An introduction to calibration:

concepts, issues, dishes/arrays, practice, examples

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Outline

— Standard calibration: principles

— Relative and Absolute astrometry

— Flux scale issues

— Image and Spectral dynamic range

— Dishes vs Arrays

— Calibration at low frequencies: some LOFAR-specific issues

(wide field, varying beams, ionosphere, image deconvolution,…..)

— Software and the Measurement Equation

— Related partly overlapping lectures:

McKean (Low frequency radio astronomy), Dijkema (DPPP calibration), Iacobelli (polarization), Mevius (ionosphere)

Standard calibration: principles, why and how

Every instrument needs to be calibrated. In radio astronomy calibration is now dominated by *self-calibration*. However, we first review traditional calibration aka *standard calibration,* a proper understanding of which is necessary to understand self-calibration.

Aperture synthesis observations produce a 3-dimensional *dataset R(u,v,freq)* of visibilities. To turn these into a *3-D imagecube B(l,m,freq)* we have to calibrate various parameters. *How often* we have to calibrate depends strongly on *instrumental stability and external factors* like the weather (troposphere/ionosphere). This therefore also depends on frequency.

The parameters that astronomers are after are spectral and temporal image cubes with information on: position(+distance), intensity, frequency, polarization and (in case of variability) time.

Hence we talk about a 5-dimensional observing phase space. Specifically we need:

1) the 2-D coordinates: we need both *relative* and '*absolute*' astrometric data (and if a parallax can be measured → 3-D information)

2) a *relative* and, if possible, an *'absolute' flux density scale*

3) the *spectral shape* and dynamic spectra (time-frequency)

4) the *polarization* properties of the sources

5) the *signal arrival time (pulsars transients, ..)*

We will address these in turn, but for polarization and time aspects there are other talks.

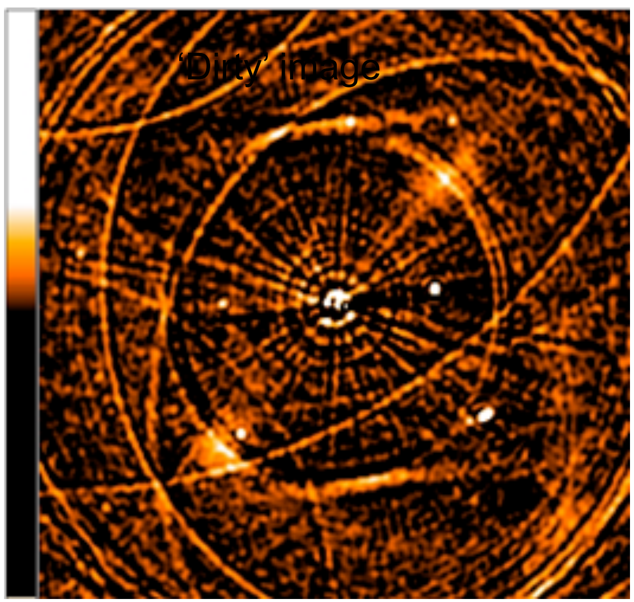
WSRT: raw and (self-)calibrated images

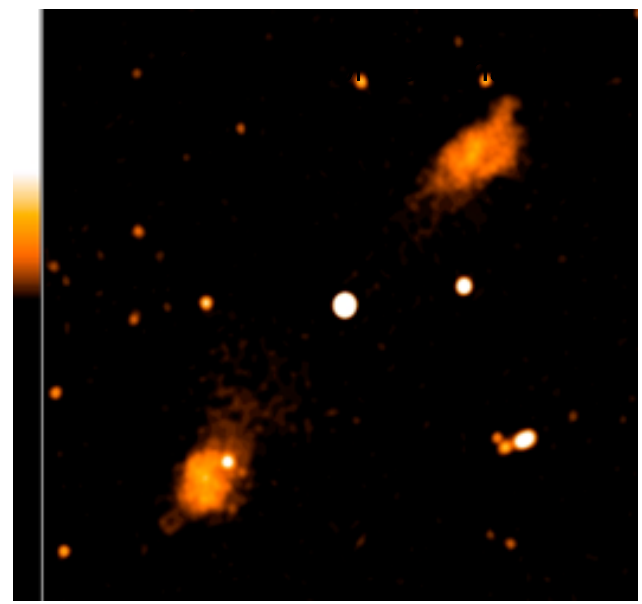
After 12h observation with the WSRT and some standard calibration we may end up with an image as shown on the bottom left. It contains many discrete and extended sources but the appearance is dominated by *imaging artefacts*.

Some of these artefacts are part of the PSF (e.g. *side lobes and grating lobes*) and some are error patterns. The latter appear to concentrate around the bright central core of this ‘giant’ extragalactic radio source (B1245+67).

This is the *‘raw’ image*, also known as the *‘dirty’ image*. It needs some work to get to the ‘true’ image which is shown on the right. How to get to that image is the field of *self-calibration.*

You will hear much more about that because LOFAR can not do without it.



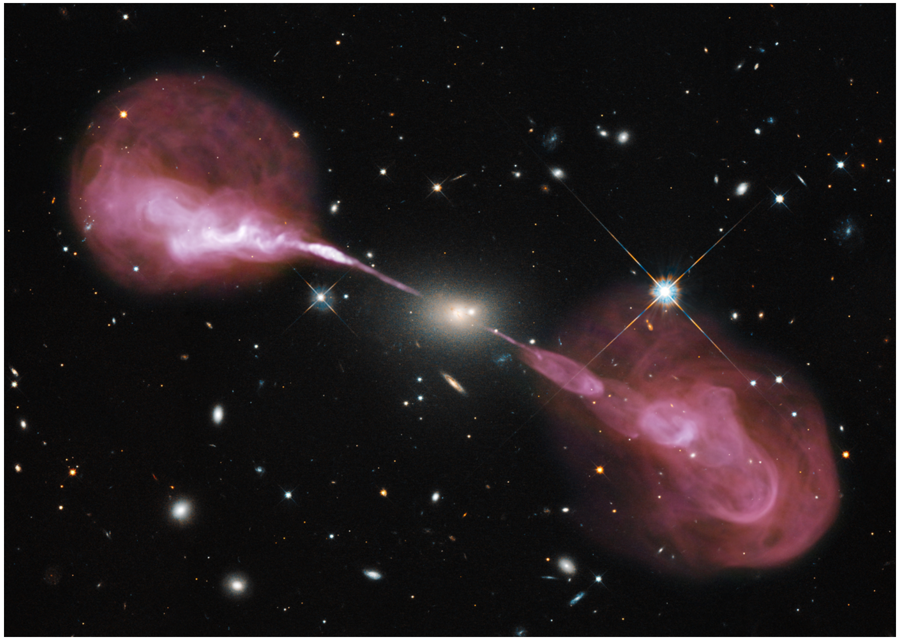


VLA: selfcalibrated high resolution images

Two very impressive selfcalibrated VLA images of A-team sources

Fornax A

Hercules A



Calibration and flux scale (dish arrays)

To convert correlation coefficients to absolute flux densities we need to measure the system noise T_{sys} (K), or the SEFD (*System Equivalent Flux Density*)

The T_{sys} can be calibrated against flux standards. E.g. for the WSRT the temperature of a stable noise source (T_N) is measured by observing bright known flux standards (e.g. CygA, NGC7027 or Mars). Thereafter T_{sys} is calibrated using a noise source injection scheme (measuring ON and OFF powers).

This two-step procedure is necessary because the system temperature of an (array of) telescope(s) usually *depends on elevation as well as Galactic coordinates* (especially at low frequencies) and on the weather (rain!) at high frequencies. Moving from target to calibrator the sky contributions to the receiver do not remain constant.

For LOFAR this is not needed because we do not have continuous gain adjustment (12-bit sampling)

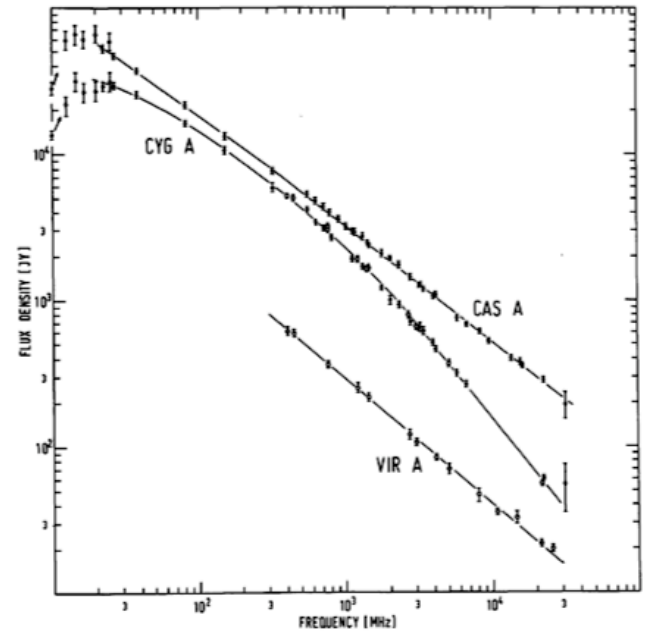


Fig. 1a. The absolute spectra of Cas A and Cyg A and the semi-absolute spectrum of Vir A. Solid symbols are absolute measurements, open symbols relative measurements

The *absolute flux scale* of synthesis arrays at cm-m wavelengths was defined in Baars et al (1977), and was based on measurements of CasA and CygA using antennas with known efficiency. 'Unfortunately', CasA decays by about -0.8% per year.

Absolute flux scale: going beyond the A-team

The absolute flux density scale is known to about 2-5 %, depending on frequency.
Traditionally the flux scale was based on CasA + CygA. From these A-team sources flux densities were derived for *secondary calibrators* like 3C286, 3C196 and 3C295, which were used for WSRT, VLA, GMRT.

All arrays now have relative scales good to <1% at high frequencies (325 MHz and up).
For the state of the art from 1-50 GHz, using VLA data, see *Perley and Butler (2013)*.

For LOFAR we obviously need to extend the flux scale to much lower frequencies.
A first step for the range 0.01 – 0.25 GHz was set by *Scaife and Heald (2012)*.

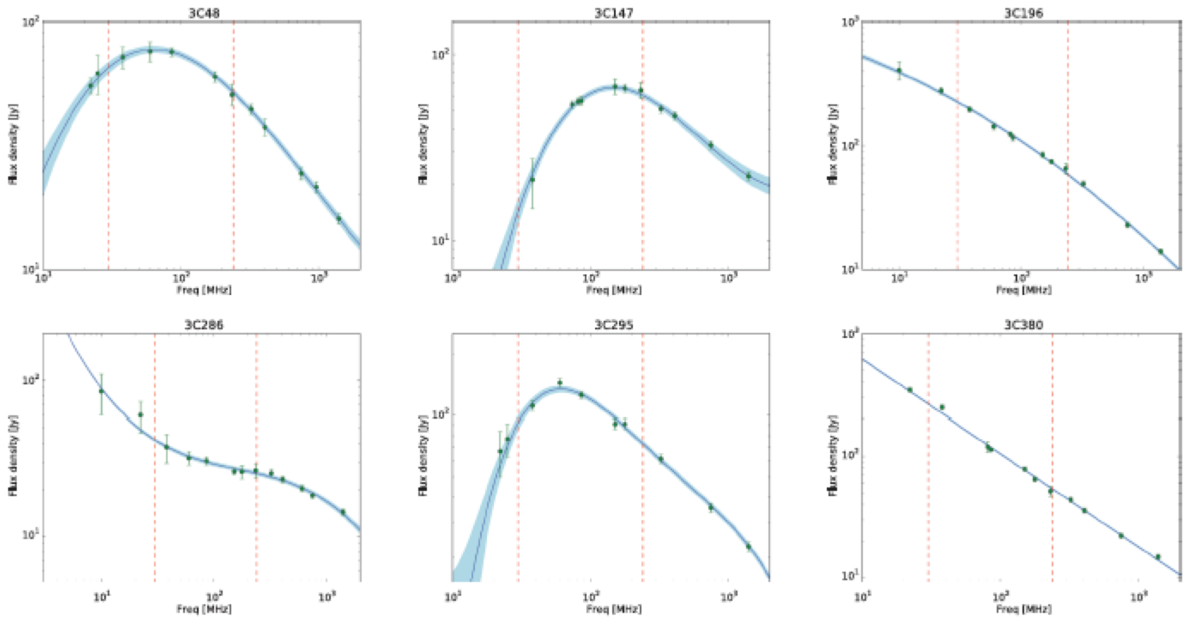


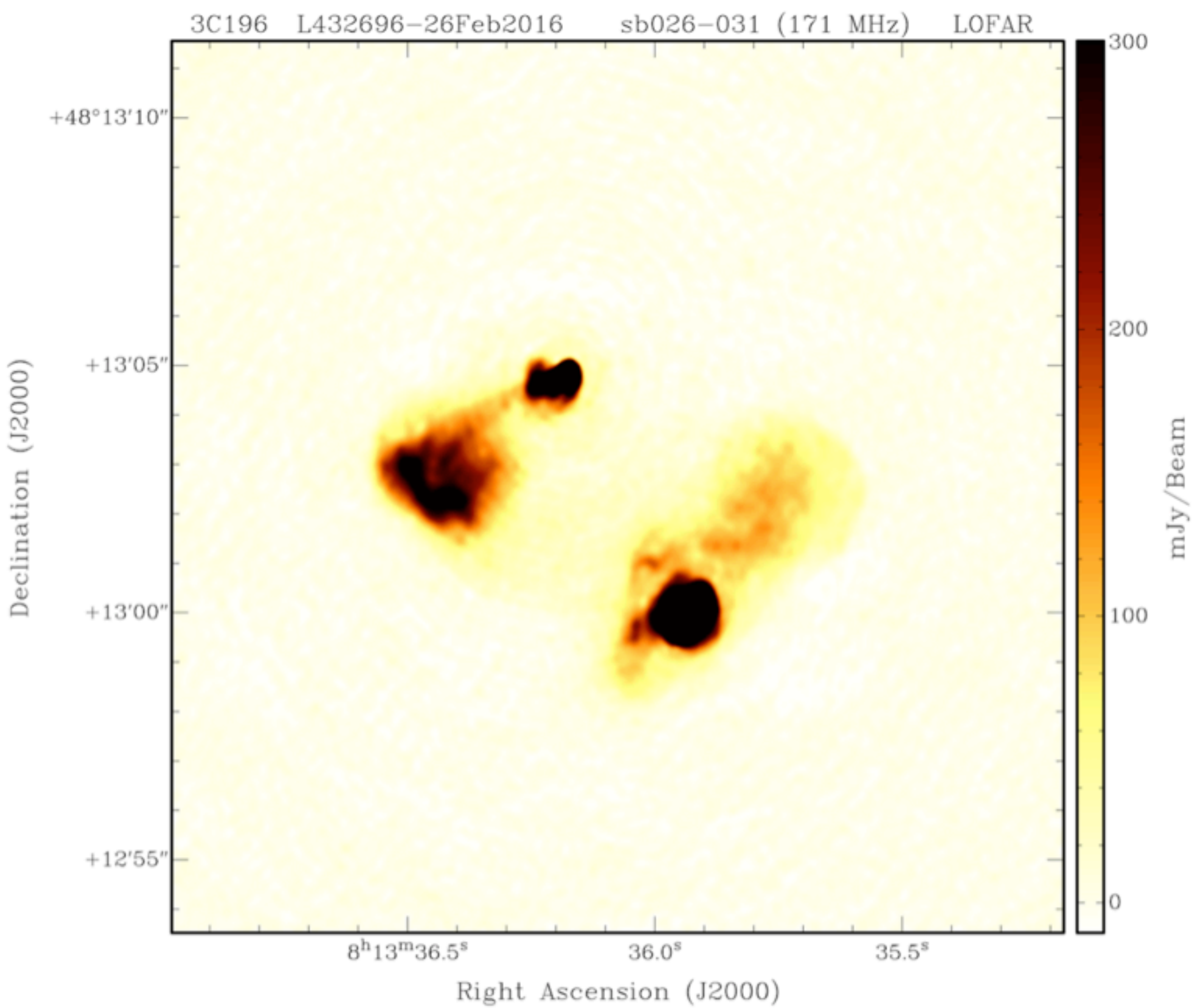
Figure 2. Best-fitting models for calibrator sources. Data from the literature are shown in black with the selected best-fitting model overlaid as a solid line. The area enclosed by the shaded region indicates the flux densities allowed at each frequency by 1σ uncertainties on the parameters. The edges of the LOFAR bandpass (low and high bands) are indicated by vertical dashed lines.

6 compact (1-10 ") 3C sources

Some of these are resolved on Dutch LOFAR baselines.

All are resolved on European LOFAR baselines

3C196: the 'best' LOFAR calibrator at 0.25" PSF



Total flux about 75 Jy (at 171 MHz)

Peak flux 4 Jy

Dynamic range ~ 3000:1

Astrometry

Absolute astrometry is very hard because of the refraction due to the troposphere (at high frequencies) and ionosphere (at low frequencies), or both at intermediate frequencies.
Most astronomers are therefore satisfied with relative astrometry,but with global calibration networks the two rapidly merge. Still, to get to 0.1" is hard work ! Radio stars and bright QSR's have played a key role (e.g. HIPPARCOS) *in aligning reference frames*

There are many applications for relative astrometry:

- cross-identification (with optical/infrared/X-ray images): need sub-arcsecond accuracy
- radio-spectral index work (e.g. in compact cores, jets, hot spots)
- very accurate distances, e.g. via parallax measurements (VLBI, pulsars, masers)
- to get motions (e.g. in relativistically moving blobs)
- etc

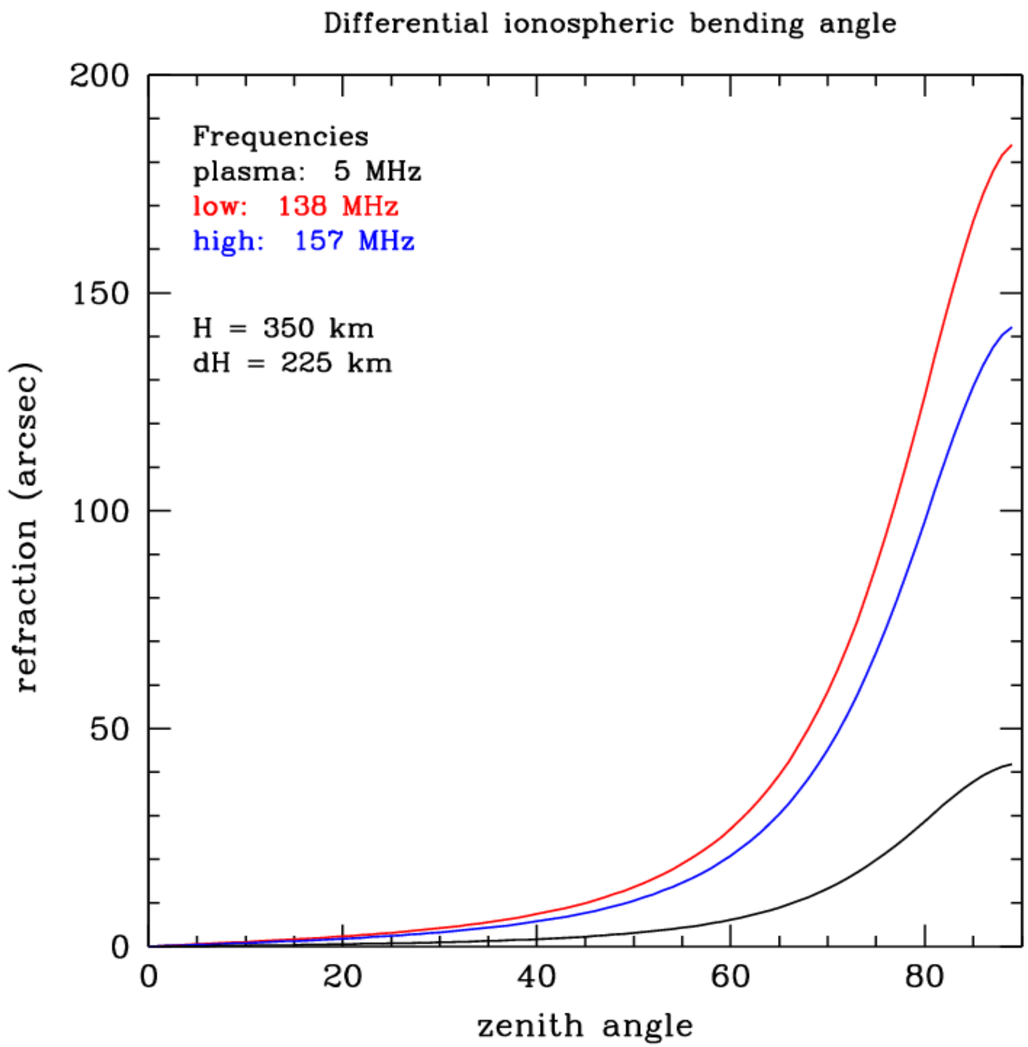
Most of these applications require a dense network of stable position calibrators.
Howeover, we also need to worry about source centroids; they often depend on frequency !
A wide freqency range therefore requires a wide range of resolutions.

How well can we measure positions in an image ? 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

To get to *sub-arcsecond (relative) positions* with LOFAR we also need to worry about *differential ionospheric refraction* as shown in the next few slides

Frequency-dependent ionospheric refraction



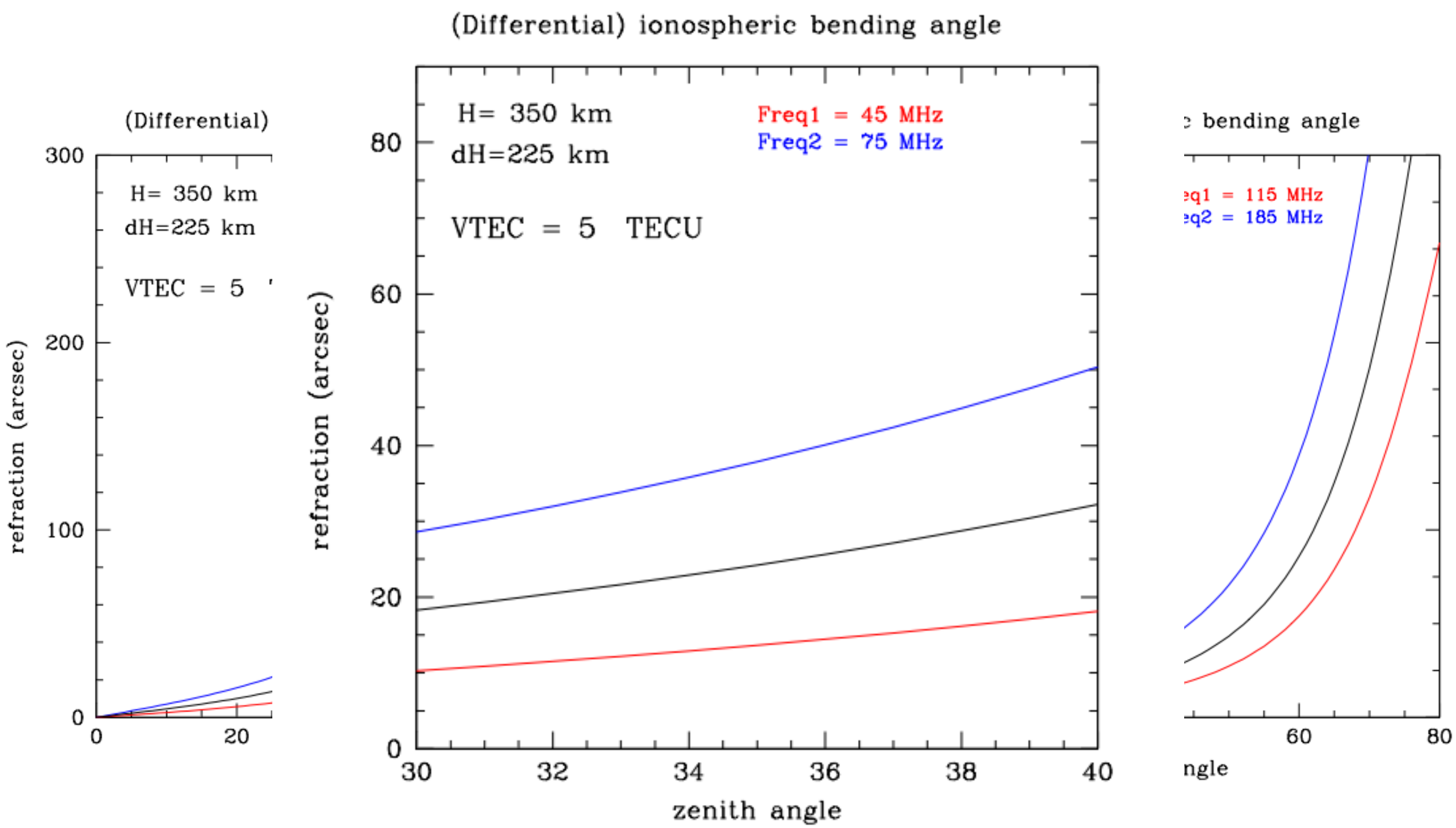
'Linear or quadratic' ?

Refraction scales linearly with TEC but quadratically with the plasma frequency

Refraction angle scales quadratically with observing wavelength

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

Differential Ionospheric Refraction



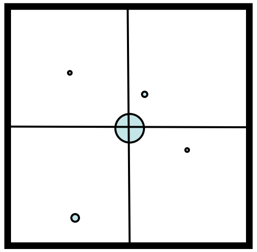
LOFAR resolution (PSF) at 60 MHz ~ 16” (50km / L)

Bright sources and/or low noise require very high Dynamic Range

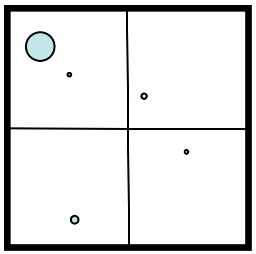
A summary of causes for dynamic range limitations

Dynamic Range: DR = peak flux / rms noise

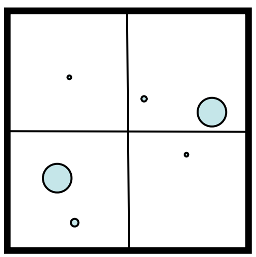
source configurations and causes



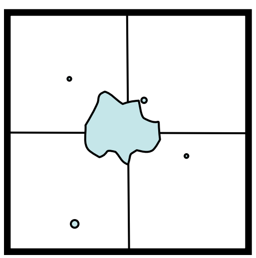
on-axis
point source



off-axis
point source



≥ **two** off-axis
point sources



extended
source

✓ (mechanical) pointing	-	X	X	-
✓ non - isoplanatism (ionosphere)	-	-	X	-
✓ decorrelation (troposphere/ionosphere)	X	X	X	X
✓ closure errors (cross-talk, ...)	X	X	X	X
✓ non-linearity (RFI, ...)	X	X	X	X
✓ ghosts (Gibbs, image rejection..)	-	X	X	X
✓ polarization leakage instability	-	X	X	X
✓ deconvolution limitations	-	-	-	X
✓ variable sources	X	X	X	X
✓ software errors/deficiencies	X	X	X	X

de Bruyn, SKA-CALIM, Capetown , Dec 2006

Illustrating a 1,000,000: 1 dynamic range

Perseus cluster

6 powers of 10

1994 data

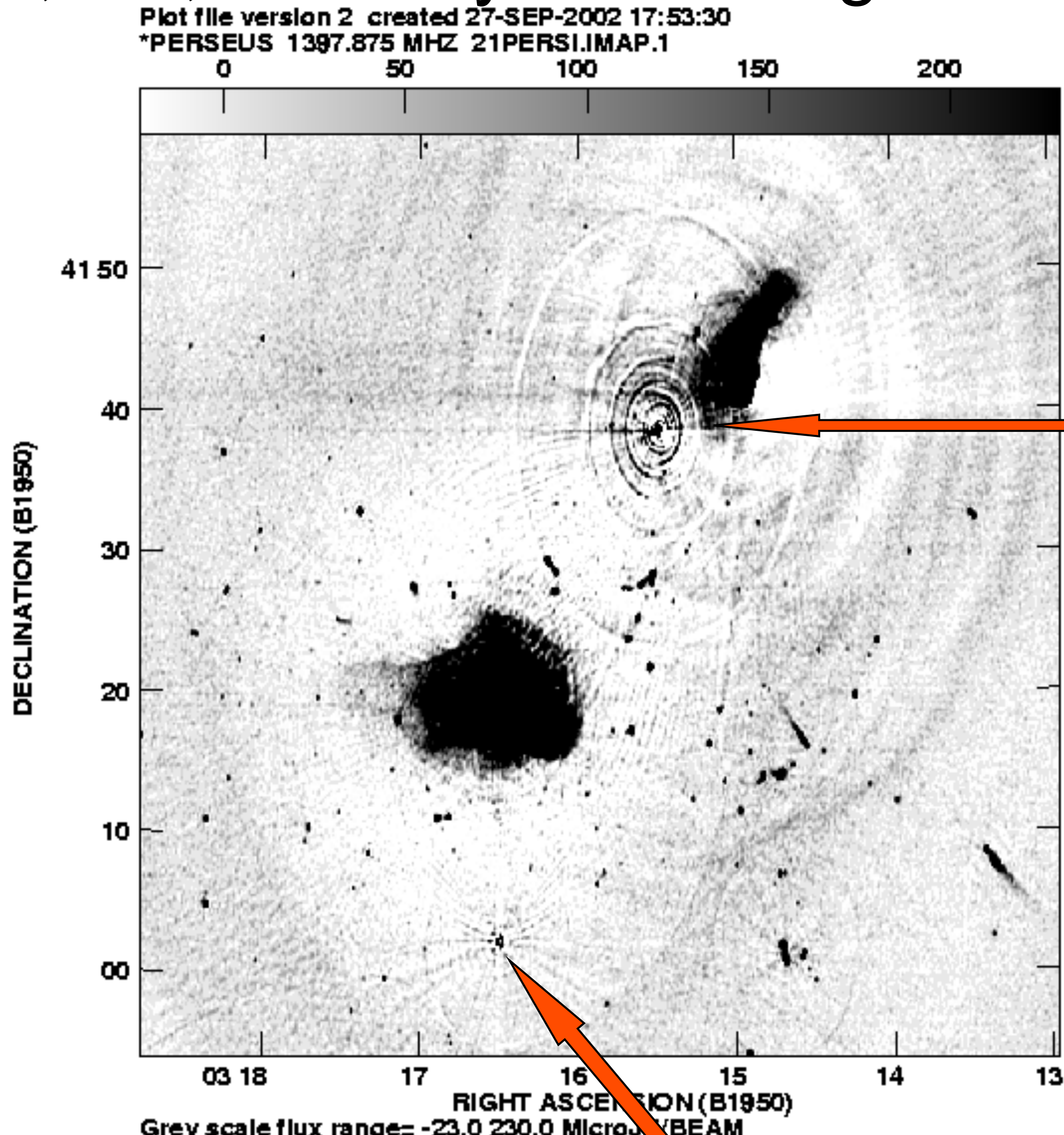
DCB - 8x5 MHz

21cm

6x12h

'noise' ~ 25 μJy

DR: ~10^6 : 1



Off-axis problems (pointing)

'ghost'

Very high DR LOFAR image of 3C196 field   Pandey

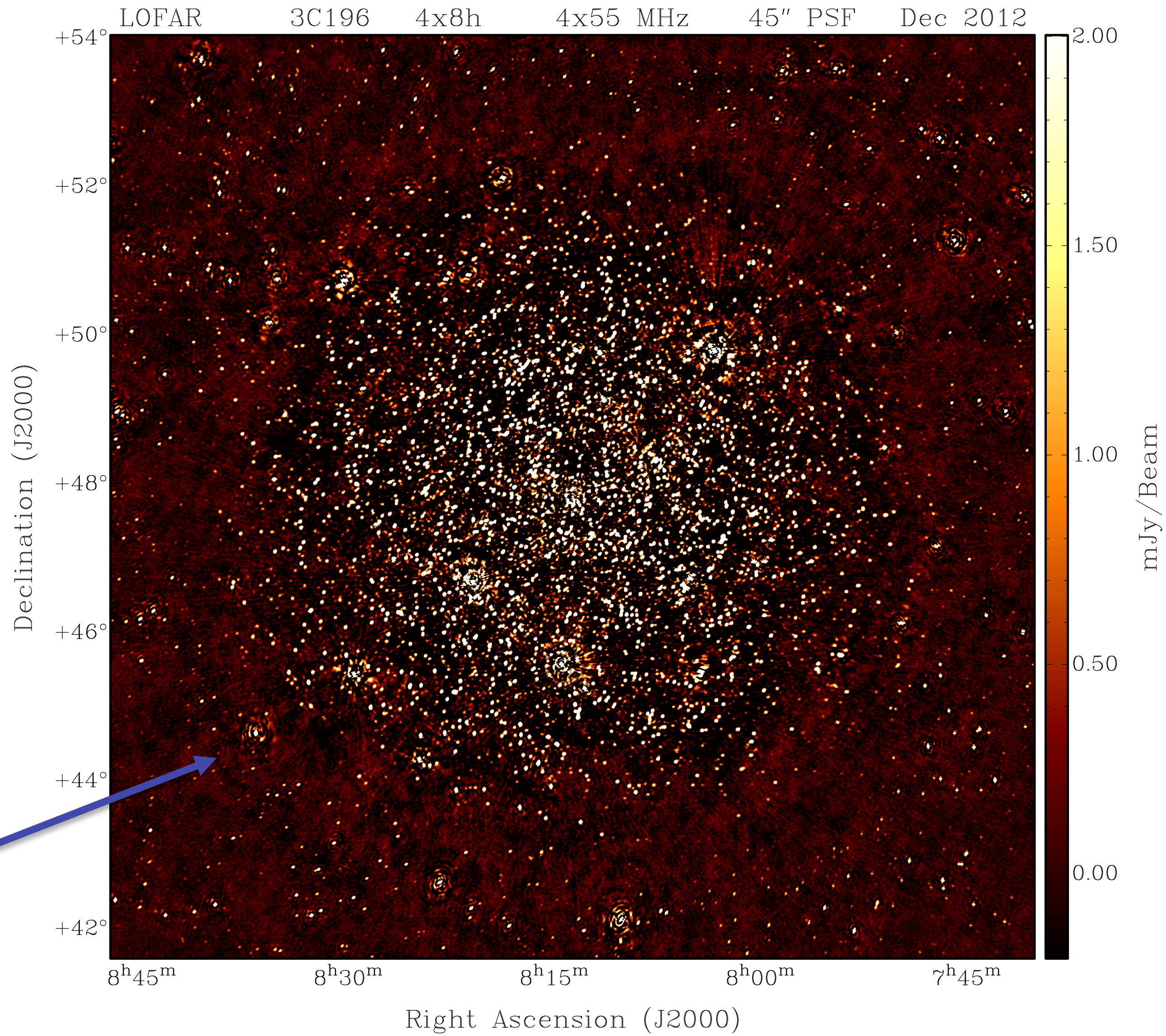
4x8h nights

12°x12°
50” PSF

80 Jy peak
80 μJy noise

→DR 10^6 : 1

Note here how bad the off-axis sources appear due to varying station beams



LOFAR (EoR) deep continuum image: Sarod Y.

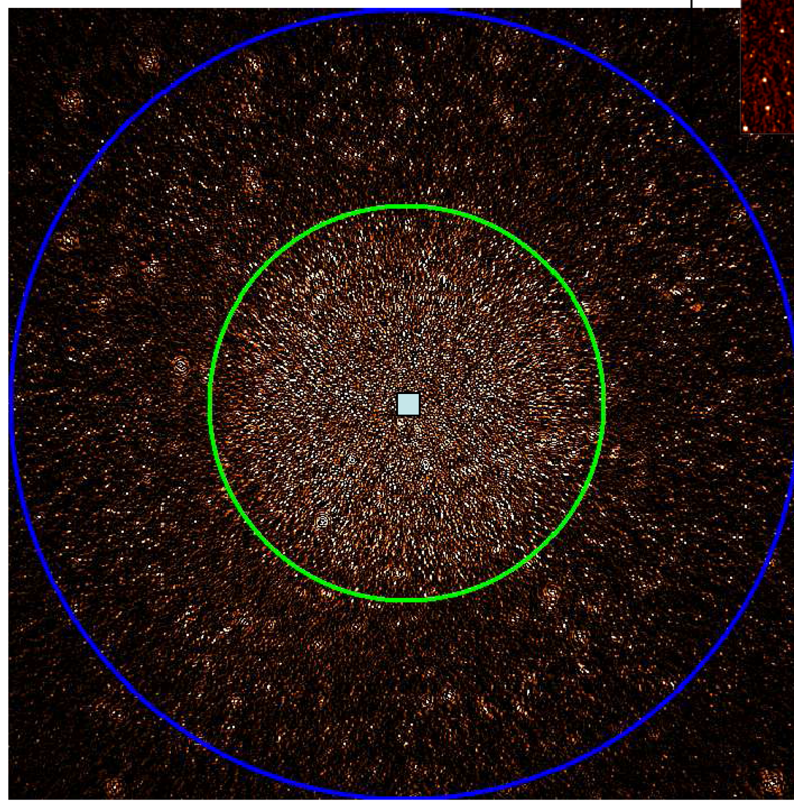
NCP = North Celestial Pole

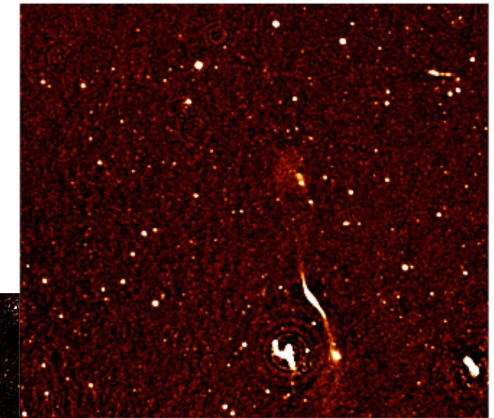
HBA: 115-175 MHz
100+ hours

4° HPBW
3' PSF

7 Jy original peak

~ 30 μJy in residual image





6" PSF

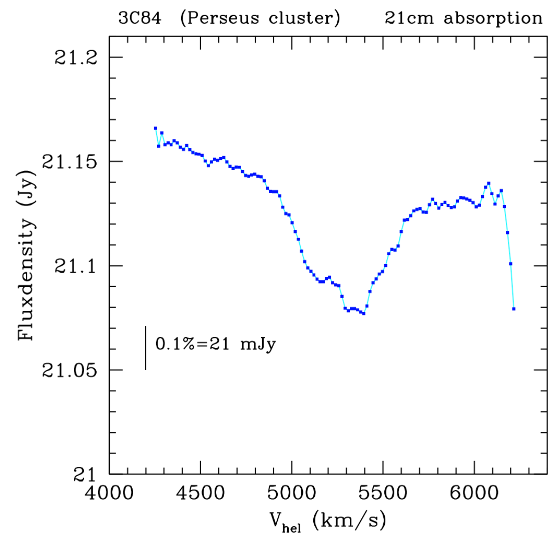
1500-2000 sources /□°

First null 10 deg. diameter, second null 20 deg. diameter

Spectral Dynamic Range

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

a SDR of 5,000:1 is very good !



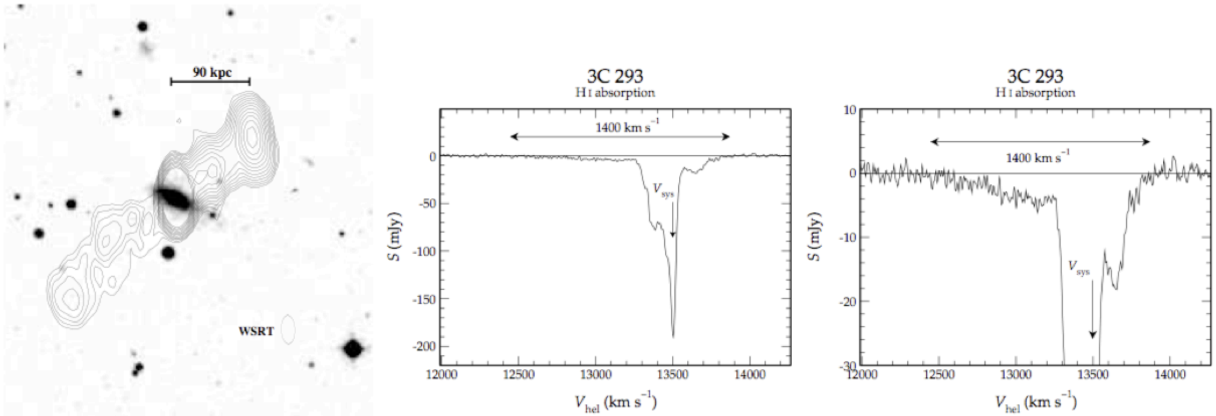


Fig. 1.— *(Left)* Continuum image of 3C 293 at the resolution of WSRT 21-cm observations (Emonts et al. in prep). *(Middle)* The H I absorption spectra with a zoom-in (*Right*) to better show the new detected broad H I absorption. The spectra are plotted in flux (mJy) against optical heliocentric velocity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

Emonts, Morganti et al, 2005

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

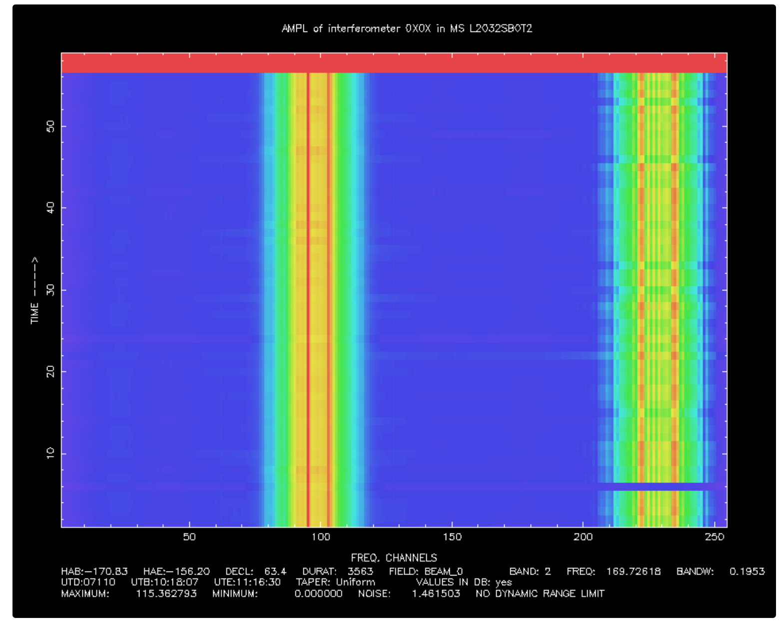
Most radio sources we want to study are very faint compared to the system+sky noise, e.g:

WSRT/VLA @21cm: T_{sys} = 30K → 300 Jy SEFD
LOFAR: SEFD ~ 2500 → 25000 Jy.

Most sources therefore produce tiny voltages in our antennas → very small correlated fraction. We therefore need to rely on linearity in our analog receiver chain. This requires a good 'instrumental dynamic range' .

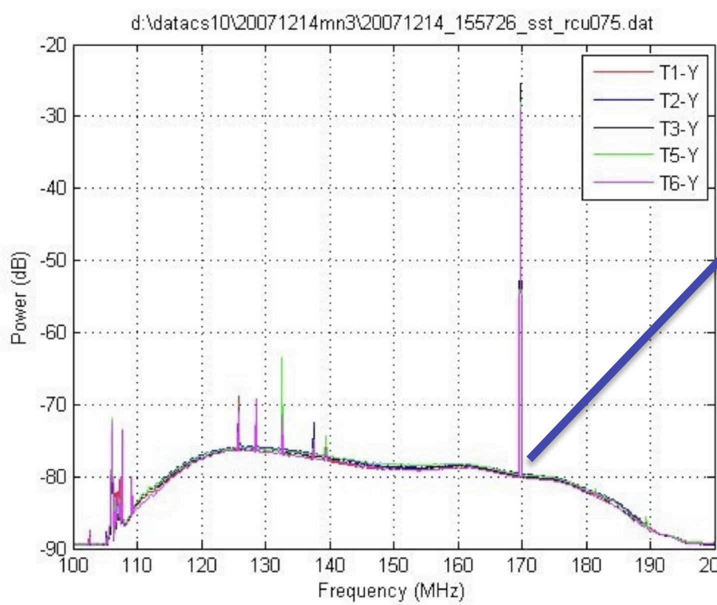
Dynamic spectrum at 1kHz and 60^s showing a 80 dB range (= 20^{mag} in the optical !)

Pagers at 169.85 and 169.75 MHz MHz



1^h

256 channels over 156 kHz



100 - 200 MHz spectrum of a LOFAR HBA dipole (at 195 kHz resolution) (Dec 2007)

Aspects defining spectral dynamic range

Single dishes: Arecibo, VLA-dish, WSRT-dish:

- standing waves between prime focus and dish*
- temperature effects/delays in analog signal chain

* but not in WSRT–Apertif (which has a Focal Plane Array)

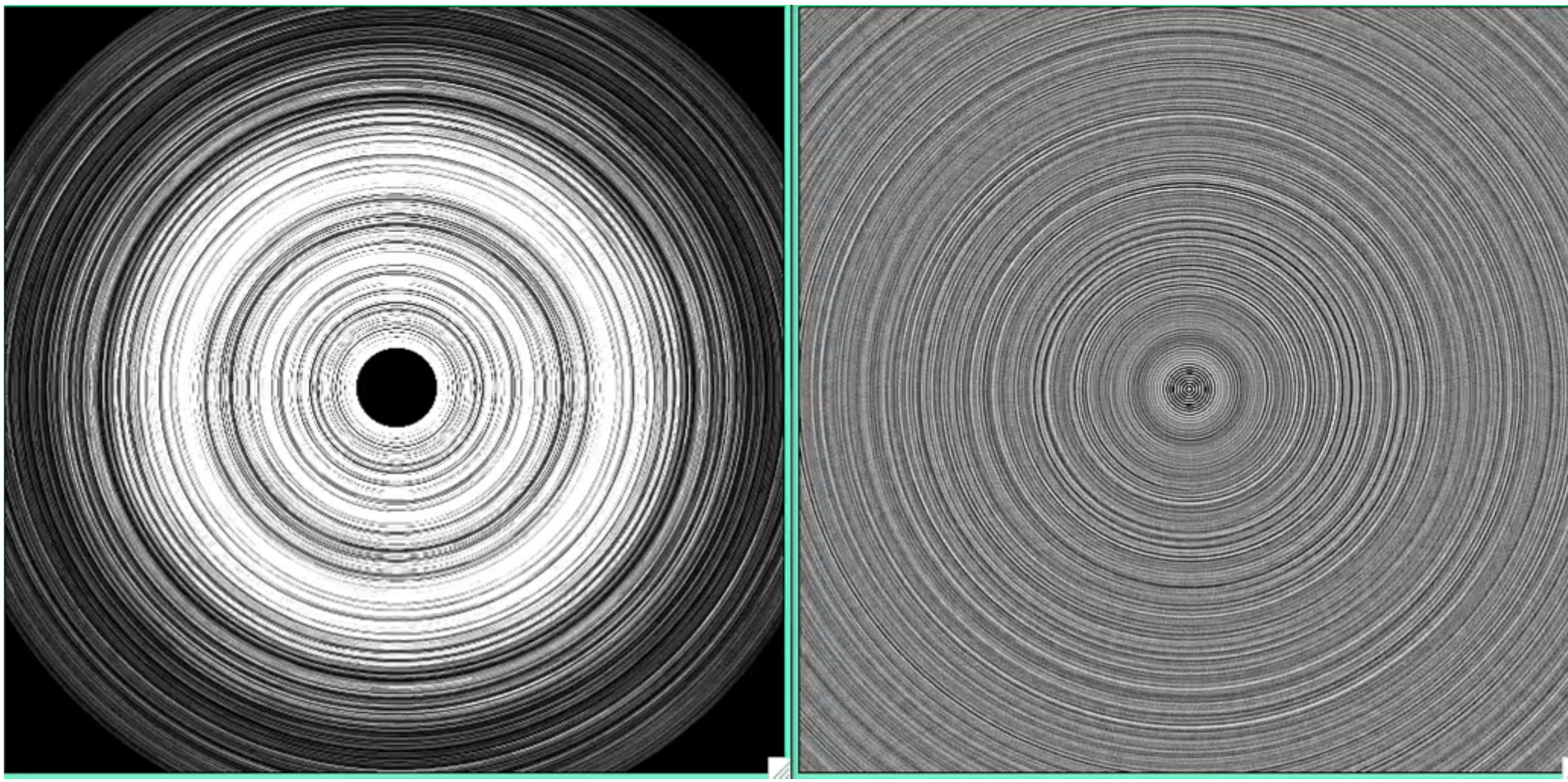
In aperture arrays (LOFAR, MWA,..):

- reflection in cables (e.g. 1.1 MHz feature in HBA)
- station and frequency dependent beams
- ionospheric distortions
- time and frequency smearing

But also frequency dependent PSF (influencing EoR project)

NCP cubes of 36 subbands (sb084-119 - Δυ = 7 MHz)

Weight (uv-density) PSF



50-800 λλ

LOFAR calibration issues: a conceptual summary:

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

- — the Sky or the Global Sky Model (= GSM)
- — the station beampattern: position (hence time), frequency & polarization dependent
- — the ionospheric phase 'screen'

Calibration is the process that solves for all stable, but most importantly, the time varying parameters (each with its own variability timescale)

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/solve for all 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 ?

Source models and image deconvolution:

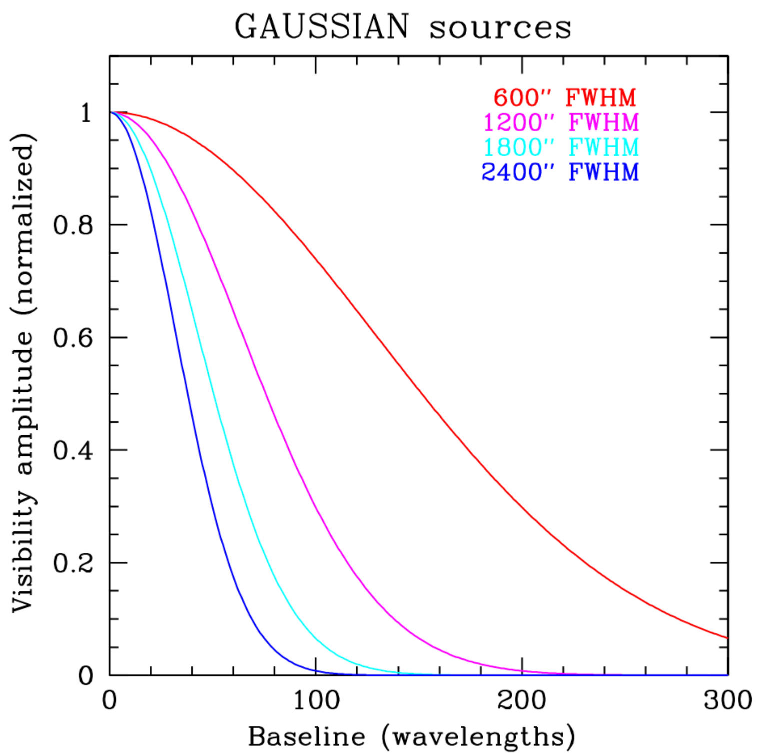
Issues in source modelling

Many structures can not be properly modelled, e.g.:

- If sources about ~1 PSF in size
- due to diffuse Galactic foreground
- Solar emission on short baselines (daytime)
- signals are polarized (→ RM(t) !)

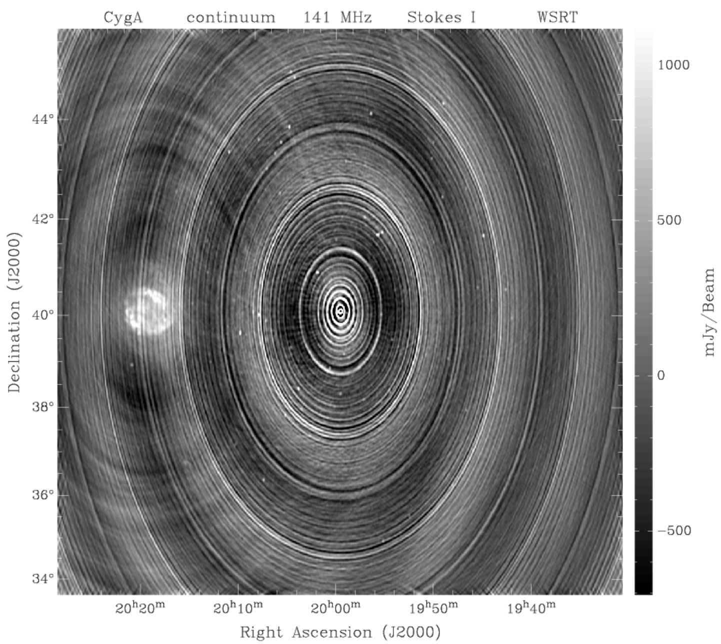
The large structures are often visible mainly, or exclusively, on very short baselines.

A possible calibration approach is then to exclude the inner part of the uv-plane from calibration solutions, i.e. use longish baselines to calibrate core stations



WSRT imaging of CygA (a source about 1 PSF in size)

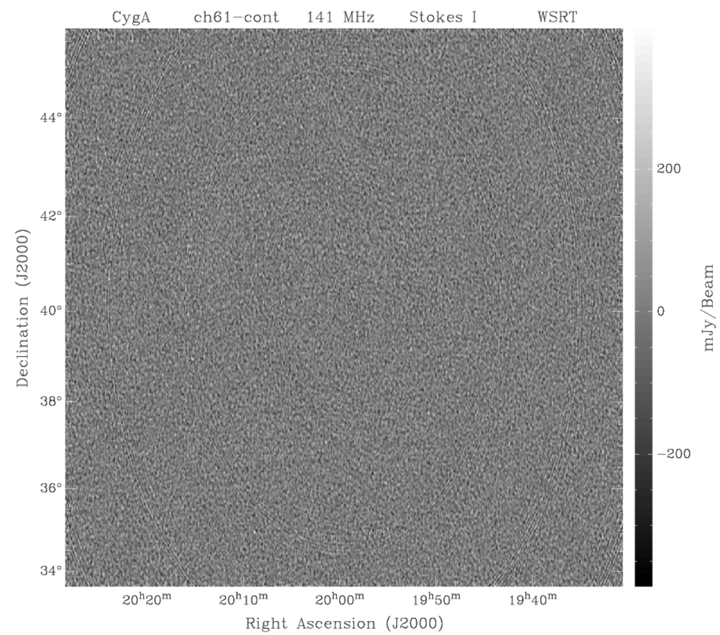
‘CONTINUUM’ (B=0.5 MHz)



(Original) peak: 11000 Jy

Dynamic Range ~ 5000:1

‘LINE’ CHANNEL (10 kHz) - CONT



noise 70 mJy

vs ~150,000 : 1 !!

So even if you can not properly deconvolve this source, differentially you can get away → Lesson: your data may be better than you think !

The Measurement Equation

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

$$\boldsymbol{v_p = J_p\, e} \quad \text{and} \quad \boldsymbol{v_q = J_q\, e}$$

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.

Multiple Jones matrices

There are many effects on the signal when it propagates from source to correlator, such as 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:

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

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, DPPP 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/imaging software …packages, packages

Aperture synthesis array (users) use many different calibration and imaging packages

— AIPS : VLA, WSRT, GMRT, ATCA, VLBI,…

— Miriad : VLA, ATCA, WSRT,…

— NEWSTAR : WSRT

— AIPS++ → CASA : WSRT, VLA, GMRT

— Difmap: VLBI, VLA

— SAGEcal, ExCon : used especially in LOFAR EoR project

For LOFAR, with all its novel and complicated aspects, we need to do much better. Several packages have been, and continue to be, developed:

— MeqTrees was (is?) being used to develop/simulate our understanding

— BBS, (N)DPPP has implemented what we have learned

— CASA, ExCon, AWimager, WSClean for imaging and deconvolution

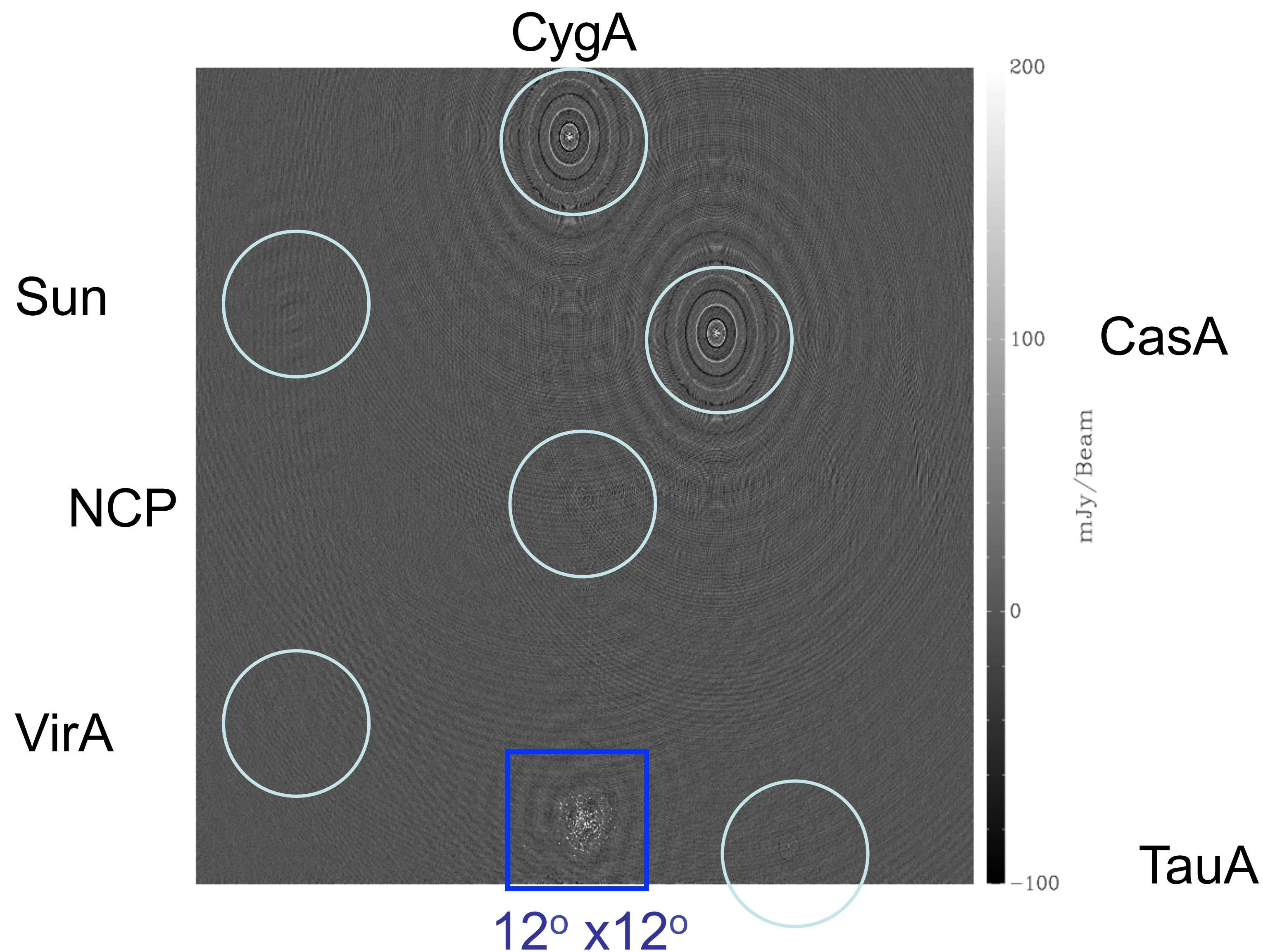
If you are not satisfied with the result: (i) blame the hardware/firmware, (ii) check the software/pipeline, or (iii) (most likely) reconsider your understanding of the problem !

If still no improvement: consult an expert.

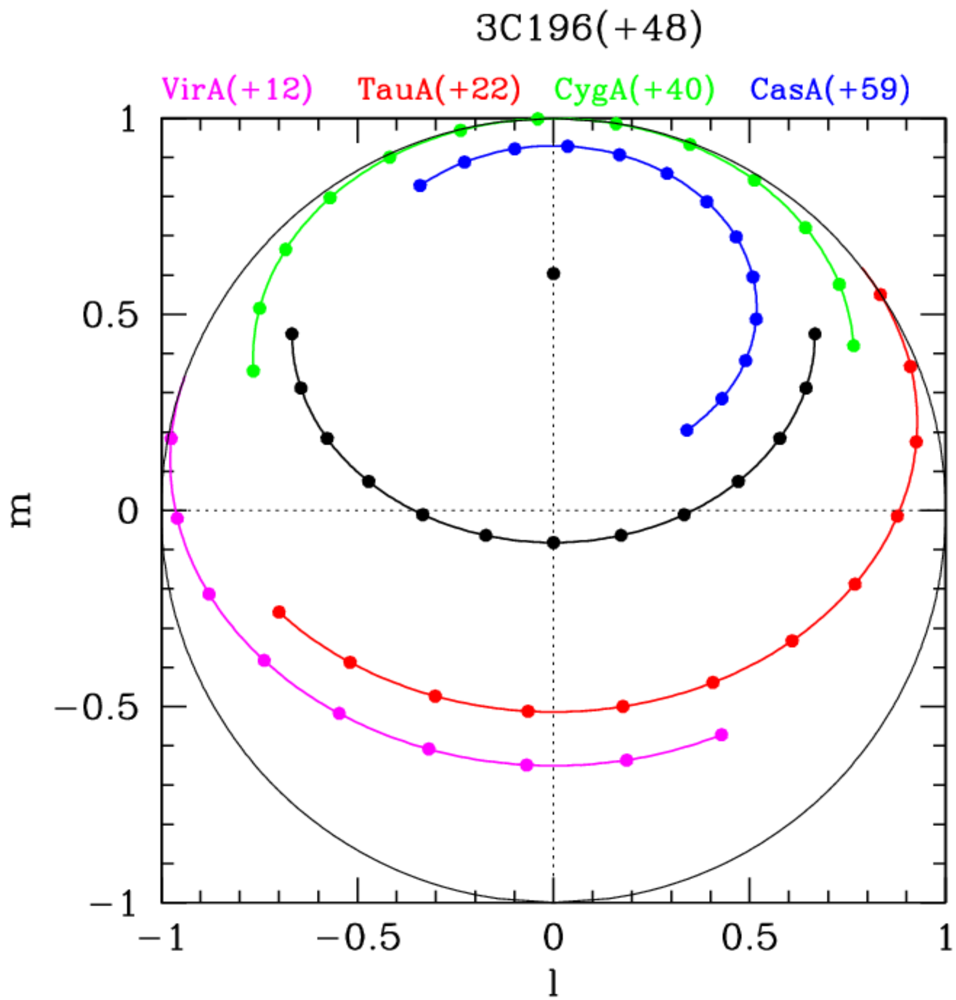
LOFAR wide field imaging: station beam issues

(see also Andre Offringa's talk and tutorial)

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



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



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

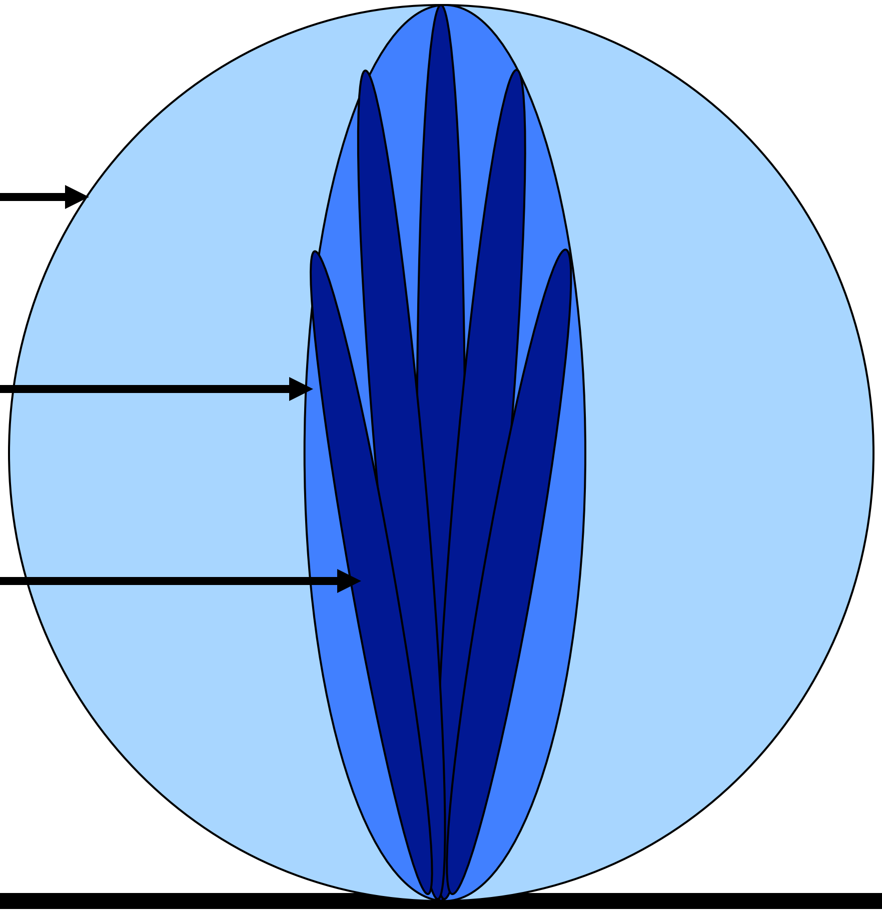
CasA and CygA are always above the LOFAR horizon !

FOV in LOFAR core (HBA ~ 150 MHz)

dipole (~100°)

tile (~ 20°)

24-tile station (~ 5°)



Wide-field wide-frequency → changing primary beam

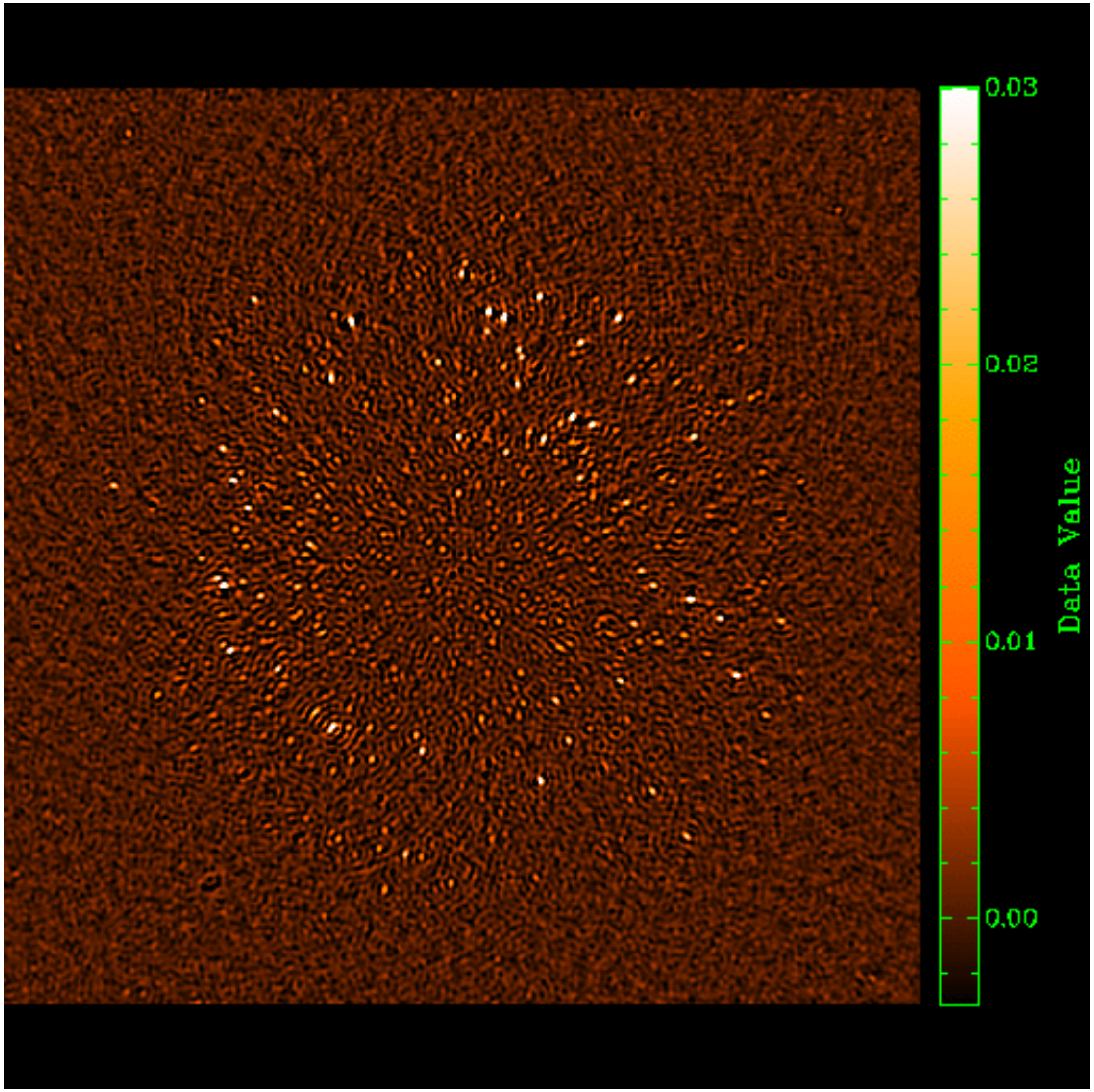
NCP residuals
(11,000 subtracts)

115→ 175 MHz

$30^o \times 30^o$

Changing location of 1st null and 1st station sidelobe

→ Complicates spectral modeling of the sky !!



Direction-Dependent (DD) calibration

There are 3 reasons why LOFAR needs direction-dependent calibration:
(but also other telescopes now need this, e.g. WSRT: see e.g. Smirnov & de Bruyn, 2011 arXiv1110.2916, GMRT, and VLA)

- LOFAR has a very wide field of view (FOV)
- the ionospheric effects at low frequencies are many PSF's
- the station beam varies with time and frequency

In how many directions should we calibrate ? This depends on whether off-axis artefacts limit your science !

LOFAR users currently use two approaches to perform DD

1) SAGEcal (as practiced by the LOFAR EoR group; see Yatawatta et al 2013). Gain solutions are derived simultaneously in 100+ directions using sky models that are concentrated in clusters (an example is shown in the next slides)
2) Facet calibration (see van Weeren et al, 2016). Here all emission outside a given facet is removed (to 1^{st} order); all facets will be treated sequentially.

DD can be very slow !!

Fast and Robust direction-dependent calibration

The next 3 slides illustrate the removal of (the response of) CasA and CygA from the NCP data by running SAGEcal with just 4 ‘clusters’:

- CasA (+58^o) (shapelets)
- CygA (+40^o) (discrete sources + shapelets)
- 3C61.1 (+86^o) (hot spots + shapelets: 45 Jy intrinsic)
- NCP source (+89.5^o) (7 Jy)

For a discussion on generating and using shapelets (which are an efficient compact way of characterizing a source) see the LOFAR Cookbook (appendix B)

Removing CasA and CygA via SAGEcal (Yatawatta)

NCP:
single subband, 13h
after BBS

Stokes V

20^o x 20^o FOV

natural weights
60-800λ uv-cut

thermal noise
~0.7 mJy slightly enhanced by CasA and CygA sidelobes

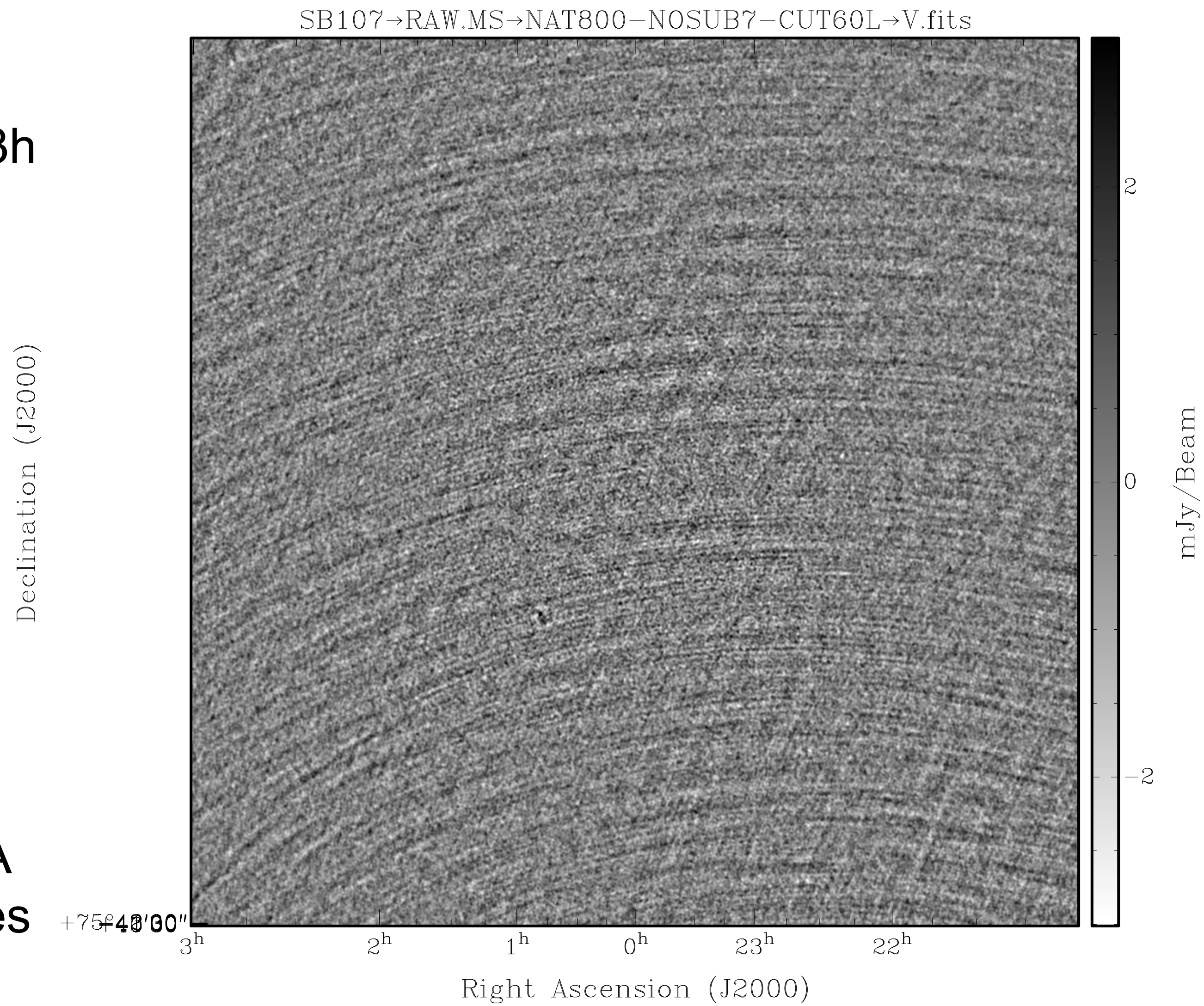
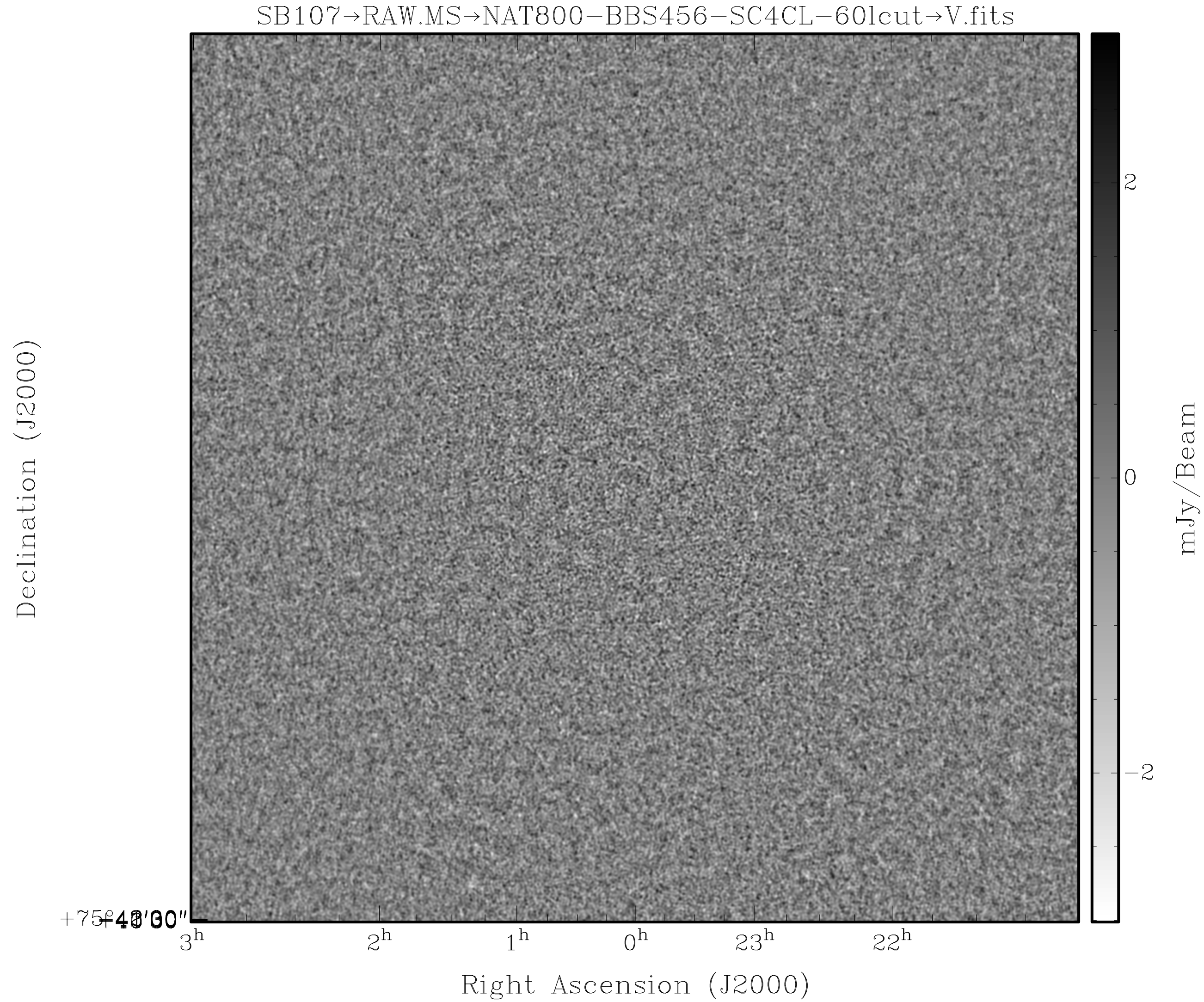


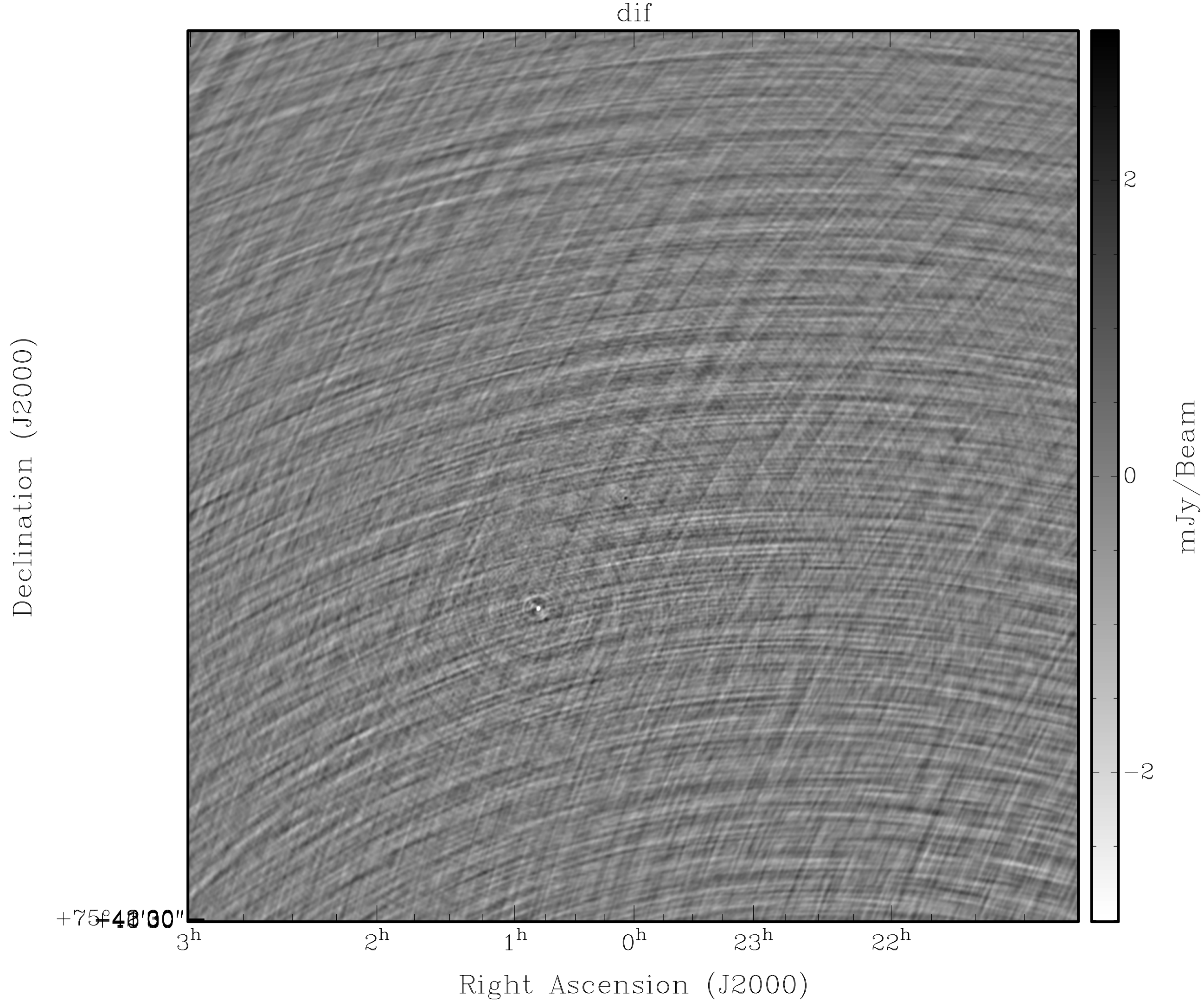
Image after 4-cluster (source) SAGEcal



…and these are the corrections that were removed

Note that SAGEcal is very effective in removing source very far away (like CasA and CygA) but also can remove sources within the FOV

The latter is an effective tool in LOFAR VLBI imaging.



LOFAR wide field imaging: ionospheric calibration issues

(much more in Maaijke Mevius' lecture)

Calibration and the ionosphere

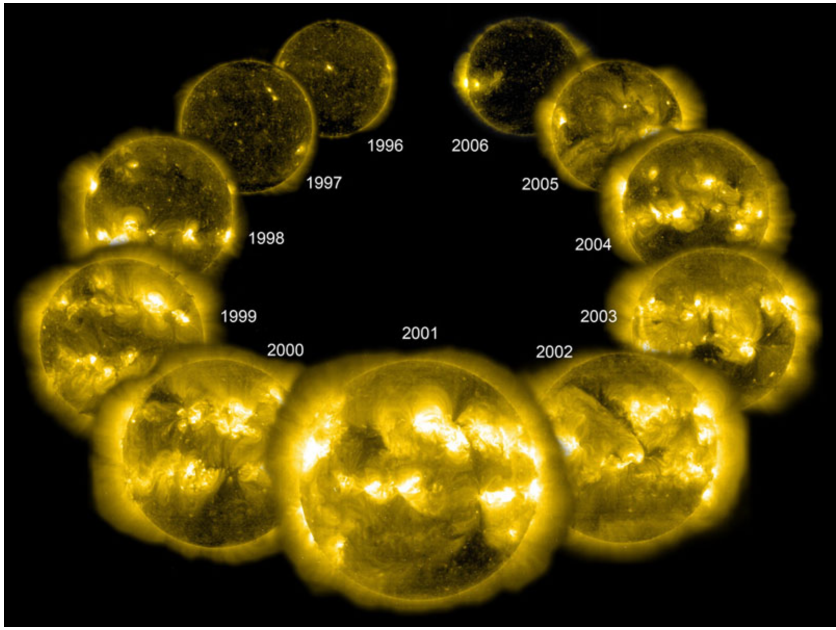
Many issues

Non-isoplanaticity (low freq, large FOV)

Solar cycle (maximum ~2013/14)

Array scale > refractive/diffractive scale

TID's, (Kolmogorov) turbulence



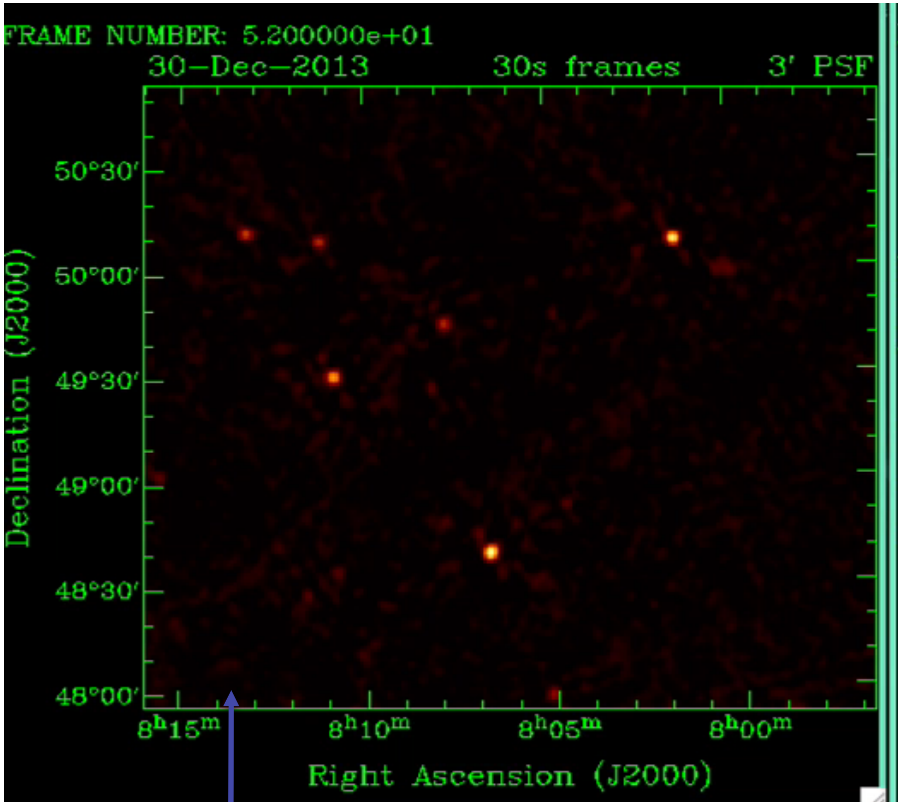
Soho-solarcycle,
APOD 5 dec07

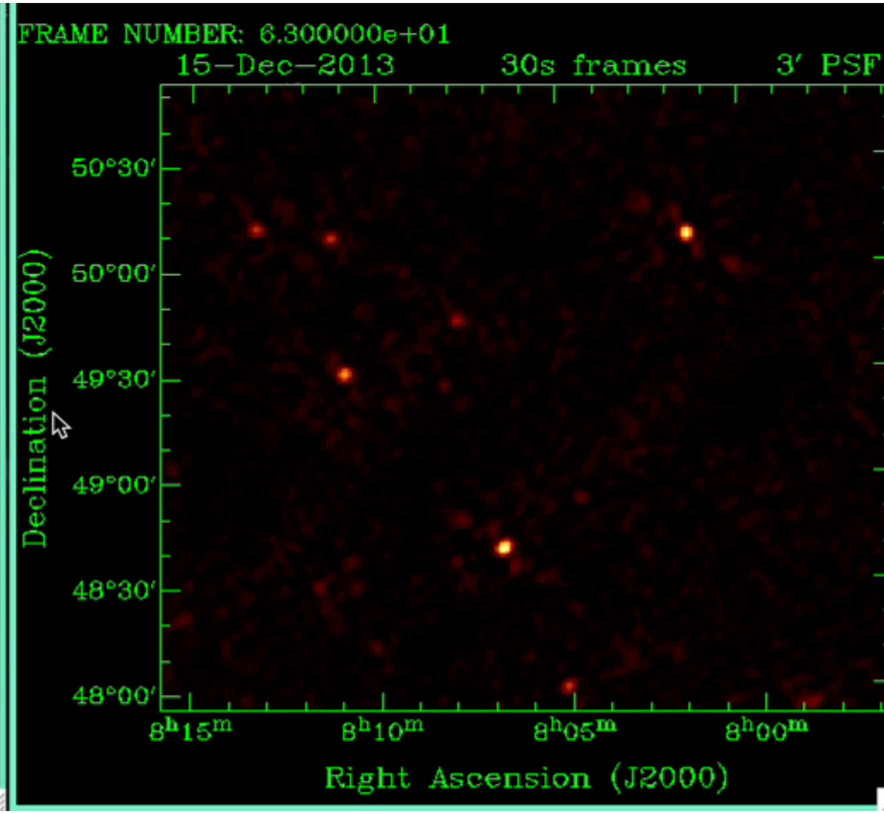
Tools/approaches to deal with this:

- 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)

3C196 field: 3° x 3° 3' PSF

Bad night Good night





720 frames at 30s time resolution = 6 hours

3C196 washere (calibrated & subtracted)

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

— Faraday rotation

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

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