Probing Ionospheric Structure Using LOFAR

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Outline

- Goal: accumulate many nights of data, remove foreground with best possible calibration
- Ionospheric errors: 1 of the main issues of calibration
- In the process of removing those errors you gain information about the ionospheric structure
- Ionospheric structure functions:
  - side product of calibration
  - useful in estimating remaining phase errors → rms noise
- Investigate night to night structure variations
- Anisotropy due to Earth magnetic field
Observations

3C196 HBA
27 observations winter 2012/2013
2 observations winter 2013/2014
6hr/8hr nighttime
all observations aligned in time around transit
30 SB distributed over 115-175 MHz
1 channel per SB
time resolution: 10s

VTEC @ LOFAR-CORE
(IONEX data from CODE)
Extracting TEC information

• Start from calibration phases:
  - 3C196 dominant:
    • single (4 component) source in skymodel
    • calibrate full polarization matrix gains with 10s time resolution
    • separate in differential Faraday rotation angle + diagonal amplitude + phases

• phases errors:
  - clock/cable length
  - ionospheric delay
  - cable reflections
  - beammodel errors
  - skymodel
Clock/TEC separation

separate clock phases from ionospheric effects:
use large bandwidth
+ different frequency behaviour:

$$d\phi = c_1 \cdot \text{dTEC}/\nu + c_2 \cdot \text{dclock} \cdot \nu$$

interferometer: only sensitive to TEC differences
residuals of clock/tec fit versus time (CS017-CS001) ignoring other phase effects
1 baseline (~1km), 1 channel
different colors: different observations
all observations aligned in SRT

correlation between residuals: beam-/skymodel effects
ignoring rest of the sky mainly source of error @ short baselines
dTEC solutions versus time, all stations (reference station: CS001)
color coding according to baseline length
dTEC solutions versus time, all stations (reference station: CS001)

color coding according to baseline length
dTEC solutions versus time, all stations (reference station: CS001)
color coding according to baseline length

- CS only
- max bl ~ 2km
Ionospheric information from dTEC solutions
phase structure: convert dTEC to $d\phi$ @150 MHz
calculate time variance of $d\phi$ per baseline
Kolmogorov turbulence: $<\phi>=(S/S_0)^\beta$,
$\beta=5/3$, $S_0$ diffractive scale
Ionospheric information from dTEC solutions
phase structure: convert dTEC to $d\varphi \ @ 150 \ MHz$
calculate time variance of $d\varphi$ per baseline
Kolmogorov turbulence: $<\varphi> = (S/S_0)^\beta$,
$\beta=5/3$,
$S_0$ diffractive scale
Ionospheric information from dTEC solutions

phase structure: convert dTEC to $d\phi @150$ MHz
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Kolmogorov turbulence: $<\phi> = (S/S_0)^\beta$,

$\beta = 5/3$,

$S_0$ diffractive scale

Power law over large range of distances

$\sim 1\text{km} - 80\text{ km}$
Ionospheric information from dTEC solutions

phase structure: convert dTEC to \( d\phi @150 \text{ MHz} \)

calculate time variance of \( d\phi \) per baseline

Kolmogorov turbulence: \( \langle \phi \rangle = (S/S_0)^\beta \),

\( \beta = 5/3 \),

\( S_0 \) diffractive scale

turn over at largest distances (?)
Ionospheric information from dTEC solutions

phase structure: convert dTEC to $d\phi$ @150 MHz
calculate time variance of $d\phi$ per baseline

Kolmogorov turbulence: $<\phi> = (S/S_0)^\beta$,

$\beta = \frac{5}{3}$,

$S_0$ diffractive scale

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noise floor
constant level for all observations

$\sim 1$ mTEC
Ionospheric information from dTEC solutions

phase structure: convert dTEC to $d\phi$ @150 MHz
calculate time variance of $d\phi$ per baseline

Kolmogorov turbulence: $<\phi>=(S/S_0)^\beta$, 
$\beta=5/3$, 
$S_0$ diffractive scale
Structure function all observations

![Graphs showing the structure function for different observations]
Structure function all observations

Clear power law structure for all observations
Main variation in offset (S0)
error bars statistical only
Diffractive scale variations between 5-40 km

$S_0 < 2 \text{km}$ (Fresnel scale) leads to scintillation (not observed in winter 12/13)

Fitted $\beta$ on average larger than 5/3

(large scale non Kolmogorov structures, TIDs?)
Correlation with RMS image noise

- Night to night fluctuations in image noise
  - direction independent calibration only

Diffractive scale anti-correlates with image noise

Measure for remaining noise after calibration

(see: Vedantham et. al. 2014, submitted to MNRAS)
non calibrator fields

- Diffractive scale is a measure of ionospheric quality of data
  - easily extracted from calibrator data
  - few solutions (~20) over large frequency range
- Can also be extracted from selfcal phase solutions of weaker fields
  - NO phase transfer from calibrator
  - TEC from Clock/TEC separation will be the determined by (flux weighted) average TEC over the field of view
- Mind: flux ratio can vary with frequency
  - eg. bright source at the edge of the beam
  - issue issue for “wild” nights, when ionosphere varies significantly over field of view
- example NCP
NCP field: 16 nights 2012-2014
BBS calibration by S. Yatawatta
~100 sources in skymodel
Diagonal Gains 10s
Clear power law structure

Higher noise levels than 3C196 data
Bandlike structure

Orientation dependent

Anisotropic structure
2D structure

Fit 2D structure all observations

$\langle \varphi \rangle = (S^\text{EW}/S_{0\text{EW}} + S^\text{NS}/S_{0\text{NS}})^\beta$

- Orientation dependent structures
- No clear preferred (NS/EW) direction
- Projected geomagnetic field lines
- projected along LOS
- axes are beam pointing angles in degrees ($0,0 = \text{zenith}$)
- Structure function binned according to orientation wrst Earth magnetic field
Geomagnetic Field Orientation
Geomagnetic Field Orientation

Red: perpendicular
Blue: parallel
Structures tend to be elongated along the magnetic field lines (leading to smaller $S_0$ values)
Conclusion

- LOFAR calibration data can be used to probe turbulent structure of the ionosphere over a long range of scales (~1-80 km)
- Diffractive scale is a measure of the ionospheric quality of the night
  - diffractive scale correlates with rms noise of the image
- Observed anisotropy in turbulent structure aligned with Earth magnetic field
  - structures elongated along magnetic field lines