LOFAR calibration: a status report

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Outline

- overview of LOFAR calibration regimes

- what will NOT be covered in this talk

Recent achievements, developments, insights:

- Data quality monitoring: the start of it all
- removing A-team: peeling, demixing, filtering
- sub-mJy noise and high DR images
- ionospheric issues and results
- polarization imaging, DFR, RM-synthesis

-- novel calibration: SAGEcal, NCP field results

LOFAR calibration requirements

- Station calibration

- Synthesis imaging calibration

    - offline
    - real-time (on-line)

- Solar imaging

- European baselines

- Pulsar calibration: tied array and polarimetry

- Interplanetary Scintillation calibration

- UHECR calibration

Related ‘synthesis’ talks following

- Imaging (casapy, cimager) → Cyril Tasse
- Polarization observations → Andreas Horneffer
- Very long baselines → Olaf Wucknitz
- Pipeline processing and MSSS → George Heald

Evolving calibration management/steering structure

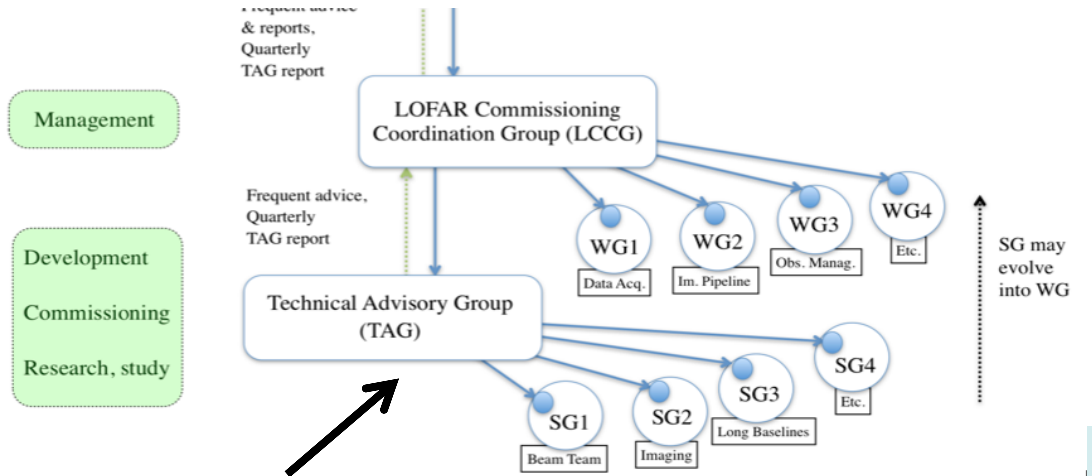
Complicated history…..

1999… Jaap Bregman
2004… Stefan Wijnholds (ITS,….)
2006 Jan Noordam (Calibration Frame Work, LOFAR ADD #15)
2006 Calibration Review (Perley, Cornwell, Rao, ...)
2007 → Ronald Nijboer (Cal PM), Ger de Bruyn (Cal PS)

- 2007 - LOFAR descope, calibration workshop

2007-09 Calibration Advisory Group (Brouw et al)

2010 LCCG → TAG → Working/Study Groups



Chair Ronald Nijboer

LOFAR synthesis calibration: complex and daunting

- time-varying station beams

- many different beamsizes
  - LBA inner/outer and 48/96 dipoles
  - HBA 24/48/96 tiles
  - rotated stations

- broad frequency range
  - LBA 20-80 MHz
  - HBA 115-240 MHz

- ionosphere:
  - large (differential) refraction effects
  - scintillation

- all-sky imaging hence need
  - Global Sky Model and Local Sky Models
  - flux scale, polarization
  - astrometry

- huge volume of data
  - several Tbytes per observation)

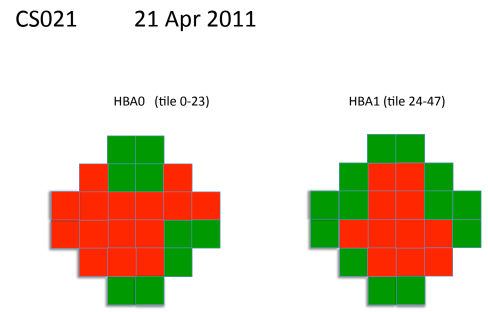
- iterating between uv-plane and image-plane
  - imaging/deconvolution
  - application of DDE's

- (new) Measurement Equation, full polarization, differential Faraday rotation, new software

Calibration steps and tools

Preliminaries (NDPPP):

- RFI flagging
- Averaging of data
- Flag intra-station (129m) baselines
- Flag bad stations, e.g. CS021



Current procedure for manual, interactive, calibration (using BBS):

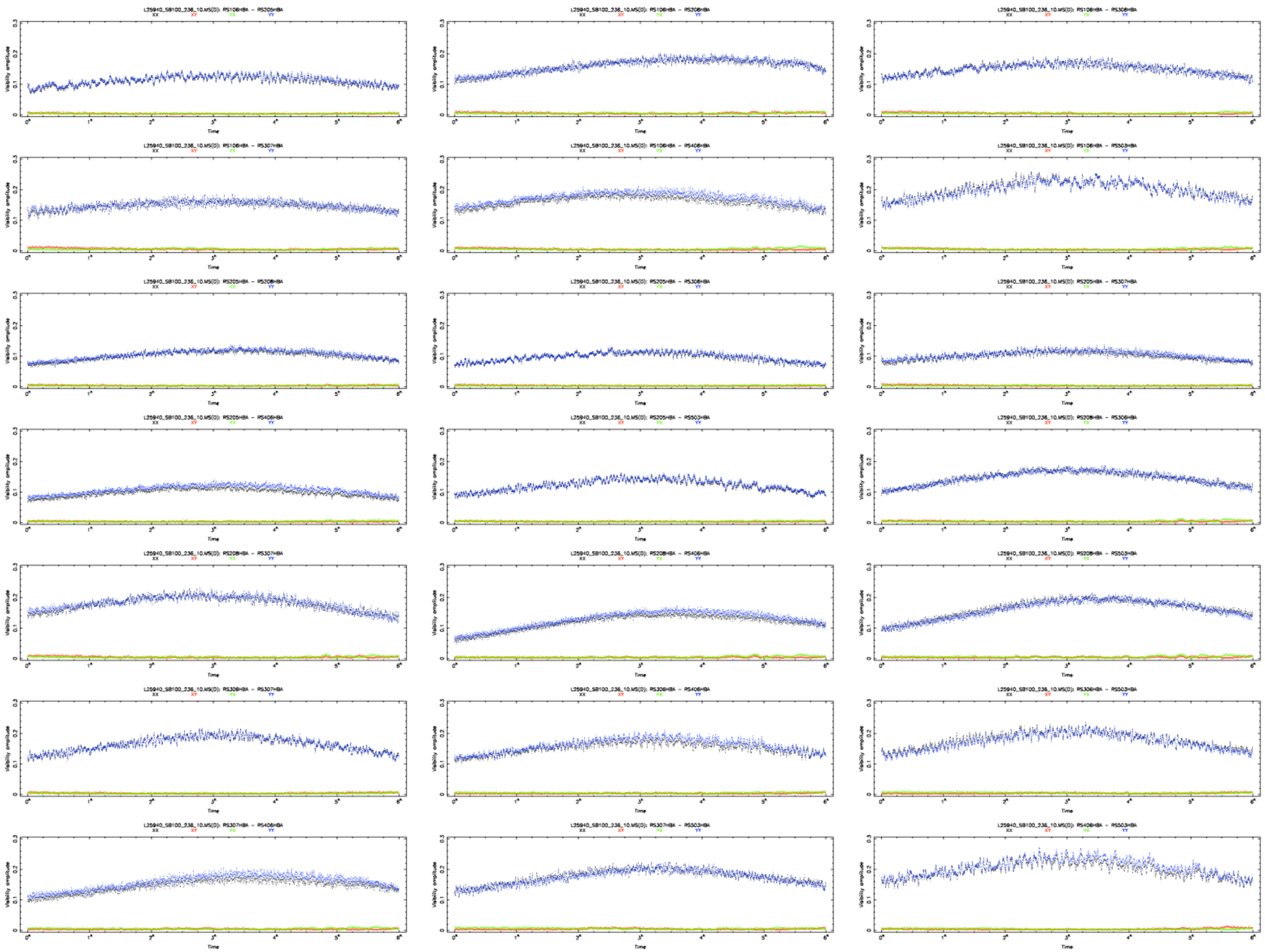
Strategy depends on a lot of things: LBA/HBA, brightest source in field, short/long baselines, nearness of A-team, etc etc.

- analyse data quality (S/N, phase stability)
- decide on required integration time (2s, 10s ?)
- use calibration transfer ? Calibrator near in time and location (?)
- construct a proper sky model (VLSS, WENSS, WSRT-LFFE, .. LOFAR GSM)
- start with single subband processing, then go to wideband (BBS-global)
- image a large field → update sky model
- start Direction Dependent calibration and remove sources

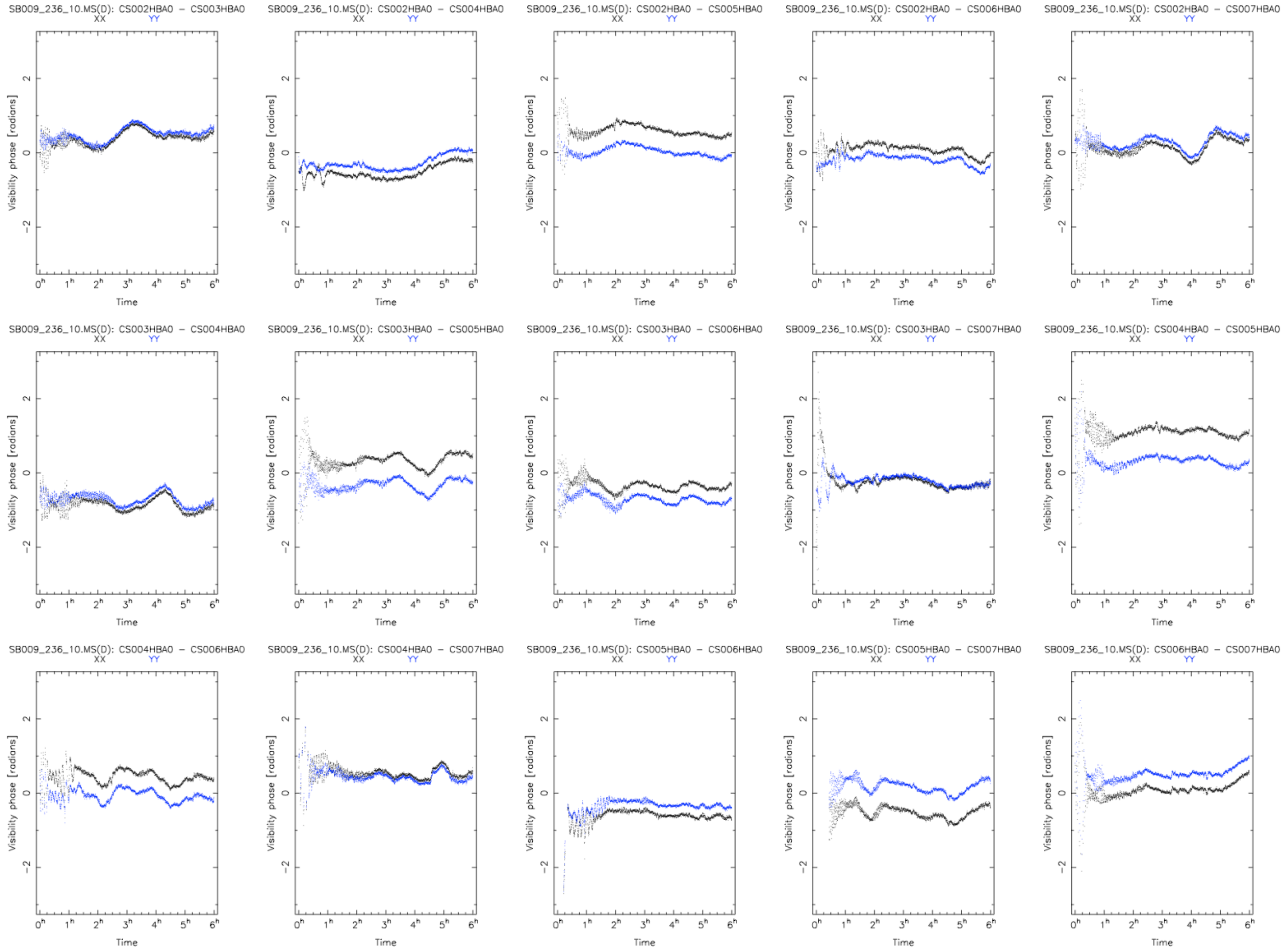
LOFAR data quality monitoring and SEFD’s (Jy)

3C196 SB100 7 May 2011

RS106
RS205
RS208
RS306
RS307
RS406
RS503

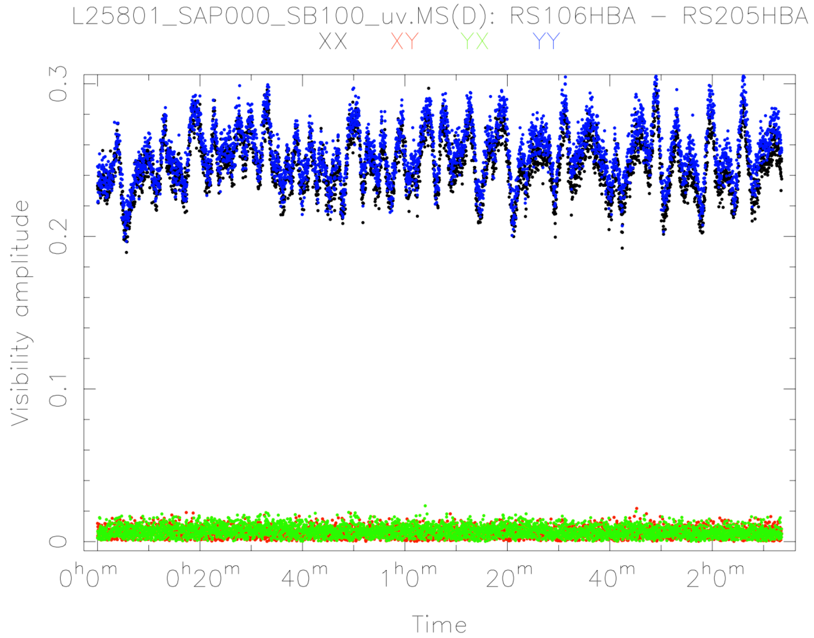


Superterp phase-stability SB009 15Apr2011

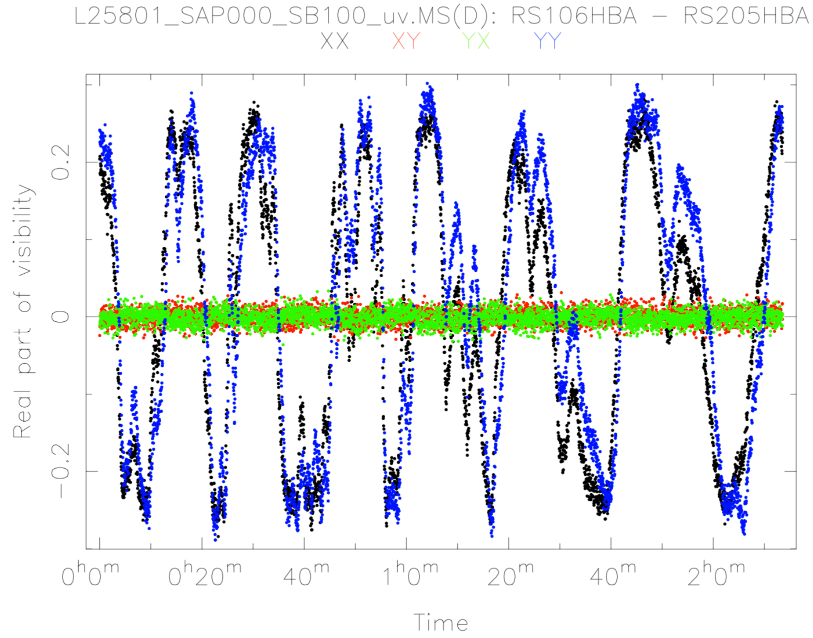


RS106-RS205 data: ~2h around transit at 2s

Amplitude



Real



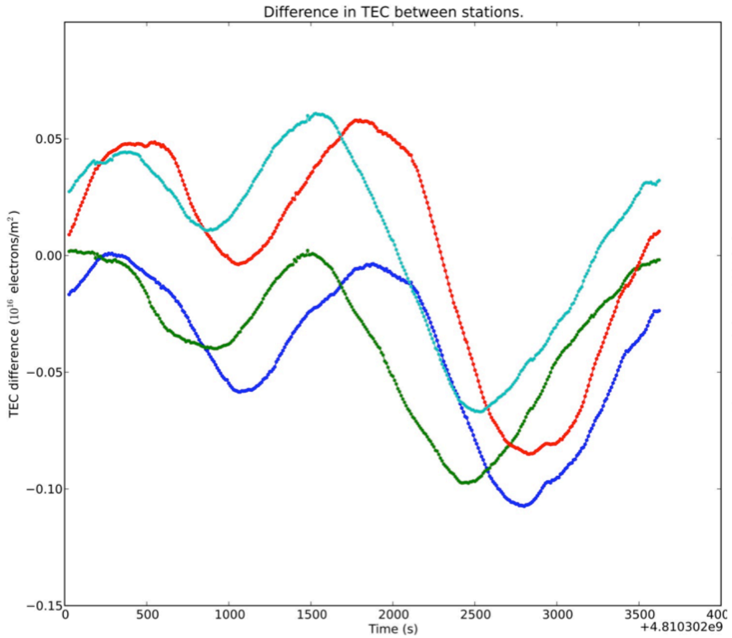
In dt=2s and df = 16ch (48.6 kHz) we find a S/N = 27.7
For a flux density of S = 83 Jy → noise ~ 3.00 Jy

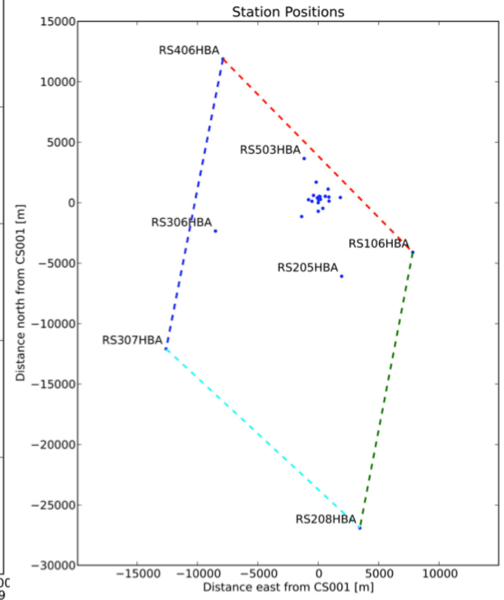
→ SEFD = 3.00 Jy * SQRT(2.dt.df) = 1321 Jy (48 tiles)

LOFAR and ionospheric effects

Ionospheric TID's over LOFAR

0.1
TECU





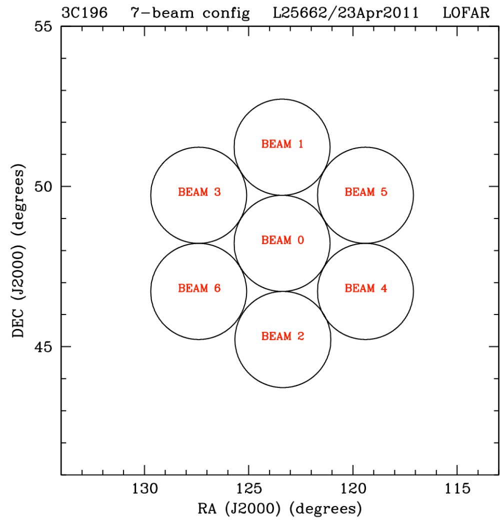
Mark Aartsen,
ASTRON 2011
Summer student

AJPOD today !

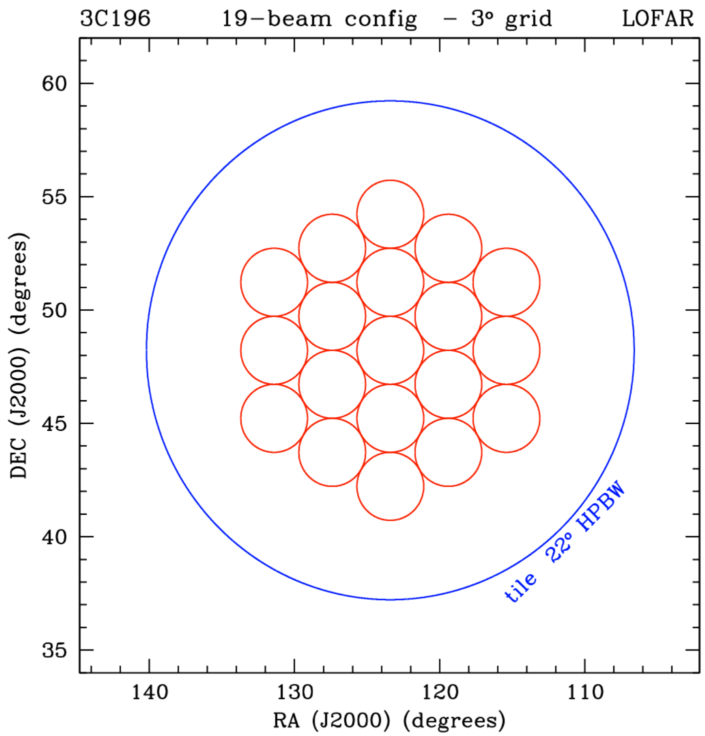
Wave duration ~ 1800s
Delay across ~20 km ~ 300s

→ TID wavelength ~ 1800/300 x 20 km = 120 km !
→ Speed 120 km/0.5h = 240 km/h

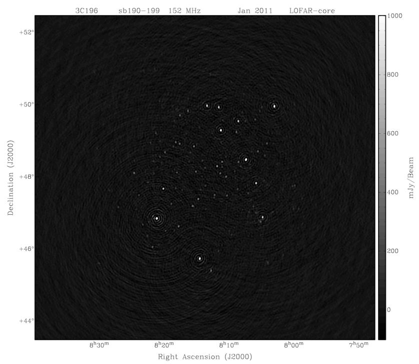
Direction of wave propagation South → North



Next step: determine height of TID's



Central beam



Matching the TEC-patterns towards many bright sources in multiple-beam observations we will be able to determine the height of the TID region !

(5.7^{o} at 300 km = 30 km)

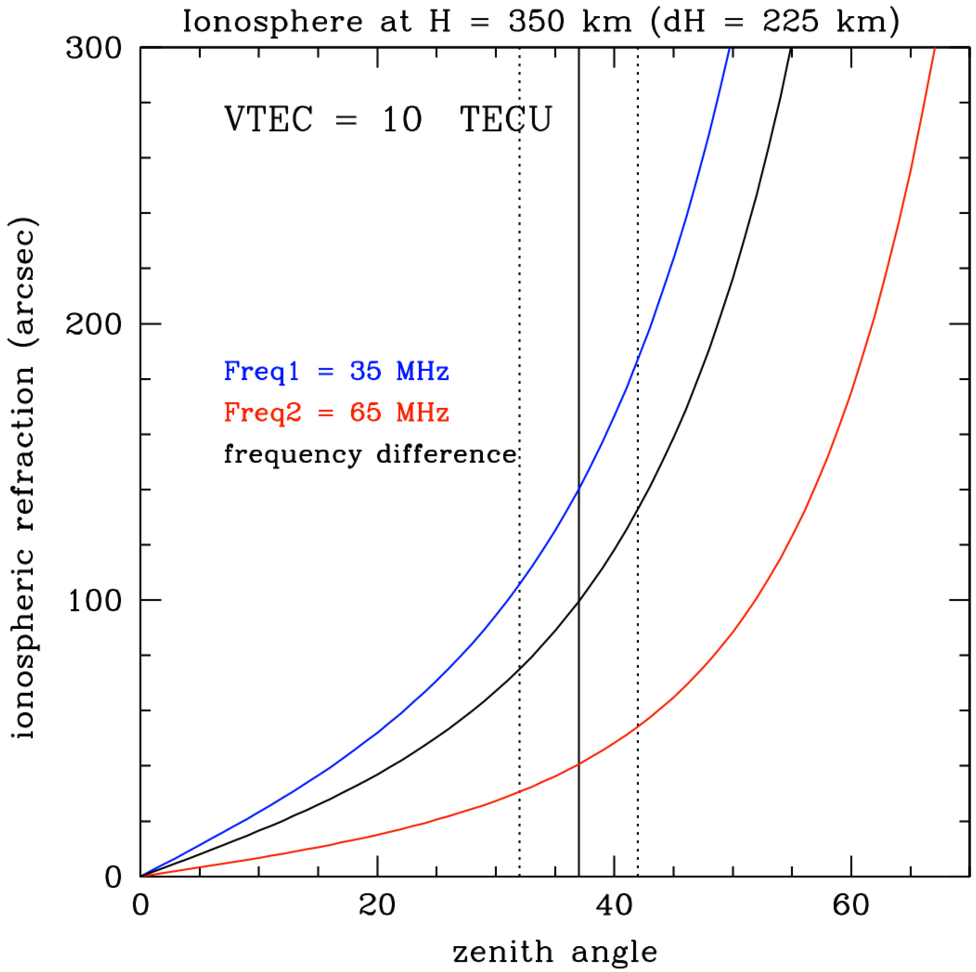
Future work:

- Going from 7 to 19 beams
- baselines to 80 km (RS509)
- using LBA data (noisier)

Initial ionospheric 2-D, (3-D?) framework, a la SPAM (Intema et al, 2010)

Ionospheric Tomography (Koopmans, 2010)

Using wide-field data to determine absolute TEC



For the NCP field (constant elevation of 37°) we can expect a **differential** shift across a 10° field of about 60” between 35 and 65 MHz.

This should be easily detectable !

Work in progress

Polarizations issues in calibration (cf Horneffer)

- Projection and Field rotation
- Time-variable ionospheric Faraday rotation
- Spatial-differential Faraday rotation (converting Stokes I into V)
- Instrumental polarization across the wide field

The first effect is taken into account in the (Hamaker) dipole beam model.

The DFR is still acceptable on short baselines. A procedure has been developed and tested by Sarod to solve for it.

Ionopsheric Faraday rotation, especailly at night, still small (and predictable)

The instrumental polarization across the FOV of an HBA station beam appear to be rather benign. This allows RM synthesis to be run on the Q,U images without sophisticated polarization calibration.

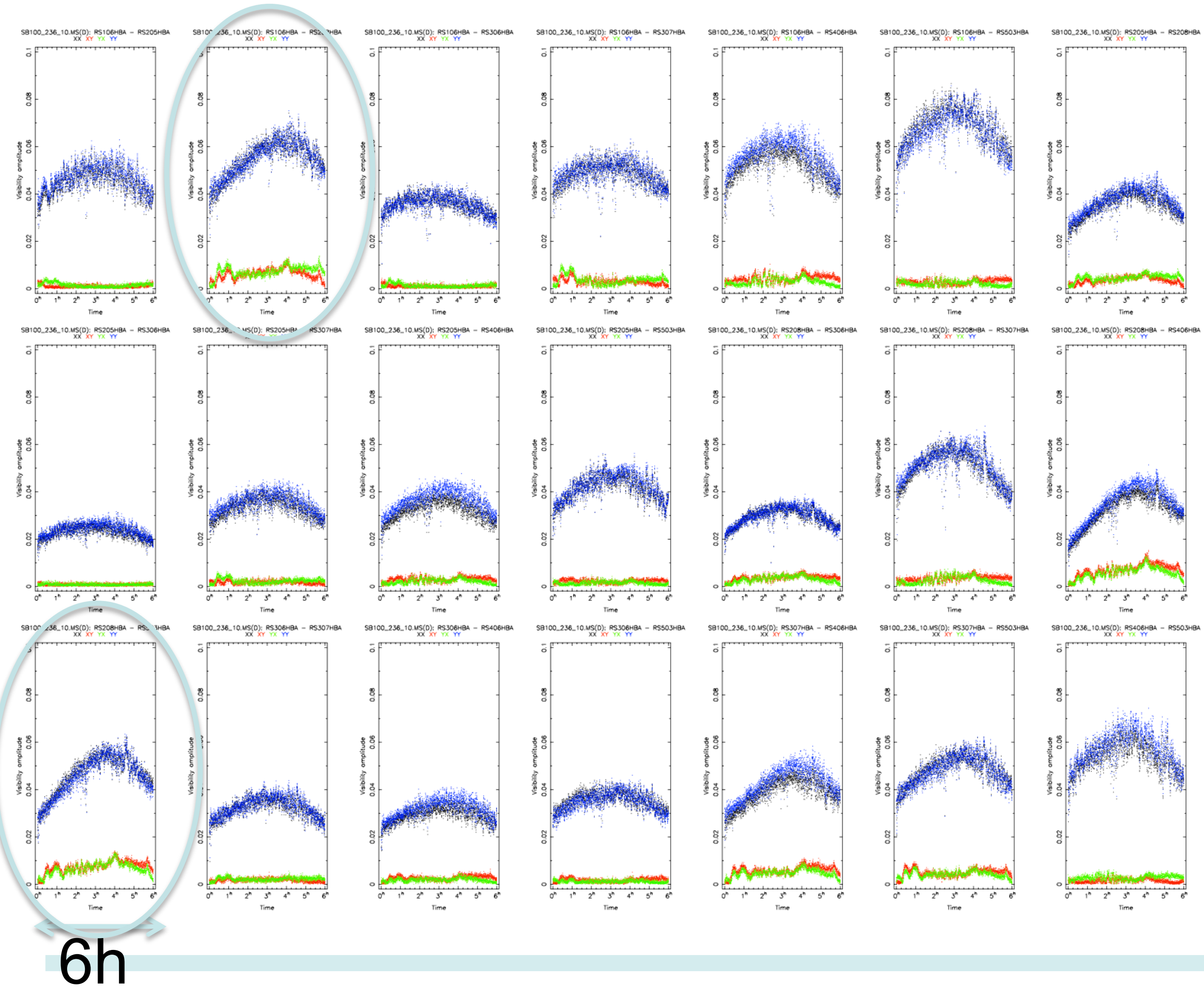
Results of extended Galactic foreground polarization (e.g. FAN) to be shown later (Horneffer, Pizzo, Jelic)

Visibilities (raw) between 7 Remote Stations

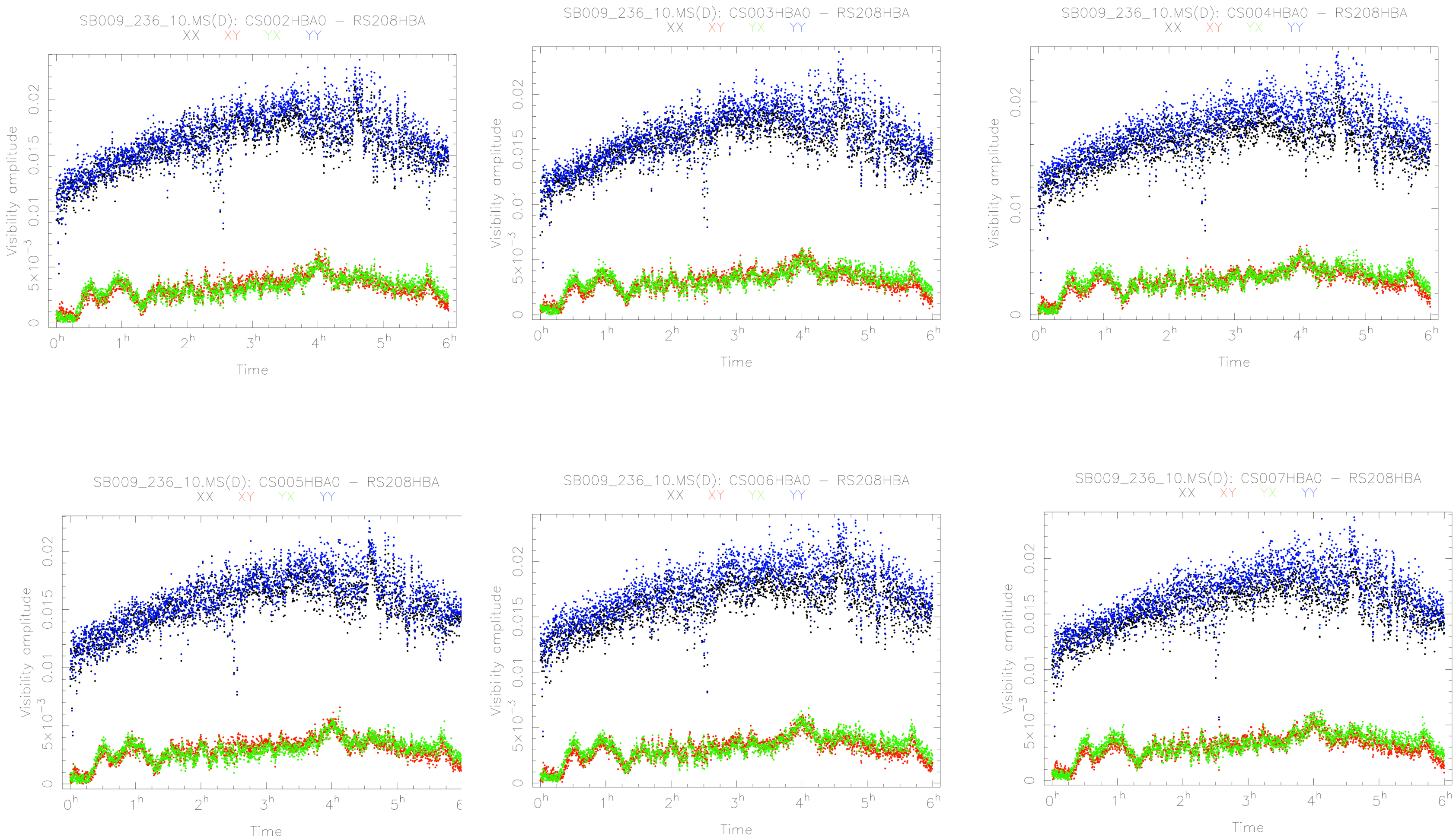
135 MHz
11 Mar 2011

RS106, RS205
RS208, RS306
RS307, RS406
RS503

Note the time variable XY and YX signals



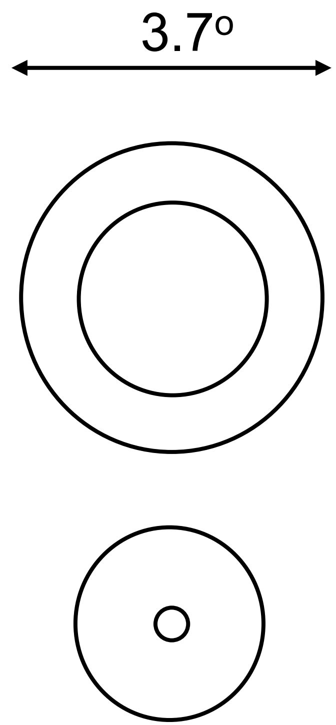
Identical DFR between RS208 and 6 superterp stations



Note the close agreement of the XY & YX signals on these 6 almost identical baselines !

European calibration issues (HBA 150 MHz)

#antennas	noise (Jy) (10s,15 MHz, 2pol)	FOV (HPBW, deg)
Eu96 - NL48 (65m - 40m)	0.04	2.3x3.7
Eu96 - ST288 (65m - 300m)	0.02	2.3x0.5



Assumed SEFD: 2600 (24 tiles) , 1300 (48 tiles) and 650 Jy (96 tiles)

Coherent addition of ST-stations before or post correlation is possible.

Very high dynamic range and source structure

In the HBA we should achieve ~0.1 mJy noise after 6h.
With typically ~ 5 Jy sources in a random field we therefore need a Dynamic Range of about 50,000:1.

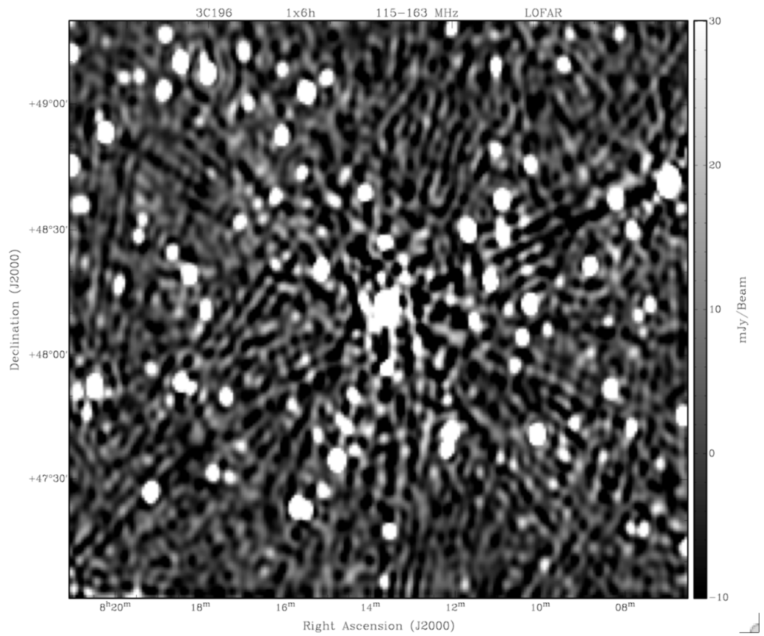
For the LBA the noise is an order of magnitude higher but brighter sources exist in the FOV so the problems eventually will be similar.

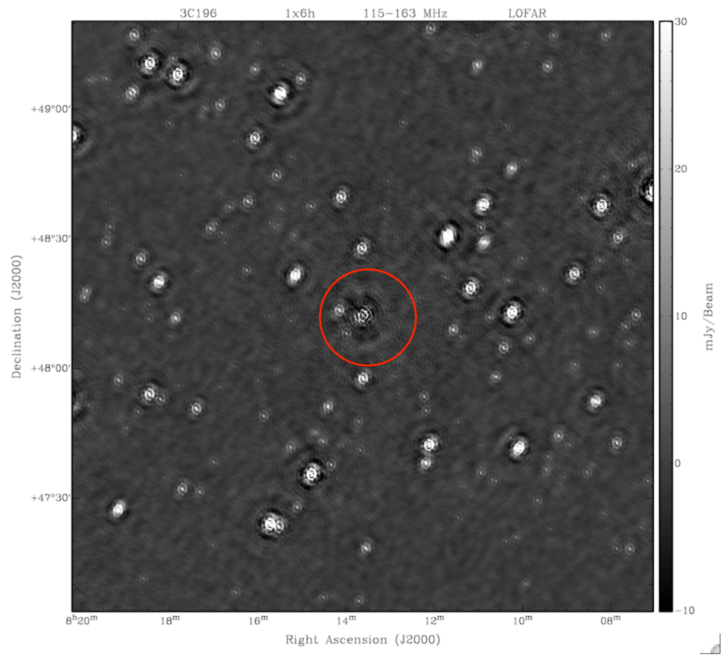
To completely remove bright sources, and their sidelobes, requires very good source models (to a resolution of ~0.1 PSF). Within the EoR group we are working to get a good model for 3C196

Here is a great and interesting task for the European baselines in LOFAR providing :

PSF 1-2” (LBA, 50 MHz) or
PSF 0.3-0.6” (HBA, 150 MHz)

3C196: WSRT versus LOFAR 115-163 MHz





WSRT 72h thermal noise 0.6 mJy
confusion noise 3 mJy

Gianni Bernardi et al (2010)

LOFAR 6h thermal noise ~ 0.1 mJy
image noise ~ 0.3-0.7 mJy

CS +RS, ~ 30 km ! 244 subbands

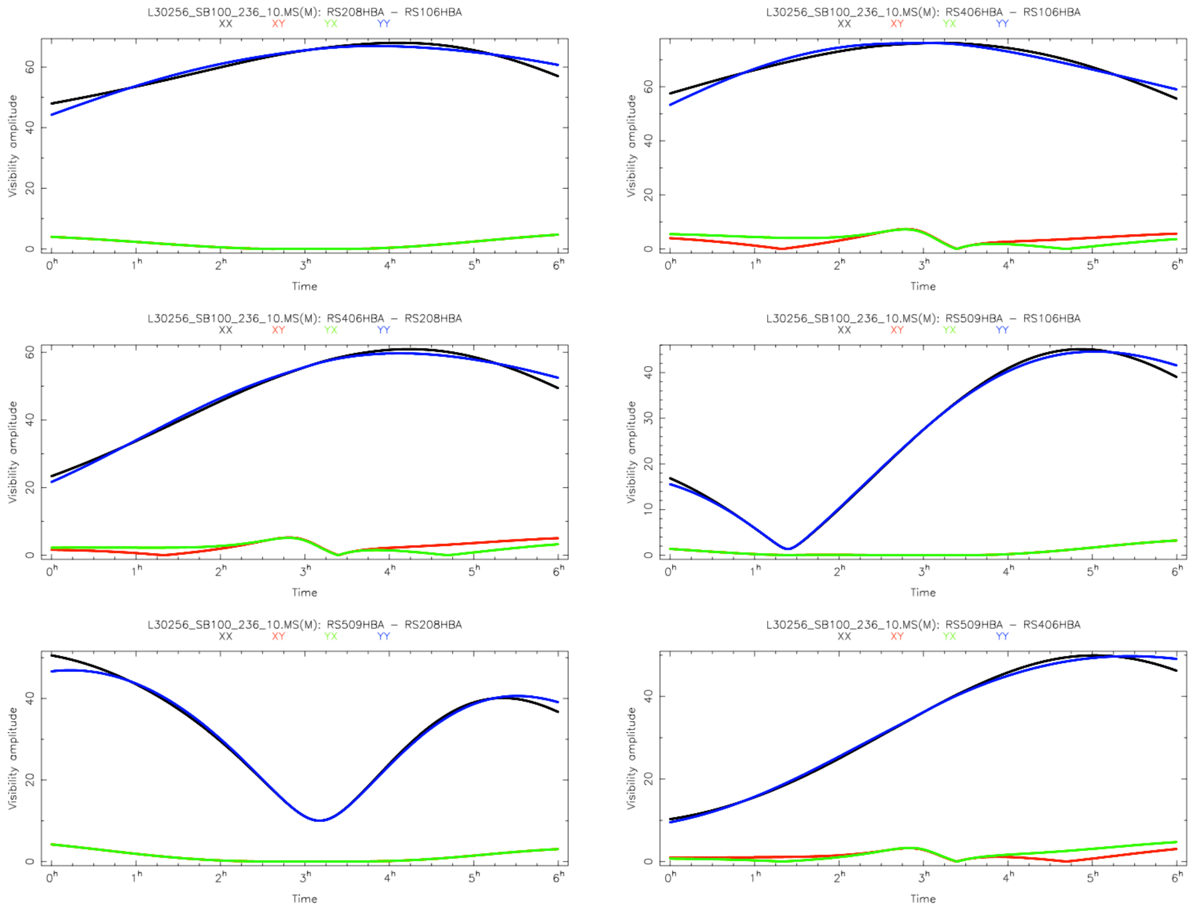
DR ~ 83 Jy/0.5 mJy ~ 200,000:1

Panos Labropoulos et al (2011)

Using BBS's 'predict' to model sources and more..

3C196
better
model

Stations
RS106
RS208
RS406
RS509 !!



Removal of the A-team

In the LOFAR LBA band the A-team (notably Cas A and CygA) often dominate signals on short baselines (where fringe rates and delay smearing are small).

Various approaches have been developed to remove these sources, and their distant sidelobe effects.

Working examples:
- Peeling: fitting and subtraction of individual sources
- De-mixing (Bas van der Tol): removing signals from A-team followed by averaging target data
- Fringe and delay-rate filtering (Parsons& Backer, 2009; Andre Offringa, work in progress)

Very soon, in day time, these methods will also need to be applied to Solar 'interference' . And at HBA frequencies (>200 MHz) grating lobes will appear adding high fringe rate signals from other, distant, parts of the sky.

Recent novel calibration and beam modelling work

Sarod Yatawatta has developed selfcalibration code based on the SAGE algorithm (see Yatawatta et al, 2010; Kazemi etal, 2011) .

The program is being excercised on the NCP (Sarod) and 3C196 (Panos, Ger) LEA128 data and you will hear more from Sarod and Panos tomorrow.

The program SAGECAL solves for 'effective' Jones matrices (J_{11},J_{12},J_{21},J_{22}) towards many sources (directions) for all stations on short segments (10-20m) of data.

It works for at least up to 100 directions, each containing 'clusters' of sources . All these (bright) sources are then removed from the data. The residual visbilities can be imaged in a standard way, followed by a restoration of the sources.

The noise in the SAGECAL-processed images has now reached 0.2-0.3 mJy (HBA, 6h, 200subbands) which is within a factor ~1.5 from the thermal noise

The output of SAGECAL contains infomation on the beam and ionosphere, a.o. These can be fitted to reasonable beam parametrizations. These beam models can then be used in the 'awimager' to properly image the other fainter parts of the field.

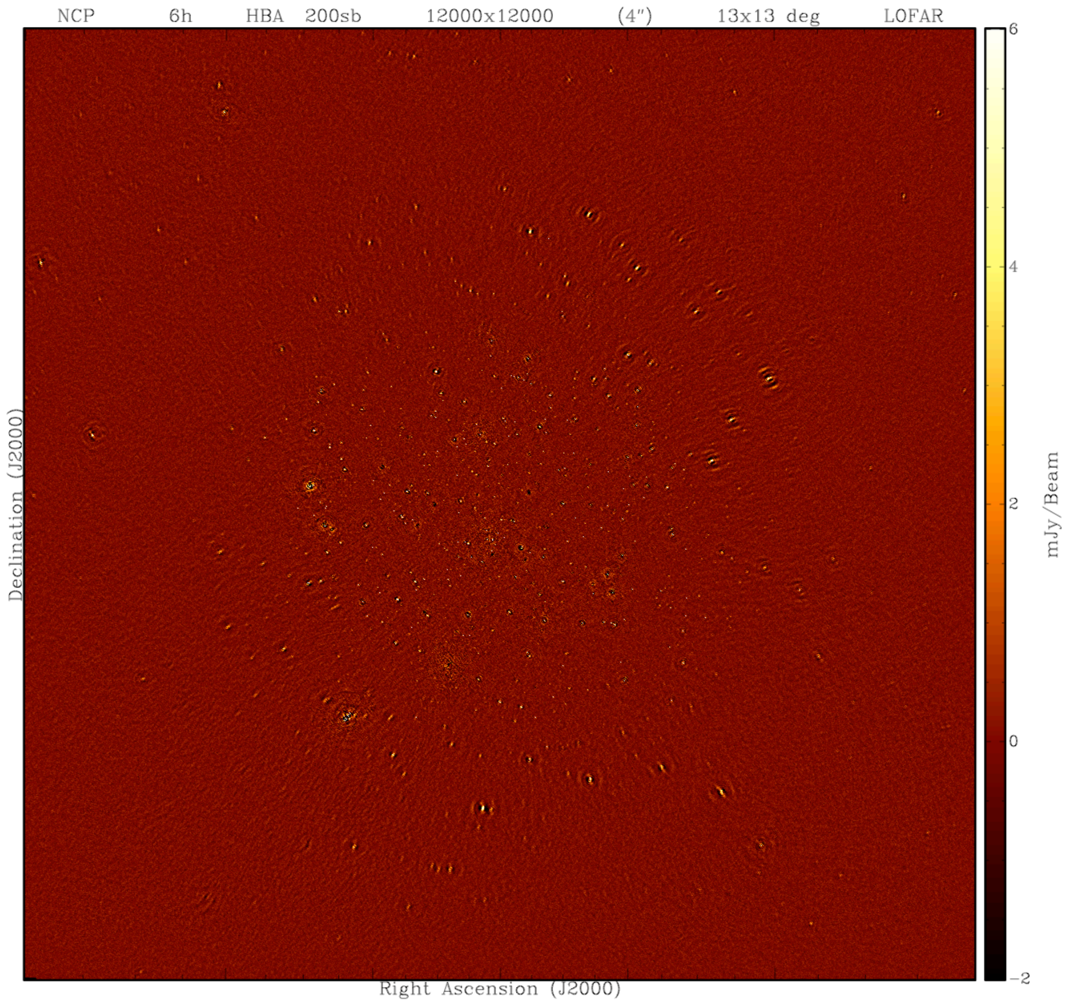
The next slides show some NCP images. They will be discussed in more detail by Sarod tomorrow.

Deep NCP imaging aspects (1)

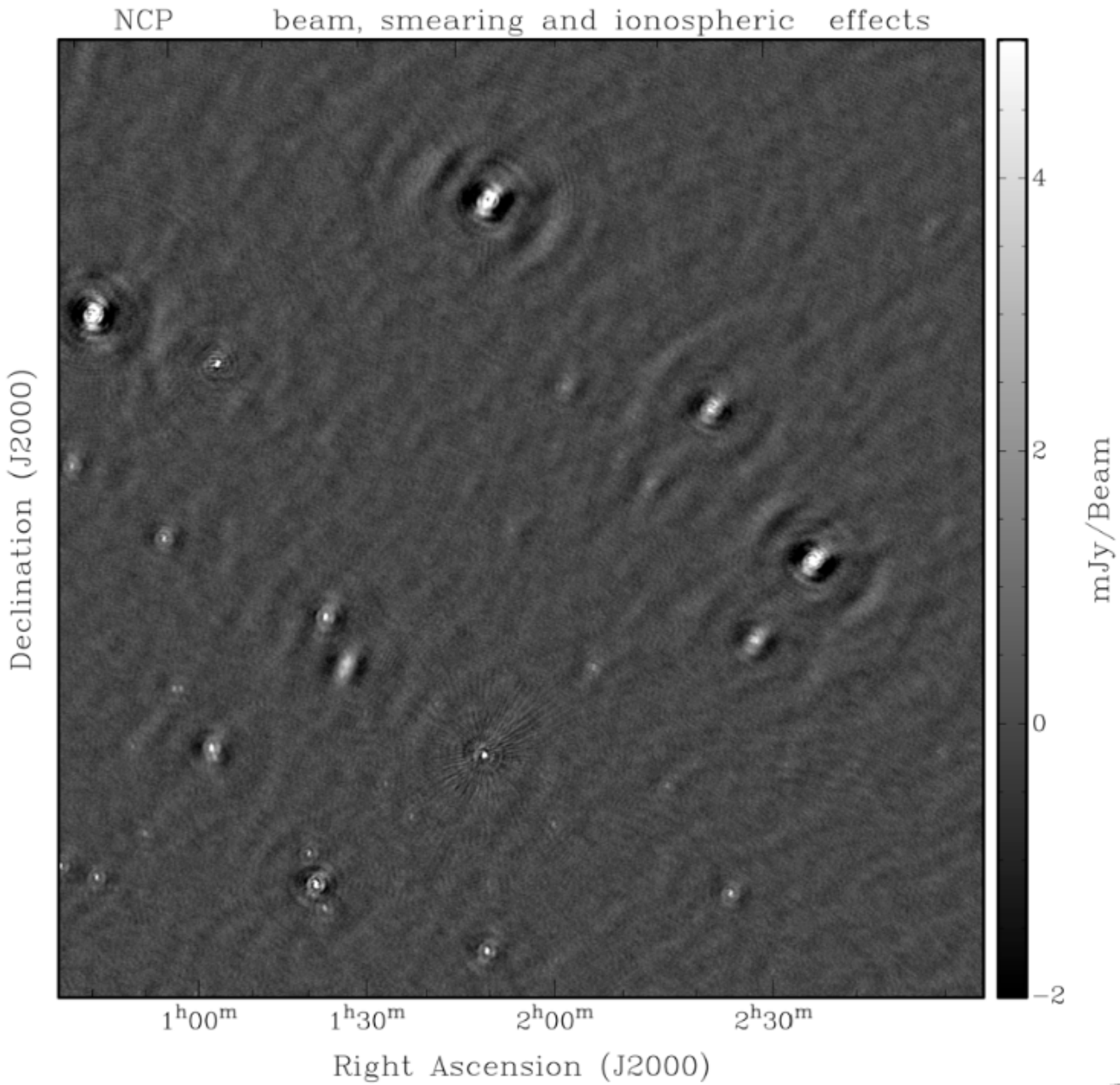
13° x 13°

1x6h
200 subbands
HBA 115-163 MHz

18CS , 7RS

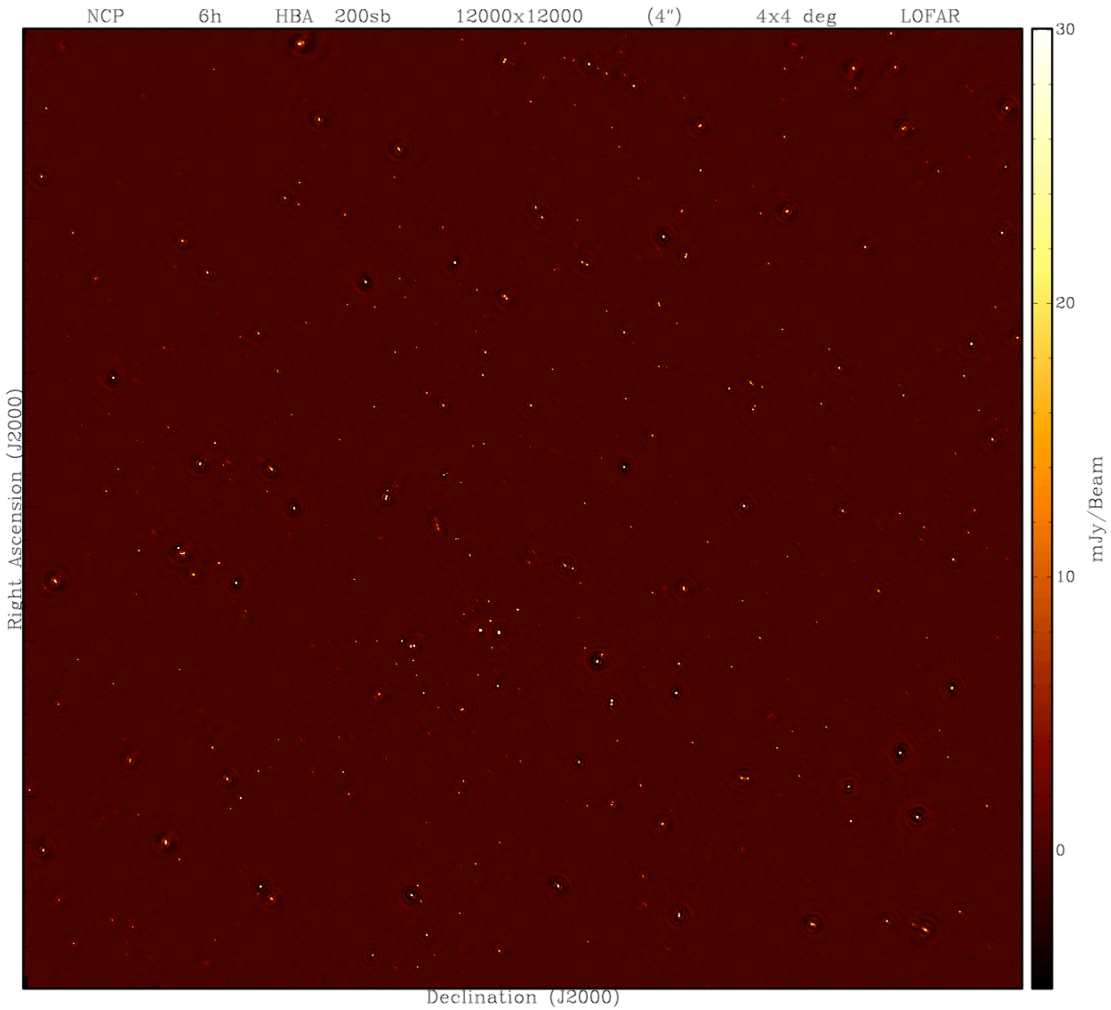


Deep NCP imaging aspects (1A)



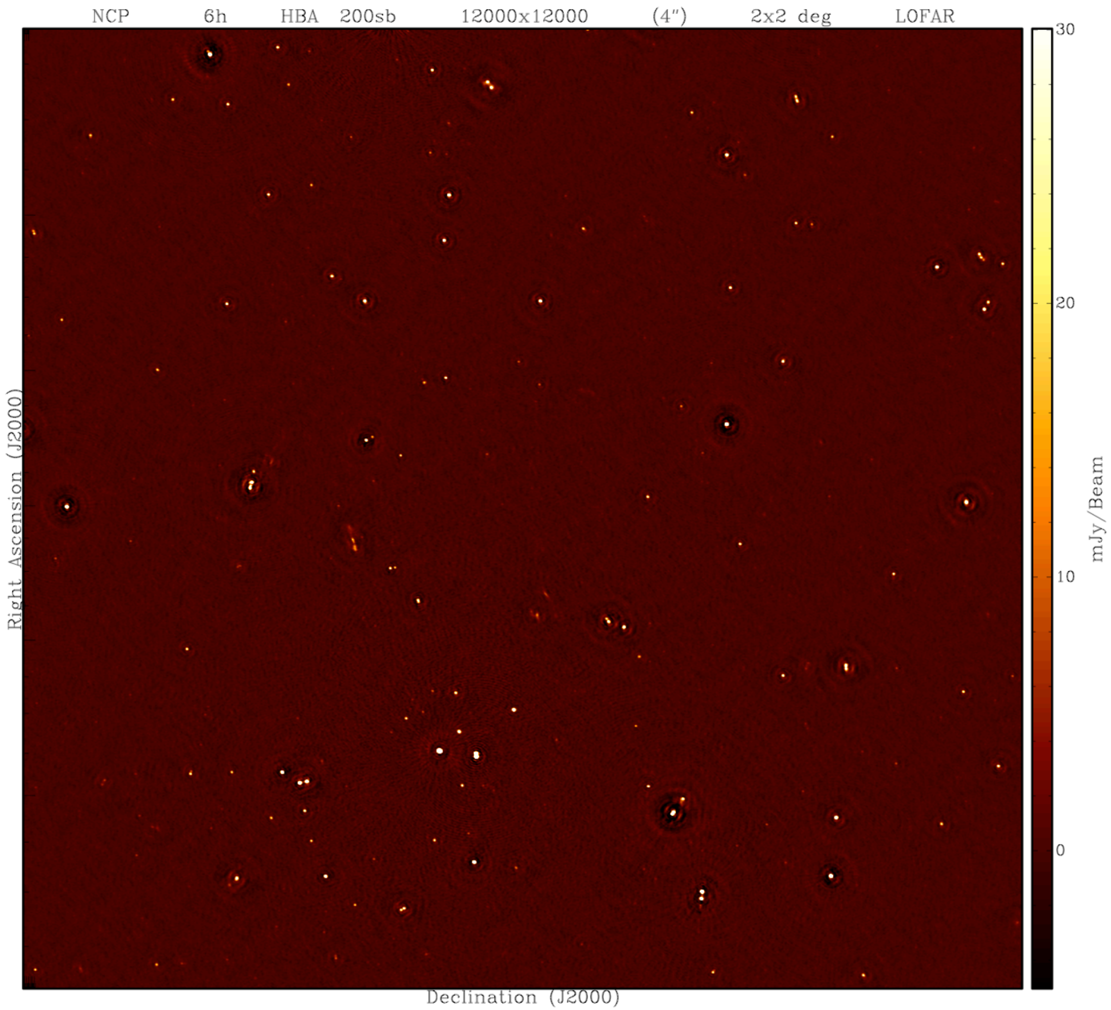
Deep NCP imaging aspects (2)

4° x 4°



Deep NCP imaging aspects   (3)

$2^o \times 2^o$



noise level

0.22 mJy

Conclusions

- LOFAR calibration is a many-faceted challenge

- There has been significant progress in some areas, and within some teams

- We mostly know what needs to be done, but progress in general is slow

- Areas for concern:
  - station calibration
  - ionospheric modeling
  - application Direction dependent effects in imager
  - beam models
  - flux scale

We need:

- Dedicated 'astronomer/developer' teams, supported by active commissioners.
- Some KSP driven/led , some should be supra-KSP
- Clear management (via LCCG-TAC)
- Much more processing power (with GPU component !)

Calibration efforts that have hardly been started…

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

— deconvolution with spatially varying beams, or source subtraction

— applying station tapering (e.g. convert 48 tile RS → 24 tile CS)

— 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 (ionospheric models)

— astrometry at sub-arcsecond level

— optimal weighting due to time-varying sensitivity

— variable and (spatial-) Differential Faraday rotation (across FOV)

Absolute flux scale: going beyond the A-team

Flux scale 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).

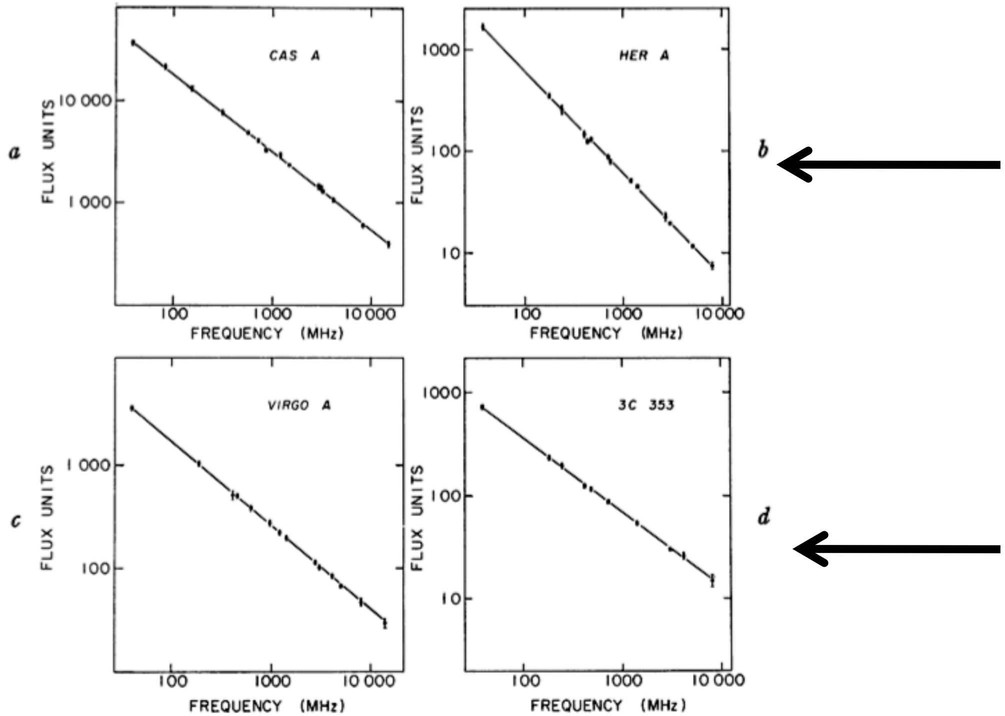


Fig. 1.—Spectra of calibration sources: (*a*) Cas A (3C 461) based on absolute flux densities corrected to the epoch 1964.4; (*b*) Her A (3C 348) based on ratios to Cas A; (*c*) Vir A (3C 274) based on ratios to Cas A; (*d*) 3C 353 based on ratios to Cas A.

Bright secondary calibrators

HerA = 3C348

2’ double

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

3C353

5’ double