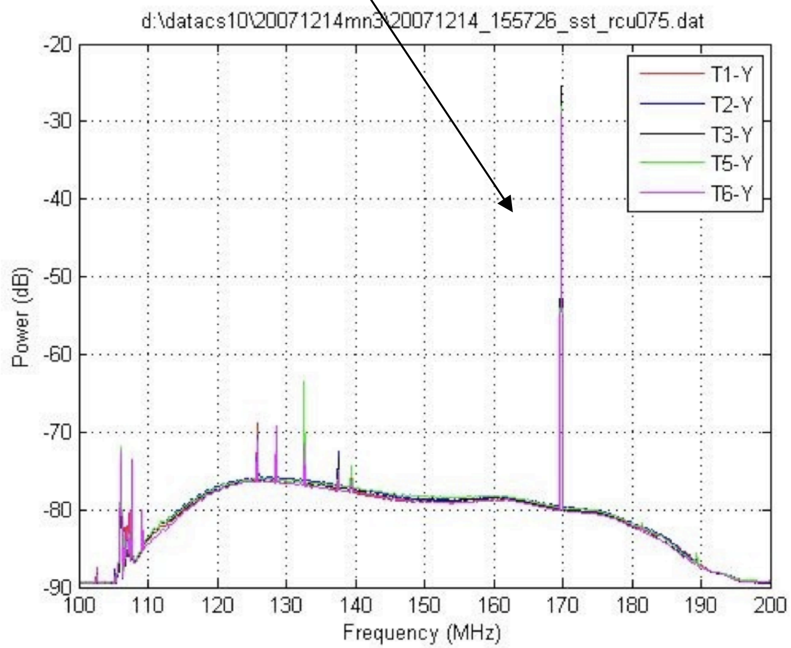
Dynamic spectrum at 1kHz and 60^s showing a 80 dB range (= 20^{mag})

Pagers at 169.75 & 169.85 MHz



1^h

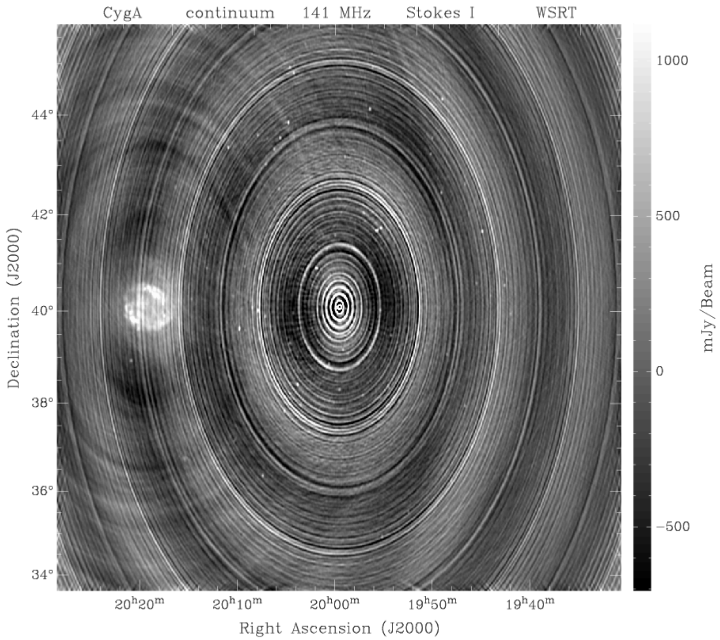
256 channels over 156 kHz



100 - 200 MHz spectrum of a LOFAR HBA dipole (195 kHz resolution)

Very bright extended sources: deconvolution limited DR

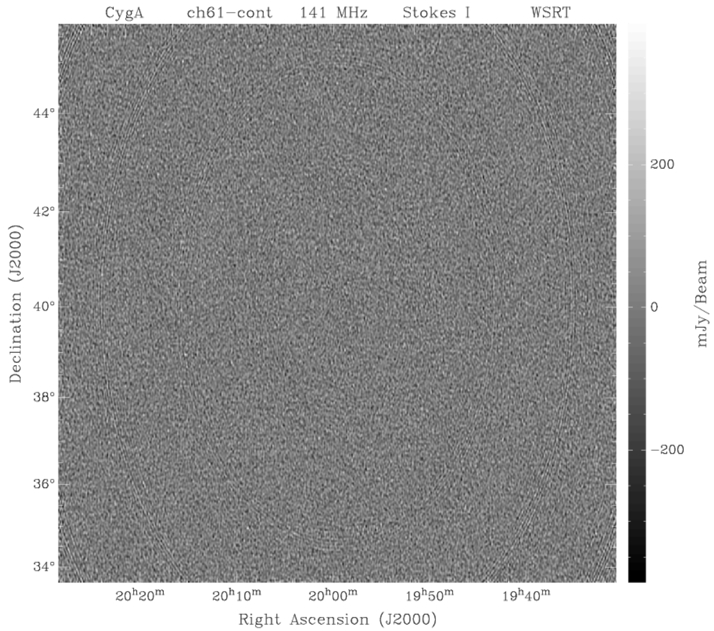
‘CONTINUUM’ (B=0.5 MHz)



(Original) peak: 11000 Jy

Dynamic Range ~ 5000:1

‘LINE’ CHANNEL (10 kHz) - CONT

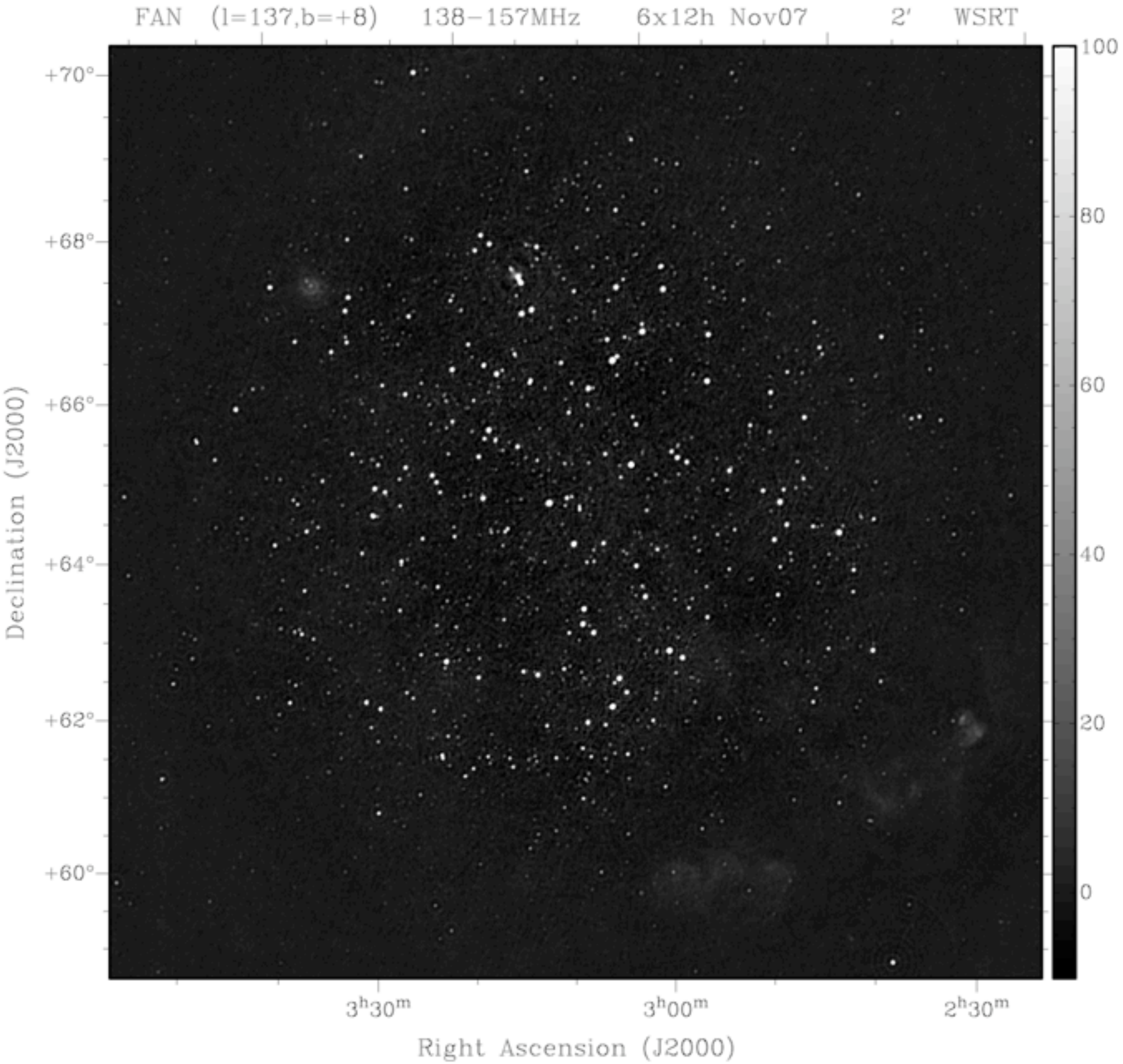


noise 70 mJy

vs   ~150,000 : 1   !!

Lesson: your data may be better than you think !

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



range

-10,100 mJy

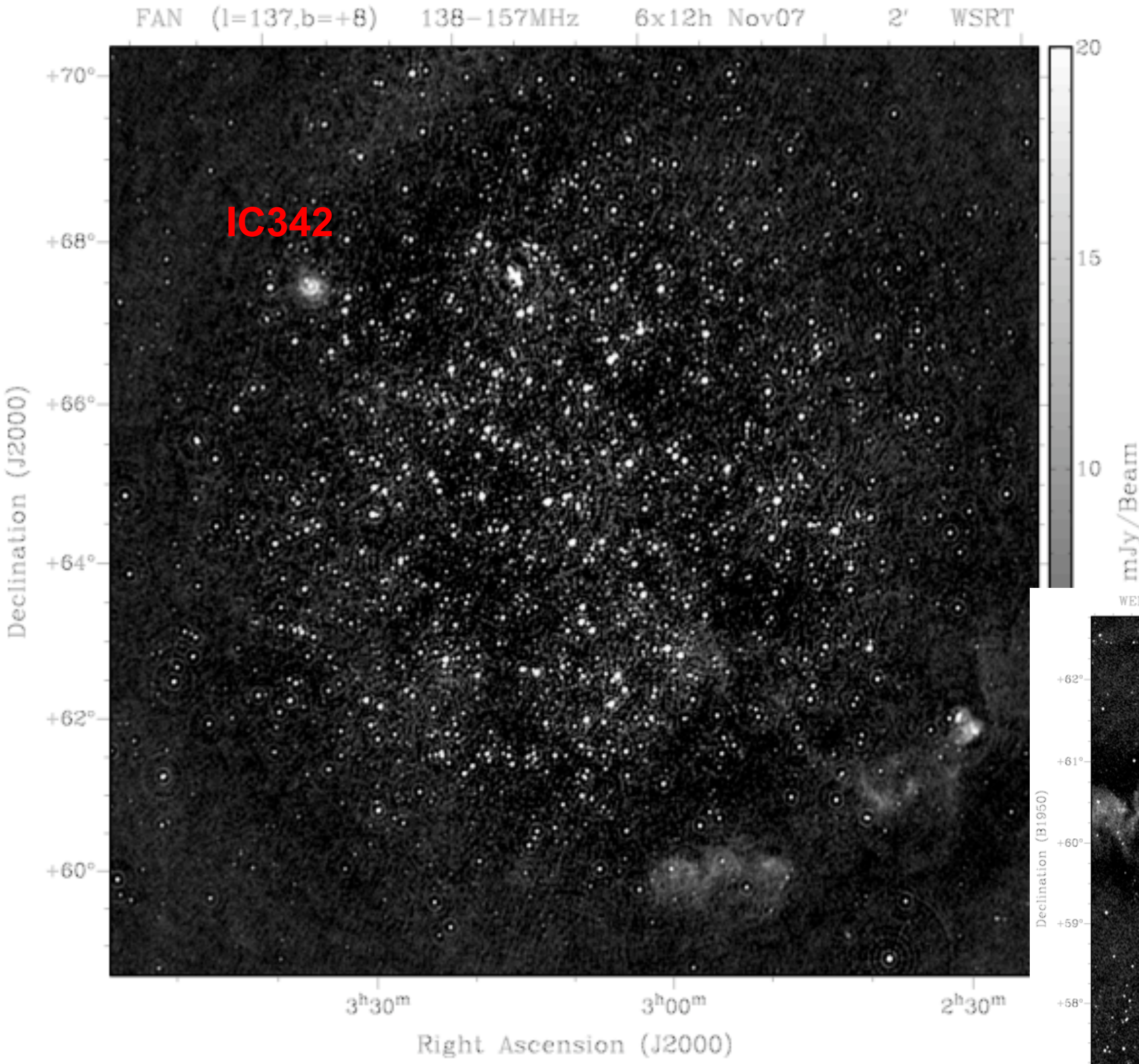
Peak ~ 3 Jy ,

Noise ~ 0.6 mJy

DR ~ 5,000: 1

Bernardi et al (2009)

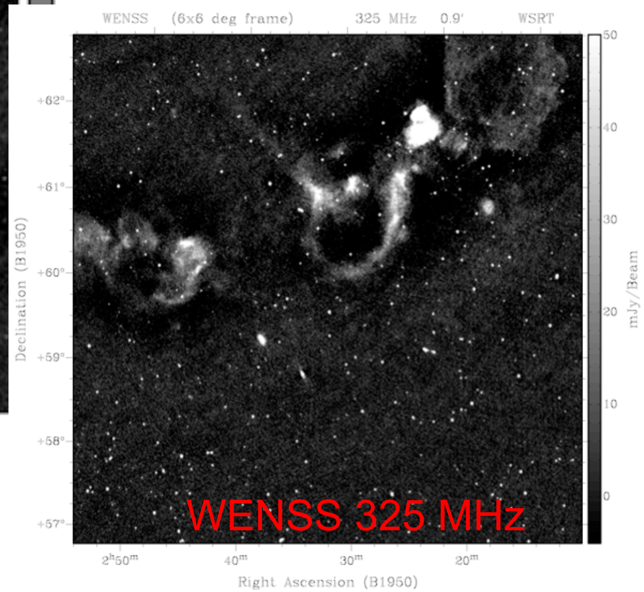
Confusion noise
~ 3 mJy (for 2' PSF)



range

-2, 20 mJy

~ 10° from Galactic plane



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

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

Several new aspects compared to 'standard' calibration and selfcal:

- Major direction dependent corrections
  - Phase => 'non-isoplanaticity' of the ionosphere (low freq, wide FOV)
  - Gain => elevation/azimuth dependent beamshape
  - ⇒ image-plane (as opposed to uv-plane) correction solving required !

- 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

The Measurement Equation (1)

The famous van Cittert-Zernike relation connects the (scalar) sky brightness distribution B(l,m) and the (scalar) visibility function R(u,v). This is slowly but steadily being recast in a modern form which is due to Hamaker et al (1996) and LOFAR calibration could not do without it.

The need for a modern matrix notation has come about because of:

1) The need to include a ***full polarization treatment*** of the ***vector signal***

2) The complexity of the polarized instrumental effects in the signal chain

The matrix notation, which is also conveniently compact, requires some conventions:

1) The electro-magnetic field is described as a vector with field components in a pair of orthogonal Cartesian coordinates x and y:

$$\mathbf{e} = \begin{bmatrix} e_x \\ e_y \end{bmatrix}$$

2) The voltages recorded at the ***antennas p and q*** are then defined as

$$\boldsymbol{v}_p = \boldsymbol{J}_p\, \boldsymbol{e} \quad \text{and} \quad \boldsymbol{v}_q = \boldsymbol{J}_q\, \boldsymbol{e}$$

where $\boldsymbol{J}_p$ and $\boldsymbol{J}_q$ are 2x2 Jones matrices converting the input signals to voltages. Note that each antenna has two, often orthogonal, dipoles.

The Measurement Equation (2)

The source intensity B($\boldsymbol{r}$) can be expressed in the Stokes parameters I, Q, U, and V

$$\mathbf{B}(\mathbf{r}) = \begin{bmatrix} I+Q & U-iV \\ U+iV & I-Q \end{bmatrix} = \begin{bmatrix} b_{xx}(\mathbf{r}) & b_{xy}(\mathbf{r}) \\ b_{yx}(\mathbf{r}) & b_{yy}(\mathbf{r}) \end{bmatrix}$$

and the b_{xx}, b_{xy}, b_{yx},b_{yy} are the intensities as a function of spatial coordinate vector $\boldsymbol{r}$ for directions x and y (where in this definition x is oriented E-W and y is oriented N-S).

The <time-averaged> correlation (=coherence) between the voltages $\boldsymbol{V_p}$ and $\boldsymbol{V_q}$, where p and q represent different antennas, is given by:

$$\boldsymbol{V_{pq} = \langle (J_p e)\ (J_q e)^\dagger \rangle = J_p \langle e\, e^\dagger \rangle J^\dagger_q}$$

The relation between the (observed) coherency $\boldsymbol{V_{pq}}$ and the source coherency $\boldsymbol{B}$ thus becomes:

$$\boldsymbol{V_{pq} = J_p\, B\, J^\dagger_q}$$

This simple equation is known as the Measurement Equation. It relates the source coherency to the observed coherences through the action of Jones matrices. When written out in detail it looks like:

$$\begin{bmatrix} XX & XY \\ YX & YY \end{bmatrix} = \begin{bmatrix} j_{xx(p)} & j_{xy(p)} \\ j_{yx(p)} & j_{yy(p)} \end{bmatrix} 0.5 \begin{bmatrix} I+Q & U-iV \\ U+iV & I-Q \end{bmatrix} \begin{bmatrix} j^*_{xx(q)} & j^*_{yx(q)} \\ j^*_{xy(q)} & j^*_{yy(q)} \end{bmatrix}$$

Multiple Jones matrices

There are many effects on the signal when it propagates from source to correlator.

There are ionospheric effects (refraction, Faraday rotation), beam-effects, instrumental polarization, (frequency)bandpass effects, parallactic rotation,…..

Each of these effects can be described by a separate Jones matrix.

The Measurement Equation can then be written as:

$$V_{pq} = J_{pn} \dots J_{p2}\, J_{p1}\, B\, J^{\dagger}_{q1}\, J^{\dagger}_{q2} \dots J^{\dagger}_{qn}$$

The order in which most of these Jones matrices appear is important !

Jones matrices have a very simple appearance. The letter used are often chosen to confirm to certain conventions used in data calibration packages: e.g. G for Gain, B for Bandpass, D for Polarization leakage, E for beam, F for Faraday rotation etc. You will come across them when you reduce data in BBS and CASA which are modern packages for reducing synthesis data and use the ME

Examples of 2x2 (Jones) matrices are.

$$\mathbf{G} = \begin{bmatrix} G_x & 0 \\ 0 & G_y \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} B_x & 0 \\ 0 & B_y \end{bmatrix} \qquad \mathbf{Rot}(\phi) = \begin{bmatrix} cos(\phi) & -sin(\phi) \\ sin(\phi) & cos(\phi) \end{bmatrix}$$

Calibration issues: a conceptual overview:

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

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

Calibration is the process that solves for all stable, but most importantly, the time varying parameters

Qualitatively our knowledge will steadily increase

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

For LOFAR, with all its novel and 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

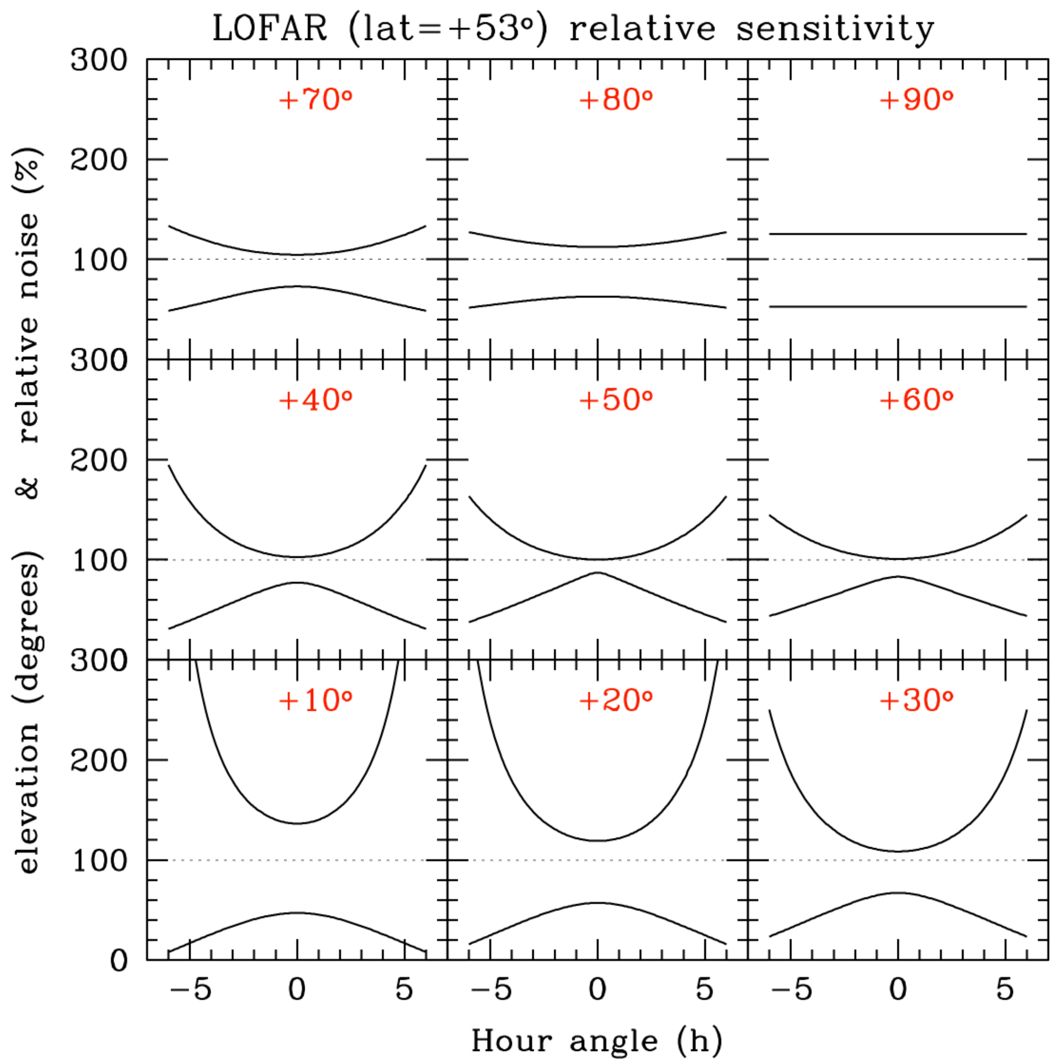
— BBS will be implementing efficiently what we have learned

— and we now 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.

LOFAR sensitivity varies with time!

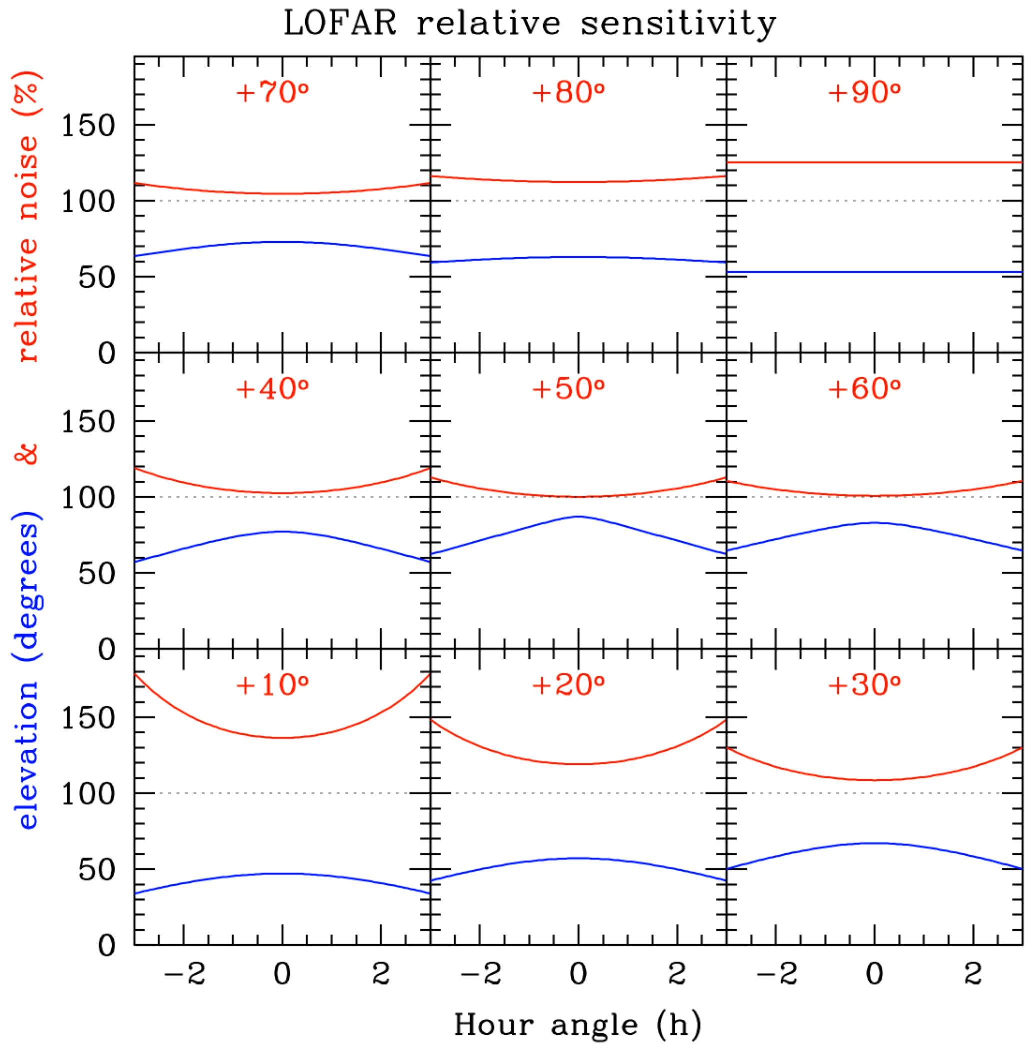
Elevation and sensitivity as function of (Dec,HA)



NCP-3C61.1
Dec=+86°

3C196
Dec=+48°

Elevation and sensitivity as function of (Dec,HA)



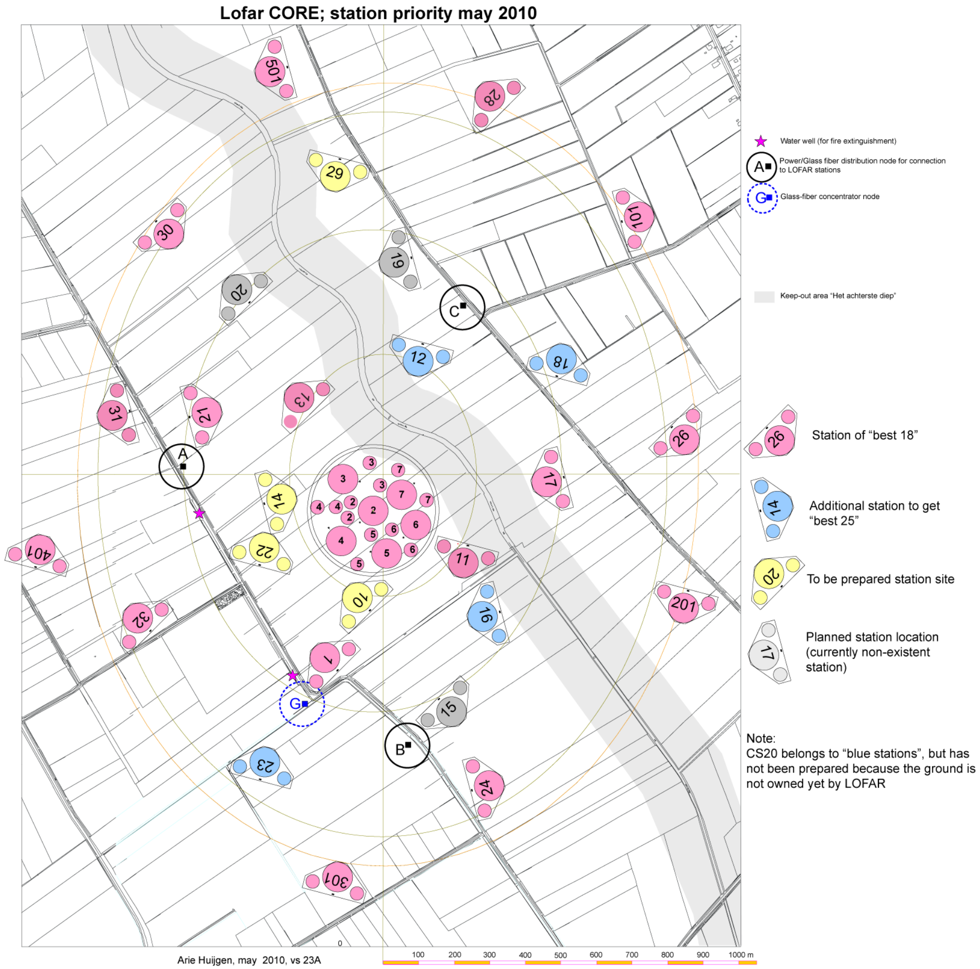
NCP - 3C61.1
Dec=+86°

3C196
Dec=+48°

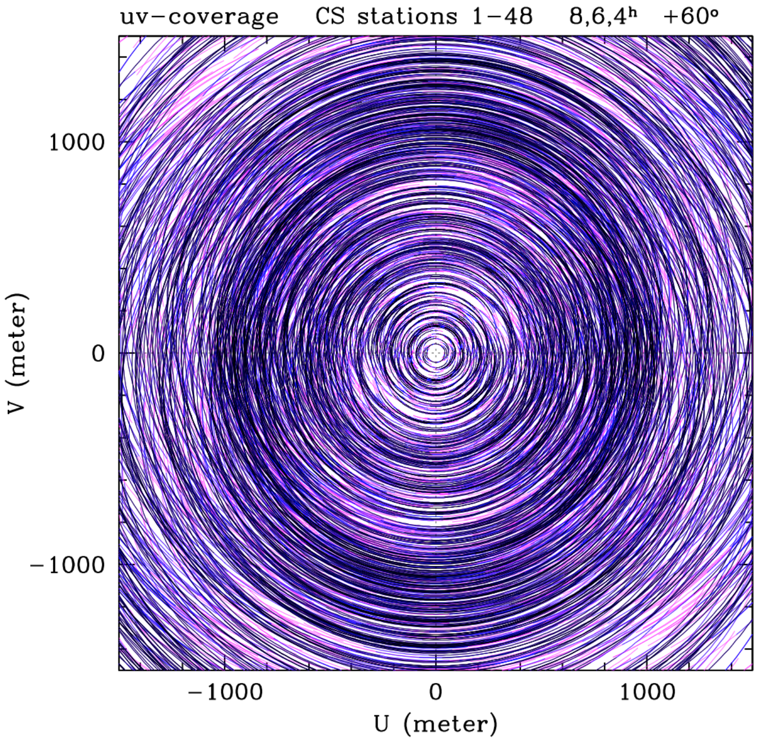
LOFAR core array (Sep 2010)

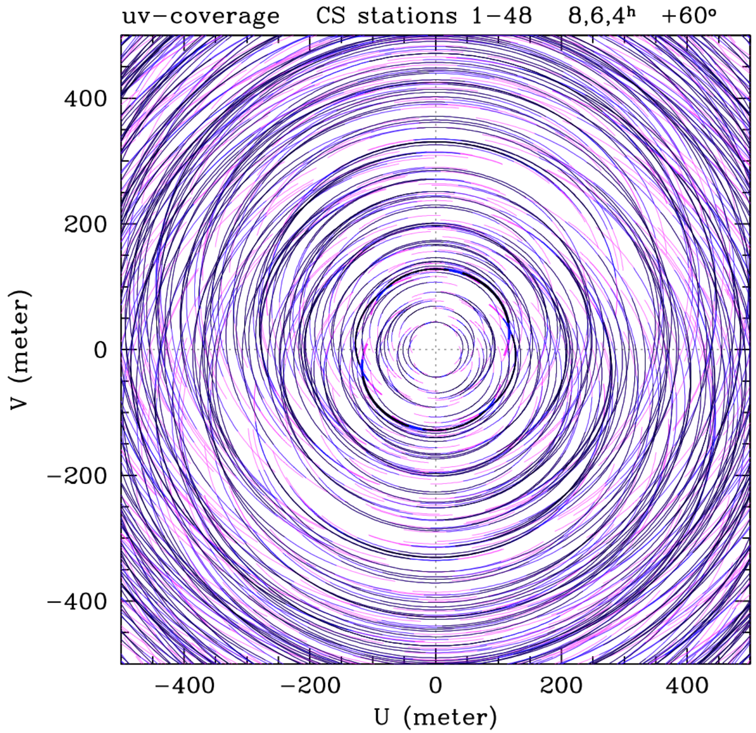
LBA: 24 stations

HBA: 24x2 stations

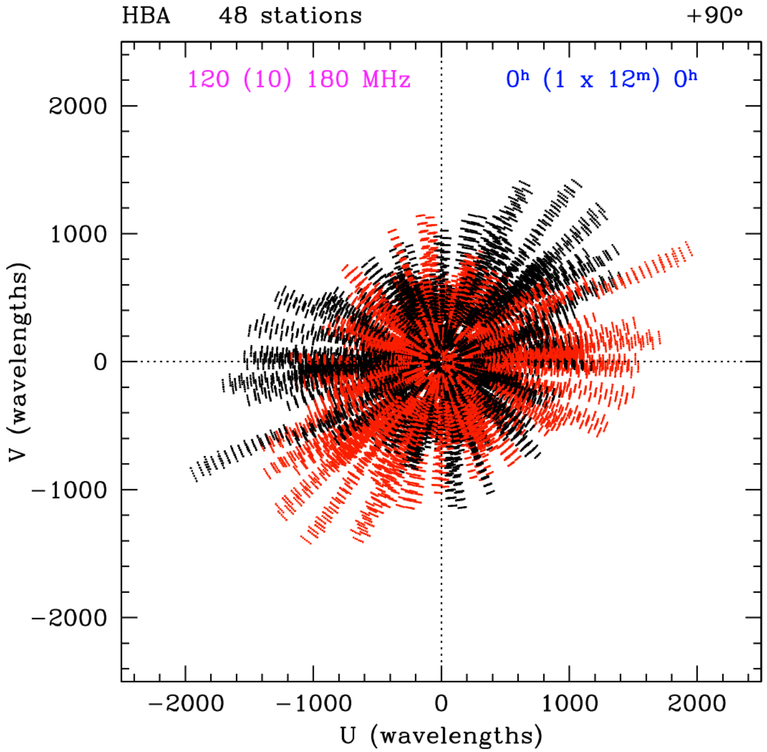


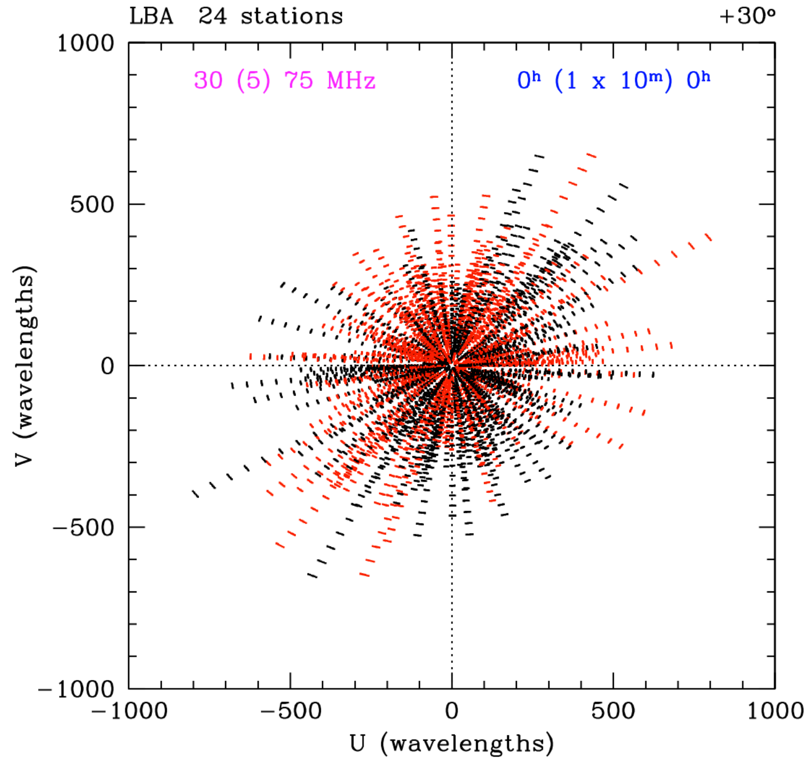
Full synthesis HBA uv-coverages in the core





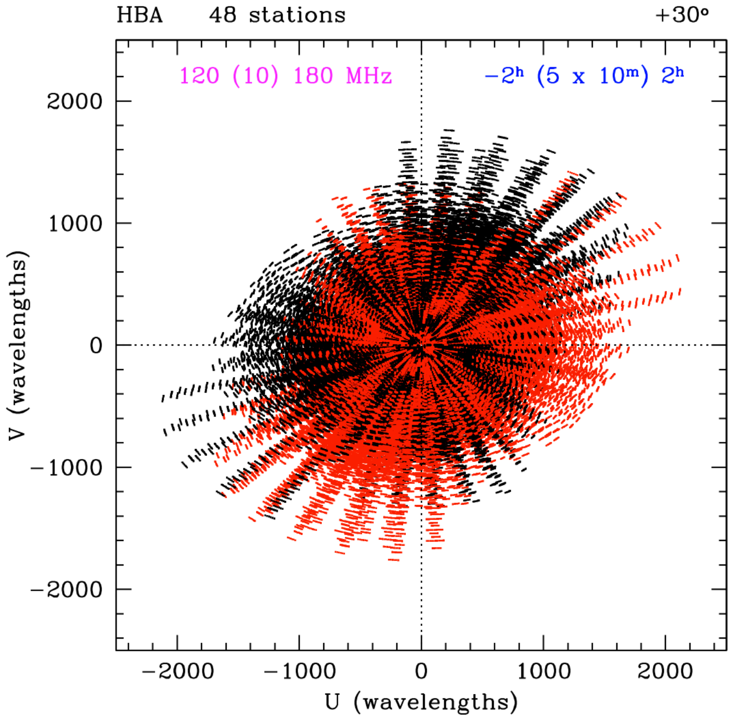
Snapshot UV-coverages in the core

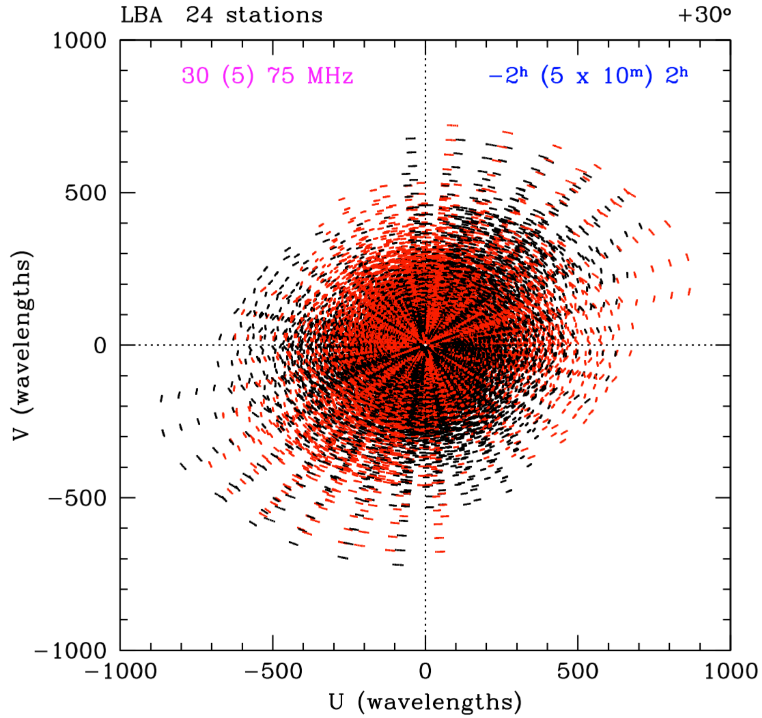




With such a good snapshot coverage the problems of imaging can be reduced. Process each observation, which has a different beam, separately and combine them later.

UV-coverages with 5 x 10m cuts and BWS





A calibration strategy once full core available

The following approach, which could become the MSSS mode of processing, is recommended on weak source fields (< 5 - 10 Jy peak in HBA)

- Calibrate on a bright dominant source and solve for clocks
- Transfer calibration per subband, or interpolate, to target field

- Then inspect data quality, noise, consistency of HBA0/HBA1, X and Y
- Flag bad stations/baselines

- Make snapshot image (within ~15m from the calibrator), create a model

- Solve for clock drifts which become important after >15m
- Combine multiple bands (BBS-global) to improve solutions etc
- Iterate

- Start with core stations (<3 km baselines) and work from inside → out
- i.e. get a proper low resolution LSM with all the flux contained in the FOV

- Process 5-15m snapshots individually and combine beam-corrected images
- Then bring in remote stations which involve longer baselines

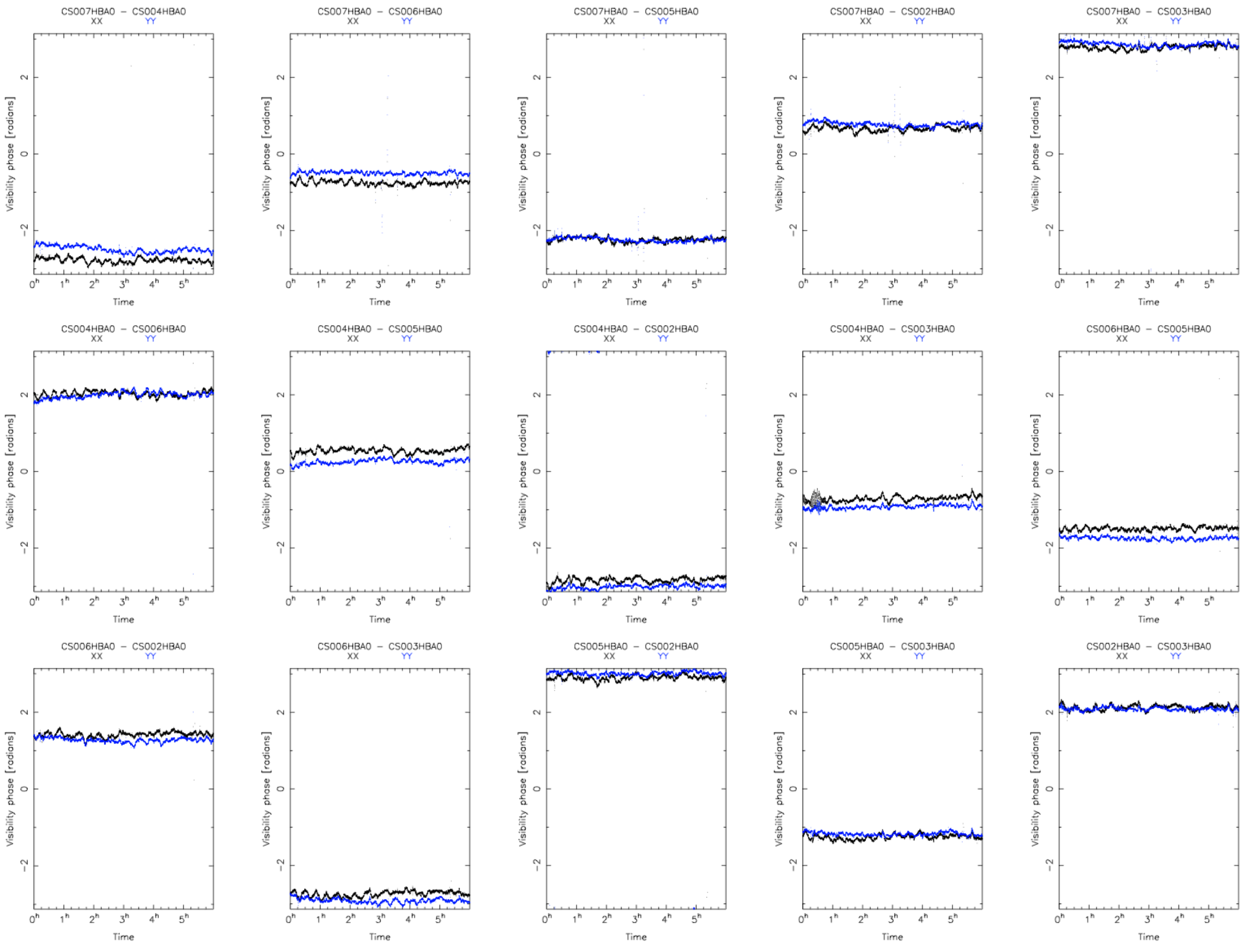
TauA superterp HBA-0 10sep2010

6h at 3s

L2010_20312
SB191
~152 MHz

All 15 superterp cross-correlations between:

CS002_HBA0
CS003_HBA0
CS004_HBA0
CS005_HBA0
CS006_HBA0
CS007_HBA0



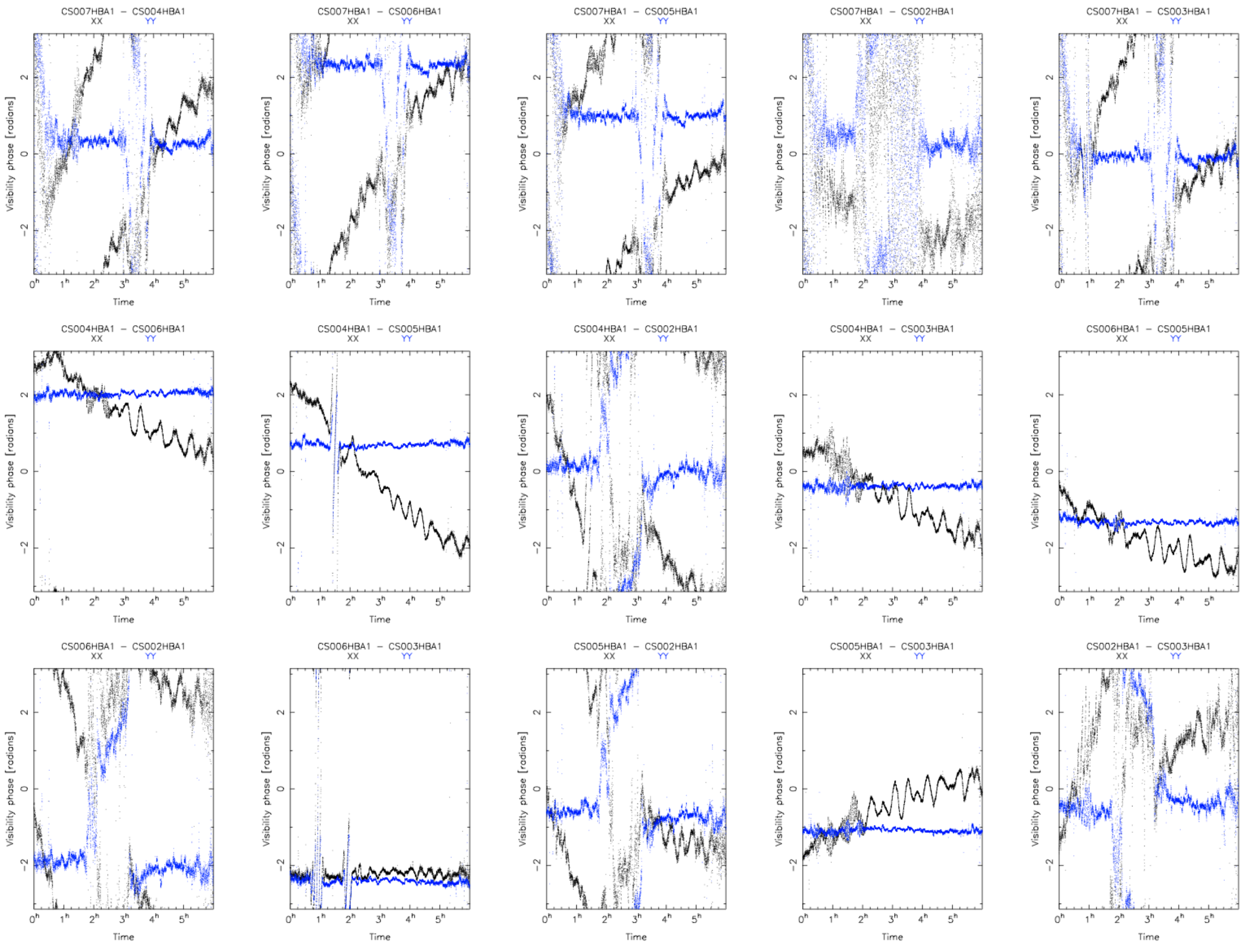
TauA superterp HBA-1 10sep2010

6h at 3s

L2010_20312
SB191
~152 MHz

All 15 superterp cross-correlations between

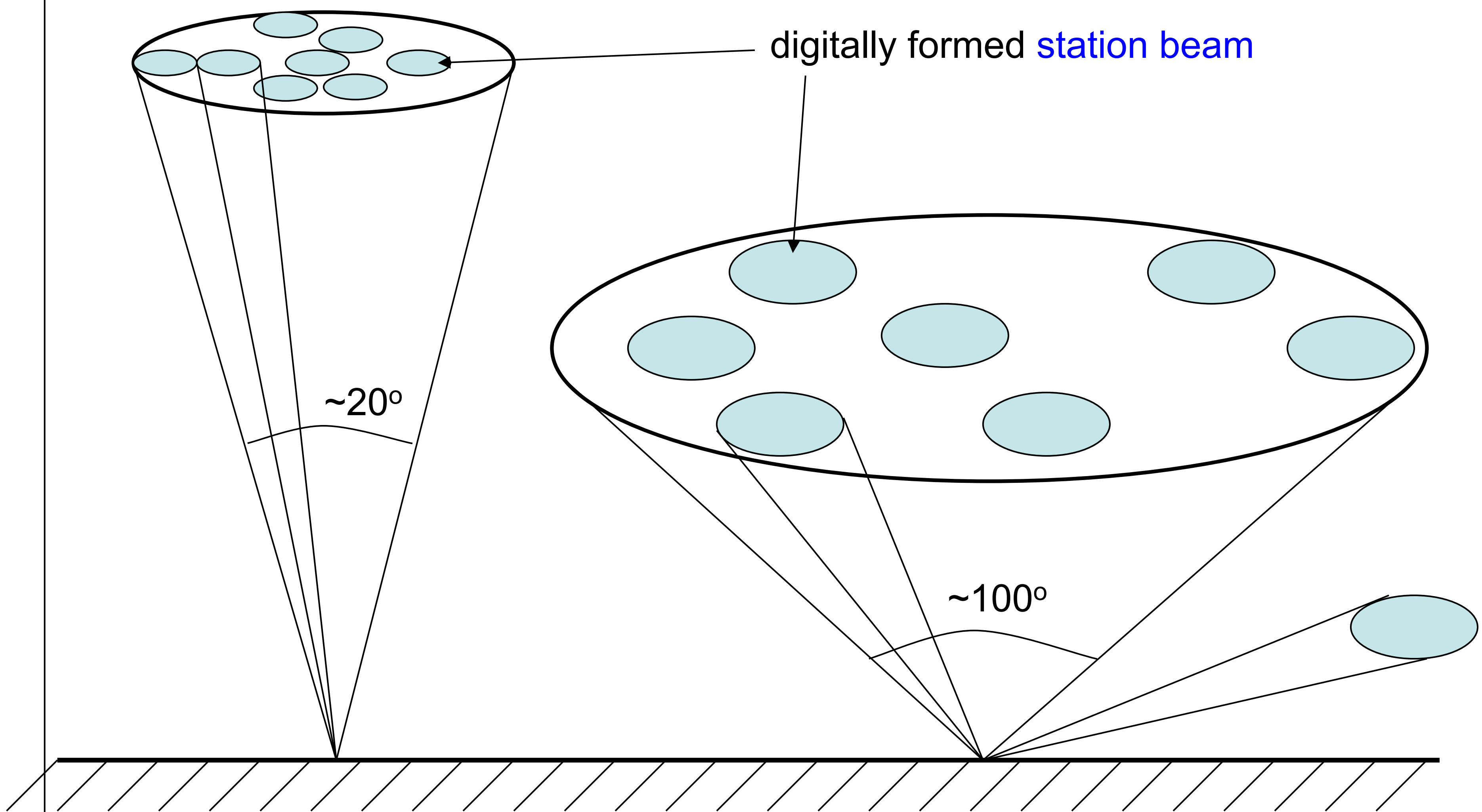
CS002_HBA1
CS003_HBA1
CS004_HBA1
CS005_HBA1
CS006_HBA1
CS007_HBA1



LOFAR = all-sky imaging

(John Baldwin, Jaap Bregman)

LOFARs very wide FOV (good & bad !)



HBA tile beam

(analog beamformer, 5-bit delay)

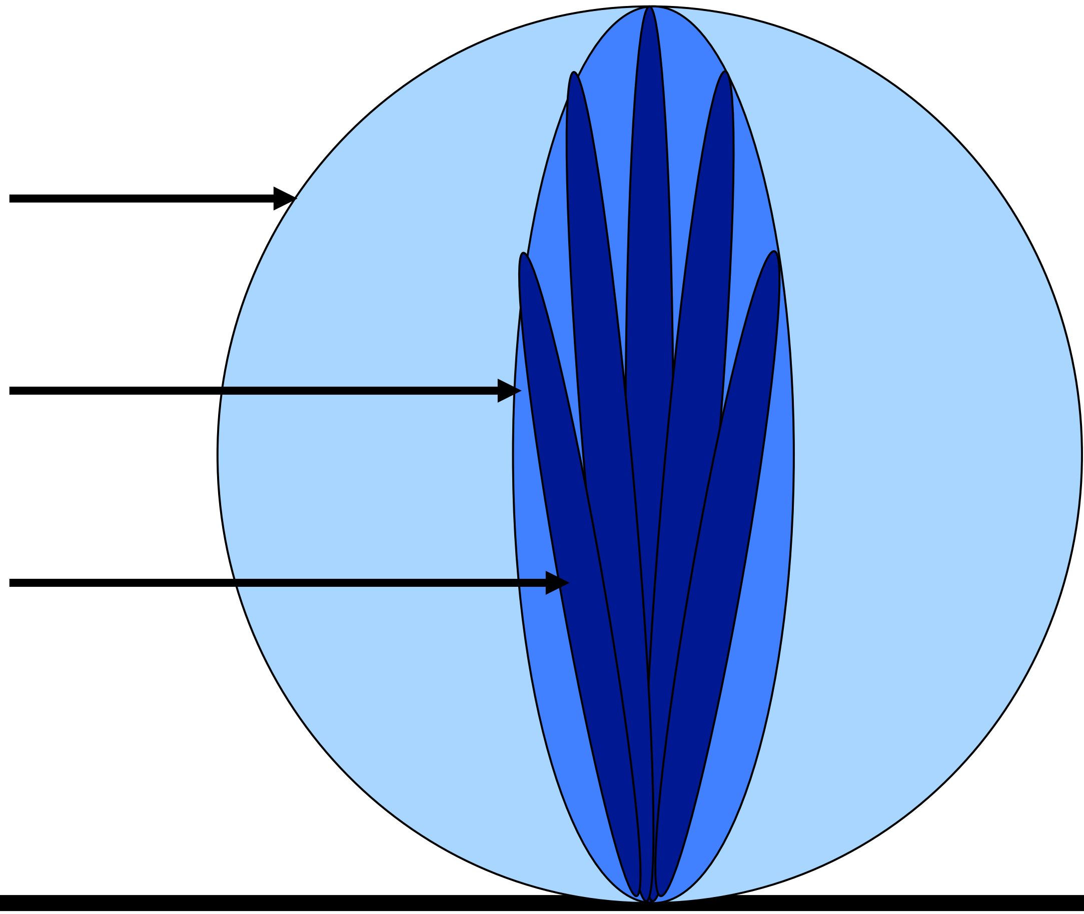
LBA dipole beam

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

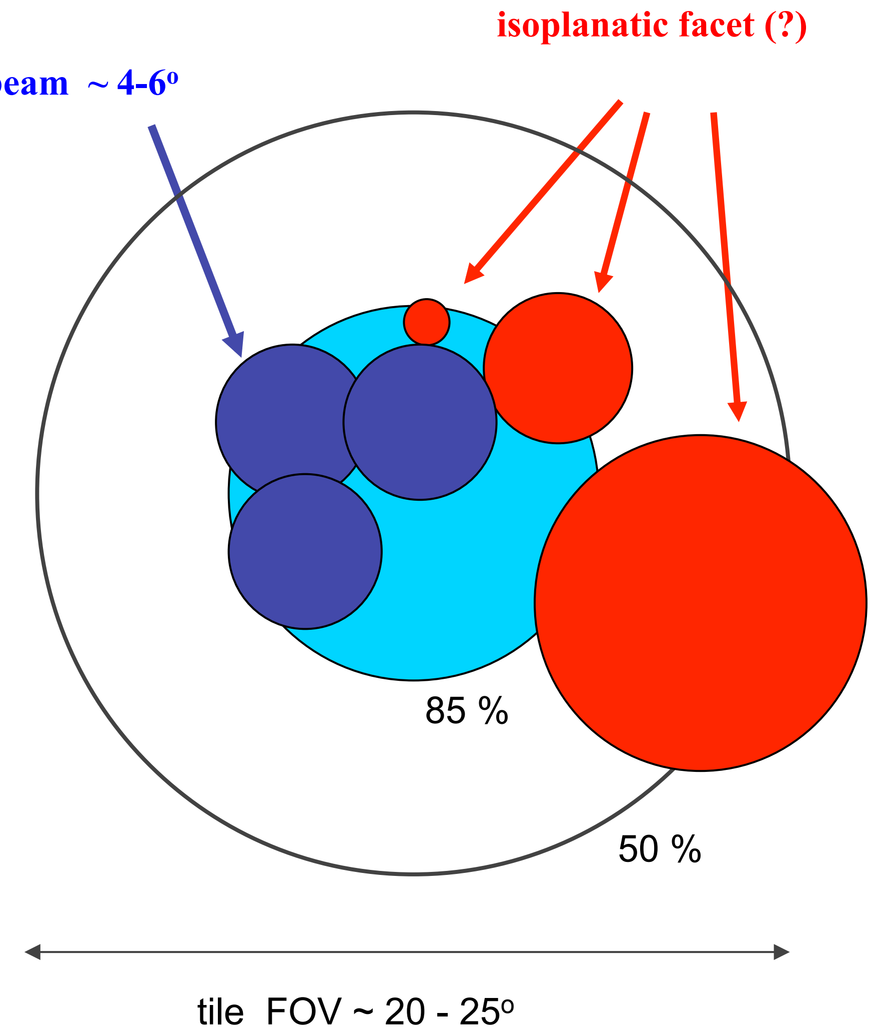
dipole (~100^{o})

tile (~ 20^{o})

24-tile station (~ 5^{o})



HBA angular scales (24 tiles/station)



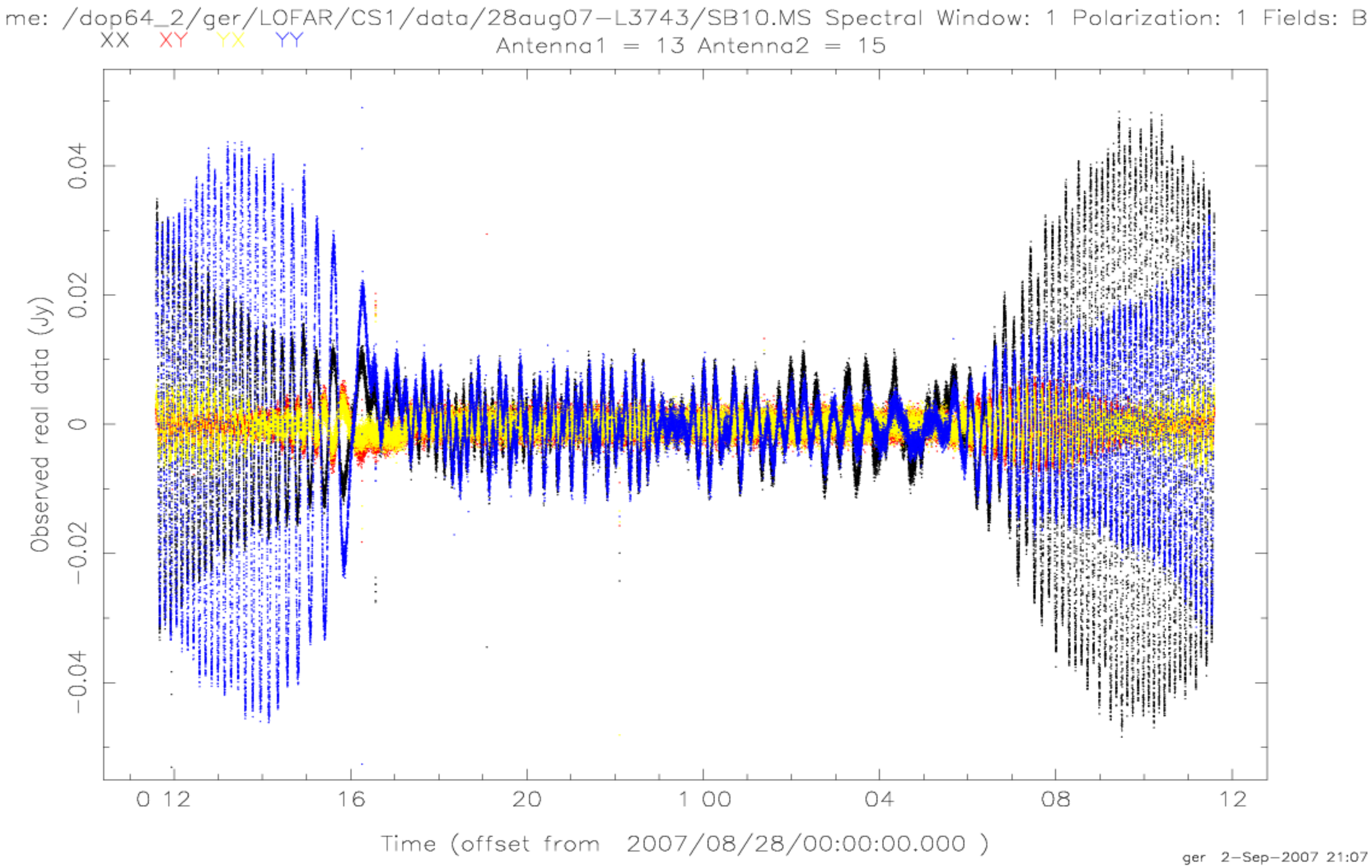
Note:

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

LOFAR and the Sun

The difference between night and day (220 MHz)

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

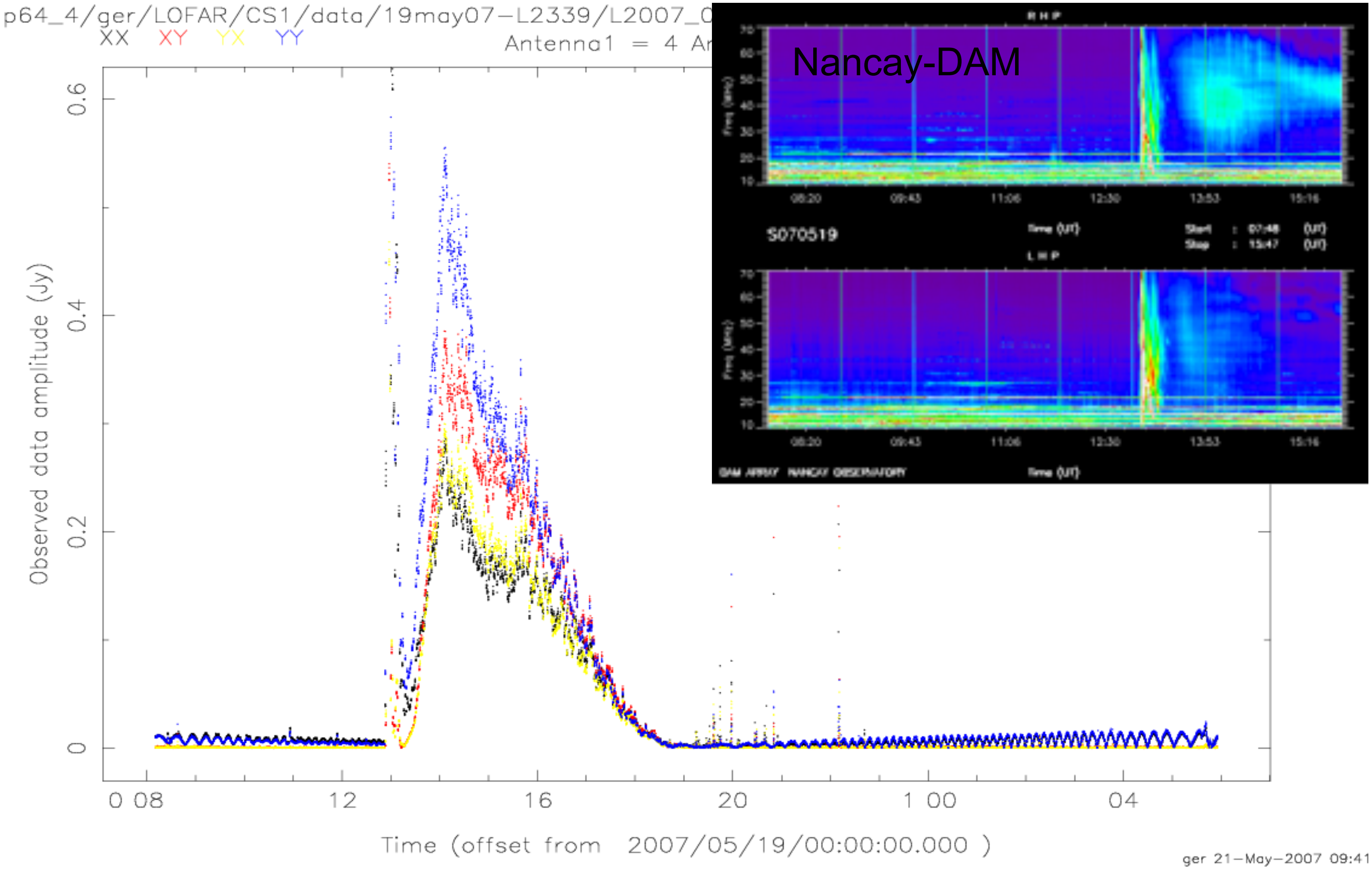


XX XY YX YY

Single dipole
(August 2007)

CS-1

The disturbed Sun ~50 MHz 19May07



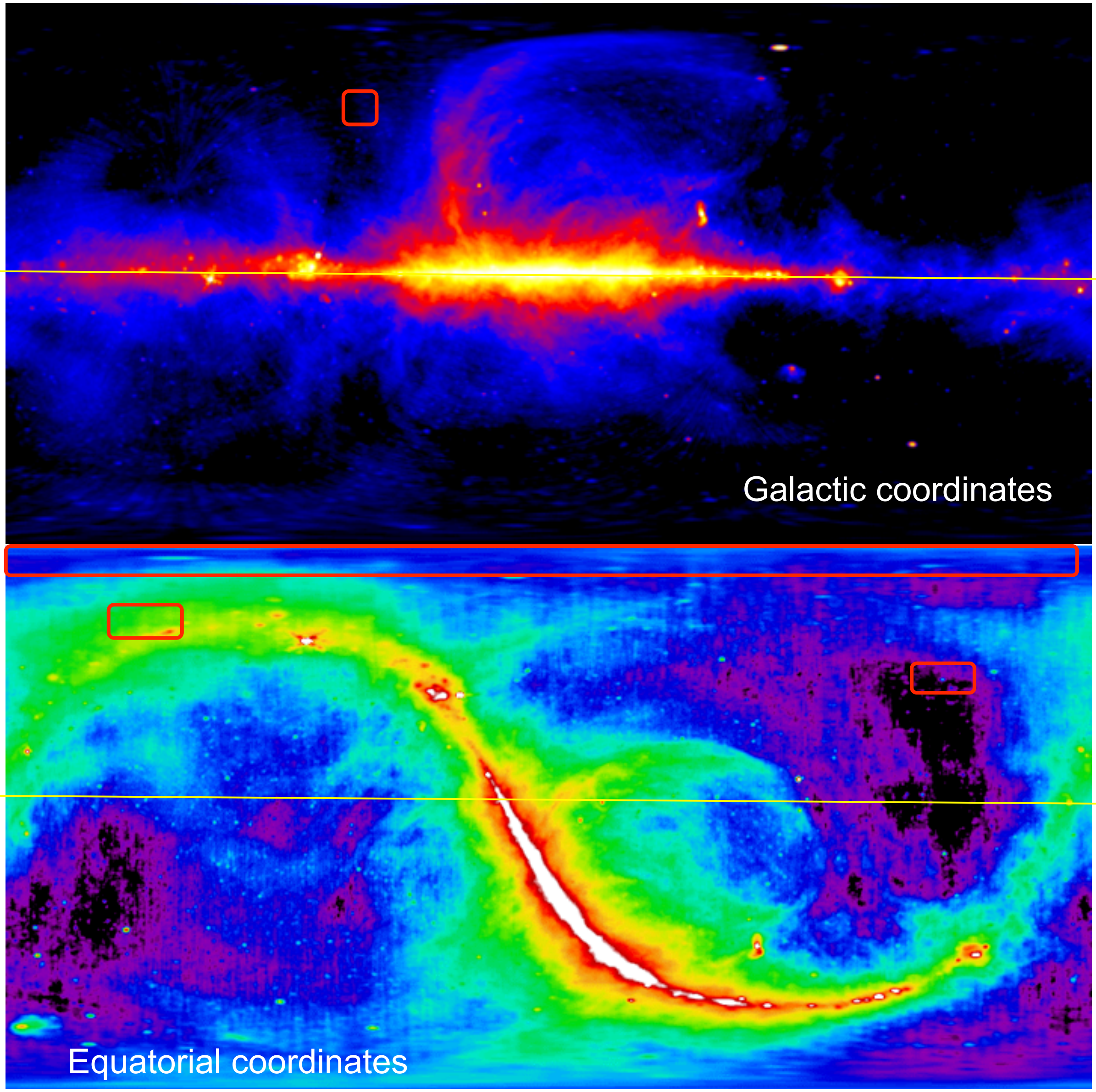
LOFAR and our Galaxy

The Galaxy is a major source of ‘noise’ !

Haslam et al (1981)

408 MHz

All-sky (0.85° PSF)



Location of 3 WSRT LFFE-fields (Nov07)

From left-to-right

— ‘FAN’

— NCP

— 3C196

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

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

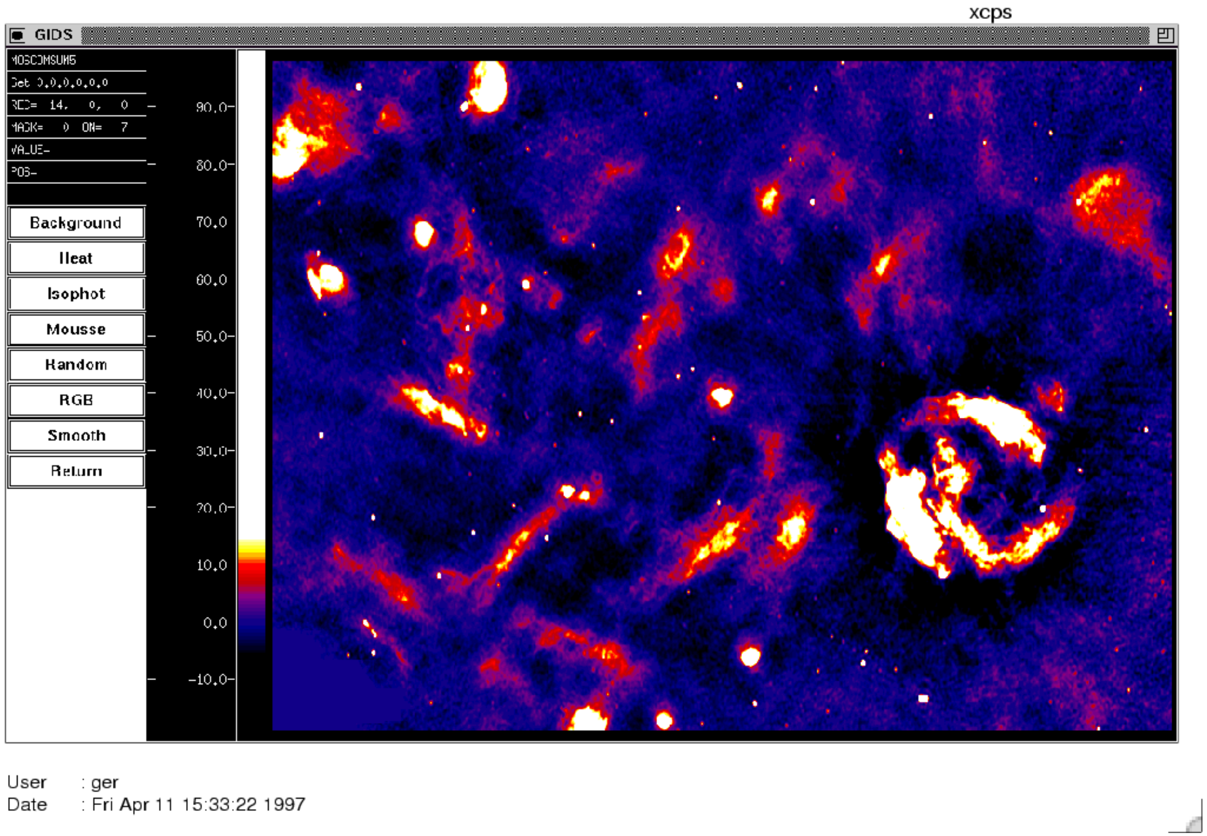
WSRT

350 MHz

6x12h synthesis

Mozaic

5^o to CygA



HII regions
SNR
OB-stars

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

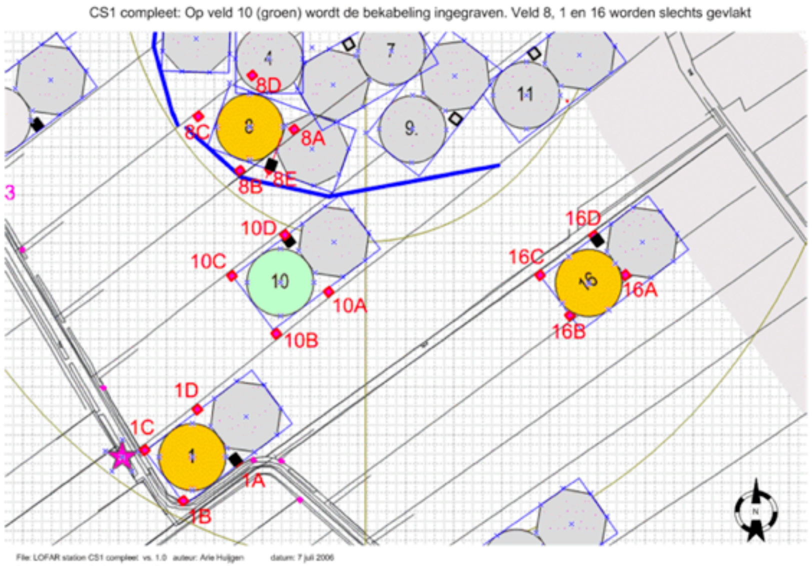


Figure 1: CS1 station locations.

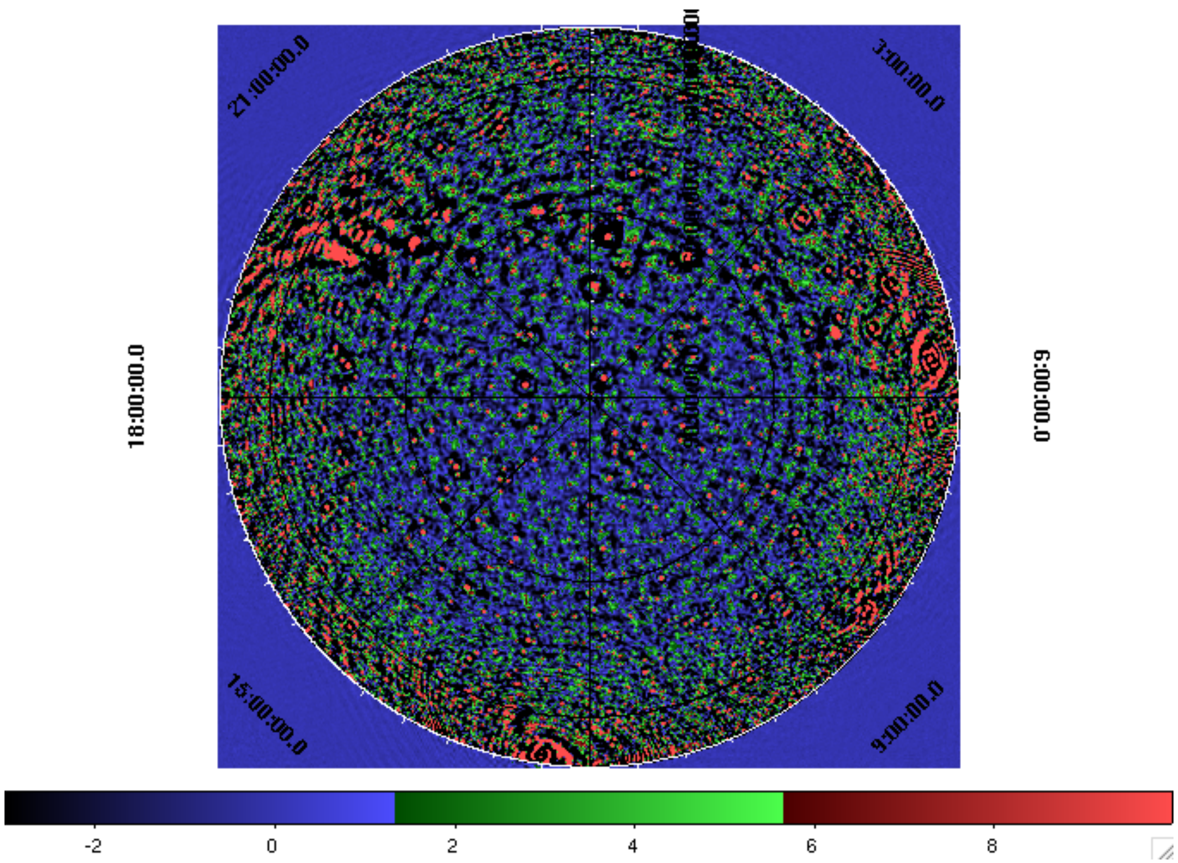
400 m

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°

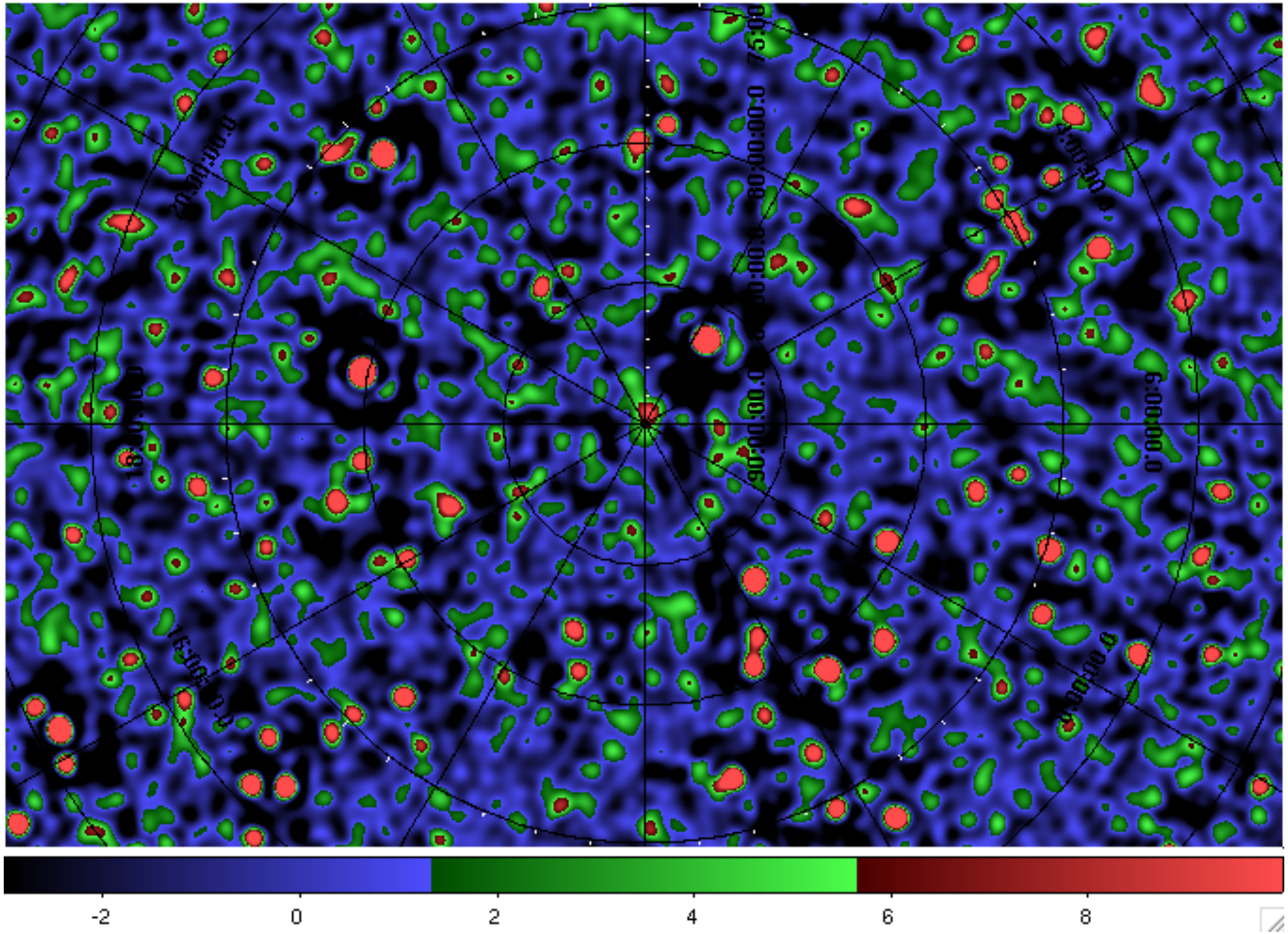
noise ~ 1 Jy

Yatawatta, 2007

CasA/CygA (20,000 Jy)
subtracted

- beam corrected -
- no deconvolution as yet

Zooming in at the NCP: confusion limited !



LOFAR and the ionosphere

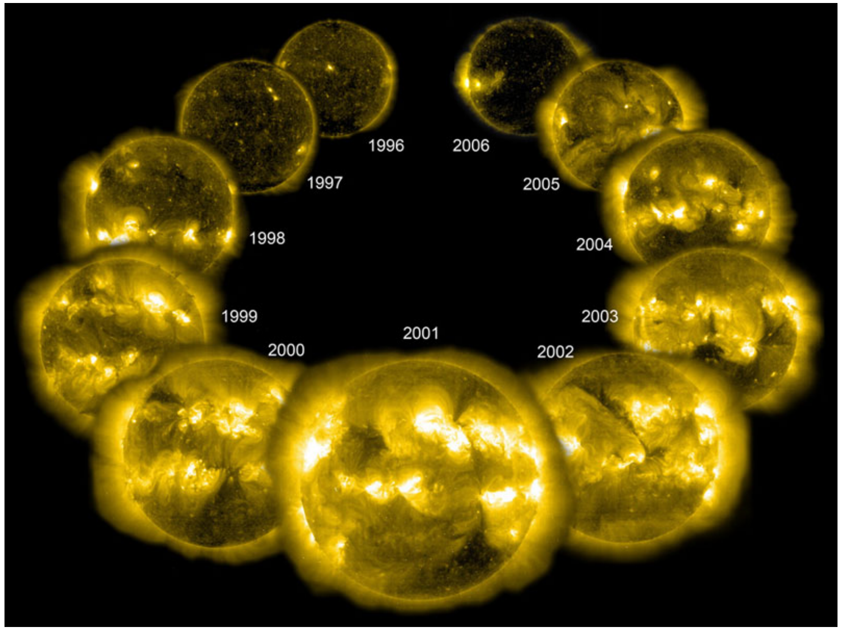
Ionospheric issues

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
- Large scale screen modelling
- GPS-TEC starting model
- Utilize 2-D frozen flow approximation (?)
- 3-D tomography solutions (multiple screens/layers)

Ionospheric TEC modeling

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

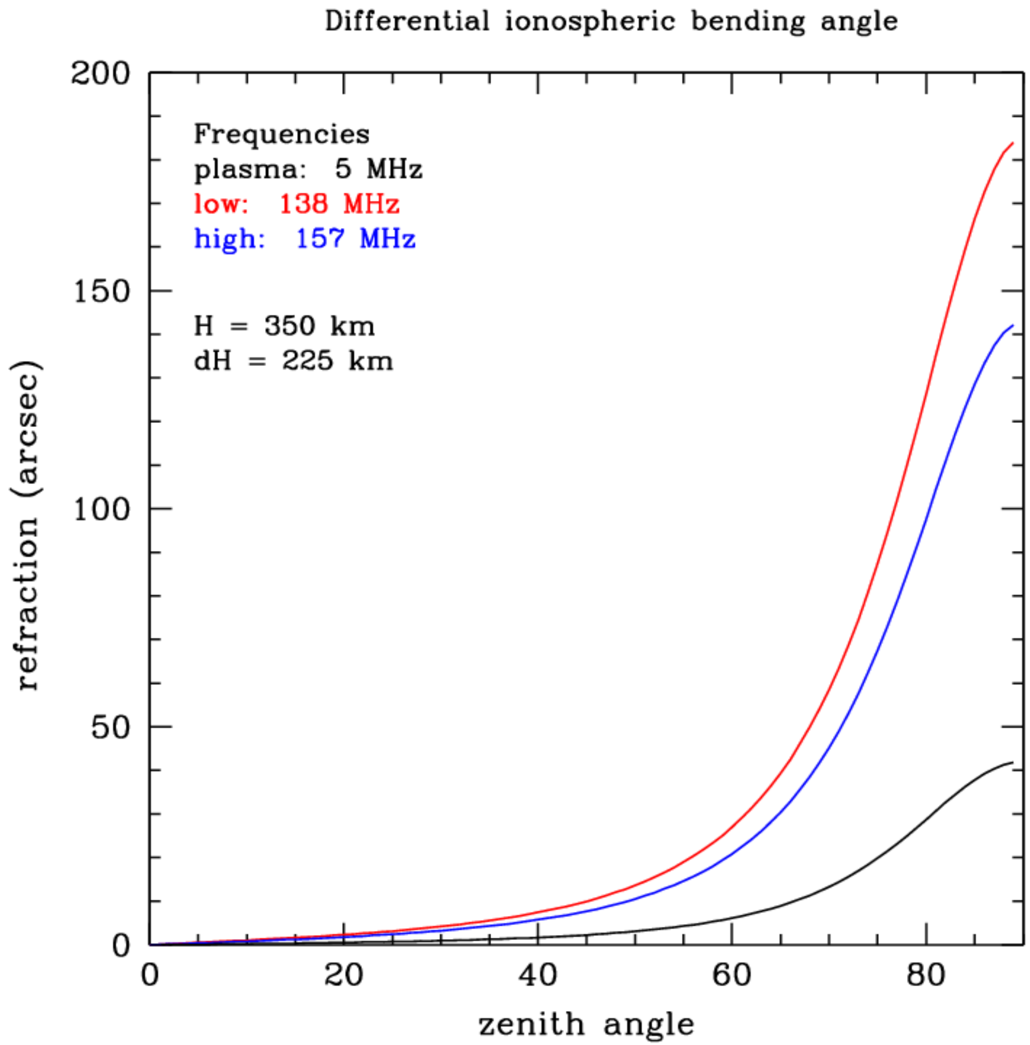
— differential angles in large FOV images (26-Nov-08 - LSM)

— Faraday rotation (29-Oct-08 - LSM)

— GPS data (not accurate enough, but check on start levels)

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

Frequency-dependent ionospheric refraction



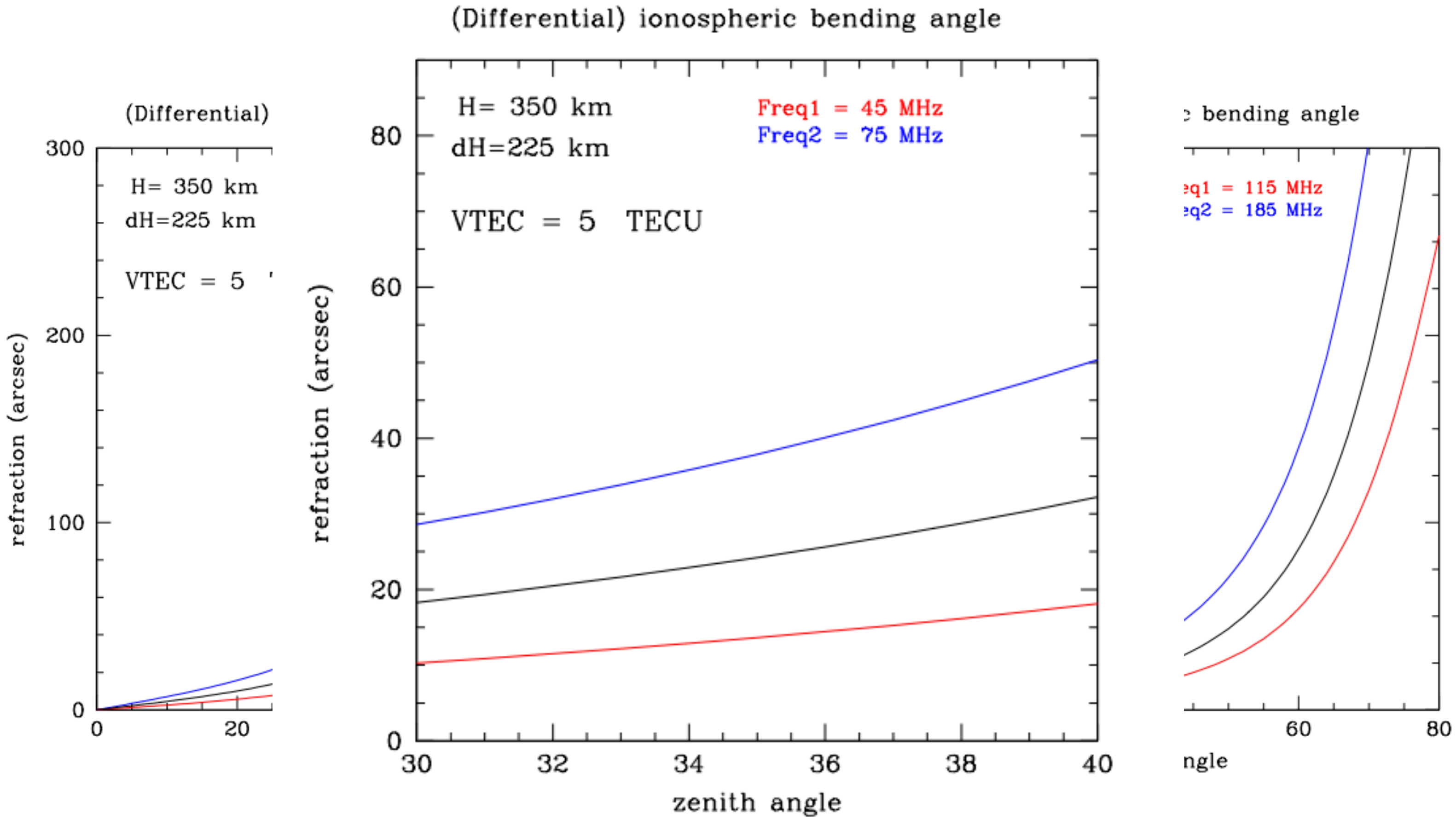
'Linear or quadratic' ?

Refraction scales linearly with TEC and quadratically with the plasma frequency

Refraction also scales quadratically with observing wavelength

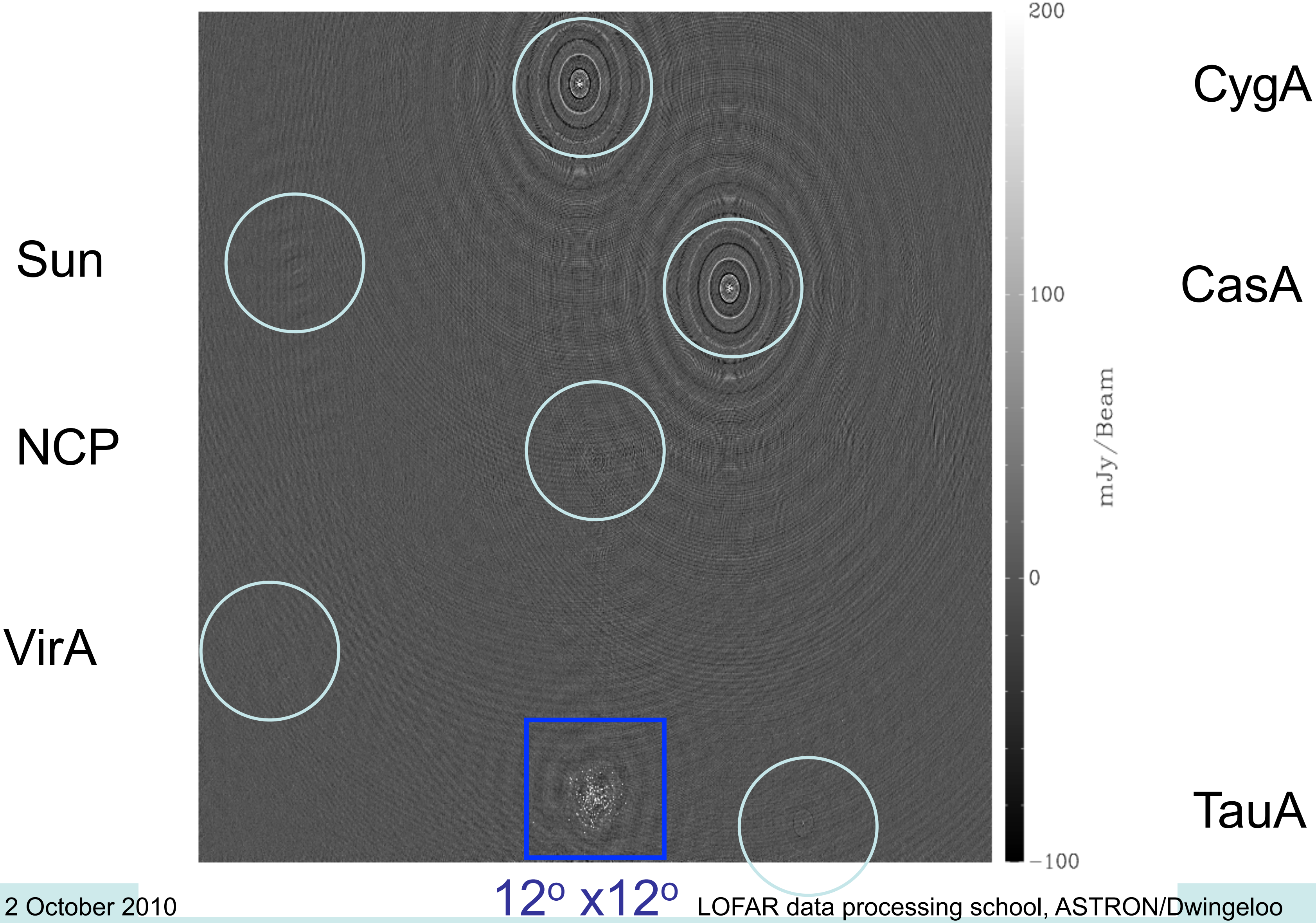
but our ability to measure this angle scales again linearly with wavelength

Differential Ionospheric Refraction Monitoring

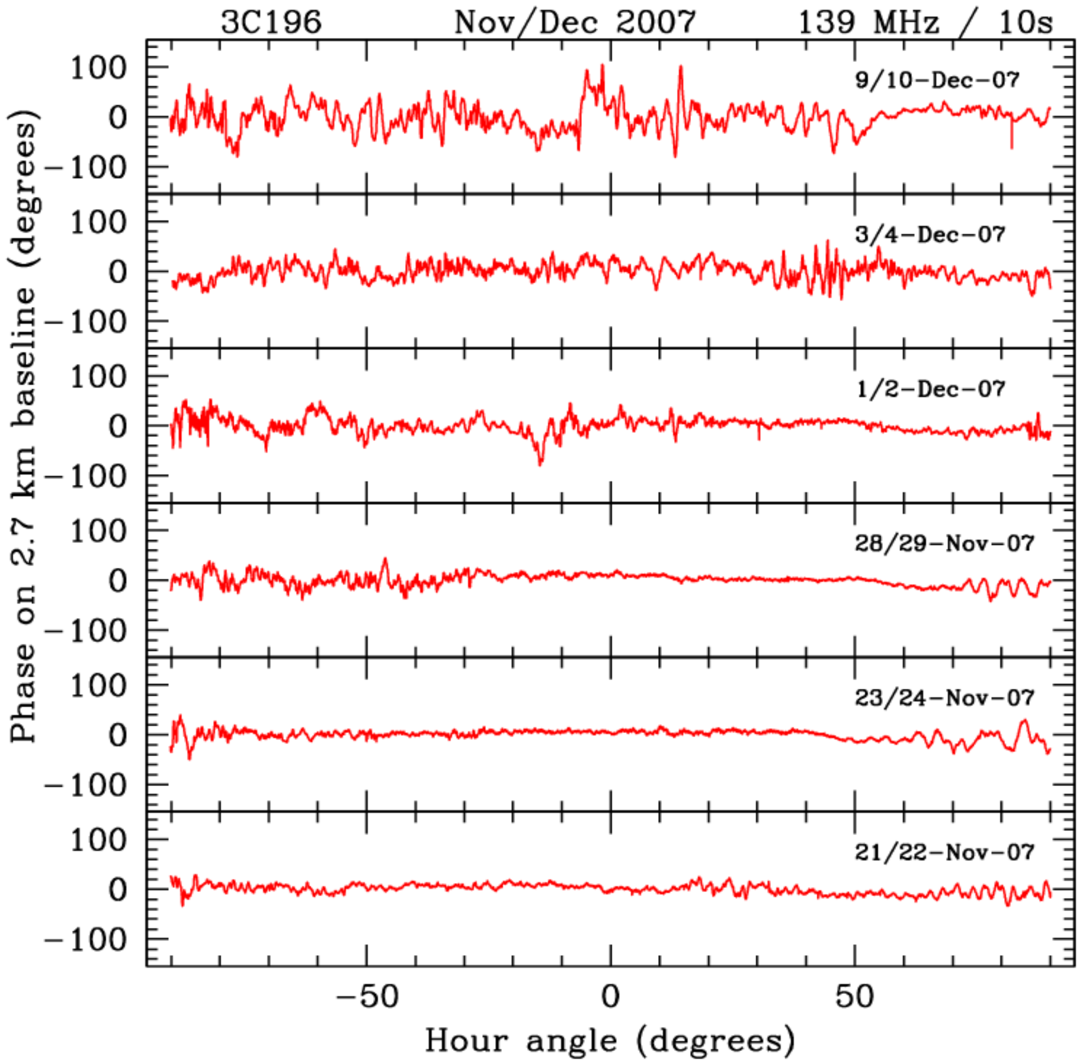


LOFAR resolution (PSF) at 60 MHz ~ 16” (50km / L)

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



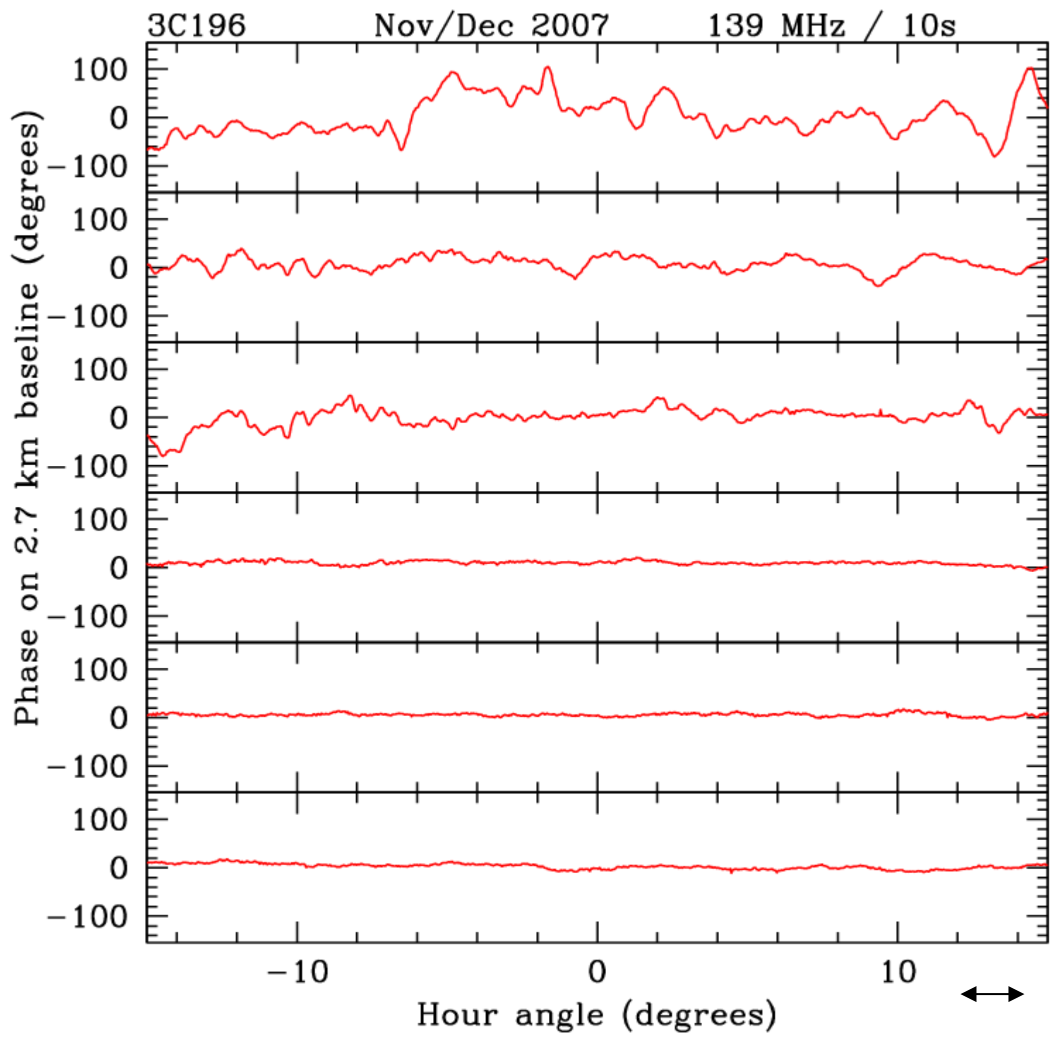
3C196 - selfcal phase solutions



6 x12h in a
3 week period

Note the very
different
ionospheres !

3C196 selfcal phase solutions: zooming in



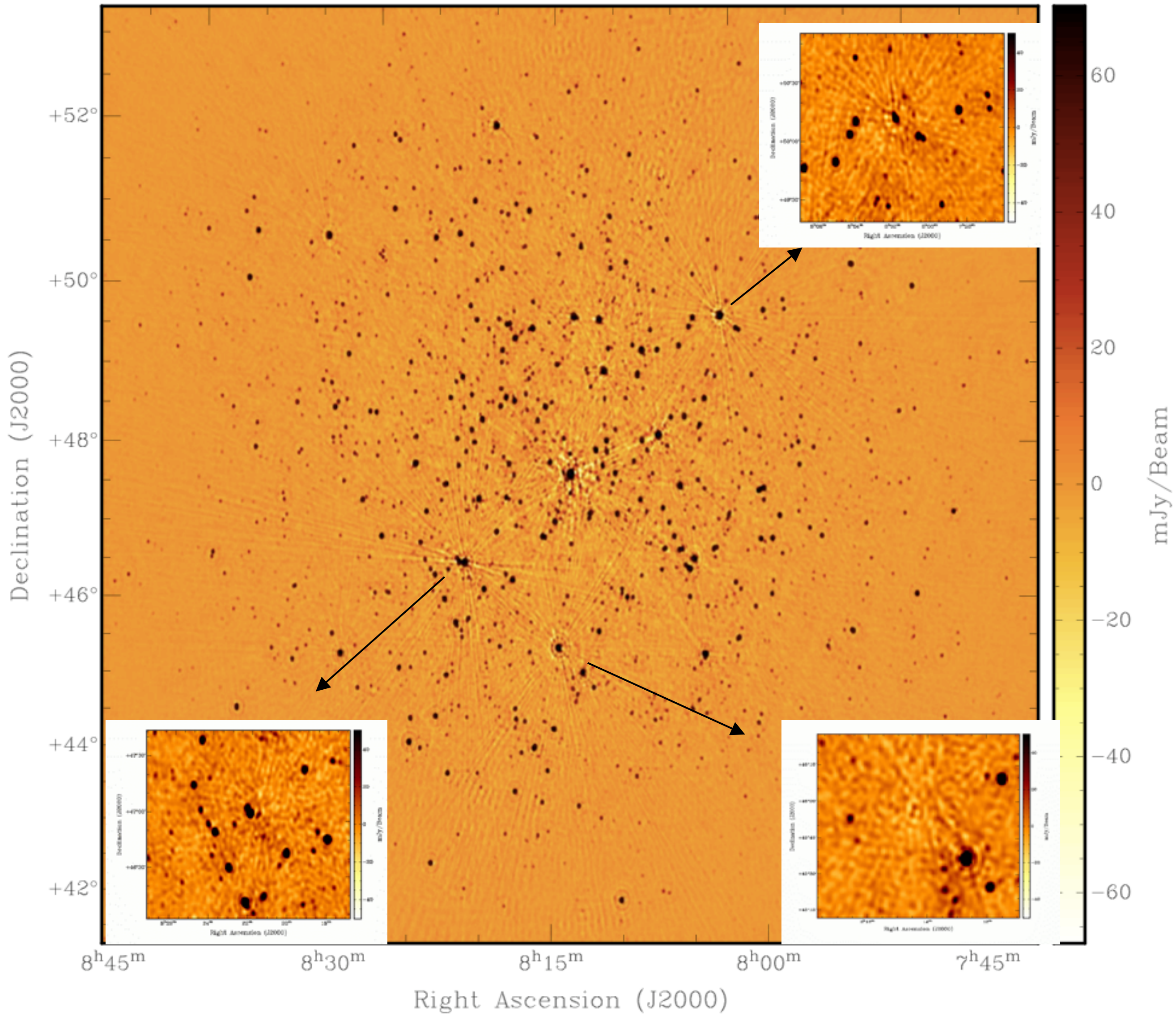
Note ‘well-resolved’ turbulence/waves

(noise

= line thickness)

2^o = 8min = 48 samples

Non-isoplanaticity & peeling   WSRT 145 MHz



3C196

80 Jy peak

~ 0.6 mJy noise

(classic confusion 3mJy)

2000+ sources

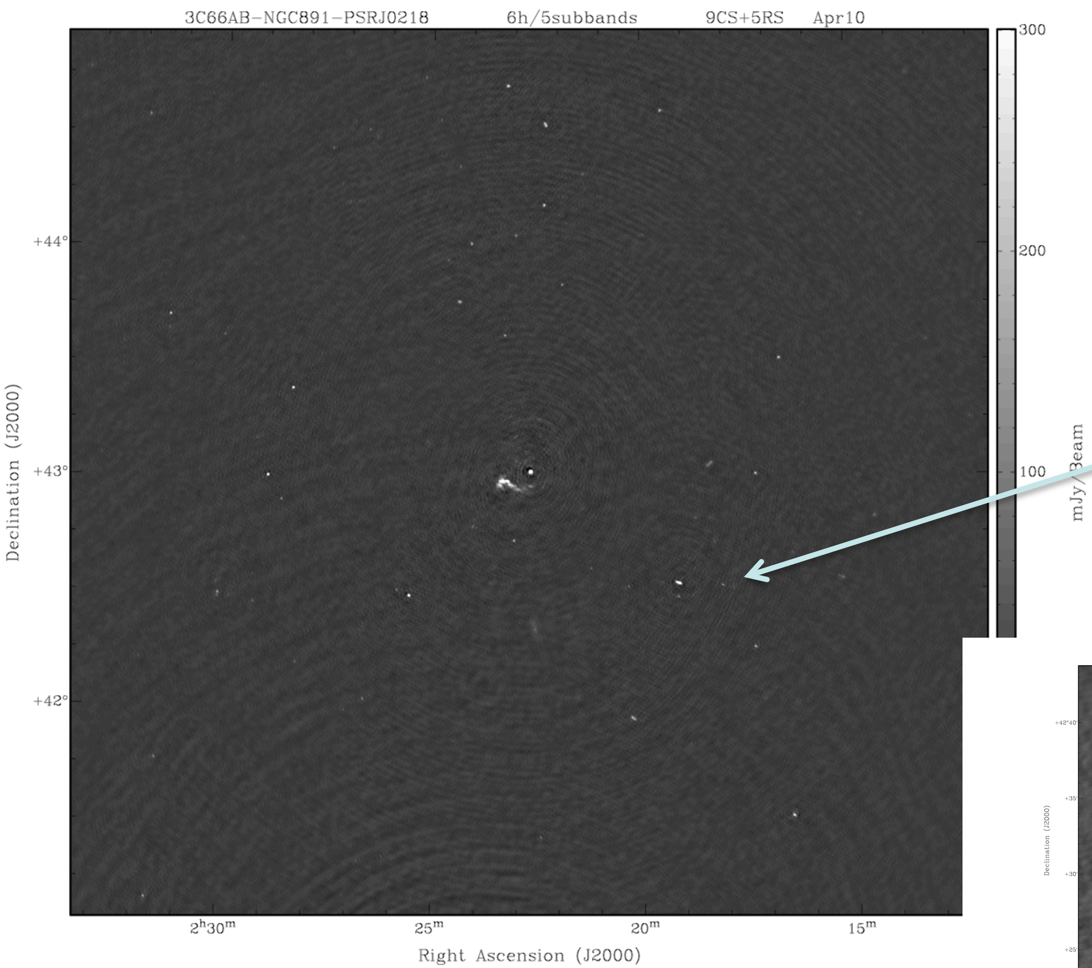
Separately peeled

DD-solutions

Bernardi etal, 2010

LOFAR and (linear) polarization

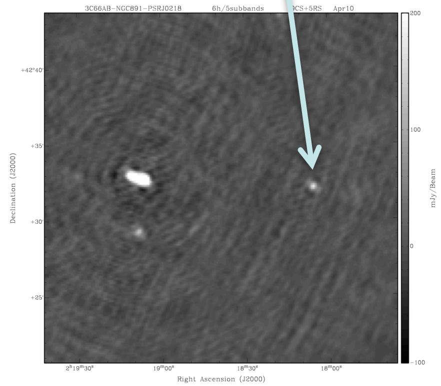
3C66AB-NGC891-PSRJ0218 6h HBA 24Apr10



PSRJ0218+4232

S_{150MHz} ~ 300-500 mJy

~ 50% linearly polarized



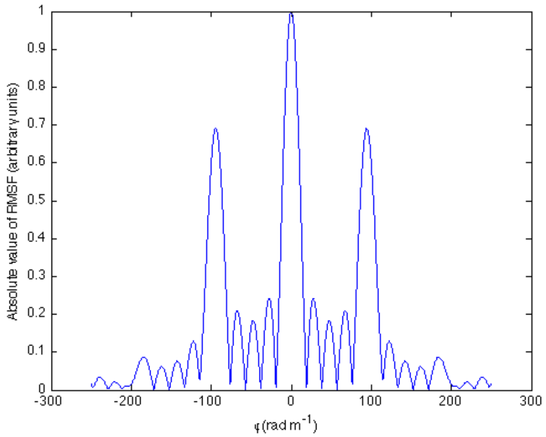
Detection of polarized emission: *Scaife, Heald, de Bruyn, Trasatti,..*

3C66-PSRJ0218

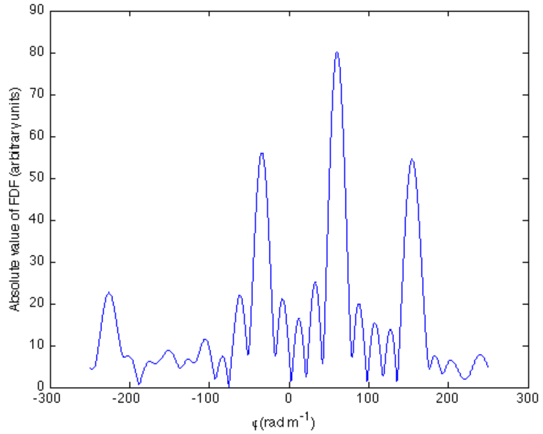
MKSP Busy Week

24 Apr10
UT 0840-1440
L2010-07096

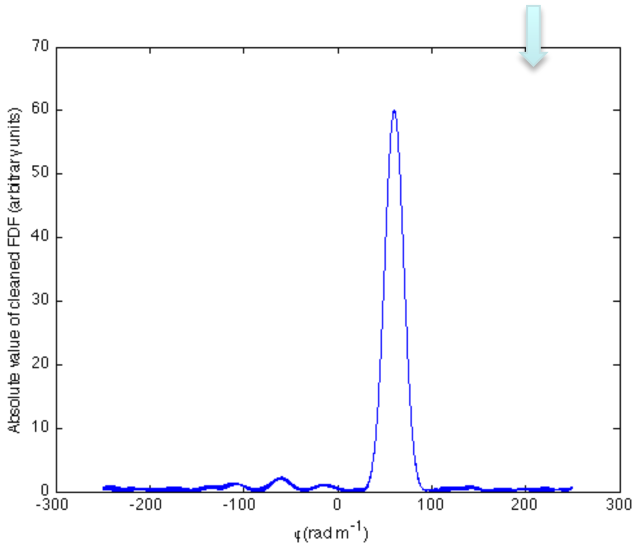
RMSF



dirty RM-spectrum



RM-clean



HBA 129 MHz

(SB10+12+14+16+18
~ 1 MHz total)

Each subband contains
four 60ch-averages

Peak flux at
RM ~ +60 rad/m^2

Should be at -61 rad/m^2

Flux density uncertain but
probably ~ 100-200 mJy

Next steps in polarization analysis

Include up to ~100 subbands:

→ RMSF narrows to ~ 1.5 rad/m^2
→ S/N goes up by factor 5.

Accuracy in RM should improve to ~ 0.002 rad/m^2 ! (in 6h)

Accuracy in (say) 15m will then be ~0.01 rad/m2

The time variable ionospheric contribution is about 1 rad/m2

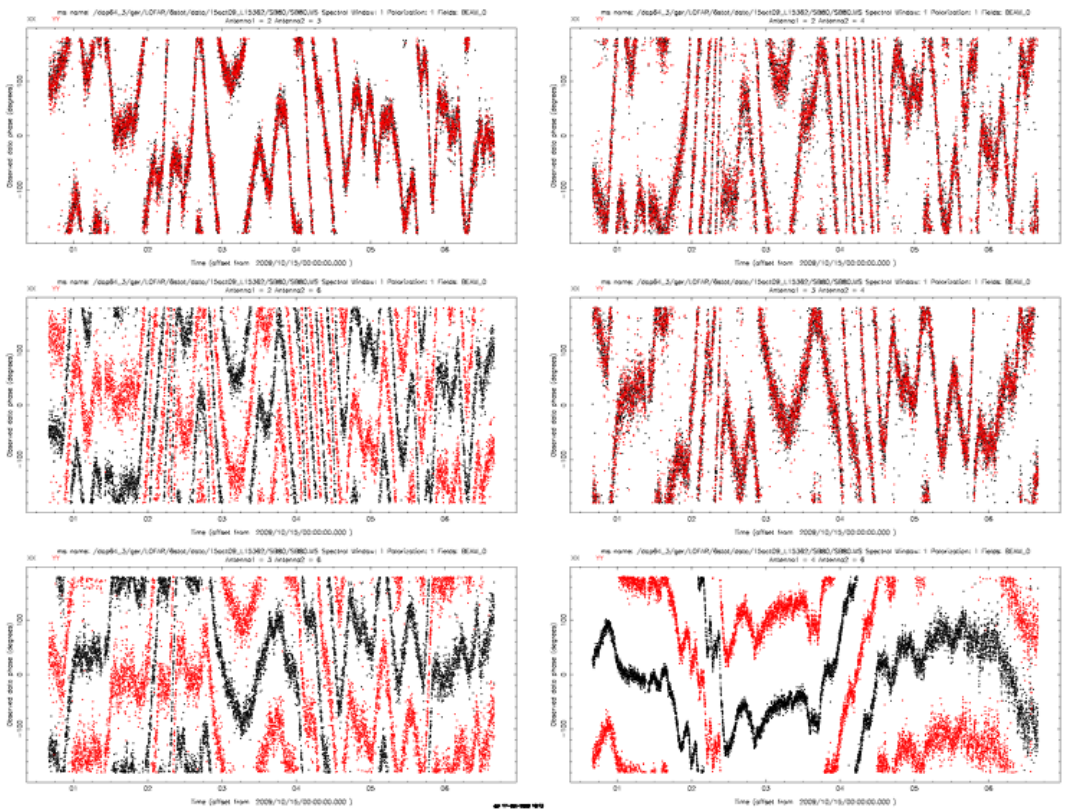
Analyse RM as a function of time
→ and compare with global TEC monitoring (through differential refraction or delay fits from frequency behaviour (work by Bas van der Tol)

Some results from a 6h LBA TauA observations

15-Oct-09 L2009_15363 Subband 80 at 45 MHz

4 stations ⇒ 6 baselines baseline length from 3 - 30 km

XX
YY



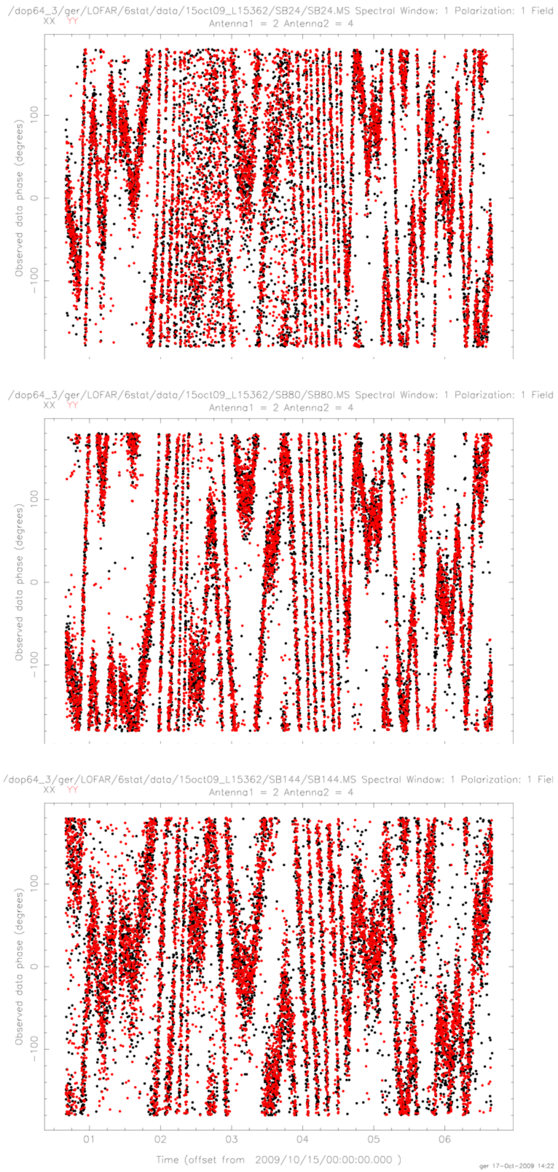
phase

time

6h

360^o

Observing a (polarized?) pulsar in TauA - LBA band



35 MHz

45 MHz

SNR ~ 3 (in 180 kHz, 3s)

Assuming station SEFD is about 25,000 - 50,000 Jy

The estimated flux of the pulsar must then be about 150 - 350 Jy (to within a factor ~2)

Fluxes still uncertain because of unknown station gain and skynoise

Calibration effort that has hardly been started…

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

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

— day/night effects on data quality (with either thermal or flaring Sun)

— absolute flux scale determination (‘interacts’ with station beam validation)

— deconvolution with spatially varying beams

— deconvolution at >> 10000:1 DR (use high resolution images for source models)

— Galactic plane imaging and very short spacings (< 10 wavelengths)

— calibrating European baselines over wide FOV

— astrometry at sub-arcsecond level

— optimal weighting due to time-varying sensitivity

— variable Faraday rotation (in time and across FOV)

Commissioning these will be a major task. We need you !

Consider, with your supervisor, which of these topics are crucial for your science and contact LOFAR calibration group.

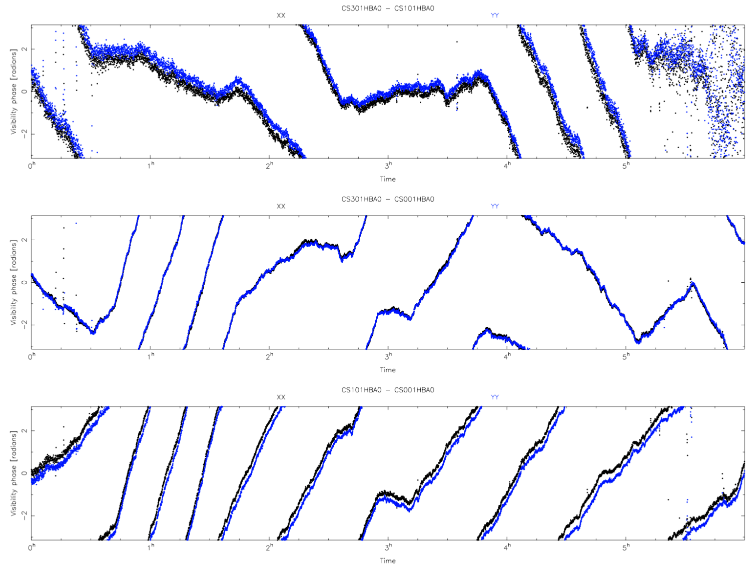
Additional slides
(not shown at LOFAR school)

Data quality

Correlations between 3 core stations **outside** superterp

CS001, CS101, CS301

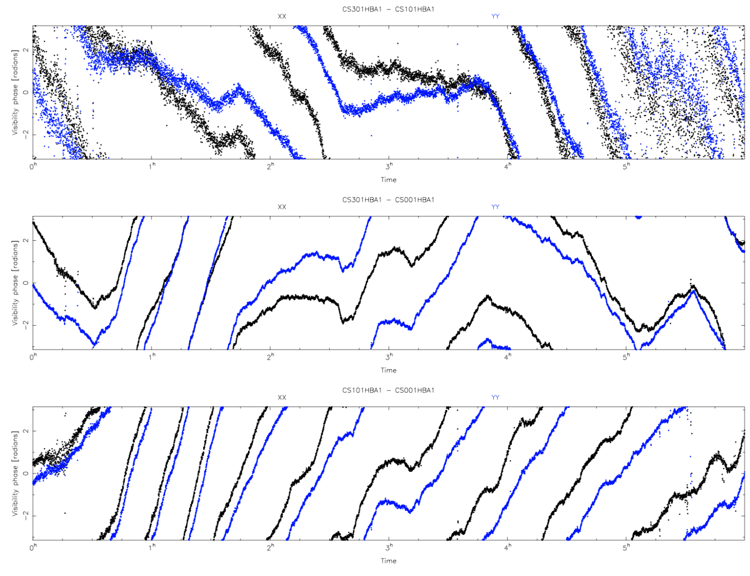
HBA0



HBA0 data look OK

HBA1 has relative phase drift between XX and YY signals (which might be calibrated away !?)

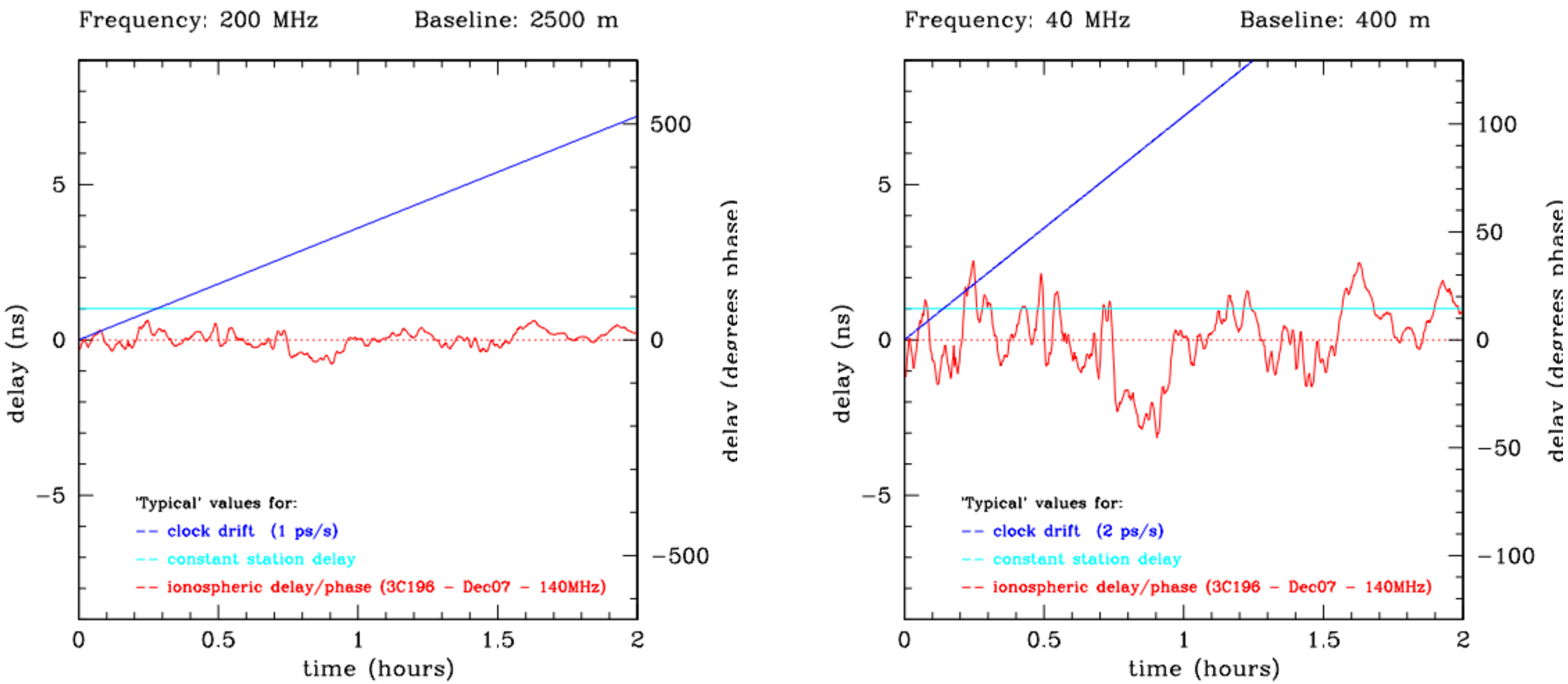
HBA1



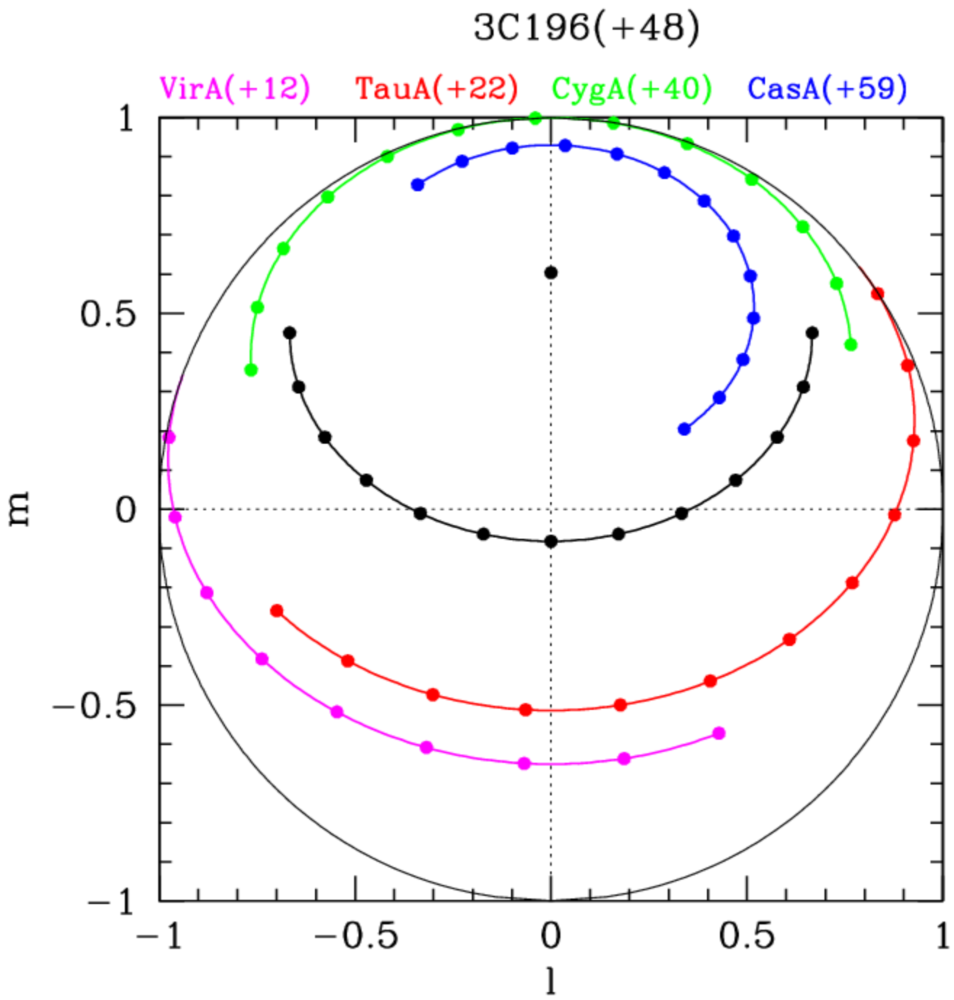
See Lofar Status Meeting 29sep10

LOFAR clocks and the ionosphere (cartoon)

LOFAR stations have independent (Rubidium-GPS disciplined) clocks. This leads to rapid phase drifts on all baselines. These drifts are larger than the ionospheric phase drifts for the core at all frequencies. At long baselines (>few km) and low frequencies this is not the case anymore (ionosphere will dominate)



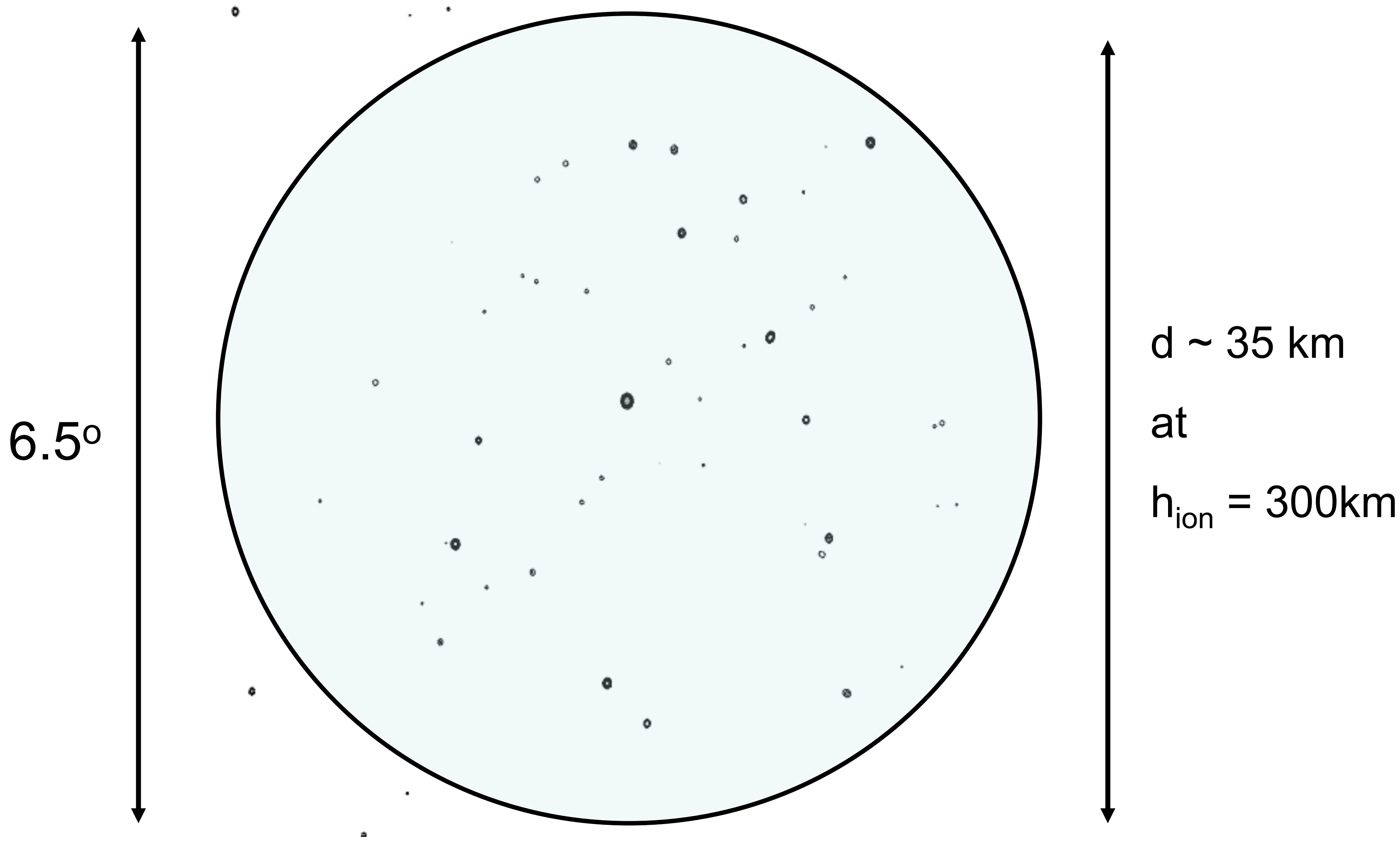
The A-team locations during a 12h WSRT 3C196 synthesis



Note that the l,m here are a zenith "'l,m" projection which is the natural coordinate system for a aperture array like LOFAR

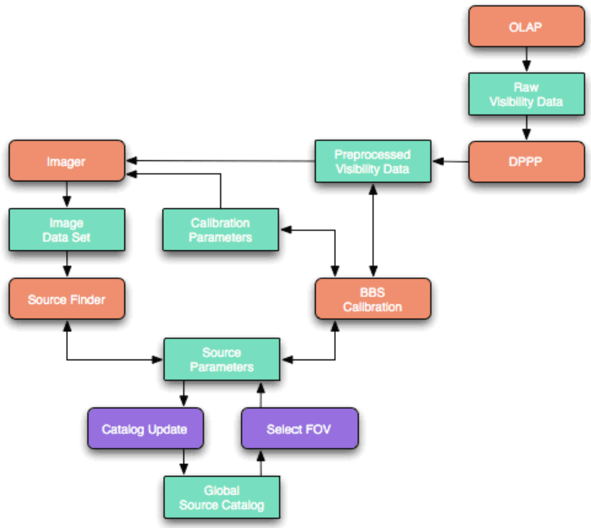
3C196 field: ~45 sources with apparent flux S_{139MHz}> 0.5 Jy

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



LOFAR calibration/imaging pipeline components

- RFI mitigation	NDPPP and/or rfisconsole (AO-flagger)
- Data selection	Compression time/frequency Bad station/ baseline flagging
- Calibration	clock correction gain/phase tables transfer
- Initial calibration	bright calibrators (‘cat I’) global (broadband) solutions ionospheric DD-solutions
- Imaging & deconvolution	
- Source finding /updating	



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

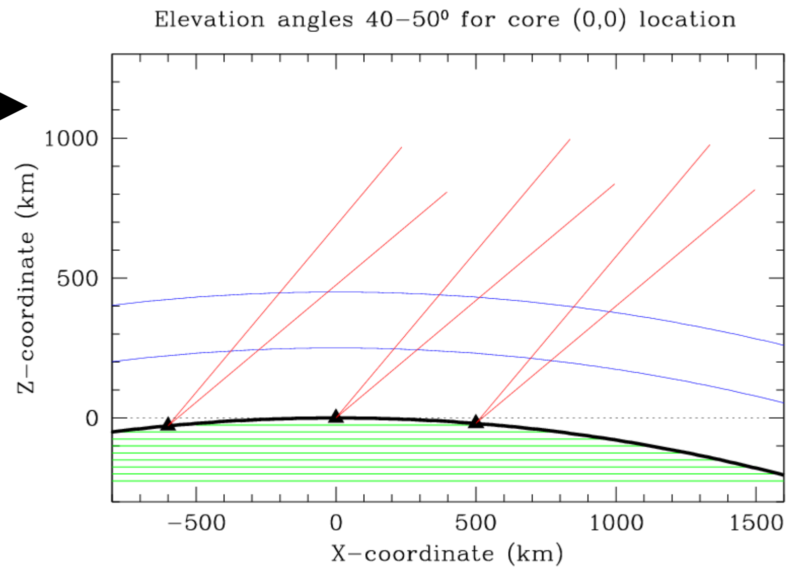
frequency space: < 30, 40-80, 120-180, 190-230 MHz

- primary beam size
- source spectra

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?)

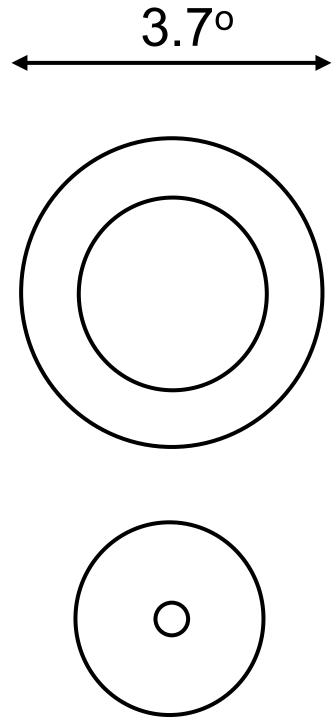


A possible solution (for HBA)

1) solve for NL screen in NL-LOFAR
2) correlate ~ 10-20 superterp 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^{o} at 300 km height

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



Required on line:

- known positions to attempt correlation, or coherent addition of complex 0.2s visibilities, using ST6 ionospheric screen)

- global TEC model to predict refraction