The LOFAR observatory:
status, issues and recent results

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[+] with lots of input/results from the LOFAR offline-pipeline and commissioning teams

Outline

- The LOFAR array : overview, specs, status & images
- RFI mitigation and statistics
- Station types and (-beam) calibration
- Wide field of view and their calibration issues
- Some recent imaging results
- European LOFAR calibration ideas
- The LOFAR calibration survey: MSSS
- Conclusions

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

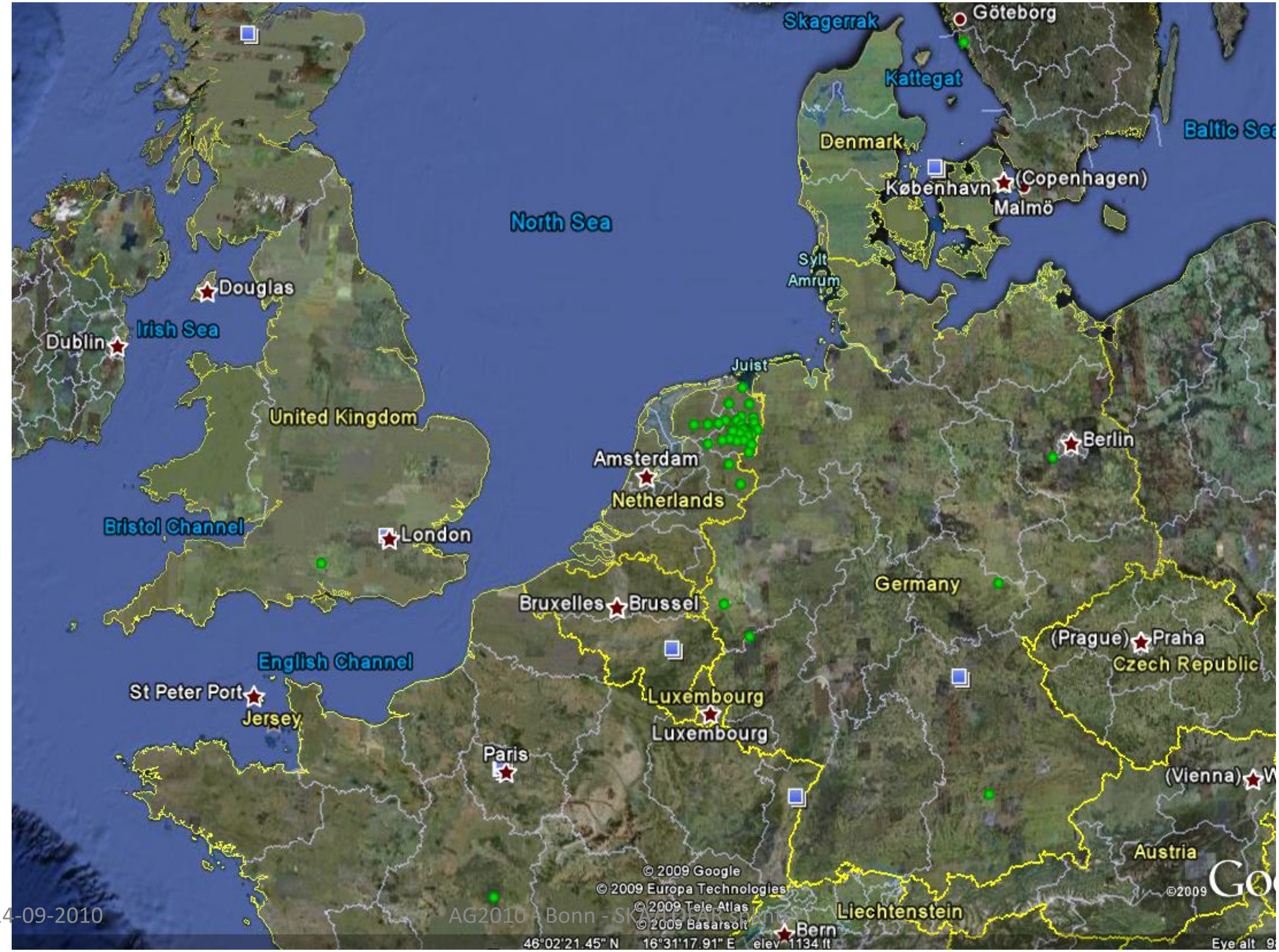
Pulsars: tied-array(s), (in)coherent sums

Sensitivity (after 4 h, 4 MHz, ~ 50 stations)

@ 60 MHz ~ 3 mJy

@ 150 MHz ~ 0.1 mJy

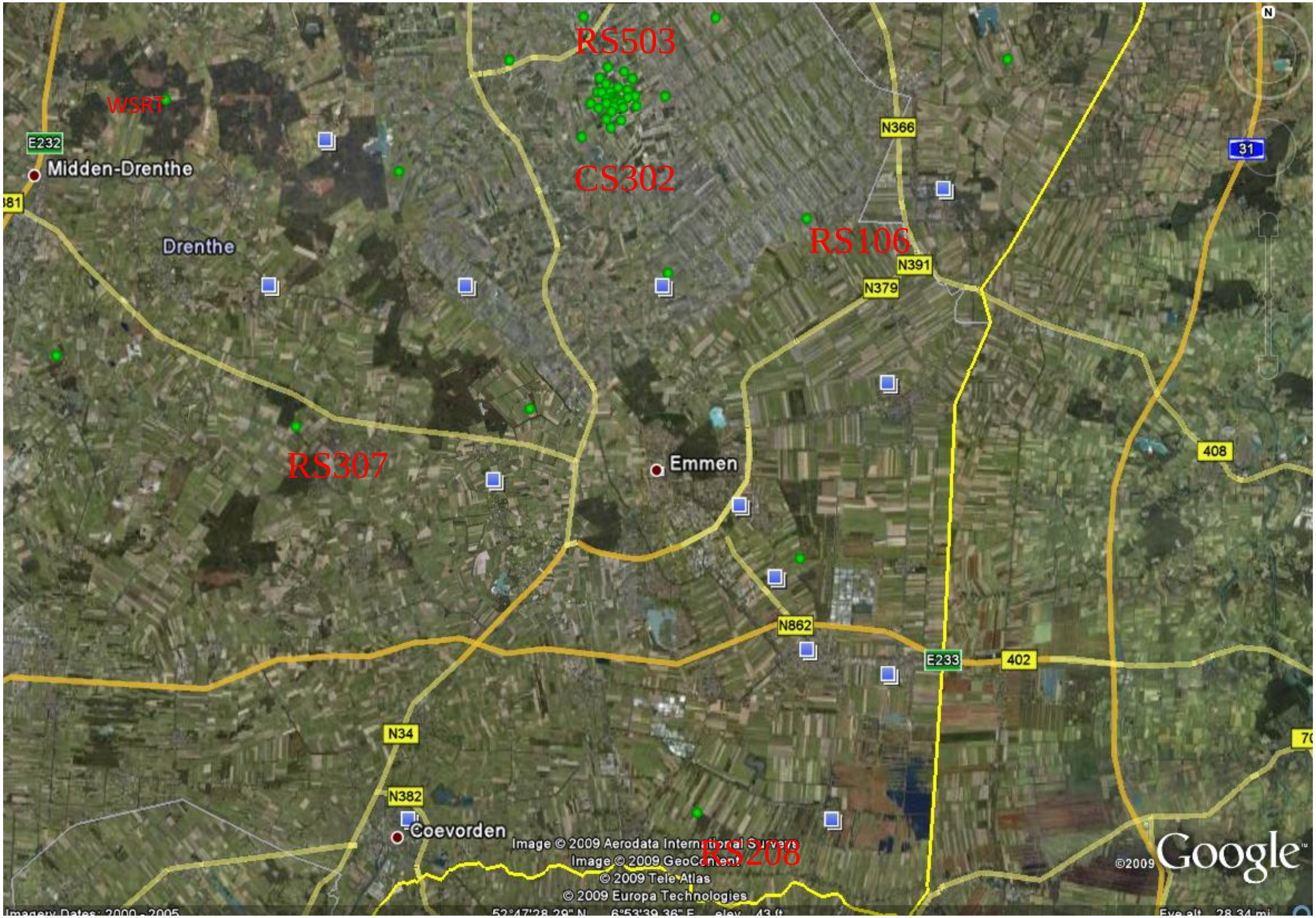
LOFAR in Europe (8+ stations)



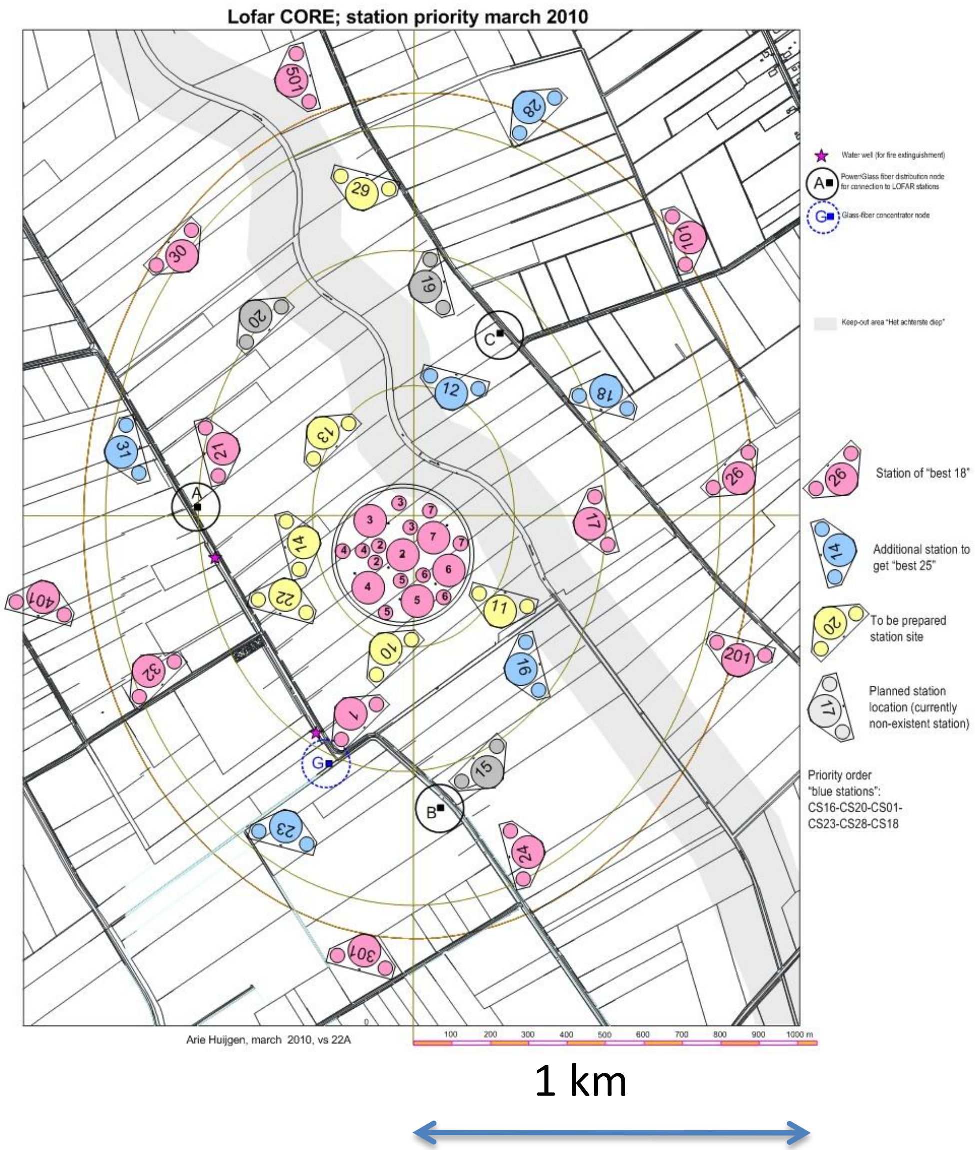
LOFAR station locations in the Netherlands

www.astron.nl/~heald

LOFAR core in South-East Drenthe



The LOFAR core area near Exloo



18 core stations (all split-stations with 2x24 tiles)

+ 4 more stations in core (CS011,013,028,031)

Core Stations (2x24 HBA-tiles, 96 LBA-dipoles)

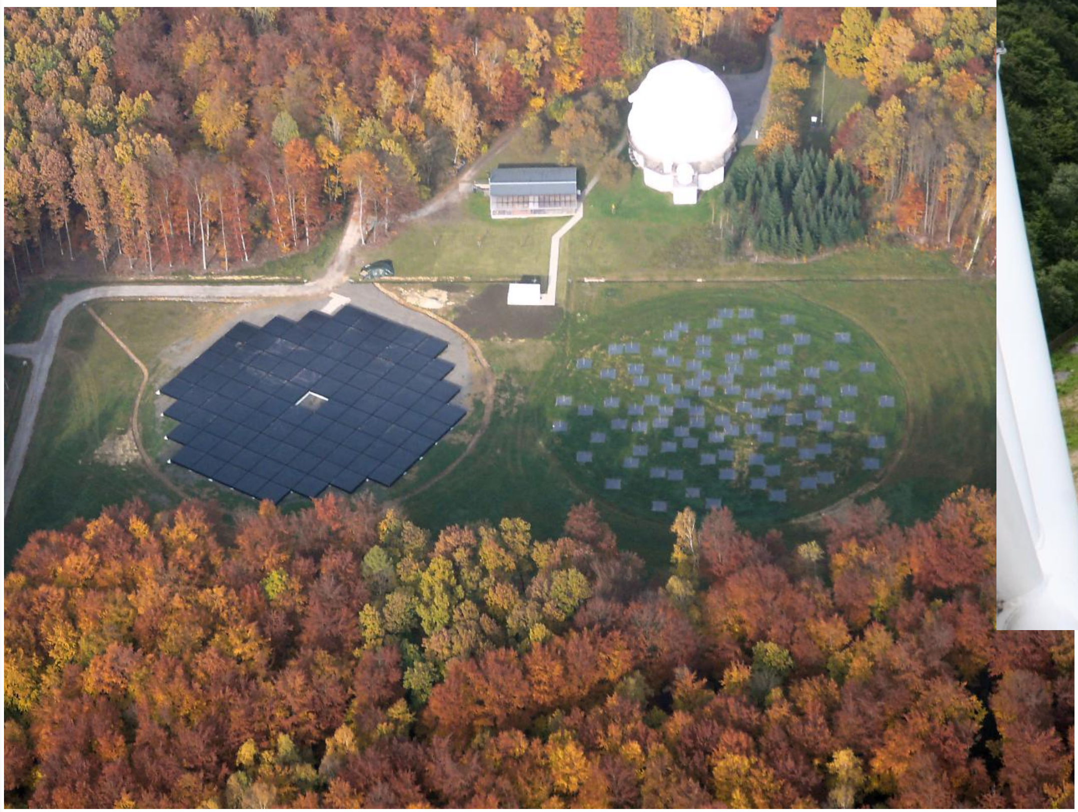
The SUPERTERP in the core (6 stations)

International stations in Germany

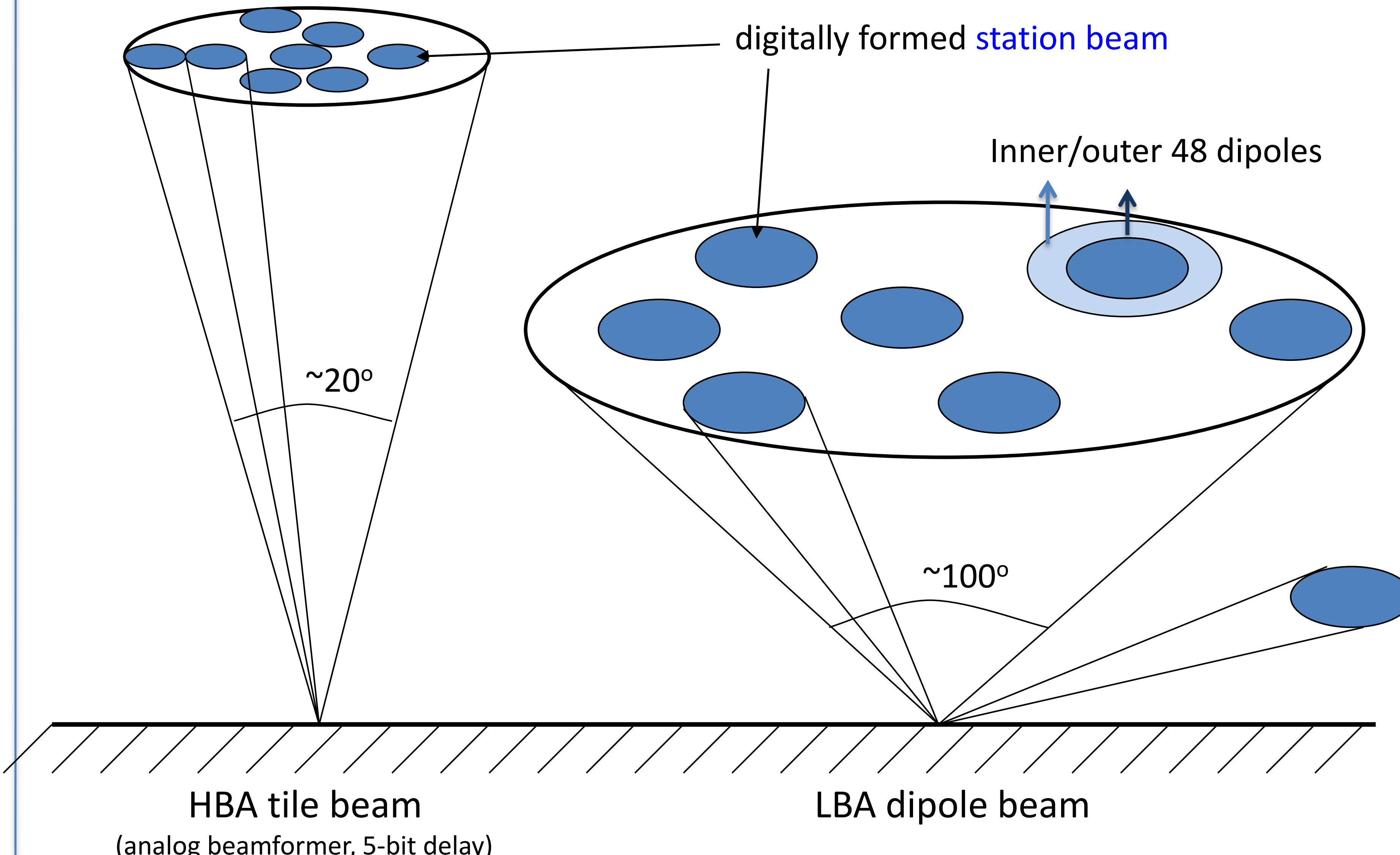
Effelsberg

Tautenburg

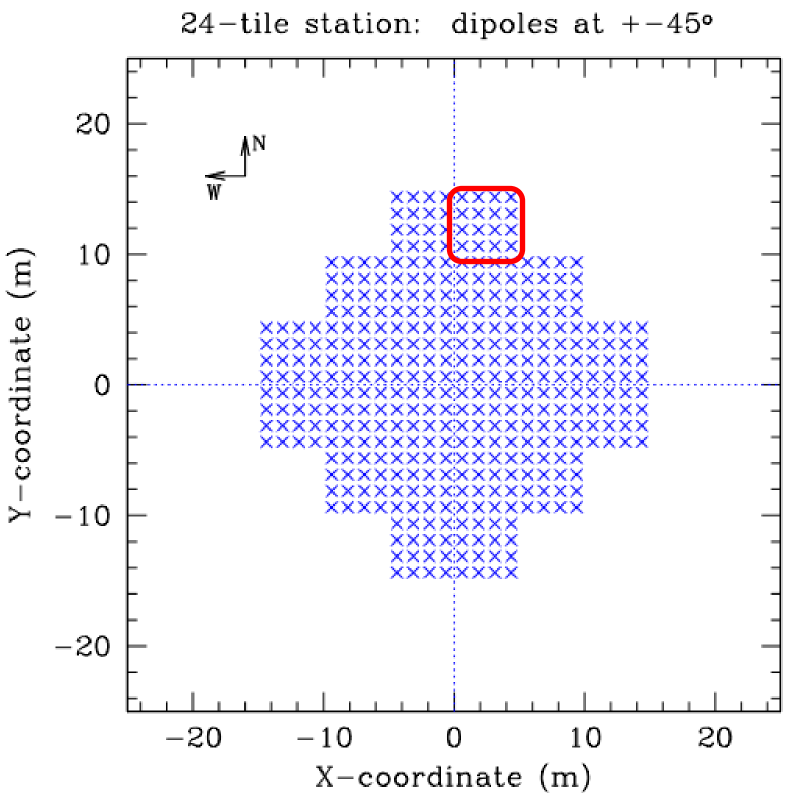
96 tiles

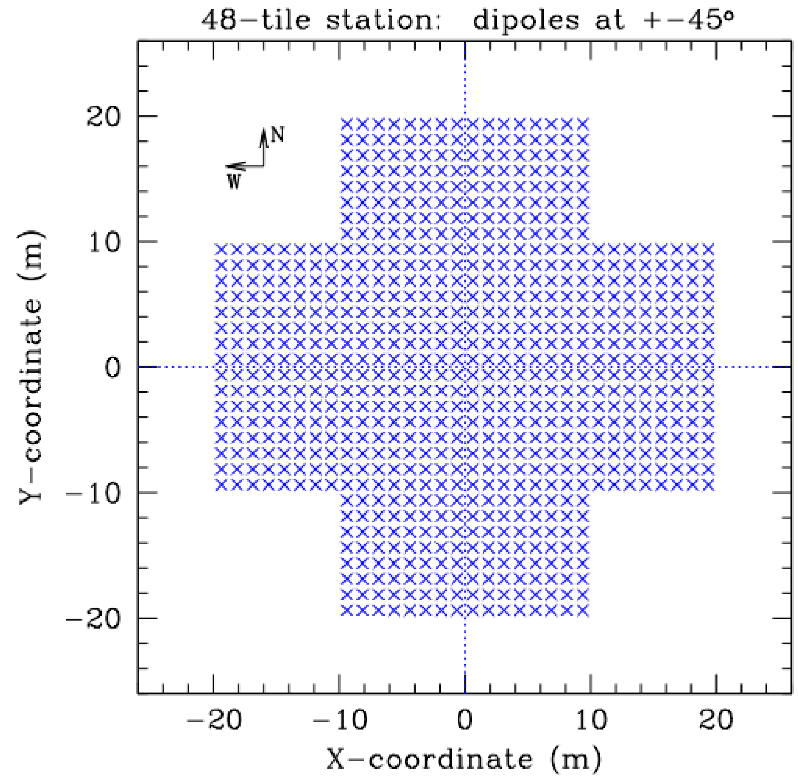


LOFARs very wide Field-of-View (good & bad !)



Two station sizes in NL: 24-tile (CS) and 48-tile (RS)





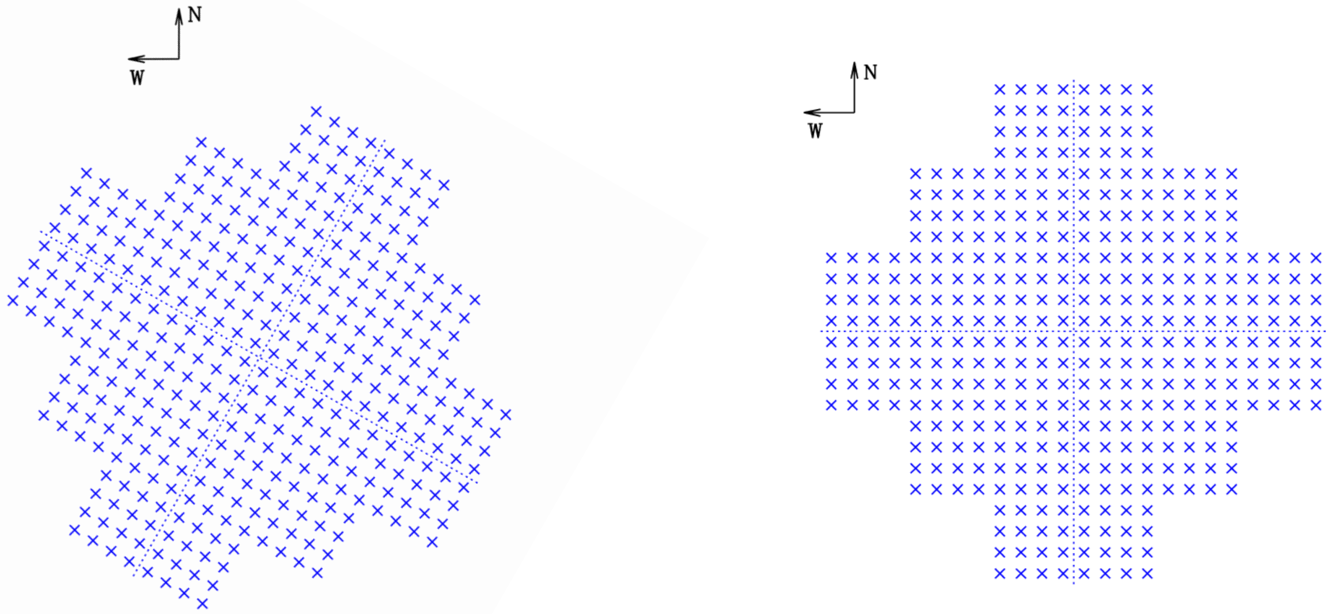
24-tile (CS)		48-tile (RS)
600 m^2	physical area	1200 m^2
~ 2000 Jy	SEFD (150 MHz, zenith)	~ 1000 Jy

Combatting grating lobes

At frequencies > 120 MHz the tiles produce grating lobes on the other side of the sky for lowish elevations. To combat these we rotate the stations, and back-rotate the antennas within the tiles

$\Rightarrow$ **all dipoles remain parallel (X)**

30° rotation



LOFAR: station rollout status (preview LSM 15-Sep-10)

Station/Item	Cabinet	LBA	HBA	Fibre	CEP connection	Validated
CS302						
RS307						
RS503						
RS106						
RS208						
CS030						
CS401						
CS021						
CS032						
RS306						
CS301						
CS501						
RS509						
CS103						
CS001						
CS002						
CS003						
CS004						
CS005						
CS006						
CS007						
CS024						
CS201						
CS101						
CS026						
RS205						
CS017						
CS011						
CS013						
CS028						
CS031						
RS104						
RS210						
RS310						
RS404						
RS406						
RS407						
RS409						
RS410						
RS508						
Effelsberg						
Tautenburg						
Garching						
Potsdam						
Juelich						
Nancay						
Onsala						
Chilbolton						
Totals	39	37	37	32	30	27

Projected to be operational
in (late) Autumn 2010

24 (x2) CS Core Stations
9 RS Remote Stations
3 IS International Stations

→ 60 HBA stations
→ 36 LBA stations

→ Largest array in the world !

LOFAR calibration framework

New aspects compared to 'standard' selfcal on existing dish-arrays:

- **Major direction dependent corrections**
  - Phase => 'non-isoplanaticity' of the ionosphere (low freq, wide FOV)
  - Gain => elevation/azimuth dependent beamshape → work with **intrinsic** sky models !

- **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)

  e.g. **B**andpass, electronic **G**ain, beam (**E**-Jones) , **I**onospheric refraction, **F**araday rotation

Developed largely in- house: Bregman, Hamaker, Noordam, Brouw, de Bruyn, Wijnholds, Yatawatta, Brentjens, Nijboer, … + Leiden ionospheric group (Rottgering, Intema, van der Tol)

LOFAR has superb frequency resolution

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

Frequency filtering done in two digital (Poly-Phase-Filter) stages:
- at station $\Rightarrow$ 512 subbands (either 156 or 195 kHz)
- at CEP (BG/P) $\Rightarrow$ 256 channels for each of 248 subbands split

RFI & wide-field VLBI

(+ 21cm & rec lines)

48 MHz total bandwidth **63,488** channels of 0.8 kHz !

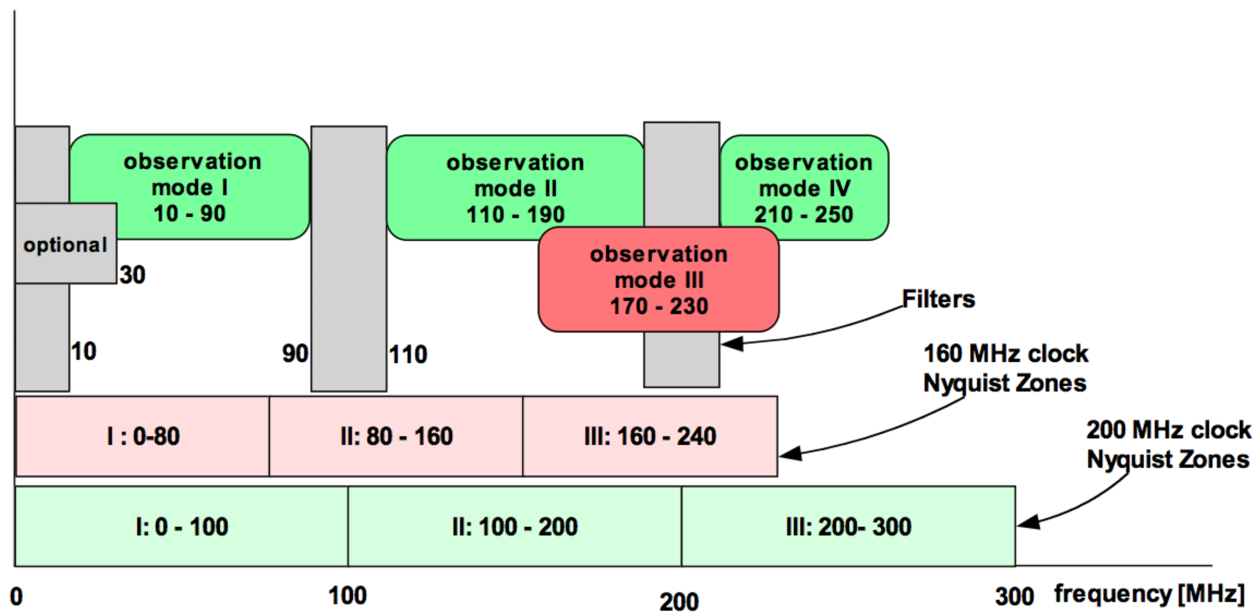
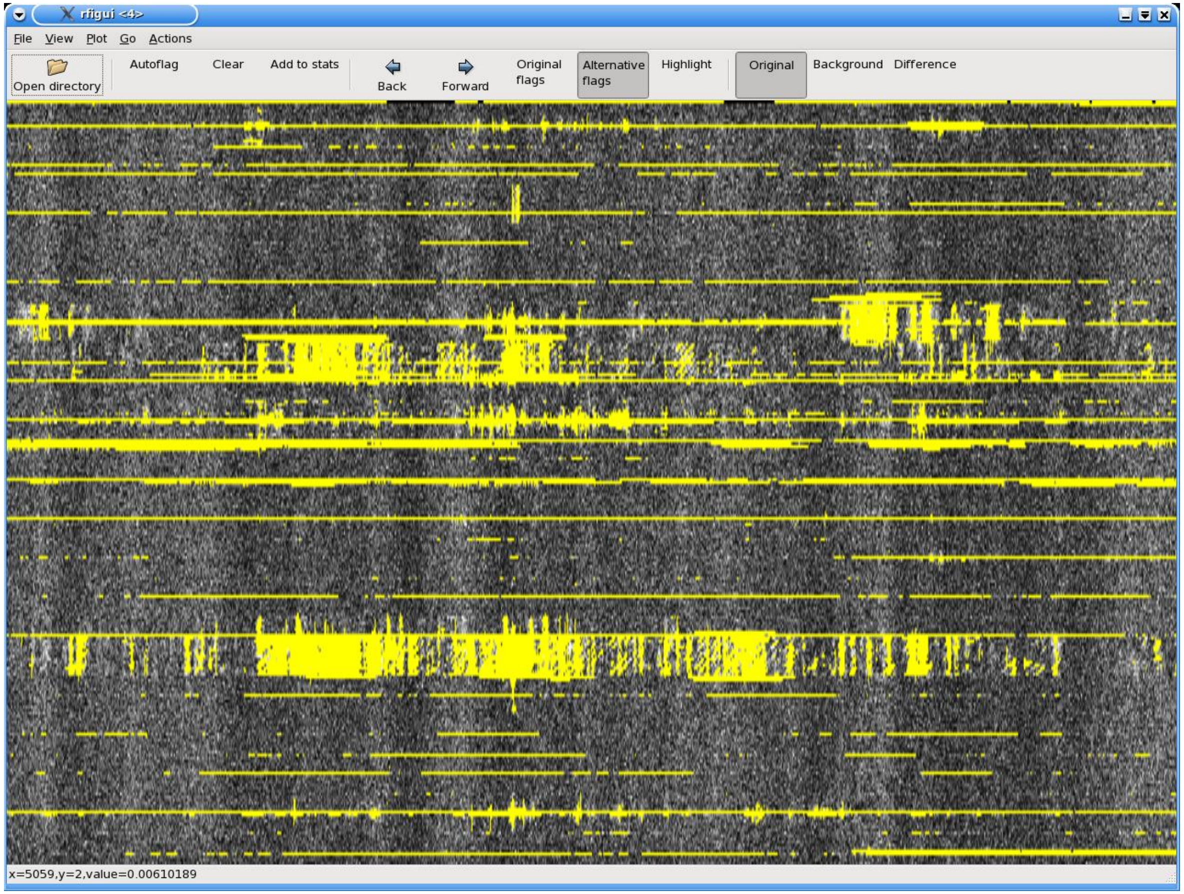
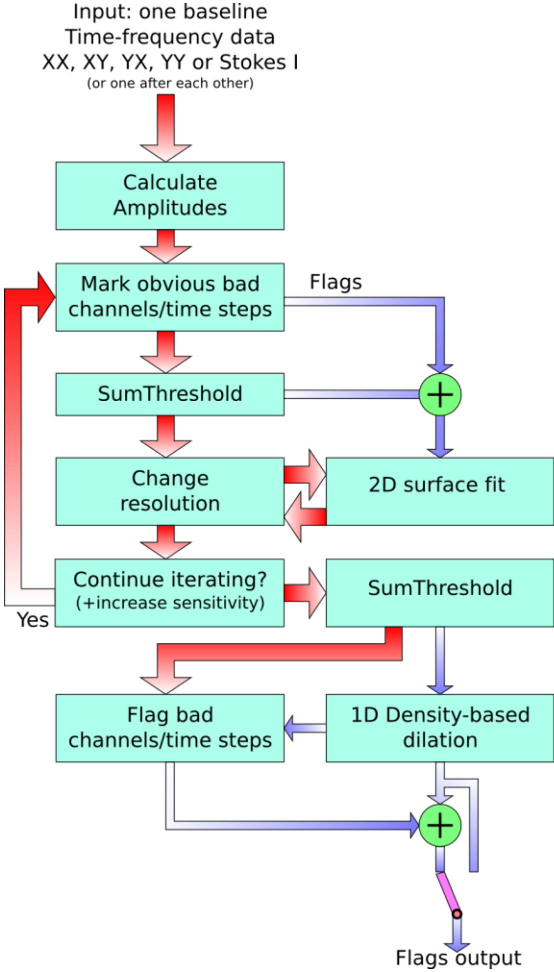


Figure 10 *Selection of Nyquist zones is used to select the observed band in the station.*

Andre Offringa's RFI-flagger (MNRAS, 405, 155, 2010)

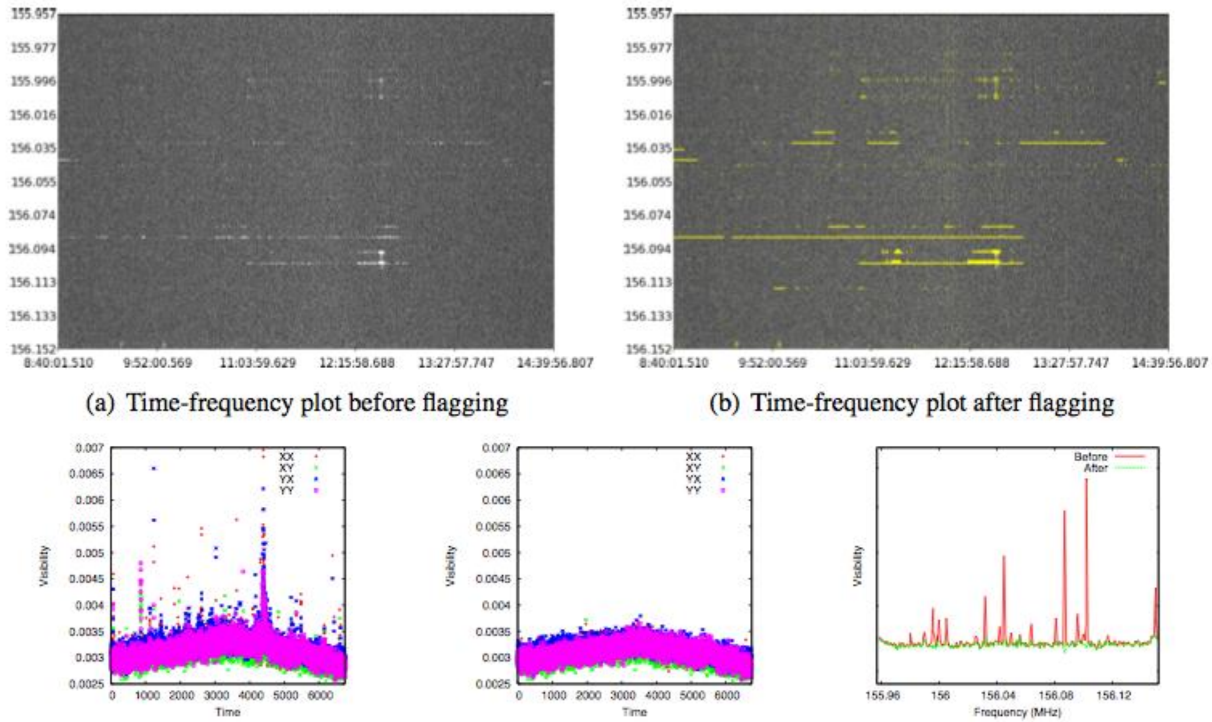
WSRT data around 145 MHz





AO-flagger performance on LOFAR data

LOFAR RFI pipeline A.R. Offringa



(a) Time-frequency plot before flagging (b) Time-frequency plot after flagging

(c) Amplitude plot before flagging (d) Amplitude plot after flagging (e) Power spectrum

Figure 3: *Flagging results of the 6 hour LOFAR observation L2010_07096 of April 24, 2010. All plots show the same sub-band around 156 MHz for baseline CS302_HBA1 × CS005_HBA0 with one second integration time. The flagging pipeline was run with its default settings, and 1.8% of the data is flagged. As can be seen from panels (a), (c) and (e), this sub-band contains relatively many interfering transmitters, yet all of them are relatively weak. The panels (b), (d) and (e) show the cleaned band after flagging.*

0.78 kHz

3s

6h in daytime
24 Apr 2010

Some recent LOFAR hw/sw developments

Station calibration algorithms/procedures ready for implementation

Rapid increase in # stations from 10 + 5 + 1 to 15 +7 +3 (target 22 +18 +8)

All 6 stations on the superterp share the same clock (→ coherent addition)

Multi beam (5 !) observations on 3C196

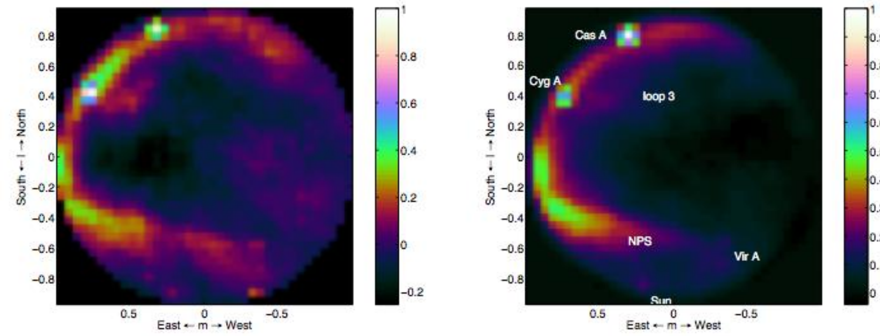
Offline cluster: 8 subclusters each with 9 nodes x8 cores

Parallellized pipeline processing

After switch from 16-bit to 4-bit transport:
Future 48MHz-beams → 192MHz-beams throughput
Limited by ~ 50 Gbit/s output/storage

Station calibration procedures:

2.4 Fish-eye imaging — Wijnholds, thesis mar10 — 29



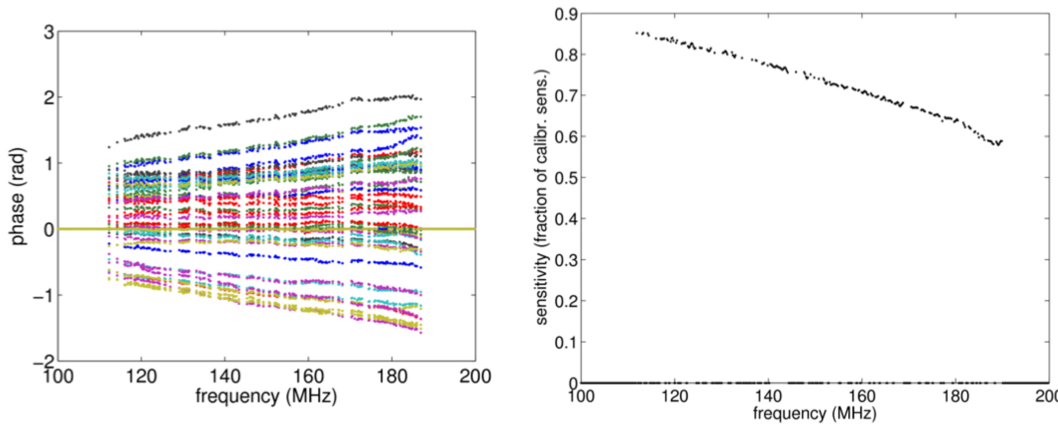
LBA station calibration via Least Squares Intensity Mapping using the whole sky (not just CasA and CygA)

Gain loss due to ill alignment of phasors

15% loss @110MHz, increasing to 40% @180MHz

HBA station calibration via intra-tile redundancy calibration

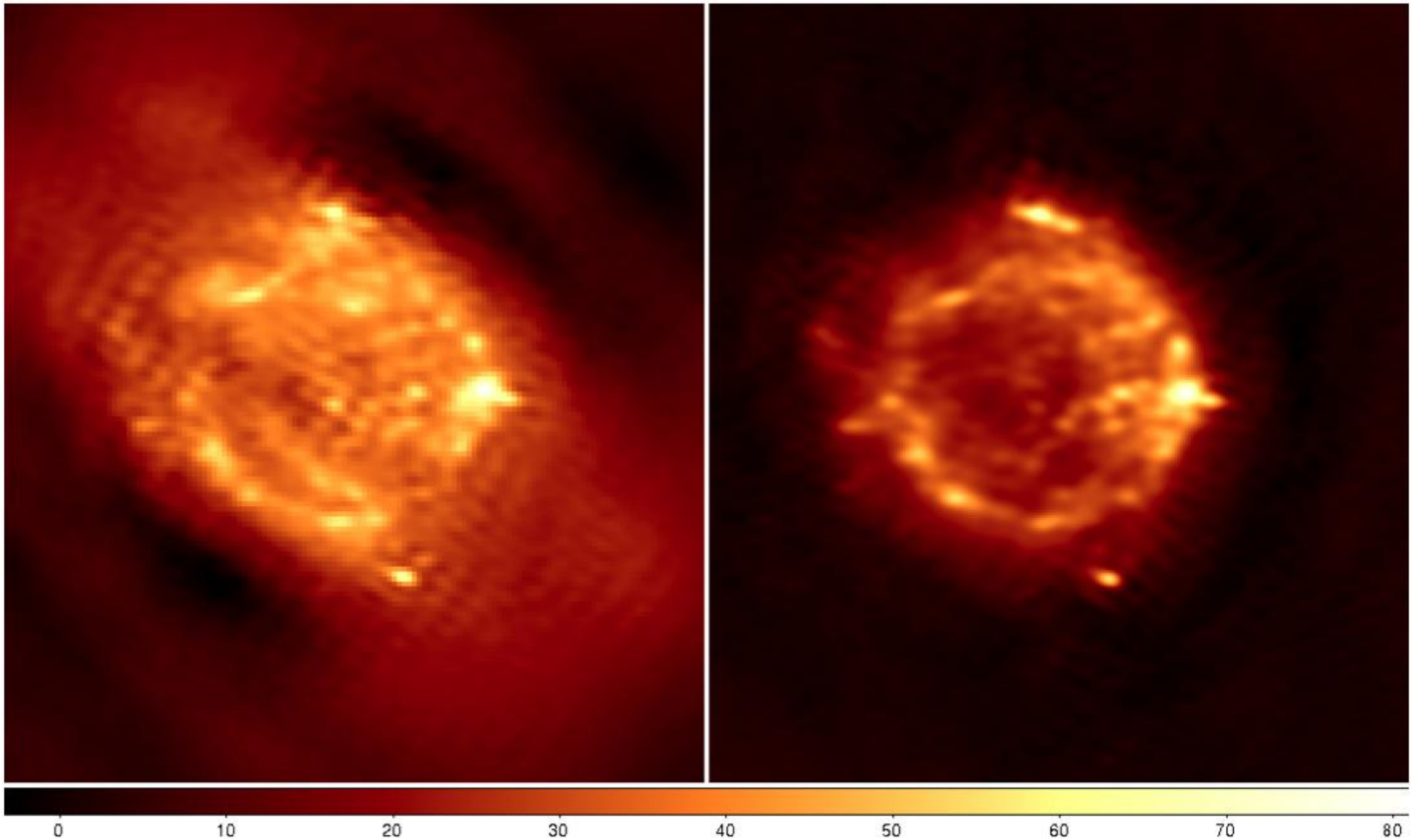
Currently still poor ‘alignment’, ‘collimation’, ‘focusing’



LOFAR Status Meeting, Dwingeloo, 9 December 2009 - 11 -

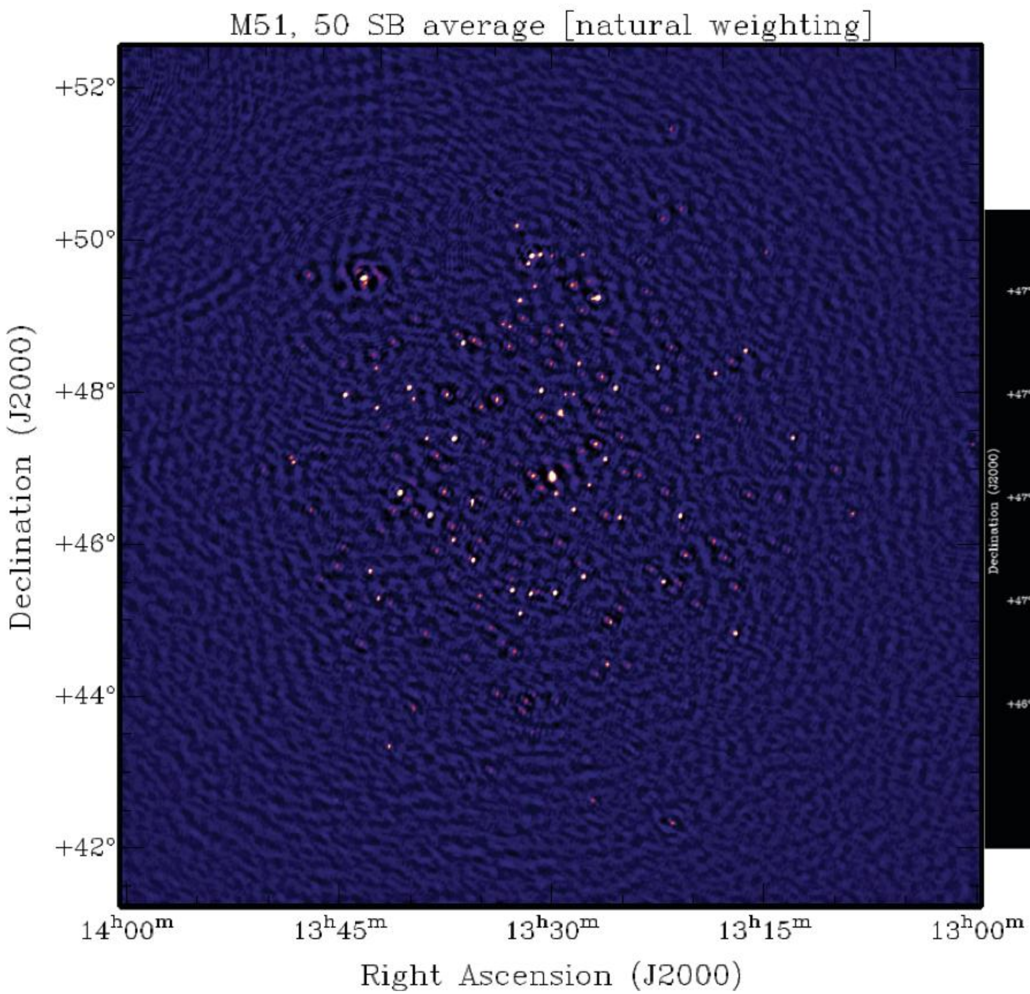
Some imaging results

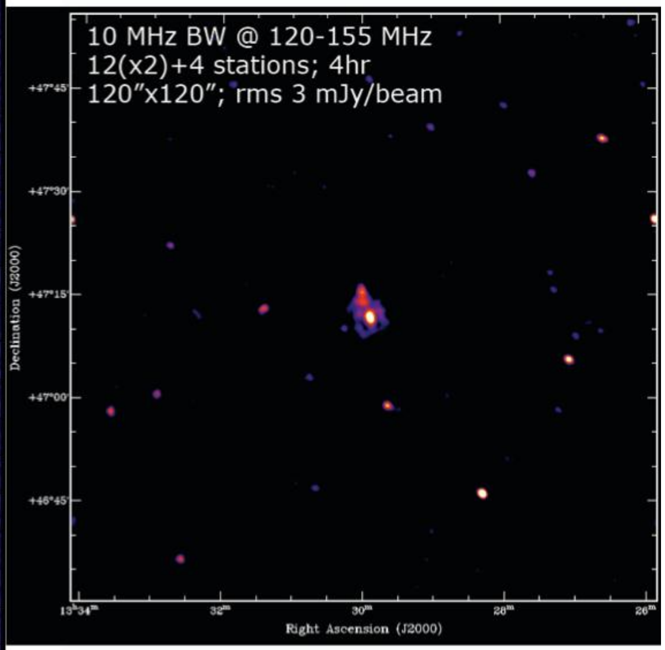
Partial array late 2009 | Array of Summer 2010



CasA 115-170 MHz [Brentjens, Yatawatta, in prep.]

Automated pipeline results



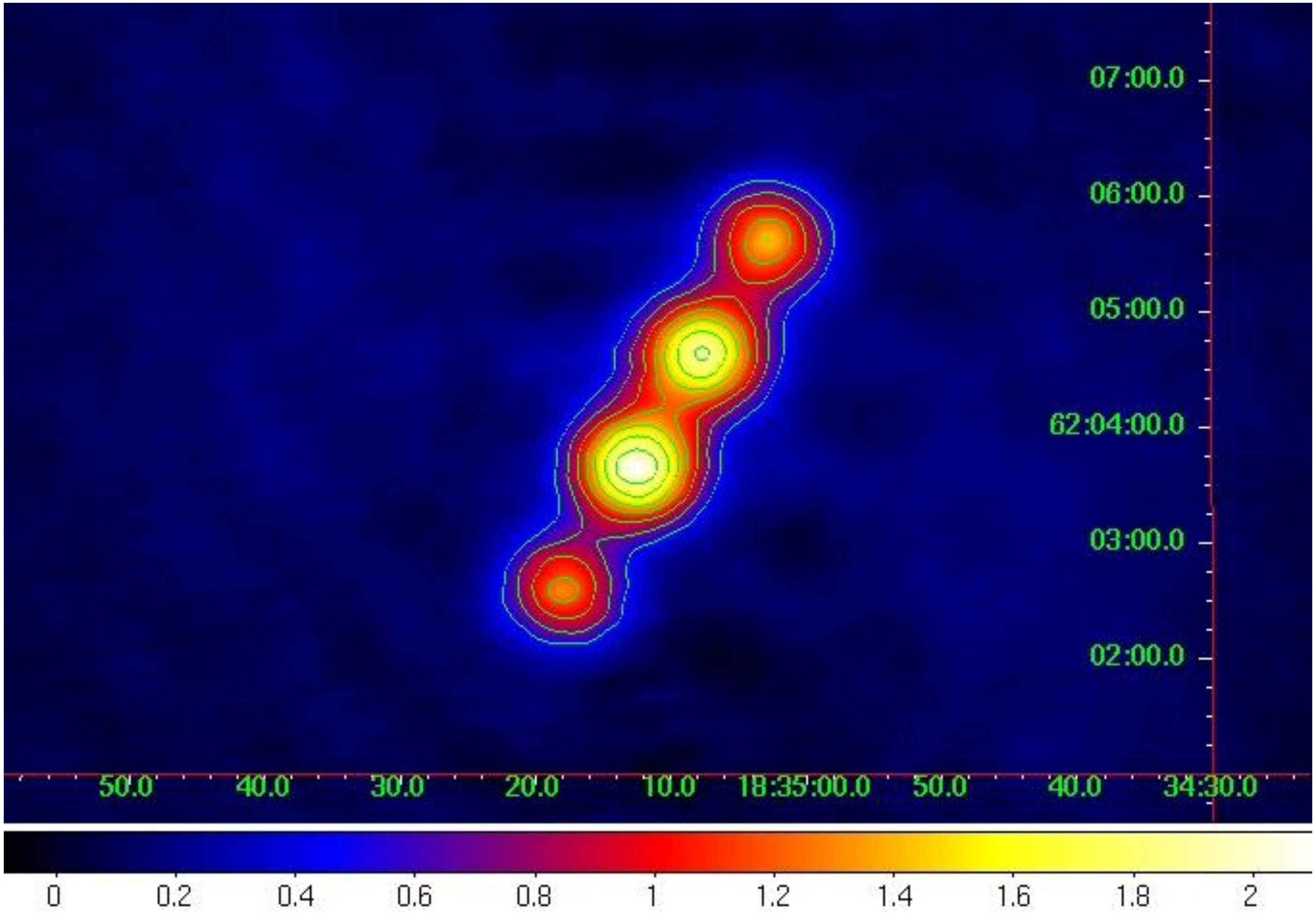


Courtesy (George Heald)

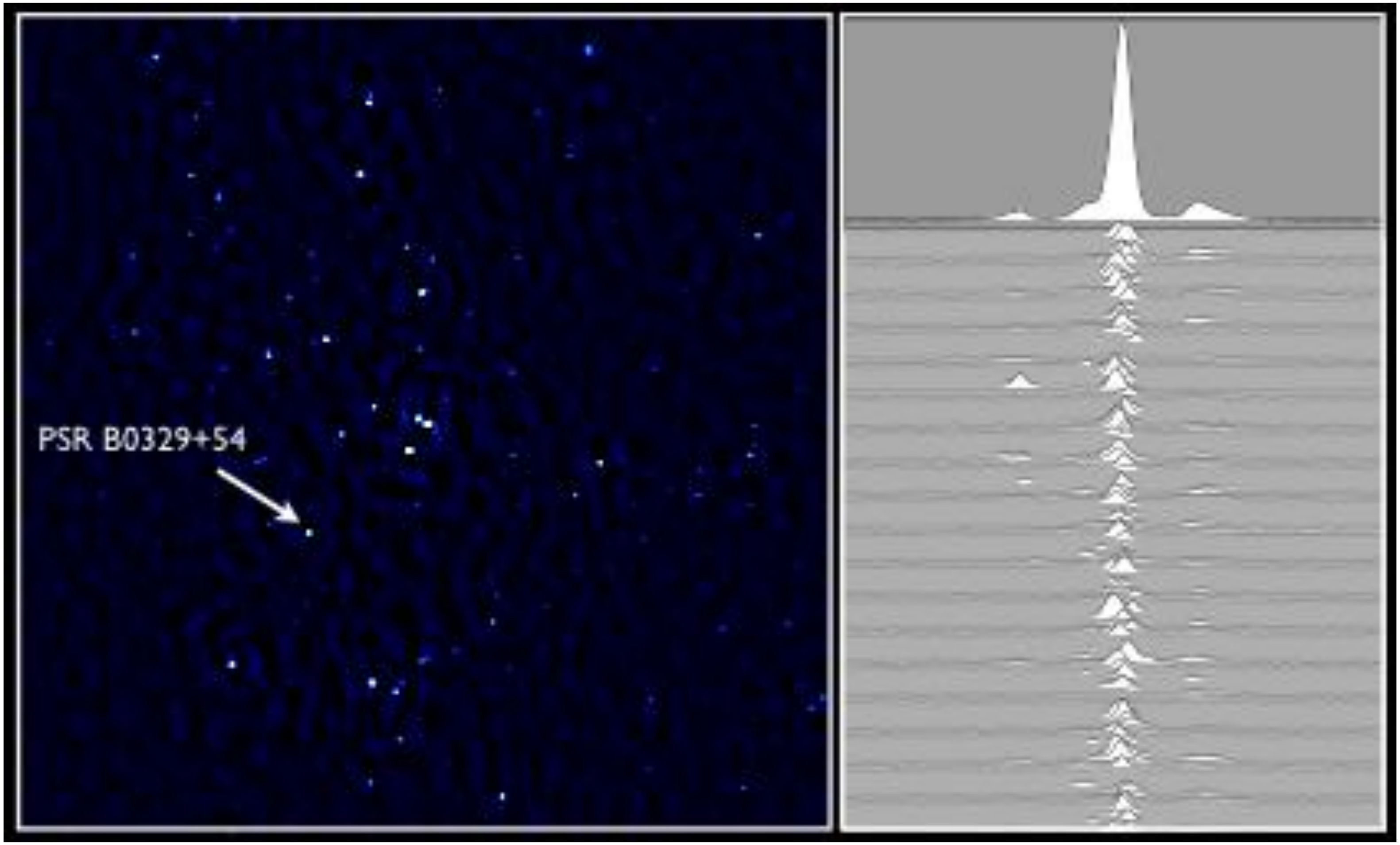
More imaging results

Polarized Double-Double Radio Galaxy B1834+620 ~ 150 MHz, ~ 10 km array

Poster Jana Köhler et al.

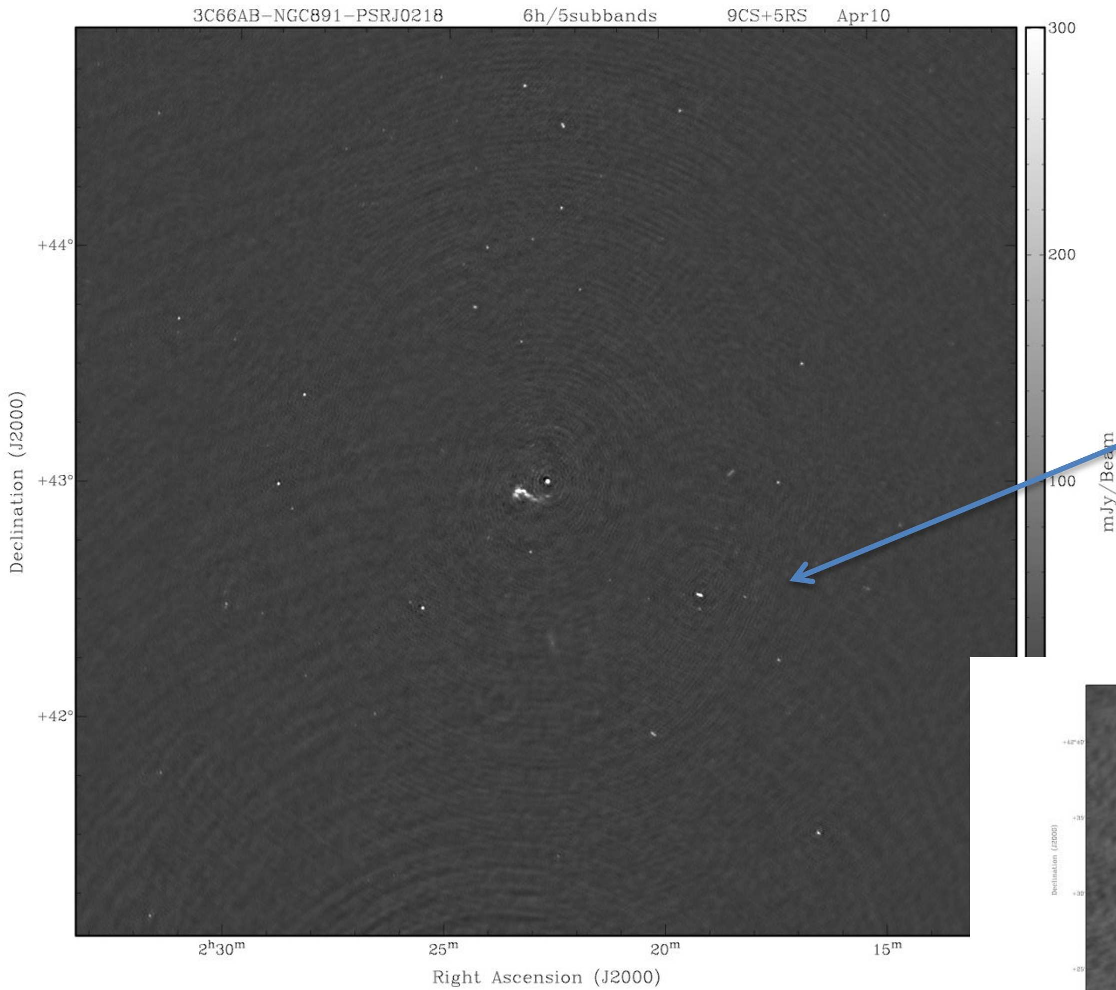


Simultaneous pulsar timing + imaging: PSR0329+54



Jason Hessels et al

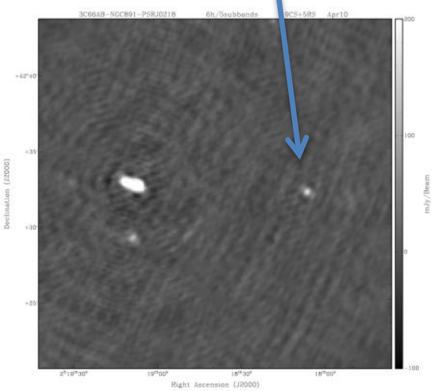
3C66AB-NGC891-PSRJ0218 6h HBA 24Apr10



PSRJ0218+4232

S $_{150MHz}$ ~ 500 mJy

50% linearly polarized



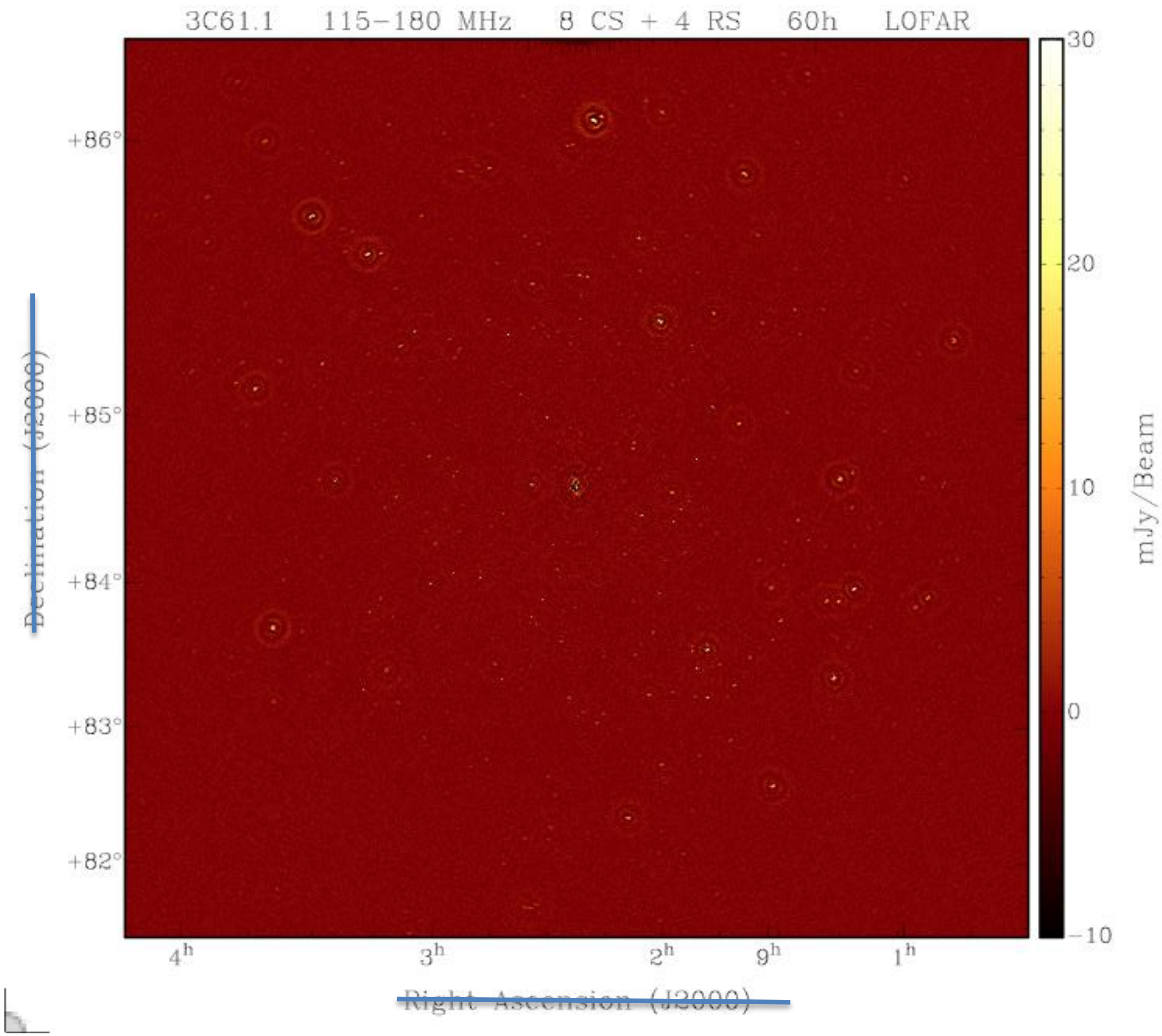
3C61.1 close to North Celestial Pole (elev=53°)

8° x 8°
7200x7200 pixels
10” PSF

60h 20-22 Dec 2009
14 MHz bandwidth
8 CS + 4 RS

Only brighter 100
sources deconvolved

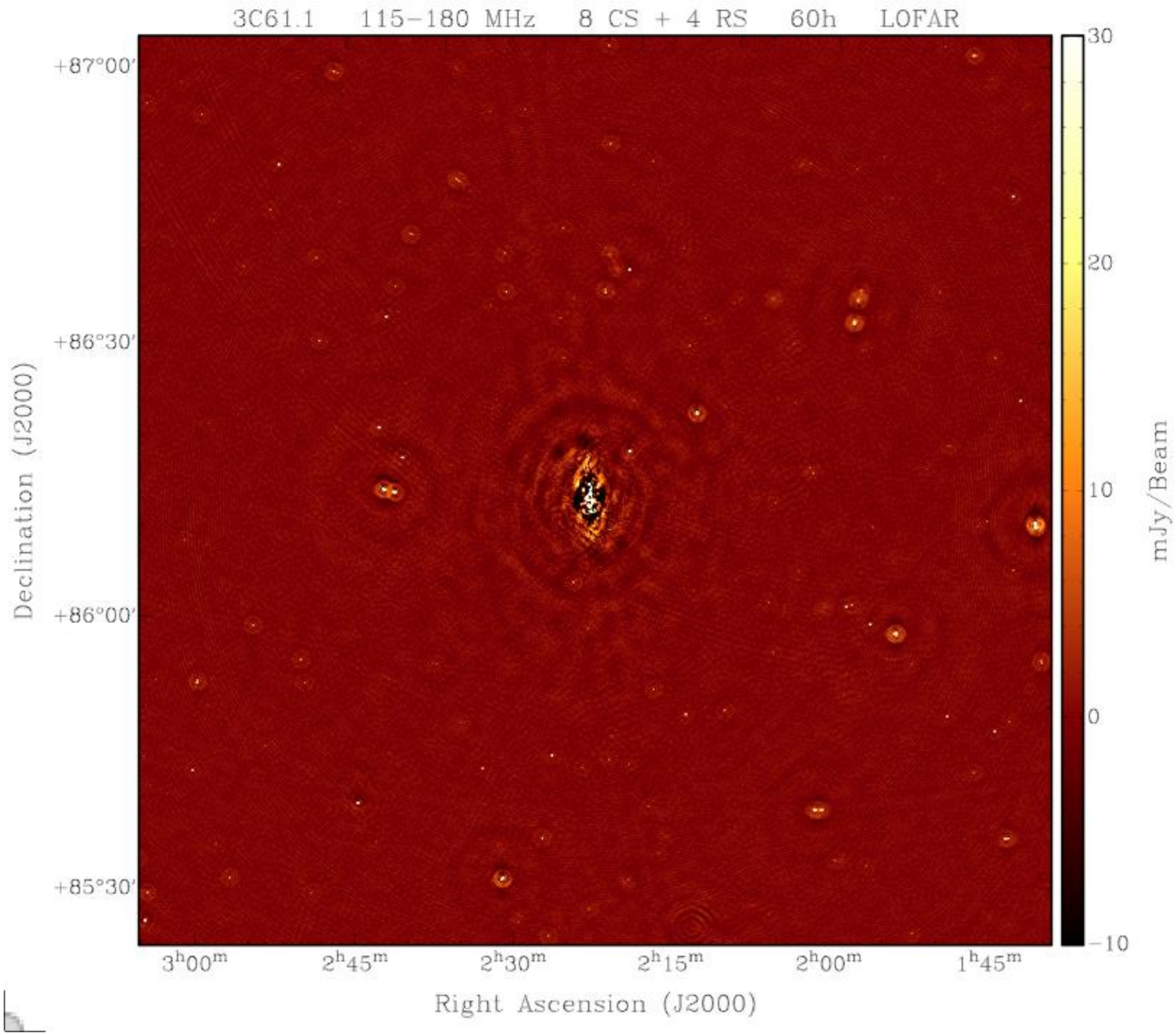
Sarod Yatawatta



Inner
1.7 ° x 1.7 °

50 sources per square degree >10 mJy

Still poor 'cup-saucer' PSF

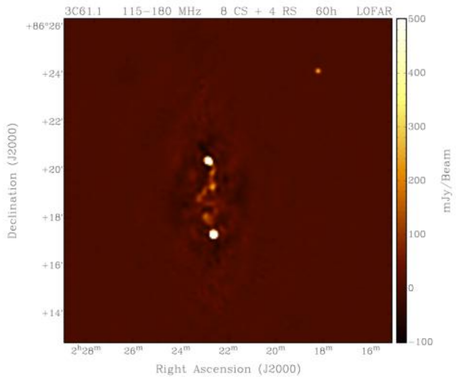


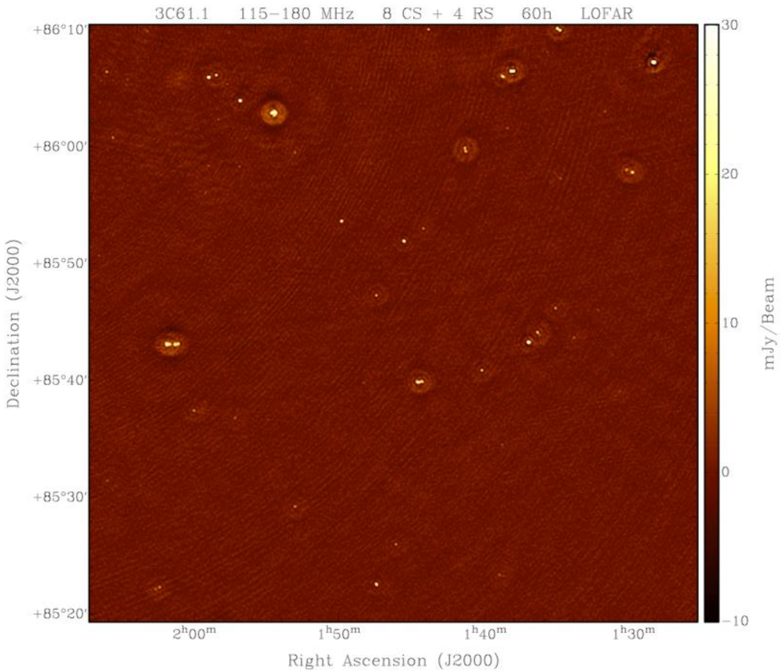
Noise level ~0.6 mJy
(only factor ~ 3 away from thermal noise)

3C 61 peak 10 Jy → DR ~ 15000:1

Remaining artefacts in this deepest LOFAR image (with only ~ 12 stations) are due to:

1) Sidelobes very distant sources
2) Very poor station beampatterns
3) 3 sizes for interferometer beampatterns
4) Deconvolution issues on 3C61.1, causing rippes across field





Ionospheric TEC modeling

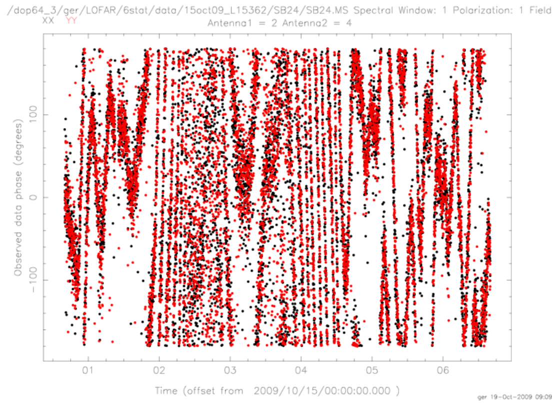
1) Both refraction and Faraday rotation depend on absolute TEC which changes relatively slowly with time and direction

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

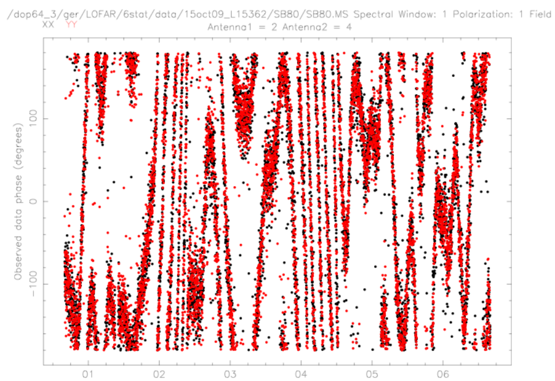
3) Ways to measure absolute TEC:

- Monitor differential refraction across wide angles
- Observe Faraday rotation (FAN-region, pulsars)
- Use GPS data
- Use snapshot all-sky observation sequences (e.g. 10s every 120s) and combining absolute+relative delays

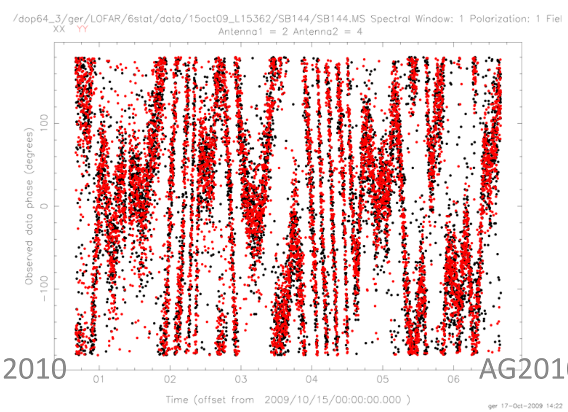
Observing a (polarized?) pulsar in the LBA band



35 MHz



45 MHz



56 MHz

SNR ~ 3 (in 180 kHz, 3s)

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

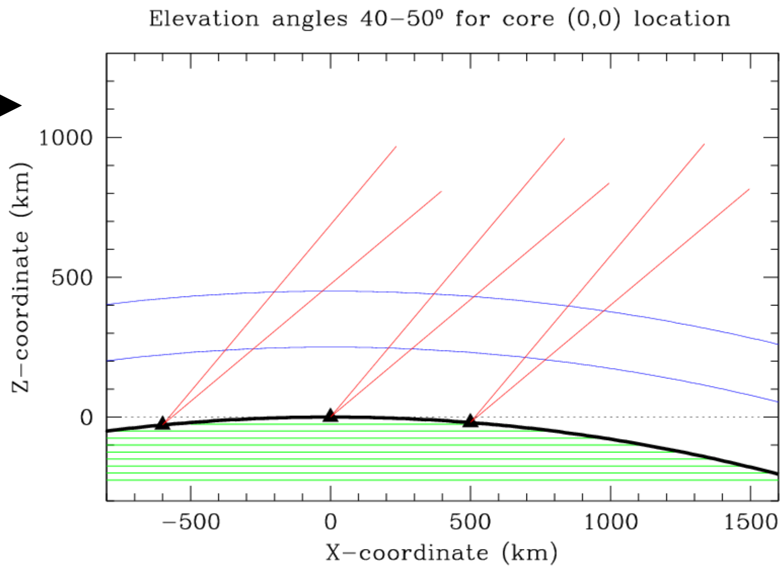
The estimated flux of the pulsar must then be about 150 - 350 Jy (to within a factor ~2)

Fluxes still uncertain because of unknown station gain and skynoise

European baselines: non-overlapping screens !

Basic problems of wide-FOV European LOFAR:

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



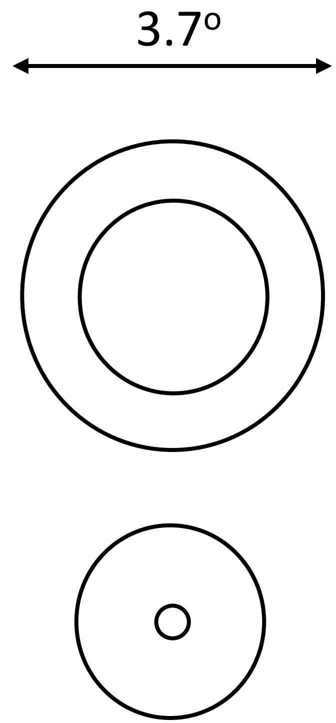
A possible solution (for HBA)

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) NB: 30s x 600 km/h ~ 5 km ~ 1^{o} at 300 km height

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

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

Summary of current commissioning issues

Final verification of single-clock superterp (benefits VLBI work)

Validating station calibration ('beamserver')

Parametrization of station beams

Streamline multiple/simultaneous direction-dependent BBS solution

Apply direction-dependent errors (beams/ionsopheric screen)

Further integration of all pipeline components

Compare ionospheric TEC solutions with Faraday rotation data on selected pulsars

Prepare for the northern sky calibrator survey: MSSS (next slide)

The LOFAR Million Source Sky Survey (MSSS)

LOFAR needs a *Global Sky Model (GSM)* for the northern sky which

- has a proper flux scale
- has validated (initial) source parameters (spectrum, structure, ..)
- is astrometrically correct to better than 0.5”
- interfaces efficiently to calibration & imaging pipeline (through the LSM)

This survey will take about 3 months at 50% efficiency at should deliver about 1 million sources.

Carrying out MS^3 will also

- create a ***joint focus for activities***
- integrates scheduling, monitoring, processing, calibration & imaging
- test all KSP-pipelines
- provides a field-test for storage and processing resource needs
- will be a dress-rehearsal of full LOFAR operations

Conclusions

- Imaging wide fields with 30 km baselines down to 30 MHz achieved
- Sub-mJy noise levels reached in HBA band (115-185 MHz)
- DR ~15000 achieved in 3C61.1 field (dec =+86^o) and 3C196 (dec=+48^o)
- Very wide field images (>5 degrees)   (still benign ionosphere)
- European LOFAR scale imaging succesfully conducted
- Scheduling(SAS), monitoring (MAC), multi-beaming and multi-application integrated

Current LOFAR dynamic range still limited (factor 10 from noise) because of:

1) Uncalibrated (=unfocused) stations beams
2) Still not very good snapshot uv-coverage (rapidly getting better)
3) 6 different effective HBA-beams (24-24, 48-48, 24-48, 96-96, 24-96, 48-96)
4) No application of direction-dependent effects (DDEs) as yet

MSSS calibartion survey expected to start in the Autumn 2010

Lots to do,   Stay tuned ,   watch the AJDI   (Astron Jive Daily Image)