Probing Ionospheric Structures Using LOFAR

M. Mevius on behalf of the LOFAR EOR team
OUTLINE

• LOFAR as ionospheric instrument
• Using Calibration solutions
• Structure Function
• Anisotropy
• Imaging ionospheric Structures
LOFAR vs GPS

GPS IONEX data available online with resolution: 2.5 x 5 degrees. 1-2hr maps.
LOFAR vs GPS
NEW ILTG maps: See poster by Kotulak et al,
High resolution GPS vTEC maps

0.5 x0.5 degrees

time resolution: 5min/15min

Uncertainty ~1TECU (corresponds to ~4 full $2\pi$ phase rotations @LOFAR HBA)

Faraday rotation correction of polarized signals
precalibration of International baselines
absolute TEC measurements
LOFAR CS: dTEC solutions with a time resolution of 10 s
Colors-scale ranges from -0.005 to 0.005 TECU

For even higher time resolution see presentation by Richard Fallows
Calibration Solutions

- Ionosphere is a major issue for the calibration of low frequency data
- Calibration solutions provide information about ionosphere
- Ionospheric characterization tool for quality assignment of radio data

In this presentation:
LOFAR-EOR 3C196 data
Direction independent calibration using 4 component model of 3C196
Analyze full Jones matrices
Snapshot imaging
Phase error:

\[ \Phi_{ion} = -\frac{2\pi v}{c} \int_{\text{LoS}} (n - 1) \, dl \]

Refractive index expansion:

\[ n = 1 - \frac{q^2}{8\pi^2 m_e \varepsilon_0} \cdot \frac{n_e}{\nu^2} \pm \frac{q^3}{16\pi^3 m_e^2 \varepsilon_0} \cdot \frac{n_e B \cos \theta}{\nu^3} \]

\[ -\frac{q^4}{128\pi^4 m_e^2 \varepsilon_0^2} \cdot \frac{n_e^2}{\nu^4} - \frac{q^4}{64\pi^4 m_e^3 \varepsilon_0} \cdot \frac{n_e B^2 (1 + \cos^2 \theta)}{\nu^4} \]

Calibration: in M.E., Jones matrices:

\[
\begin{pmatrix}
G_{xx} & G_{xy} \\
G_{yx} & G_{yy}
\end{pmatrix}
= \begin{pmatrix}
\cos(\alpha) & \sin(\alpha) \\
-\sin(\alpha) & \cos(\alpha)
\end{pmatrix}
\cdot
\begin{pmatrix}
G_{xx} & 0 \\
0 & G_{yy}
\end{pmatrix}
\]

\[ \alpha = RM \cdot \lambda^2 \]
After clock-TEC separation:

dTEC vs. time

each line corresponds to a different baseline (wrst center LOFAR)
darker colors correspond to longer baselines

LOFAR HBA data (115-170 MHz)
4 component model of calibrator (3C196) in phase center

solution every 10s

(almost) independent fit for each time point!

estimated accuracy from scatter round trend (calibrator data):

dTEC: < 0.001 TECU
**2\textsuperscript{nd} order:** Differential Faraday rotation

\[
\begin{pmatrix}
G_{xx} & G_{xy} \\
G_{yx} & G_{yy}
\end{pmatrix}
= \begin{pmatrix}
\cos(\alpha) & \sin(\alpha) \\
-sin(\alpha) & \cos(\alpha)
\end{pmatrix}
\begin{pmatrix}
G_{xx} & 0 \\
0 & G_{yy}
\end{pmatrix}
\]

Rotation of the linear polarization angle
\[dRM_{12} \sim TEC_1 \cdot B_{||1} - TEC_2 \cdot B_{||2}\]

differential RM also for unpolarized signal

large TEC gradients: even visible in raw visibilities

Fit for rotation angle (or extract it from full Jones) per channel. Combine all channels to get dRM
3rd order

LBA:
2 parameter Clock/TEC fit not sufficient for very low frequencies (<40 MHz)

2 parameter fit ($\phi(\nu)=A\nu+B/\nu$)
3 parameter fit ($\phi(\nu)=A\nu+B/\nu+C/\nu^3$)
LBA: dTEC (TECU), dRM (rad/m$^2$) and 3$^{rd}$ order (arbitrary units) versus time. all stations (F. de Gasperin)

Every dot independent fit!

correlation between stations, correlation between different effects

Combine measurements to extract more information about the underlying structure of the ionosphere. e.g.: 3$^{rd}$ order related to $h_{\text{max}}$

absolute TEC from dRM, B$||$ and dTEC
Structure function

Extract information from dTEC vs. time

Spatial fluctuations:
\[ D_\phi(||r_1-r_2||) = \langle (\phi_1 - \phi_2)^2 \rangle \]

Kolmogorov turbulence, thin layer approximation:
\[ D_\phi(r) = (r / s_0)^\beta \quad \beta = 5/3, \]
\[ s_0: \text{diffractive scale}, \]
\[ D_\phi(s_0) = 1 \text{ rad}^2 \]

Measure structure function by calculating variance of dTEC vs. time for all baselines

fit \( \beta, S_0 \)

Typical nighttime \( S_0 \) @150 MHz: 2-40 km scintillation conditions \( S_0 < 2 \text{km} \)

Characterize ionospheric quality
distribution of $\beta$ and $r_{\text{diff}}$ for 29 3C196 observations nighttime, winter

typically $\beta$ larger than $5/3$
$r_{\text{diff}}$ varies between 3 and 30 km

Correlation with image noise after DI-calibration only.
Even possible to extract $r_{\text{diff}}$ from high time resolution raw GPS data

Estimate ionospheric quality just before or during observation

Needs dense network of GPS receivers
(here: public data from several receivers in US-earthquake area)
Diffractive scale as quality measure

diffractive scale is length scale for which phase variance $= 1 \text{ rad}^2$

(freqeency dependent, here @ 150MHz)
correlates with image noise (after DI-calibration)
can be used to assign ionospheric quality to observation:

- discard bad observations
- select very good observations for sky modelling
- determine typical length scale for DD-calibration:
  - number of facets
  - maximum baseline length
- expected scintillation noise after calibration

(e.g. Vedantham and Koopmans (MNRAS 2015))

Easy to obtain from calibration phases, also for non-calibrator fields, without clock-TEC separation and from GPS data
Large Scale Field Aligned Structure

*bandlike* structure $\rightarrow$ orientation of the baseline

Earth magnetic field aligned?

projected field lines along LOS

single ionospheric height

perspective view $\rightarrow$ time dependent orientation

bin data in according to angle wrst projected field lines

field aligned structure observed in $\sim$ 50% of the observations
Loi et al. GRL 2015

Real-time imaging of density ducts between the plasmasphere and ionosphere

MWA data snapshot images of source shifts ionospheric gradient → position shift elongated slowly moving field aligned structures
HBA beam

Do we observe the same structures with LOFAR? single beam: too small FOV

Loi et al, GRL (2015) 42, 10
flanking fields

Do we observe the same structures with LOFAR?
single beam: too small FOV
multiple beams
standard observing mode for EOR: 1 central beam + 6 flanking fields
18 SB each
Use 1min CS only
snapshot images (wsclean, Offringa) +
frequency dependent position fits on ~400 sources
CONCLUSION

- LOFAR probes ionospheric structures on scales ranges from 100m to 100 km
- Using just calibration gains one gets access to different orders of ionospheric corruptions
- Diffractive scale is a quality measure easily obtained from calibration data
- Anisotropic larger scale magnetic field aligned structures visible in many observations
- Imaging structures using snapshot views from core only data (multibeamming)