LOFAR calibration

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ASTRON & Kapteyn Institute

LOFAR Technical Status meeting, Dwingeloo, 18 May 2009

Outline

— Calibration goals: traditional and new software

— Overview of the calibration framework

— LOFAR station beams and digital beams

— The learning phase: WSRT-LFFEs and CS1: all-sky imaging !

— Early LOFAR-array configurations

— Calibration bootstrapping scenarios

— LOFAR and the Sun

— Ionospheric TEC: large and small scale, Faraday rotation

Standard calibration

Calibration is needed for:

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

Method used:

Determine Gain/Phases (frequency) on

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

Apply selfcalibration --> 3)

Absolute flux scale: going beyond the A-team

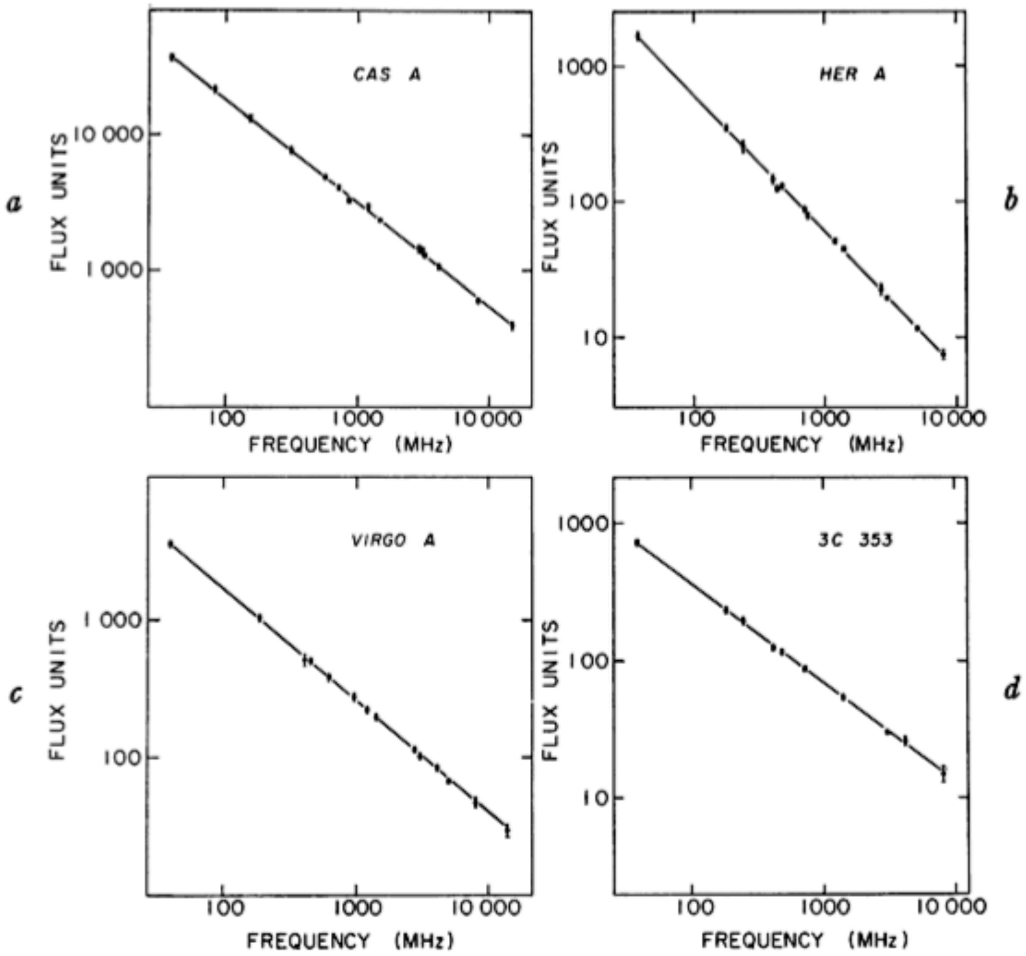


FIG. 1.—Spectra of calibration sources: (*a*) Cas A (3C 461) based on absolute flux densities corrected to the epoch 1964.4; (*b*) Her A (3C 348) based on ratios to Cas A; (*c*) Vir A (3C 274) based on ratios to Cas A; (*d*) 3C 353 based on ratios to Cas A.

3C348

2' double

(tied to 3C196 via WSRT fluxscale project Jeffrey Bout/Michiel B.)

3C353

5' double

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 used to develop/simulate our understanding

— BBS will be implementing efficiently a strategy

— and we use AIPS++/CASA for imaging

All 'standard' initial calibration eventually to be done in automated pipelines !

LOFAR calibration framework *(Noordam, 2006, LOFAR-ADD15)*

New compared to 'traditional' VLA/WSRT/GMRT selfcal:

- Major direction dependent corrections (DDE, as opposed to DIE)
  - Phase ⇒ 'non-isoplanaticity' of the ionosphere (low freq, wide FOV)
  - Gain ⇒ elevation/azimuth dependent beamshape (+ ionosphere ?)

  ⇒ image-plane (as opposed to uv-plane) correction/solving required !

- All-sky calibration, very wideband synthesis and imaging
  - Global Sky Model (GSM) needed (= spectrum, structure , (polarization))
  - w-term often 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 (B), Elec. Gain (G) , Beam (E), Ionosphere (I), Faraday rotation (F)

Additional LOFAR calibration challenges

Separate clocks in all stations (except superstation) --> phase drifts

- continuous/frequent observation of very bright calibrator (CasA, …
- applied in core only (?), or part of general calibration strategy (?)
- needed to jump start calibration process !

Grating lobes in the HBA band (>150 - 180 MHz)

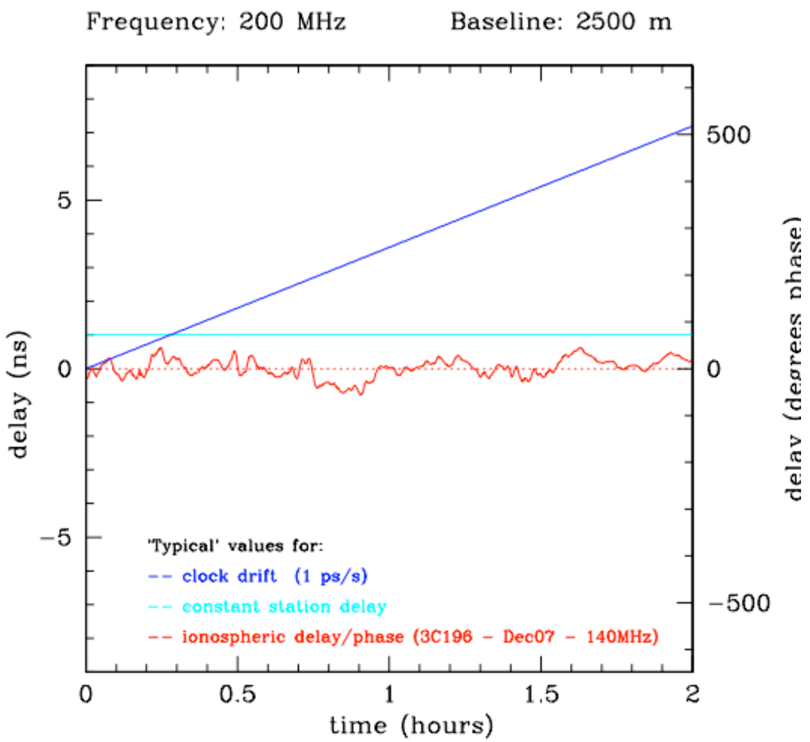
- station rotation reduces distant grating lobe levels
- stay at high(ish) elevation, if possible

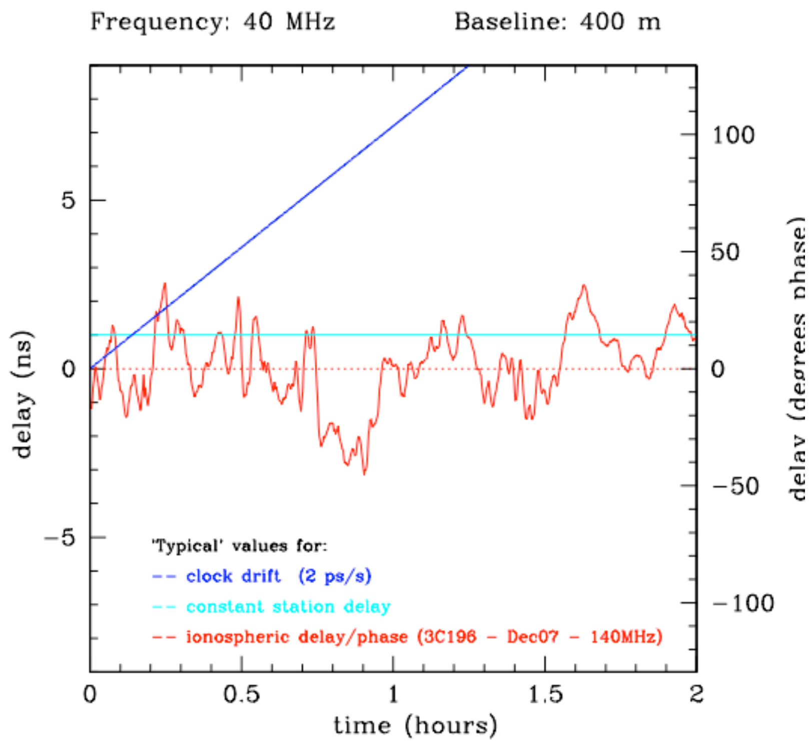
Many different station sizes (HBA 24-48-96 tiles, LBA 30-70-87m) !!

- use digital station tapering if problematic (in early phases)

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)





Calibration: solving for the (many) unknowns

Calibration conceptually involves 3 major unknowns:

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

Qualitatively our knowledge will steadily increase stepwise

1. After MSSS we will know the GSM: I,Q,U,V (RA,Dec, freq, (time))
2. Through improved modeling of beampatterns
   (we expect/hope these to be stable = predictable)
3. Remaining challenge (every 1 - 60s !) is solving for phase-screen

Quantitatively: # unknowns, convergence, speed,…. ?

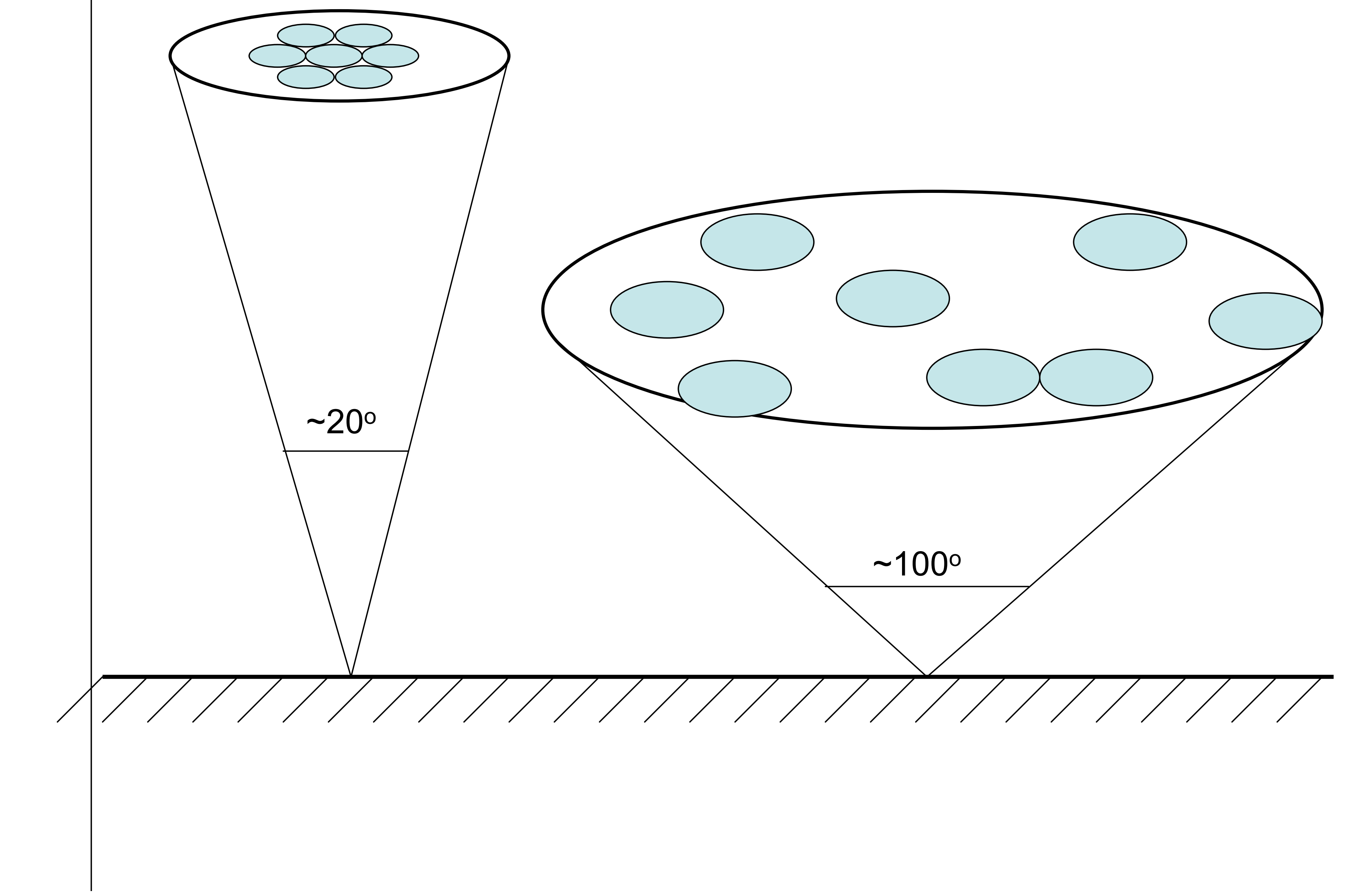
LOFAR is all-sky imaging

(Baldwin, Bregman)

(CS-1 + WSRT lessons)

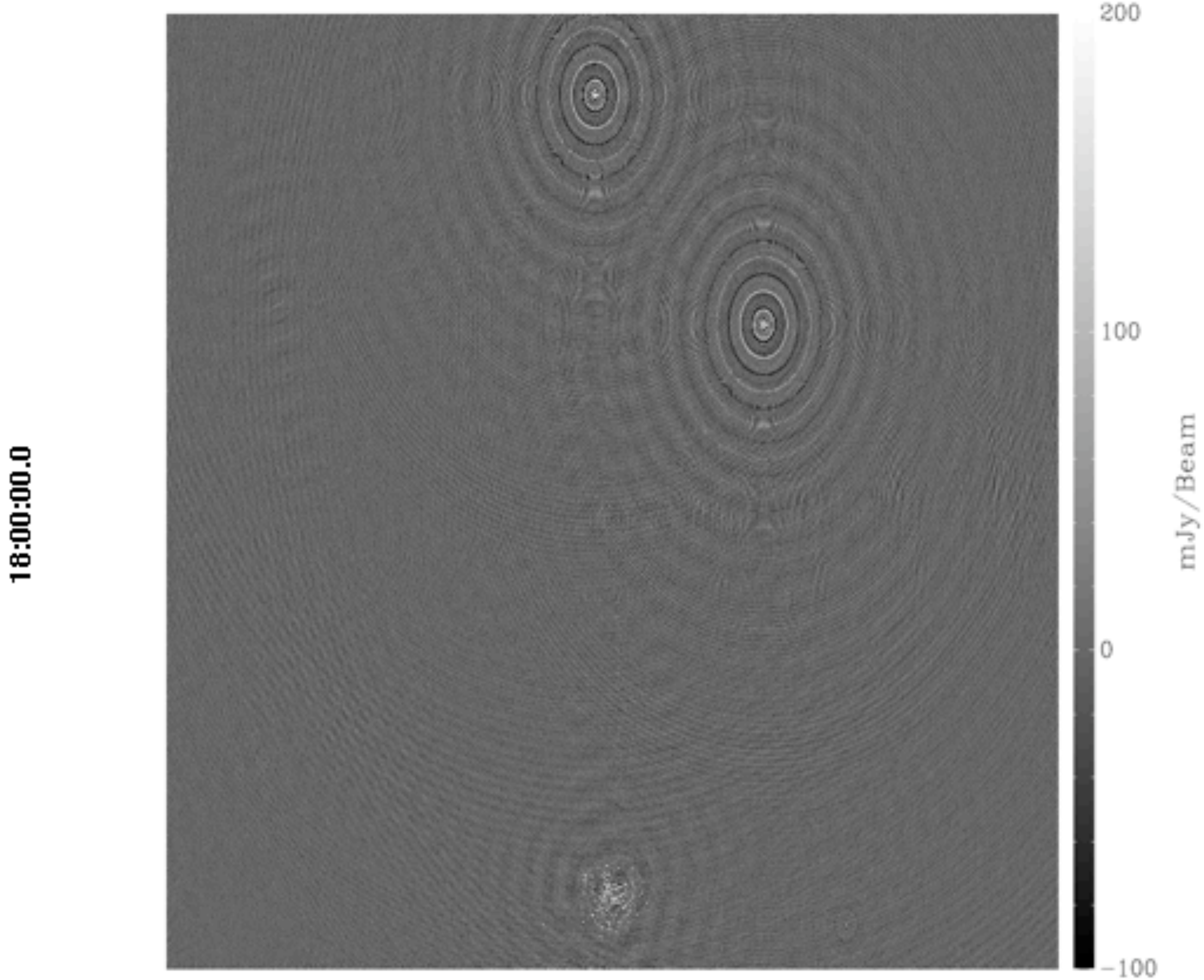
(Wijnholds, Yatawatta (CS-1) , Bernardi, de Bruyn (WSRT-LFFE))

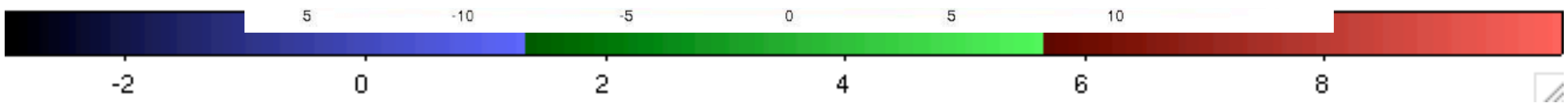
HBA tile/station FOV & LBA dipole/station FOV



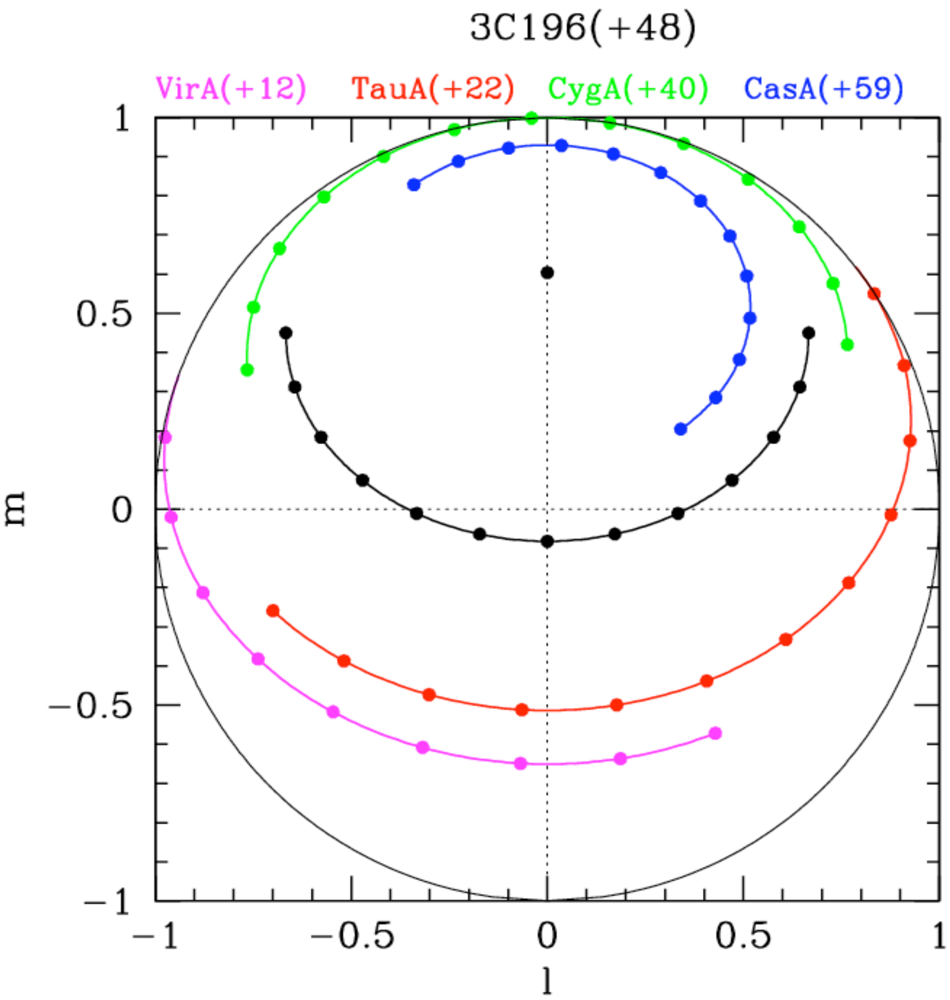
All-sky imaging: with dipoles and 25m-telescopes !

2007



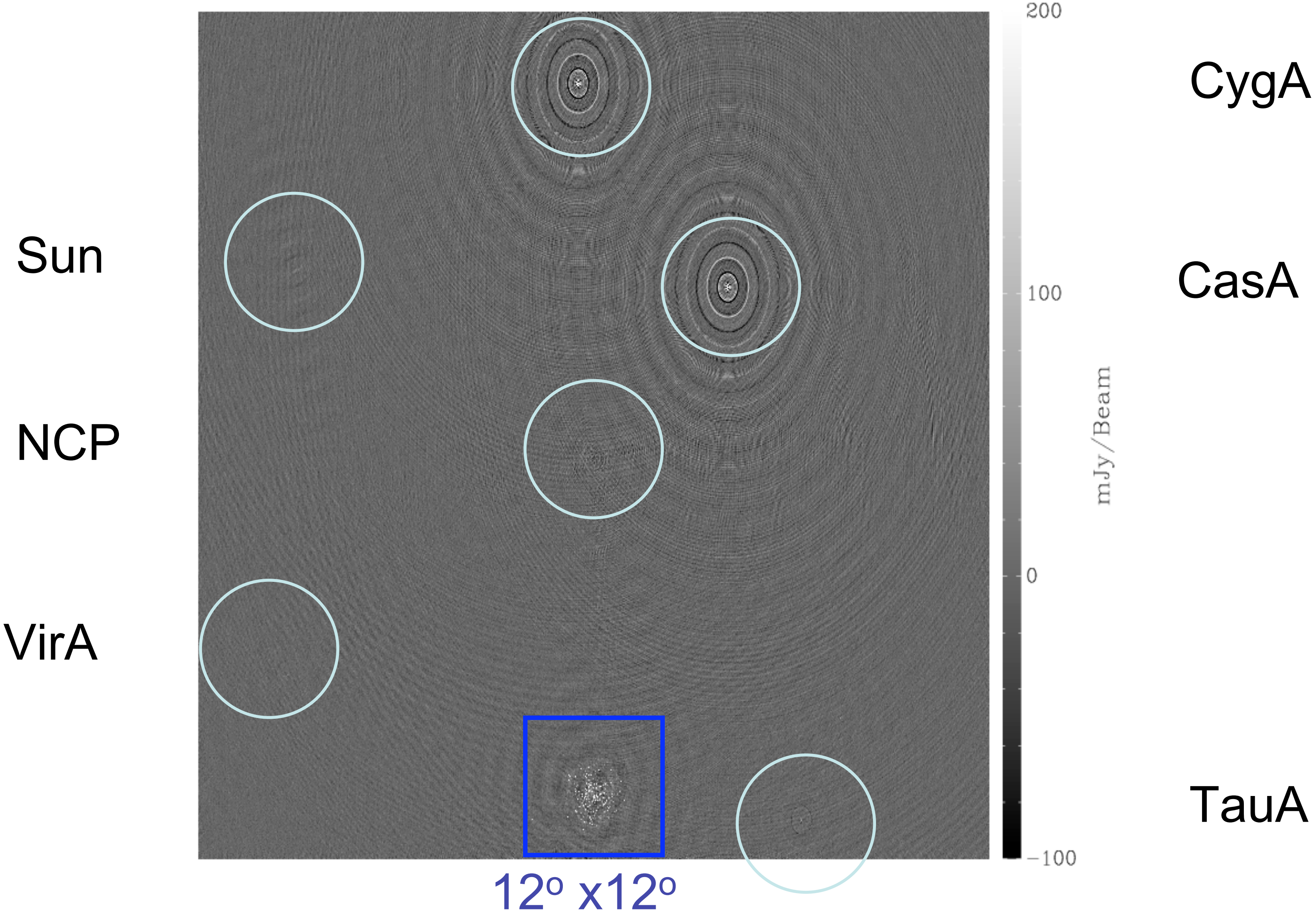


The A-team locations during a 12h WSRT 3C196 synthesis

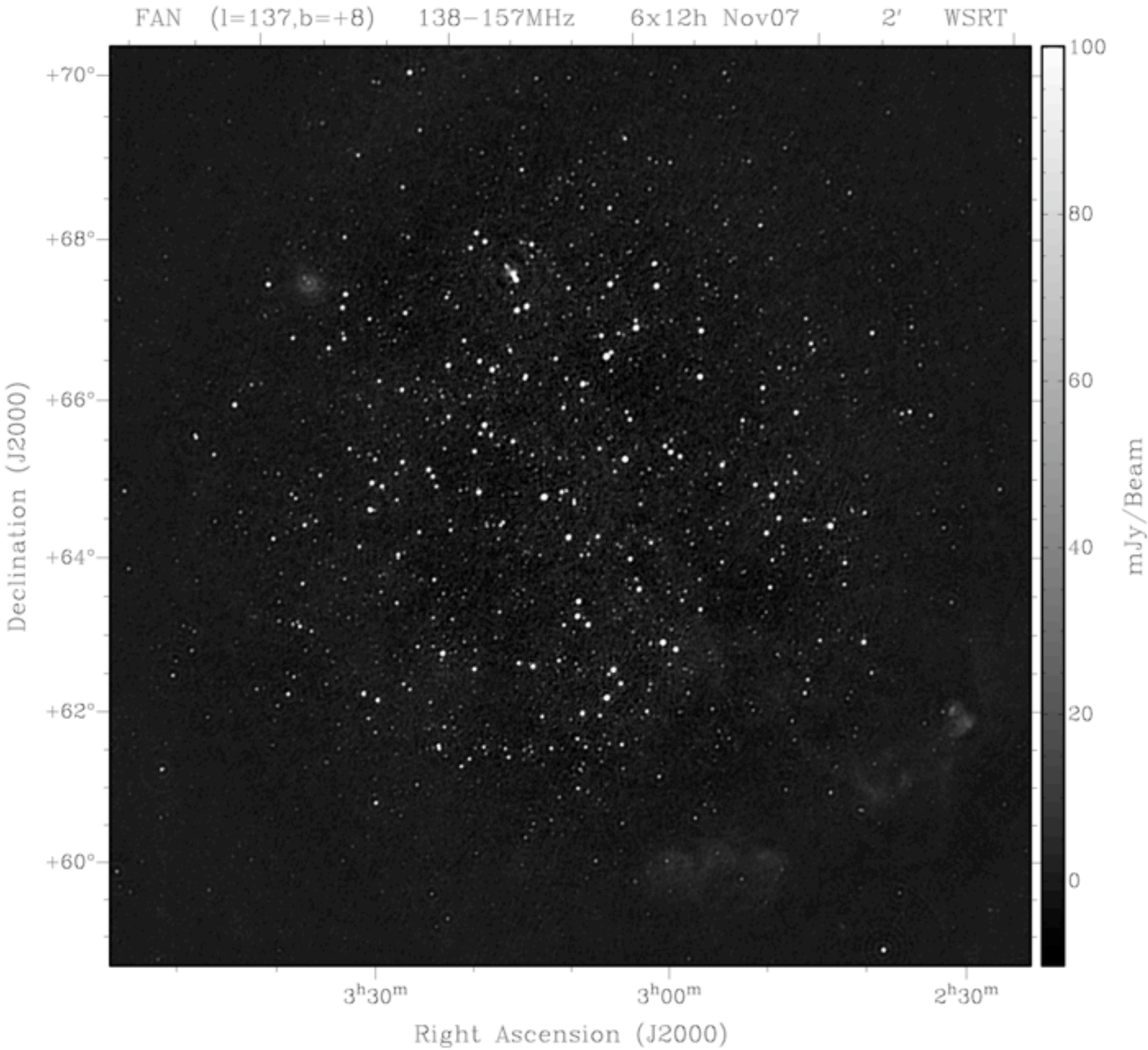


Note that the l,m here are a zenith "'l,m" projection which is the natural coordinate system for an earth-bound aperture array

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



Deep WSRT 150 MHz imaging: 2.7 km

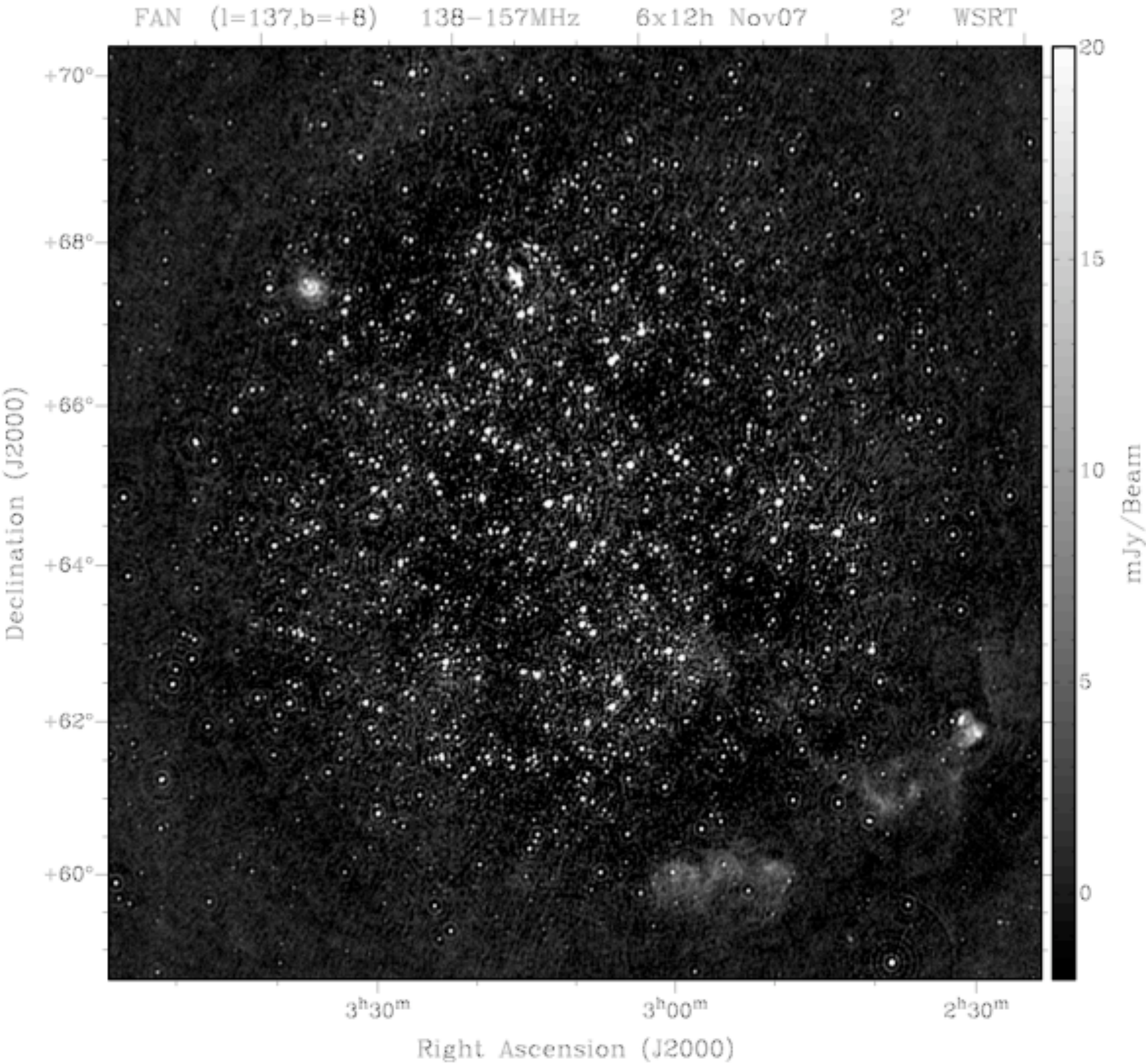


range

-15,150 mJy

Bernardi et al, 09

Classical confusion noise limited: 2.7 km 2' PSF



range

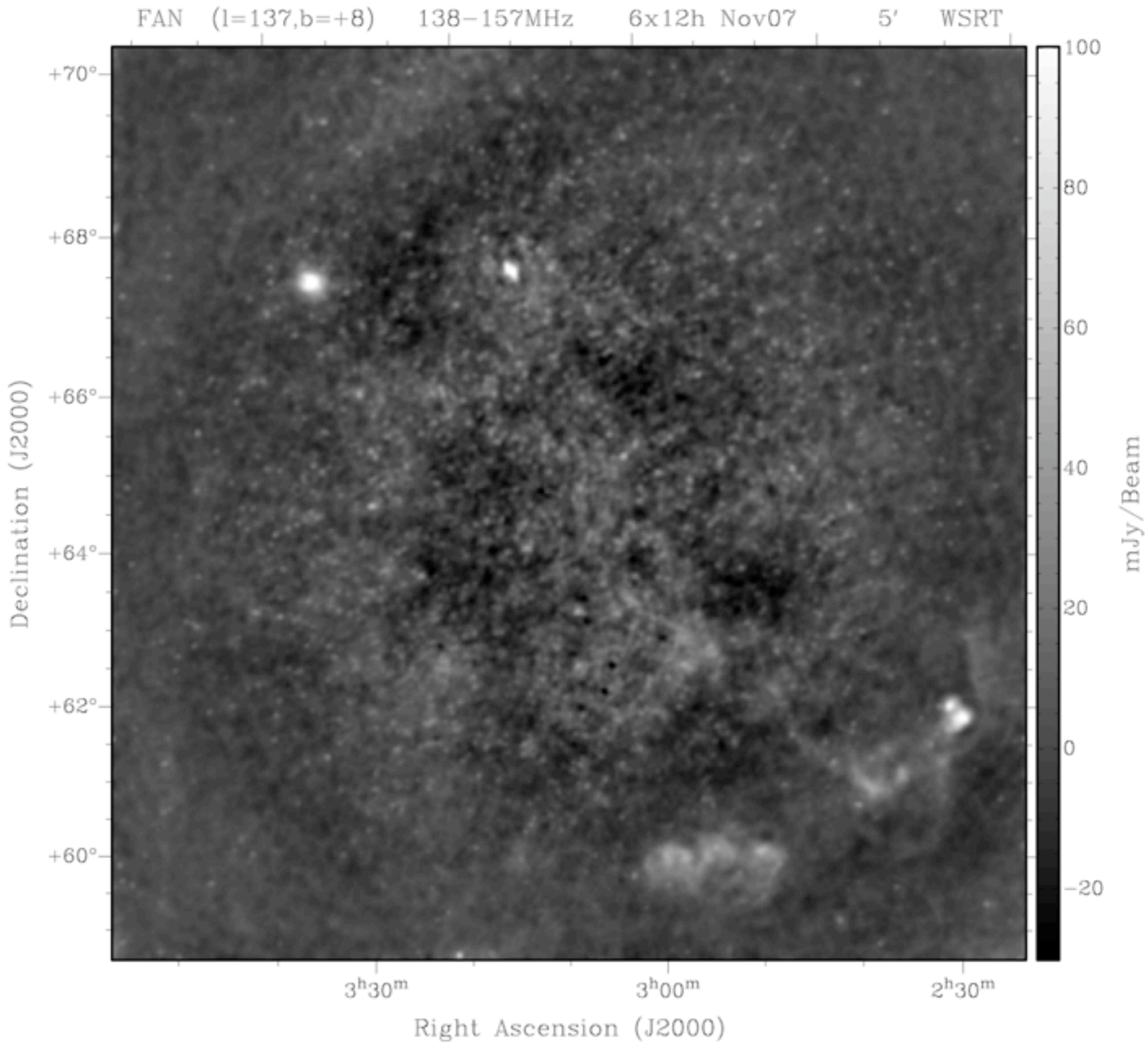
-3, 30 mJy

0.7 mJy thermal noise

3 mJy confusion noise (inner part)

> 2000 sources !

Diffuse Galactic emission (>10 K) !



Residual image after subtracting sources to 30 mJy and smoothed to 5’

range

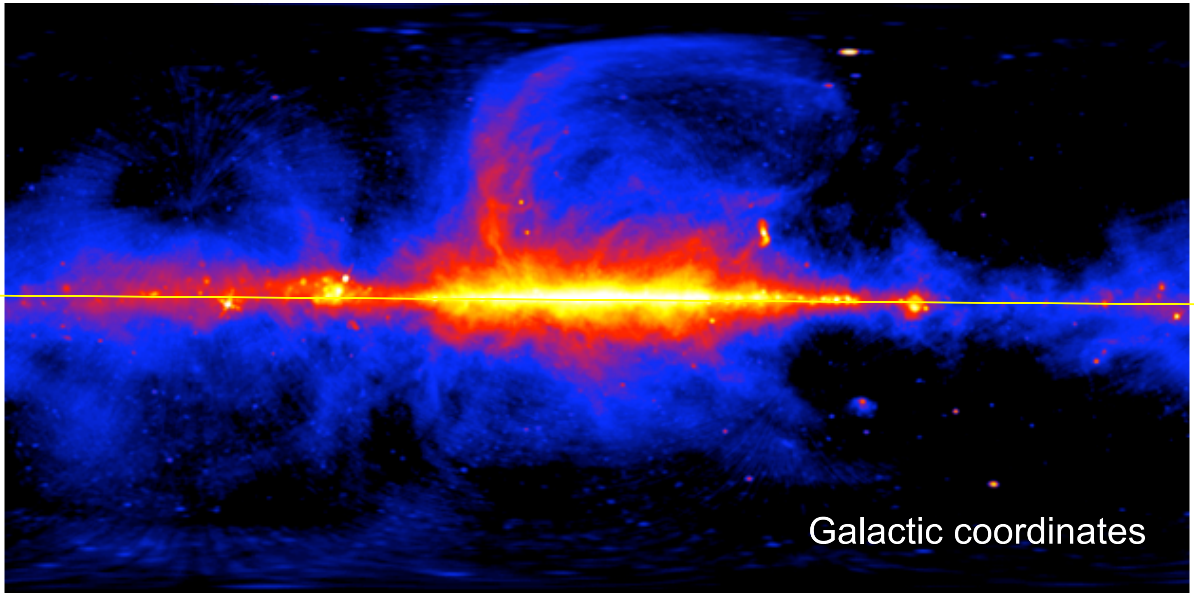
-45,150 mJy

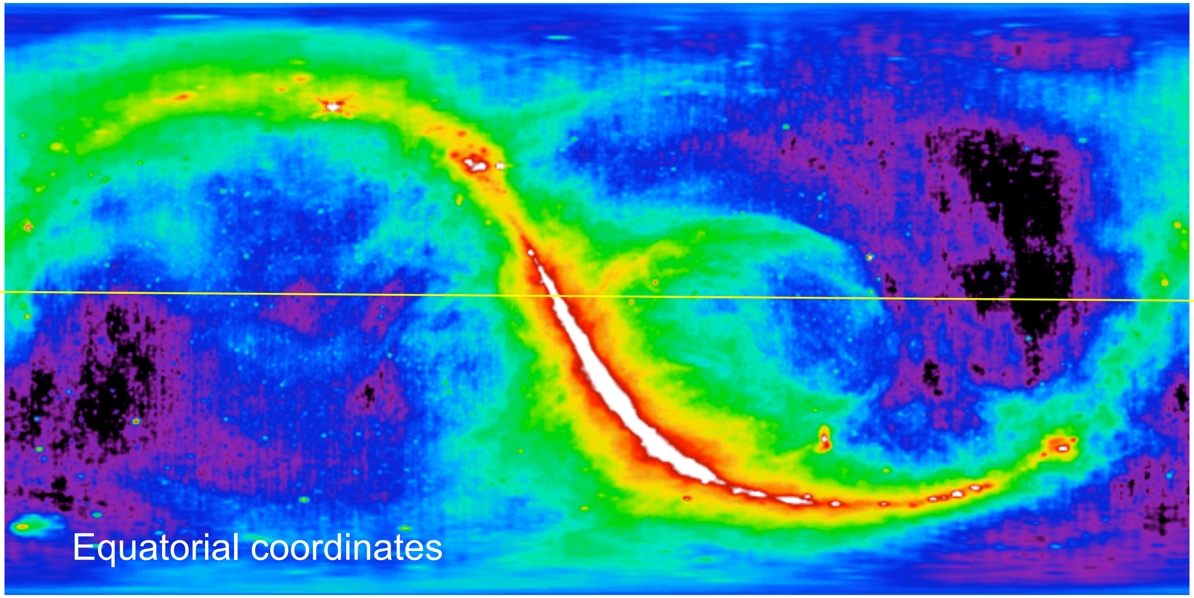
Calibration and the Galaxy

Haslam et al (1981)

408 MHz

All-sky (0.85° PSF)



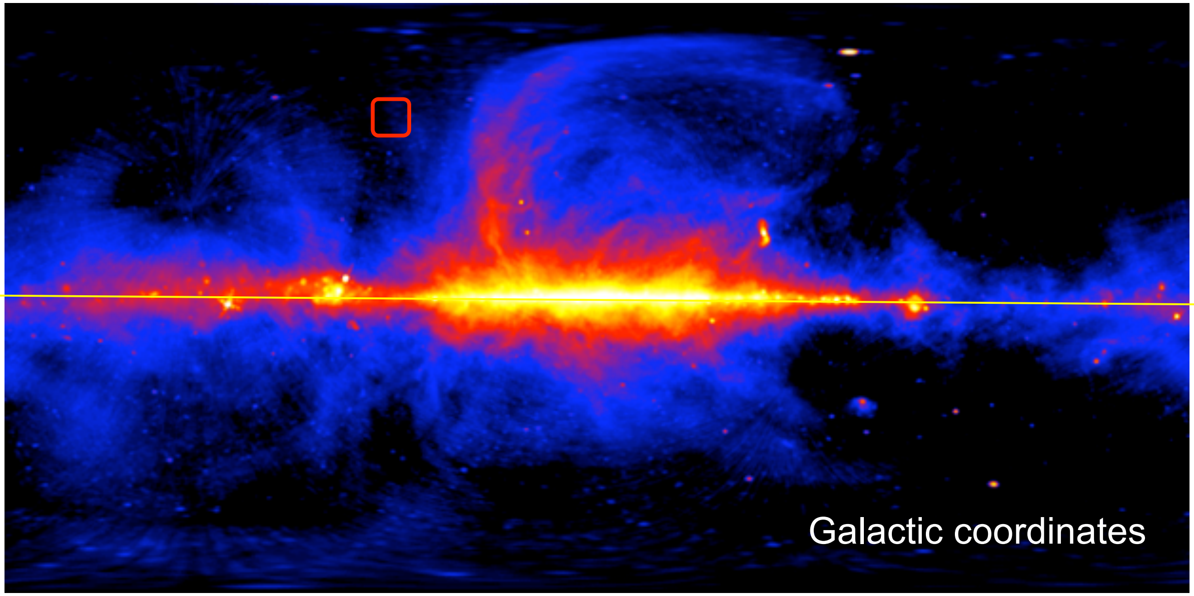


Note that a significant fraction of the sky contains diffuse Galactic emission !

E.g the FAN region

(l=137°+8°; 3h, +66°)

WSRT 150 MHz imaging (EoR project)



Location of 3 WSRT LFFE-fields (Nov07)

From left-to-right

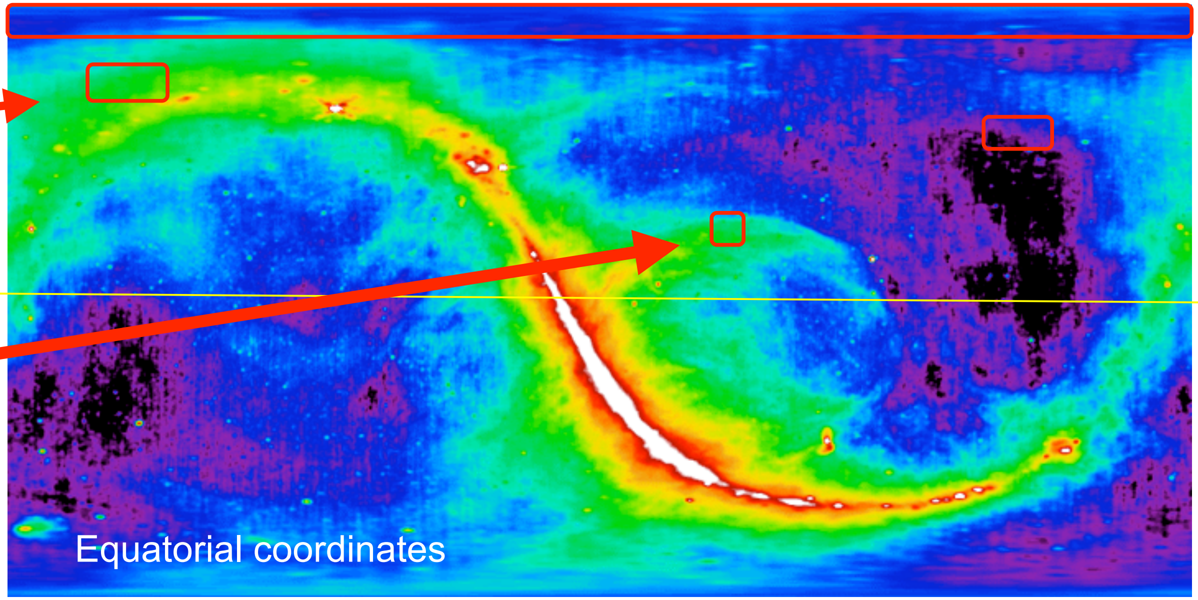
— NCP

— ‘FAN’

— 3C196

May 2009: NPS field !!

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



Calibration/imaging pipeline components

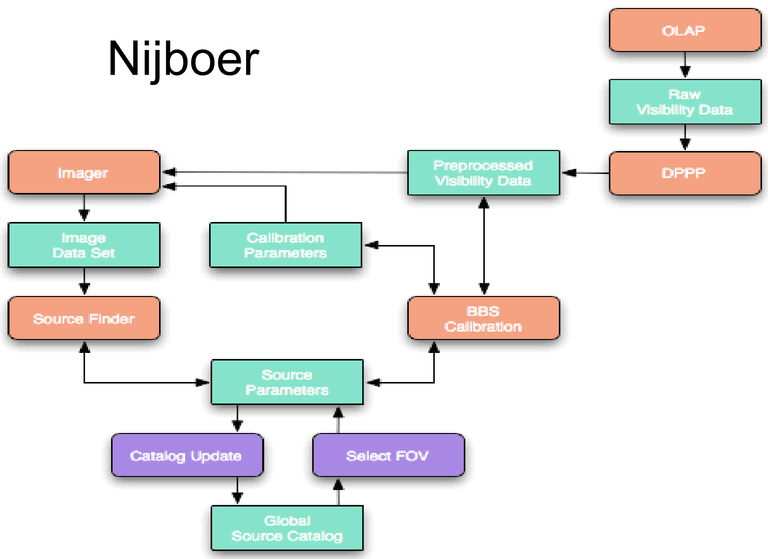
- DPPP including — RFI mitigation
  Data compression
  Clock correction
- Calibration — gain/phase tables transfer

-Initial BBS calibration — bright calibrators (‘cat I’)
  global (broadband) solutions
  ionospheric solution

- Imaging

- Source finding

Nijboer



Another look at 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

Calibration bootstrapping (Jun - Jul 09) 1/3

A calibration bootstrapping sequence with increasing complexity, and milestones, based on the current Rollout schedule, could look as follows:

Step 1) 1-3 stations

Testing Station beamforming on Brightest sources,

Testing DPPP and BBS (+global solver),

Testing Imager and Source finding (LSM/GSM) , Pipeline integration

Snapshot datasets (< 5m-15m) mostly (no beam models as yet!)

Step 2) 3-5 stations, short(ish) baselines (<5 km)

Rough top-level GSM/LSM available,

Simple fields (fainter sources), Simple Beam models

Testing deconvolution/clean, High dec (longer syntheses possible)

Snapshot datasets, Still no Peeling

Calibration bootstrapping (Jul - Sep 09) 2/3

Step 3) 5-10 stations , longer baselines (~ 30 km)

Improved GSM/LSM + Rough preliminary flux scale

Use of beam models

Complex fields, DR ~ 100:1

Imaging with multiple snapshots (w- and A-projection ?)

Use of bandwidth synthesis (uv-coverage, ionosphere)

Testing Peeling and BBS-SPAM

Ionospheric TEC modeling and calibration strategies using, a.o.

Polarized pulsar observing (PSR1937+21, TauA-PSR, PSRJ0218+42)

Calibration bootstrapping (Aug-Oct 2009) 3/3

Step 4) 10-15 stations, more CS and RS

Good GSM/LSM with relative flux calibration,

Source spectra

Multiple snapshots, Wideband synthesis --> deeper images

Dynamic Range >1000:1

First polarization imaging

Step 5) 15-20 stations, including Superstation (6) and Europe (3-5)

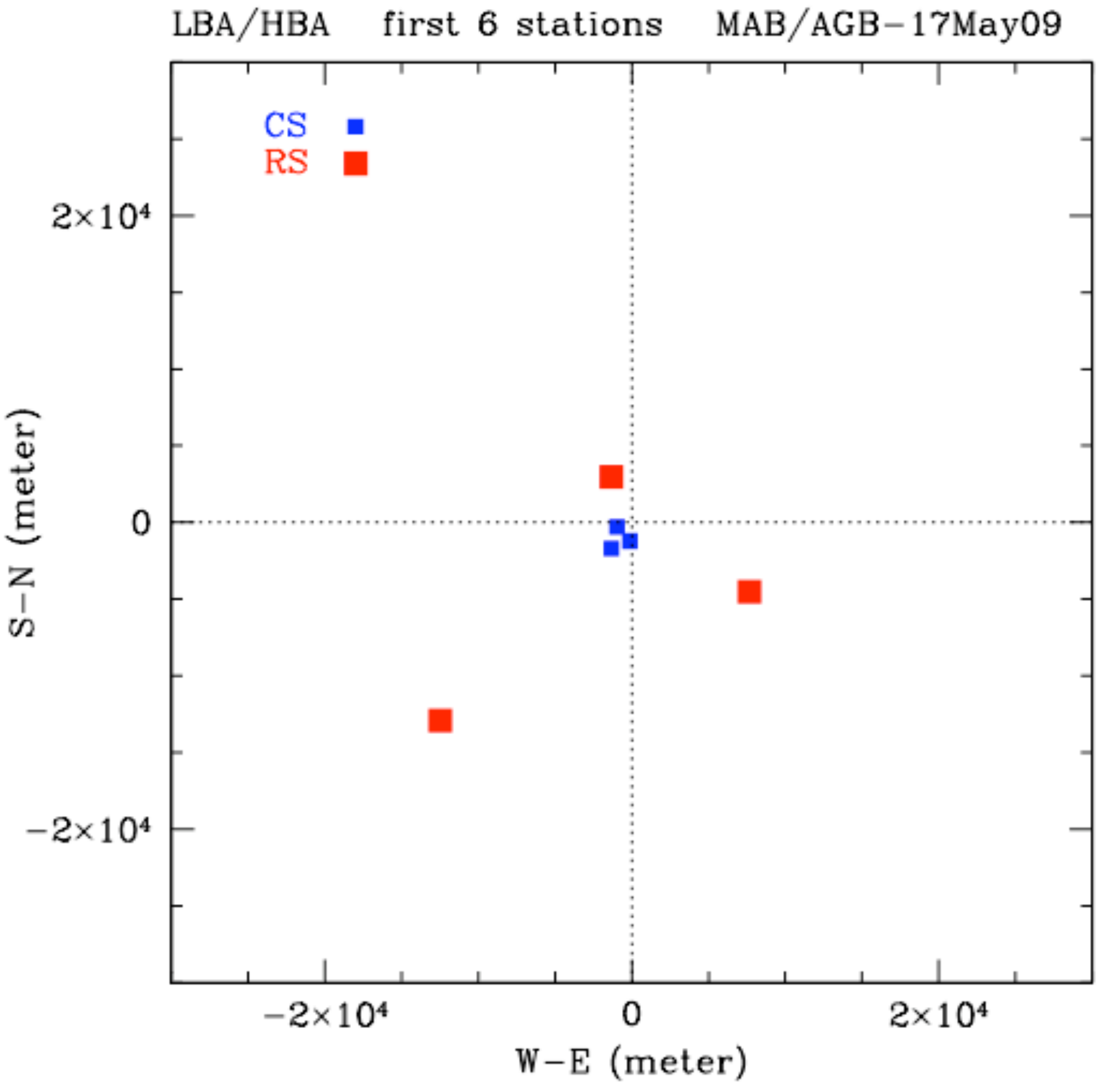
Galactic plane imaging

Long syntheses, Wider bandwidth,

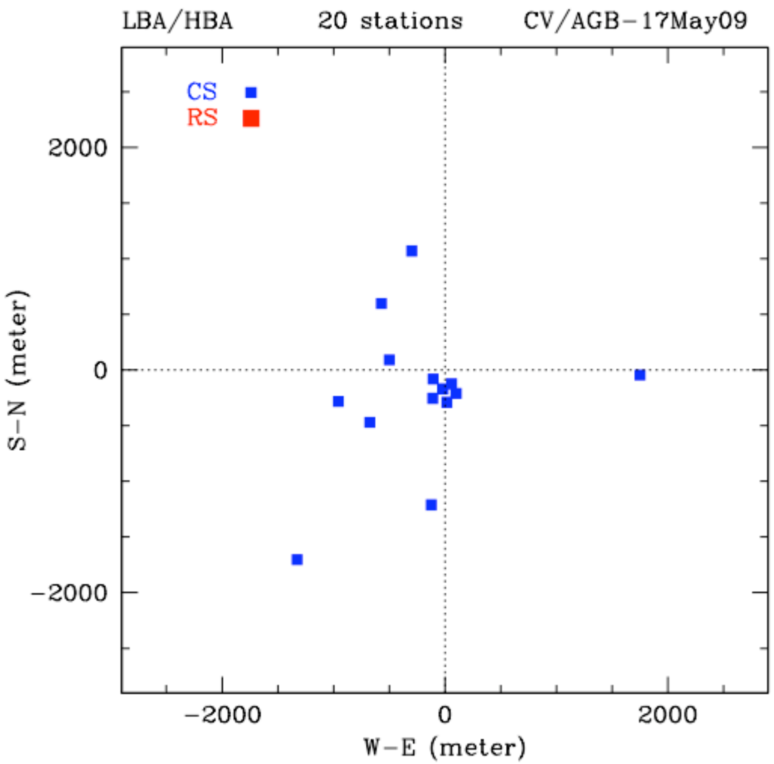
Peeling, BBS-SPAM, large-scale TEC modeling

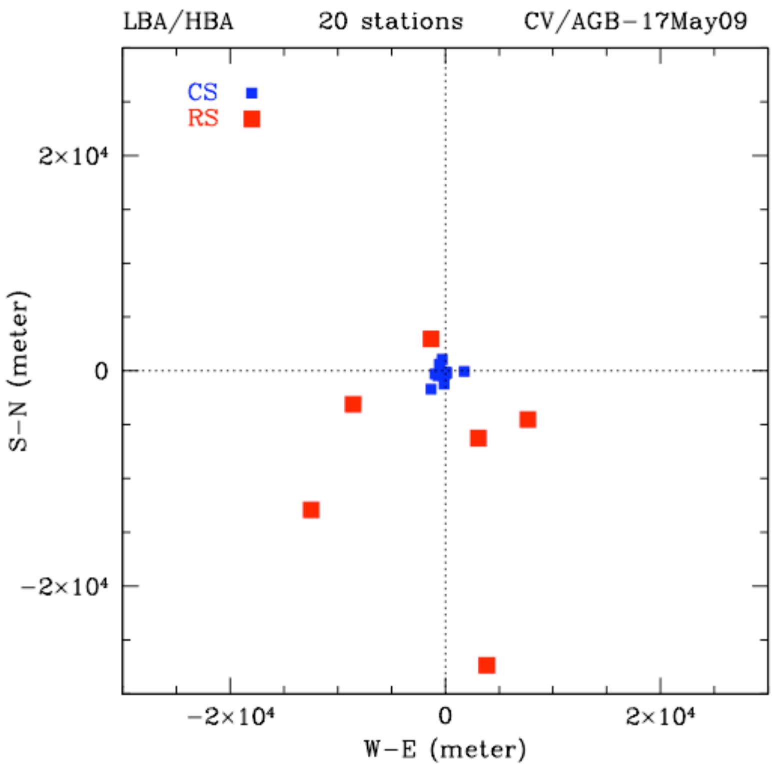
Early LOFAR array configurations

Early array configuration: 6 stations, late Jul09 ?



MSSS configuration: 20 stations, Oct09



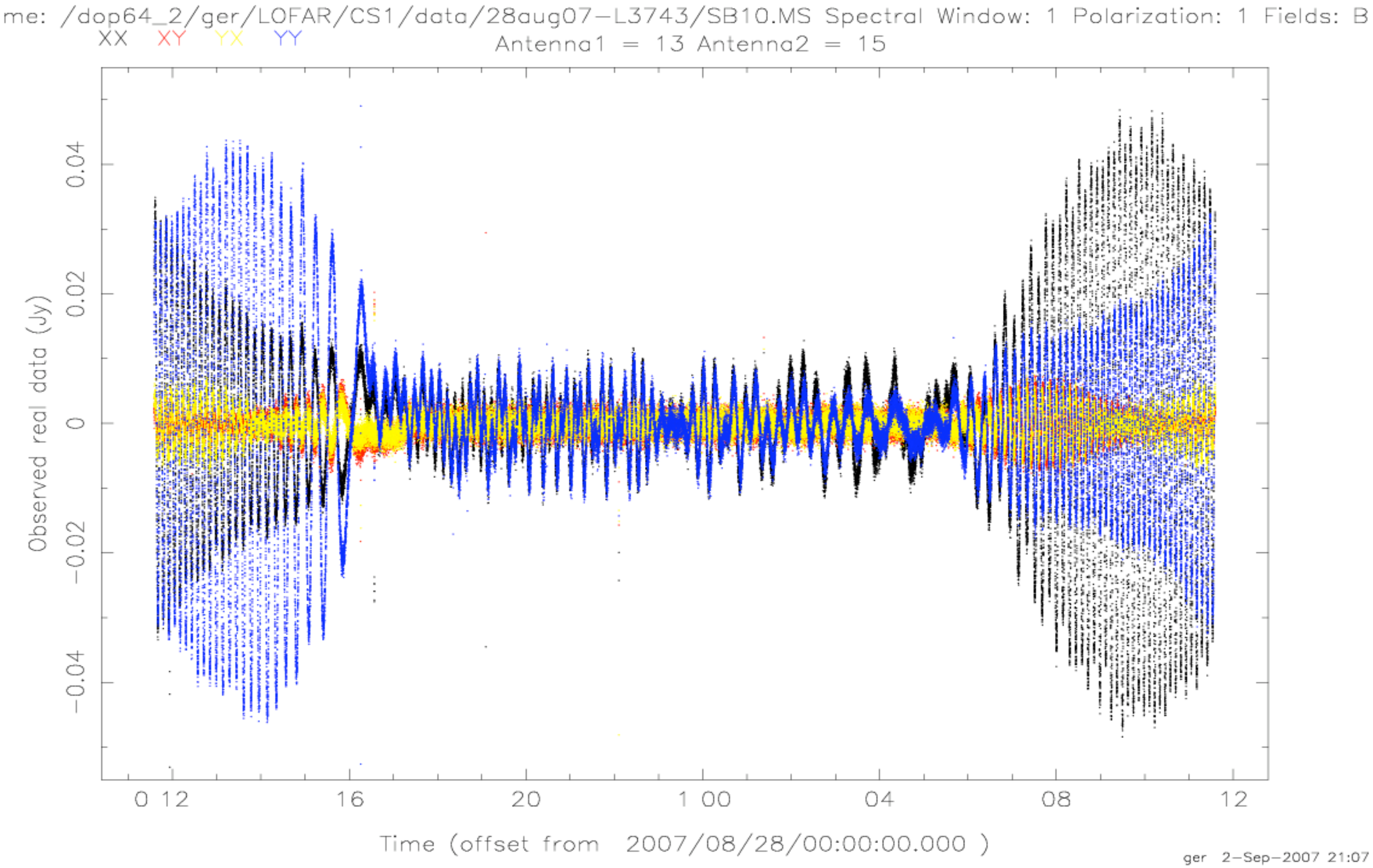


LOFAR and the Sun

(or what is the difference between daytime and nighttime observing)

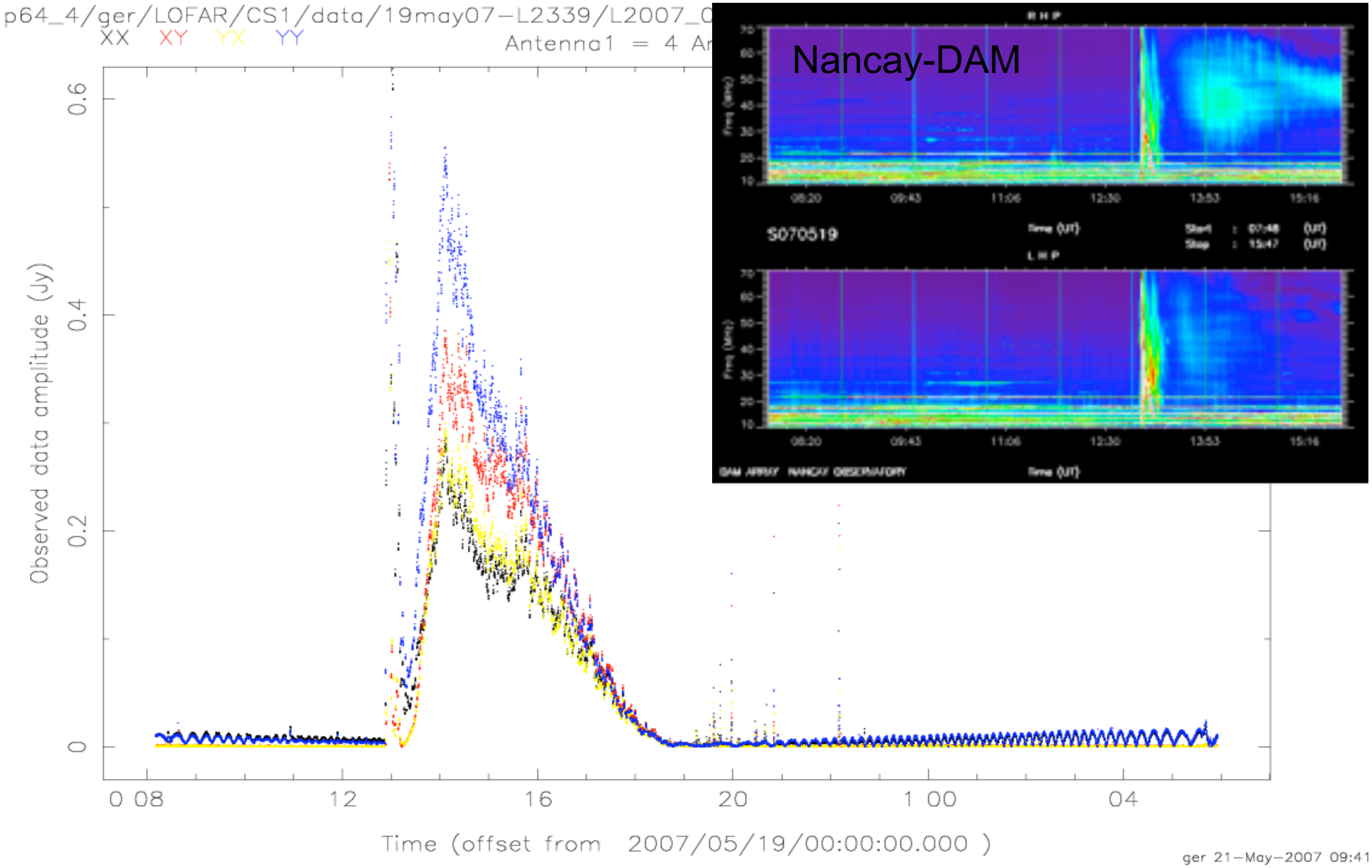
The difference between night and day (220 MHz)

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



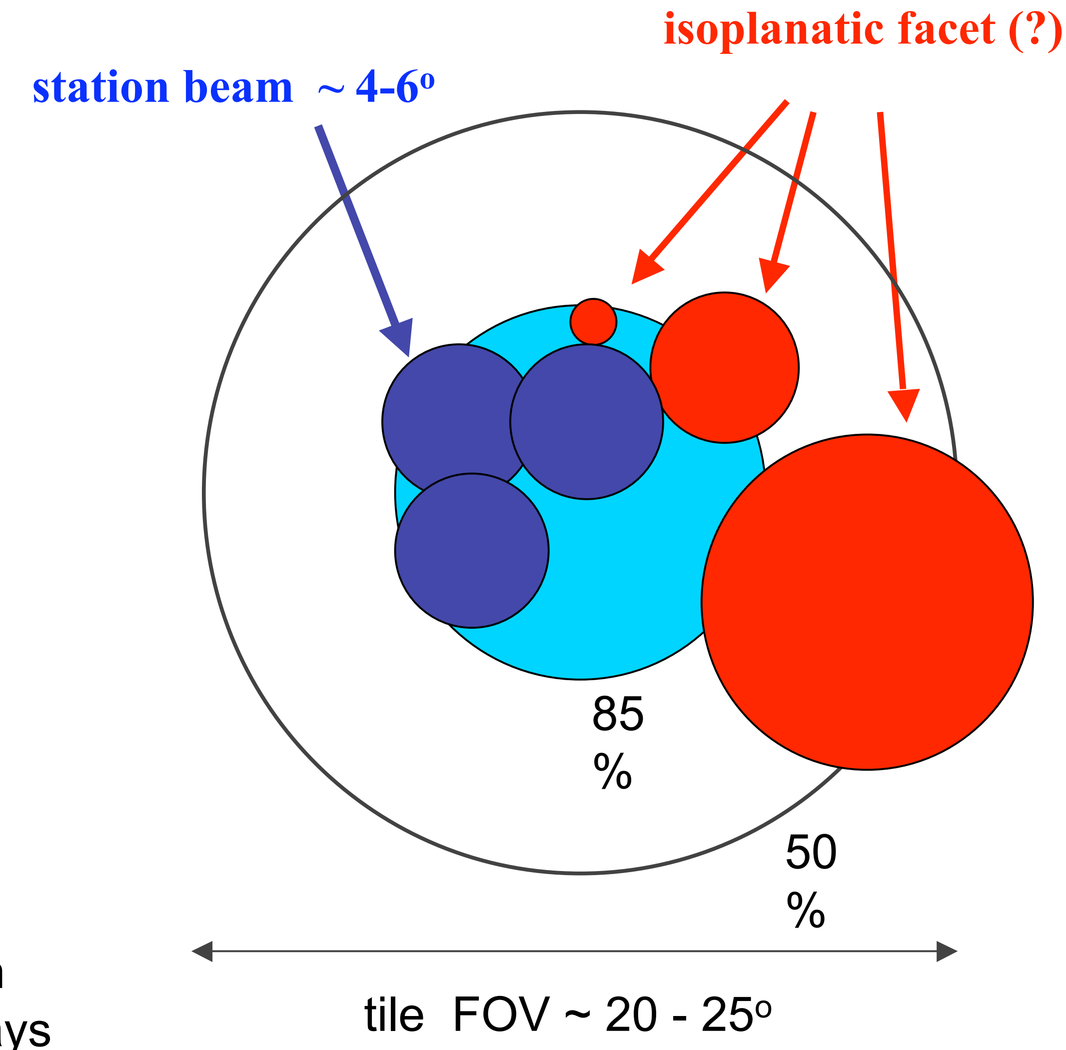
XX XY YX YY

The disturbed Sun ~50 MHz 19May07



LOFAR and the ionosphere

HBA angular scales (24 tiles/station)



Note:

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

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:

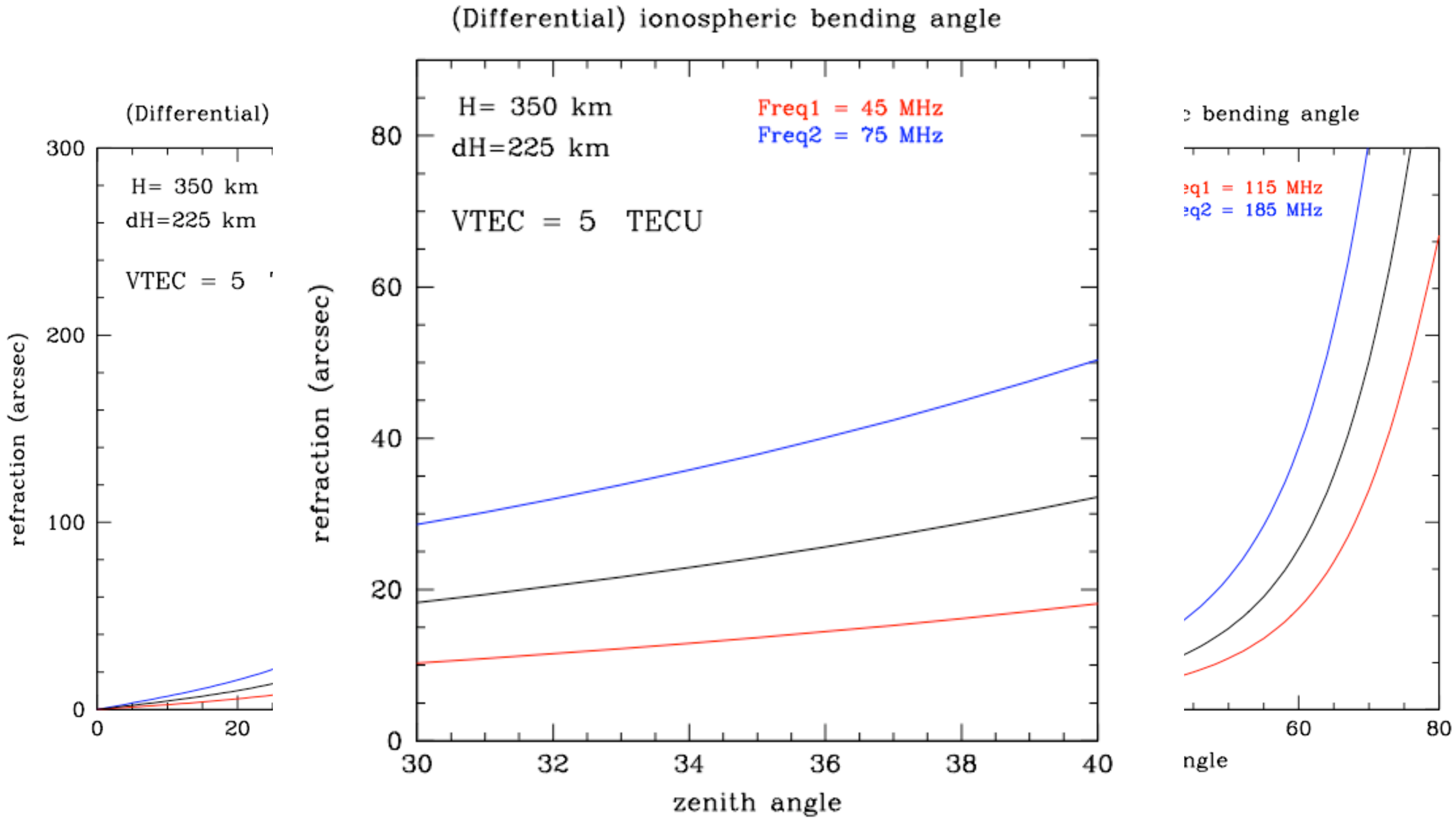
— GPS data (not accurate enough)

— differential angles in large FOV images

— Faraday rotation of polarized sources (Pulsars !)

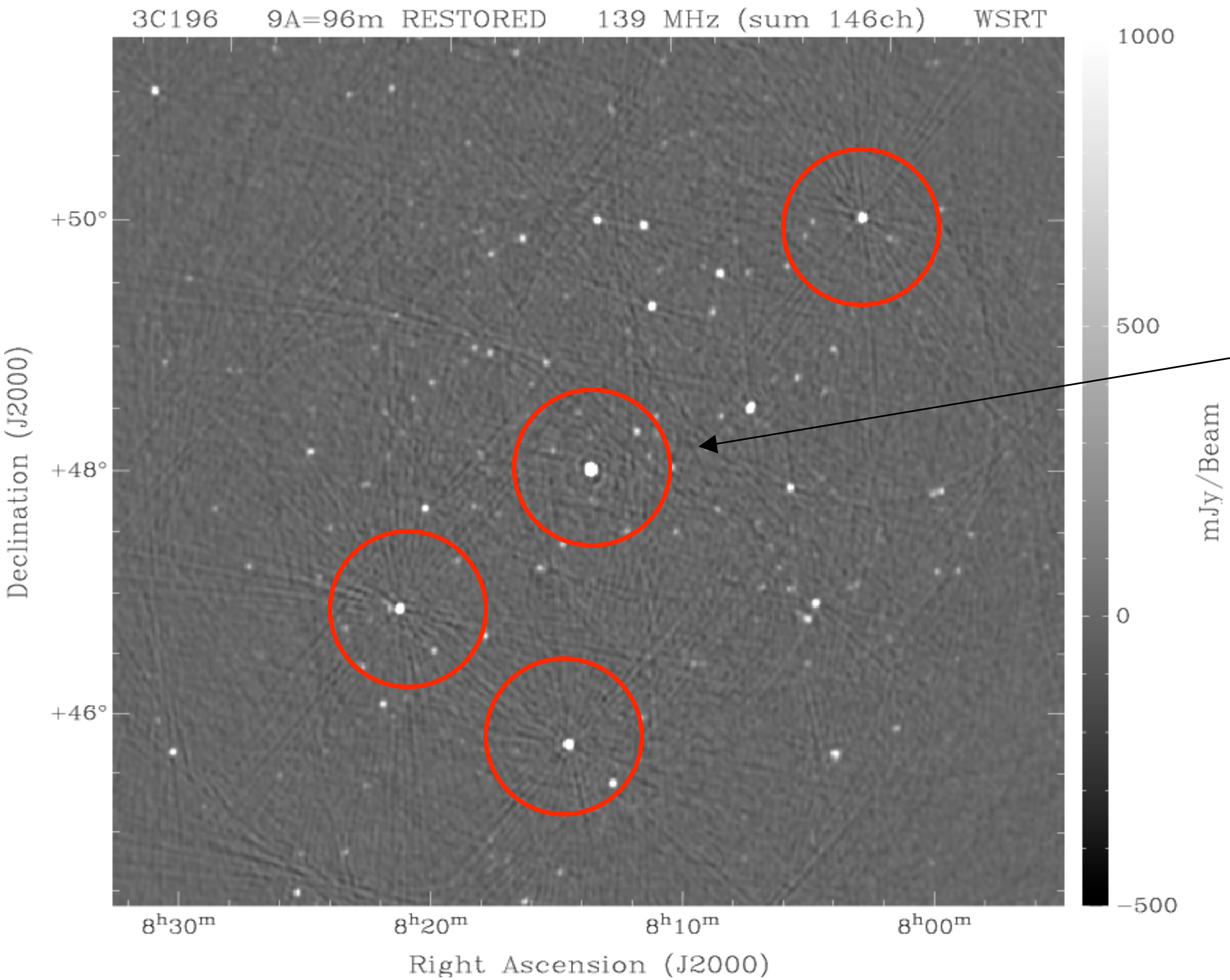
— snapshot all-sky observation sequences combining absolute+relative delays

Differential Ionospheric Refraction Monitoring



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

3C196 in ‘worst’ night: some nonisoplanaticity !



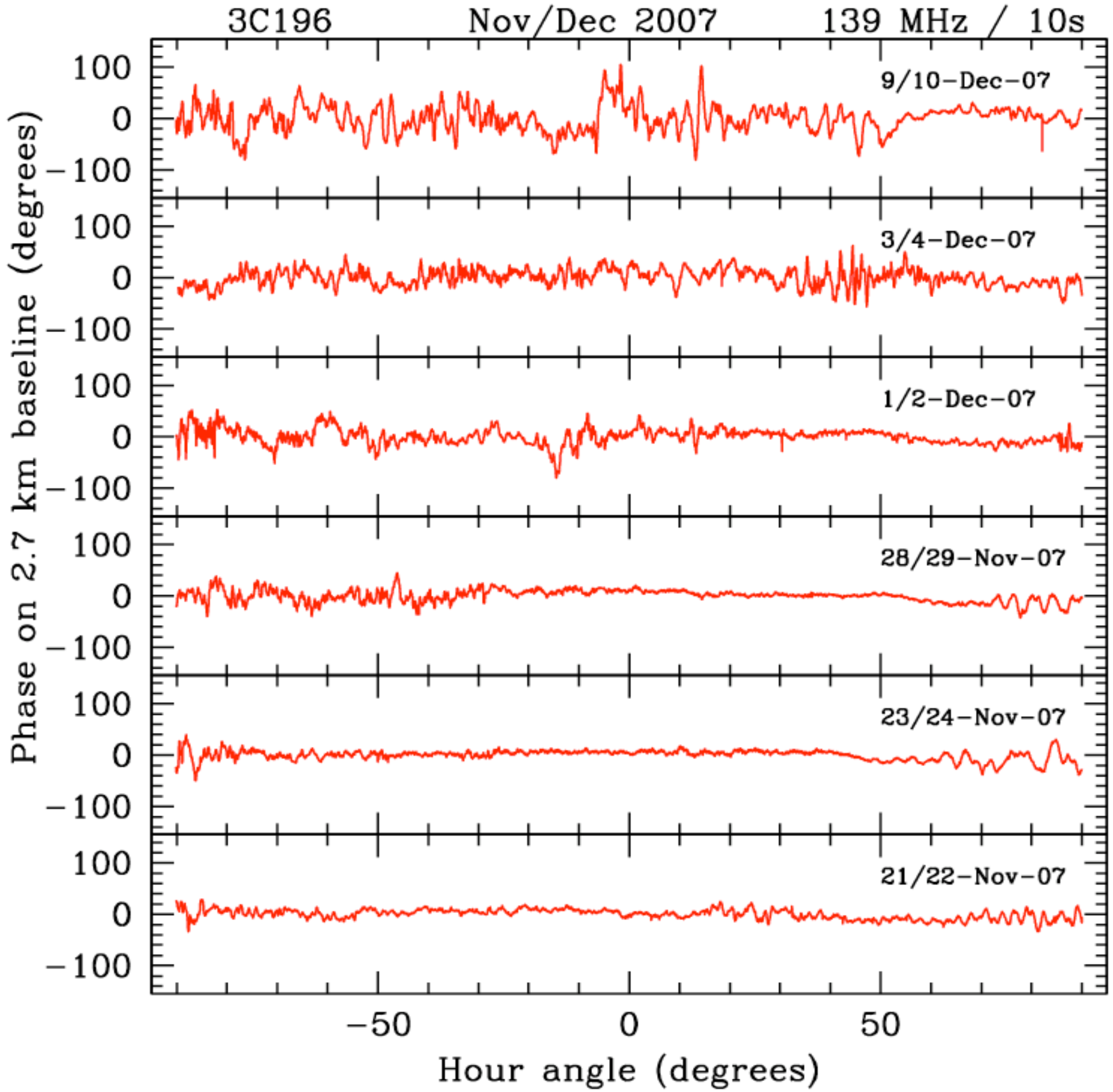
3C196

80 Jy

3 other sources

6-8 Jy

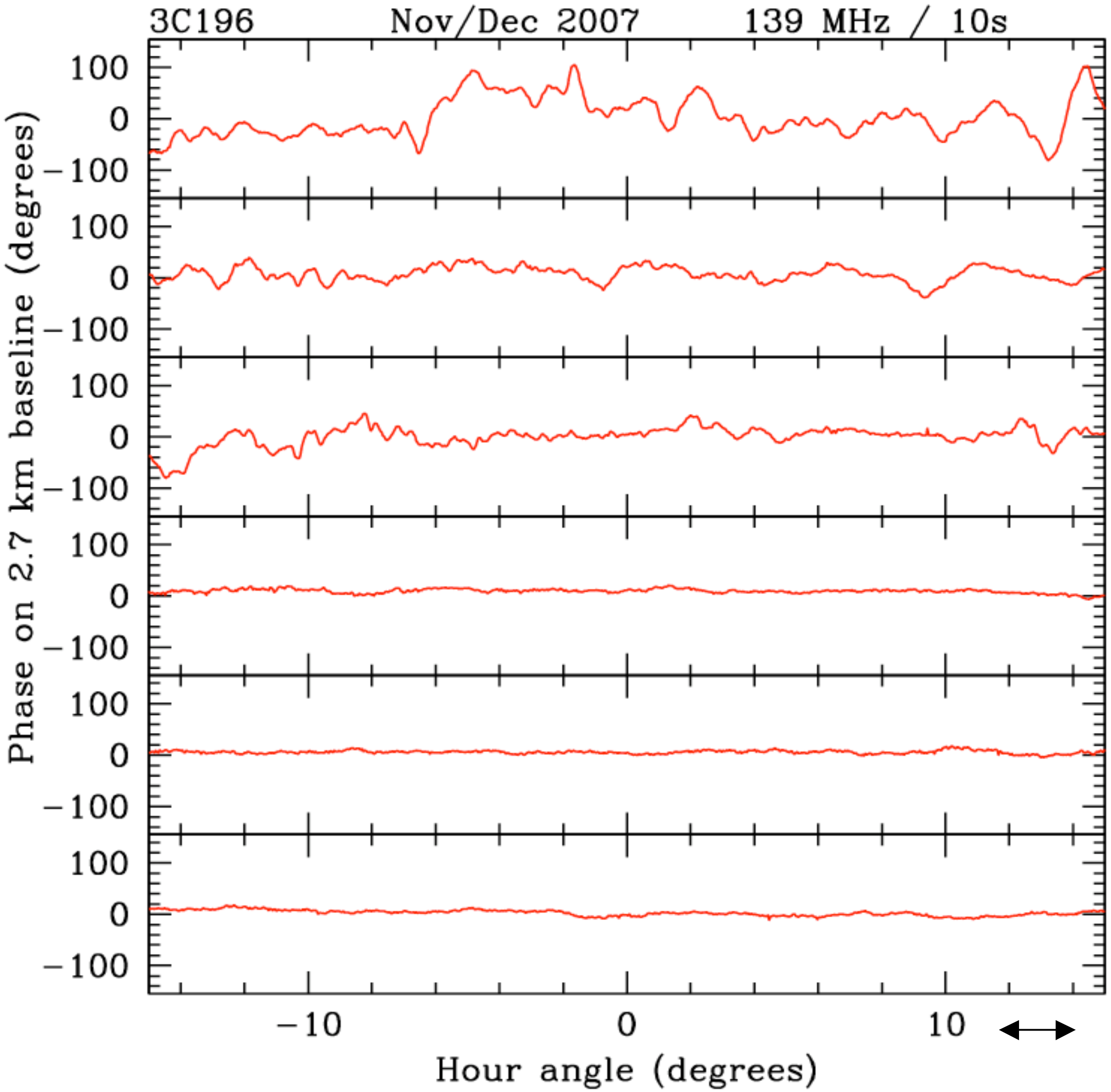
3C196 - selfcal phase solutions



6 x12h

Note the very different ionospheres !

3C196 selfcal phase solutions: zooming in



Note 'well-resolved' turbulence/waves

(noise

= line thickness)

↔ 2^o = 8min = 48 samples

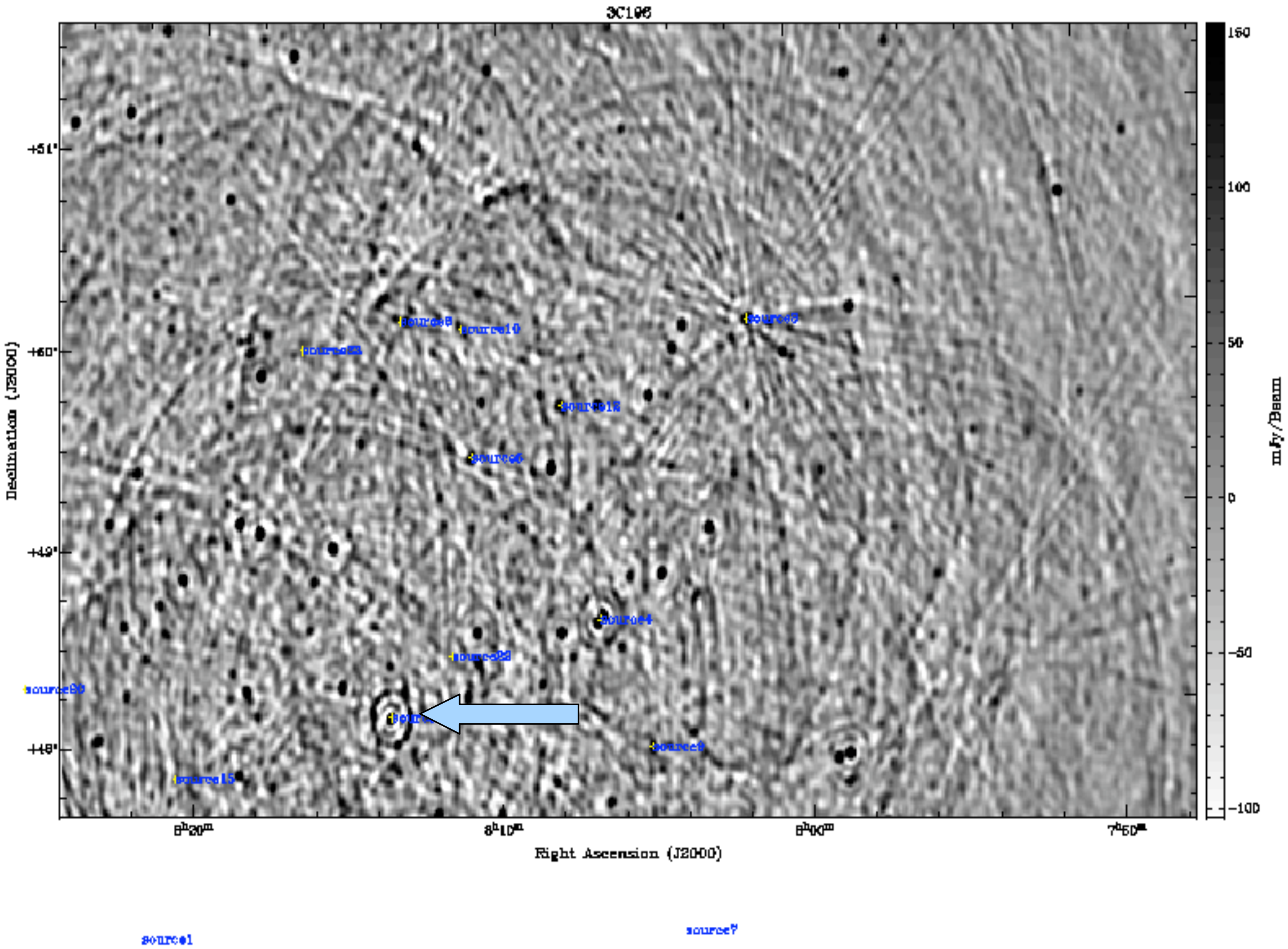
BBS and MIM-modeling on 3C196 WSRT data

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

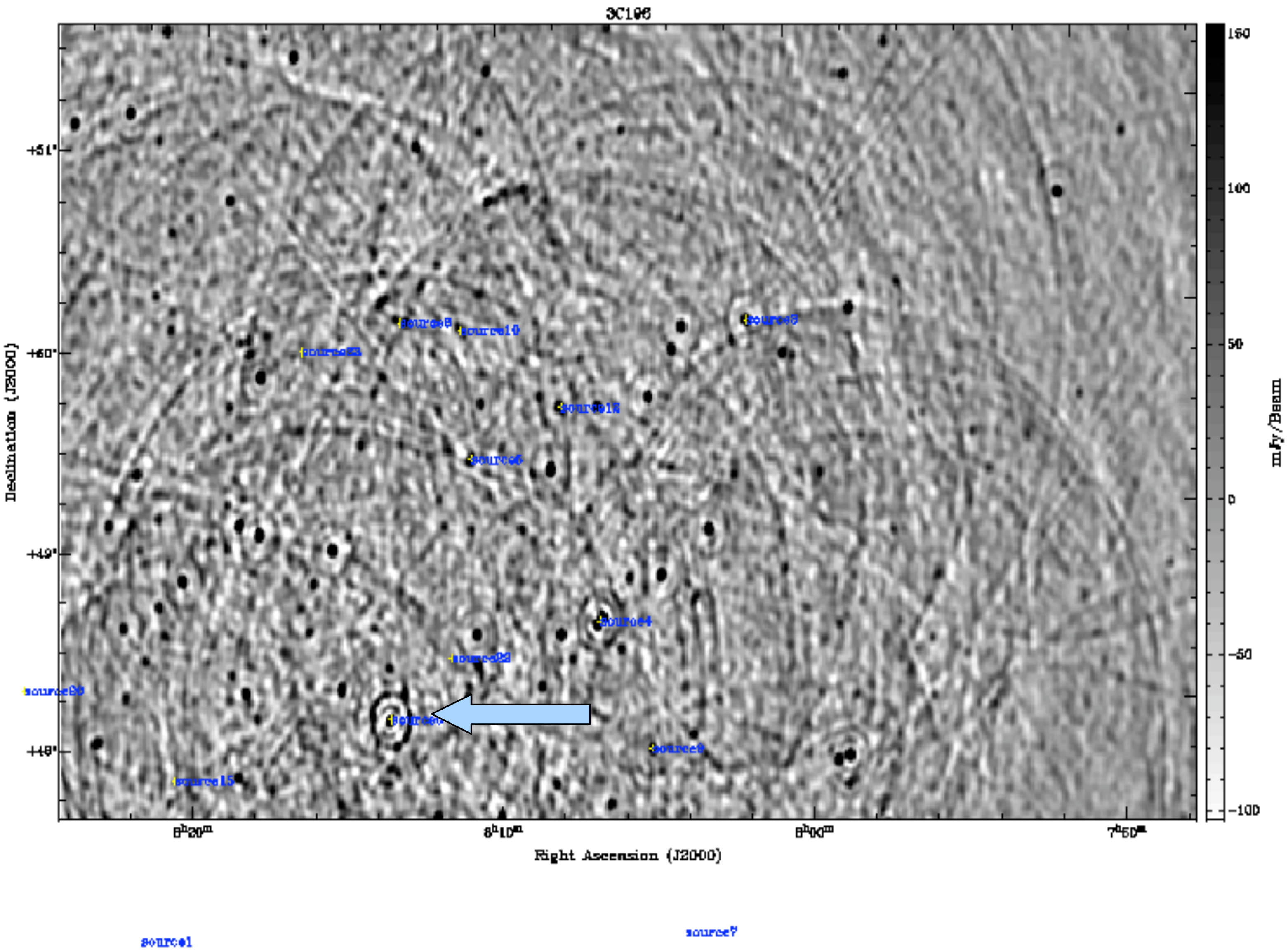
Fitting 2-dimensional phase screen at altitude of 300 km

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

2 parameters

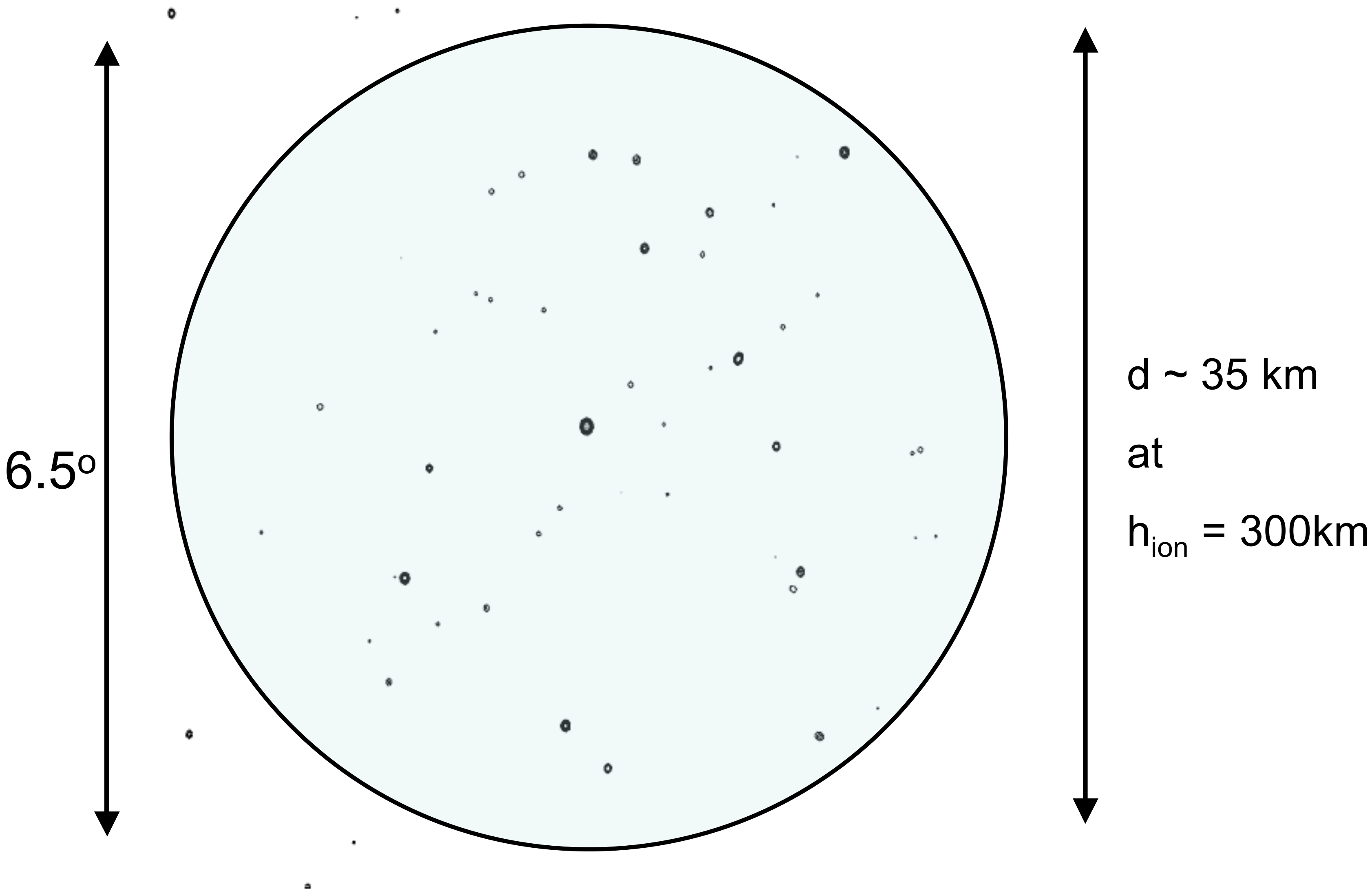


5 parameters

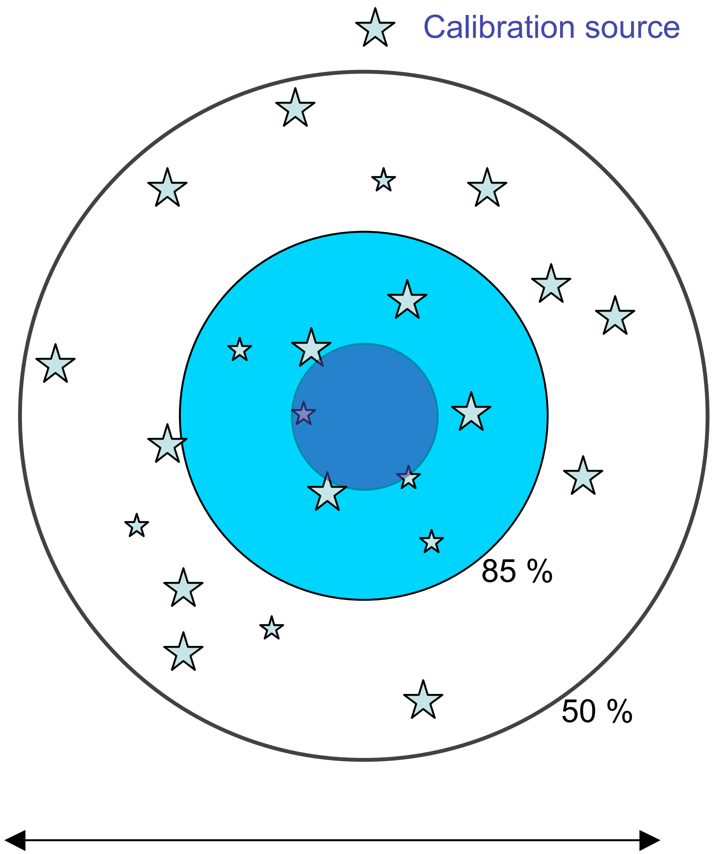


3C196 field: ~45 sources with apparent flux S_{139MHz}> 0.5 Jy

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



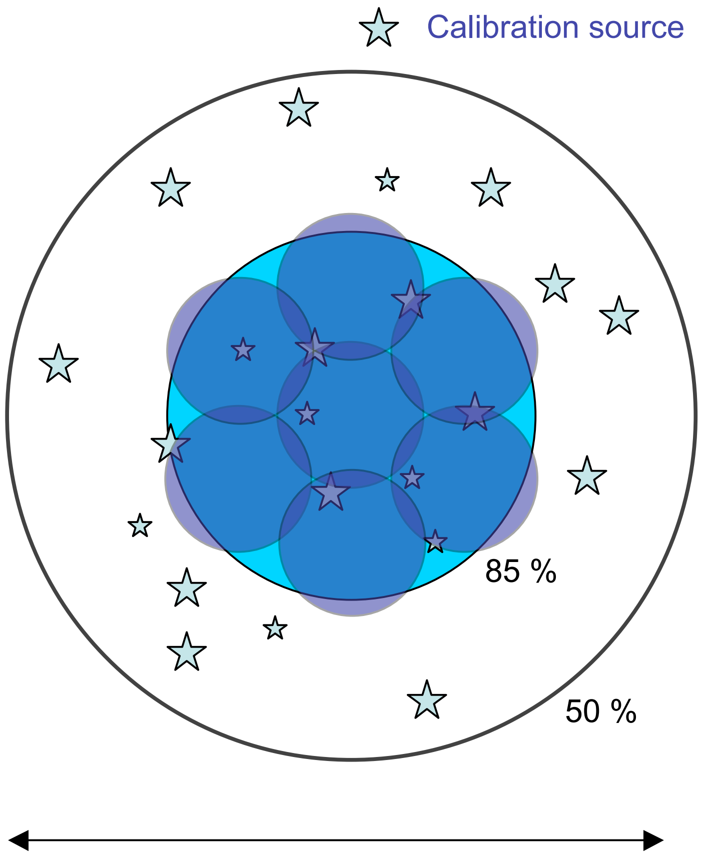
Dynamic ionospheric phase-screen mapping ?



tile beam 20-25^{o}

16-bit case

e.g. 1 beam x 48MHz



tile beam 20-25^{o}

4-bit case

e.g. 7 beams x 27 MHz

To be continued tomorrow in Commissioning/MSSS section