SPAM
10 years of ionospheric calibration

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22-6-2017

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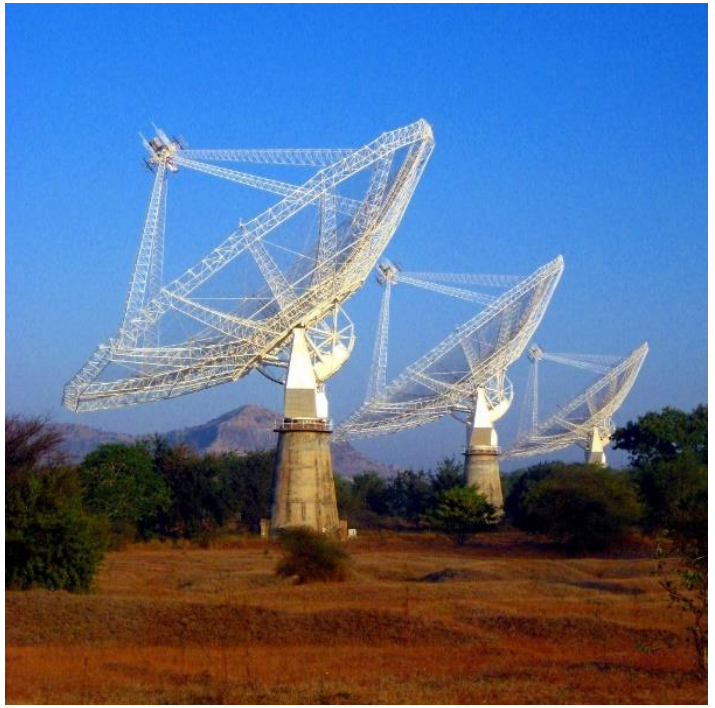
Overview

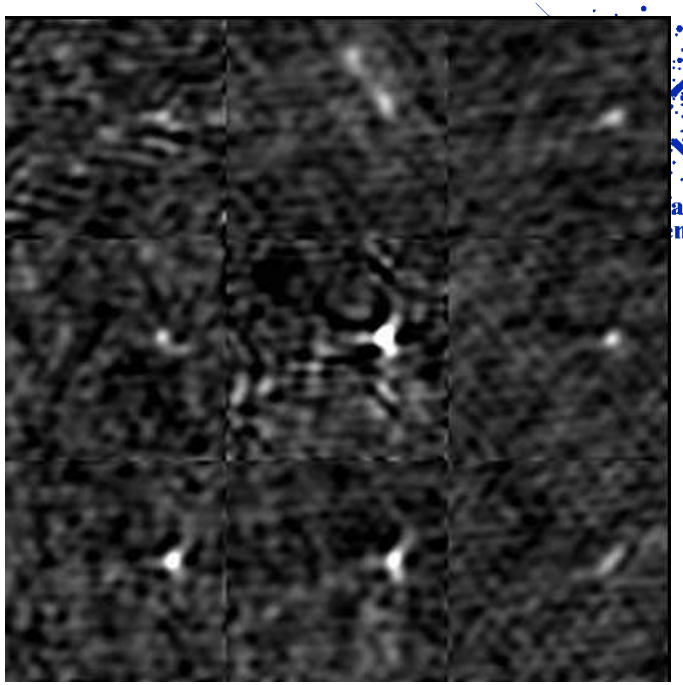
- Introduction to SPAM ionospheric calibration
- Applications of SPAM
- Links to current DD developments
- Future plans for SPAM



Giant Metrewave Radio Telescope

SPAM

VLA@74 MHz, 10sec frames
(B. Cotton, NRAO)

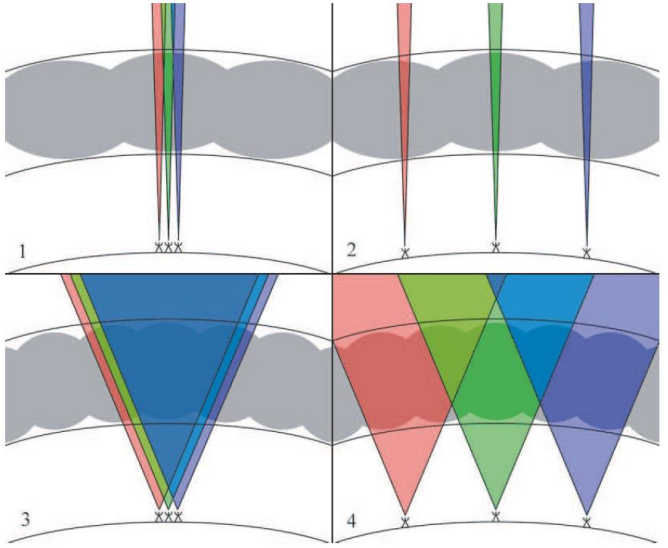


Ionospheric effects on radio interferometry

- Partially ionized medium with density fluctuations that can vary strongly with time and position
- Ionospheric phase delay ($\Delta\phi \propto \mathrm{TEC}/\nu$) is cumulative along the ray path and depends on the total electron column density (TEC) and the wavelength
- LF radio interferometer mostly sensitive to ΔTEC, causing source distortions that vary per antenna as a function of time and viewing direction

Source Peeling and Atmospheric Modeling (Intema+ 2009)

- Among the first (implemented!) calibration strategies to address direction-dependent ionospheric effects on LF radio observations
- Designed to calibrate phase delays, the main issue below ~500 MHz
- Designed to work with larger arrays (>few km), where phase structure is no longer linear over the array
- Makes use of a simple model to describe / constrain the spatial variation of ionospheric phase delay



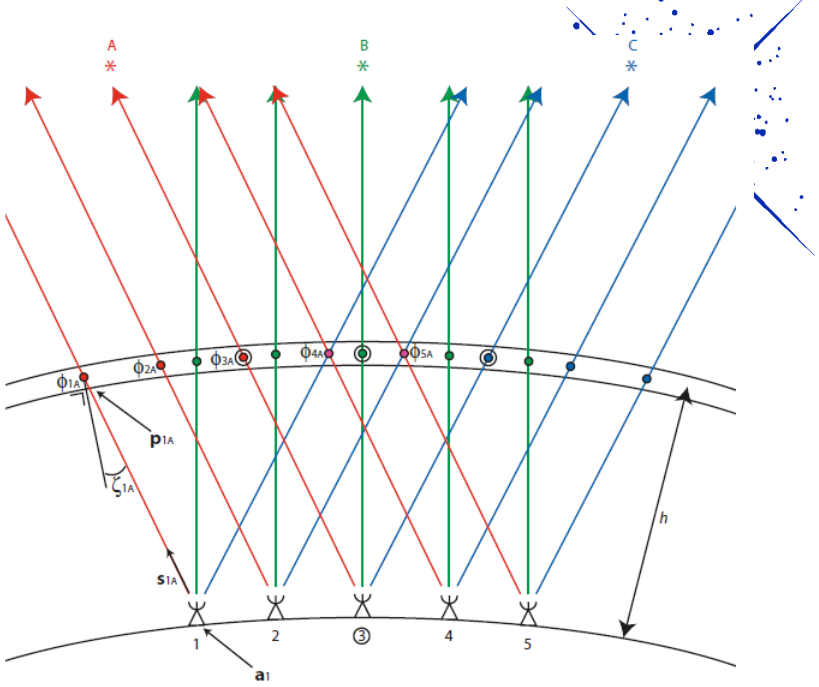
SPAM model

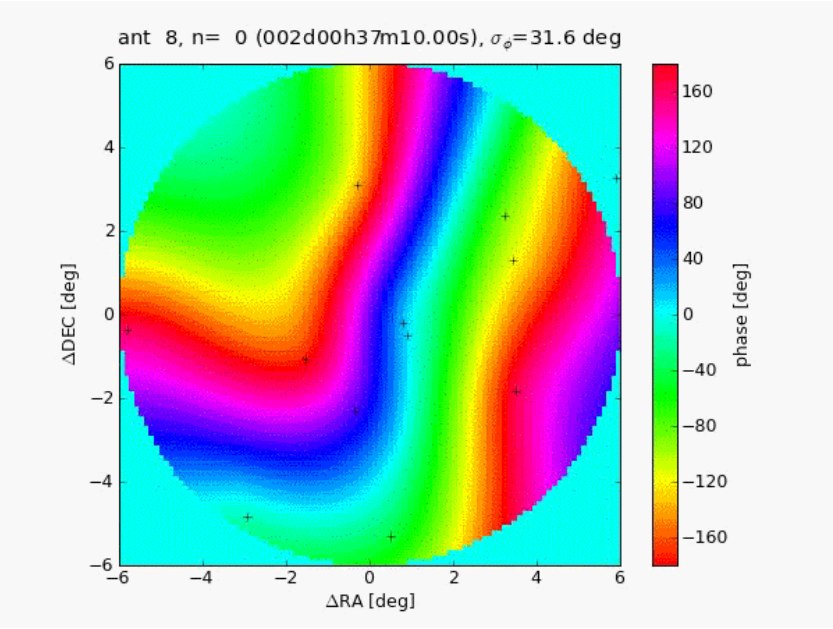
Calibration and imaging loop

- Iteratively, phase calibration(*) on bright in-beam sources yields measures of ionospheric phase delay in 10-20 viewing directions
- Every 10-20 seconds, the measured phases along all lines-of-sight are mapped onto the pierce points of a single virtual ionospheric layer
  - Modeling the 3D ionosphere with a screen may be valid if the dominant ΔTEC contributions are located in a relatively small height range
- The phases are fitted with a screen model using a specialized set of base functions (van der Tol, 2009) assuming Kolmogorov turbulence
- During imaging of the full field-of-view, the model is used to predict phase corrections in arbitrary directions
- Like self-calibration, these steps can be repeated to improve the result

(*) Needs an accurate reference model of the radio sky!

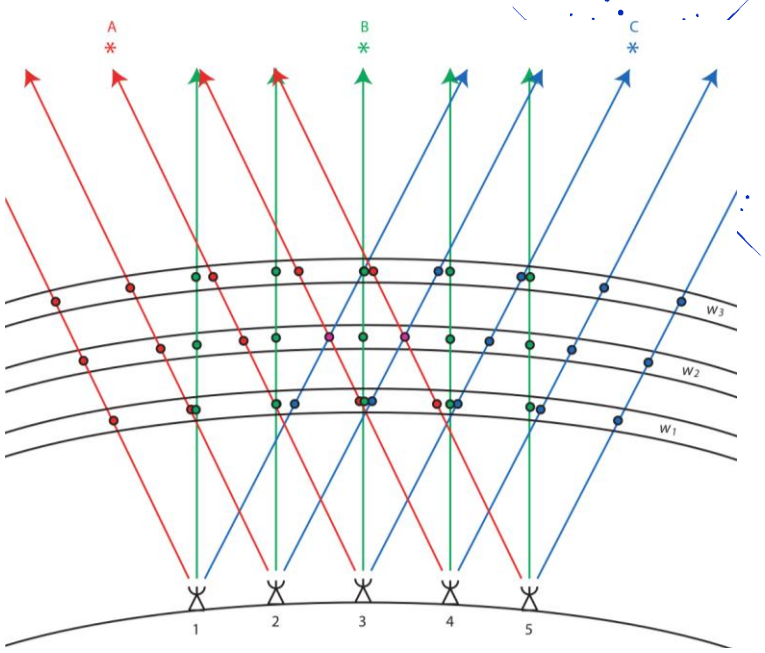
- Can be derived from NVSS, FIRST, WENSS, SUMSS, TGSS, etc.

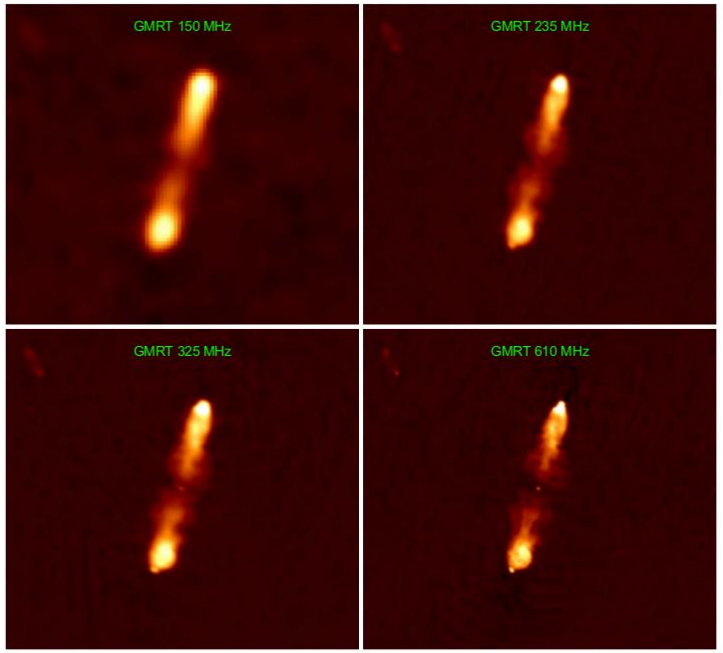




SPAM implementation

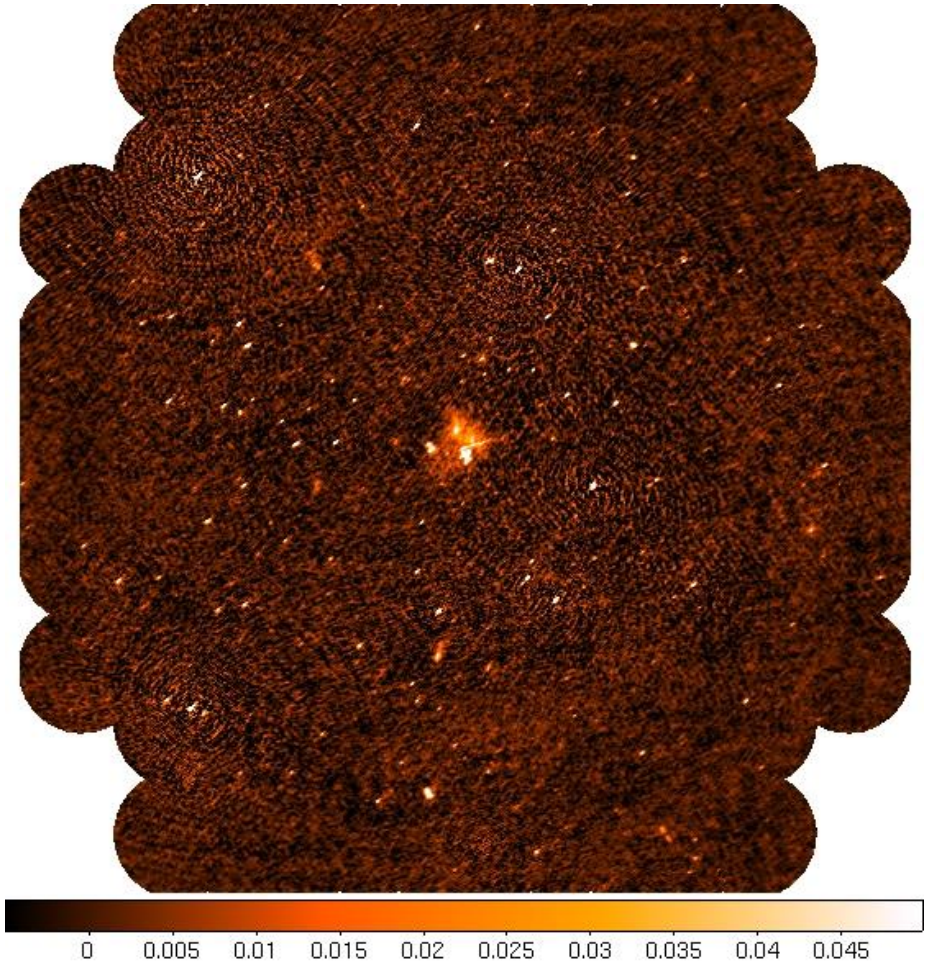
- Python/C implementation based on AIPS functionality accessed through ParselTongue interface (Kettenis+ 2006)
  - Limited support for wide-band and polarization observations
- A multi-layer model is available to better represent the 3D ionosphere
- Integrated into robust, end-to-end data processing pipeline for GMRT (and VLA) low-frequency observations, producing (near-) science-ready data products that rival manual efforts
- Pipeline has been successfully applied to 100's of GMRT observations
- Pipeline is freely available online and has a small but increasing user group (currently 20-30 known users) (http://www.intema.nl/doku.php?id=huibintemaspam)



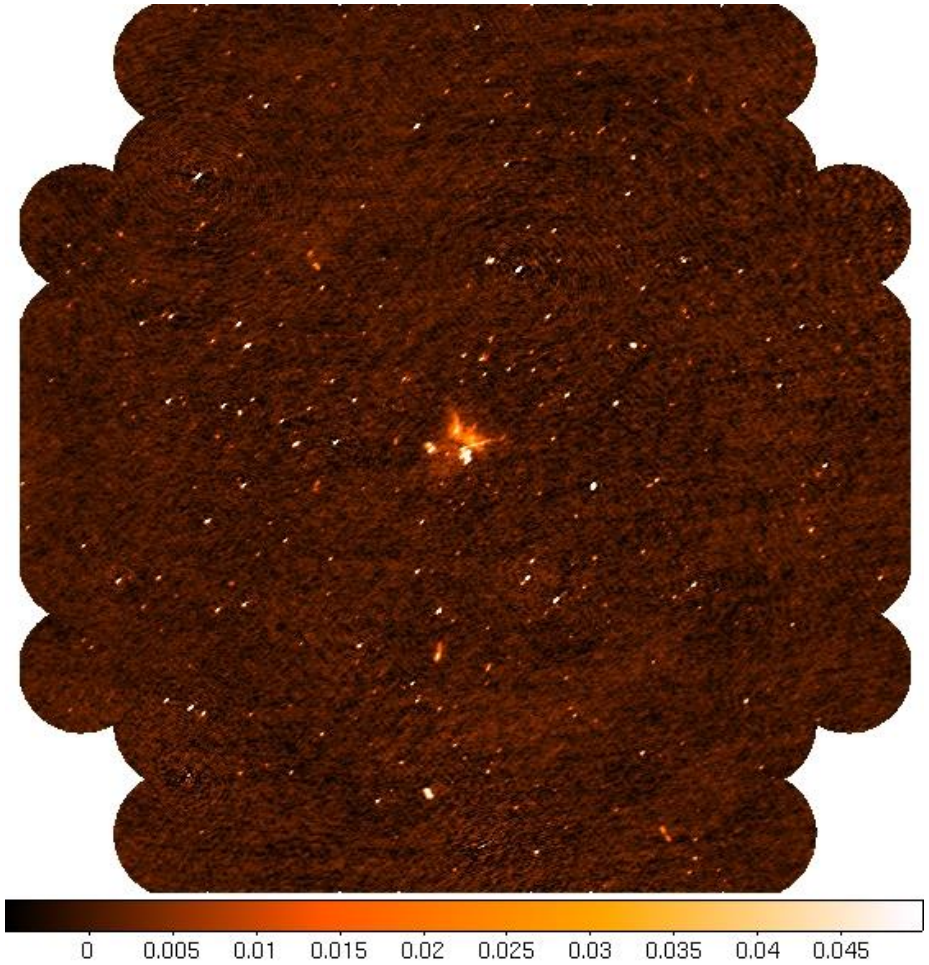


SPAM example: 3C 223 (Harwood+ 2016)

Archetype SPAM application

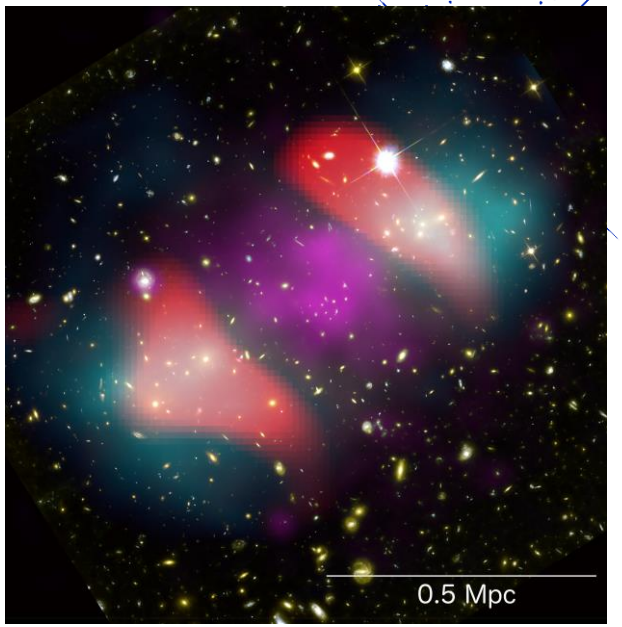


Self-calibration result on Abell 2256
GMRT 150 MHz



SPAM result on Abell 2256
GMRT 150 MHz

Recent SPAM applications

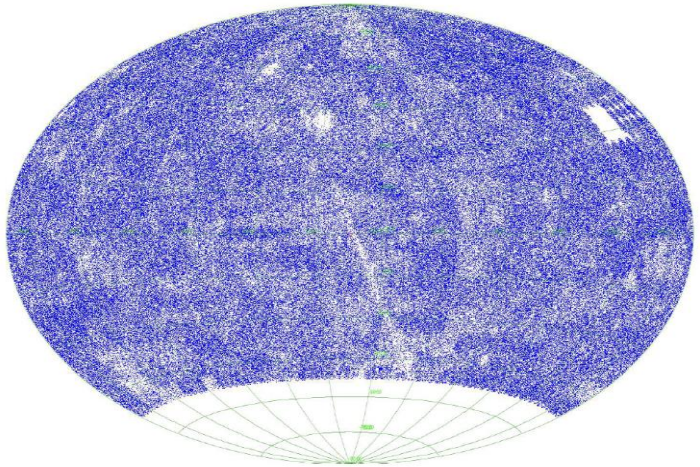


Galaxy cluster MACS J0025.4-1222
Riseley+ (2017)

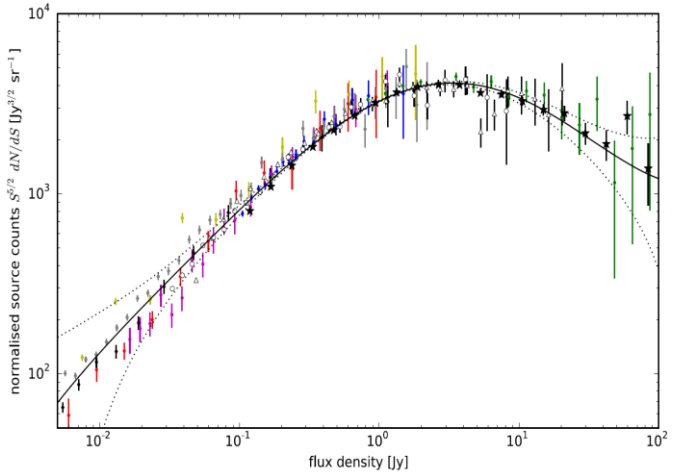
- *Multifrequency study of a new Hybrid Morphology Radio Source*, de Gasperin 2017
- *Mpc-scale diffuse radio emission in two massive cool-core clusters*, Sommer+ 2017
- *The GMRT 150 MHz All-sky Radio Survey: TGSS ADR1*, Intema+ 2017
- *Diffuse radio emission in MACS J0025.4–1222*, Riseley+ 2017
- *What are the megahertz peaked-spectrum sources?* Coppejans+ 2016
- *Deep observations of the Super-CLASS supercluster at 325 MHz*, Riseley+ 2016
- *A giant radio halo in a low-mass SZ-selected galaxy cluster: ACT-CL J0256.5+0006*, Knowles+ 2016
- *FRII radio galaxies at low freq's: Morphology, magnetic field strength and energetics*, Harwood+ 2016
- *Multi-wavelength Observations of the Merging Galaxy Cluster CIZA J0107.7+5408*, Randall+ 2016
- *Radio haloes in Sunyaev-Zel'dovich-selected clusters of galaxies: the making of a halo?*, Bonafede+ 2015
- *A powerful double radio relic system discovered in PSZ1 G108.18-11.53*, de Gasperin+ 2015

TIFR GMRT Sky Survey (TGSS)

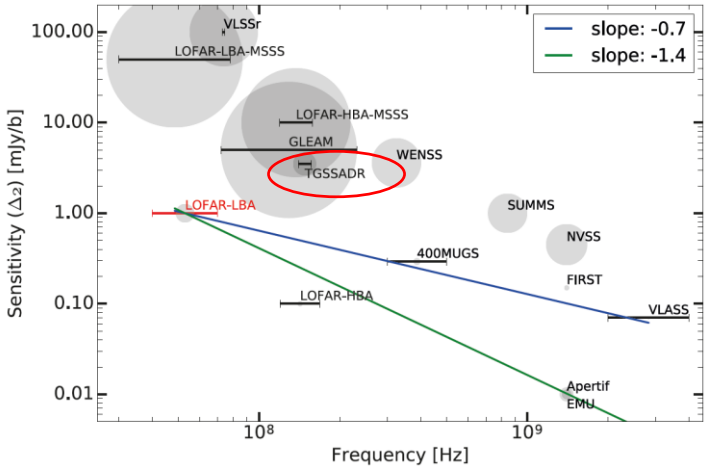
- 150 MHz continuum sky survey with the GMRT at 25” resolution and 2-5 mJy/beam noise
- Covers 90 percent (37,000 deg²) of the radio sky north of -53° DEC
- Alternative Data Release (ADR1) released in March 2016 (Intema+ 2017)
  - 5000+ images (5° x 5°) and catalog of 0.62 Million sources (http://tgssadr.strw.leidenuniv.nl)
  - Positional accuracy better than 2”, flux density accuracy of 10-20 percent
  - Large sky overlap with LOFAR, MWA, and future SKA-low
  - Also hosted by ASTRON VO server (http://vo.astron.nl), CDS Aladin, and NASA SkyView



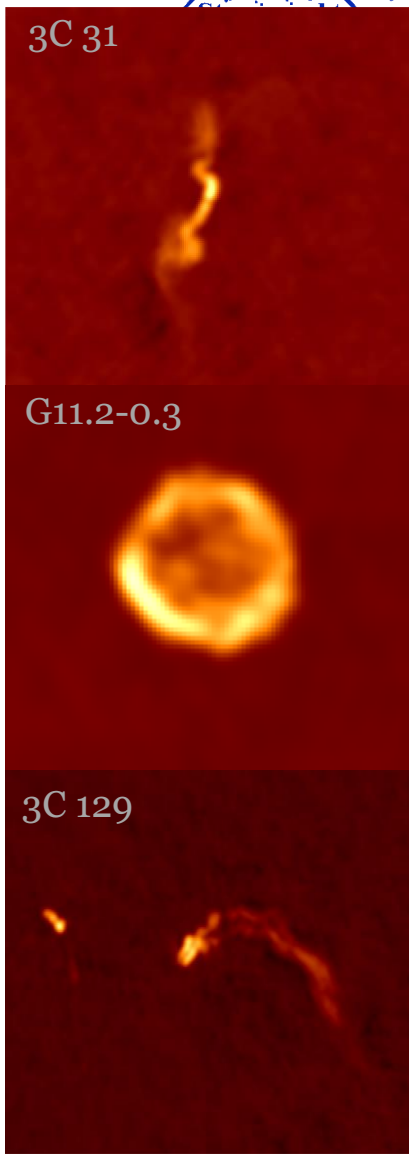
sky coverage



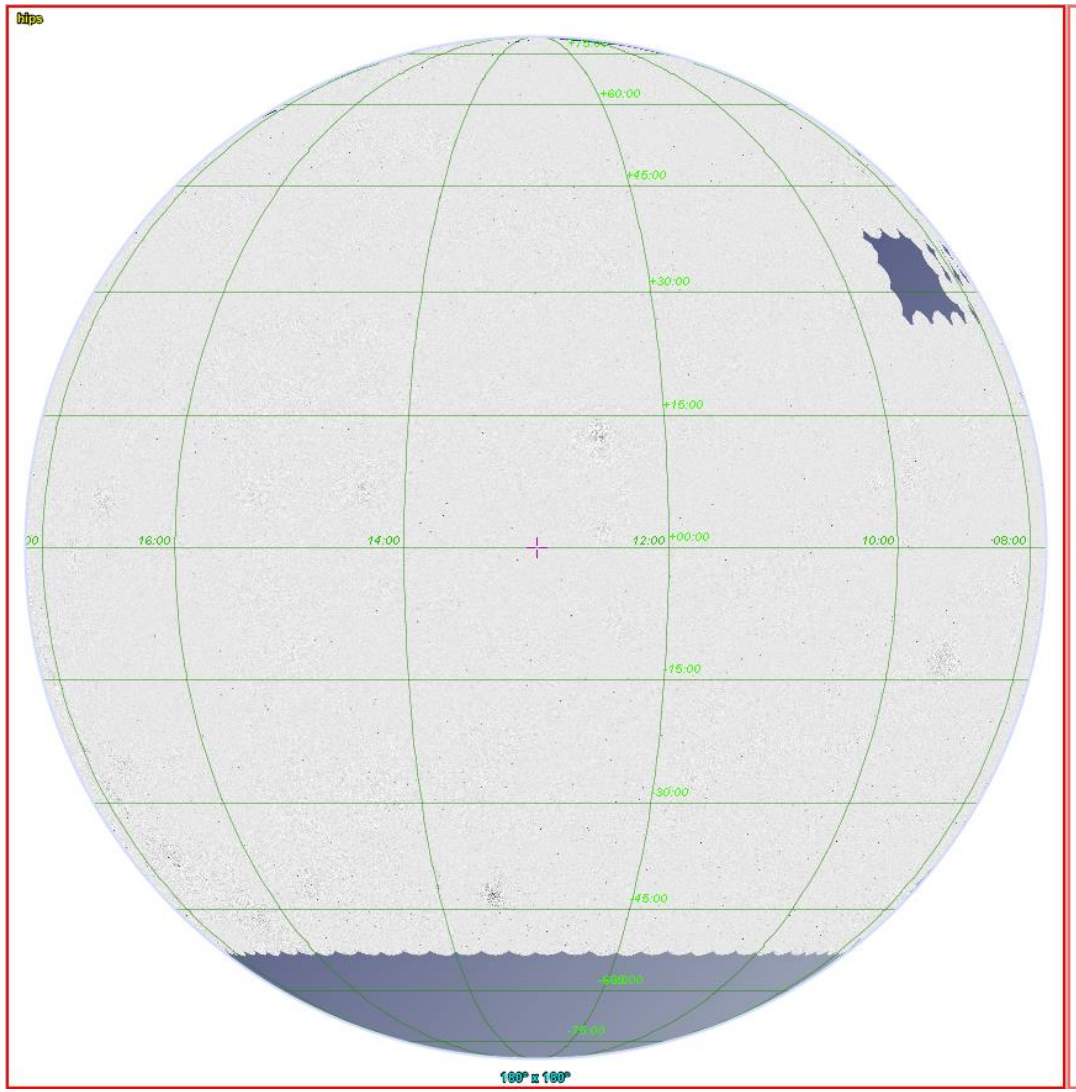
source counts at 150 MHz



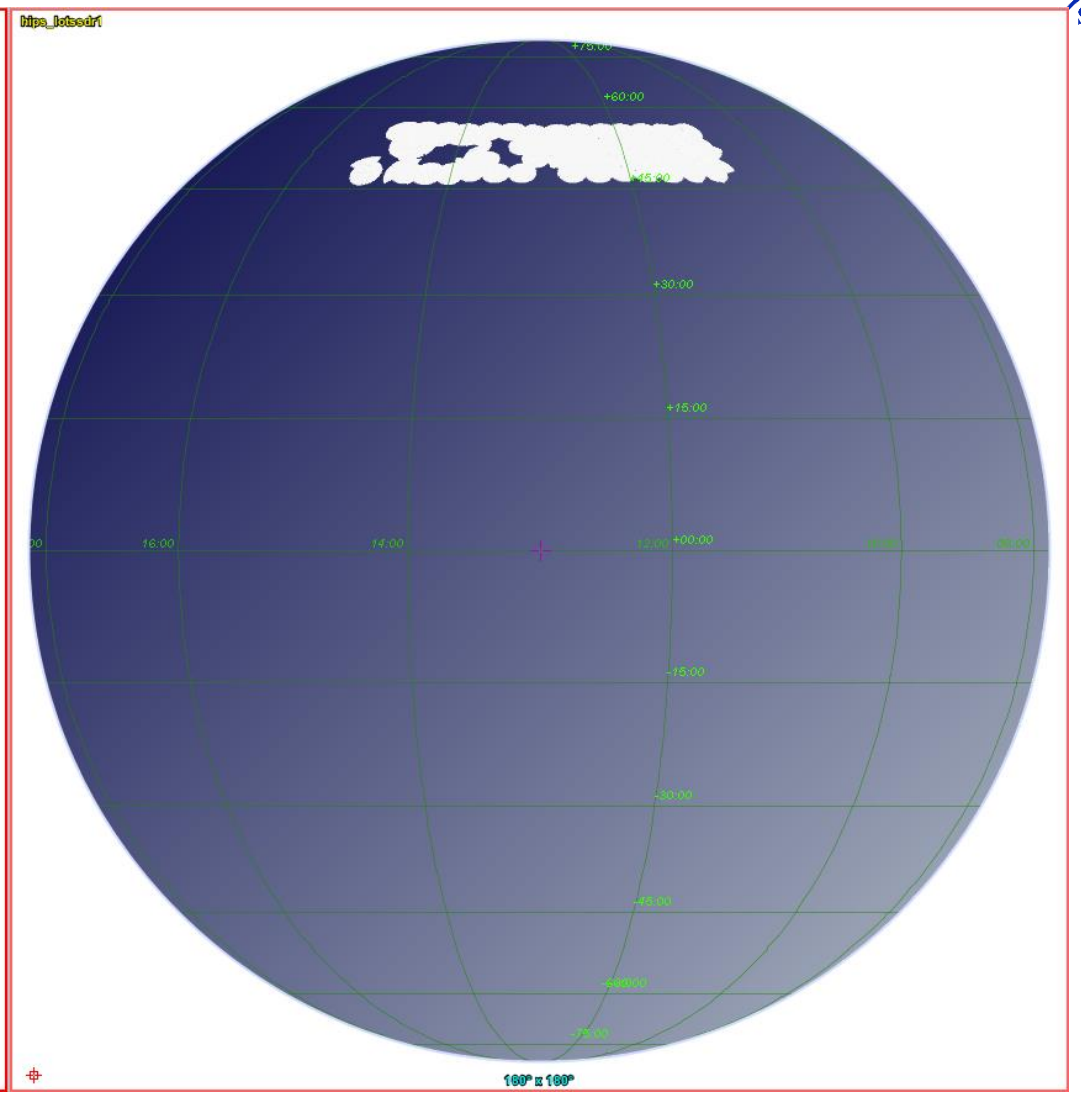
large-area survey overview



TGSS has large(st) sky coverage



TGSS sky coverage



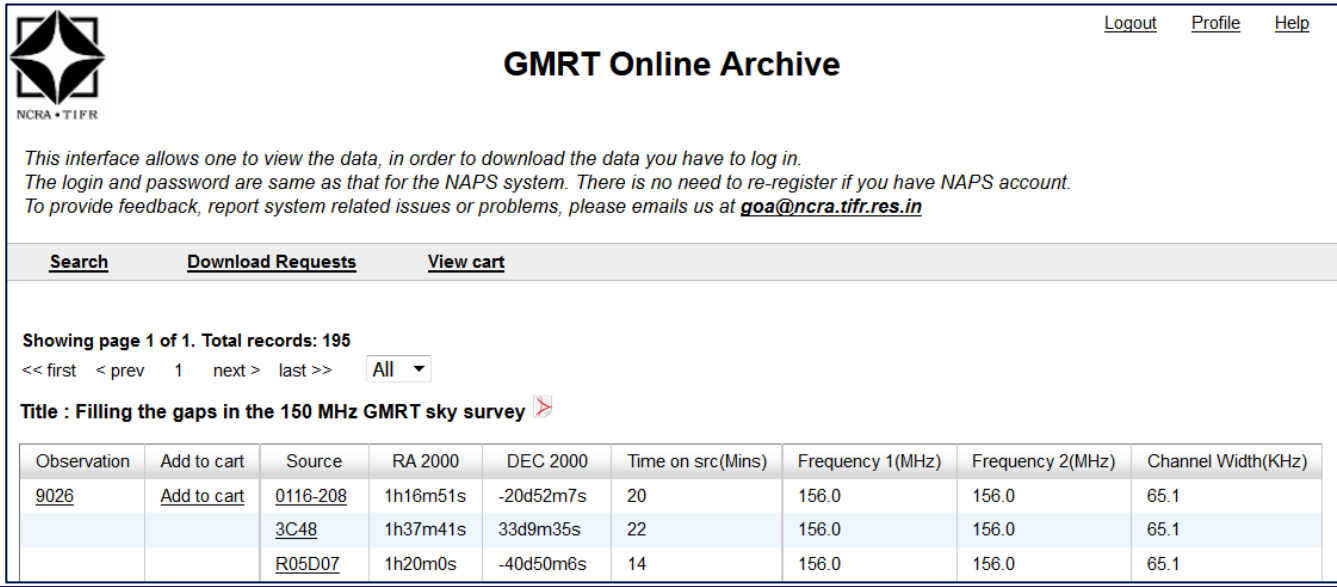
current LoTSS sky coverage

GMRT archival survey project

New application for SPAM pipeline to process all legacy continuum observations in the GMRT archive

Core team: Ishwara-Chandra, Y. Wadadekar (NCRA) and HTI (Leiden)

- Aims at delivering (near-) science-ready data products to astronomical community
- Project data older than 5 years will be automatically processed on a best effort basis
  - Newer data can be processed on request by PI
- Existing Indian compute and storage infrastructure will be used
- Estimated success rate >50-70 percent (biased by old HW-correlator data)
- Data products will be linked to observations regular GMRT archive interface
- Potentially enormous enhancement of the productivity of GMRT
- Opens up the GMRT to a larger group of researchers without the need of an expert



Observation	Add to cart	Source	RA 2000	DEC 2000	Time on src(Mins)	Frequency 1(MHz)	Frequency 2(MHz)	Channel Width(KHz)
9026	Add to cart	0116-208	1h16m51s	-20d52m7s	20	156.0	156.0	65.1
		3C48	1h37m41s	33d9m35s	22	156.0	156.0	65.1
		R05D07	1h20m0s	-40d50m6s	14	156.0	156.0	65.1

C-SPAM project

Wide-band receivers on JVLA and uGMRT are being installed and commissioned

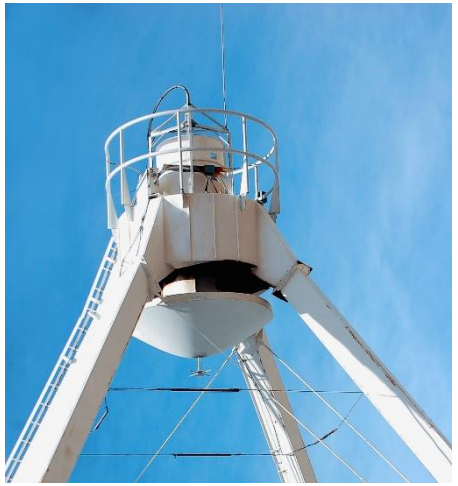
- uGMRT: 250-500 MHz, 550-900 MHz, [120-250 MHz]
- JVLA 230-480 MHz, 55-85 MHz

C-SPAM: ongoing project to port SPAM pipeline to CASA for support of wide-bandwidth calibration and imaging (and be polarization compatible)

- To provide the user community with proper tools to process these data, including direction-dependent effects

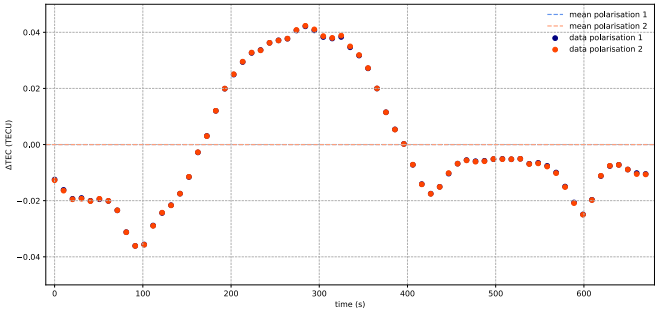
Master students project, supervised by FdG and HTI (Leiden)

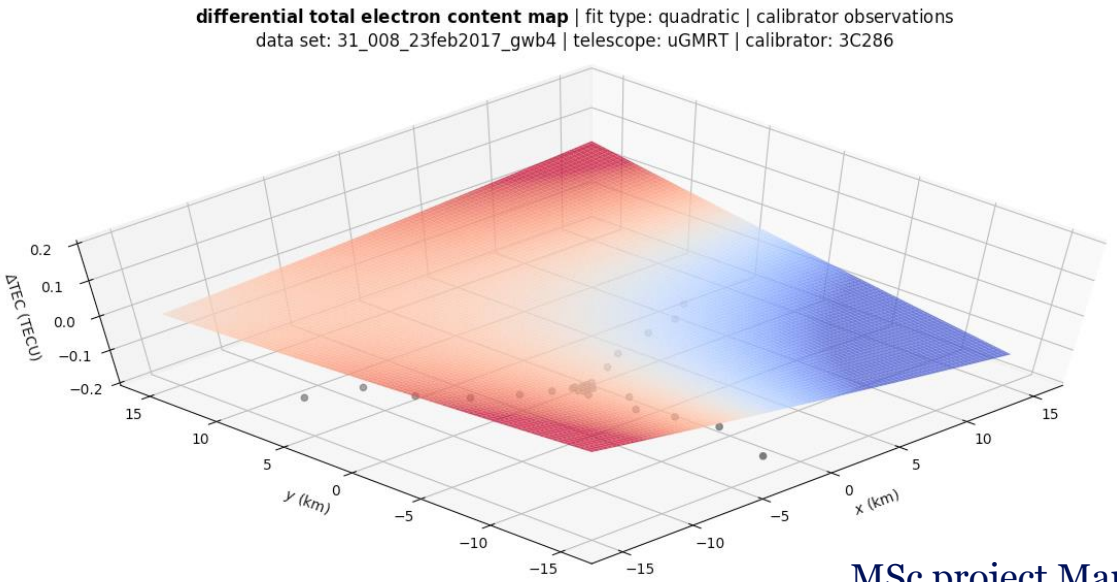
- **Kasper van Dam** (2015-2016) has implemented a regular python interface for CASA to allow for easy scripting and imports of 3rd party libraries (CASANOVA project), and provided a first (rough) version of a pipeline (https://github.com/kaspervd/casanova)
- **Martijn Oei** (2016-2017) is further developing the pipeline to apply it to pilot uGMRT data of the 400MUGS survey, a 300-500 MHz survey north of DEC -40°

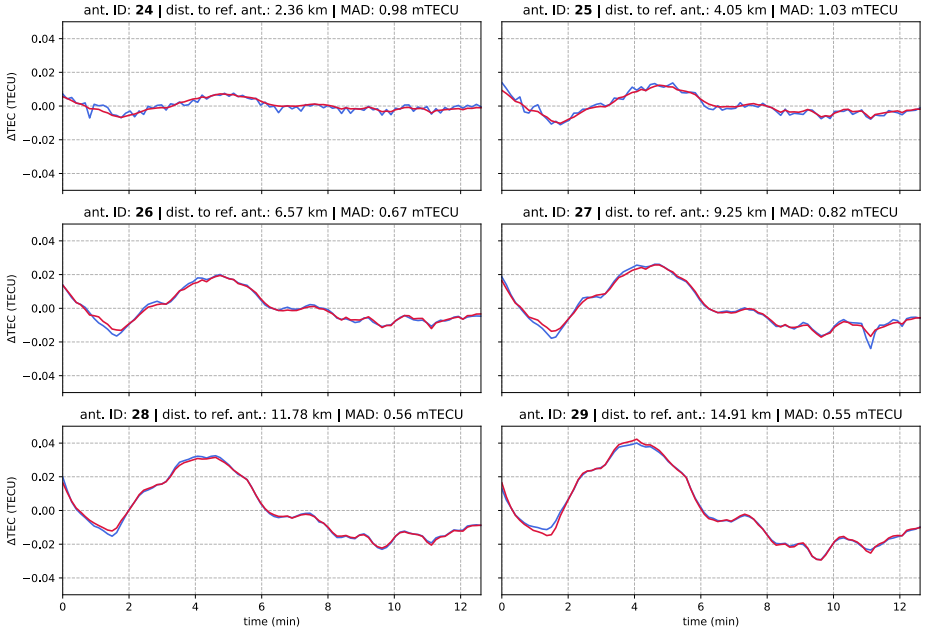


Example uGMRT ΔTEC measurements

- New 300-500 MHz band allows direct fitting of ΔTEC to gain phases obtained from CASA bandpass
- Test on calibrator 3C286 (single direction, high SNR)
  - Same ΔTEC solutions for different polarizations
  - Spatial variation is accurately reproduced by time-variable 2nd order polynomial fit
  - Fit error on the order of 0.1-1 mTECU



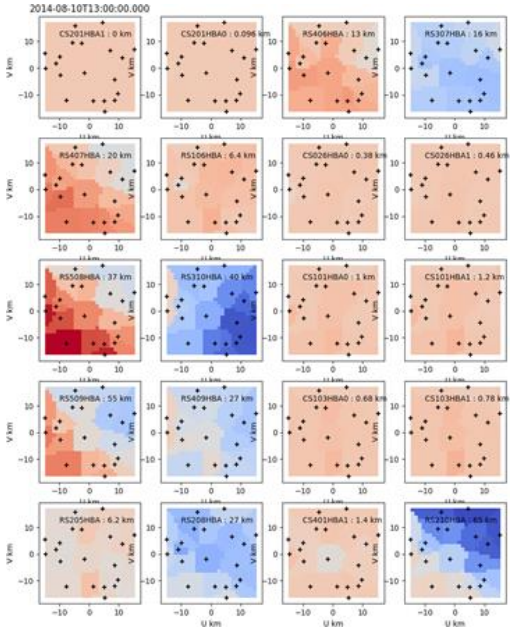




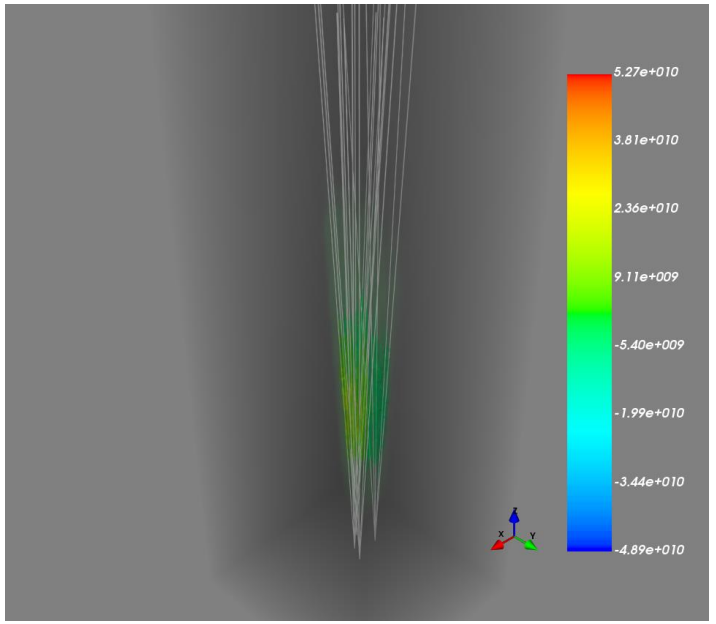
MSc project Martijn Oei (Leiden)

Towards 3D ionospheric tomography

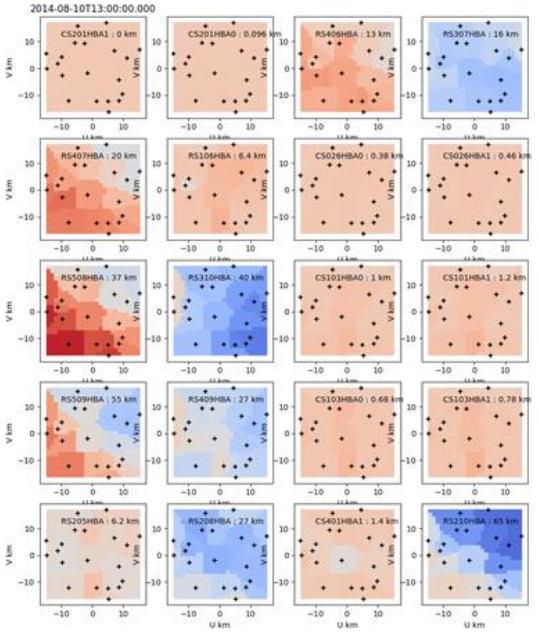
- Accurate correction of LF radio observations of larger arrays (>10 km) likely needs a proper 3D model
- Ongoing work by Josh Albert (PhD candidate Leiden) to use tomography to reconstruct 3D electron density
  - Assumes underlying turbulent medium (Gaussian process with fixed coherence scale, Matern 5/2 covariance function) on top of Chapman layers
  - Constraining model through convex optimization using 3D geometry of ray paths through the medium
  - First results using simulations look very promising, now under test using DD calibration results from LOFAR observations



"measured" 2D ΔTEC per station



reconstructed 2D ΔTEC per station



Summary

- SPAM has been (and still is) a demonstrator for
  - Fitting ionospheric screen models to DD calibration data
  - Showing significant improvement of DD ionospheric modeling over non-DD calibration
  - Robustness of such an approach when processing many different data sets
  - Viability of automating / pipelining LF data reduction
- Principles of SPAM have been adopted for LOFAR data processing, and provide a reference for future SKA-LOW calibration discussions
- C-SPAM is under development, and will provide support for wide bandwidth and polarization observations
- New ionospheric modeling is being developed to better represent the 3D ionospheric electron density distribution

- Of possible interest: TGSS ADR2 is underway, expected to be released late summer
  - Replacement of bad/missing data, better recovering of extended emission, fixes of various flux scale issues, better imaging of A-team sources