LOFAR specs (rescoped), some CS-1 results and (long) baseline calibration issues

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(LOFAR Calibration Project Scientist)

Outline:

1. LOFAR configuration overview and rescope effect
2. uv-coverage in core, LOFAR core 'superstation'
3. FOV, # sources and sensitivity
4. CS-1 and WSRT-LFFE: some lessons learned
5. Review of main calibration issues
6. Some long baseline (~500-1000 km) calibration issues

The LOFAR observatory

descoped / preliminary

hybrid array ! (Sep07)

Frequency ranges : LBA 20 - 80 MHz
HBA 115 - 240 MHz
Collecting area: ~ 0.03 - 0.06 km^2
Dimension at start ~ 100 km
eventually > 1000 km (Eu-LOFAR)

Configuration: 40 - 50 stations (of 24 - 96 antennas)
core (~ 2 km diameter) 20 - 50 stations
+ '5-armed spiral / expo shell' 20 - 25 stations

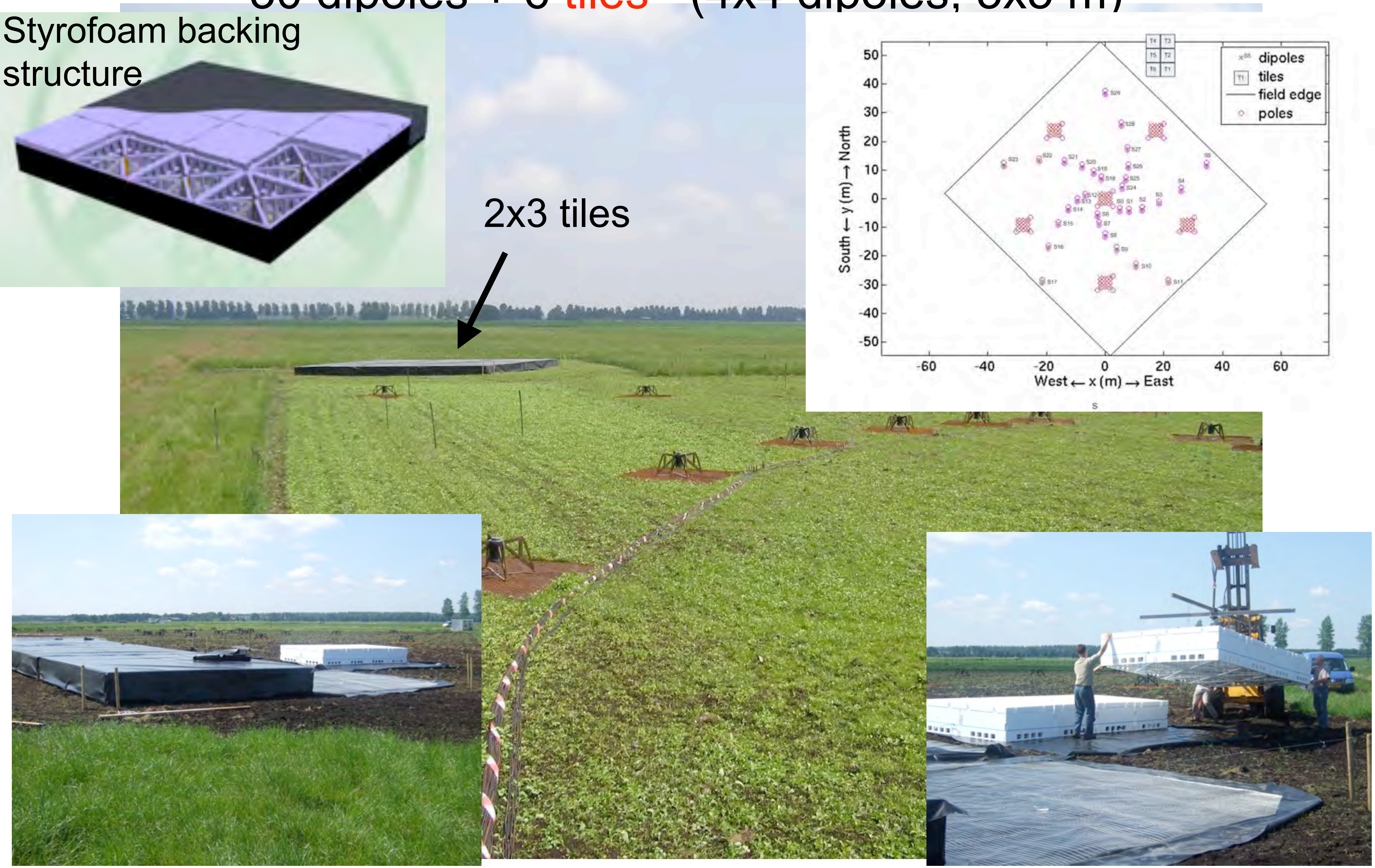
Phased array of dipoles
Aperture synthesis array like: WSRT, VLA, GMRT..

Sensitivity (after 4 h, 4 MHz)
- @ 50 MHz ~ 5 mJy
- @ 150 MHz ~ 0.3 mJy

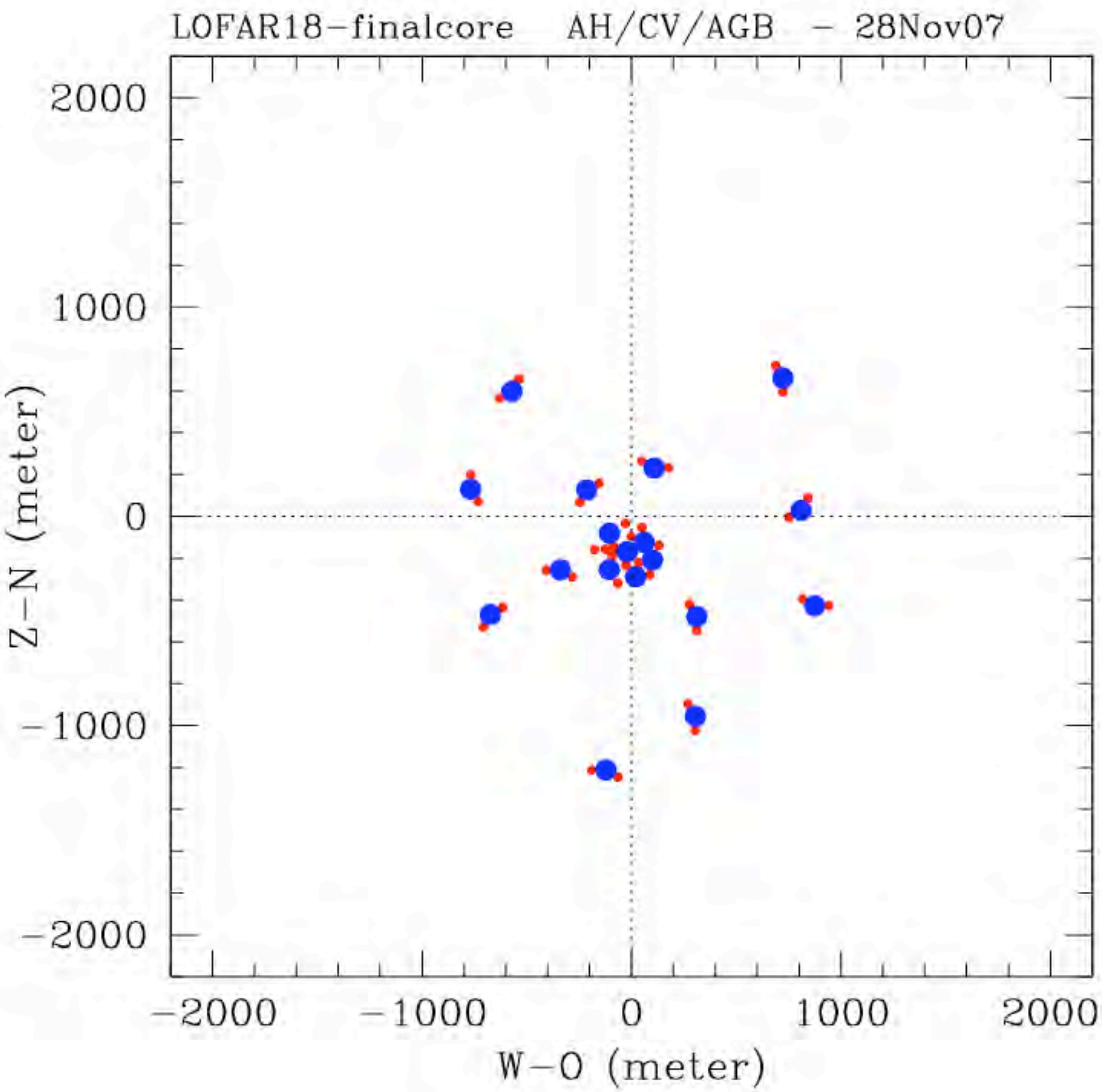
Many simultaneous users (beams) possible !

HBA initial test configuration (June 07)

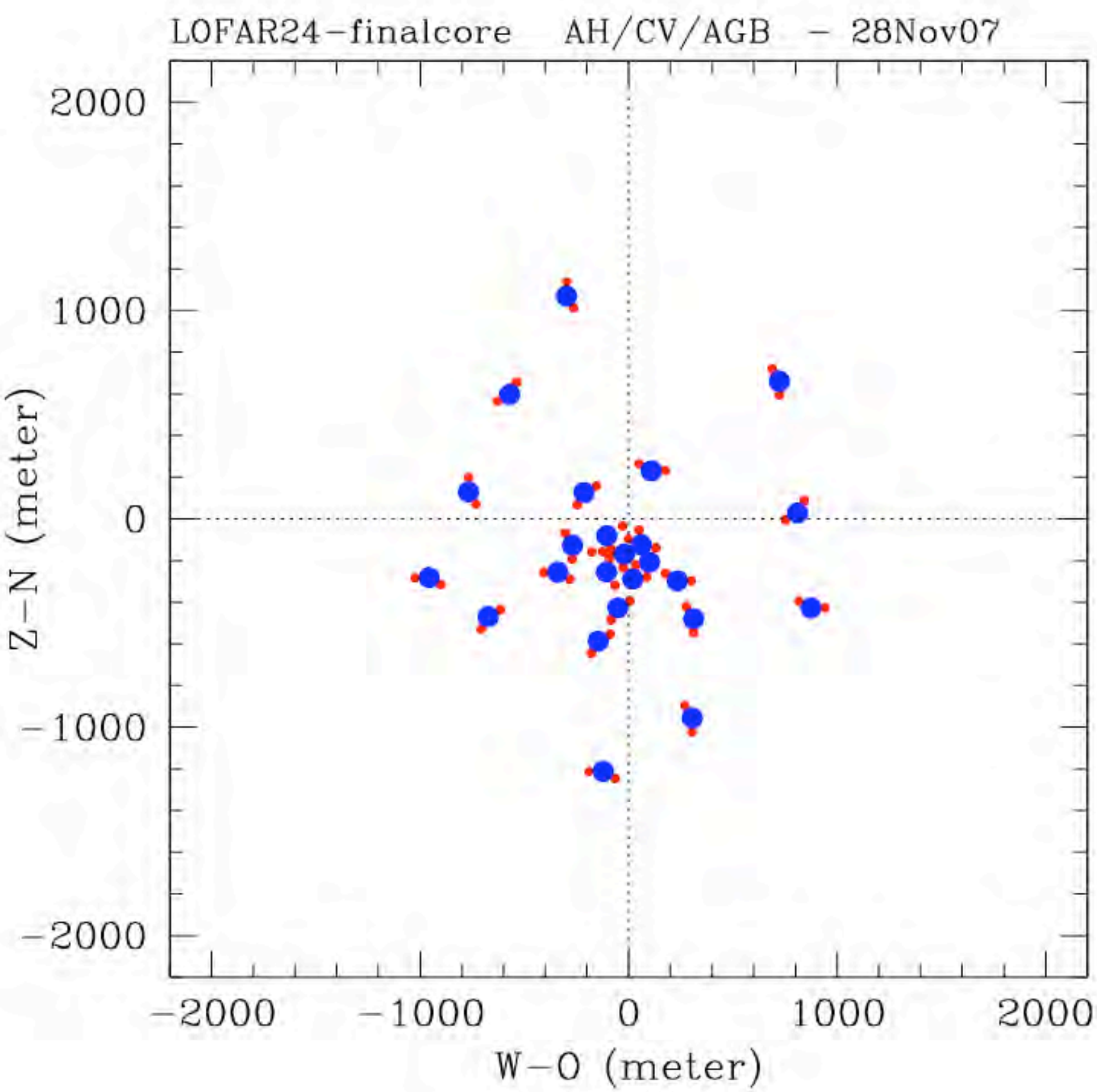
30 dipoles + 6 tiles   (4x4 dipoles, 5x5 m)



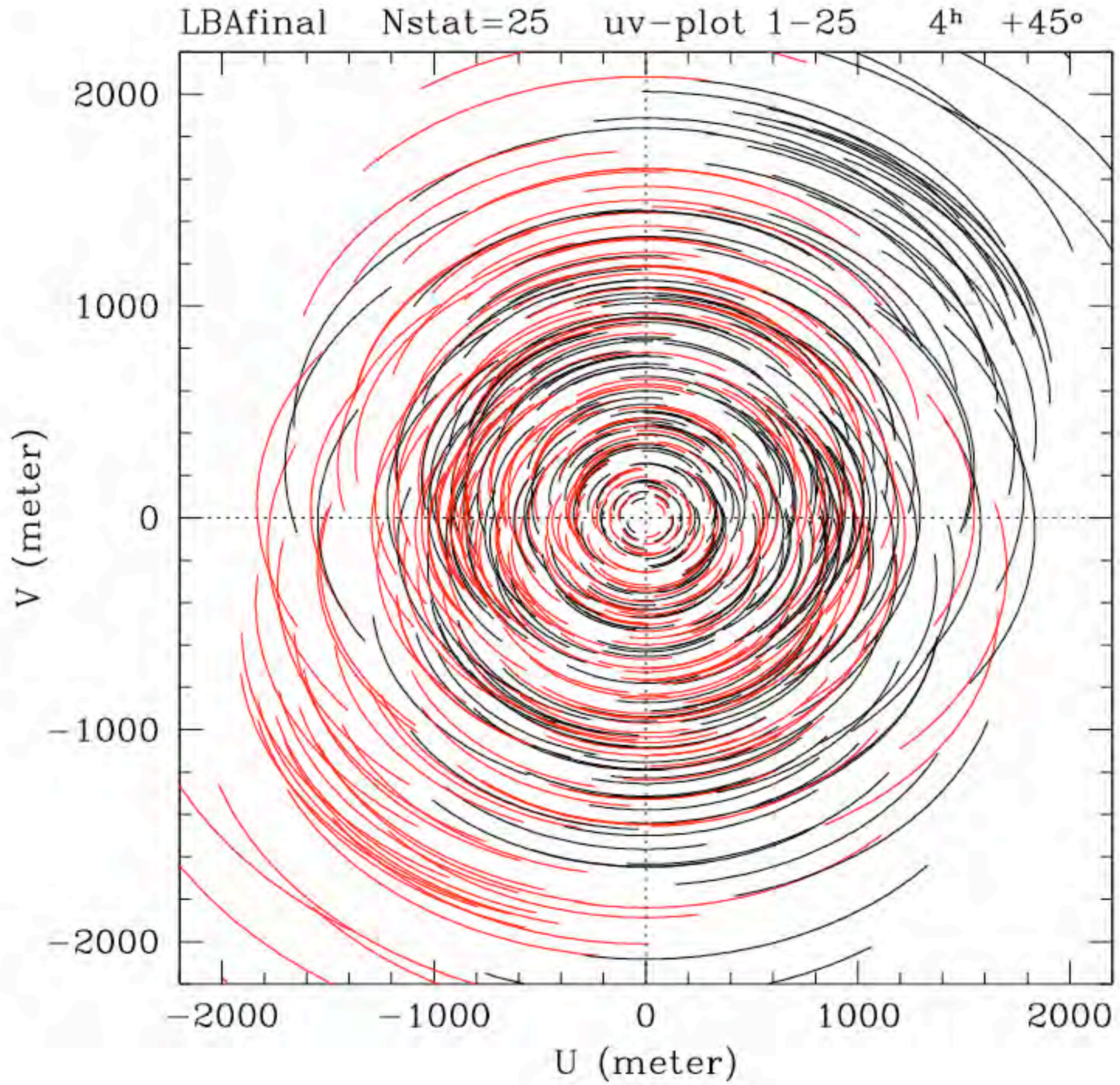
LOFAR18 core



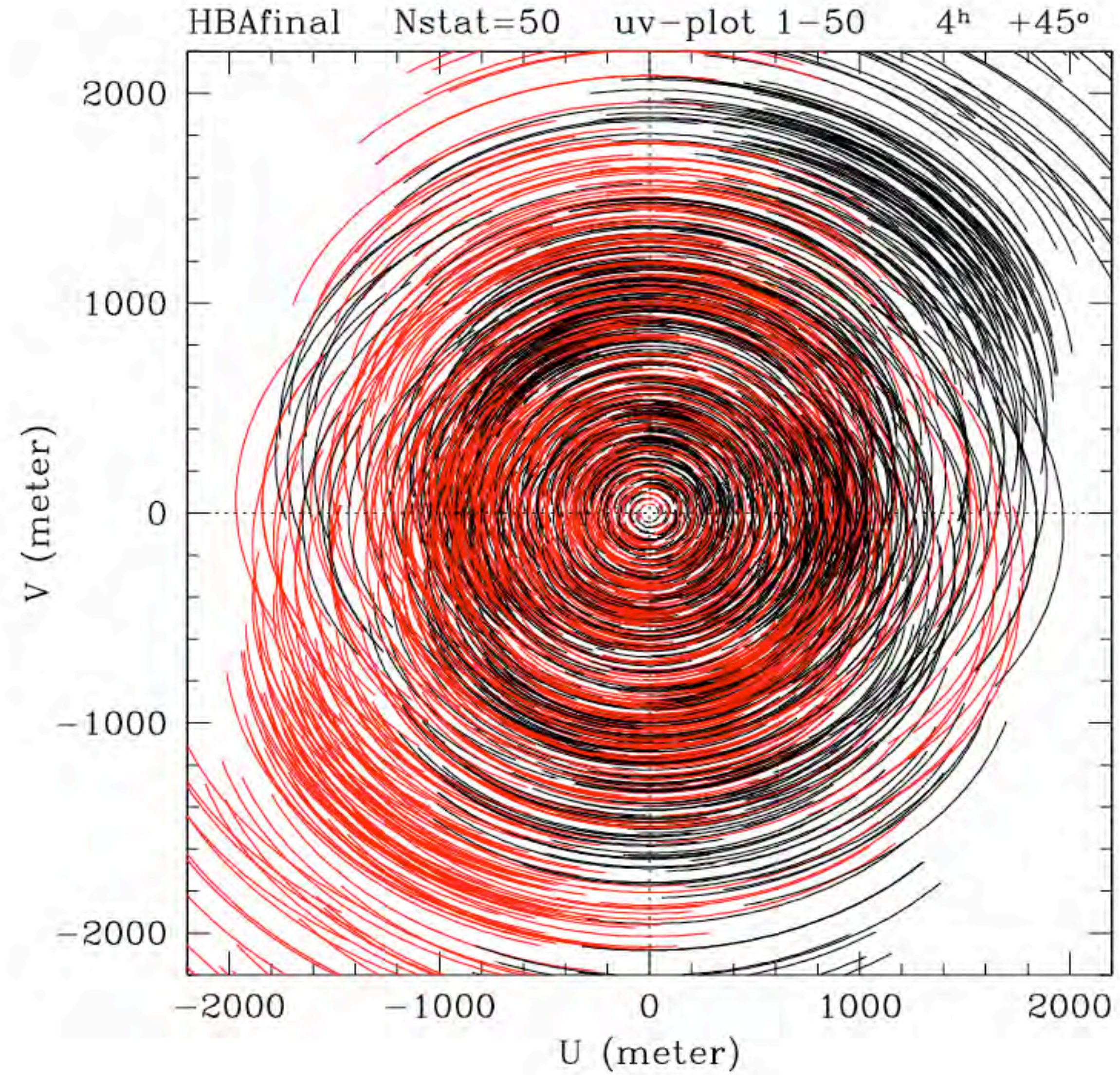
LOFAR24 core



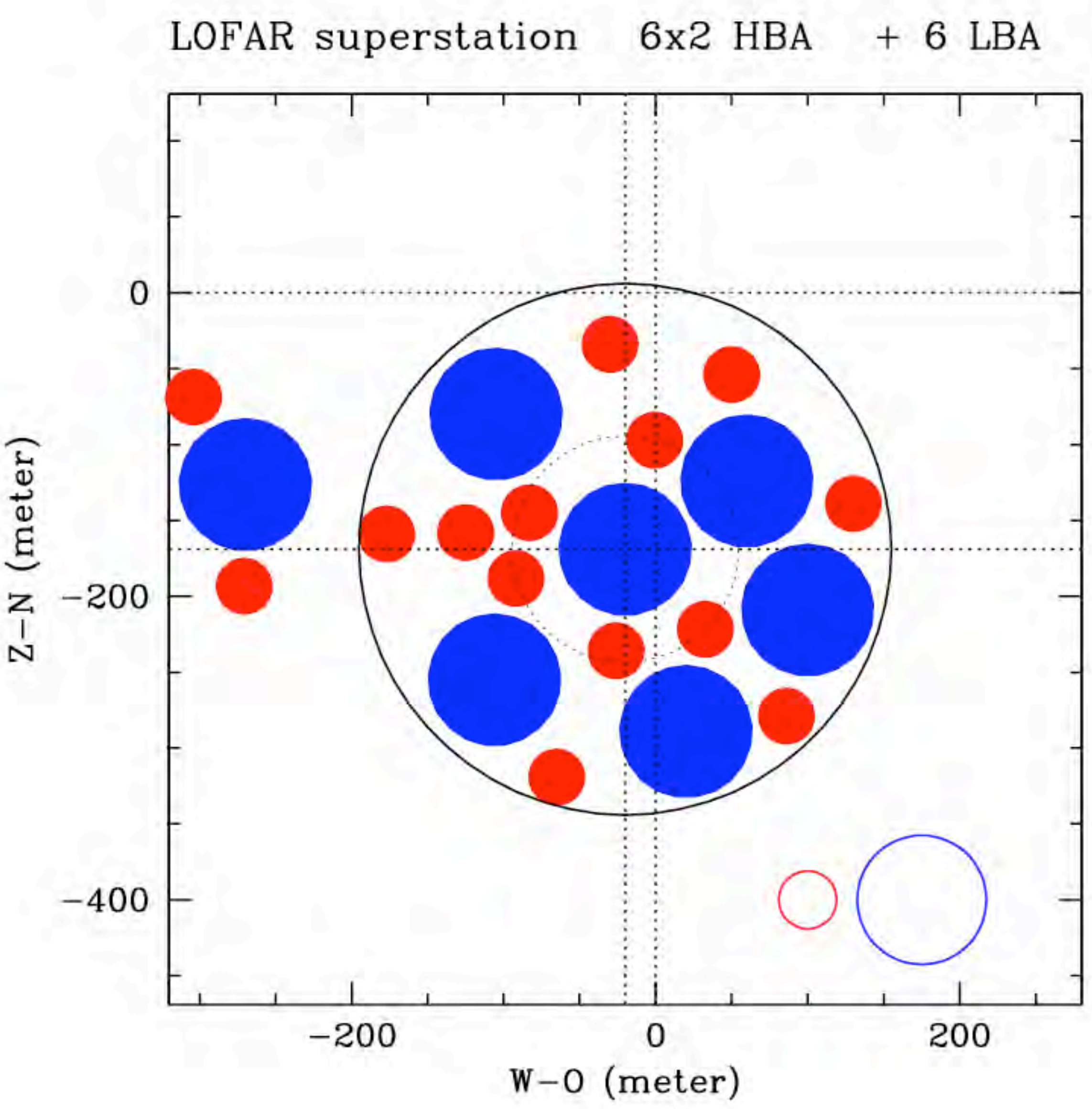
LBA 25 stations 4^h $+45^o$



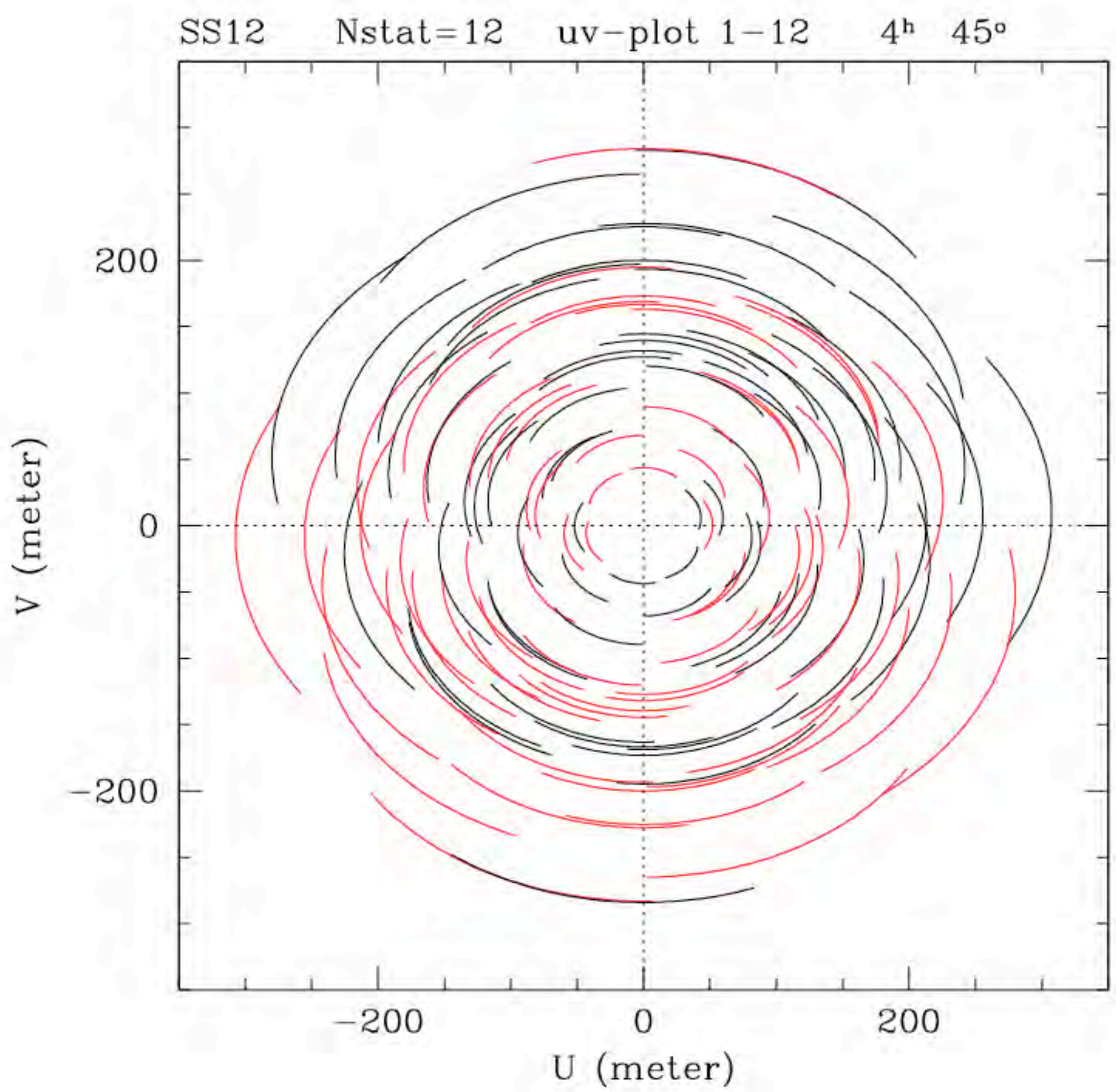
HBA 25x2 stations 4^h $+45^o$



‘Superstation’ in core: 6 LBA and 6x2 HBA

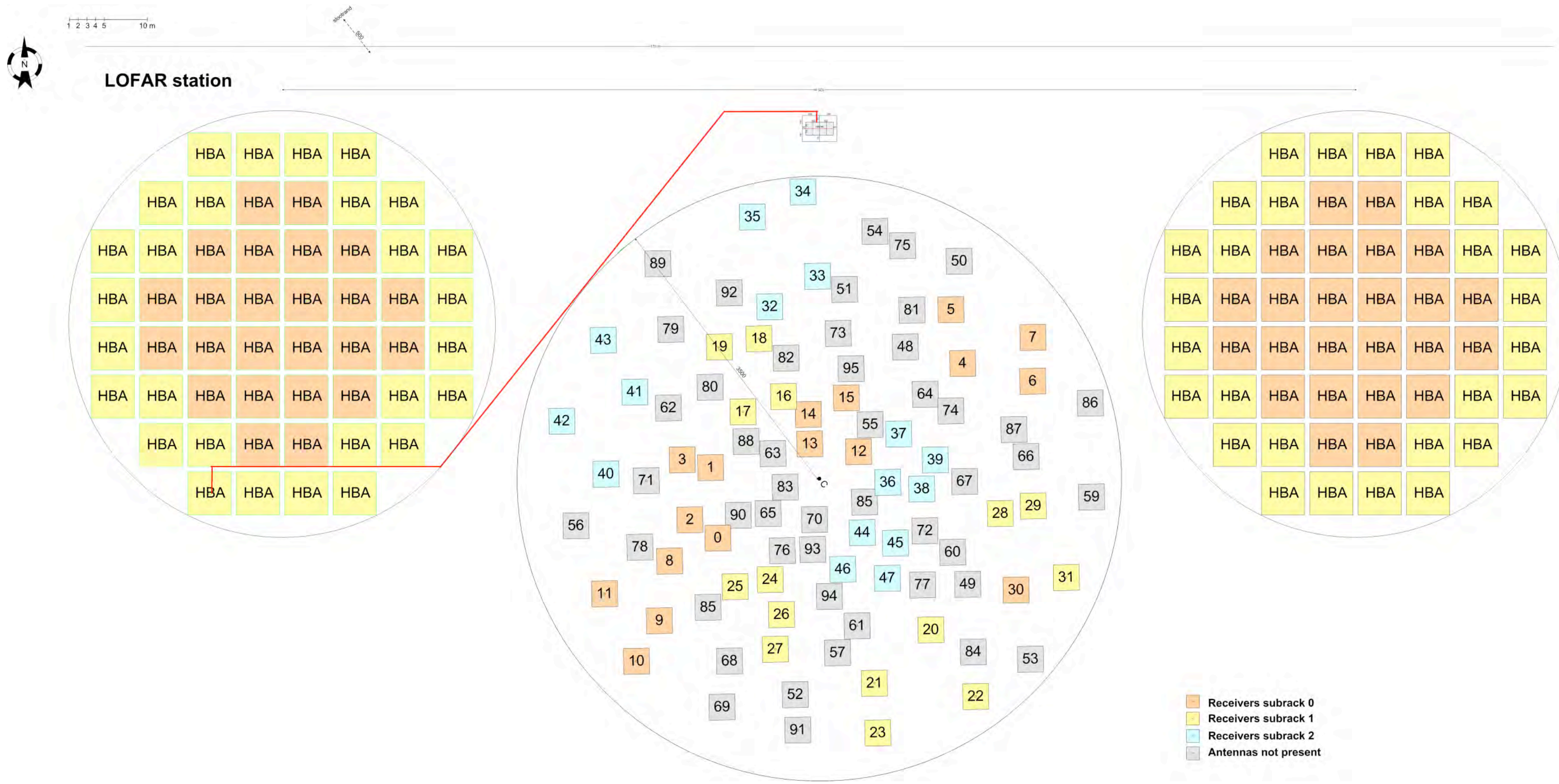


6x2 HBA uv-coverage 4^h $+45^o$



Core station layout after rescope

HBA24 LBA48-96 HBA24



LOFAR sensitivity table (Dec07)

HBA (150 MHz)		Unit	LBA (50 MHz)	
Station noise				
1 dipole	1,600,000	Jy	1,600,000	1 dipole
1 4x4 tile	100,000	Jy		
1 24-tile station (core)	4,200	Jy		
1 48-tile station (NL)	2,100	Jy	33,000	1 48-dipole station
1 96 tile station (EU)	1,050	Jy	20,000	1 96-dipole station
Visibility noise (core array)				
1 ifr, 10s, 1pol, 0.18 MHz	3.1	Jy	25	
1 ifr, 10s, 1pol, 20x0.18 MHz	0.7	Jy	~~2.8~~ 5.5	
Snapshot image noise (core array)				
780 ifrs, 10s, 2 pol, 0.18 MHz	78	mJy	1640	190 ifrs
780 ifrs, 10s, 2 pol, 20x0.18 MHz	17	mJy	370	190 ifrs
780 ifrs, 10s, 2 pol, 164x0.18MHz	6	mJy	130	190 ifrs
Synthesis image noise (core-NL hybrid array)				
1770 ifrs, 4h, 2 pol, 0.18 MHz	1.0	mJy	22	780 ifrs
1770 ifrs, 4h, 2 pol, 20x0.18MHz	0.22	mJy	4.8	780 ifrs
1770 ifrs, 4h, 2 pol, 164x0.18MHz	0.08	mJy	1.7	780 ifrs

N=40

N=20

N=60

N=40

LOFAR beam/FOV table

LOFAR station diameter and resulting FOV in HBA and LBA bands (after Oct2007 rescope)

HBA			**120 MHz**	**220 MHz**
Array	# tiles/station	station diameter (m)	HPBW (deg)	HPBW(deg)
Core	24 +24	~ 35	~ 5.3	~ 2.9
NL	48	~ 50	~ 3.7	~ 2.0
Europe	96	~ 65	~ 2.9	~ 1.6

Adopted HBPW = 1.3 λ /D (depends on beamformer spatial taper used)
Note that the synthesized FOV has to be typically ~ 2x larger !

On core-NL, core-EU or NL-EU baselines the geometric mean values have to be taken !

LBA			**30 MHz**	**60 MHz**
Array	# dipoles/station	station diameter(m)	HPBW (deg)	HPBW(deg)
Core	48	~ 30 – 82m	9.1 (for 82m)	12.4 (for 30m)
NL	48	~ 30 – 82m	9.1 (for 82m)	12.4 (for 30m)
Europe	96	65	11.5	5.7

Example ! NancaySS 9x96 195m 3.8° 1.9°

Excel sheets to give sensitivity, FOV, # sources (S/N) etc for rescoped core, NL and European LOFAR arrays

(Nijboer & de Bruyn, in prep)

# LBA Core Stations	20	Note: Yellow fields are inputs
# LBA Remote Stations	20	
# LBA EU Stations	0	
# HBA Core Sations	40	
# HBA Remote Stations	20	
# HBA EU Stations	0	
LBA dipole noise (Jy) 50 MHz	1600000.00	Note: average elevation of 45 degrees (projection factor 0.7)
HBA dipole noise (Jy) 150 MHz	1600000.00	
Effective width of a subband (Hz)	160000.00	Note: flanks of the subbands will be neglected and some channels will be flagged for RFI
Image noise increase factor: Core	1.00	Note: increase in image noise due to weighting scheme
Image noise increase factor: Core + Remote	1.30	
Image noise increase factor: Core + Remote + EU	1.30	

	LBA Core	LBA Remote	LBA EU	HBA Core	HBA Remote	HBA EU
# dipoles per tile	1	1	1	16	16	16
# tiles per station	48	48	96	24	48	96
noise per dipole	1600000.00	1600000.00	1600000.00	1600000.00	1600000.00	1600000.00
noise per tile	1600000.00	1600000.00	1600000.00	100000.00	100000.00	100000.00
noise per station	33333.33	33333.33	16666.67	4166.67	2083.33	1041.67

Noise per baseline: 1 s. 1 Hz, 1 pol	Core	Remote	EU	Core	Remote	EU
Core	33333.33	33333.33	23570.23	4166.67	2946.28	2083.33
Remote		33333.33	23570.23		2083.33	1473.14
EU			16666.67			1041.67

Noise per baseline, 10 s., 1 subband, 1 pol	Core	Remote	EU	Core	Remote	EU
Core	24.85	24.85	17.57	3.11	2.20	1.55
Remote		24.85	17.57		1.55	1.10
EU			12.42			0.78

Noise per baseline, 10 s., 20 subband, 1 pol	Core	Remote	EU	Core	Remote	EU
Core	5.56	5.56	3.93	0.69	0.49	0.35
Remote		5.56	3.93		0.35	0.25
EU			2.78			0.17

# baselines	Core	Remote	EU	Core	Remote	EU
Core	190	400	0	780	800	0
Remote		190	0		190	0
EU			0			0

Image noise 1 s., 1 Hz, 1 pol. (Jy) — Note: assuming equal weighting of all baselines, but including the increase in noise factor

	Core	Core + Remote	Core + Remote + EU	Core	Core + Remote	Core + Remote + EU
Image noise 1 s., 1 Hz, 1 pol. (Jy)	2418.25	1551.58	1551.58	149.19	96.68	98.86
Snapshot image noise (mJy)						
10 sec., 1 subband, 2 pol	1274.53	817.76	817.76	78.63	50.95	50.95
10 sec., 20 subband, 2 pol	284.99	182.86	182.86	17.58	11.39	11.39
10 sec., 164 subband, 2 pol	99.52	63.86	63.86	6.14	3.98	3.98
Synthesis image noise (mJy)						
4 hr, 1 subband, 2 pol	33.59	21.55	21.55	2.07	1.34	1.34
4 hr., 20 subband, 2 pol	7.51	4.82	4.82	0.46	0.30	0.30
4 hr., 164 subband, 2 pol	2.62	1.68	1.68	0.16	0.10	0.10

Some results from LOFAR CS-1
(Core Station 1)

CS-1 frequency selection aspects

Sampling modes: 160 or 200 MHz --> LBA & HBA frequency modes

- Station: 512 subbands (156 or 195 kHz)
- CEP: per subband 256 channels (0.6 or 0.8 kHz)

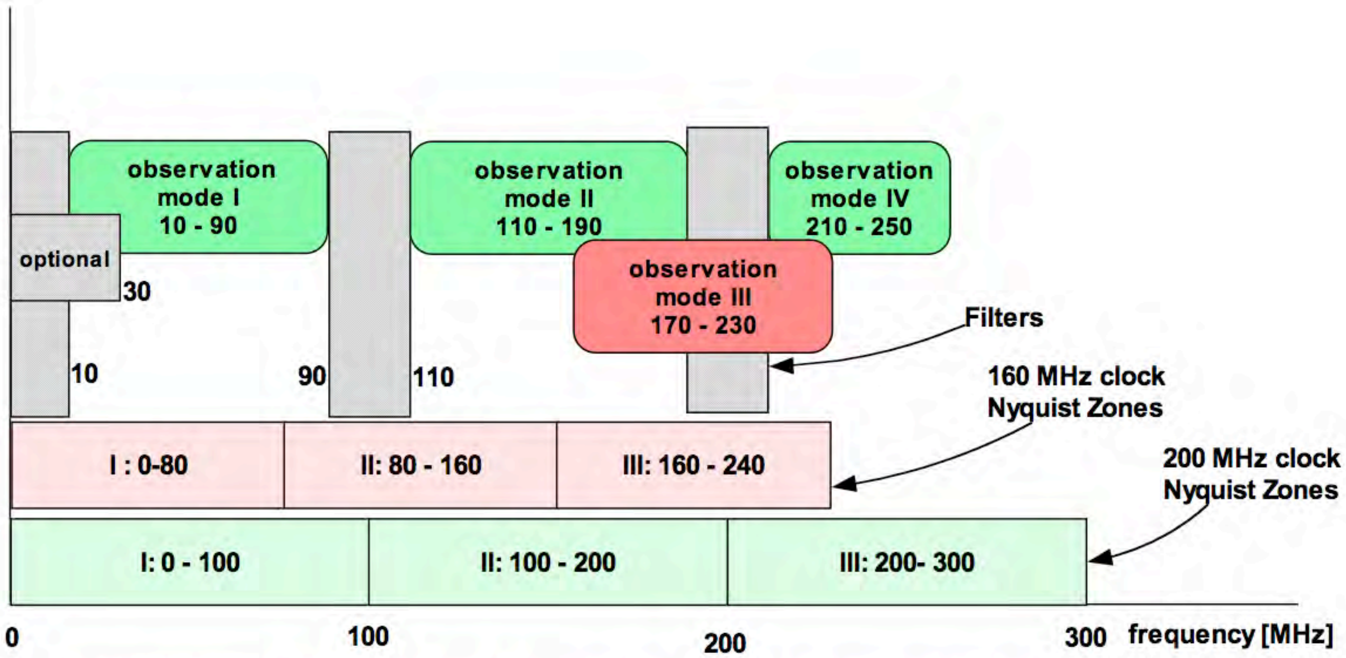


Figure 10 *Selection of Nyquist zones is used to select the observed band in the station.*

CS-1 configuration ('mini'-LOFAR)

Dec 06 --> Summer 08

- hardware across 4 stations:
  - LBA: 96 dipoles (48 + 3x16)
  - HBA: 32 dipoles + 6 tiles
- per station there are 4 -12 'micro'stations
- digital beamforming (with 4 - 48 dipoles)
- baselines from ~10 - 450 meter
- 16 'micro'stations ⇒ 120 (~ 60) interferometers
- 24 microstations ⇒ 276 (~ 180) interferometers

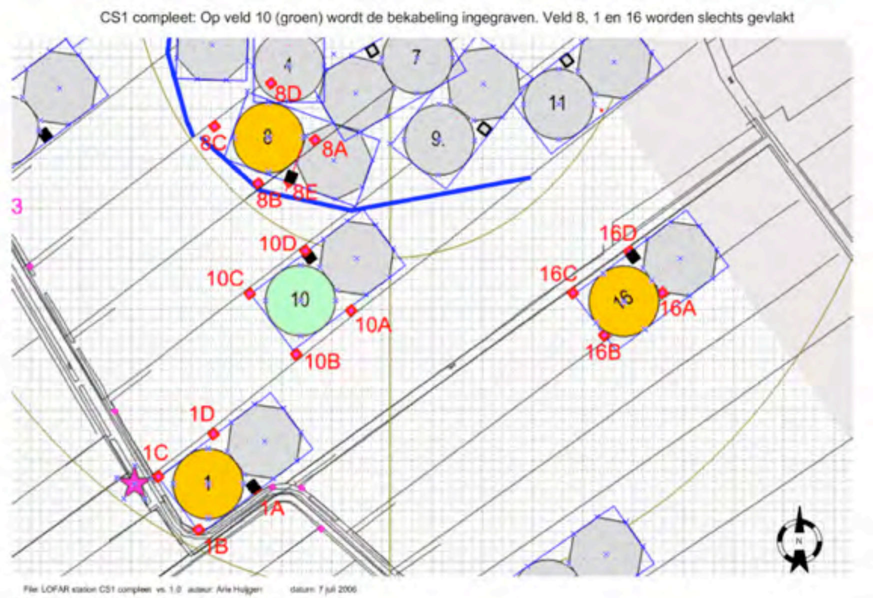
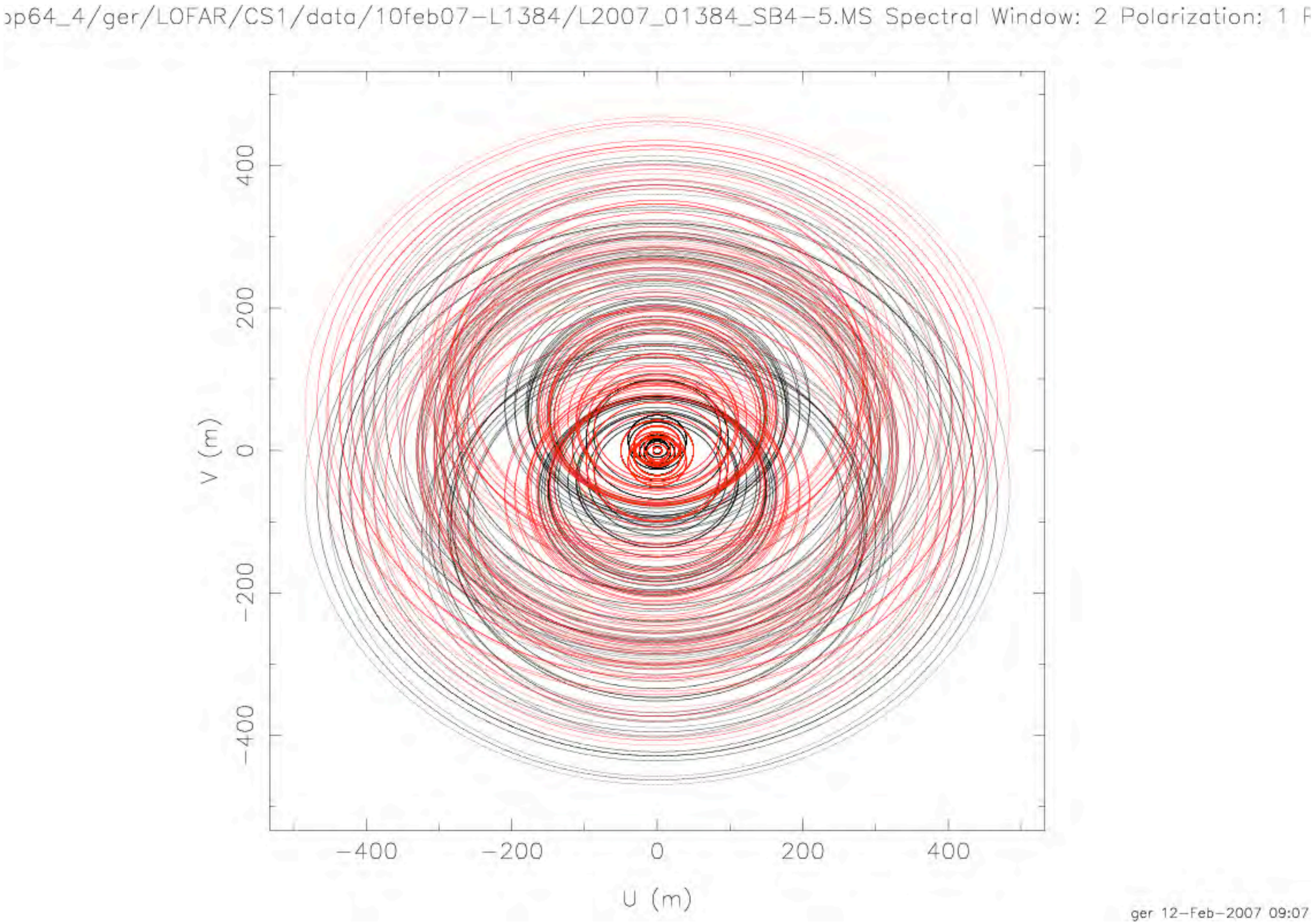


Figure 1: CS1 station locations.

400 m

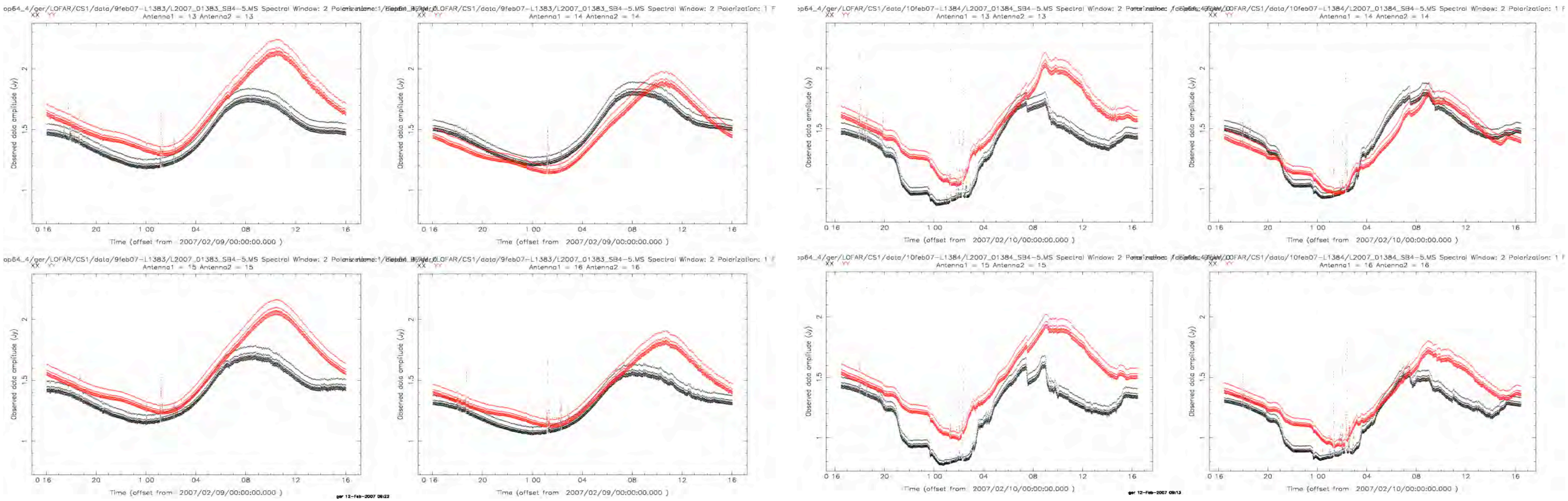
CS-1 uv-coverage (projected baseline+orientation)

after 24 h on CasA , dec +59^{o}



(indirect) effects of rain on total power (gain)

dry day   very wet day



- Rain: resonance frequency of antenna shifts down in frequency -->
- Gain effects typically ~ +10% (ν < 58 MHz) or ~ -10 % (ν > 58 MHz)

How will we deal with this?

1) correct through selfcalibration or 2) observe with HBA's and 3) reduce effects (?)

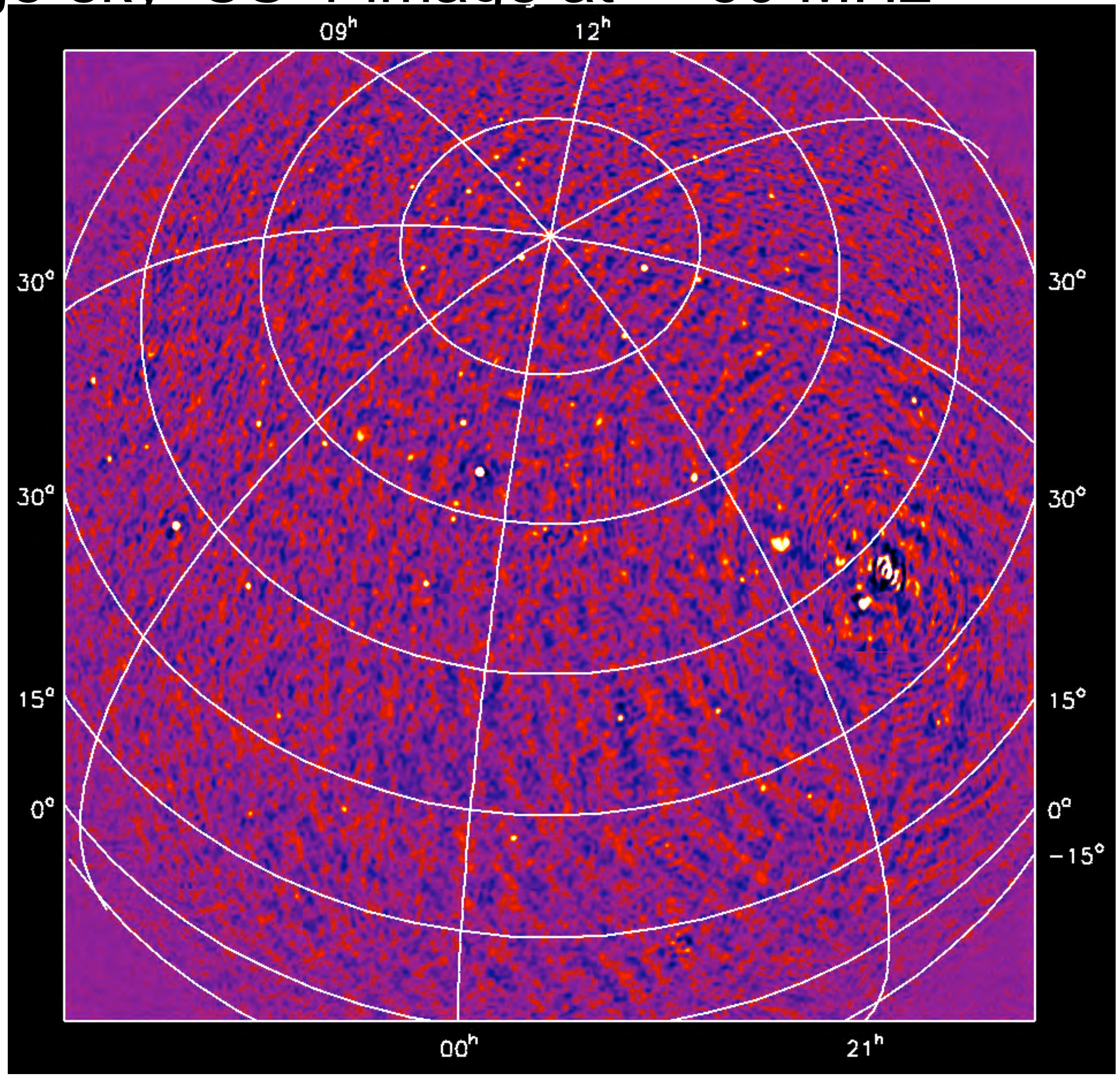
First high quality 'large-sky' CS-1 image at ~ 50 MHz

Centered on CasA

- 24 Feb 2007 (29h obs)
- 0.5 MHz bandwidth

- 16 microstations (15 dipoles and 1 with ∑ 48 dipoles)
- only baselines > 5 λλ
- PSF ~ 0.5^{o}

- ~ 40 sources visible
- CasA: 20,000 Jy (subtracted)
- Image noise ~ 3 - 5 Jy
  --> peak/noise range ~ 5,000:1
- Thermal noise ~ 0.5 Jy



Sarod Yatawatta

Confusion limited LOFAR CS-1 image at ~ 50 MHz

(Sarod Yatawatta, Sep07)

16 dipoles (~70 baselines)

3 x 24h

38 - 59 MHz
Bandwidth ~ 6 MHz

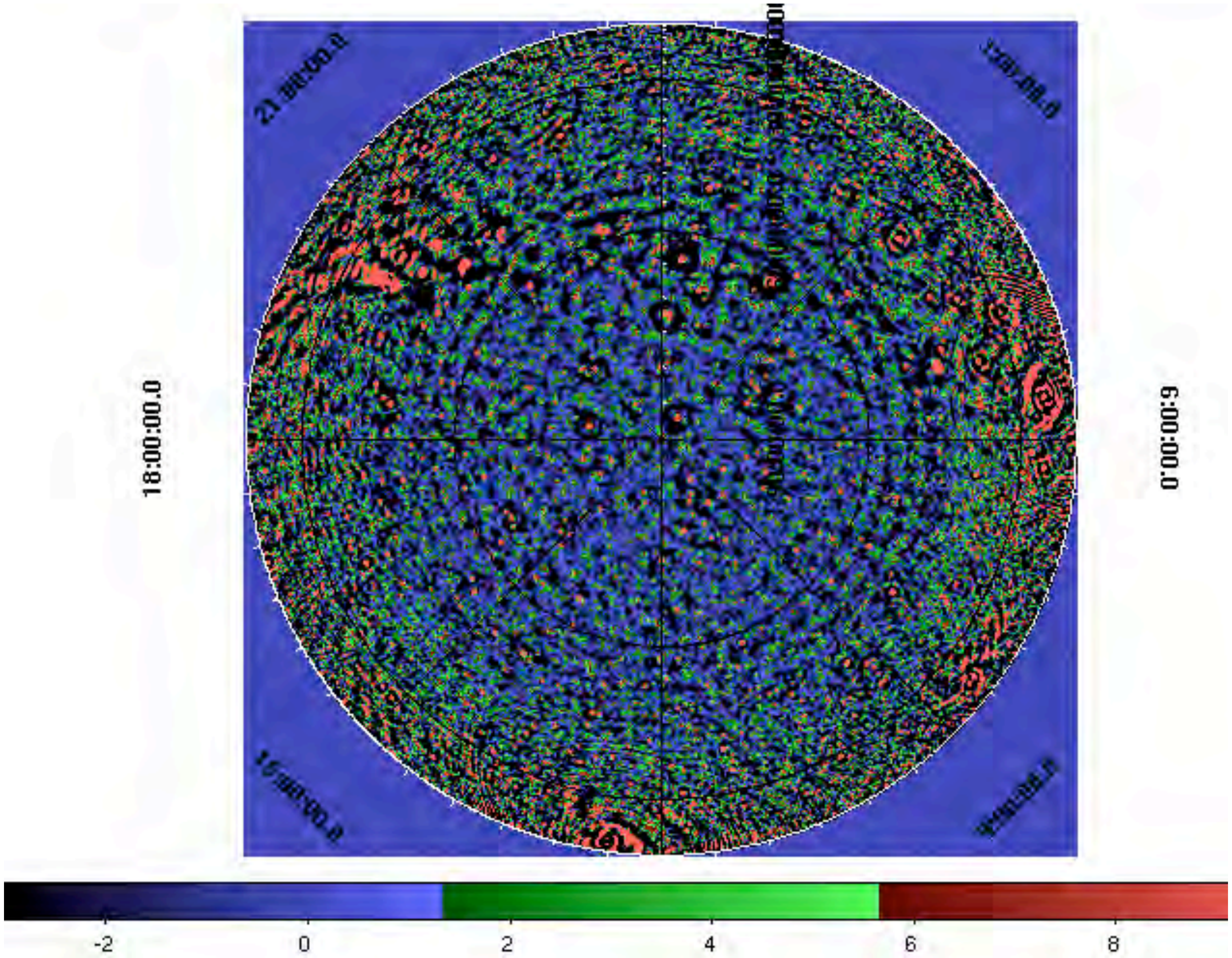
~ 800 sources !

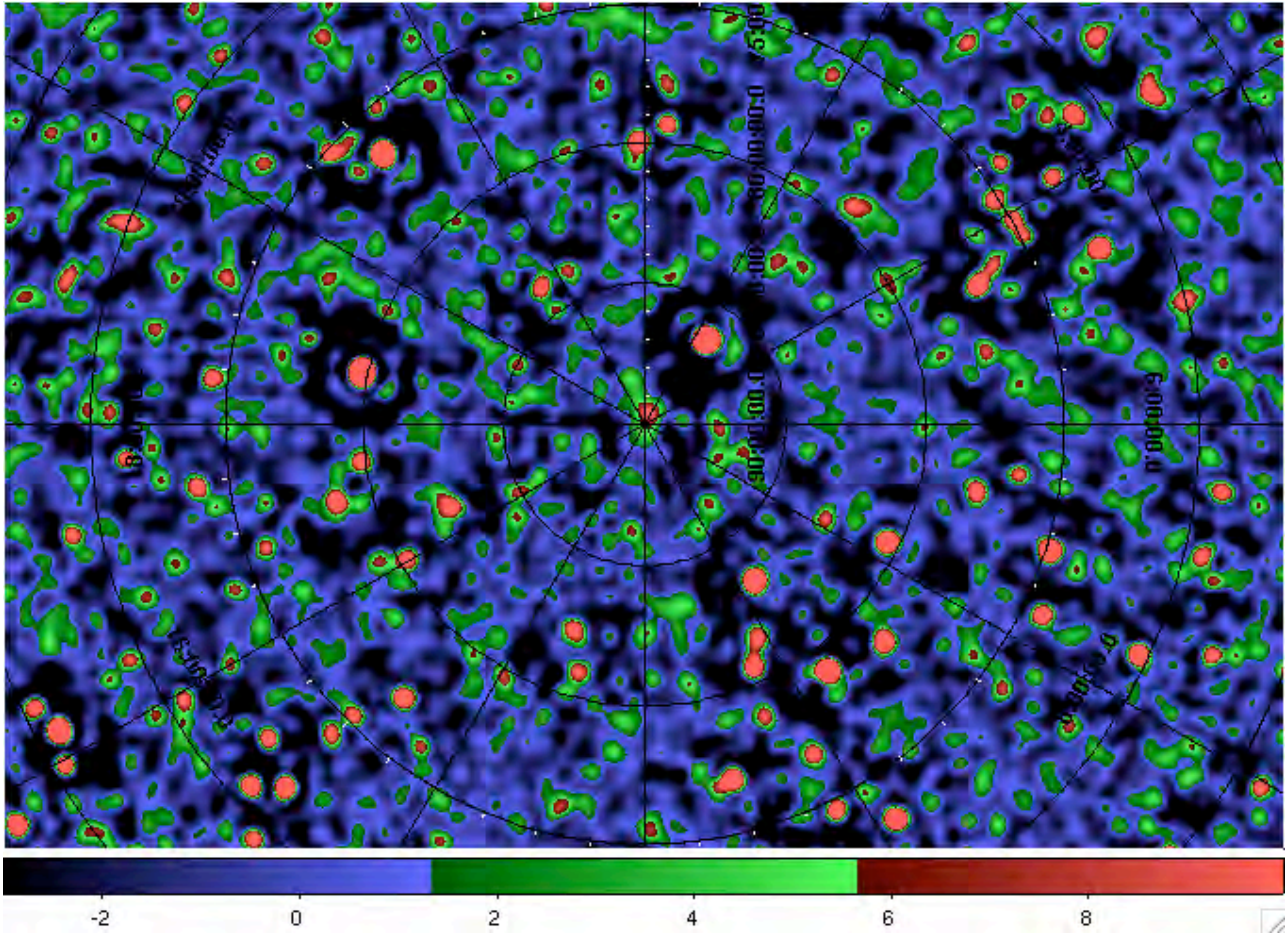
PSF ~ 0.5°

noise ~ 1 Jy

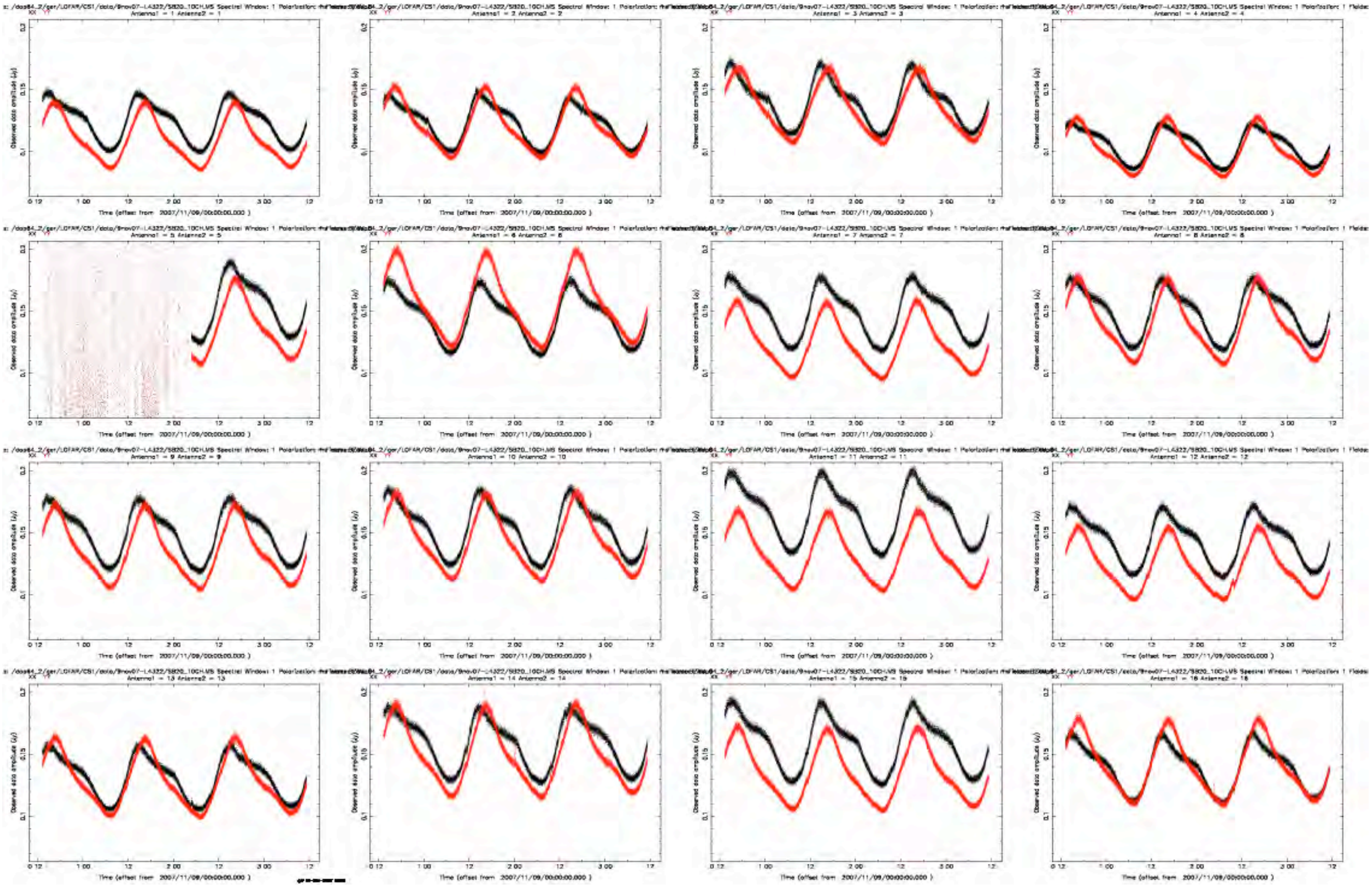
CasA/CygA (20,000 Jy)
subtracted

- beam corrected
- no deconvolution as yet

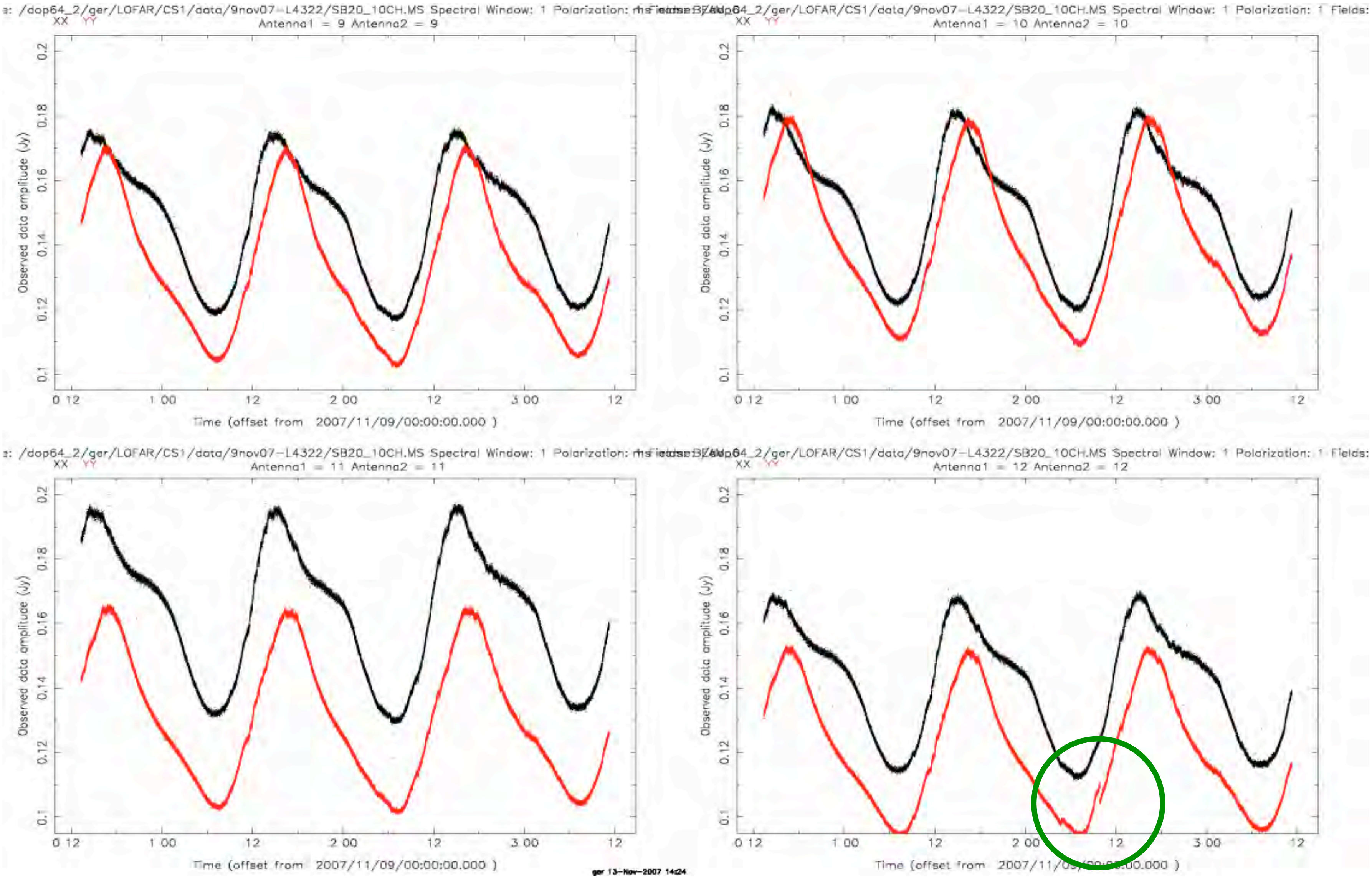



-2
0
2
4
6
8

70h HBA (dipoles) observation, 155 MHz , SB20
(9-12 Nov 2007, L4322)

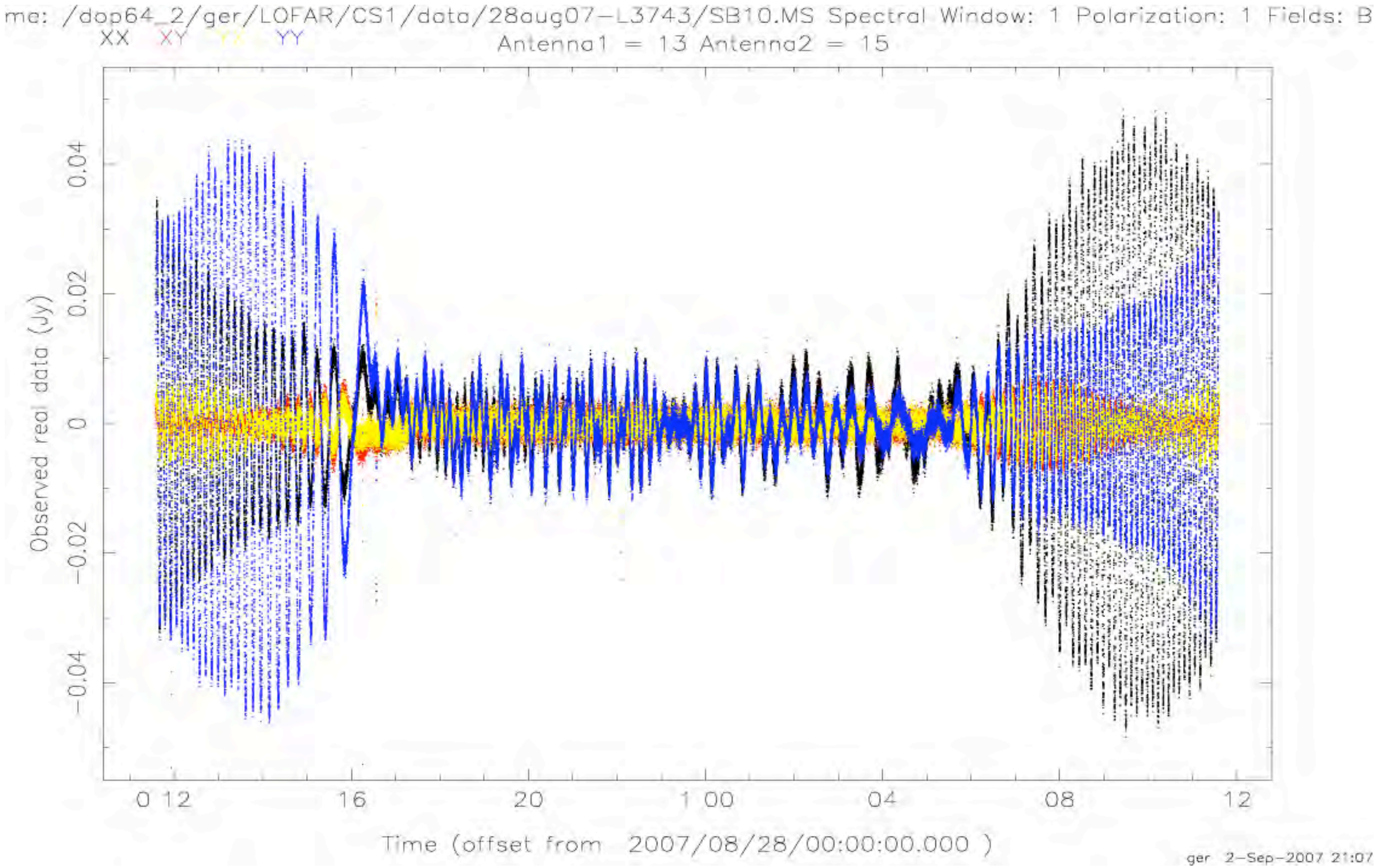


CS008

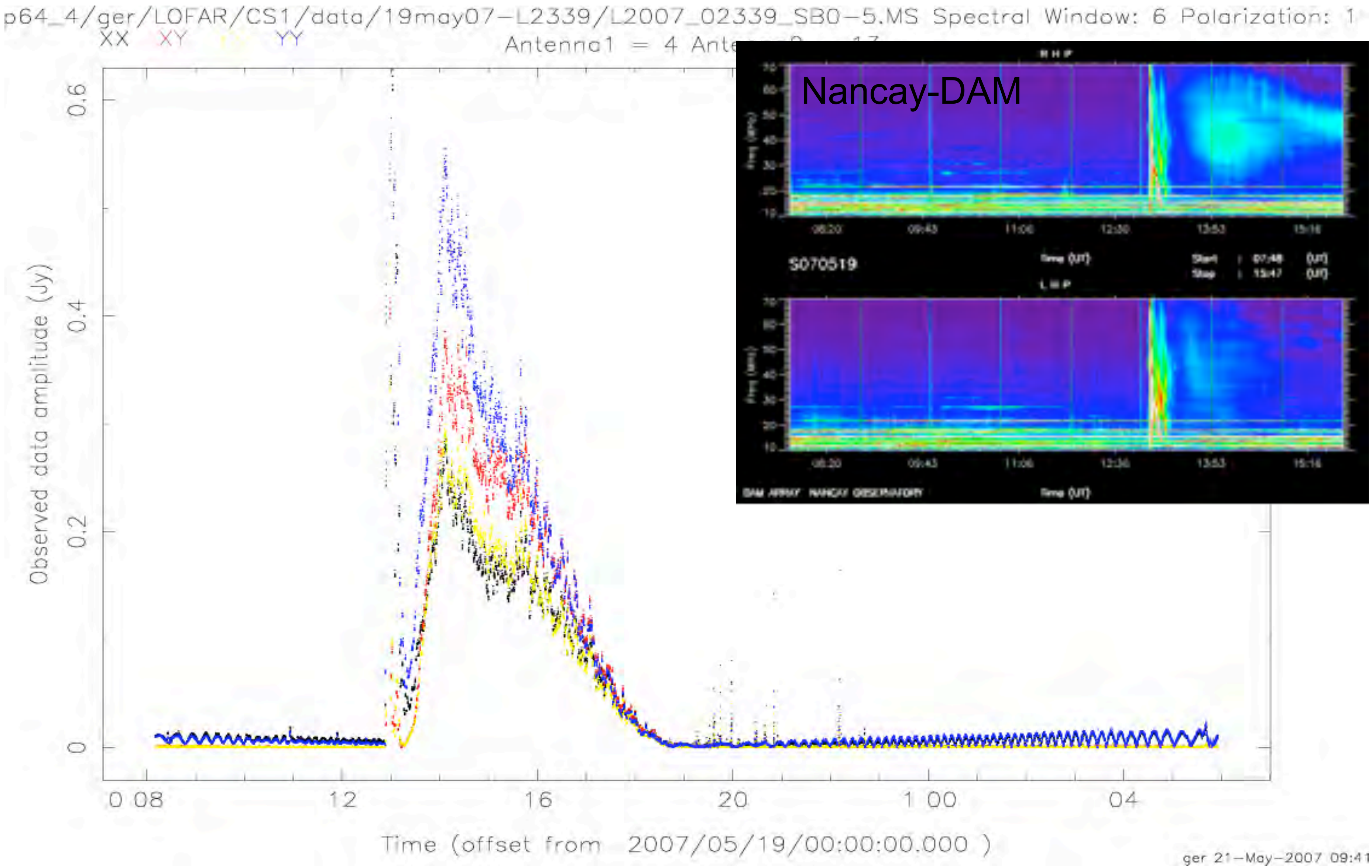


/dop64_2/ger/LOFAR/CS1/data/9nov07-L4322/SB20_10CH.MS Spectral Window: 1 Polarization: 1 Fields:
XX YY
Antenna1 = 9 Antenna2 = 9
Antenna1 = 10 Antenna2 = 10
Antenna1 = 11 Antenna2 = 11
Antenna1 = 12 Antenna2 = 12
Observed data amplitude (Jy)
0.1
0.12
0.14
0.16
0.18
0.2
0 12
1 00
12
2 00
12
3 00
12
Time (offset from 2007/11/09/00:00:00.000)
ger 13-Nov-2007 14:24

The difference between night and day
HBA 220 MHz



The disturbed Sun ~50 MHz 19May07

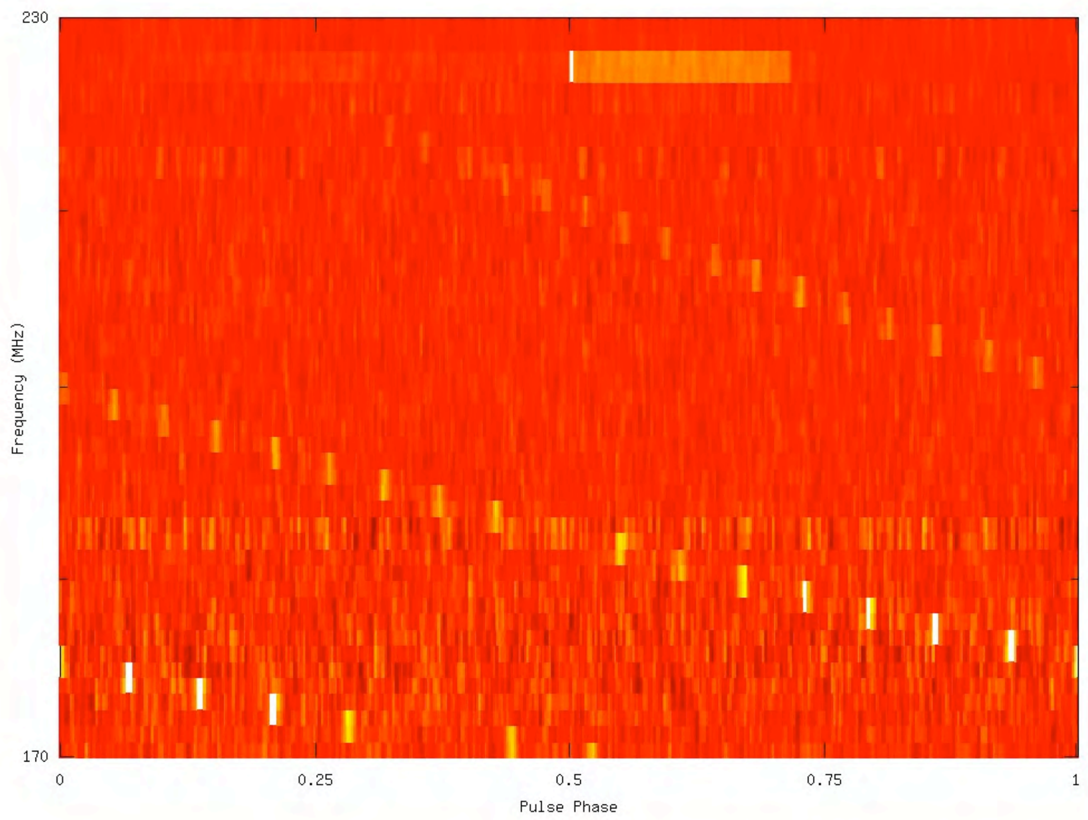


Pulsar B0329+54 dispersion delay (DM = 26.6)

230 MHz

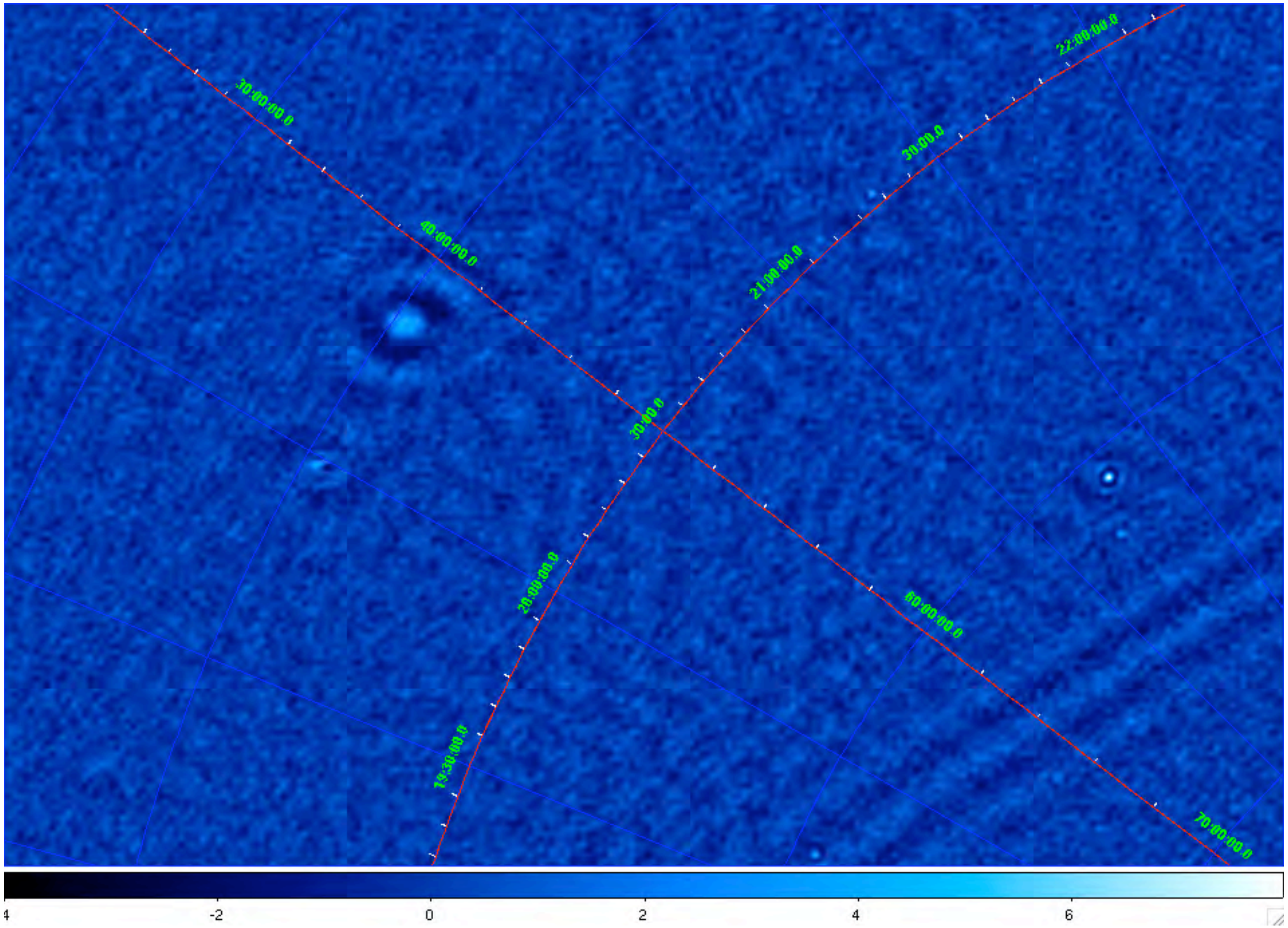
48
subbands

170 MHz

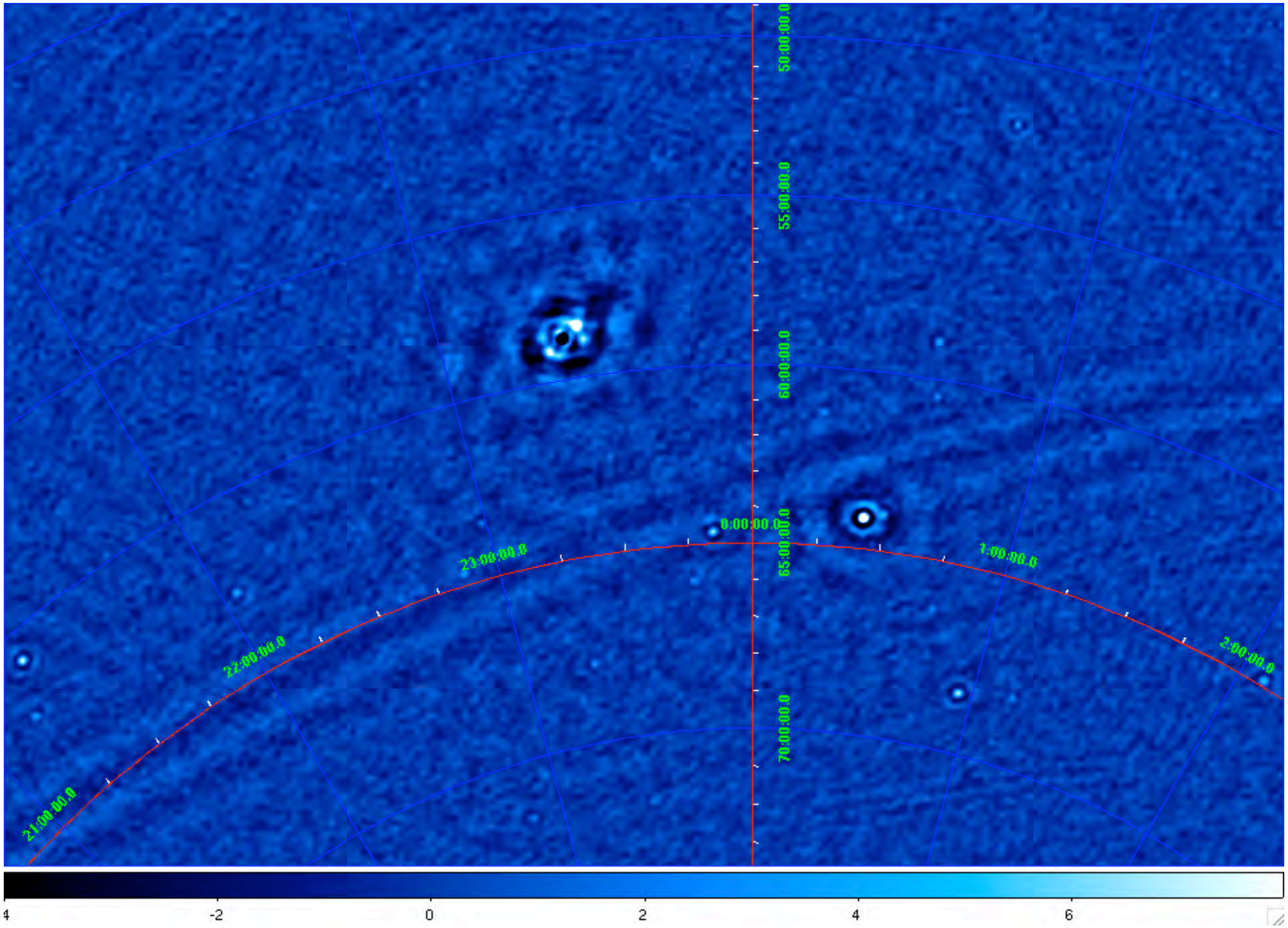


pulse phase (0.71s)

HBA L3743
area near CygA / HB20



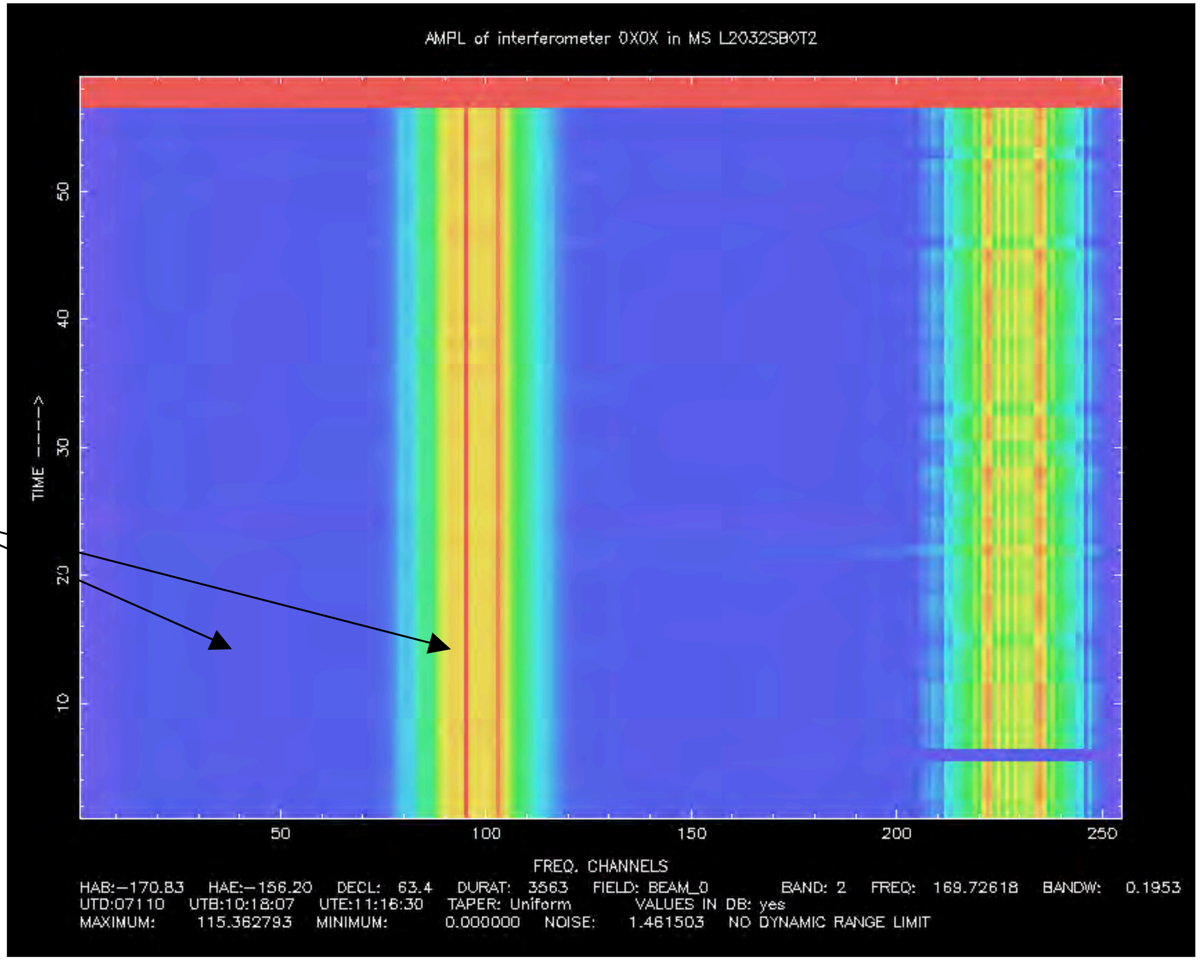
HBA L3743
area near Cas /Tycho



Very intense ‘pager signals’ at 169.75 MHz and 169.65 MHz

> 80 dB range !!

(= 10^8 = 20^{mag})

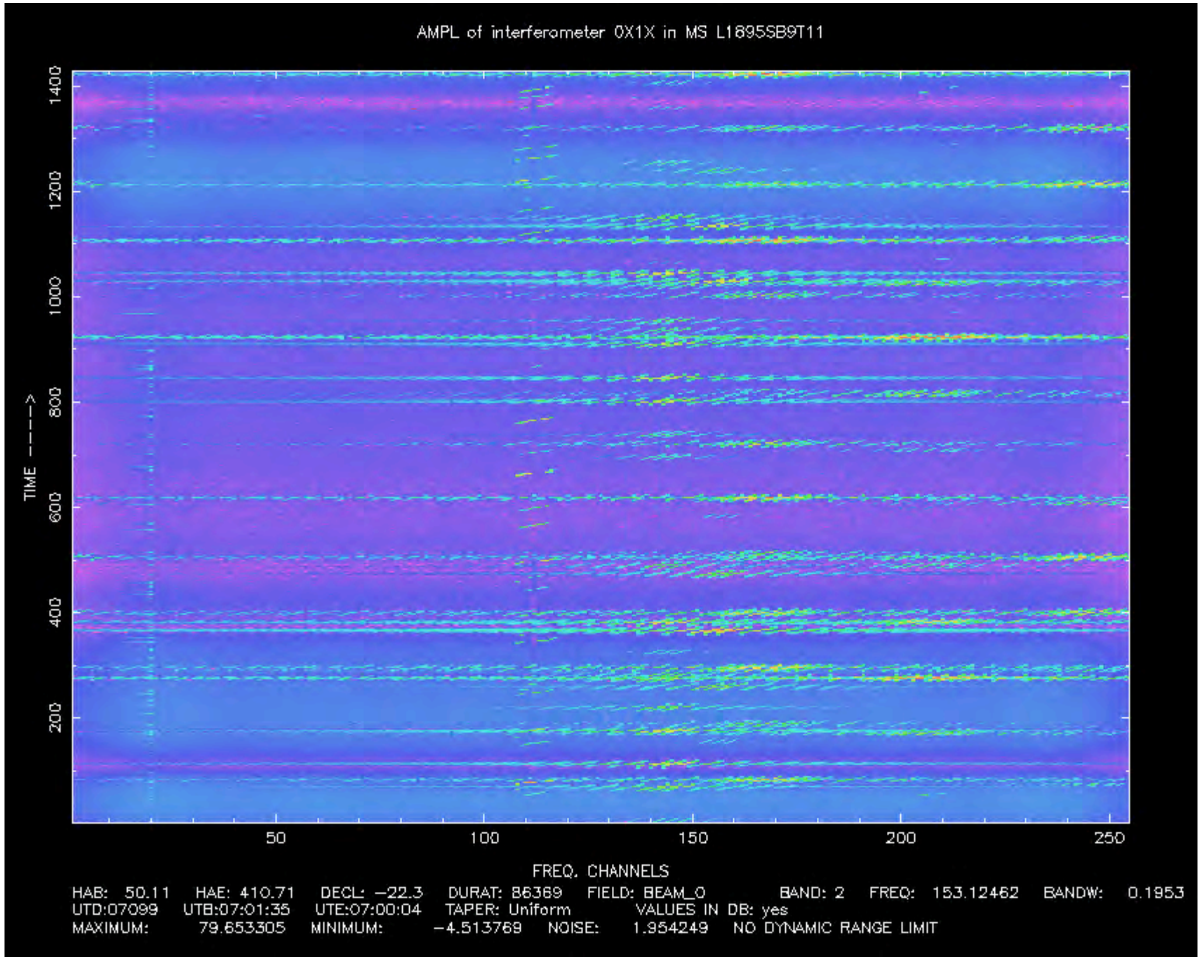


1 hour

256 channels over 156 kHz

Dynamic spectrum at ~147 MHz 9apr07

24h

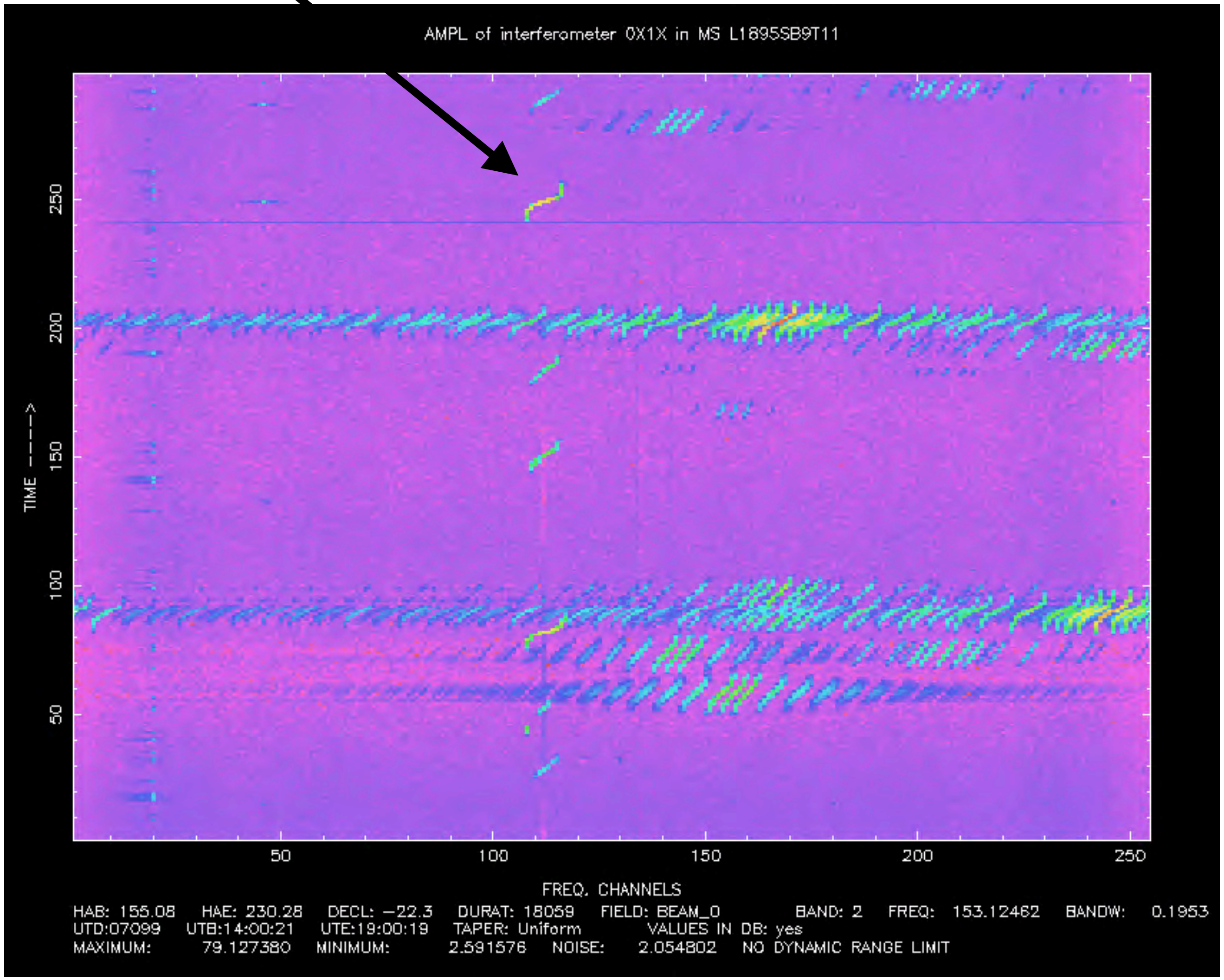


~ 84 dB intensity range !!

156 kHz in 256 channels

LEO satellites around 147 MHz

8 kHz Doppler shift (~ ± 8 km/s)



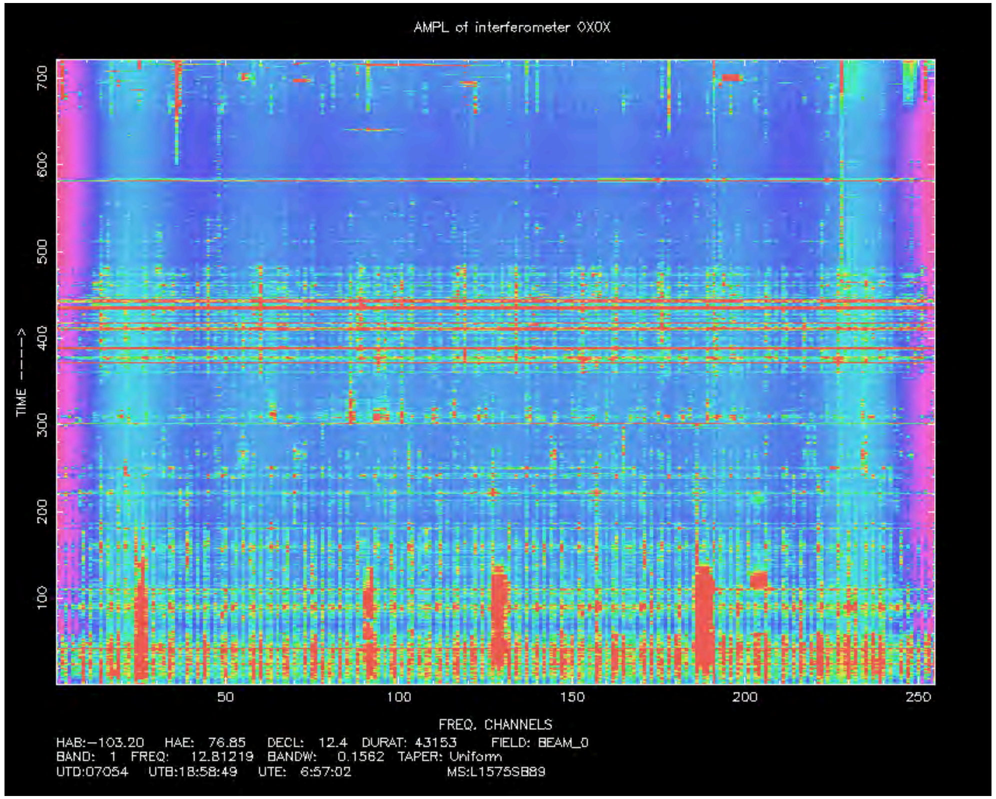
time

frequency

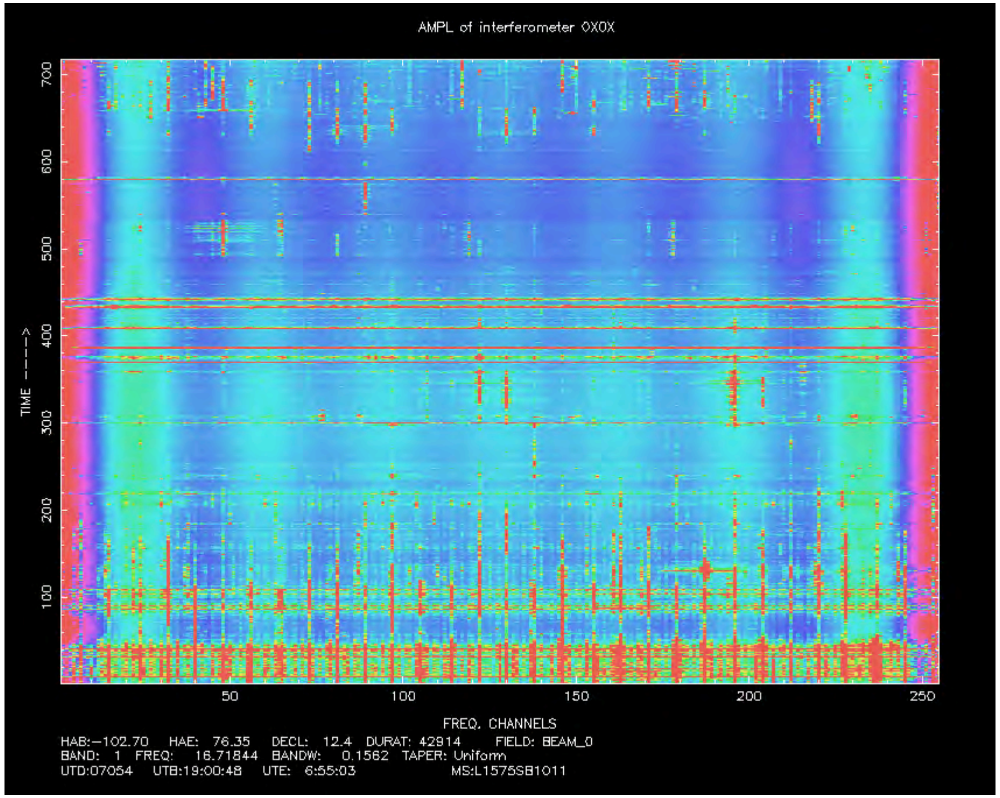
RFI in the 10 - 30 MHz LBA band

(23 Feb 2007, 12h observation)

12.8 MHz



16.7 MHz



LOFAR (array) calibration

Basic LOFAR calibration framework

(see e.g. Noordam, 2006, LOFAR-ASTRON-ADD No.15)

‘Novel’ ingredients (compared to standard selfcal)

- Direction/position dependent corrections
    - Phase (ionosphere) => ‘non-isoplanaticity’
    - Gain (beam) => elevation/azimuth dependent sensitivity

    => image-plane vs uv-plane correction solving/treatment

- All sky calibration, 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 etal)

  (Jones matrix description: B, G, E, I, .. : 2x2 matrices , complex and scalar)

Review of calibration problems/challenges and ‘solutions’

Question: How to get to the thermal noise in full FOV?

What are relevant ‘noise’ contributions?

- Thermal (see Table)
- Sidelobe noise from large # sources: ~ $2 \times S_{min} \times \varepsilon_{psf} \times \sqrt{N}$
- Classic confusion noise (~ 0.2 mJy at 30 MHz, L ~ 75 km)
- Ionospheric calibration noise (will vary strongly (>10x) !)
- Dynamic Range related (multiplicative noise ..)
- Other: RFI, cross-talk,...

1. (Too) low S/N in LBA band in some (many?) fields
   - A serious problem was made more serious due to RESCOPE
   - use wider bandwidth (fewer ‘beams’) for S/N improvement
   - calibrate phase-screen on HBA (120 MHz) and transfer to LBA
   - use snapshot-calibration approach (=> adds overhead !)
   - Wait for the best nights ...

2. Fields with extreme DR requirements (> 10^5 : 1)
   - Due to deconvolution problems on bright sources
   - Instrumental cross talk, faint RFI, closure errors,..
   - Spatial and temporal filtering , subspace projection

     (see e.g. 3C196 - NCP ‘garbage’)

3. Too many parameters to solve
   - Can convergence be reached ? Both fundamental and speed issue !
   - Use shorter syntheses to limit station beam-variation
   - More calibration observations and reliance on system stability
   - Use optimized hierarchical calibration schemes
   - Wait for best nights (fewer ionospheric parameters)

4. Different station sizes (new issue since rescope)
   - HBA: core - NL - EU LBA: NL - EU
   - full FOV calibration/imaging, bandwidth synthesis complications
   - weighting and sensitivity issues
   - not given much thought thusfar

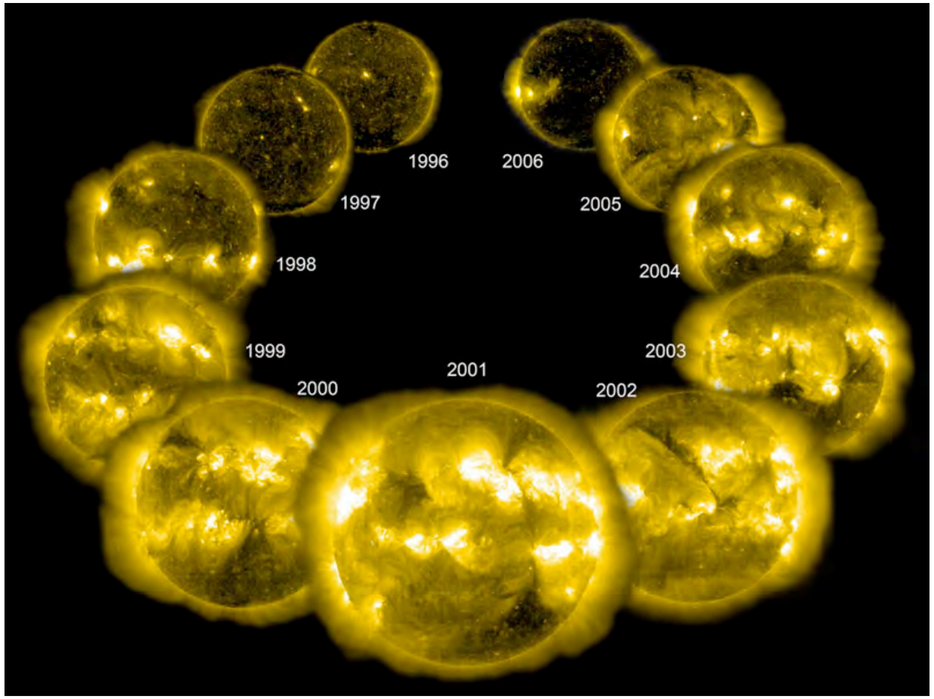
Ionospheric issues

Non-isoplanaticity (low freq, large FOV)

Solar cycle (next maximum ~2012)

Array scale > refractive/diffractive scale

TID's, (Kolmogorov) turbulence

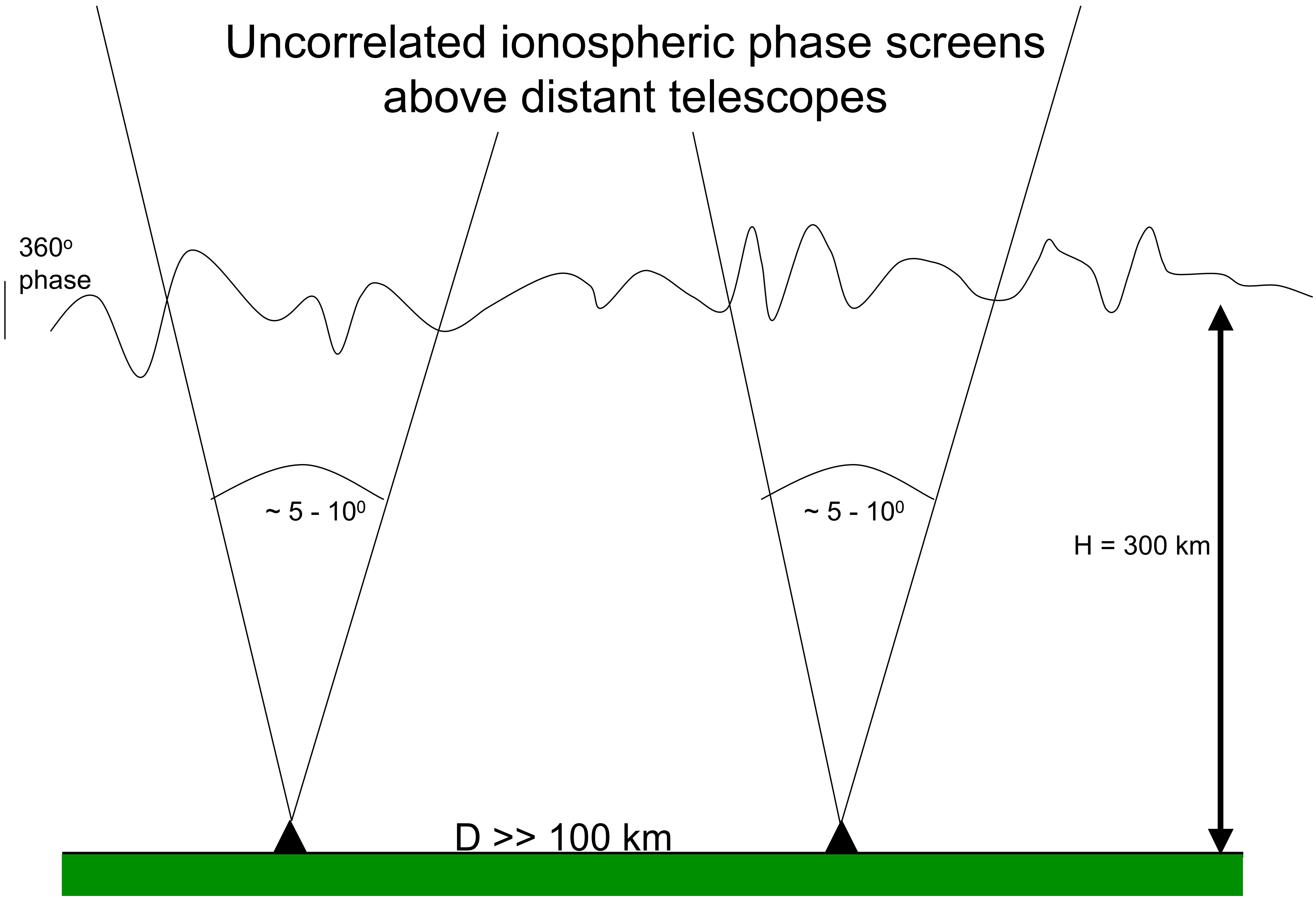


Soho-solarcycle,

APOD 5 dec07

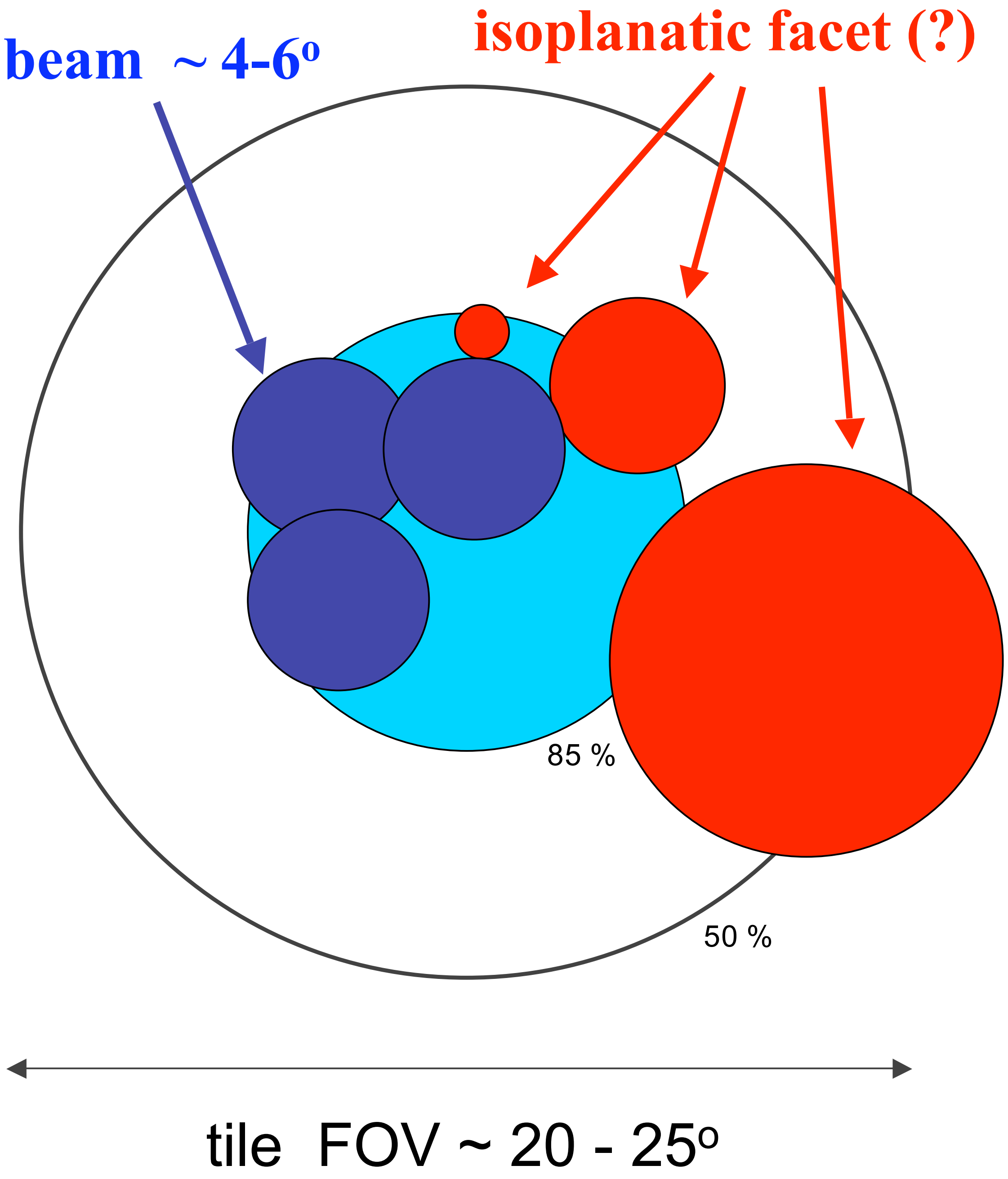
Tools/approaches:

- Bandwidth synthesis (sensitivity, freq-dependence,..)
- Peeling individual sources
- Large scale screen modelling (MIM, Noordam)
- GPS-TEC starting model (Anderson, Mevius)
- Utilize 2-D frozen flow approximation
- Simulations (LIONS, van Bemmel et al)
- 3-D tomography solutions (multiple screens/layers: => EoR KSP needs ?)



Uncorrelated ionospheric phase screens
above distant telescopes
360o
phase
~ 5 - 10
~ 5 - 10
H = 300 km
D >> 100 km

Angular scales in LOFAR HBA-observations (24 tiles/station)



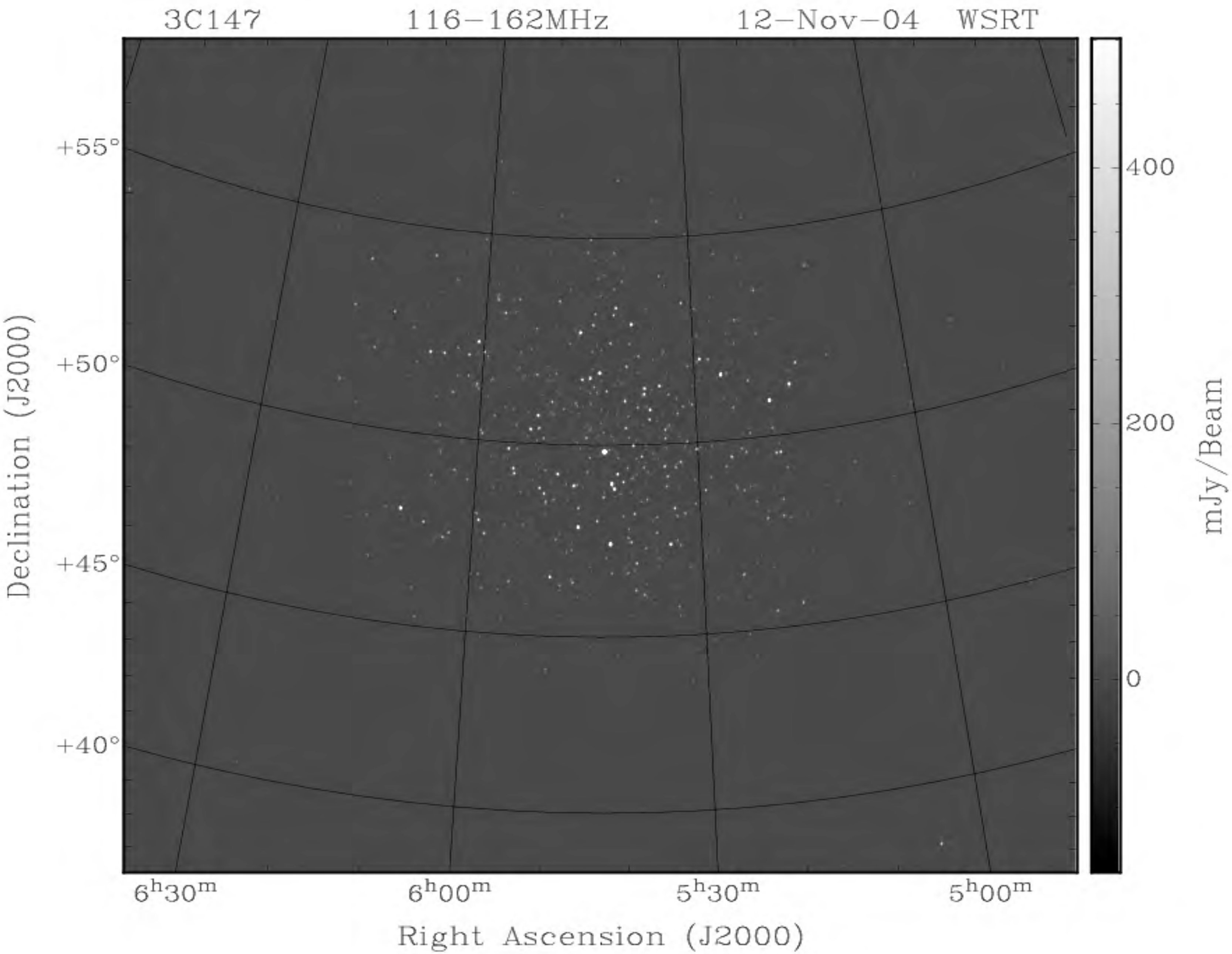
Note:

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

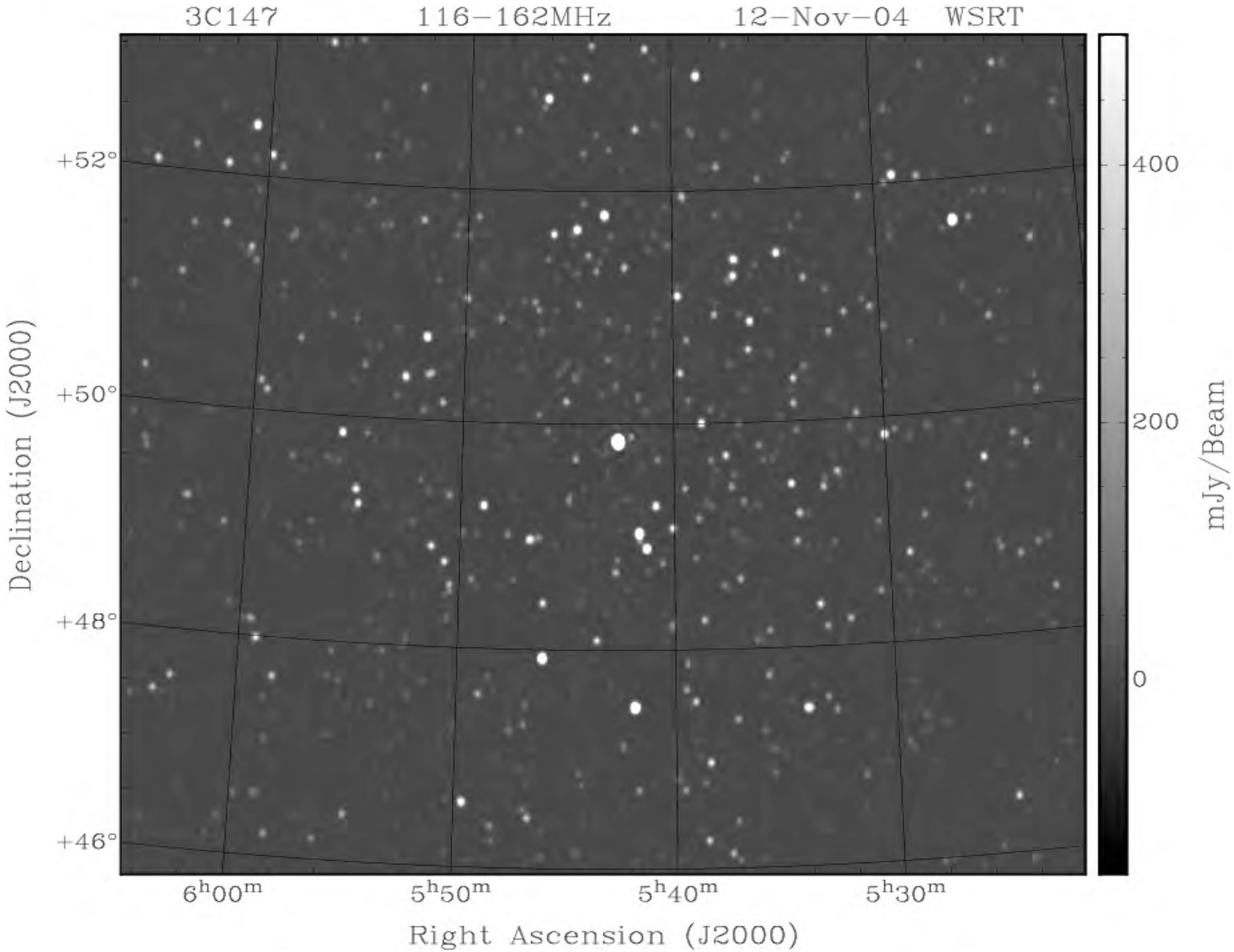
WSRT-LFFE preparations and lessons

WSRT	LOFAR
115 - 180 MHz	115 - 240 MHz
25m diameter dish	~35m station (core)
2.7 km baseline	~2 km baselines
8 x 2.5 MHz x 512 ch	20 x 0.2 MHz x 256 ch
10s integration	10s integration
91 baselines	1128 baselines (N=48)
60 GByte dataset/12h	310 GByte dataset/4h
Newstar, AIPS++ and BBS	MeqTrees and BBS

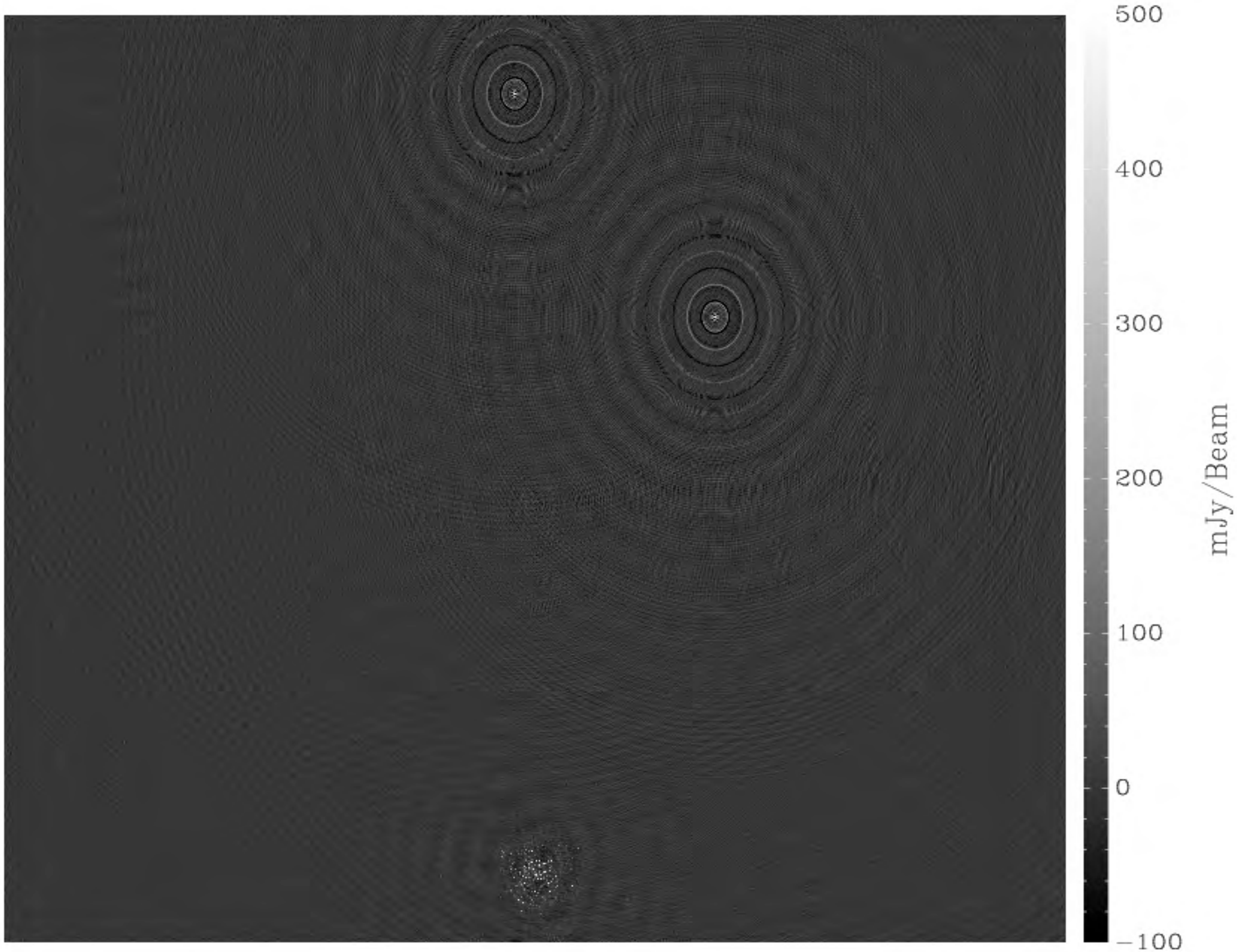
3C147 116 - 162 MHz WSRT



3C147 116 - 162 MHz WSRT



3C196 138-157 MHz 20Nov07 WSRT



LOFAR calibration in action (e.g. survey KSP):

Starting visibility data volume (NL array only: HBA, 72 stations, 32 MHz):

- 2500 x 4 x 40,000 x 8 Bytes = 3.2 GByte/s = 25 Gbit/s
- 12h intensive data taking EVERY 24h **=> 130 TByte/24h**

Processing phases overview:

1. processing on 1s-1kHz dataset: RFI excision & A-team peel off
2. integrate to 5-10 kHz and 5-10s (time-delay smearing limited)
   => 25-100x less data

Day 1

3. Major cycle calibration (~ 3 iterations, e.g. 4%-20%-100% data)
   - global ionospheric refraction (GPS-TEC, MIM)
   - snapshot-calibrator data (external calibration)
   - Interaction with GSM (and LSM)
   - Solving for Cat-I (individually) and Cat-II sources (S/N> 3 per sample)
4. Cat-I and Cat-II source removal => output cubes (compressed/cleaned (?))

Day 2-7

Survey KSP (100 - 100 km baselines) (Leiden-meeting 10-13dec07)

Calibration/processing issues:

1) Observation/scheduling strategies and their effects on calibration

   (e.g. dynamic scheduling ?)

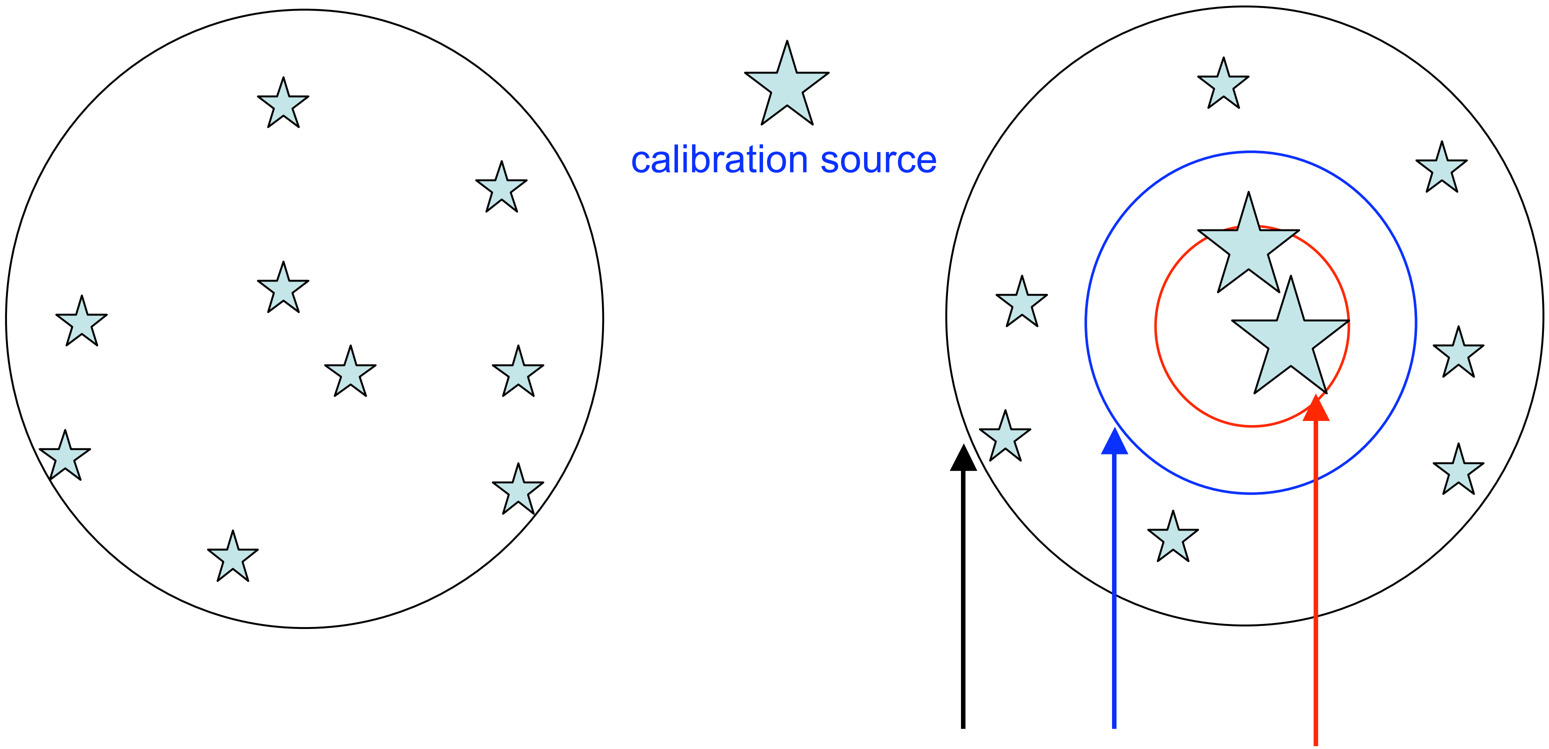
2) Involvement during Phase 2 in off-line processing (i.e. days 2-7)
3) Update/interaction with Global Sky Model
4) Is there a need for storing (calibrated) visibilities and need for possible re-processing (beyond day 7)
5) Polarization calibration: (quasi) real-time vs off-line (==> need visibilities)
6) Some other questions:

- IF storage and reprocessing needed: Where / How / Who?
- How many spectral channels in image cubes and why ?
- Observing mode priorities: e.g. mozaicing (not ready on day 1...?)
-

The size of Eu-stations and LOFAR wide-field calibratibility

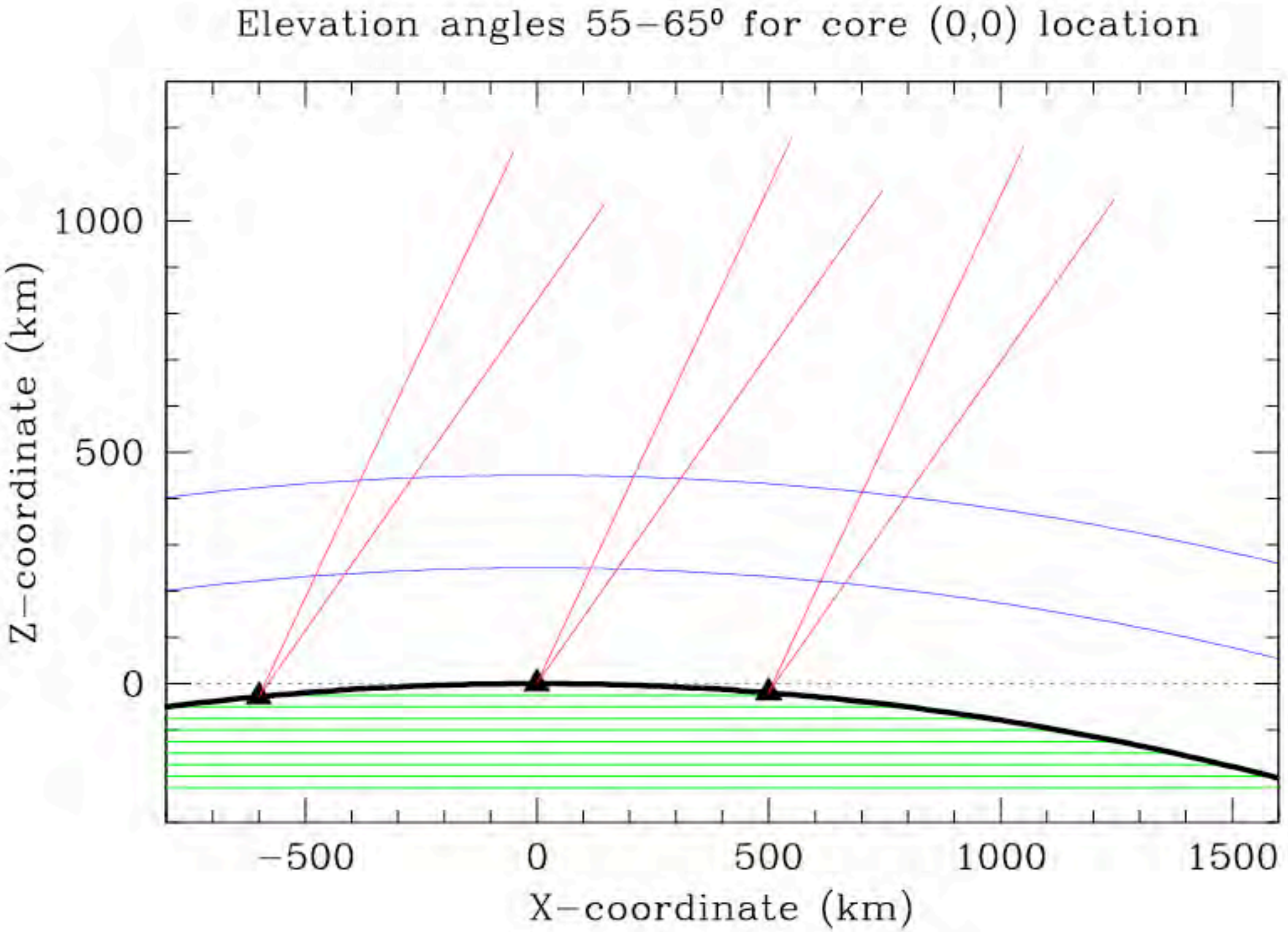
1) The number of detectable sources per beam does hardly depend on the size ($\propto$ sensitivity) of the station !

2) But the S/N per source in the smaller effective beam does increase by a factor 3 !!

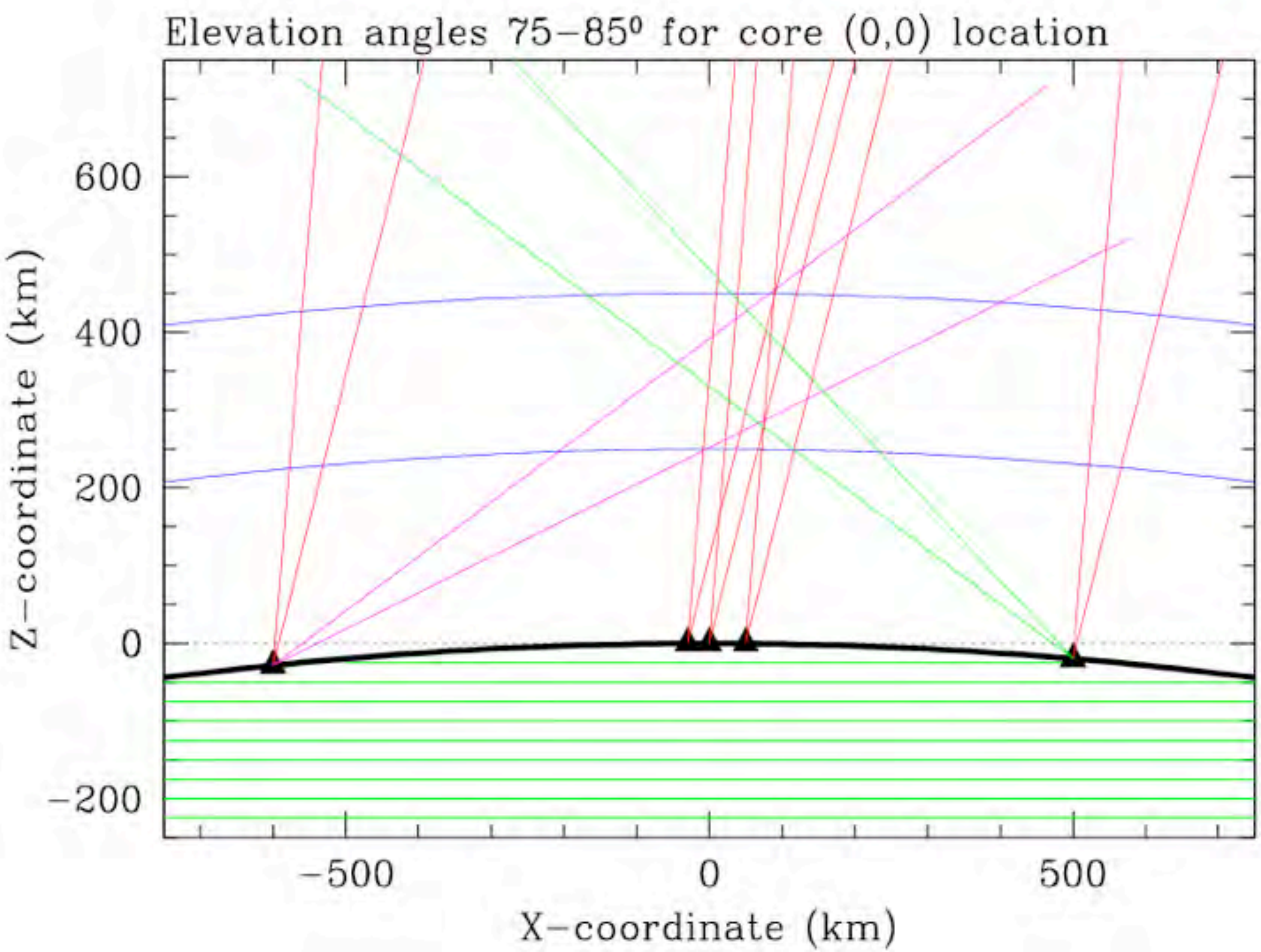


Relative beamsizes for stations of: 65^{m} ~110^{m} and 195^{m}

When stations are > 100 km apart signal from celestial sources do not traverse same ionospheric volume



Ionospheric modelling across the wide FOV will require rapid multi beaming and 3-D tomography



Astro-ph 0710.1946

Calibrators with structure on <0.25" structure ?!

Global VLBI at 325 MHz

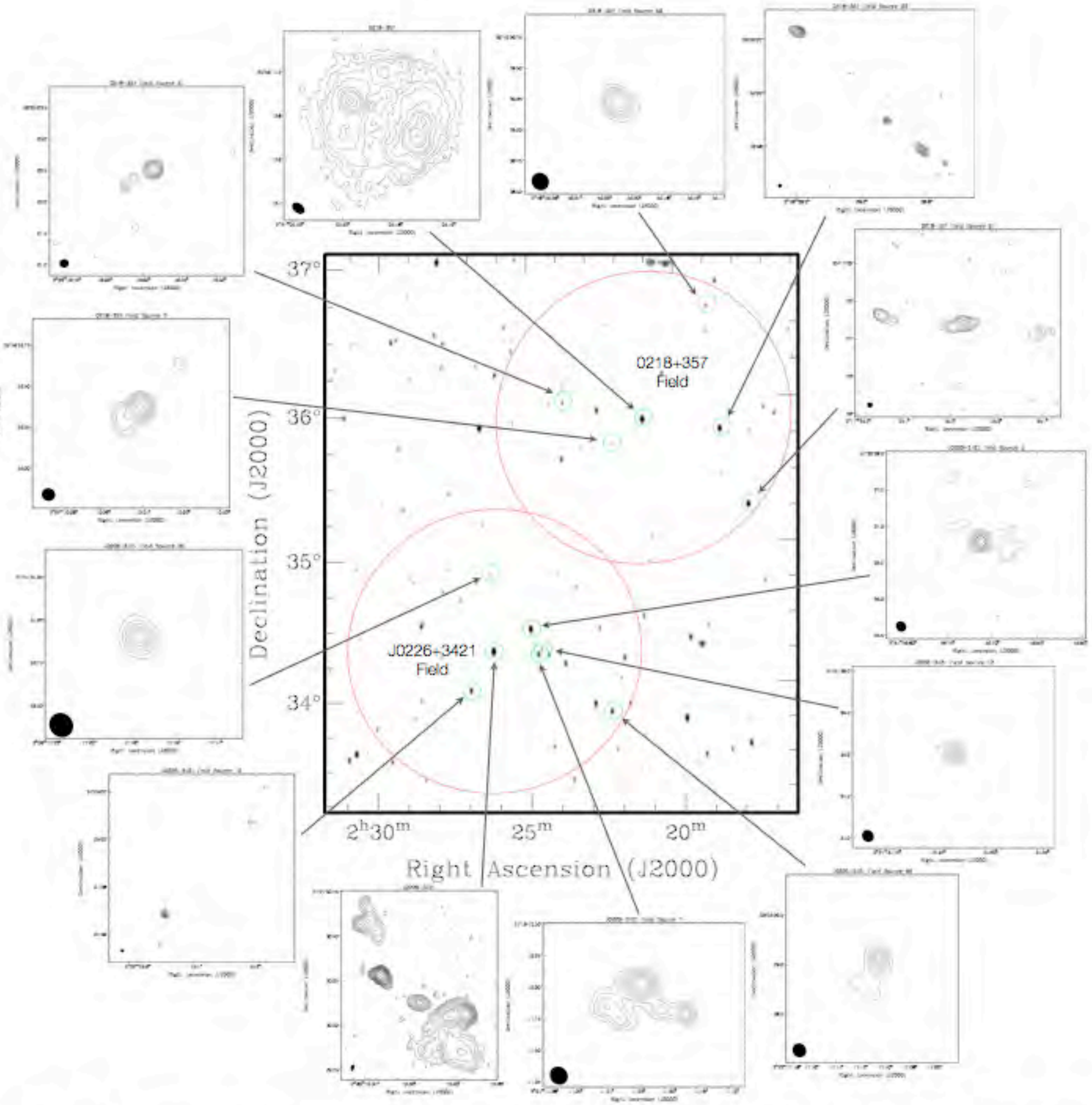


Figure 1: Source detections using wide-field VLBI at 90 cm in 3.1 degree^2 fields around J0226+3421 and 0218+357.