Ionospheric calibration for radio interferometers

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SPAM

LOFAR HBA/LBA survey teams

SKA NL ionospheric calibration team Leiden

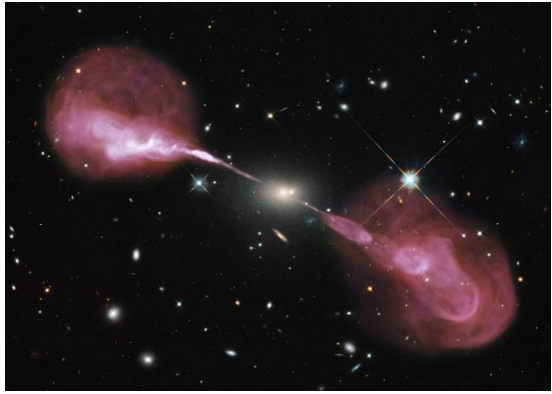
Universiteit Leiden
The Netherlands

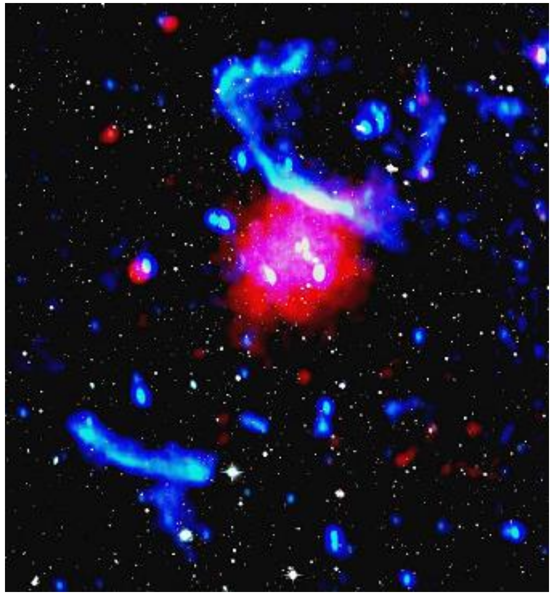
Talk outline

- Ionospheric effects on radio interferometry observations
- Ionospheric calibration
- SPAM calibration
- Summary

Scope

- The Universe is very transparent for long radio waves
- Rich tradition on surveying the sky at low radio frequencies
  - Cambridge catalogs (UK), NRAO surveys (USA), Westerbork (NL), Molonglo (AUS)
- The intrinsic large field-of-view provides a high survey speed
  - But the resolution is typically poor
- Renewed astronomical interest to survey the radio sky at sub-GHz frequencies
  - Higher resolution, better sensitivity, new technologies (LOFAR, SKA-low)
- Some main science drivers are
  - High-redshifted neutral hydrogen (Epoch-of-Reionization)
  - Pulsars and transients (GRBs, FRBs, GRWs, …)
  - Exo-planets
  - Galaxy cluster formation and evolution
  - Cosmic magnetism





Bonafede+ 2014

Why do we (need to) care about the ionosphere?

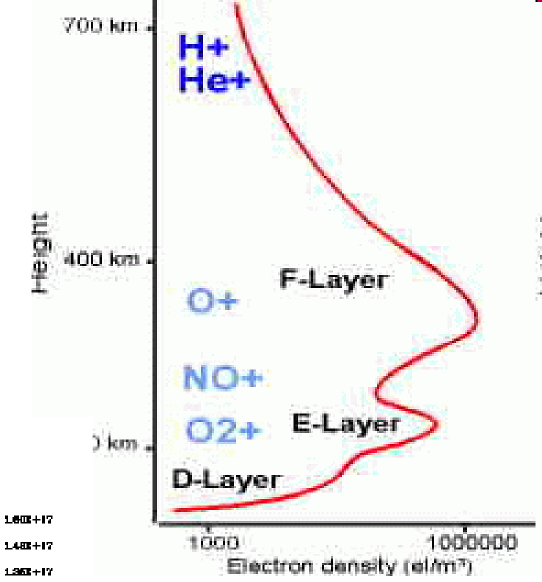
- Radio interferometers are extremely sensitive to ionospheric refractive effects
  1-2 orders of magnitude more than GPS

- Ionospheric effects are a major limiting issue for low-frequency telescopes like LOFAR
  Big nuisance for HBA observations, show-stopper for LBA observations
  International baseline decorrelation
  Polarization decorrelation

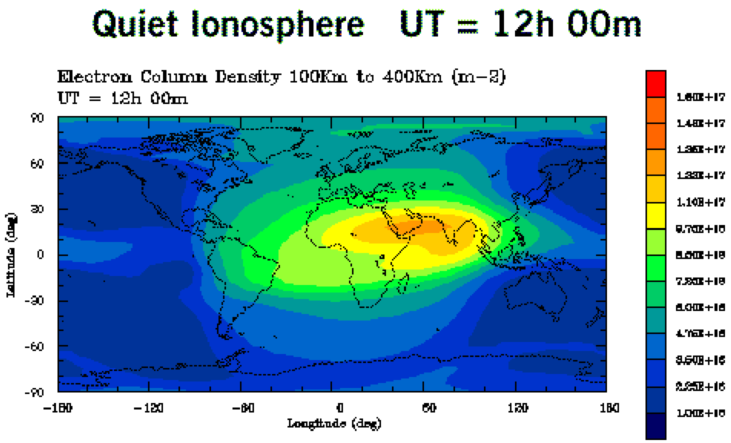
- Main driver behind development of direction-dependent (DD) calibration schemes
  sagecal, facet calibration / factor, Wirtinger / killms, field-based calibration, spam, etc.

- Allows for detailed modeling of the ionospheric
  Constrain the number of calibration parameters
  Benefit from the intrinsic coherence of ionospheric effects in space and time
  Enables detailed studies of ionosphere itself

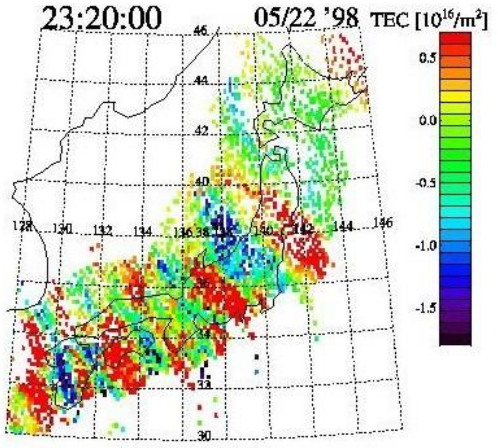
The simplistic ionosphere



- Partially ionized gas layer between ~50 and ~1000 km height, permeated by Earth's magnetic field
- Free electron density is variable in space and time
- Mainly ionized by Sun through UV and short X-ray (also solar wind, meteors, cosmic particles, lightning, …)
- Strong daily cycle, annual cycle, solar activity cycle
- Typical free electron column density at night is 10^{16} m^{-2} = 1 TECU

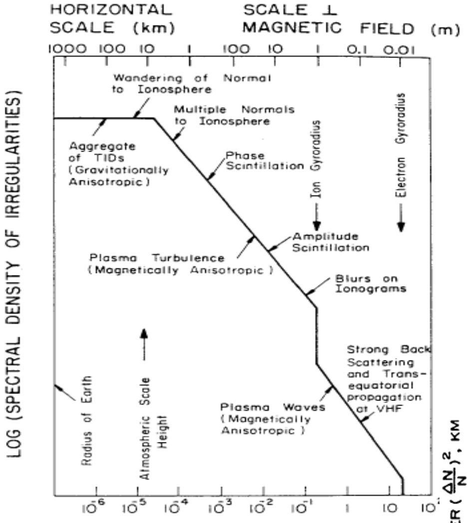


- Traveling Ionospheric Disturbances (TIDs): Coherent density waves, 200-400 km height, 300-700 km/h, 1-5 percent TEC variations
- Small-scale fluctuations (down to few km), up to 0.1 percent TEC variations on minute time scales

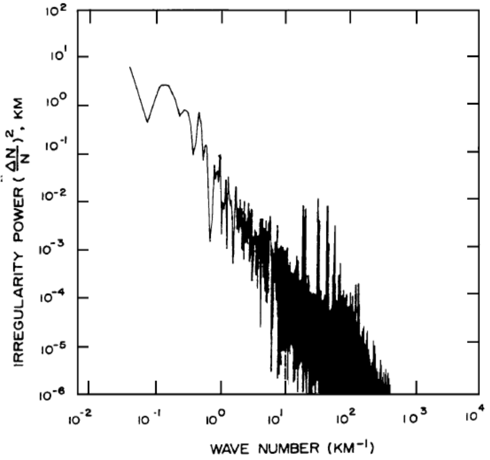


Small-scale fluctuations

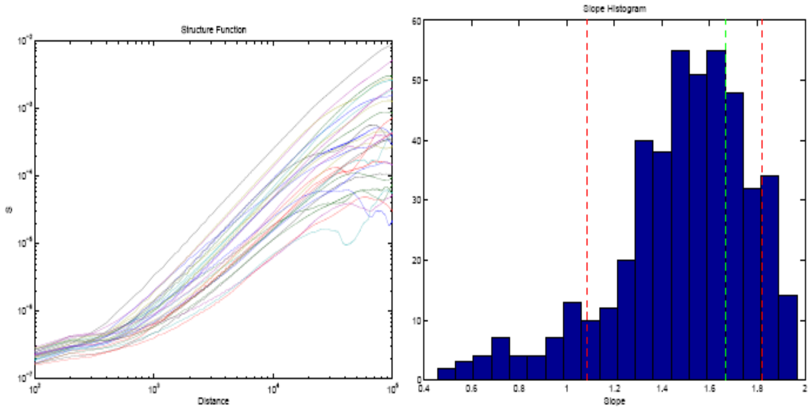
- Physics behind smaller scale fluctuations less well understood
- “Waves” may be highly dispersive and not restricted to a single height
- Temporal and spatial behaviour may be coupled through quasi-frozen patterns (e.g., Jacobson & Erickson 1992)
- Statistical behaviour suggests the presence of a turbulent medium with a power-law spectral density of electron density fluctuations
- Kolmogorov-type structure function $D_\phi(r) = \left\langle \left[\phi(\vec{x}) - \phi(\vec{x}+\vec{r})\right]^2 \right\rangle \propto \left(|\vec{r}|/r_0\right)^\gamma$
- Satellite measurements show a range of best fitted values for γ and r_0



Booker 1956



Kelley 1980



van der Tol 2007

Radio wave propagation through the ionosphere

- Dispersive delay due to free electron column density (TEC)

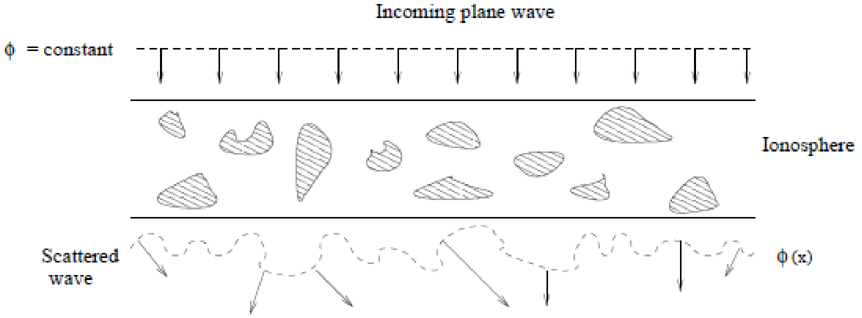
$$\phi = \frac{e^2}{4\pi\varepsilon_0 m}\lambda\int_0^d n_e(s)\,ds$$

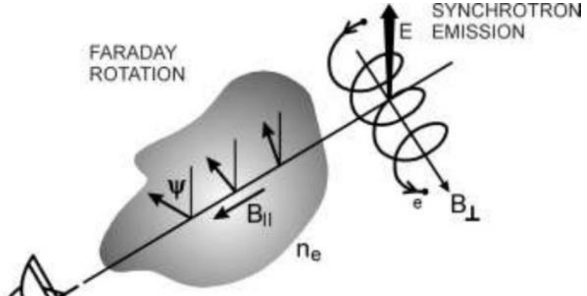
- Faraday rotation (birefringence) β due to TEC and Earth's magnetic field B

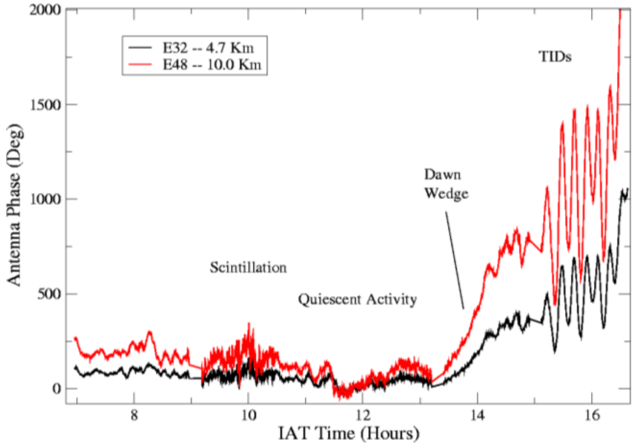
$$\beta = \mathrm{RM}\lambda^2 \qquad \mathrm{RM} = \frac{e^3}{8\pi^2\varepsilon_0 m^2 c^3}\int_0^d n_e(s)B_{||}(s)\,\mathrm{d}s$$

- Dispersive (phase) delay depends on differential TEC
  - 1 radian per 0.01 TECU at 75 MHz
- Faraday rotation depends on absolute [TEC times $B_{||}$]

- Both effects vary with time, location and viewing direction

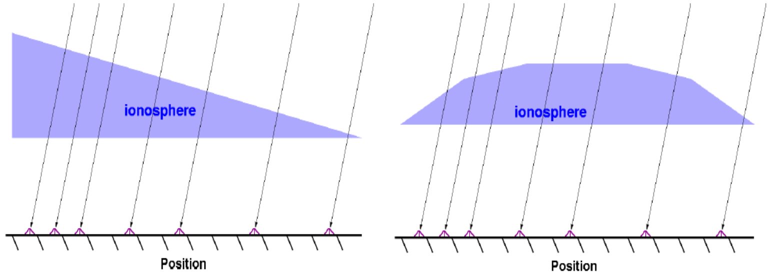






Ionospheric phase distortions

- The interferometer measures phase differences, therefore senses the differential structure in the electron column density (TEC)

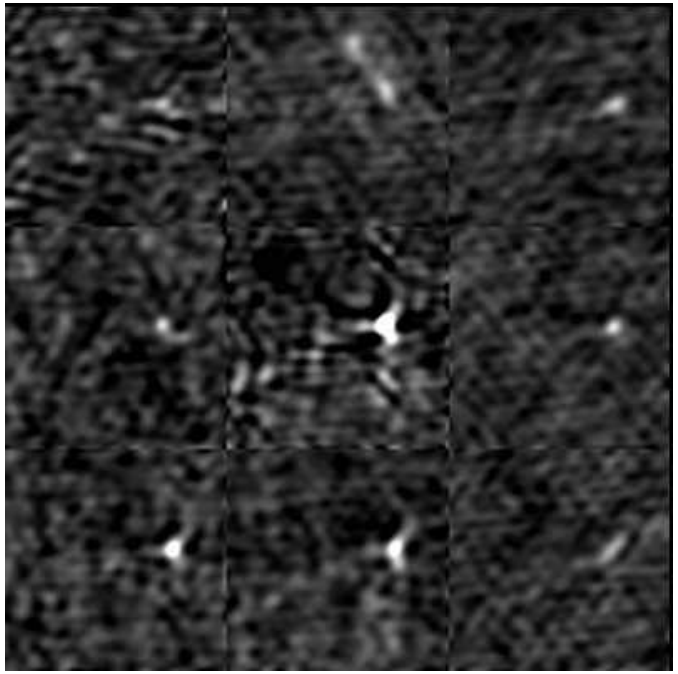


- TEC gradients cause apparent source shifts
- Higher TEC structures cause source distortions

- TEC structure varies with time and direction

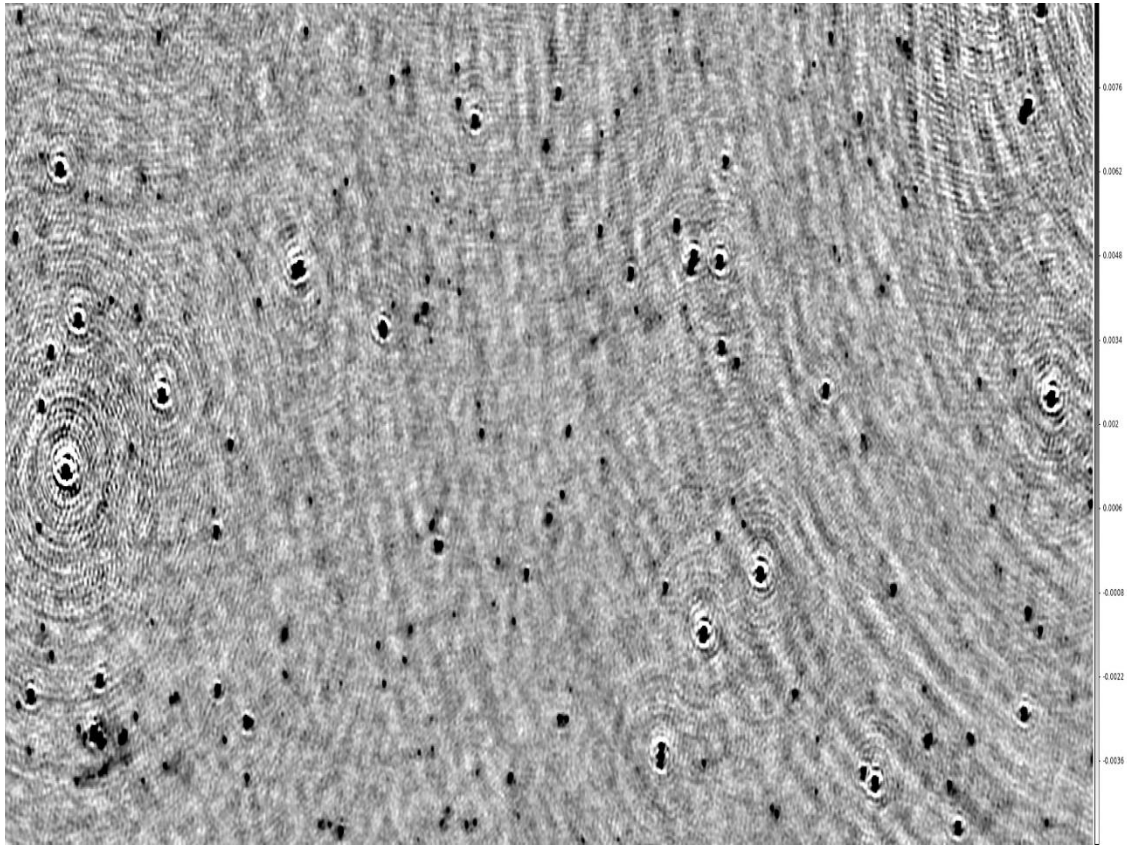
- Time series of 1-minute snapshot images of 9 sources distributed over a single 10-degree field-of-view of the VLA at 74 MHz

(movie created by Bill Cotton)



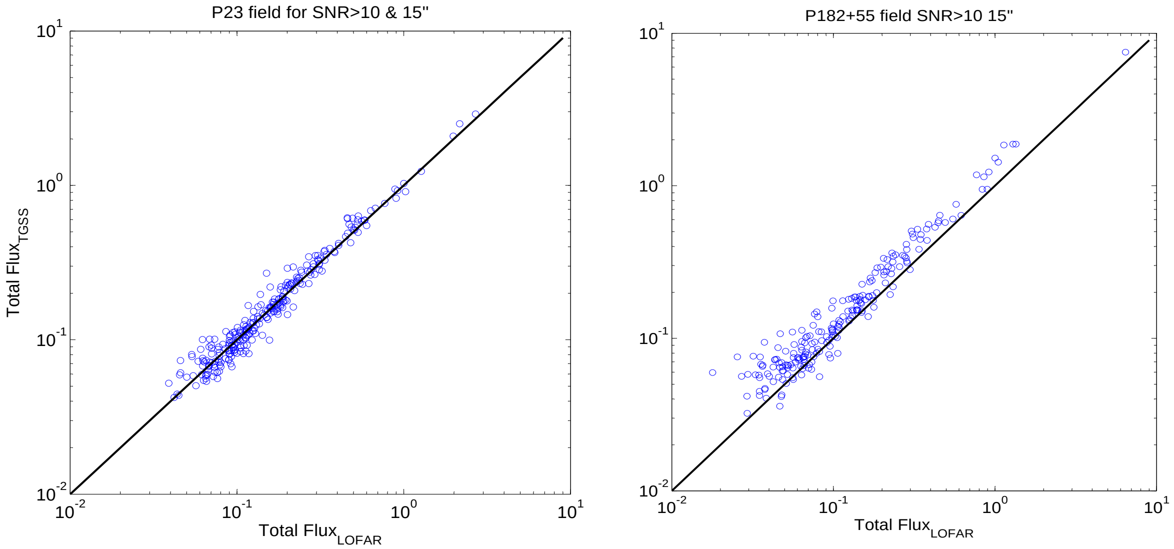
Ionospheric effects on radio data

- Time-averaged phase effects cause source smearing, which leads to limitations in the contrast and fidelity of the resulting image.
- It also causes astrometric errors and loss of flux density.



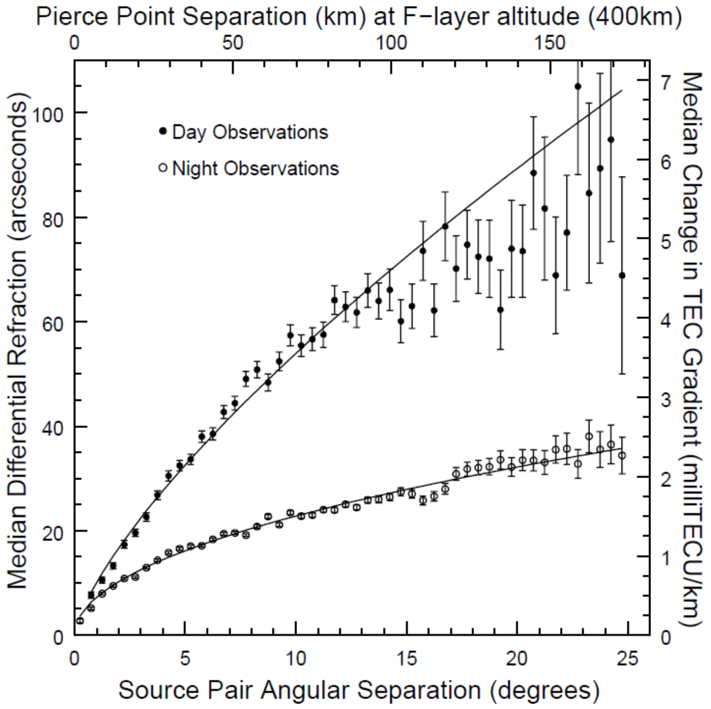
LOFAR HBA image of the Lockman Hole with application of direction-independent corrections

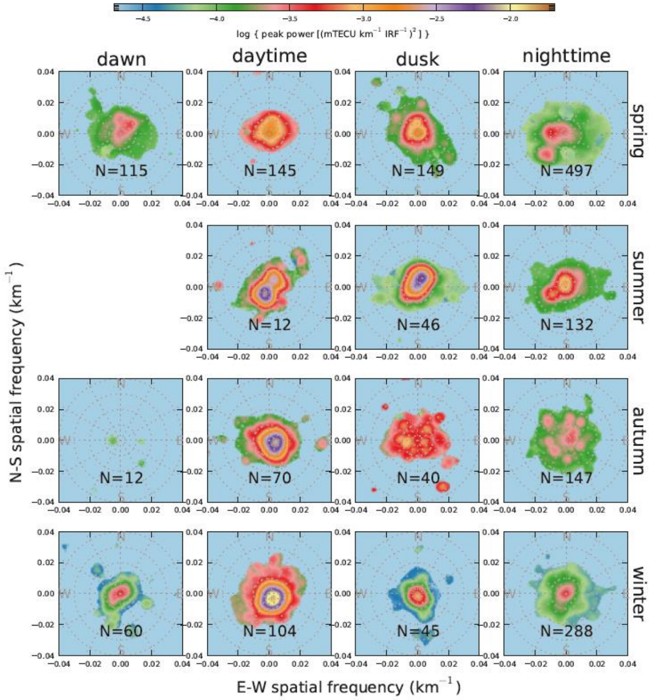
Flux density comparison between LOFAR HBA and TGSS under mild (left) and active (right) ionospheric conditions



Analysis of source shifts across space & time

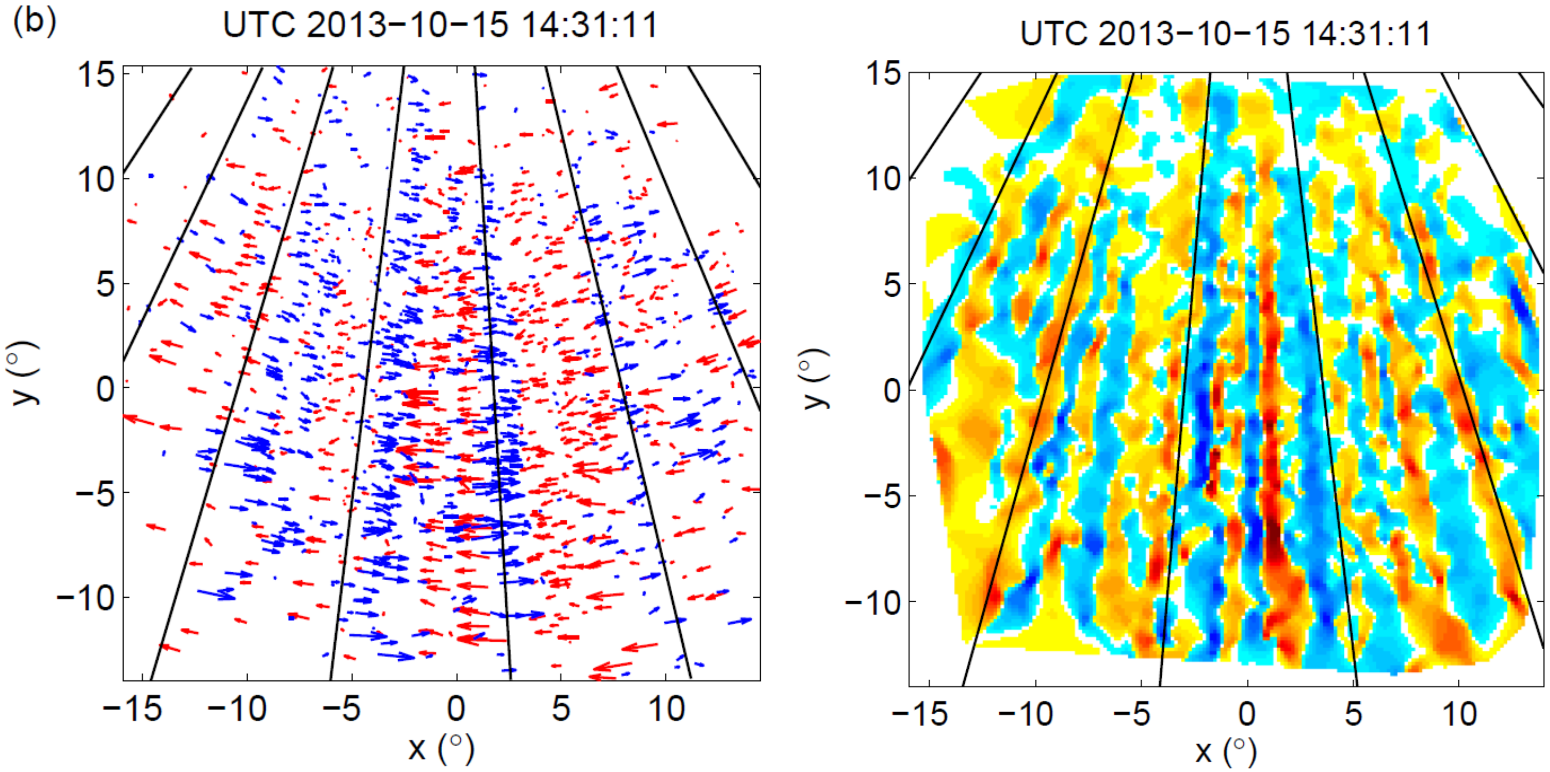
- Regime 3 low-frequency radio observations allow for analysis of local ionospheric gradients through source shifts
- For example, systematic study of differential source shifts by Cohen & Rottgering (2009) using the full VLSS survey (500+ fields at 74 MHz, 80” resolution, 10-15 degree field-of-view)
  - Allows for statistical study during many different conditions, times-of-day/year, etc.
- Helmboldt et al. (2012) performed a spectral analysis to calibration products from the same data
- This and similar studies using VLA are now published regularly in geophysical journals

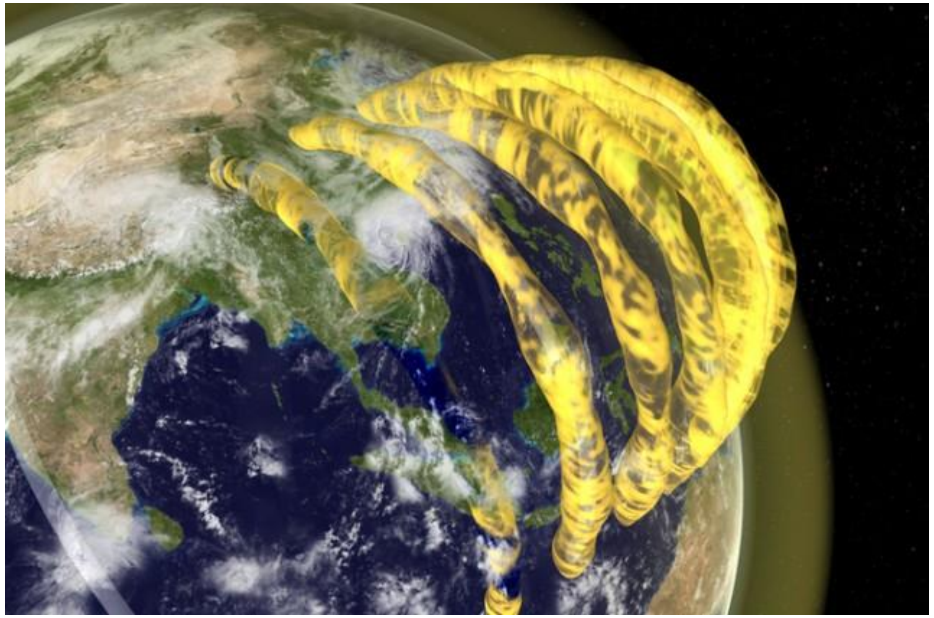




MWA detection of ionospheric plasma tubes

- Source position shifts measured across large sky area are found to organize along local magnetic field lines
- Infers the presence of theoretically predicted plasma tubes
- Similar result found by M. Mevius using LOFAR data

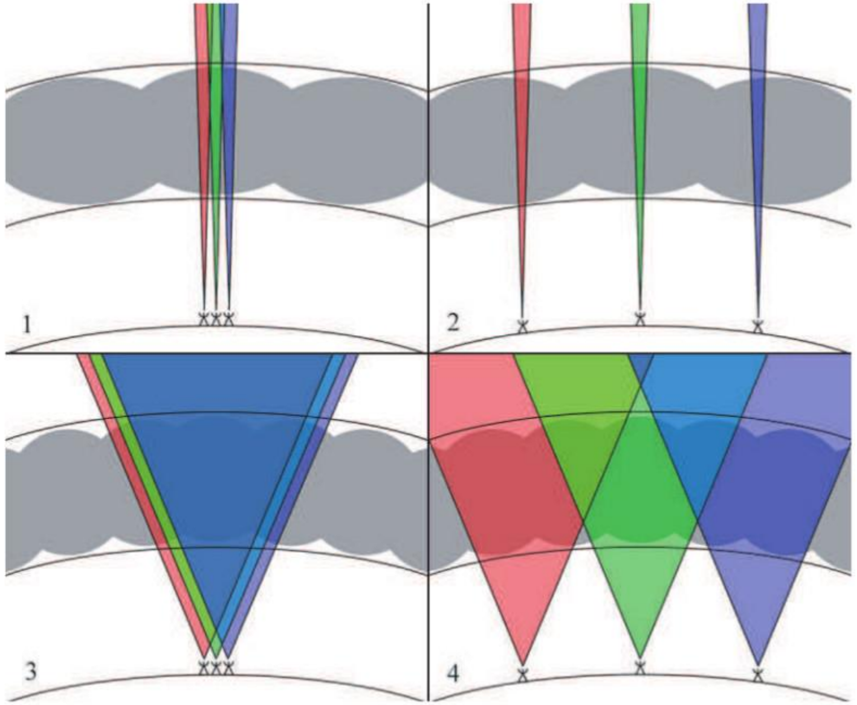




Loi et al. (2015)

Ionospheric phase calibration

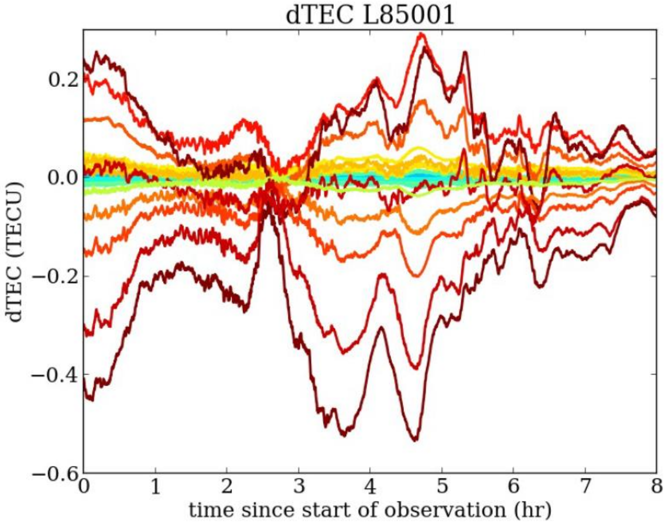
- Visibilities as measured by the interferometer contain contributions from the sky intensity from all visible directions, modulated with the antenna/station beam patterns
- Measured visibilities are corrupted by (mostly) antenna-based gains that can depend on time, frequency, polarization, antenna positions and viewing direction
- Direction-dependent gain corrections cannot be applied upfront, but have to be applied on-the-fly during imaging
- The required calibration strategy depends on the array size, field-of-view and TEC structure
  - Self-calibration is only valid in regimes 1 & 2
  - Regimes 3 & 4 require direction-dependent (DD) phase corrections



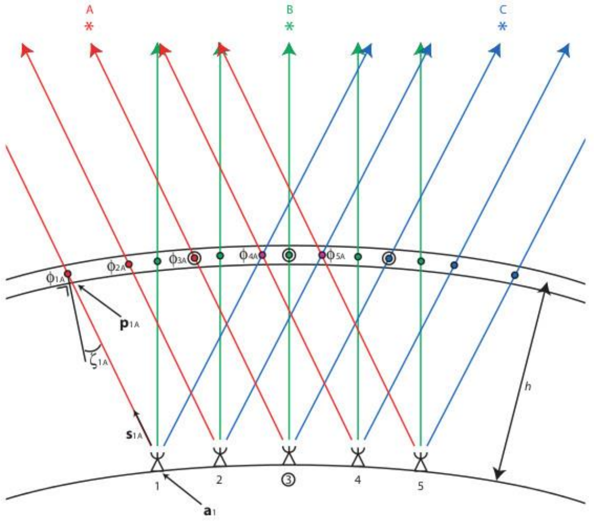
(after Lonsdale 2005)

Analysis of calibration results

- Time series of calibration gain phases / delays represent measurements of integrated electron densities (and magnetic field) at high precision (mTECU)
- Analysis of these phases resulted in various publications (e.g., Helmboldt+ 2010, 2012, 2014 using VLA)
- Huge potential using LOFAR data
  Gain phases are by-product of all types of processing
  (but needs separation between TEC and instrumental clock drift)

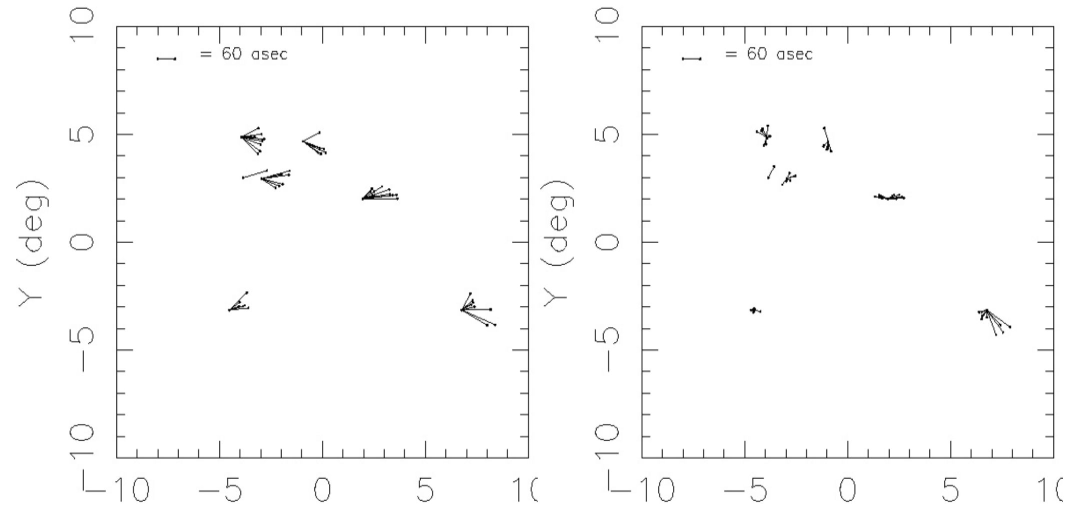


- Multi-directional calibration produces many instantaneous dTEC measurements, proportional to $N_{antennas} \, x \, N_{directions}$
- Can be modeled on some common domain (e.g., dTEC screen)
- More flexibility in calibration when incorporating multi-beam and/or combined LBA-HBA in observations



Ionospheric calibration methods

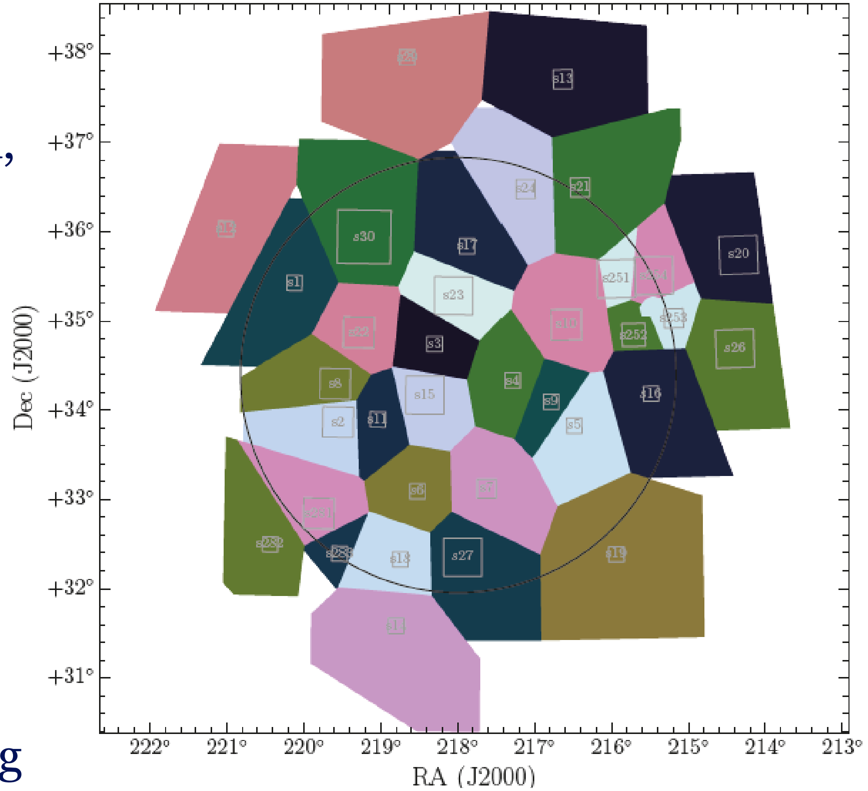
- Calibration schemes including ionosphere models are rare
- Field-based calibration (Cotton+ 2004),
  - Tracks apparent movement of multiple radio sources, fits de-distorting Zernike screen
- SPAM method (Intema+ 2009)
  - Multi-directional phase calibration, fits turbulent multi-layer phase screen
- Other DD calibration schemes exist, but without constraint on the ionosphere
  - E.g., facet-calibration (van Weeren+ 2015), SAGECal (Yattawata+ 2008, arXiv:0810.5751)



field-based calibration
(Cotton+ 2004)

Why use an ionosphere model?

- Current LOFAR HBA calibration schemes already deal with DD effects Sagecal, extreme peeling, FACTOR, KillMS …
- But the physical connection between the calibration parameters is ignored, which leads to over-fitting of the data
- Naively: $N_{meas} \propto N_{ant}^2 N_p N_f N_t, \quad N_{cal} \propto N_{ant} N_d N_p N_f N_t$
- Minimum requirement: $N_{cal} \ll N_{vis} \rightarrow N_d \ll N_{ant}$
- A parabola can be sampled with 1 million noisy measurements, but that doesn't allow for the fitting of 1 thousand parameters to it
- Will lead to inaccuracies in the image reconstruction
- Degrees of freedom in corrupted visibility data are difficult to quantify
- Best practice: try to minimize the number of fitted parameters by modeling the ionosphere (and other DD effects) with a suitable model
- But also: increase S/N of calibration by combining visibilities, improve accuracy (and continuity) in space, time, frequency,



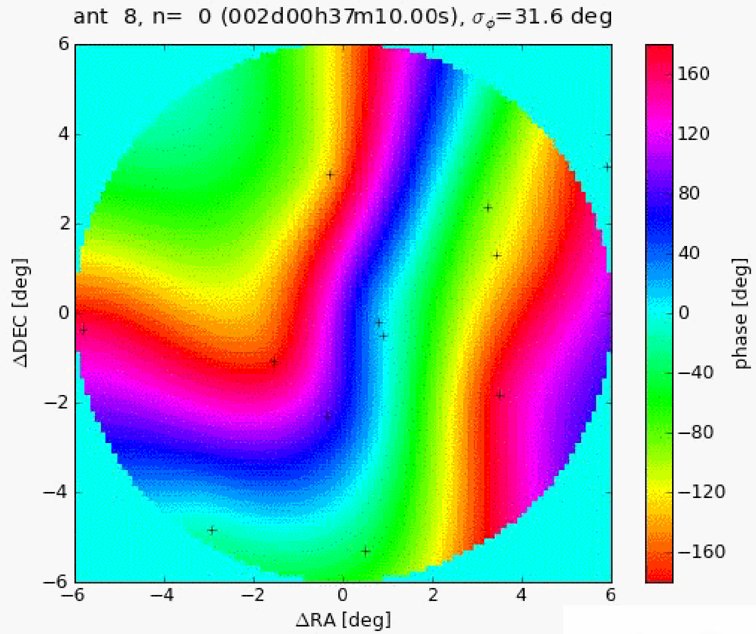
LOFAR facet calibration
van Weeren+ 2016

Source Peeling & Atmospheric Modeling

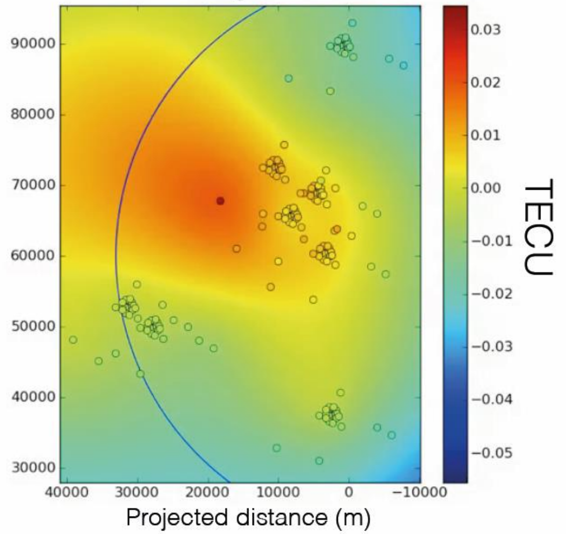
Sterrewacht Leiden

SPAM core functionality

- A measurement of the local ionospheric TEC structure is obtained by phase calibrating on bright sources within the field-of-view (e.g., peeling)
- The measured phases of all source-antenna pairs can be mapped onto ionospheric layer
- All phases per time interval are fitted with a single model (based on thesis work by van der Tol, 2009)
- Model predicts phases corrections in arbitrary directions for imaging full field-of-view
- Example time series of a dual-layer phase screen model for narrow-band VLA 74 MHz observation
  - Phase screens fitted each 10 sec to peeling phases of ~10 sources
- First steps towards dTEC screen fitting on LOFAR data



Intema+ 2009

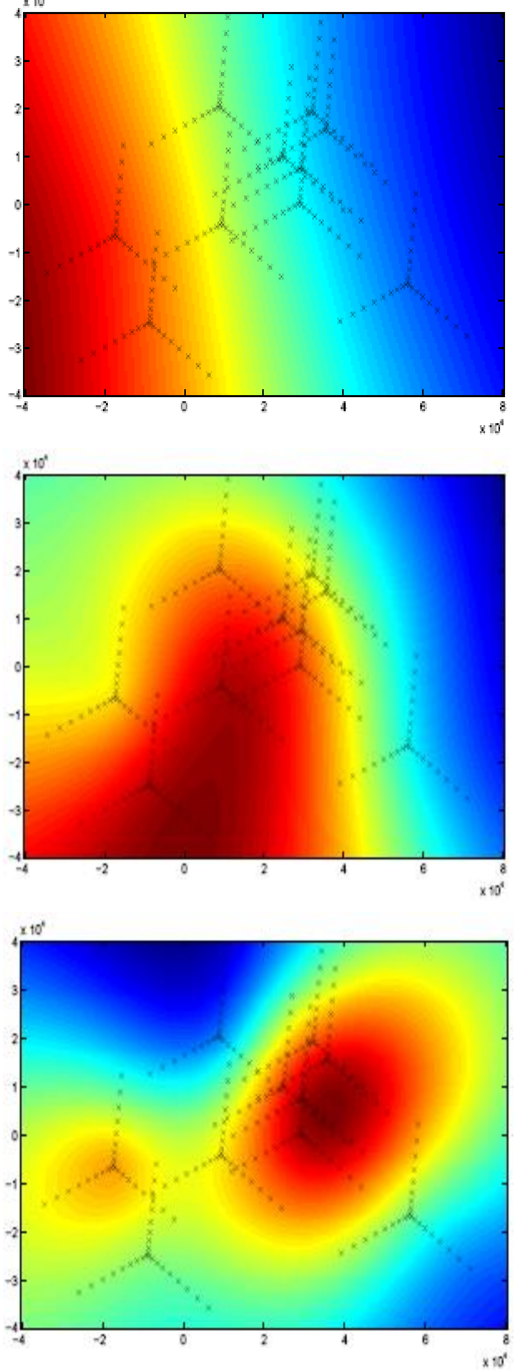


Rafferty / Mevius

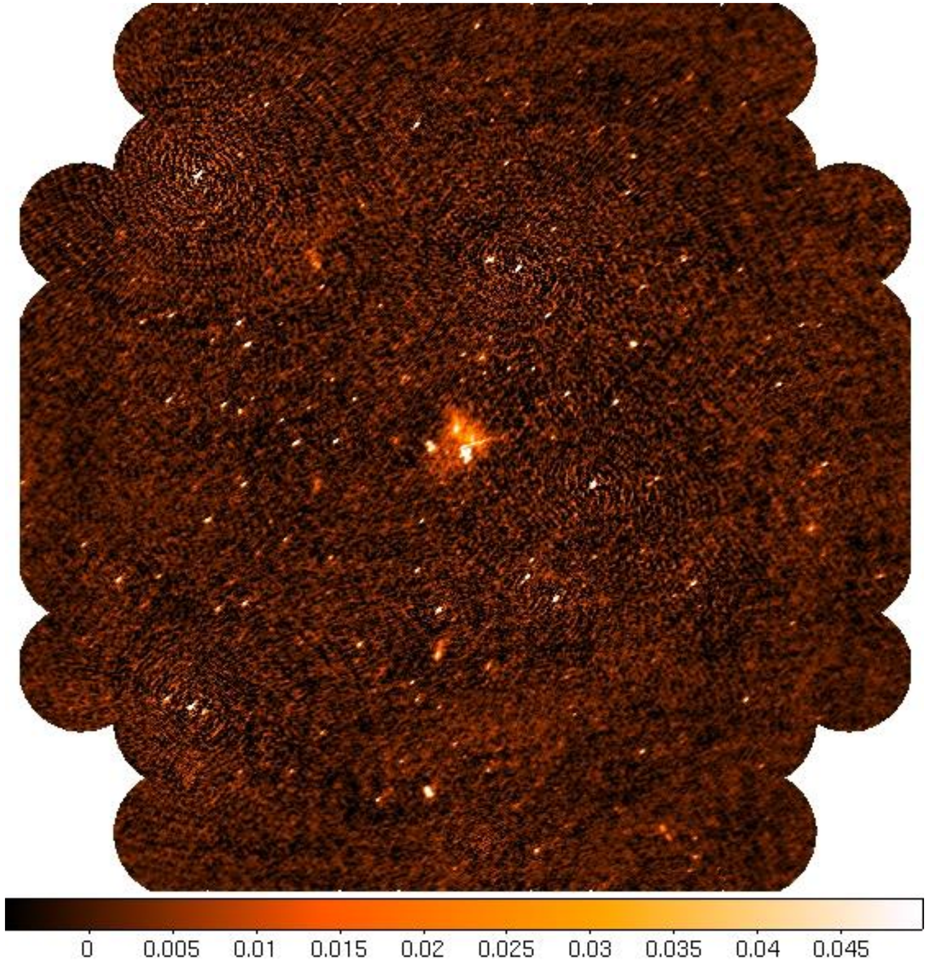
SPAM ionosphere model

- Independent phase screen per time stamp
- Optimized set of Karhunen-Loeve base “functions” (using Kriging for interpolating between IPPs)
- Model has most structure near pierce points
- Model obeys the imposed statistical behaviour
- Model converges to zero at infinite distance
- Reduction of model order gives minimal loss of accuracy

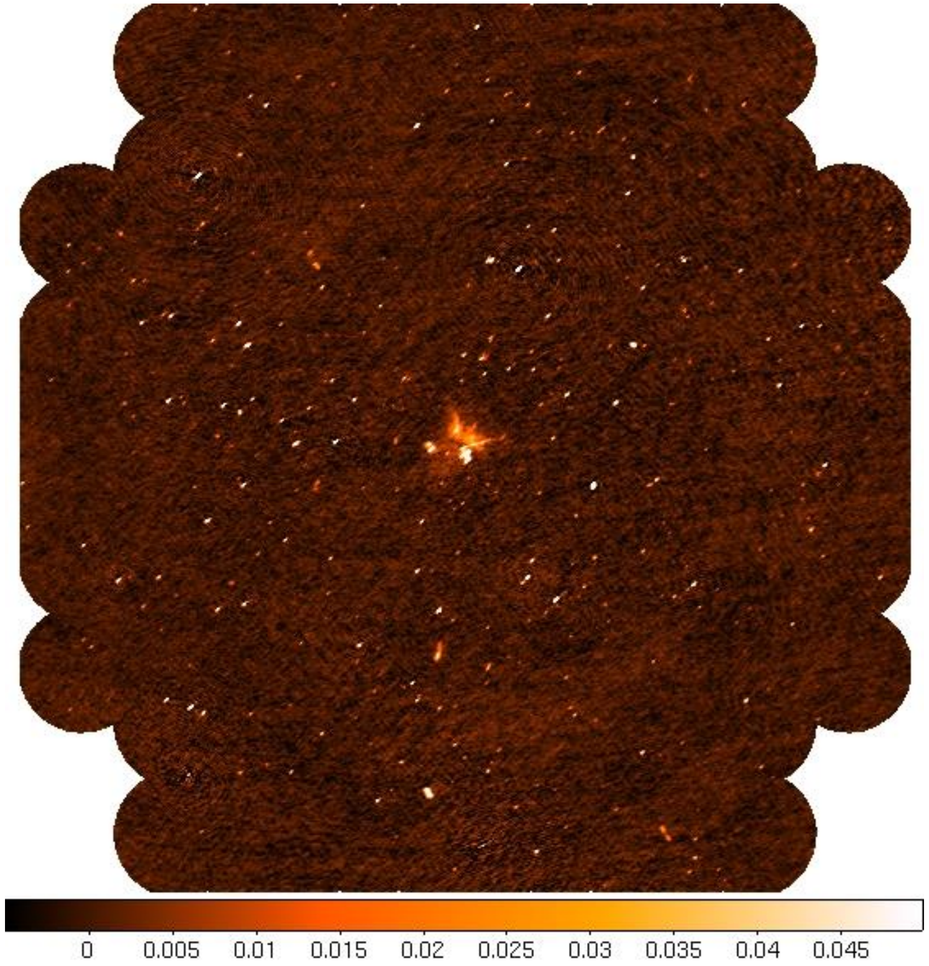
- Model fitting is sometimes troubled by 2π phase ambiguities
- Initial guess from overall gradient fit greatly helps to overcome this
- Multi-layer model is implemented



Example SPAM application



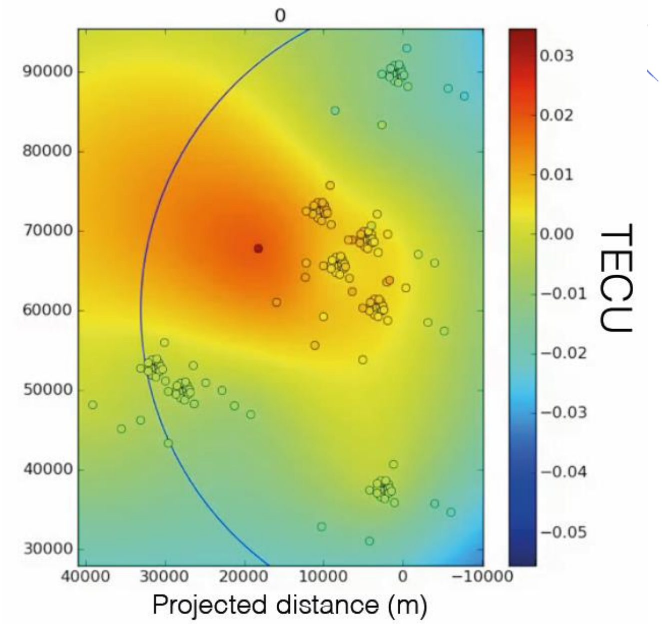
Self-calibration result on Abell 2256
GMRT 150 MHz

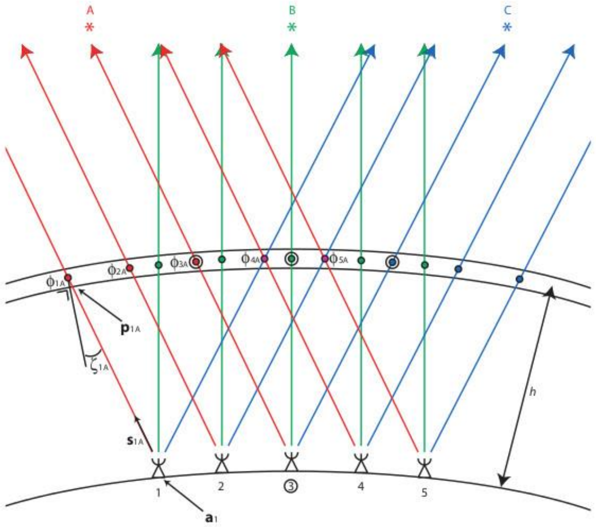


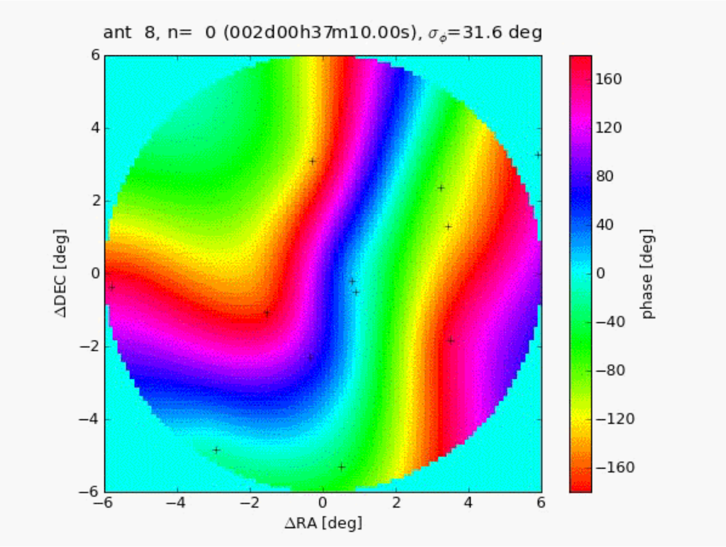
SPAM result on Abell 2256
GMRT 150 MHz

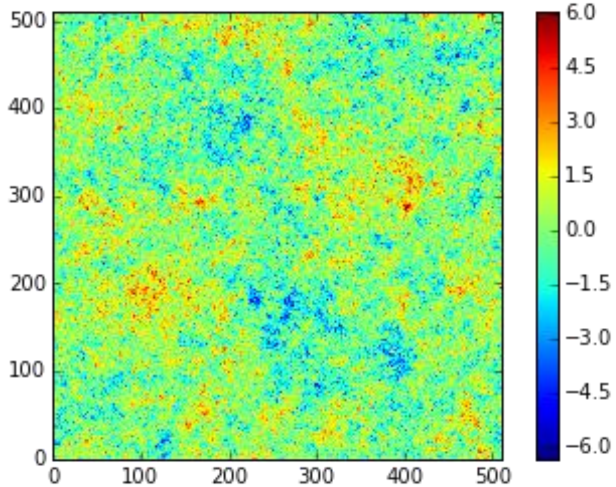
Current activities

- Initial steps in expanding existing SPAM ionospheric calibration scheme
  - Apply single-/multi-layer SPAM model fitting on LOFAR HBA dTEC data
  - Extend SPAM model fitting using time coherence (multi-dimensional SVD)
  - Migration of SPAM pipeline to CASA to support wide-bandwidth calibration and imaging for other SKA pathfinder telescopes (JVLA-lowband, uGMRT)
- Initial steps in modeling effects of ionospheric effects on visibilities
  - Adoption of optical AO methods under investigation









Summary

- All high-fidelity radio interferometric images at low frequencies require ionospheric corrections
- Calibration challenge is most severe for lowest frequencies and longest baselines (= ILT)
- Radio interferometers provide ionospheric measurements at unprecedented accuracy and resolution
- Both size of the array and size of the field-of-view can be utilized for measuring the ionosphere
- A close collaboration between radio astronomy and ionospheric physics is inevitable