Correcting the ionosphere

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R. van Weeren, D. Rafferty, S. van der Tol, H. Intema

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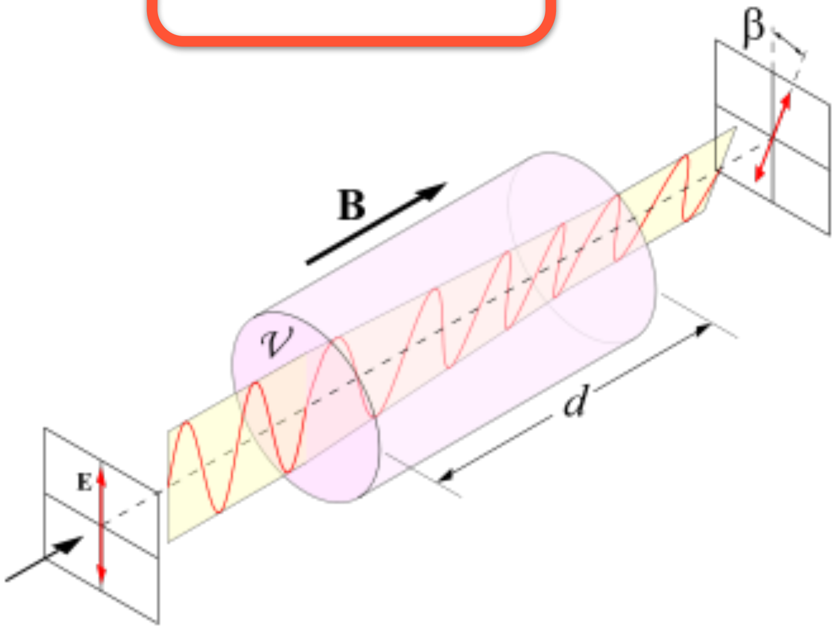
LOFAR ASTRON

EM in plasmas

Phase delay: $$\phi_{\text{ion}} \approx \frac{e^2}{4\pi\epsilon_0 m\nu} \int_0^d n_e ds$$

Faraday rotation: $$\beta = \text{RM}\nu^{-2}\ , \ \text{RM} = \frac{e^3}{8\pi^2\epsilon_0 m^2 c^3} \int_0^d n_e(s) B_{||}(s) ds$$



Ionosphere

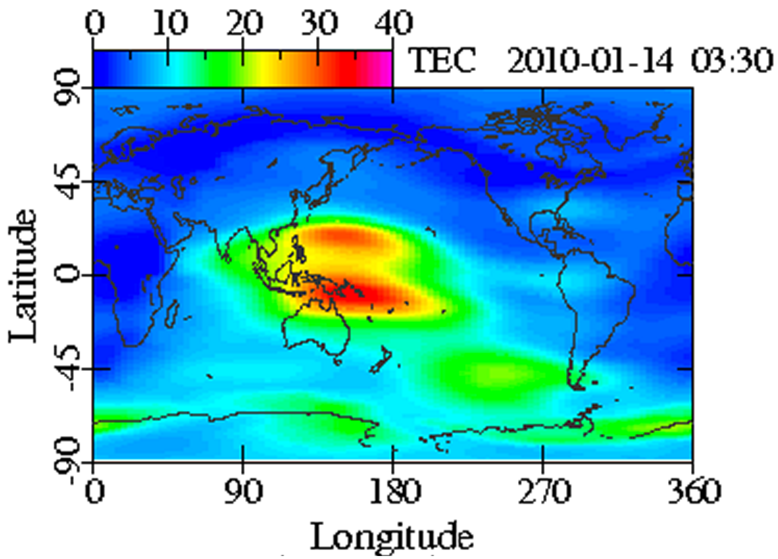
- Partially **ionized** gas layer
- Permeated by Earth's **magnetic field**
- Mainly ionized by **Sun** through UV and short X-ray
- Strong daily **cycle**, annual cycle, solar activity cycle

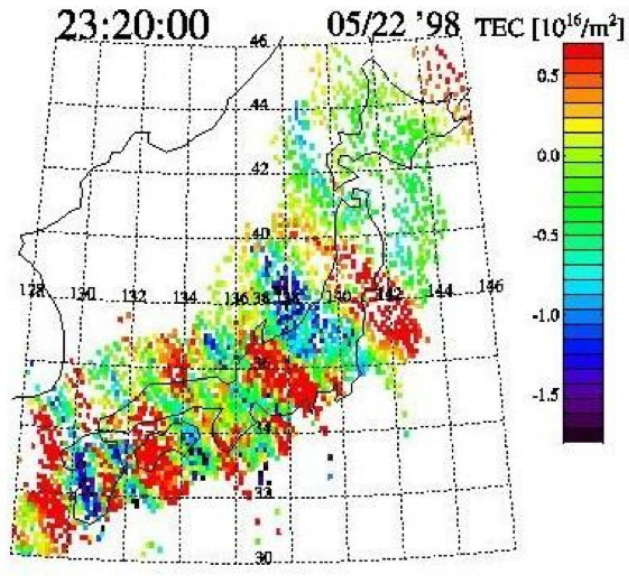
- Free electron density is **variable in space-time**
- Typical vertical column density at night: 10^{16} m^{-2} = 1 TECU

The ionosphere

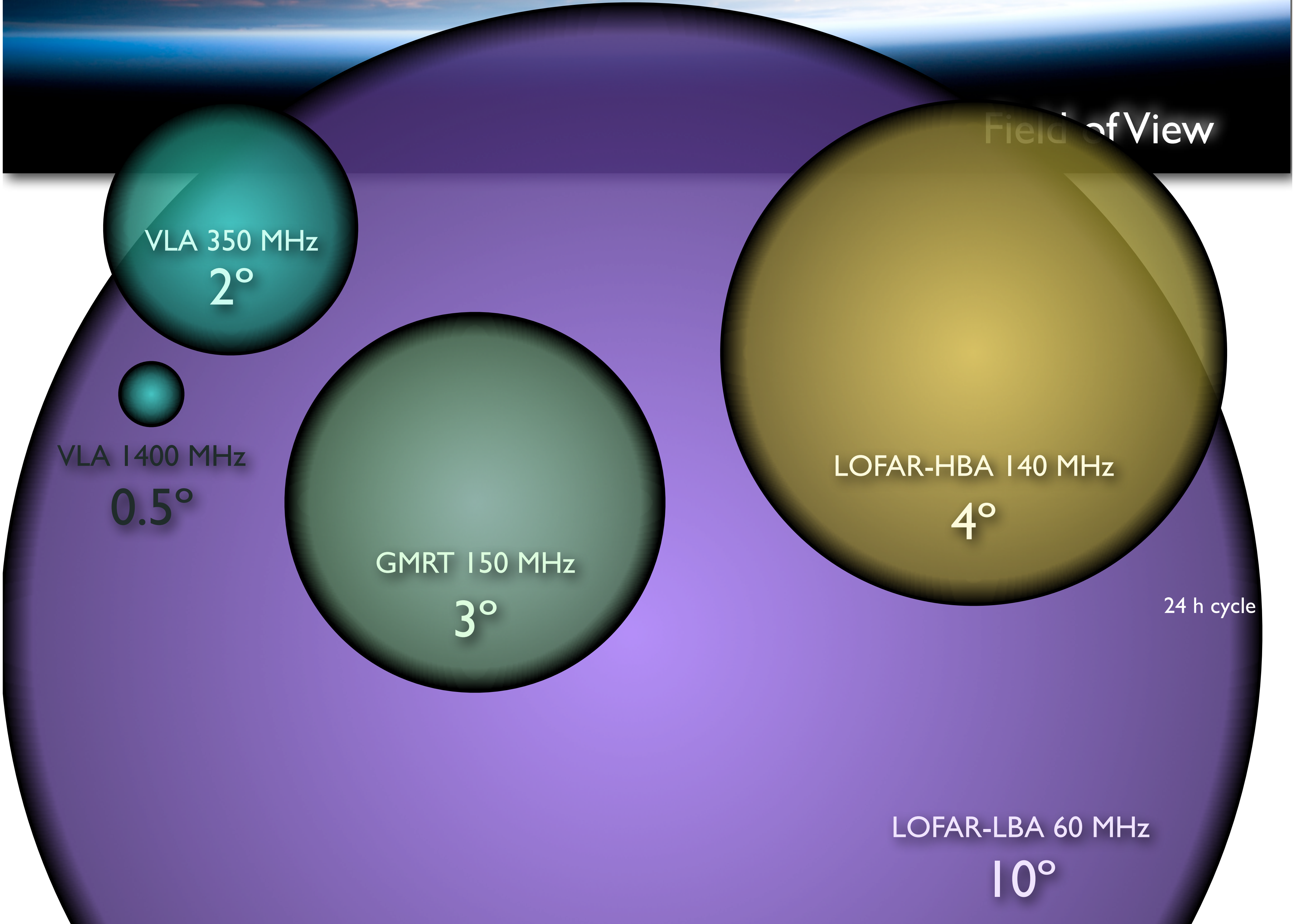
- Large-scale variations:
  - TEC varying orders of magnitude
  - Cause: shift of the observing field

- Traveling Ionospheric Disturbances (TIDs):
  - 200 - 400 km height
  - 250 - 400 km wavelength
  - 300 - 700 km/h
  - 1 - 5% TEC variations
  - Cause: local source shift and distortions





Field of View

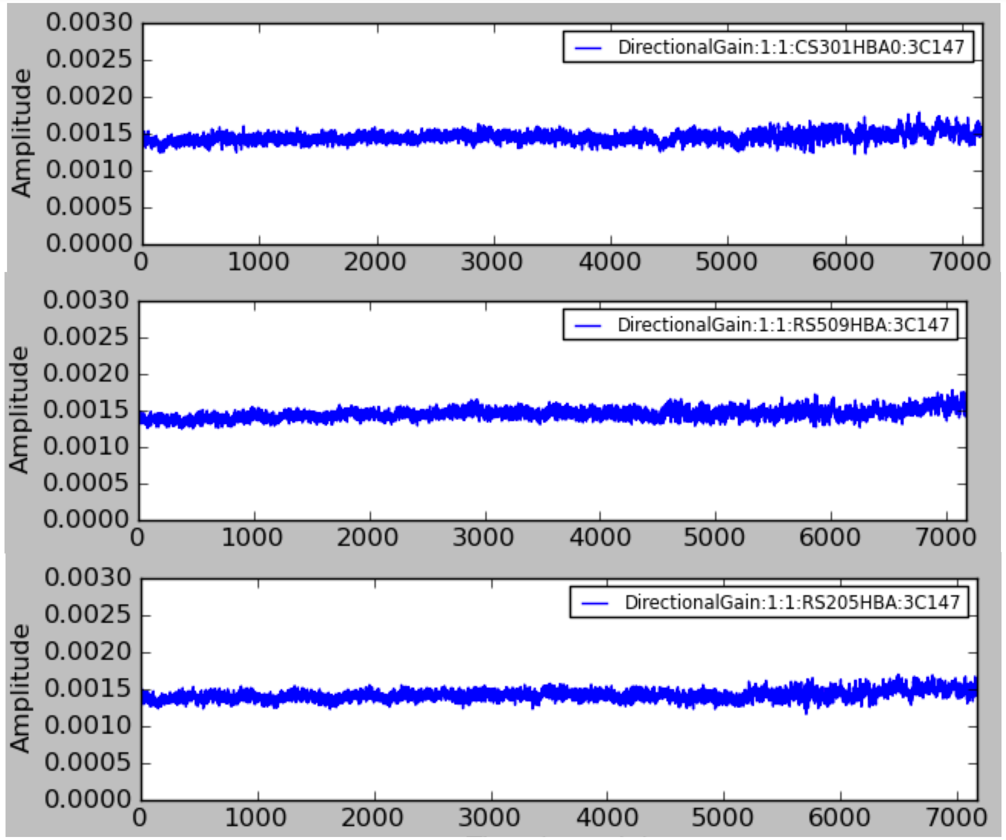


Status

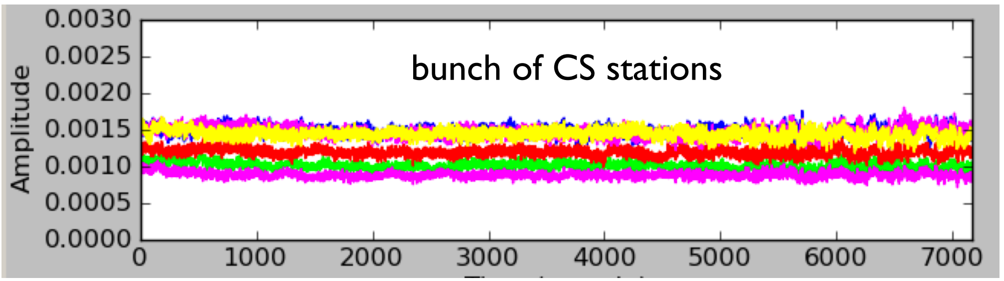
- Goal (Tier-I HBA):
  - Noise level: ~100 microJy/beam with 10 h of data
  - Resolution: ~5 arcsec
  - Image quality (DR: 10^4 - 10^5)
  - Reliable fluxes: < 5%

- Current status:
  - No selfcal → few mJy noise (arcmin resolution)
  - Selfcal → ~1 mJy "effective noise", arcsec resolution
  - HBA: no fundamental limitations in terms of S/N
  - LBA: situation looks (much) more problematic

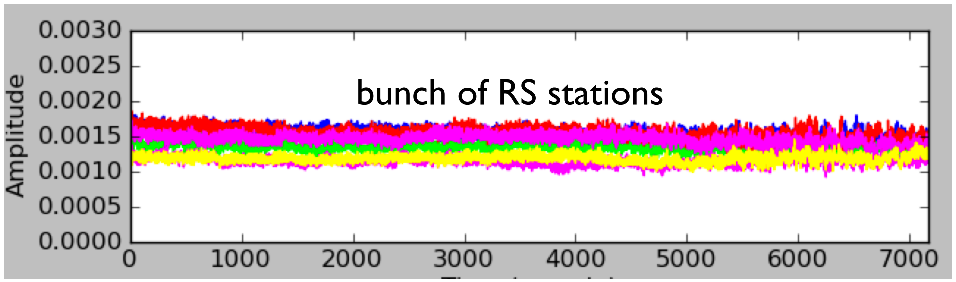
Calibrator stability



10 h



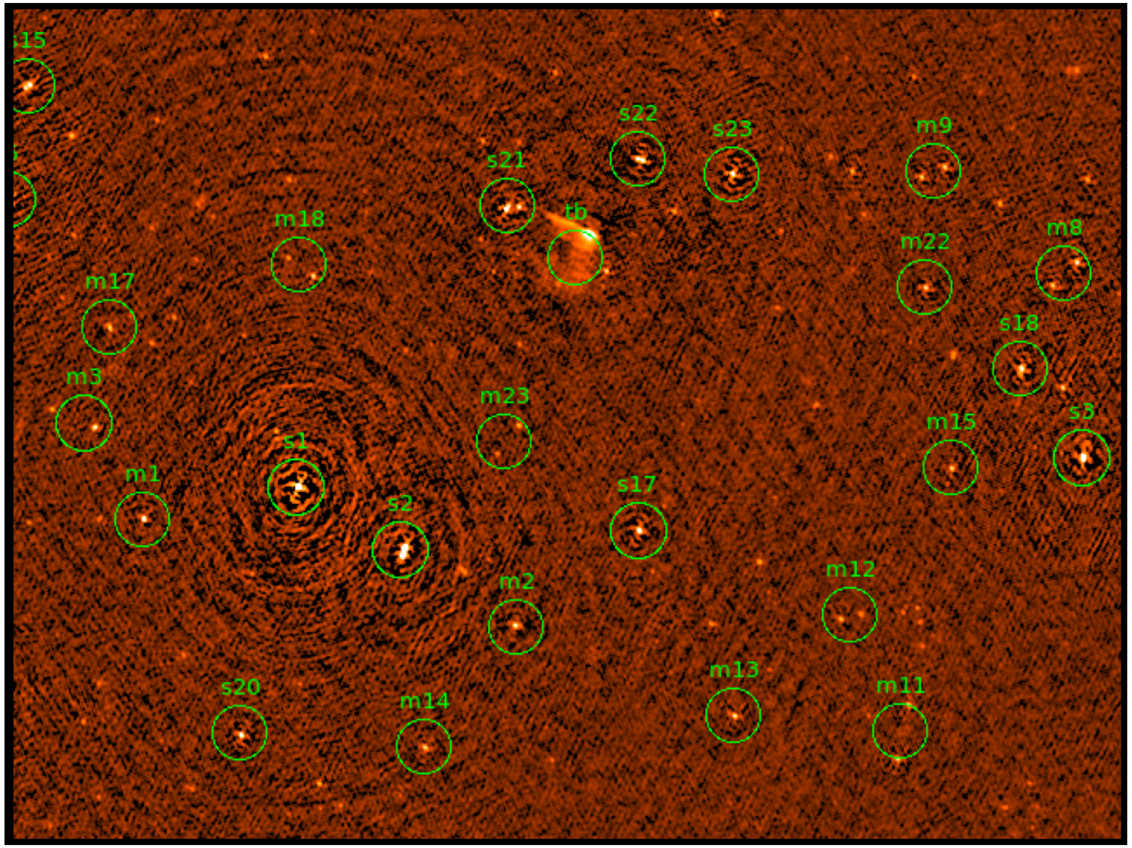
- Large elevation changes (40-90 deg)
- No time dependent gain corrections needed
- Single correction sufficient to get the amps calibrated
- We could just have observed 3C147/3C295/196 for ~30 min
- Variations that people report are likely calibration issues
  - A-team signal
  - not properly treating the field around the calibrator



Implementations

- Extreme peeling (van Weeren)
  - Proven working (HBA)
  - Slow (1 month/10h obs)
  - User interaction
- dTEC fitting (Rafferty, van der Tol)
  - Proven working (for LBA!)
  - Slow
  - Automated
- CSPAM (Intema, de Gasperin)
  - Proven working
  - Less slow
  - Automated

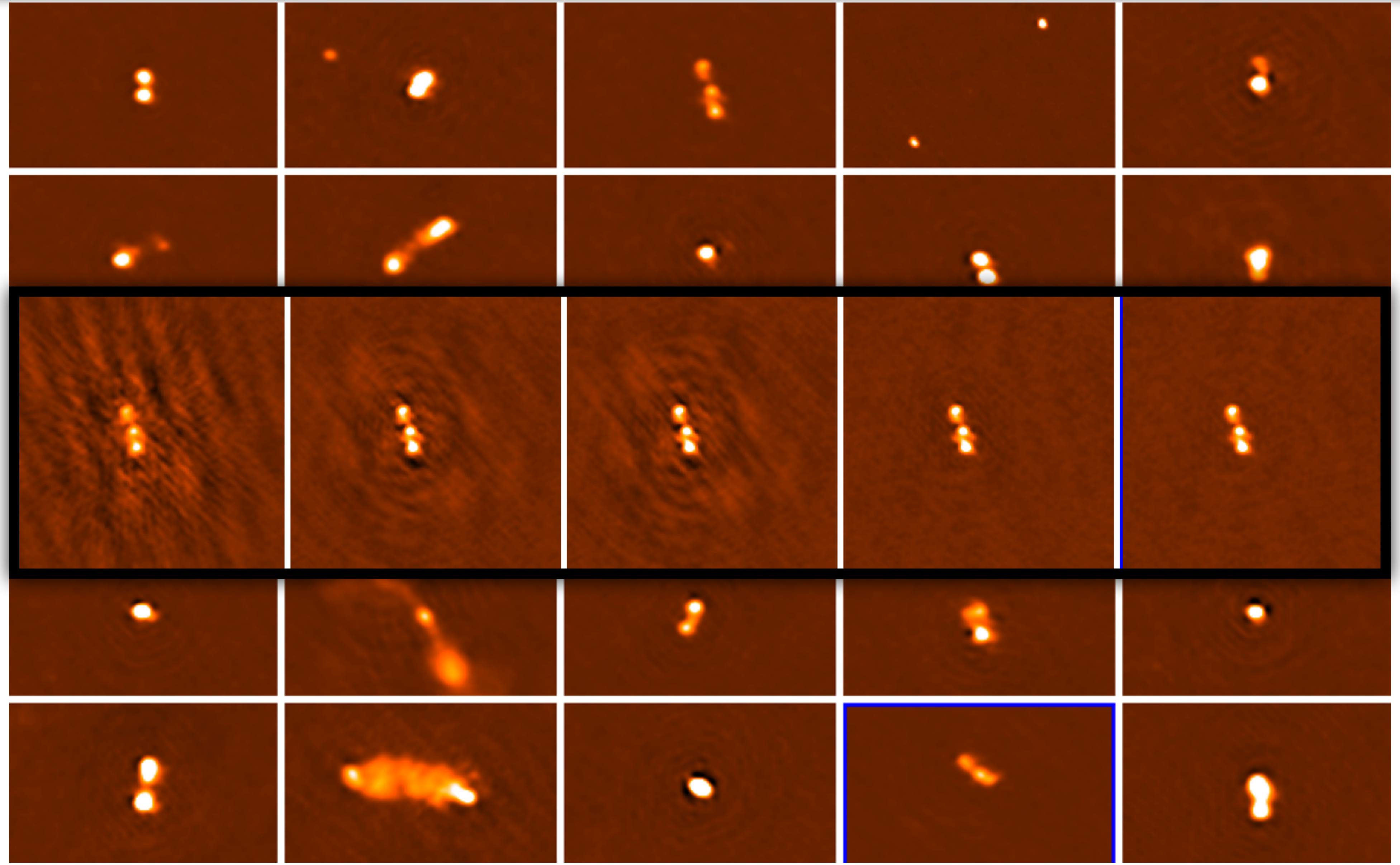
Extreme peeling: define directions



- iterate over directions for direction dependent calibration
- computing time simply scales with number of directions
- full selfcal+imaging cycle per direction (source models are updated all the time)

- All compact sources above ~ 0.1 Jy
- Bright extended sources
- Done manually

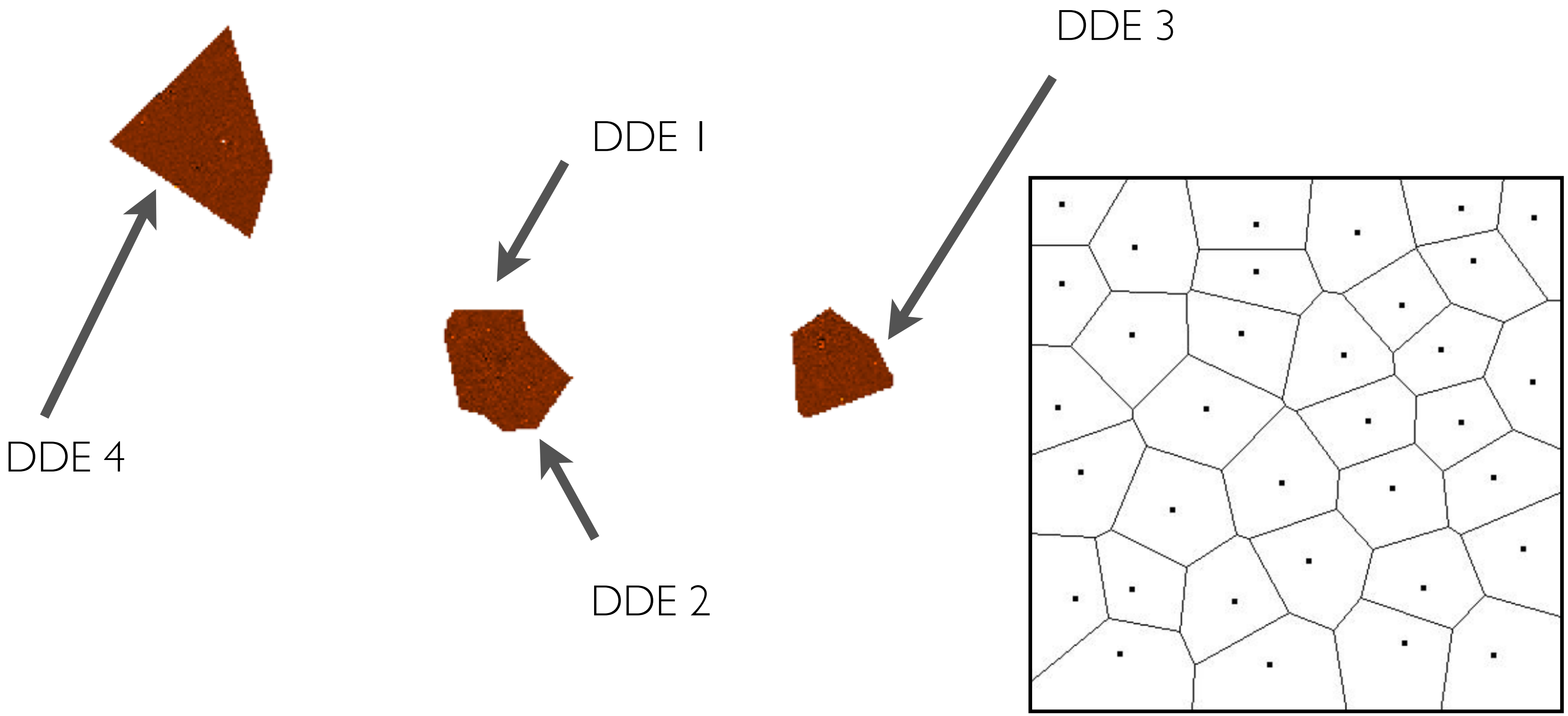
Tessellation



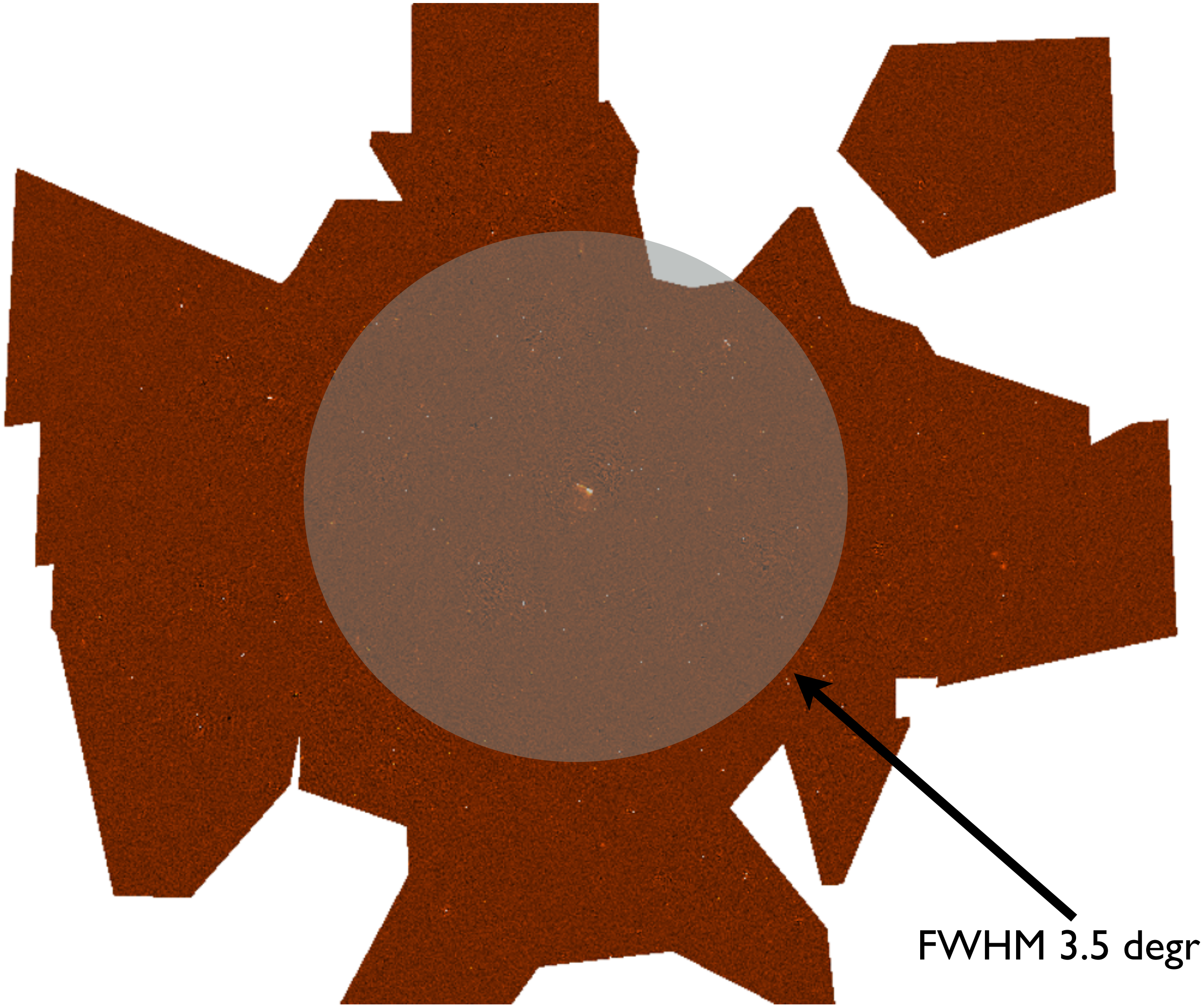
Tessellation

DD calibration:

1. Add back one of the "peeling source"
2. Selfcal on the source for all SBs
3. Add the fainter sources back in the region around the peeling sources
4. Apply the DDE/peeling solution and image this part of the sky
5. Subtract the "updated model" from the original "residual datasets"

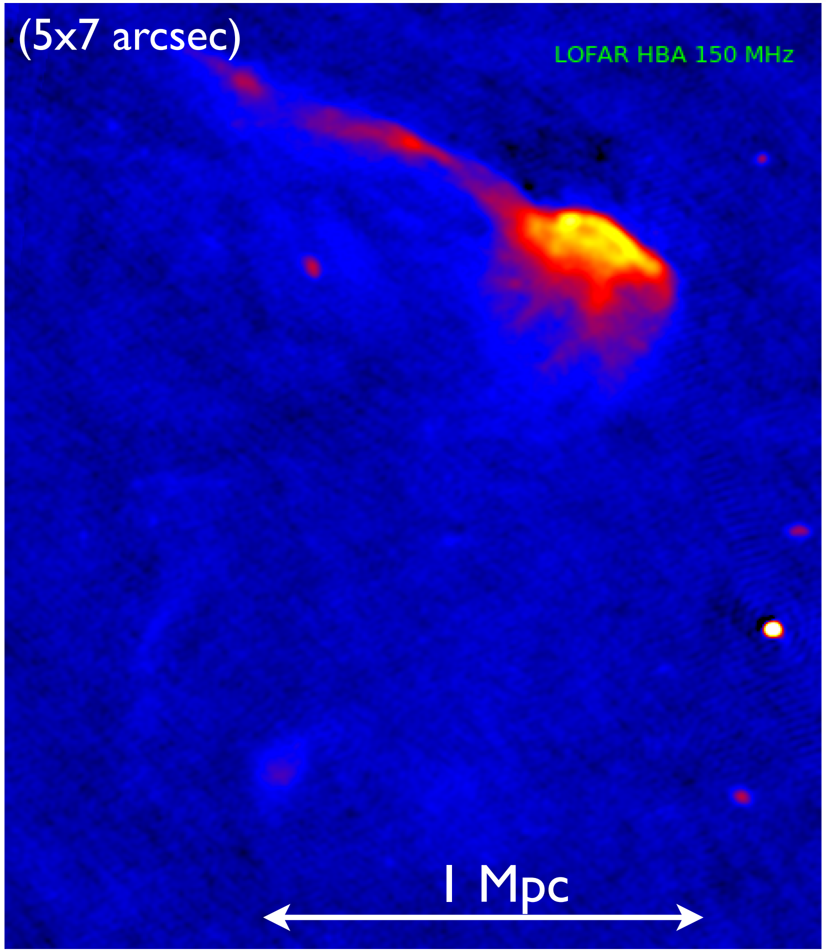


Result



Result

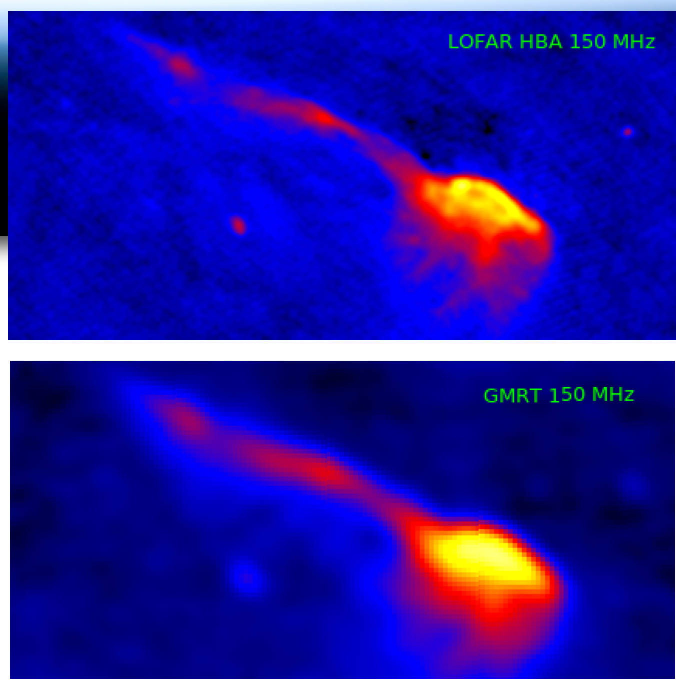
(courtesy of R. van Weeren)



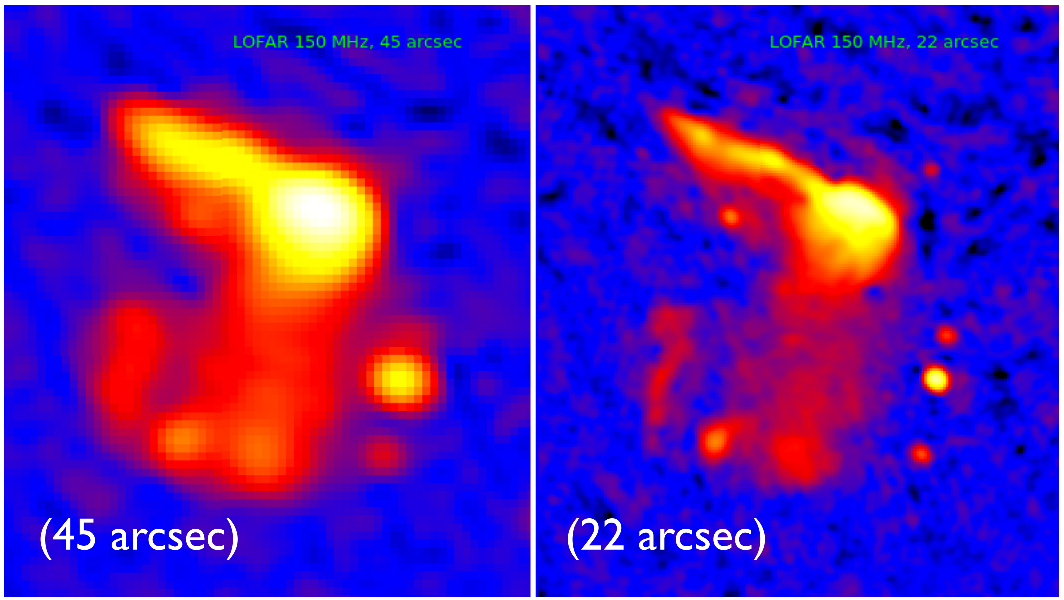
full resolution (5x7 arcsec), 140-160 MHz
close to thermal noise (190-250 microJy/beam)

only 30% of available bandwidth.....

LOFAR vs GMRT



emphasize large-scale emission with weighting



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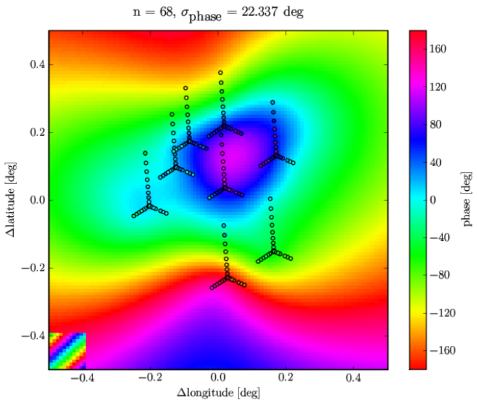


dTEC fitting

- Perform direction-dependent calibration for bright sources

- Assume that instrumental effects are the same in all directions for a given station:

Source 1:

$$\phi_1^{\mathrm{cal}} = \phi^{\mathrm{instr}} + \phi_1^{\mathrm{ion}}$$

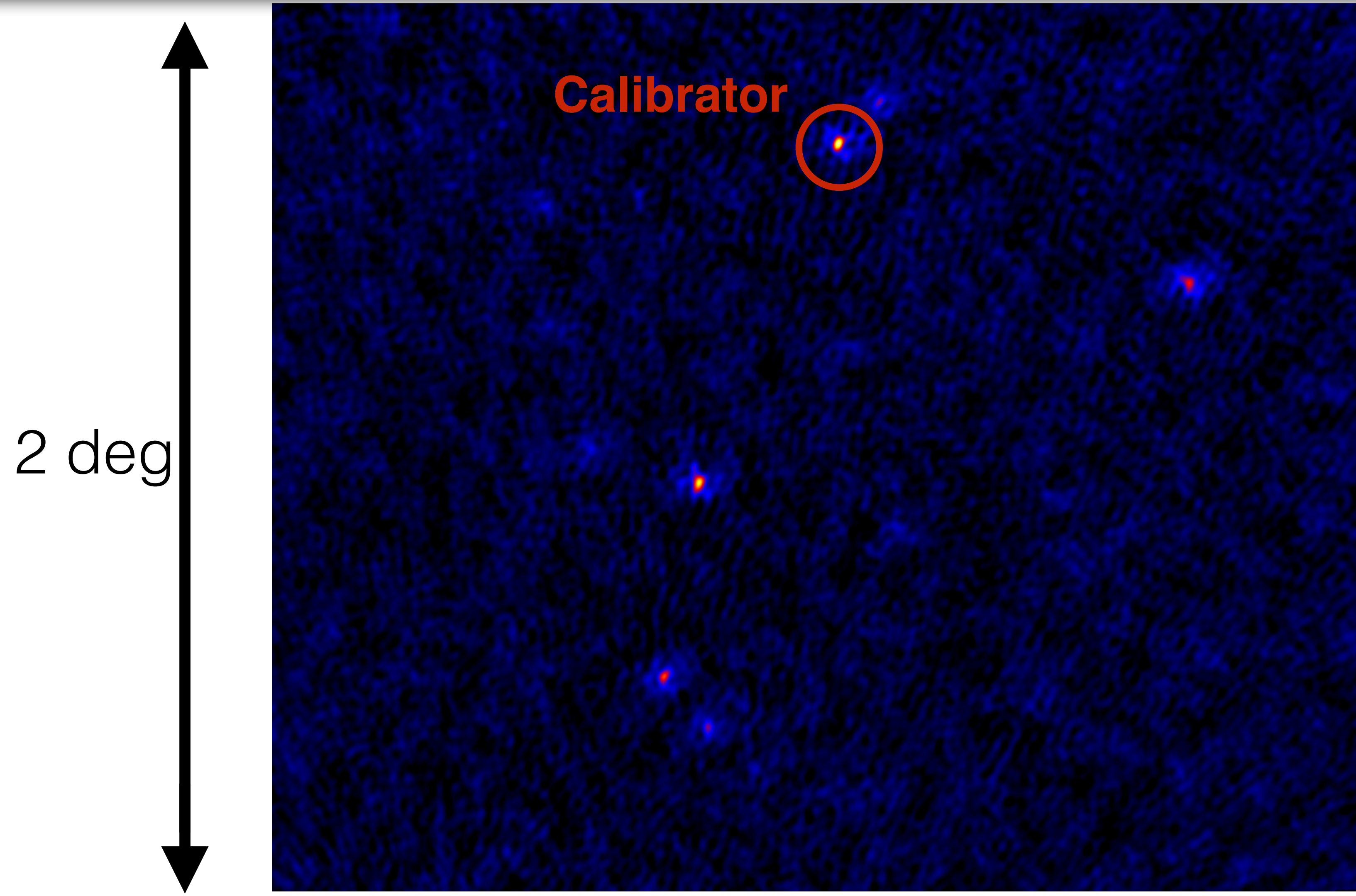
Source 2:

$$\phi_2^{\mathrm{cal}} = \phi^{\mathrm{instr}} + \phi_2^{\mathrm{ion}}$$

$$\phi_1^{\mathrm{cal}} - \phi_2^{\mathrm{cal}} = \cancel{\phi^{\mathrm{instr}}} + \phi_1^{\mathrm{ion}} - \cancel{\phi^{\mathrm{instr}}} - \phi_2^{\mathrm{ion}}$$

- Test with MSSS (MVF) LBA data: 8 2-MHz bands, 9 11-minute snapshots

dTEC fitting: 30 MHz Images



With phase screen
Without phase screen

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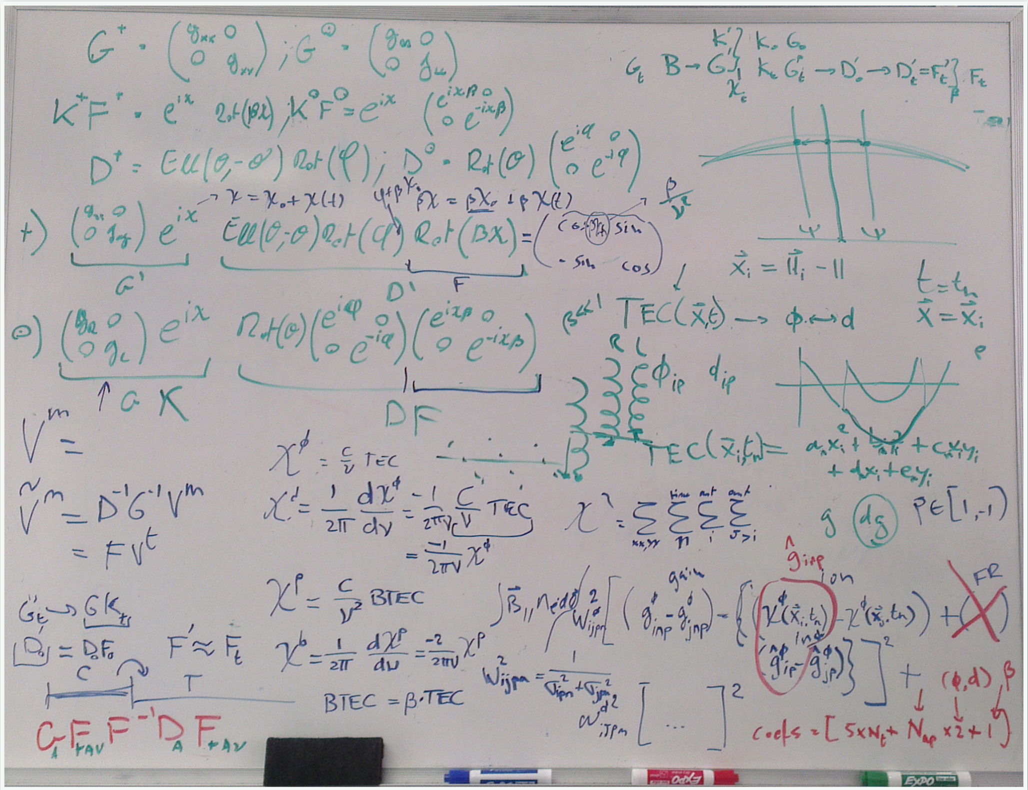
CASA low-freq pipeline:

- EVLA, GMRT, LOFAR…
- SPAM DD-calibration
- Polarization-friendly
- Wide-band



Ionosphere effect is:

- Time variable
- Spatially coherent
- Frequency dependent
- Polarization dependent

Instrumental effects are:

- Time constant
- Spatially incoherent
- Frequency independent
- Polarization dependent (different dependency of ionosphere)

CSPAM: linear polarisation

$$G = \begin{pmatrix} g_{xx} & 0 \\ 0 & g_{yy} \end{pmatrix}$$

Instrumental gain

$$KF = e^{i\chi} Rot(\beta\chi)$$

Ionosphere
(delay + Faraday rot.)

$$D = Ell(\theta, -\theta) Rot(\phi)$$

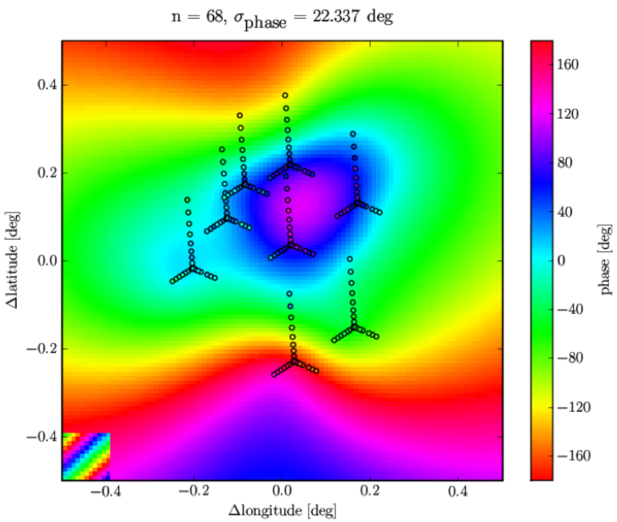
Leakage

Instrument

Ionosphere

$$\begin{pmatrix} g_{xx} & 0 \\ 0 & g_{yy} \end{pmatrix} e^{i\chi} Ell(\theta, -\theta) Rot(\phi) Rot(\beta\chi)$$

Separation



Ionosphere effect is:

- Time variable
- Spatially coherent
- Frequency dependent
- Polarisation dependent

Free parameters

Full calibration:

100 x 50 x 350 x 8 parameters = 14e6 (1 sol interval: cannot track ionosphere)

#directions

#stations

#SB

Full Jones

Extreme peeling:

Gain XX & YY

100 x 50 x [(3 x 60) + (35 x 4)] = 1.6e6 (60 sol intervals: track ionosphere)

#directions

#stations

Clock, TEC, StokesI-phase

10s solution intervals (=60 intervals in 5min)

35 groups of 10SB

TEC fitting:

5 x 60 + 1 = 301 (60 sol intervals: track ionosphere)

screen param

10s solution intervals (=60 intervals in 5min)

Magnetic field

LoSoTo

Lofar Solutions Tool

RESET
PLOT: 1D/2D/TEC
SMOOTH: multidimensional smoothing
CLIP
ABS: absolute value
FLAG
NORM: normalize solutions
INTERP: interpolate solutions along (even multiple) axis.
TECFIT: fit TEC values to phase solutions
TECSCREEN: fit TEC screens to TEC values
CLOCKTEC: clock/tec separation.
EXAMPLE

Python

Developers welcome!

https://github.com/revoltek/losoto

Check it in the LOFAR imaging cookbook!