Probing Ionospheric Structures Using LOFAR

M.Mevius
on behalf of the LOFAR EOR team

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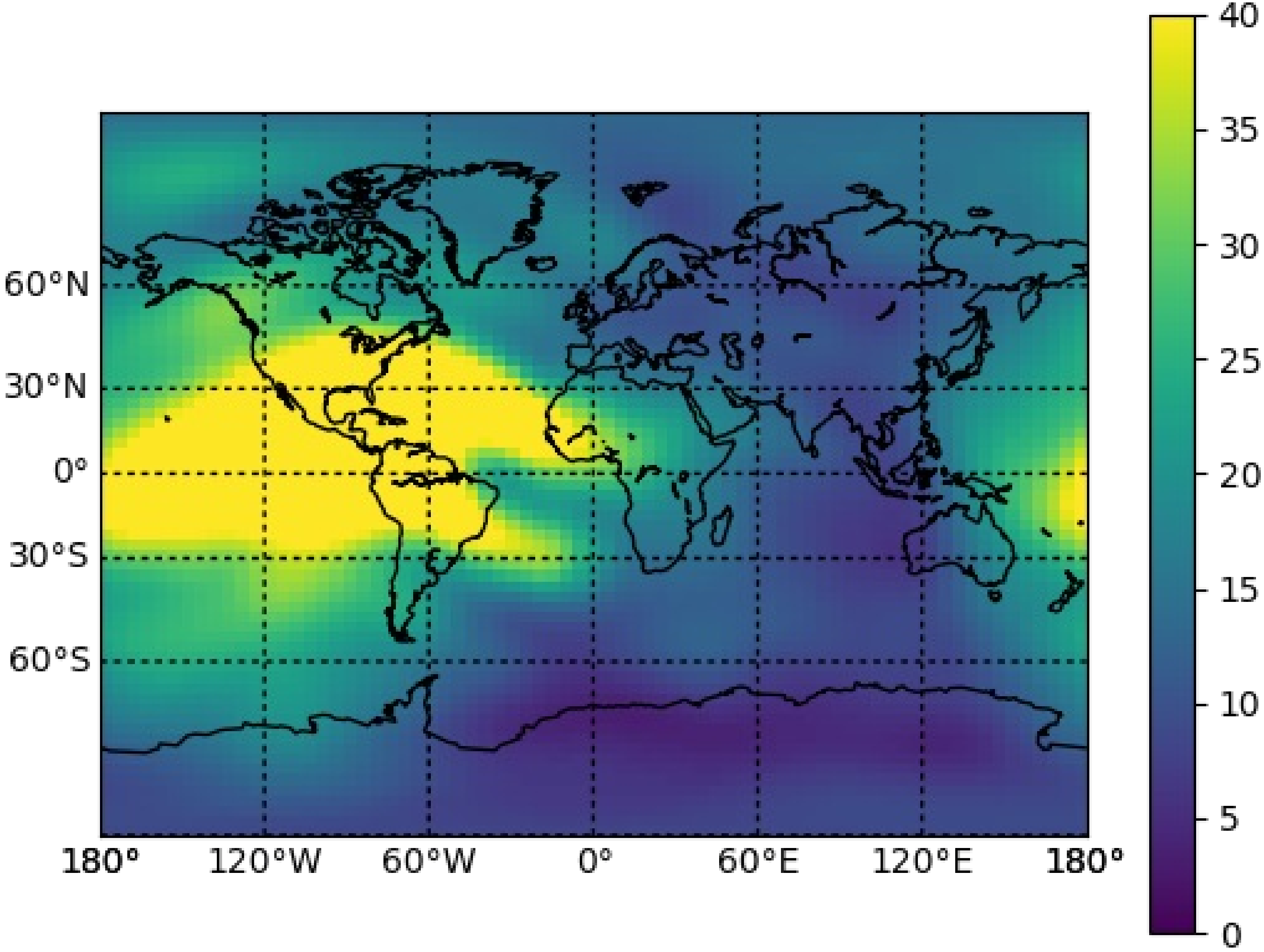
LOFAR

OUTLINE

- LOFAR as ionospheric instrument
- Using Calibration solutions
- Structure Function
- Anisotropy
- Imaging ionospheric Structures

LOFAR vs GPS

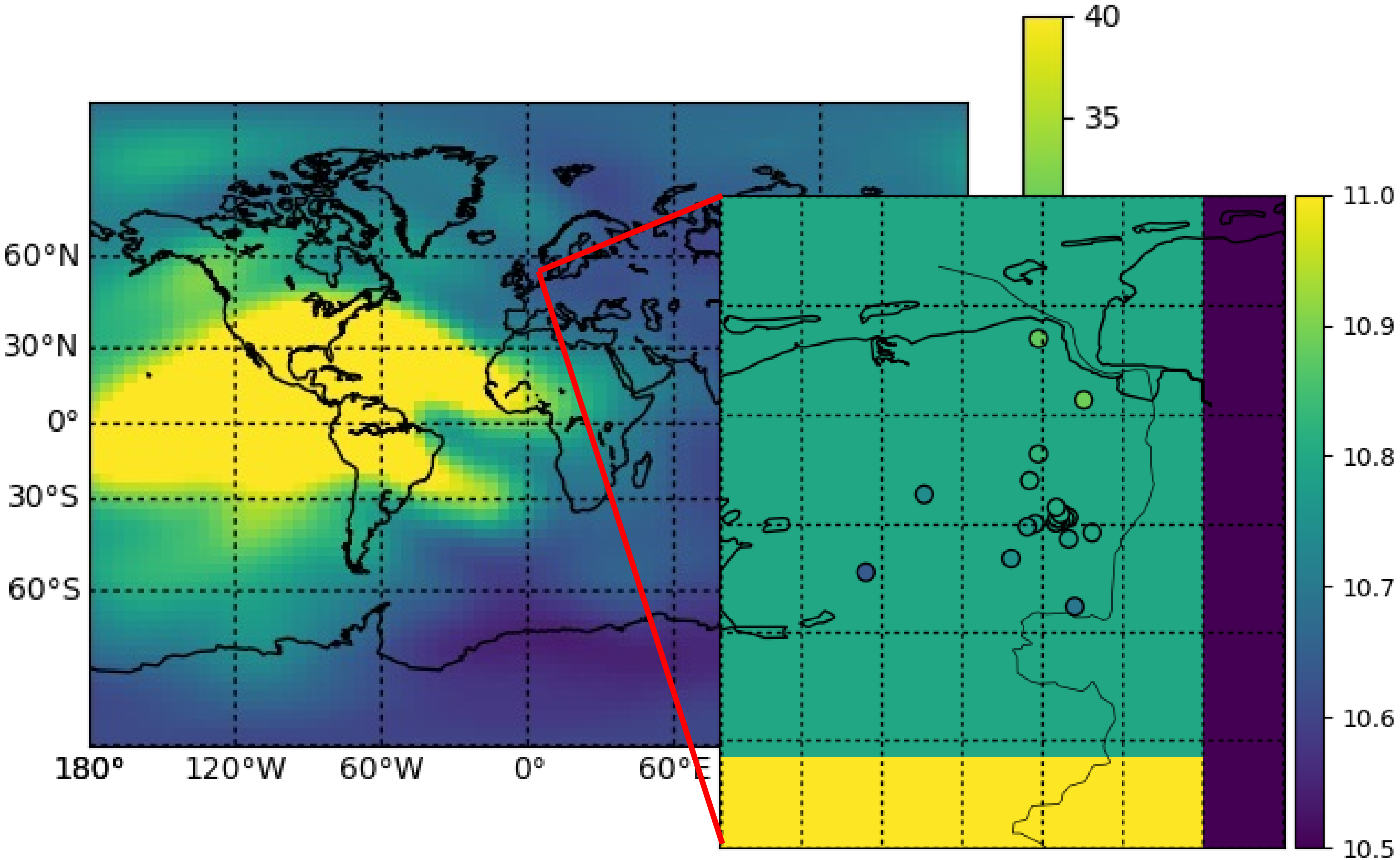


GPS IONEX data online available

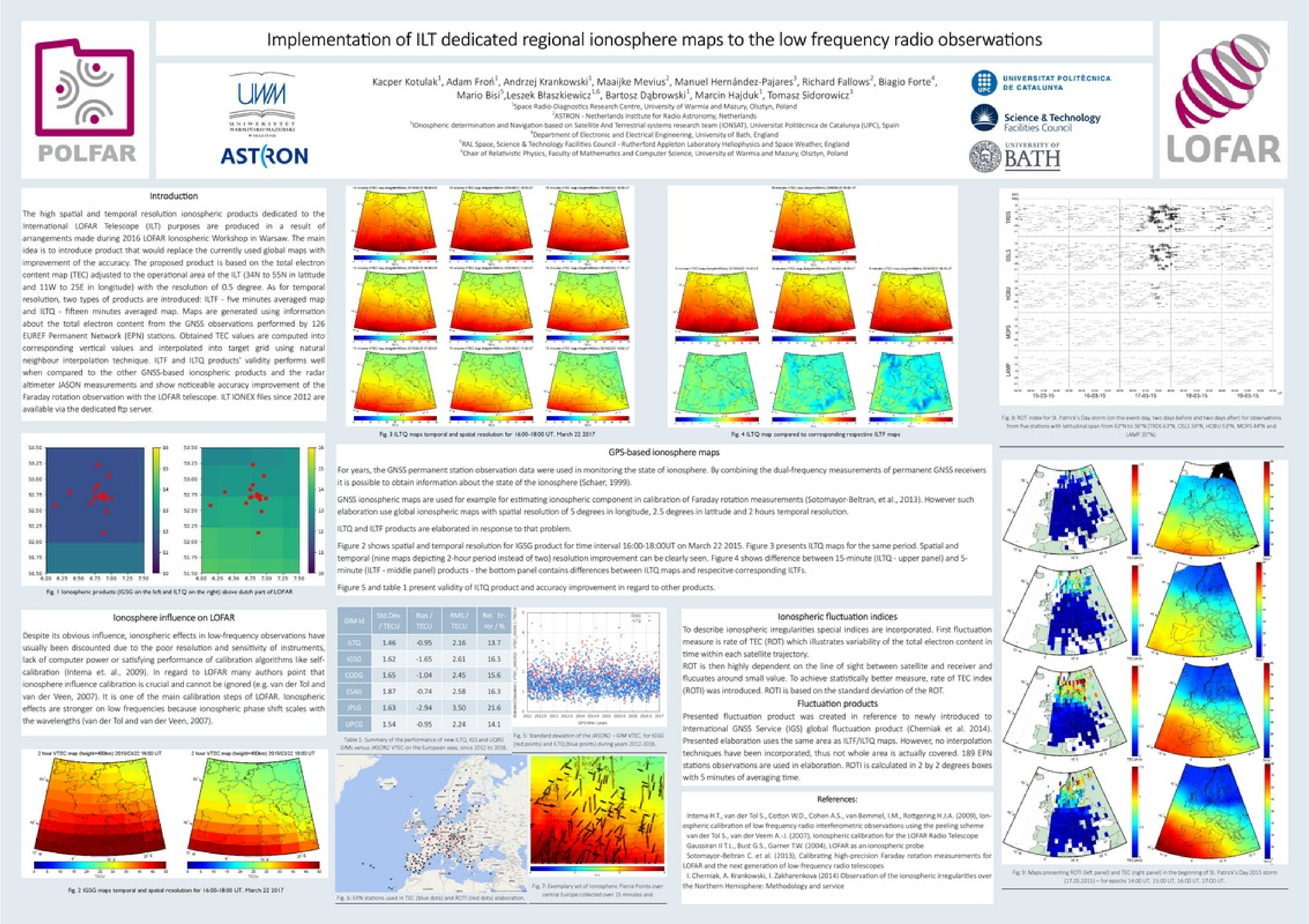
resolution:
2.5 x 5 degrees

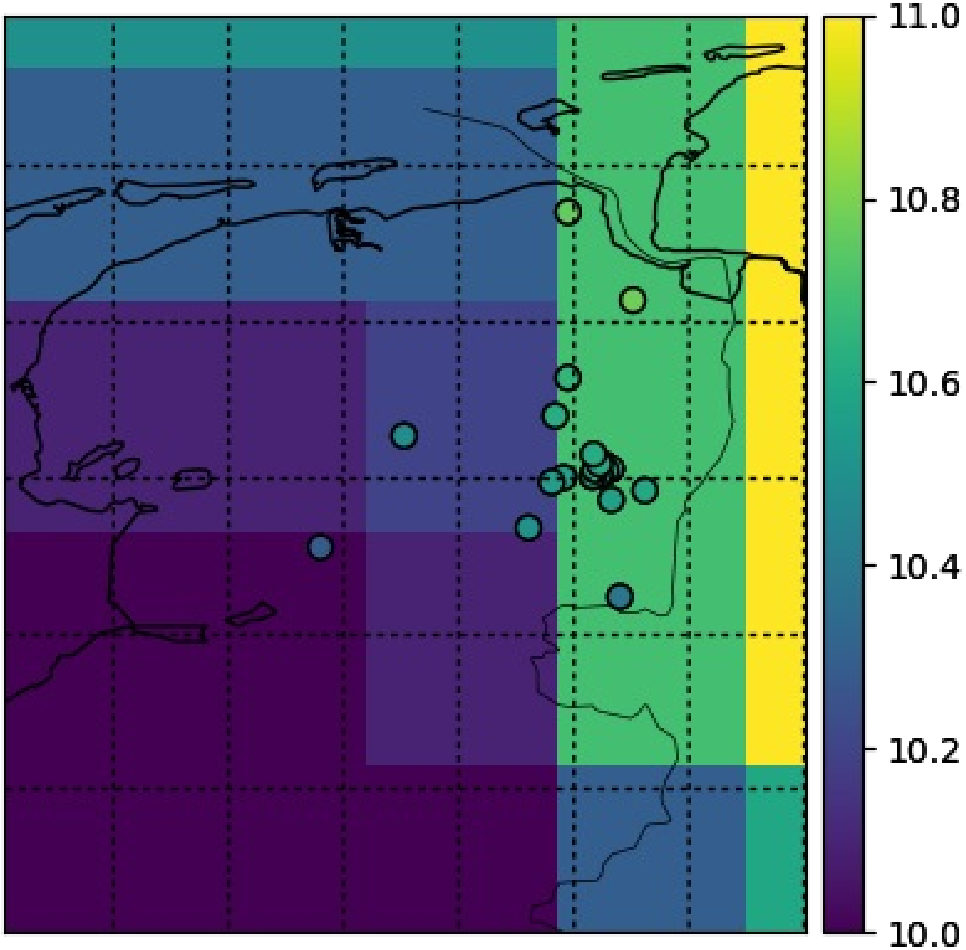
1-2hr maps

LOFAR vs GPS



NEW ILTG maps: See poster by Kotulak et.al,





High resolution GPS vTEC maps

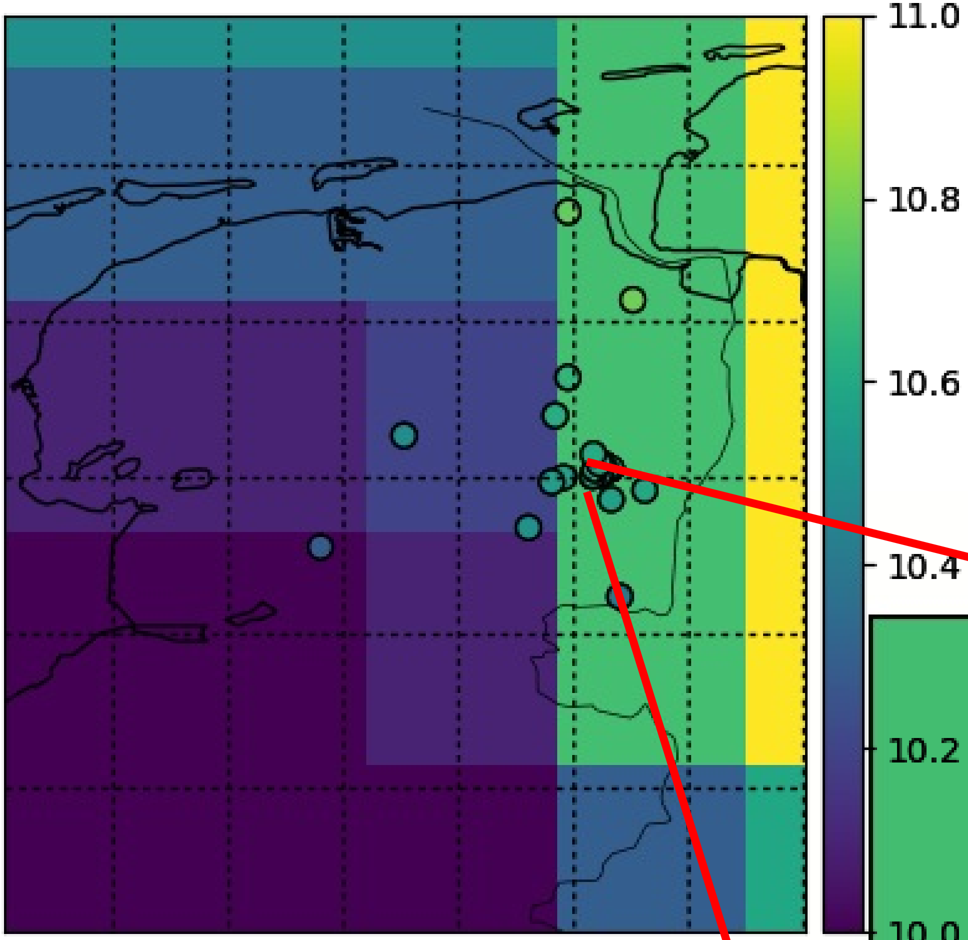
0.5 x0.5 degrees

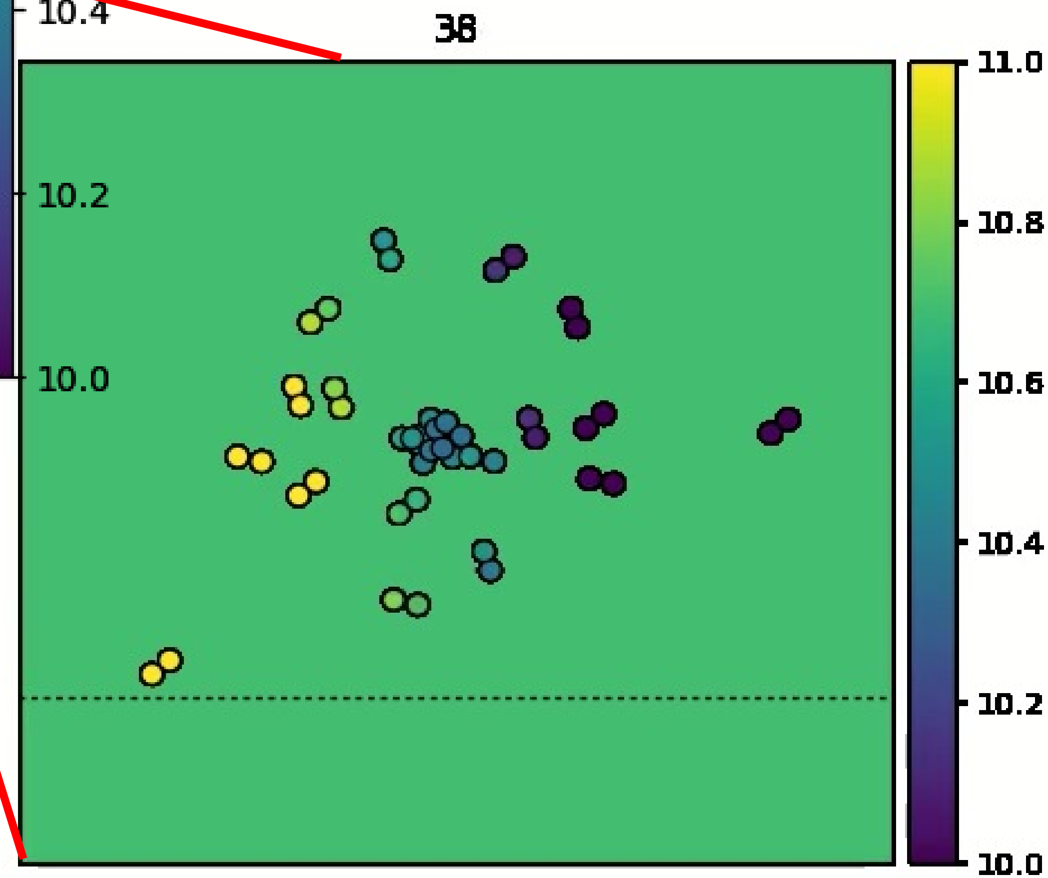
time resolution: 5min/15min

Uncertainty ~1TECU (corresponds to ~4 full 2π 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
Colorscale 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

F. de Gasperin et al.

32nd URSI GASS, Montreal, 19–26 August 2017

Phase error:

$$\Phi^{\text{ion}} = -\frac{2\pi\nu}{c}\int_{\text{LoS}}(n-1)\,\mathrm{d}l$$

Refractive index expansion:

$$n = 1 - \frac{q^2}{8\pi^2 m_e \varepsilon_0}\cdot\frac{n_e}{\nu^2} \pm \frac{q^3}{16\pi^3 m_e^2 \varepsilon_0}\cdot\frac{n_e B\cos\theta}{\nu^3} - \frac{q^4}{128\pi^4 m_e^2 \varepsilon_0^2}\cdot\frac{n_e^2}{\nu^4} - \frac{q^4}{64\pi^4 m_e^3 \varepsilon_0}\cdot\frac{n_e B^2(1+\cos^2\theta)}{\nu^4},$$

dTEC (TECU)	I ord 30 MHz	II ord (day/night) 30 MHz	I ord 60 MHz	II ord (day/night) 60 MHz	I ord 150 MHz	II ord (day/night) 150 MHz
0.5 (remote st., bad iono.)	8067	294 / 214	4033	73 / 50	1613	12 / 8
0.1 (remote st., good iono.)	1613	126 / 46	806	31 / 10	322	5 / 2
0.03 (across FoV)	404	97 / 16	242	24 / 4	96	4 / < 1
0.01 (core st.)	160	88 / 8	80	22 / 2	31	4 / < 1

Calibration: in M.E., Jones matrices:

$\alpha = RM \cdot \lambda^2$

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

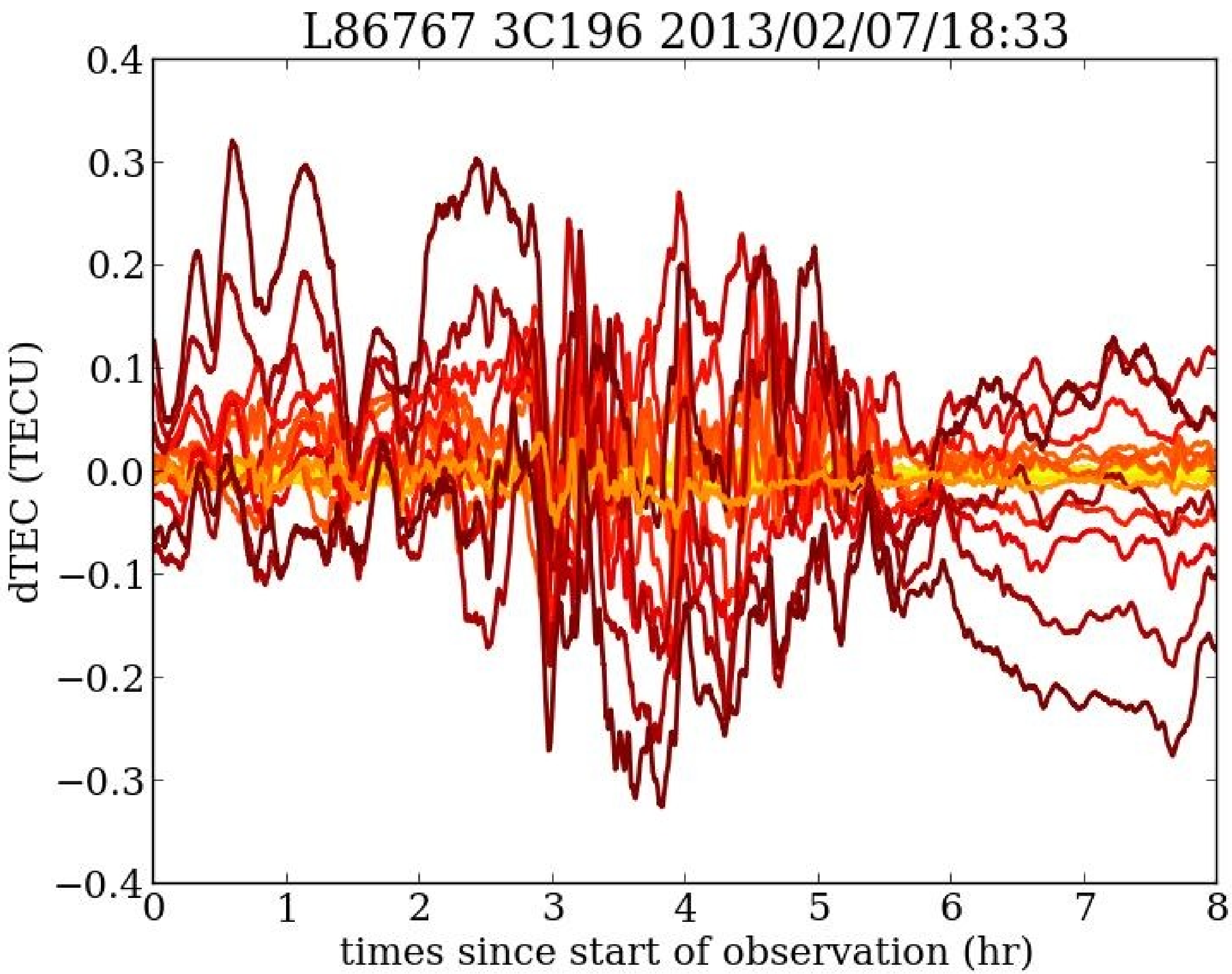
After clock-TEC separation:

dTEC vs. time

each line corresponds to a different basline (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



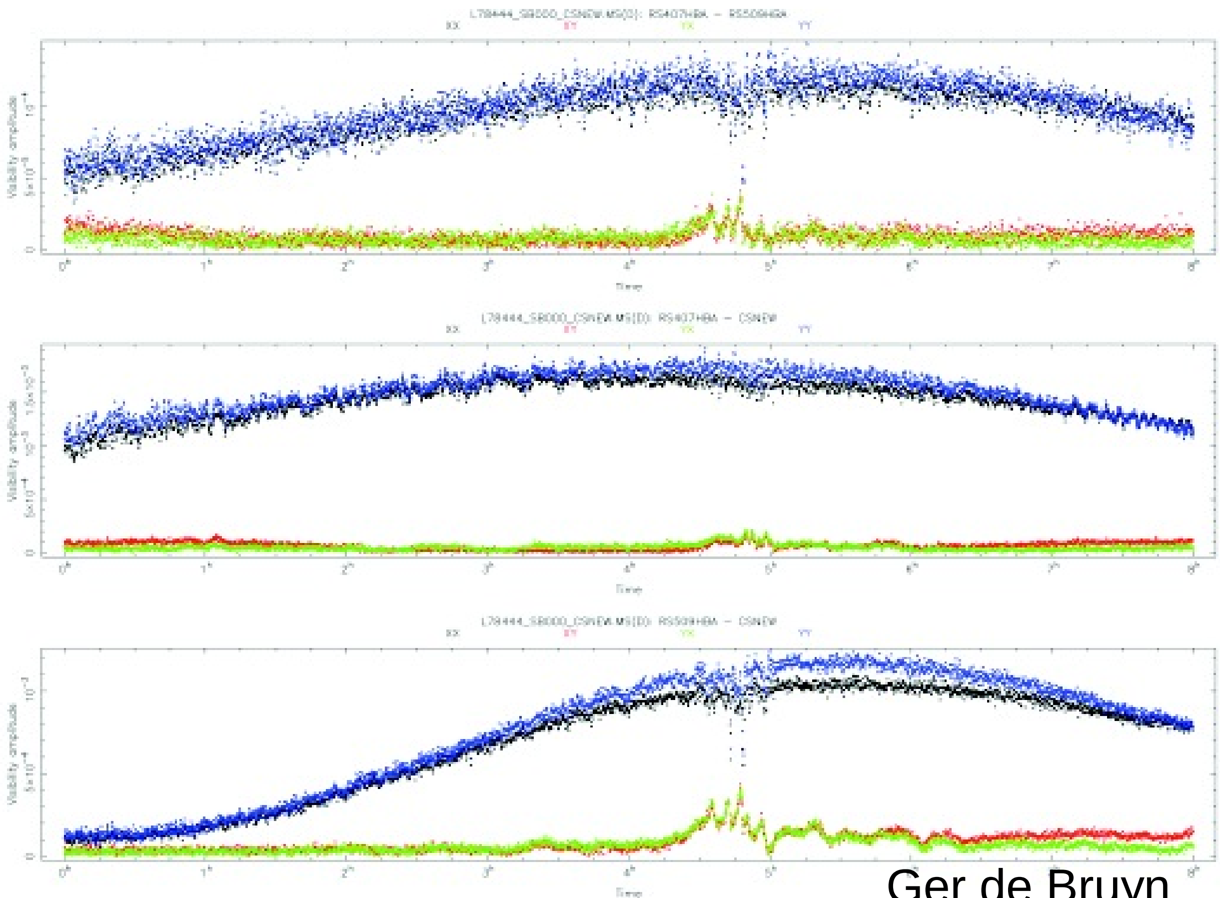
(almost) independent fit for each time point!

estimated accuracy from scatter round trend (calibrator data):

dTEC: < 0.001 TECU

2^{nd} order:Differential Faraday rotation

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



Ger de Bruyn

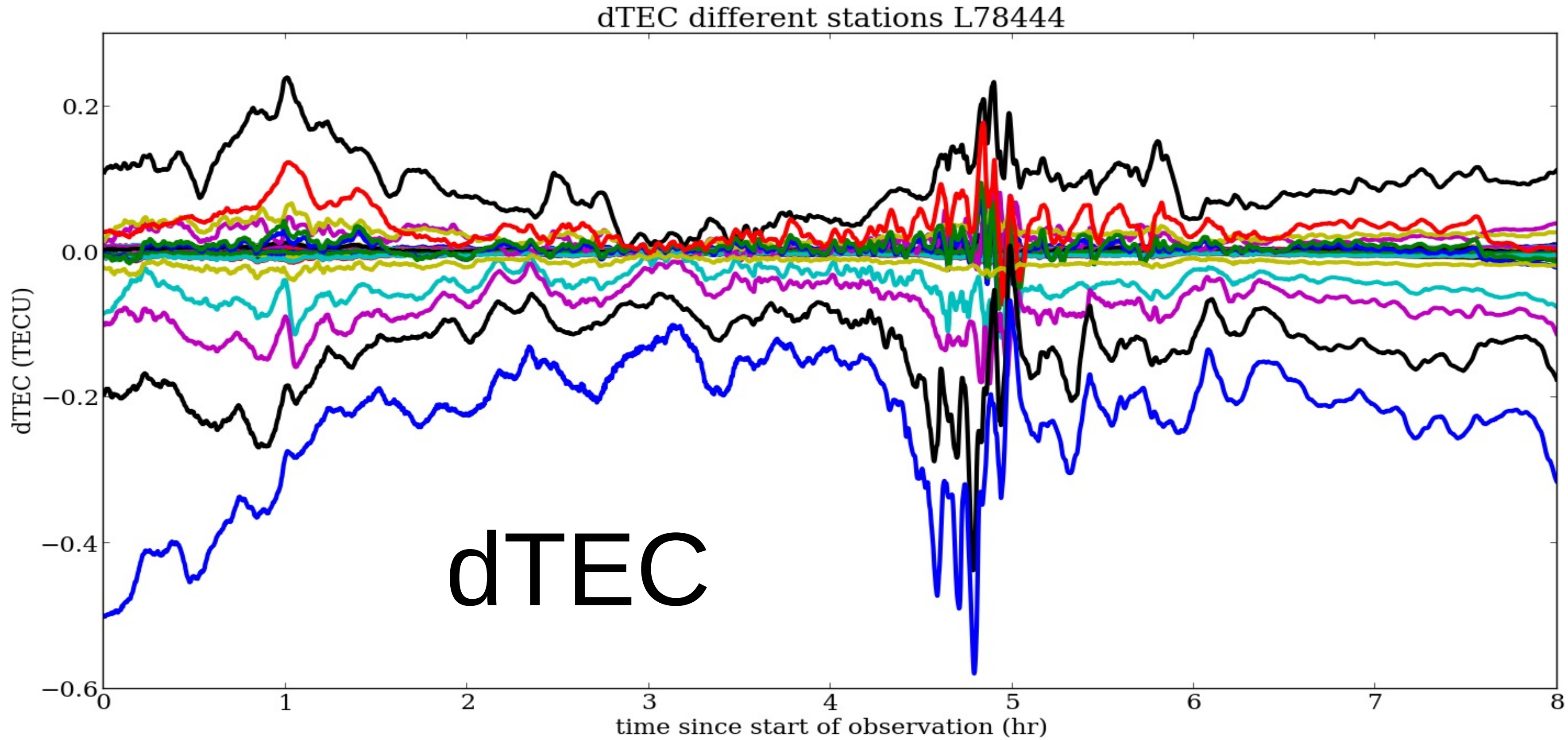
Rotation of the linear polarization angle

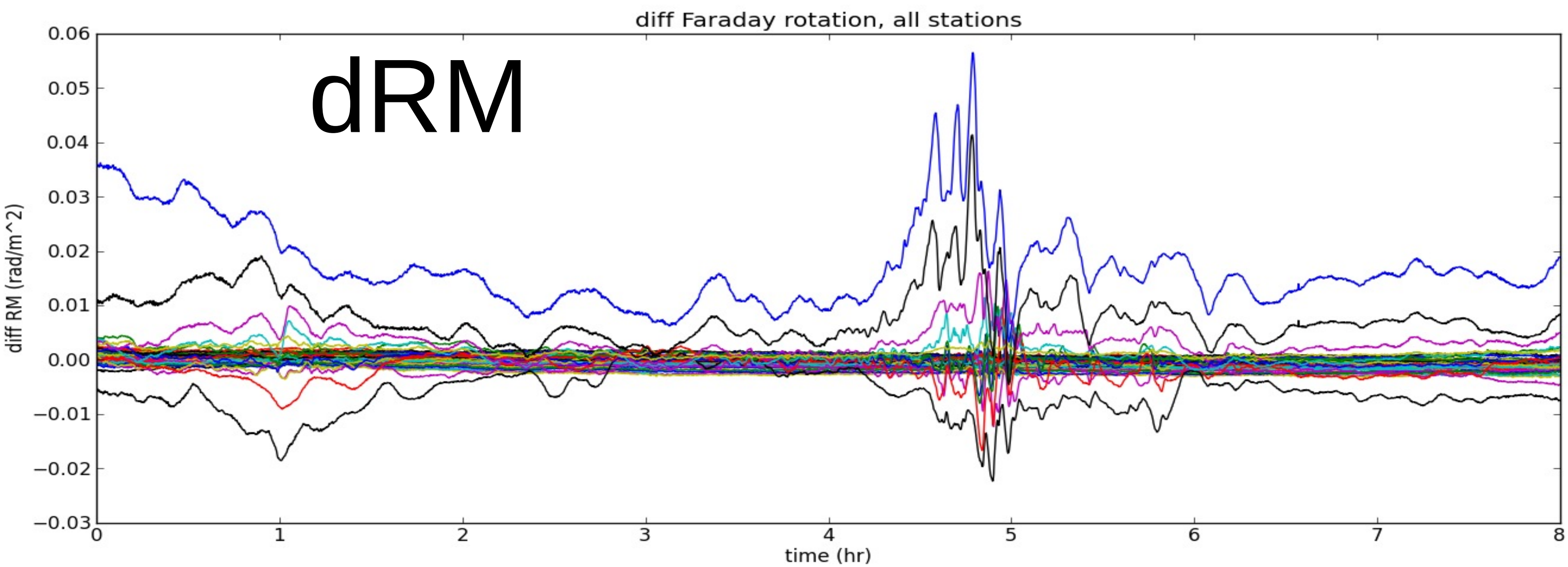
$dRM_{12} \sim TEC_1 * B||_1 - TEC_2 * B||_2$

differential RM also for unpolarized signal

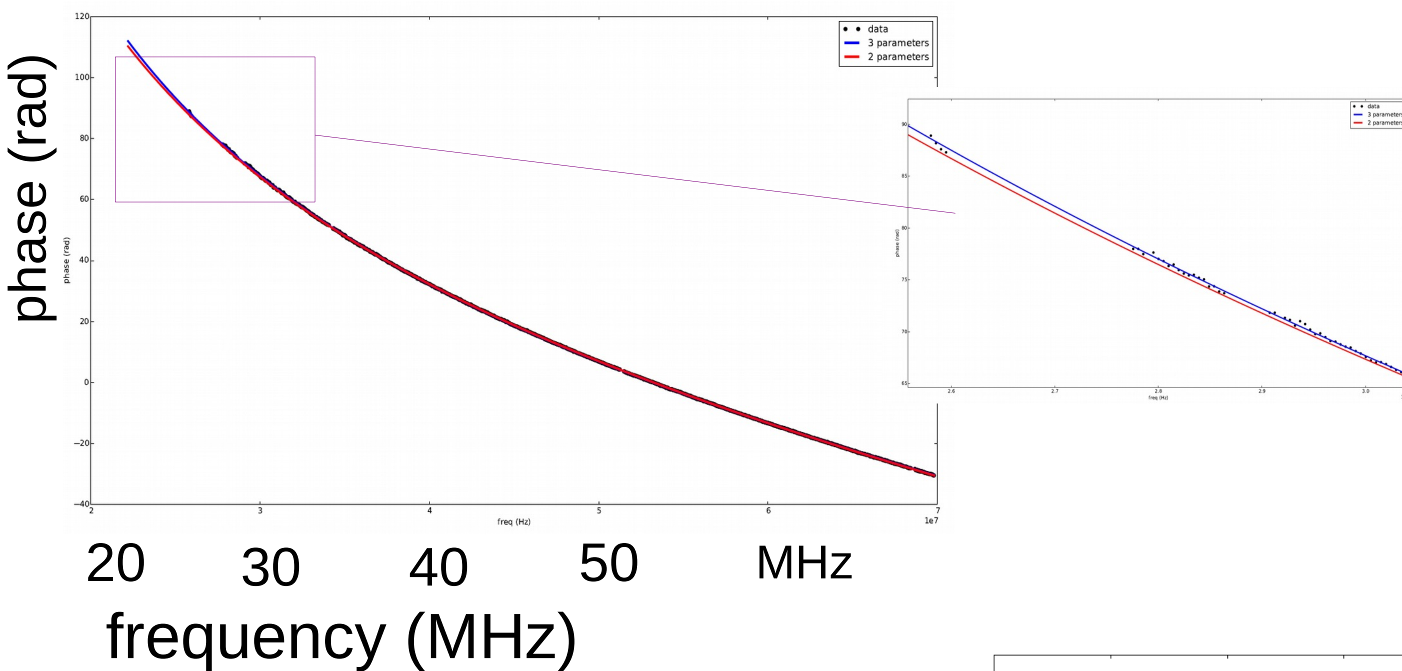
large TEC gradients: even visible in raw visibilities

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


dTEC different stations L78444
dTEC (TECU)
time since start of observation (hr)
0.2
0.0
−0.2
−0.4
−0.6
0
1
2
3
4
5
6
7
8
dTEC


diff Faraday rotation, all stations
diff RM (rad/m^2)
time (hr)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
0
1
2
3
4
5
6
7
8
dRM

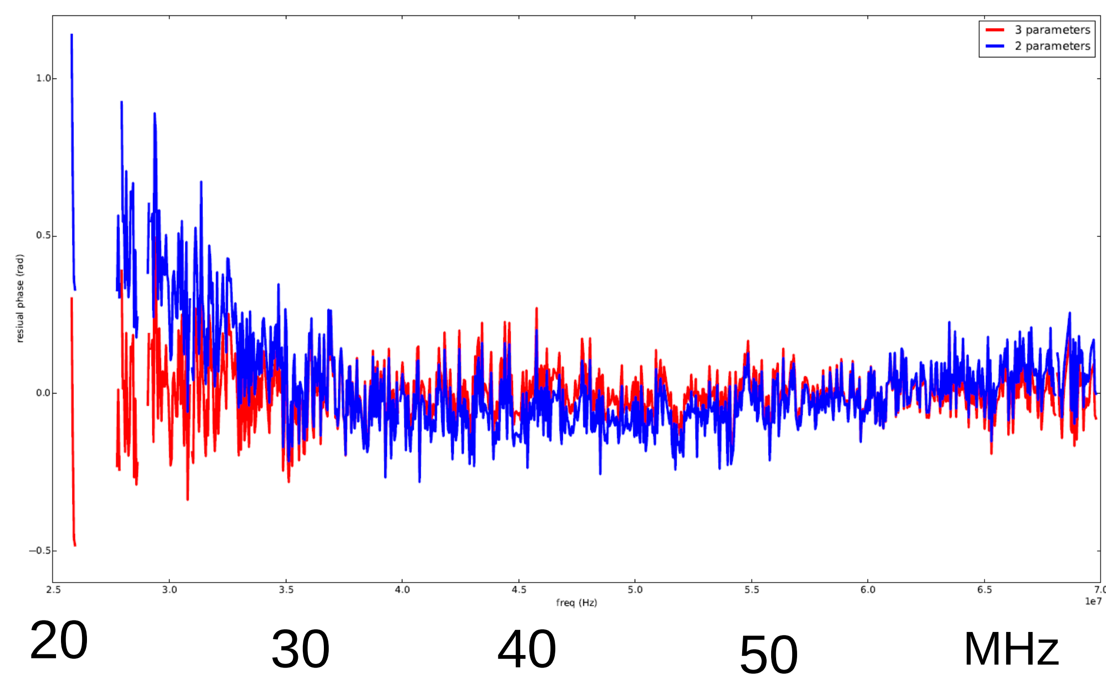
3^{rd} order



LBA:

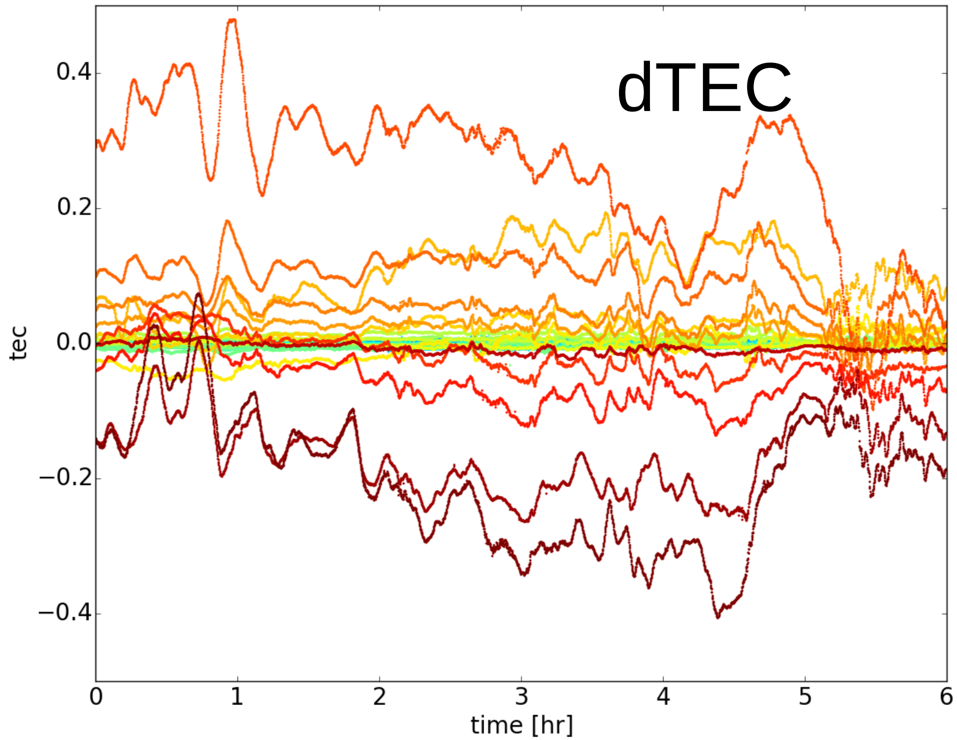
2 parameter Clock/TEC fit not sufficient for very low frequencies(<40 MHz)

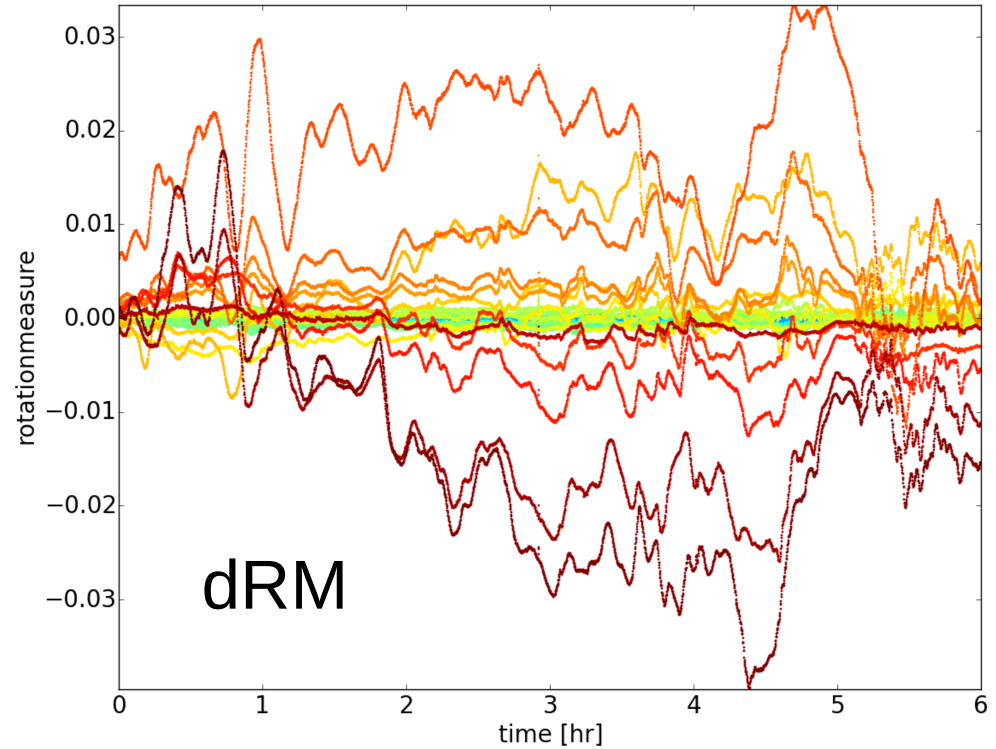
Residuals



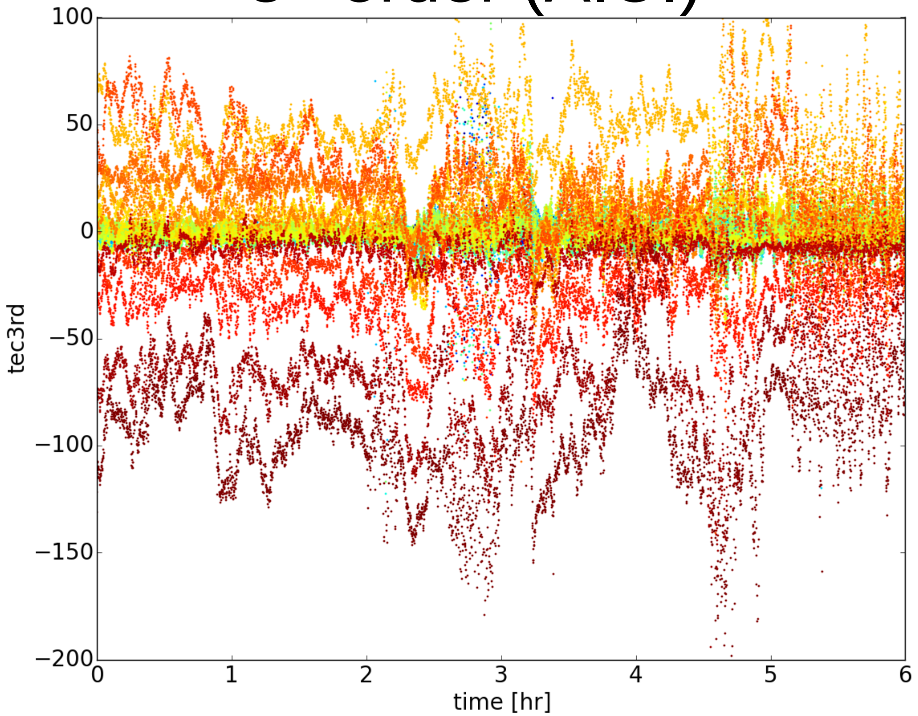
2 parameter fit ($\varphi(\nu)=A\nu+B/\nu$)

3 parameter fit ($\varphi(\nu)=A\nu+B/\nu+C/\nu^3$)





3^{rd} order (A.U.)



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_{max}

absolute TEC from dRM, B|| and dTEC

Structure function

Extract information from dTEC vs. time

Spatial fluctuations:

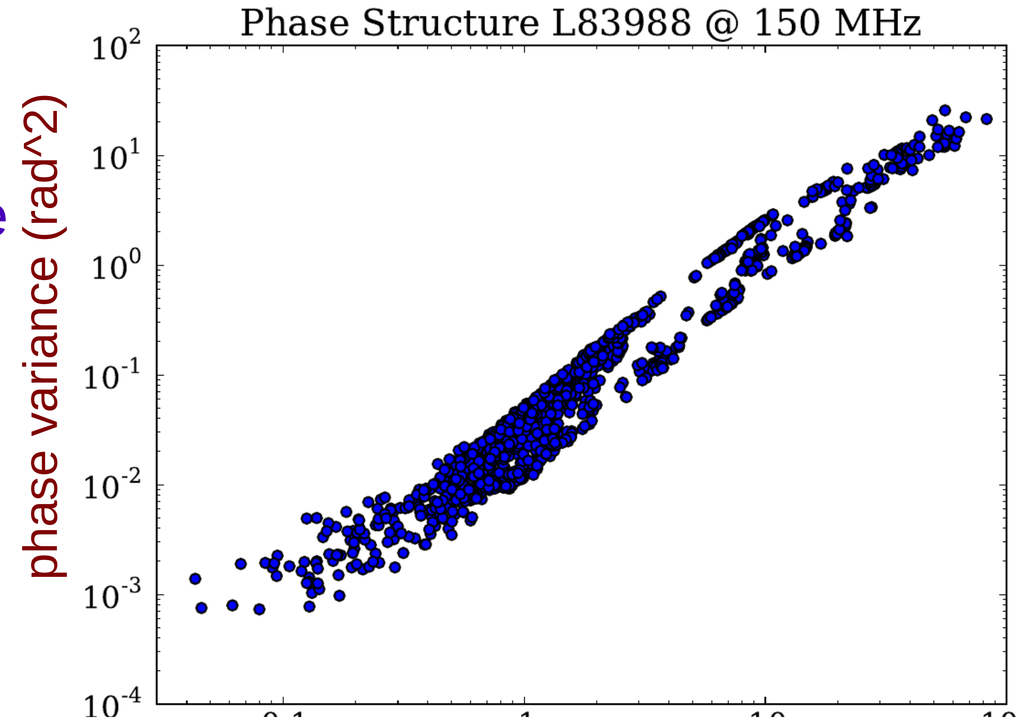
$$D_\varphi(||r_1 - r_2||) = \langle(\varphi_1 - \varphi_2)^2\rangle$$

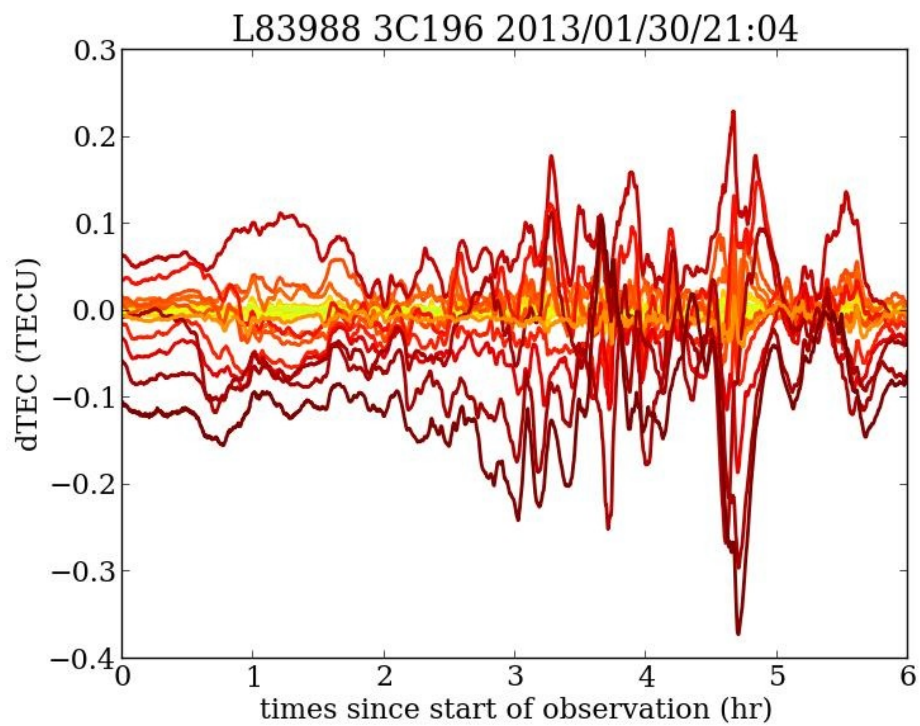
Kolmogorov turbulence, thin layer approximation:

$D_\varphi(\mathbf{r}) = (\mathbf{r} / s_0)^\beta$ $\beta = 5/3$,

s_0: diffractive scale,

$D_\varphi(s_0) = 1\ \mathrm{rad}^2$





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

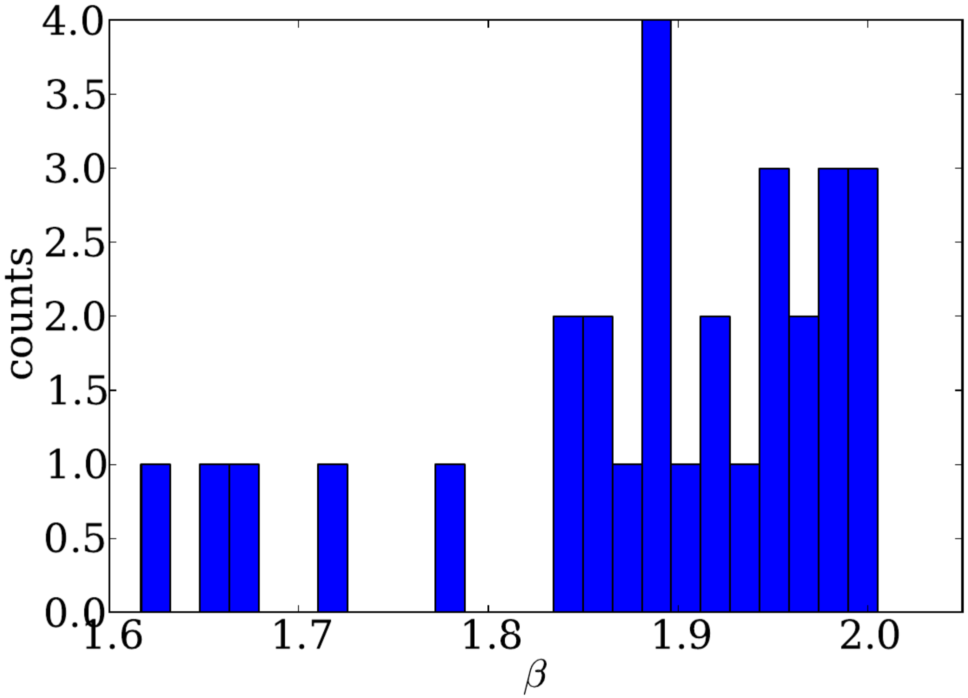
fit β, S_0

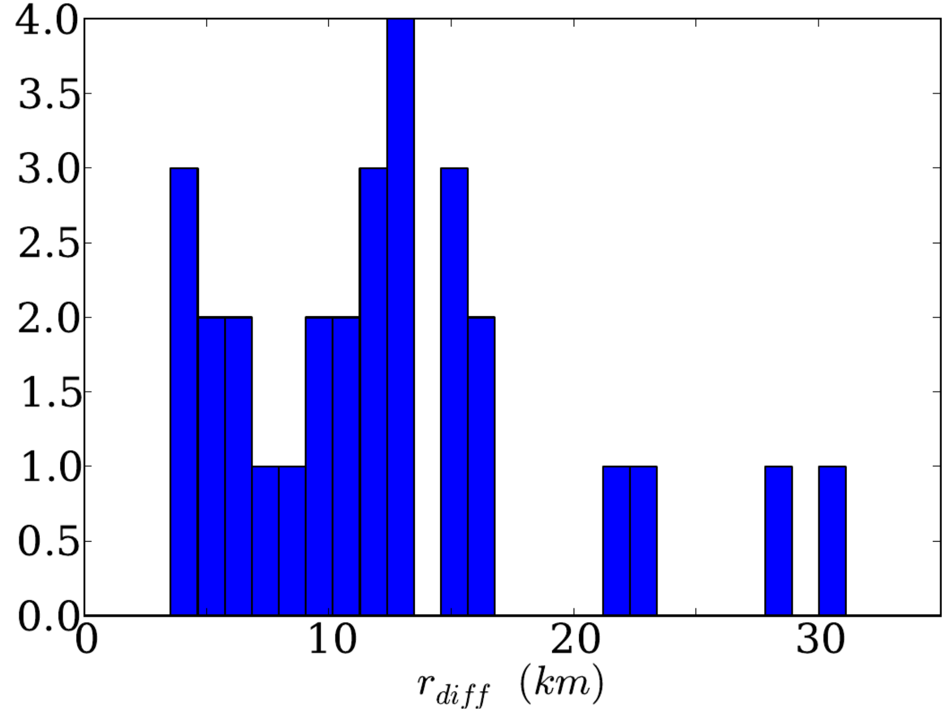
Typical nighttime S_0 @150 MHz: 2-40 km

scintillation conditions S_0<2km

Characterize ionospheric quality

Mevius et al. Radio Sciene 2016





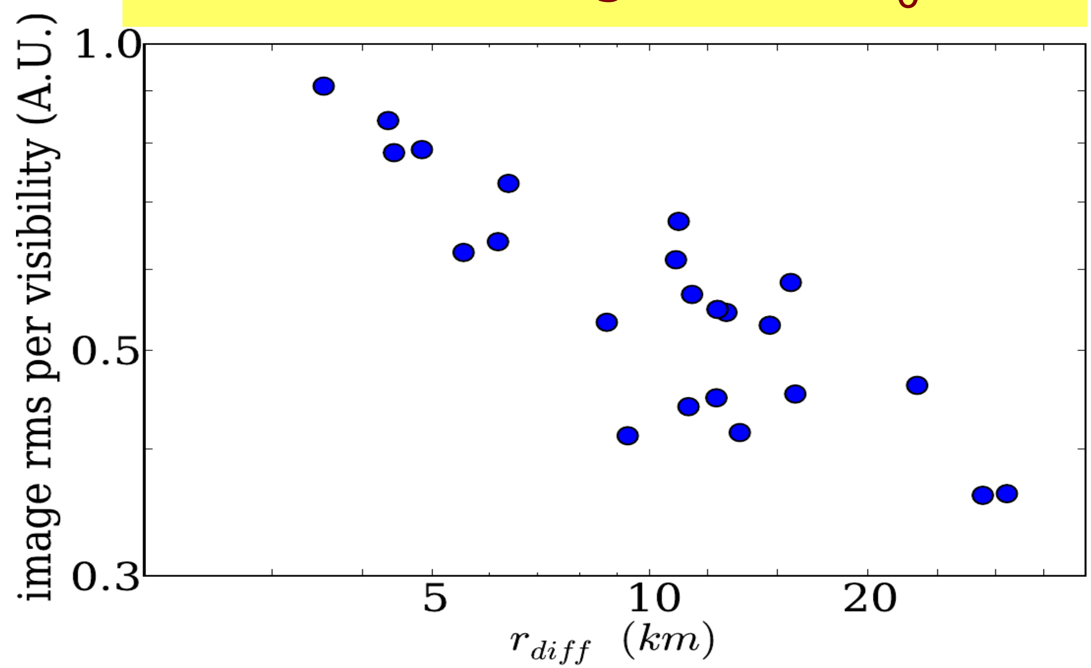
distribution of β and r_diff for 29 3C196 observations nighttime, winter

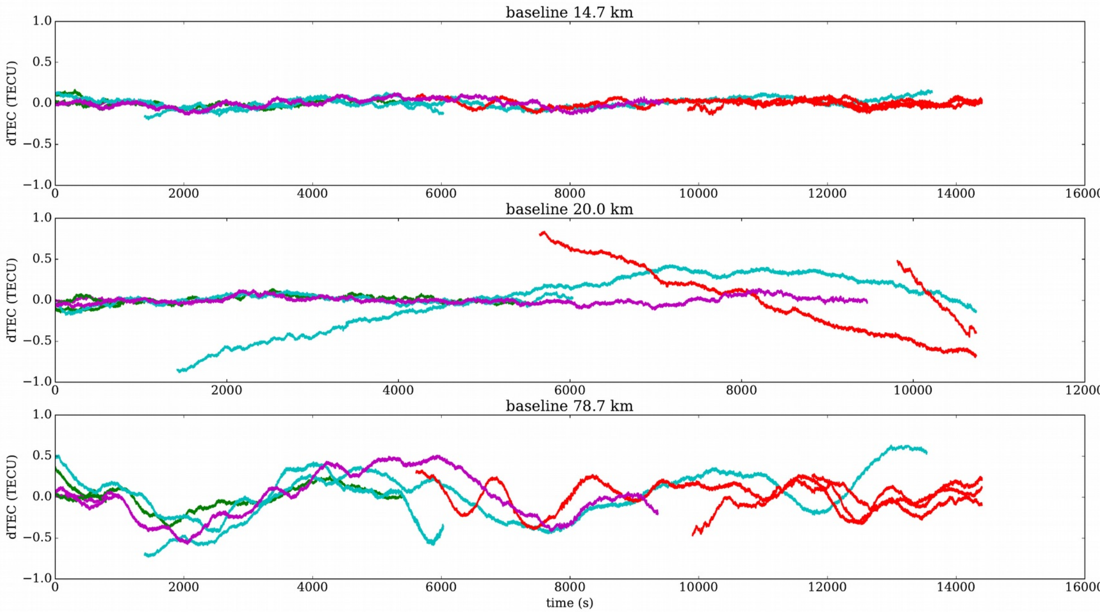
baseline length (km)

typically β larger than 5/3
r_diff varies between 3 and 30 km

Correlation with image noise after
DI-calibration only.

Correlation image noise S_0

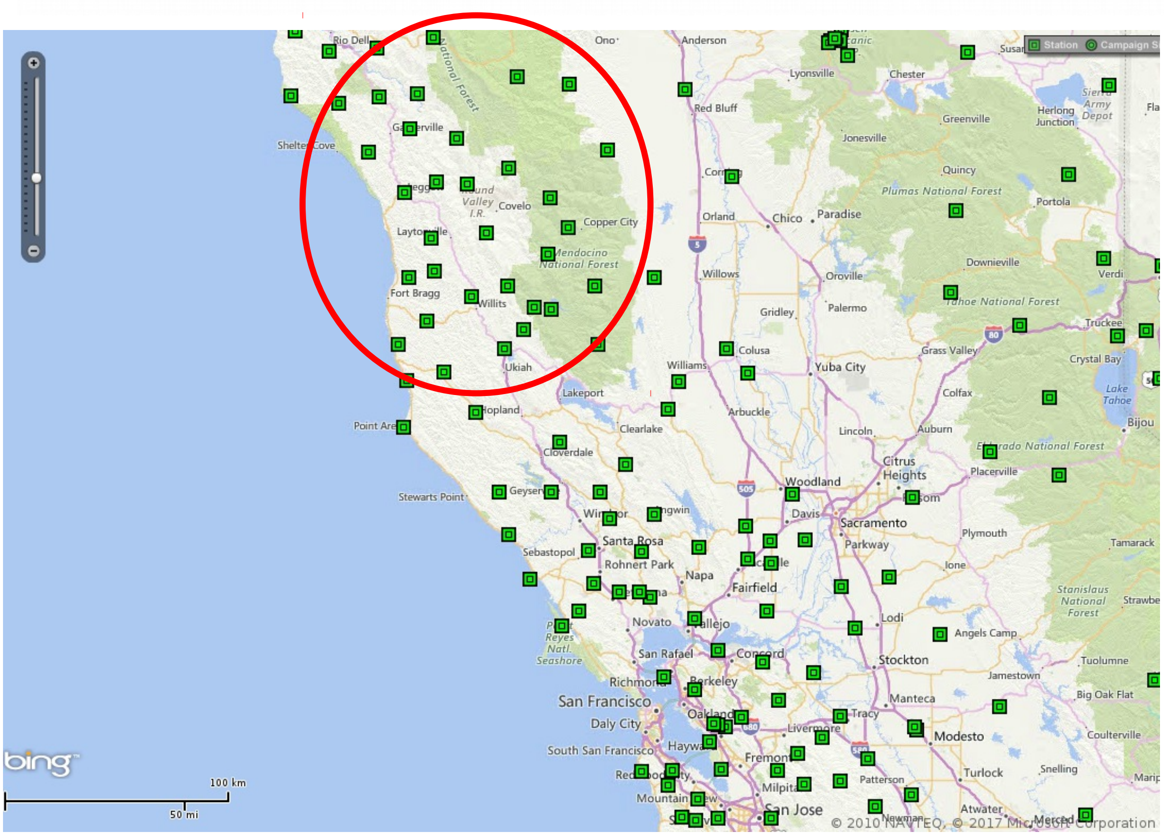


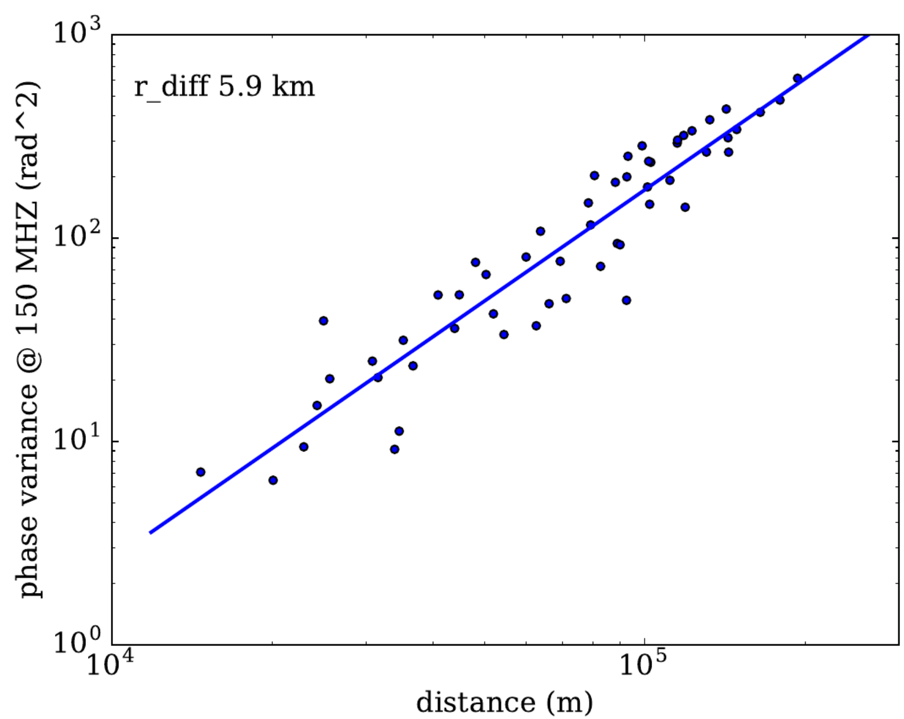


Even possible to extract r_diff from high time resolution raw GPS data

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 rad2

(frequency 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))

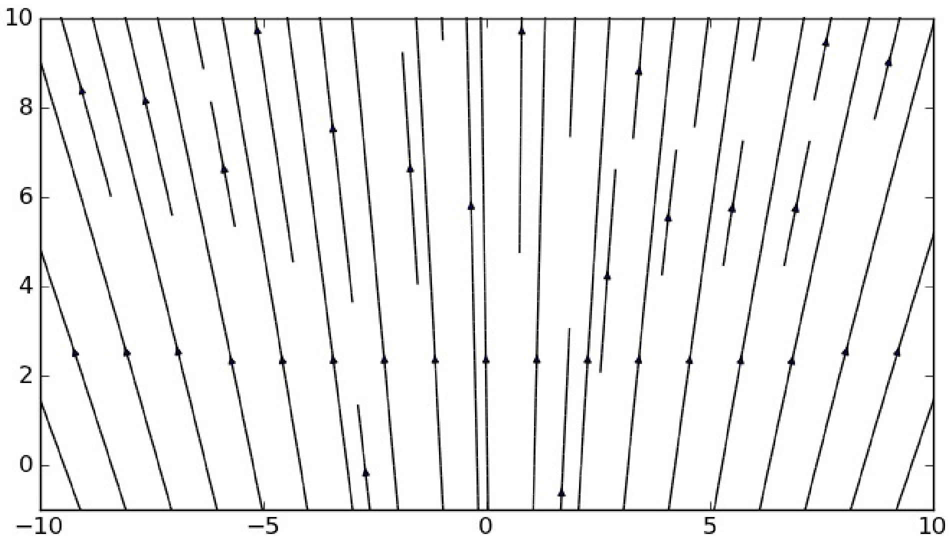
Easy to obtain from calibration phases, also for non-calibrator fields, without clock-TEC separation and from GPS data

Large Scale Field Aligned Structure

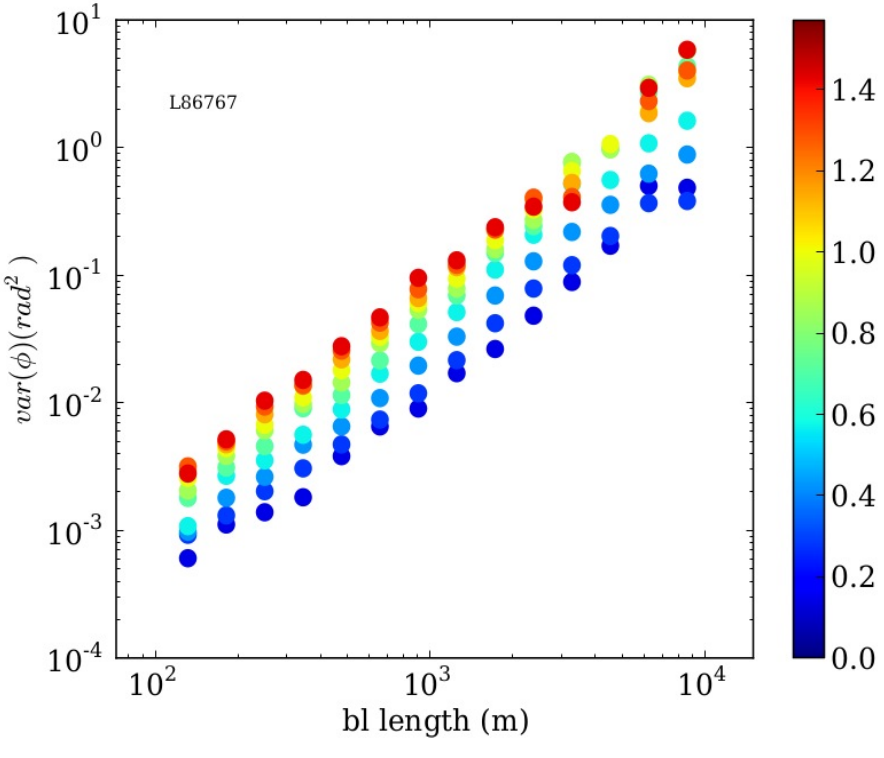
bandlike structure → orientation of the baseline

Earth magnetic field aligned?

projected field lines along LOS single ionospheric height



Earth magnetic field lines along viewing angle (NS/EW beam angle, zenith = 0,0)



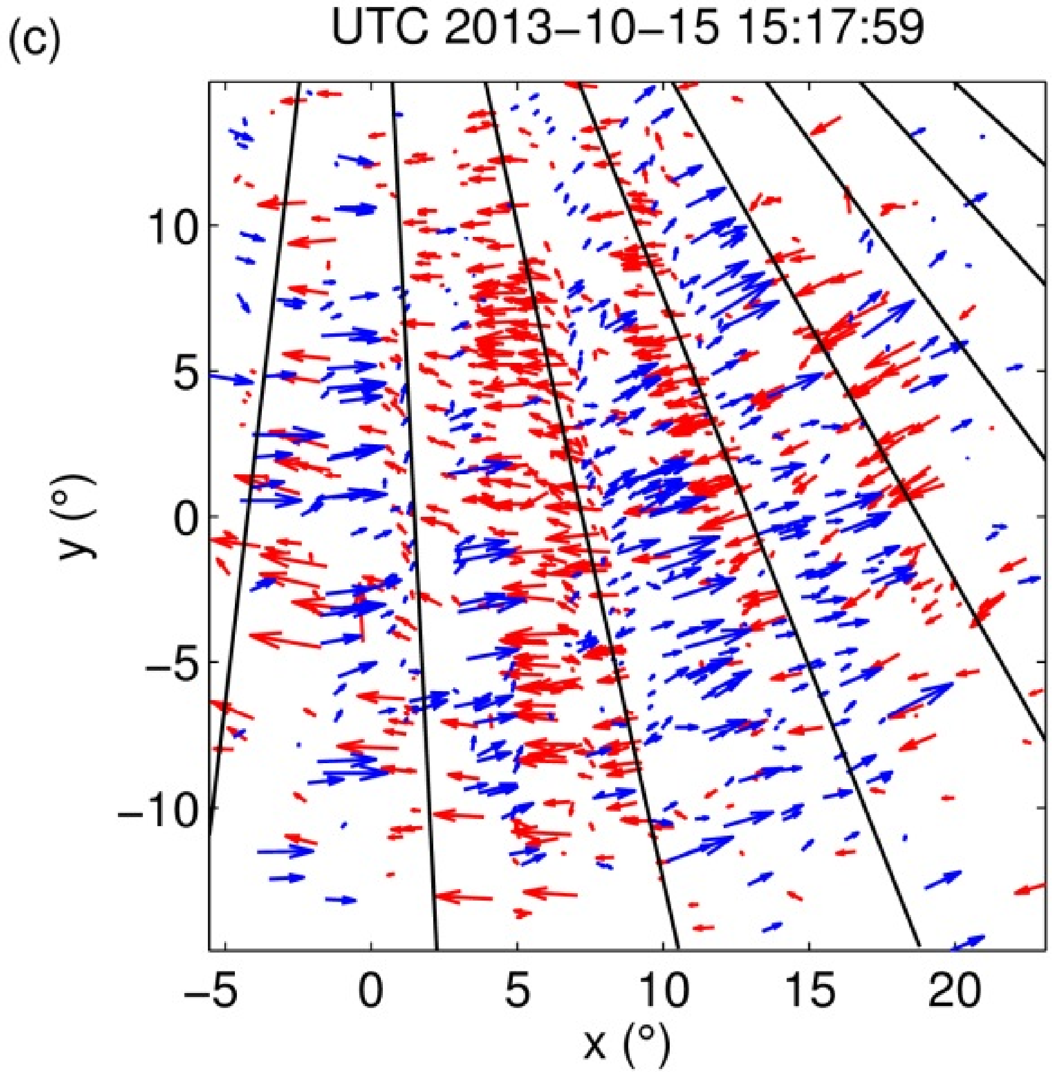
perspective view → time dependent orientation

bin data in according to angle wrst projected field lines

field aligned structure observed in ~ 50 % of the observations

Loi et al. GRL 2015

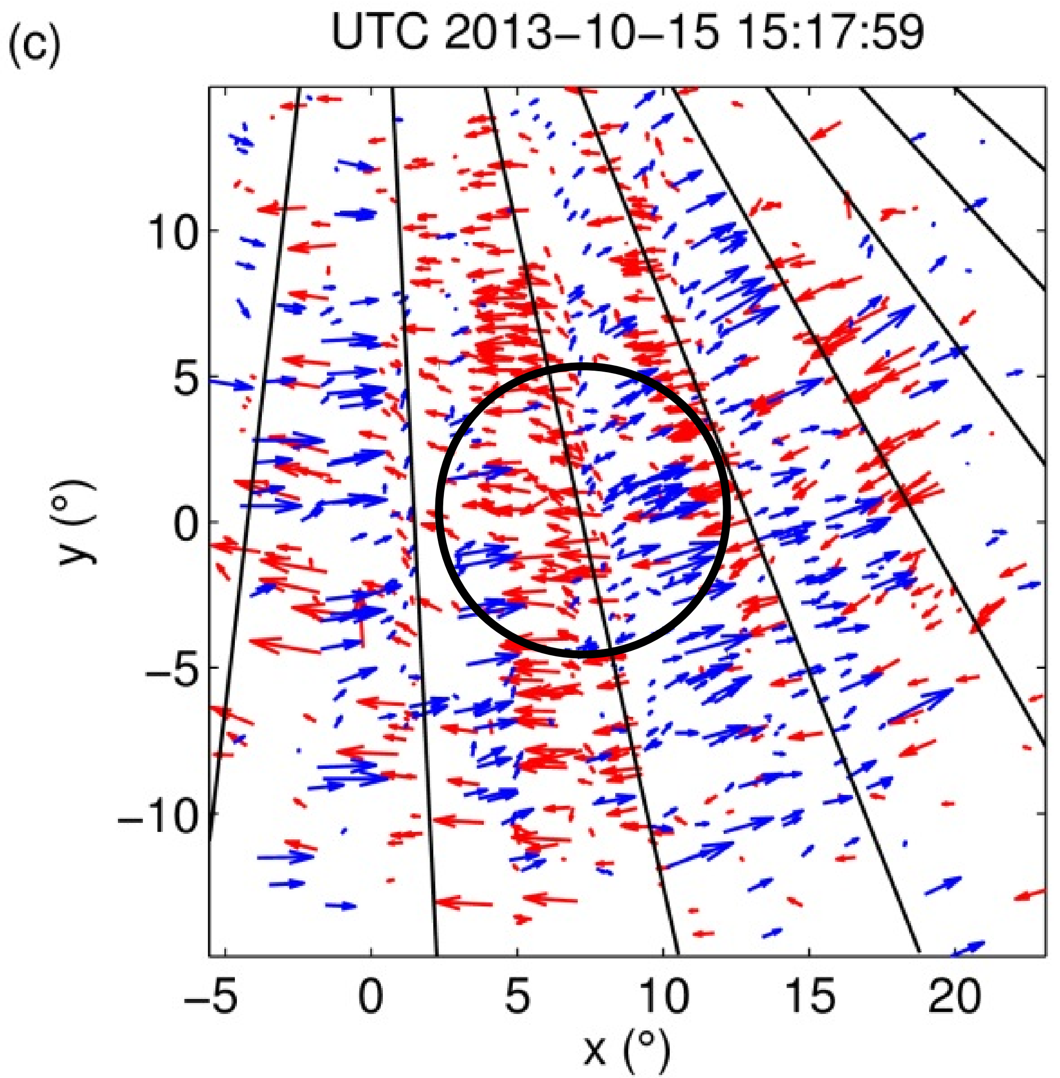
Real-time imaging of density ducts between the plasmasphere and ionosphere



Loi et al, GRL (2015) 42, 10

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

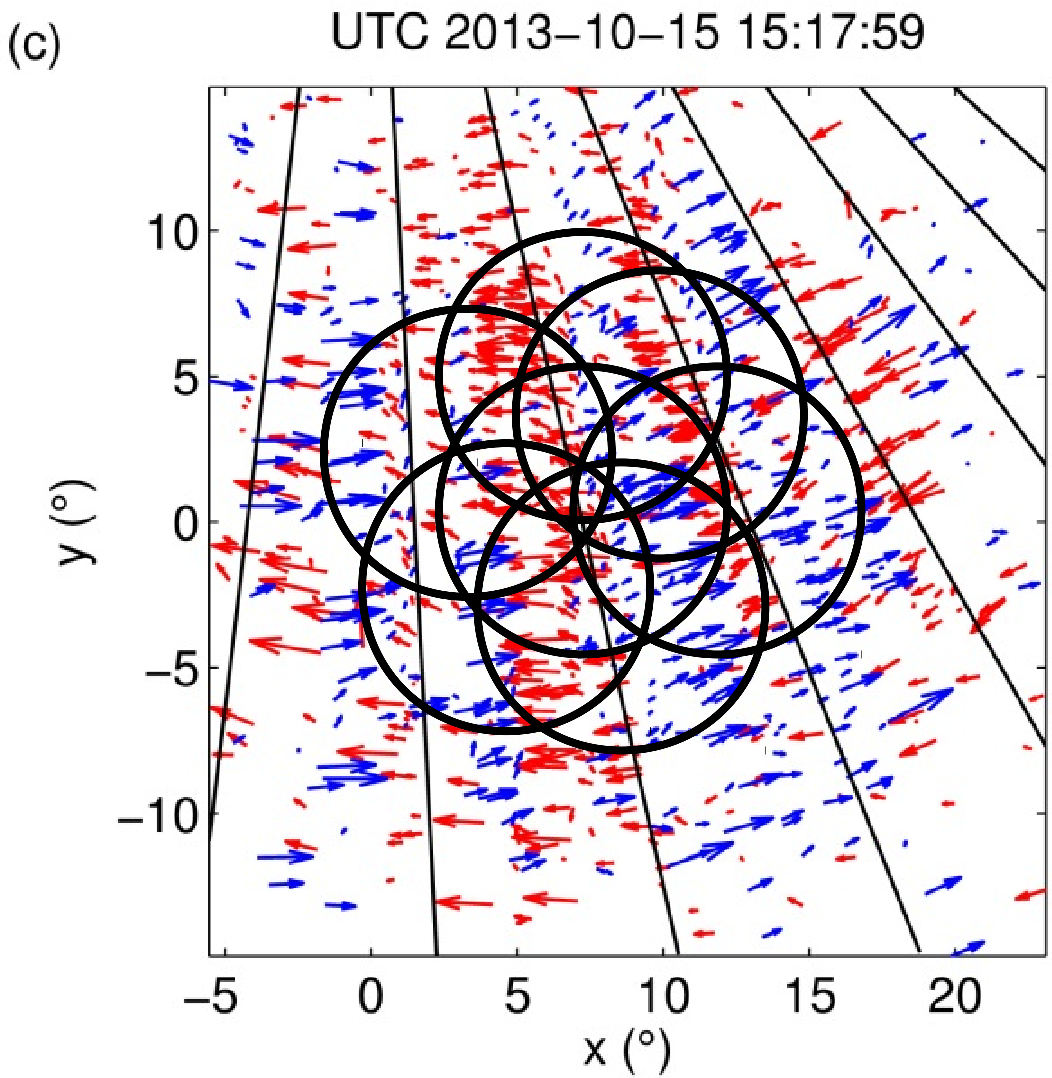
HBA beam



Loi et al, GRL (2015) 42, 10

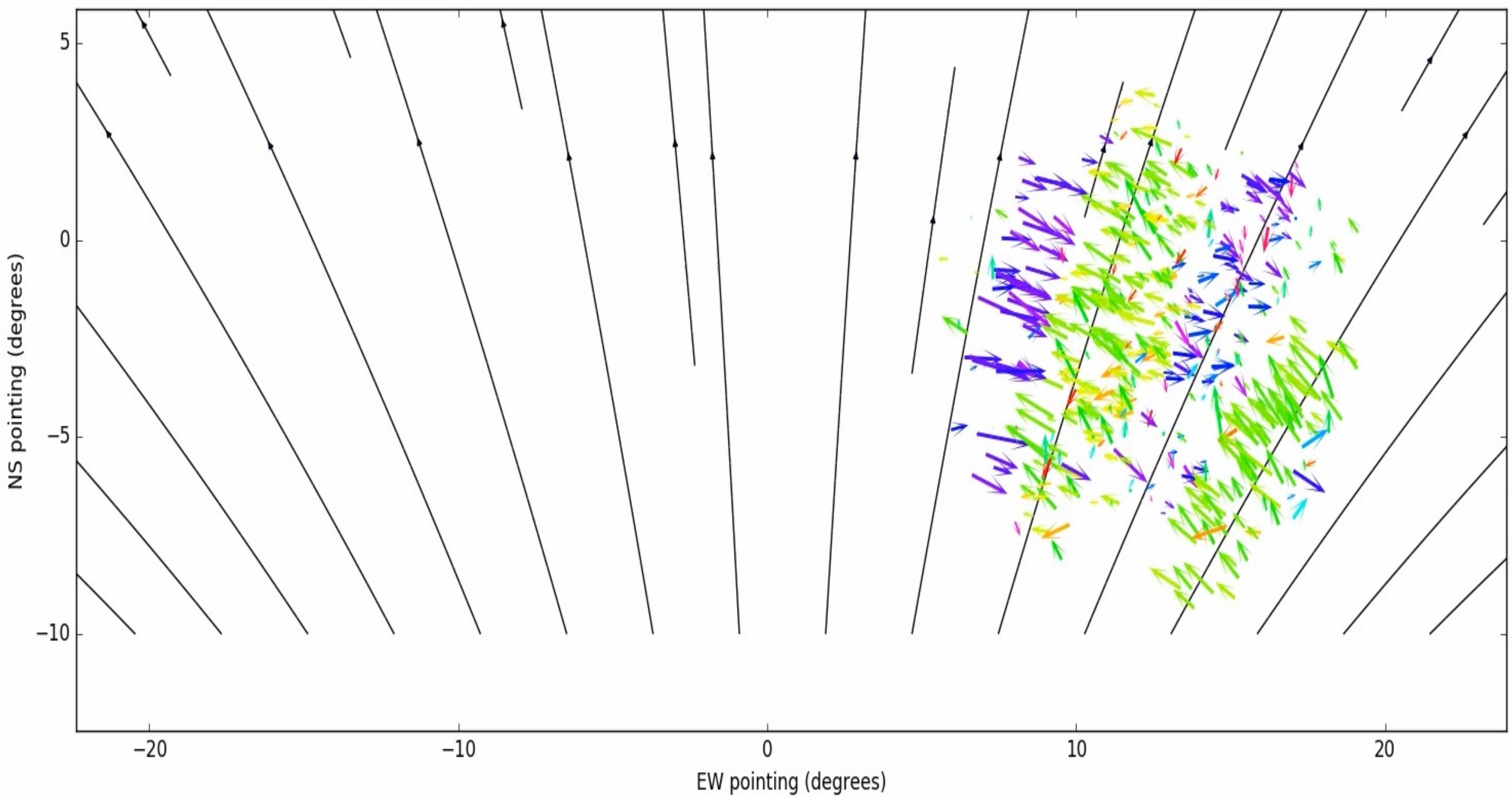
Do we observe the same structures with LOFAR?
single beam: too small FOV

flanking fields



Loi et al, GRL (2015) 42, 10

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



5
0
−5
−10
−20
−10
0
10
20
EW pointing (degrees)
NS pointing (degrees)

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 (multibeaming)