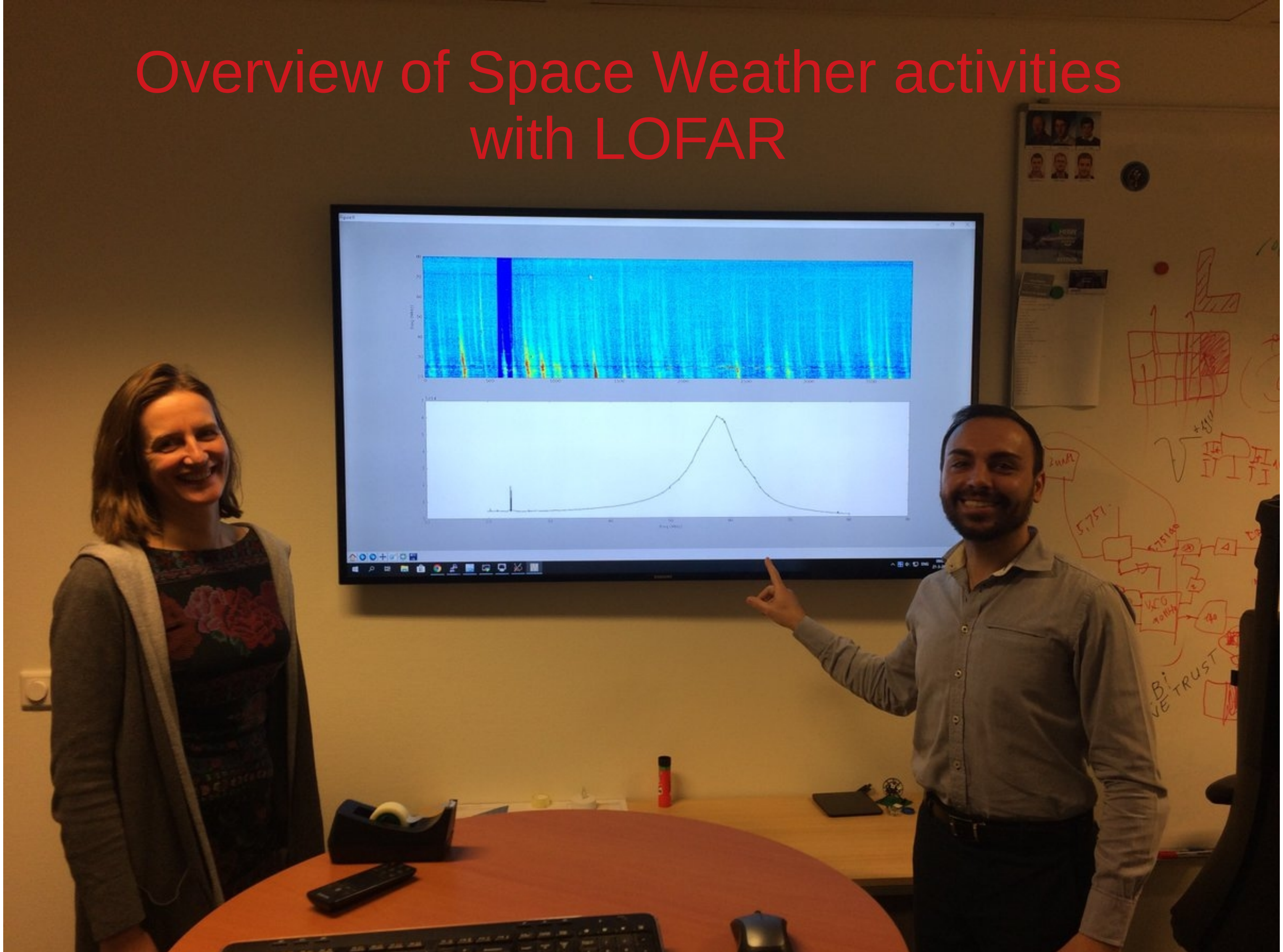
Overview of Space Weather activities with LOFAR



Absolute TEC Measurements using calibration solutions

M.Mevius
S.vd Tol
F. de Gasperin

ASTRON

LOFAR

Method

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

LOFAR calibration:

High accuracy phase solutions → c/t separation →
Very accurate differential TEC solutions (~1mTECU)

$$\Delta\phi(\nu) = A \cdot 2\pi\nu + B \cdot 8.4479745 \cdot 10^9 / \nu$$

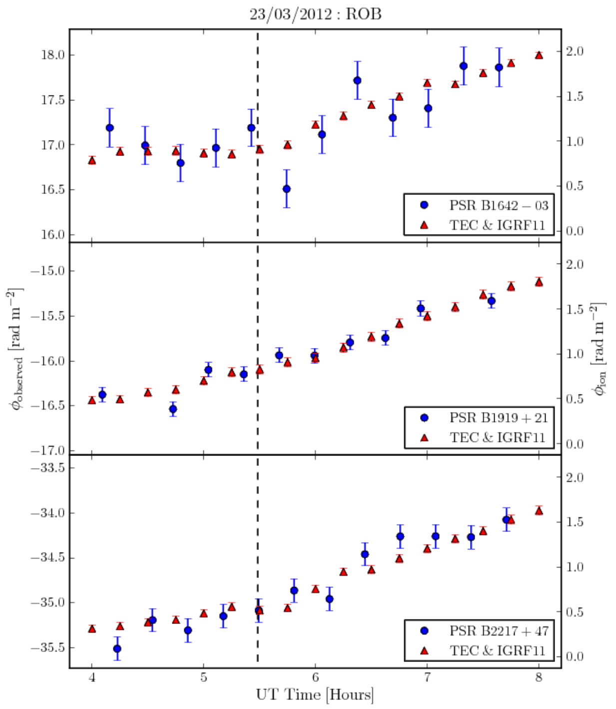
Differential Faraday Rotation: Artificial Polarization due to different Faraday Rotation Angle along two LOS →
ΔRM from rotation matrix

Differential only: NO information about absolute ionospheric electron density

Exception → Measure ionospheric Faraday rotation of polarized emission

Different method: Measure absolute TEC using correlation between ΔRM and ΔTEC from calibration

Sotomayor-Beltran et al (2013)



Faraday rotation:

$$\mathrm{RM} = C \int_{LOS} n_e \cdot B_{||}$$

Differential Faraday rotation:

$$C^{-1} \Delta \mathrm{RM}_{ij} = \int_{LOSi} n_e \cdot B_{||} dh - \int_{LOSj} n_e \cdot B_{||} dh$$

Thinscreen approach at altitude h

$$C^{-1} \Delta \mathrm{RM}_{ij} = \mathrm{STEC}_i \cdot B_{||hi} - \mathrm{STEC}_j \cdot B_{||hj}$$

$$\boxed{C^{-1} \Delta \mathrm{RM}_{ij} = \Delta \mathrm{STEC}_{ij} \cdot B_{||i} - \mathrm{STEC}_i \cdot \Delta B_{||ij}}$$

Faraday rotation:

$$\mathrm{RM} = C \int_{LOS} n_e \cdot B_{||}$$

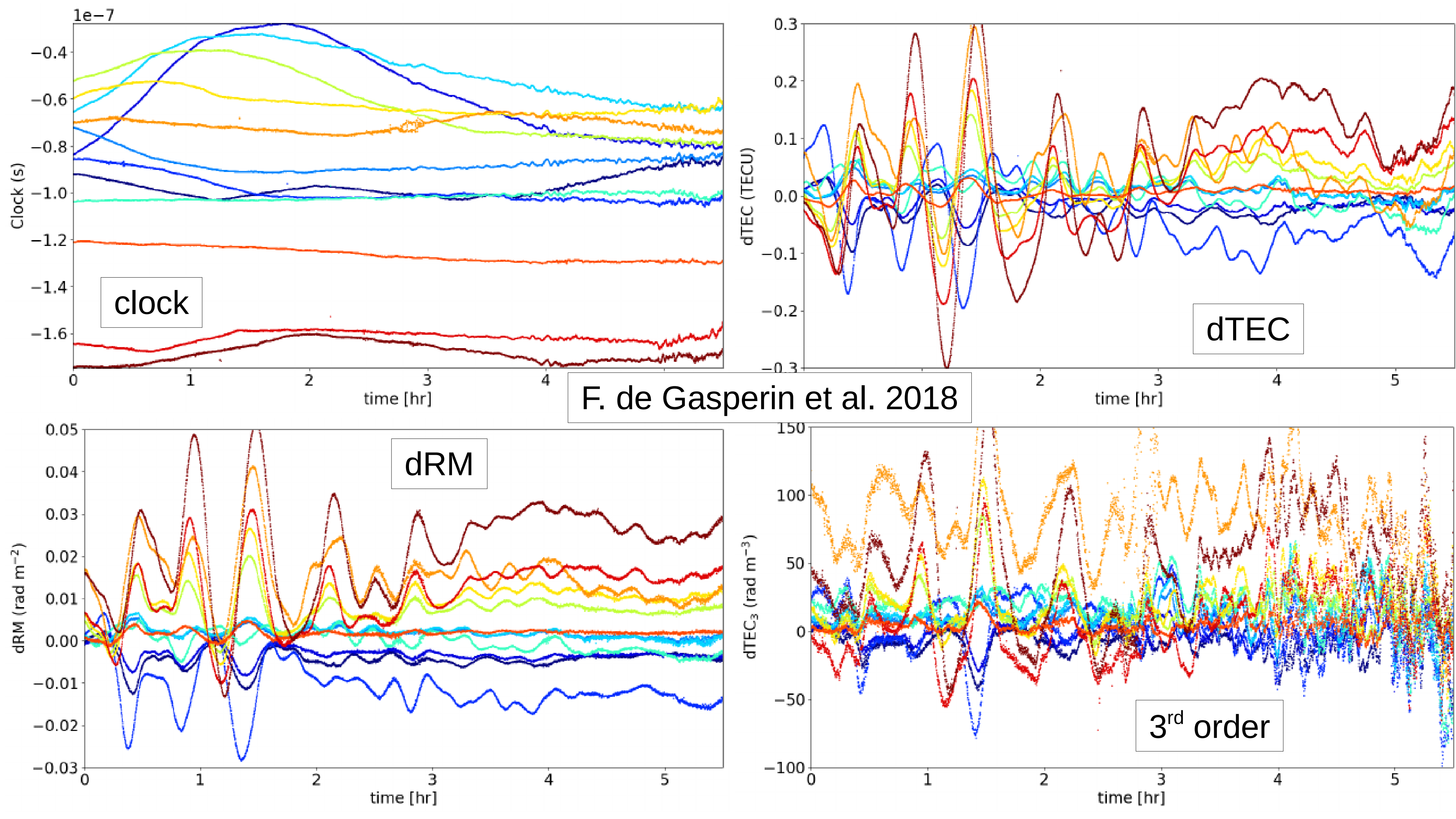
Differential Faraday rotation:

$$C^{-1}\Delta\mathrm{RM}_{ij} = \int_{LOSi} n_e \cdot B_{||} dh - \int_{LOSj} n_e \cdot B_{||} dh$$

Calibration solutions

$$C_j \cdot B_{||hj}$$

$$C^{-1}\Delta\mathrm{RM}_{ij} = \Delta\mathrm{STEC}_{ij} \cdot B_{||i} - \mathrm{STEC}_i \cdot \Delta B_{||ij}$$


1e−7
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
Clock (s)
clock
time [hr]
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
dTEC (TECU)
dTEC
time [hr]
F. de Gasperin et al. 2018
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
dRM (rad m⁻²)
dRM
time [hr]
150
100
50
0
−50
−100
dTEC₃ (rad m⁻³)
3rd order
time [hr]

Faraday rotation:

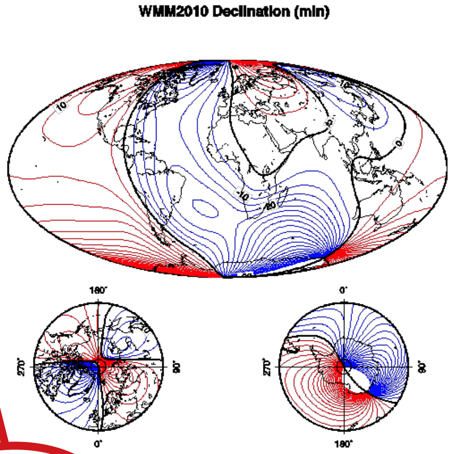
$$\mathrm{RM} = C \int_{LOS} n_e \cdot B_{||}$$

Differential Faraday rotation:

$$C^{-1}\Delta \mathrm{RM}_{ij} = \int_{LOSi} n_e \cdot B_{||} dh - \int_{LOSj} n_e \cdot B_{||} dh$$

External Models (WMM)

Calibration solutions



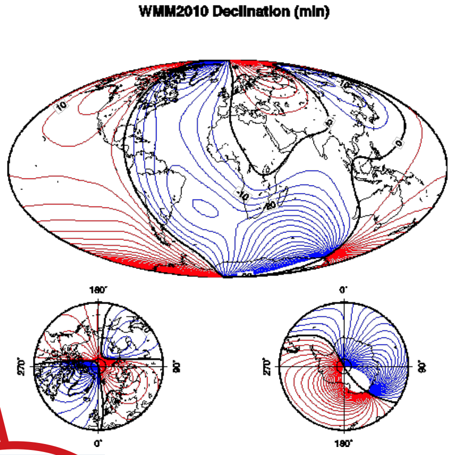
$$C^{-1}\Delta \mathrm{RM}_{ij} = \Delta \mathrm{STEC}_{ij} \cdot B_{||i} + \mathrm{STEC}_i \cdot \Delta B_{||ij}$$

Absolute slant TEC

External Models (WMM)

Differential Faraday rotation:

$$C^{-1}\Delta \mathrm{RM}_{ij} = \int_{LOSi} n_e \cdot B_{||} dh - \int_{LOSj} n_e \cdot B_{||} dh$$



Calibration solutions

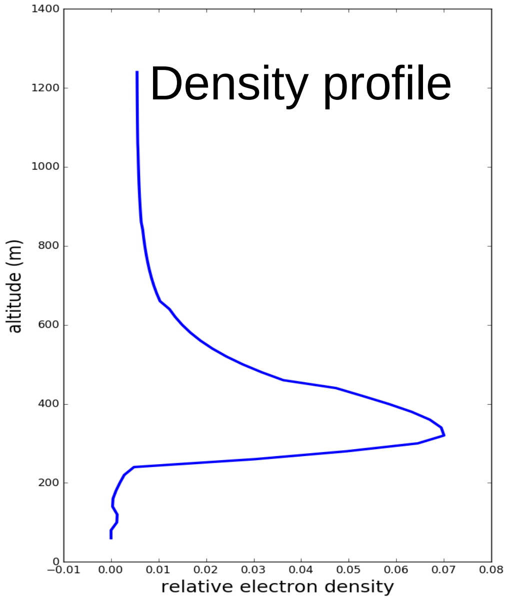
$$C^{-1}\Delta \mathrm{RM}_{ij} = \Delta \mathrm{STEC}_{ij} \cdot B_{||i} + \mathrm{STEC}_i \cdot \Delta B_{||ij}$$

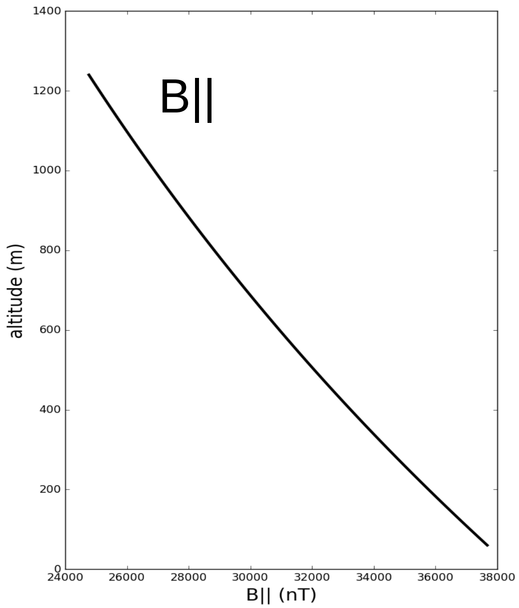
Method

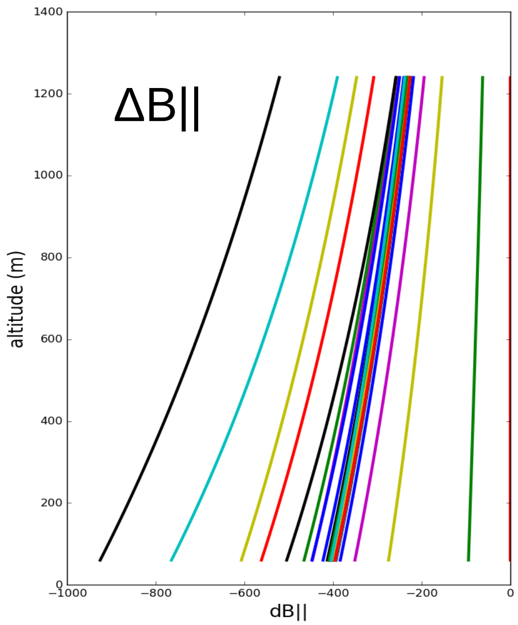
RMextract [ascl:1806.024]

$$\mathrm{STEC}_i = (C^{-1}\Delta\mathrm{RM}_{ij} - \Delta\mathrm{STEC}_{ij} \cdot B_{||i})/\Delta B_{||ij}$$

Bfield models reasonably well know (~5%)
Large uncertainty from ΔB||
Longer baselines → lower uncertainty
Select data where ΔB||> 100 nT







Thinscreen approach:

Altitude dependence of B||, ΔB||

h=300km

Use airmass correction to convert sTEC→ vTEC
Comparison with IONEX

data: LBA calibrator data

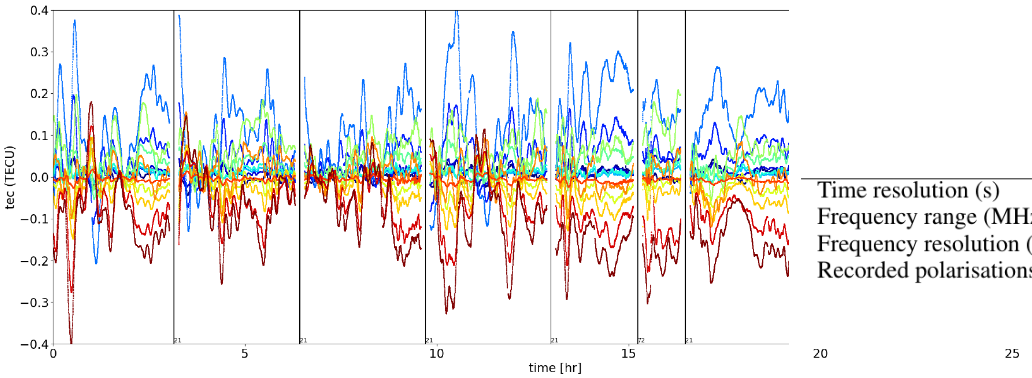
Provided/calibrated by
F. de Gasperin

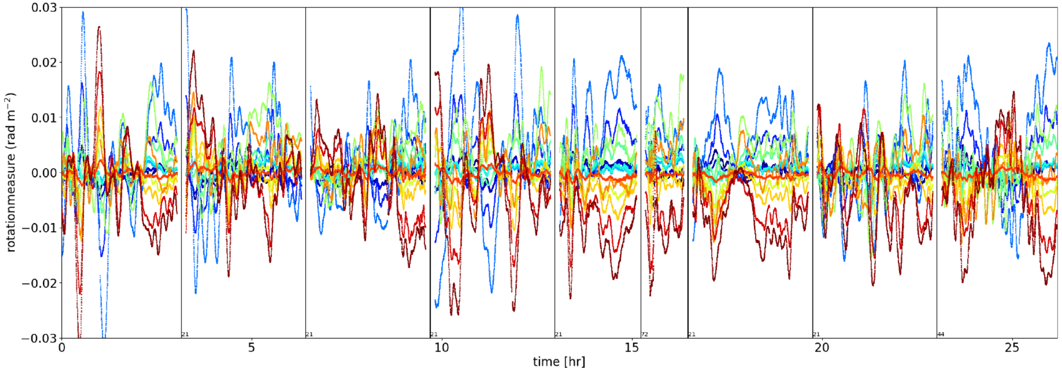
3c295/3c380 (Nov 2017)

3c196(Bootes 2013/2018)

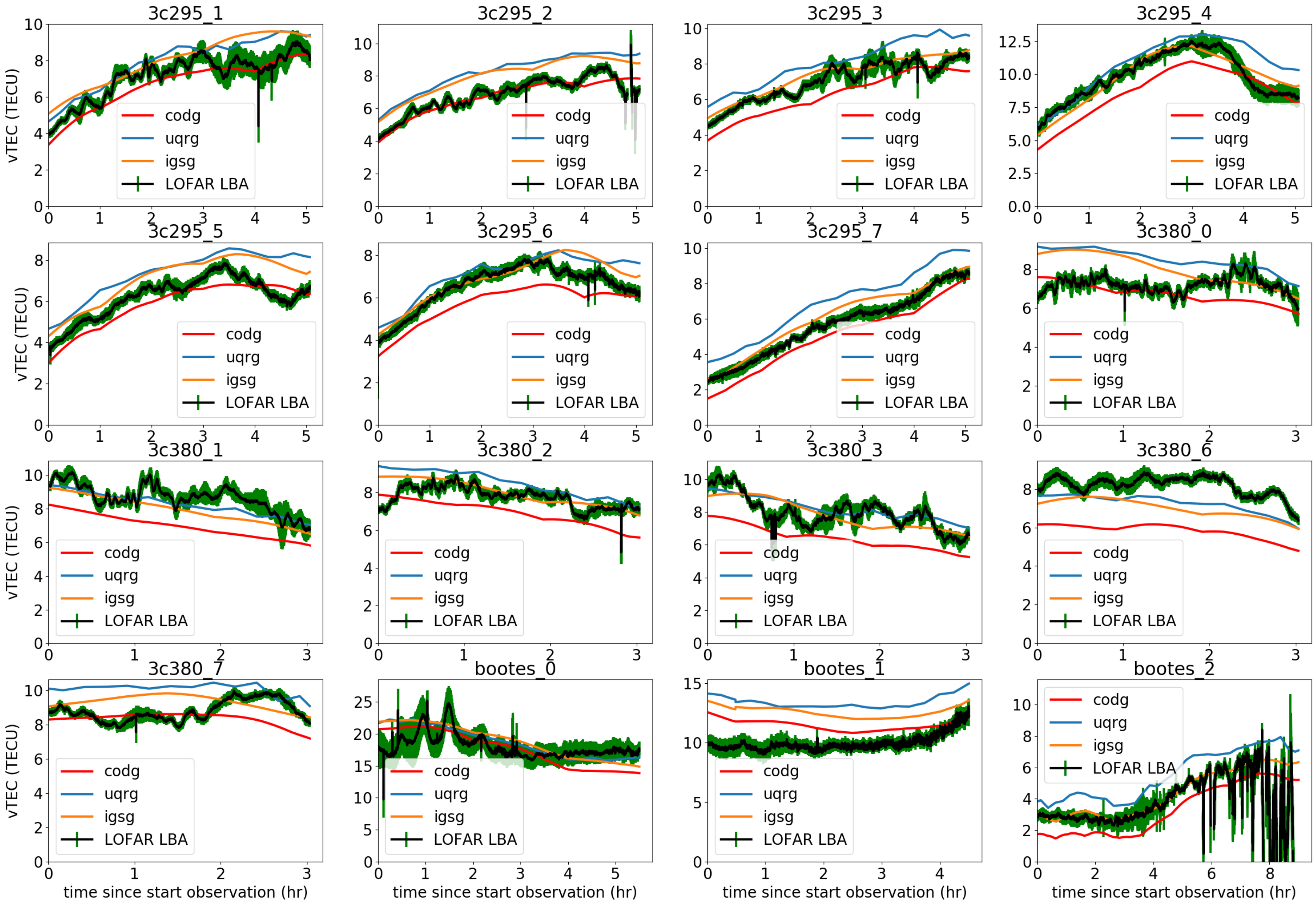
Target Name	3C196	3C295	3C380
RA (J2000)	08:13:36.1	14:11:20.3	18:29:31.8
Dec (J2000)	+48:13:02	+52:12:10	+48:44:46
Date	03 May 2013	17 Nov 2017 18 Nov 2017 19 Nov 2017 20 Nov 2017 21 Nov 2017 25 Nov 2017 26 Nov 2017 28 Nov 2017	17 Nov 2017 18 Nov 2017 19 Nov 2017 20 Nov 2017 21 Nov 2017 24 Nov 2017 25 Nov 2017 26 Nov 2017 28 Nov 2017
Time range (UTC)	18:00 → 23:30 (5.5 hr)	07:00 → 12:04 (5 hr) 07:00 → 12:04 (5 hr) 07:00 → 12:04 (5 hr) 07:00 → 12:04 (5 hr) 07:00 → 12:04 (5 hr) 07:00 → 12:04 (5 hr) 07:00 → 12:04 (5 hr) 06:00 → 11:04 (5 hr)	12:05 → 15:07 (3 hr) 12:05 → 15:07 (3 hr) 12:05 → 15:07 (3 hr) 12:05 → 15:07 (3 hr) 12:05 → 14:06 (2 hr) 14:00 → 15:00 (1 hr) 12:05 → 15:07 (3 hr) 12:05 → 15:07 (3 hr) 11:05 → 14:07 (3 hr)
Time resolution (s)	5	4	4
Frequency range (MHz)	22 – 70	42 – 66	42 – 66
Frequency resolution (kHz)	195.3 (244 channels)	48.8 (122 channels)	48.8 (122 channels)
Recorded polarisations	XX XY YX YY	XX XY YX YY	XX XY YX YY

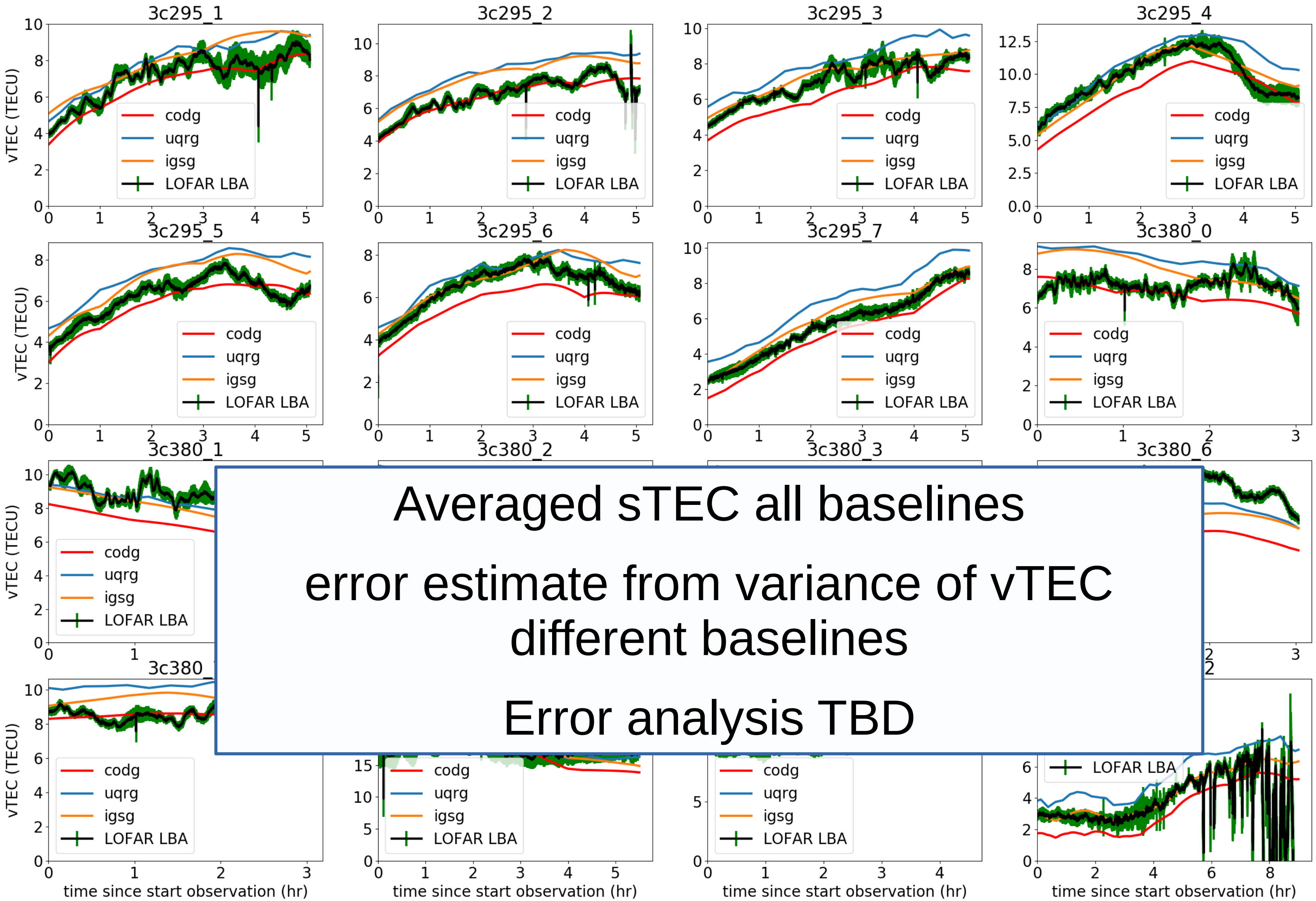
Table 2: Observation details





de Gasperin et al. A&A2018

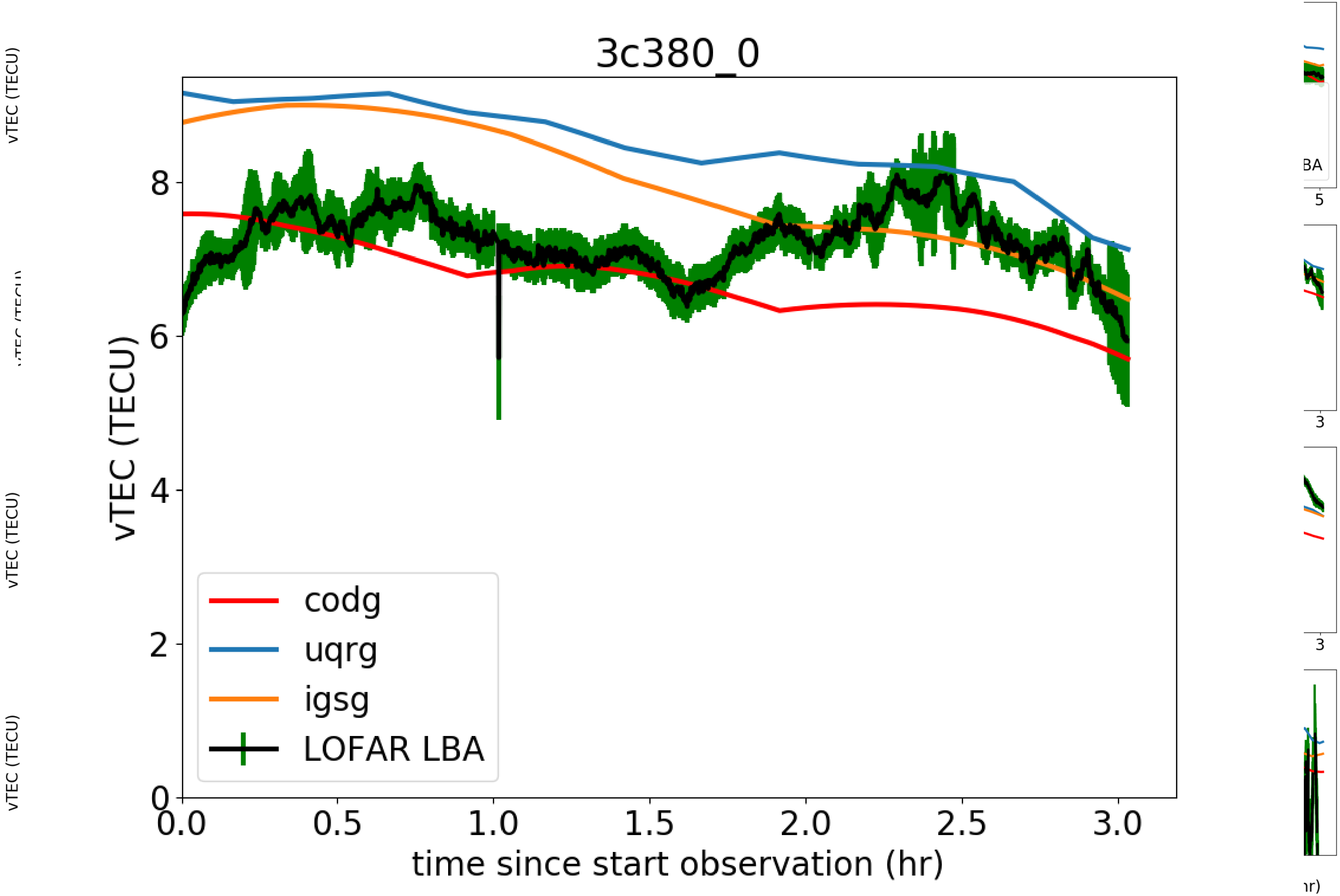

3c295_1
3c295_2
3c295_3
3c295_4
3c295_5
3c295_6
3c295_7
3c380_0
3c380_1
3c380_2
3c380_3
3c380_6
3c380_7
bootes_0
bootes_1
bootes_2
vTEC (TECU)
time since start observation (hr)
codg
uqrg
igsg
LOFAR LBA



Averaged sTEC all baselines

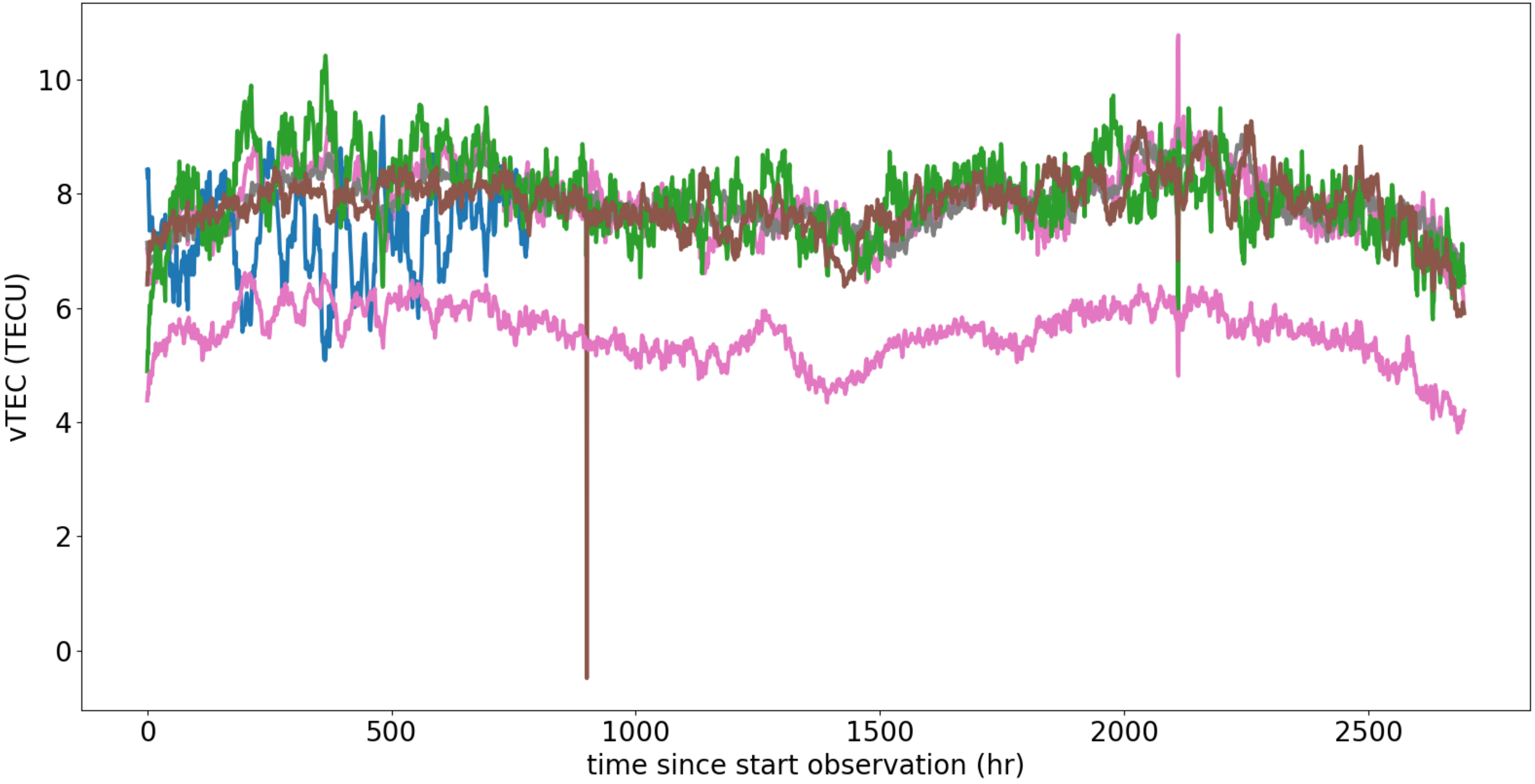
error estimate from variance of vTEC different baselines

Error analysis TBD



3c380_0
vTEC (TECU)
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
time since start observation (hr)
codg
uqrg
igsg
LOFAR LBA

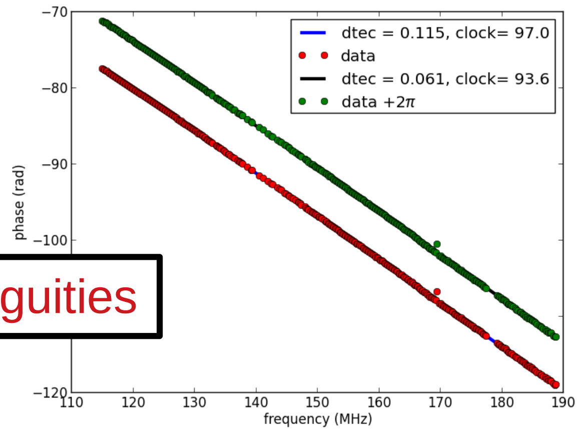
TEC variation different baselines



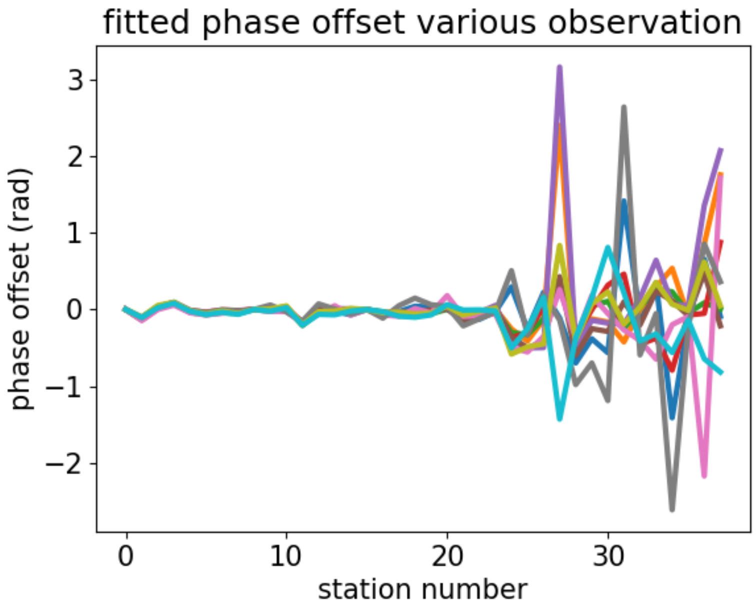
dTEC systematic uncertainty phase offset

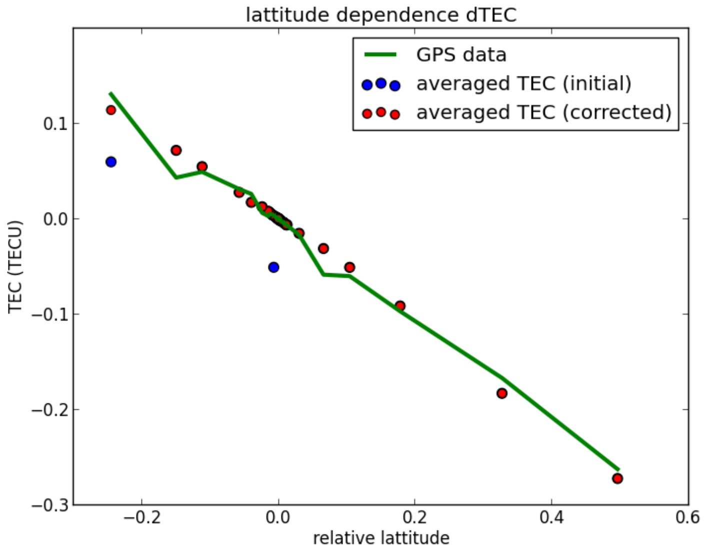
$$\Delta\phi(\nu) = A \cdot 2\pi\nu + B \cdot 8.4479745 \cdot 10^9/\nu$$

A constant (t,ν) phase offset will result in a constant dTEC offset if not taken into account
Fit using spatial constraint on average dTEC
Works reasonable for CS, not for RS



2π ambiguities

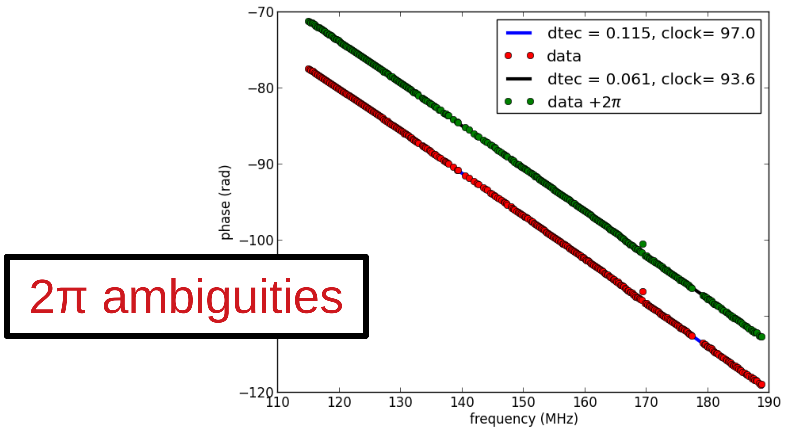


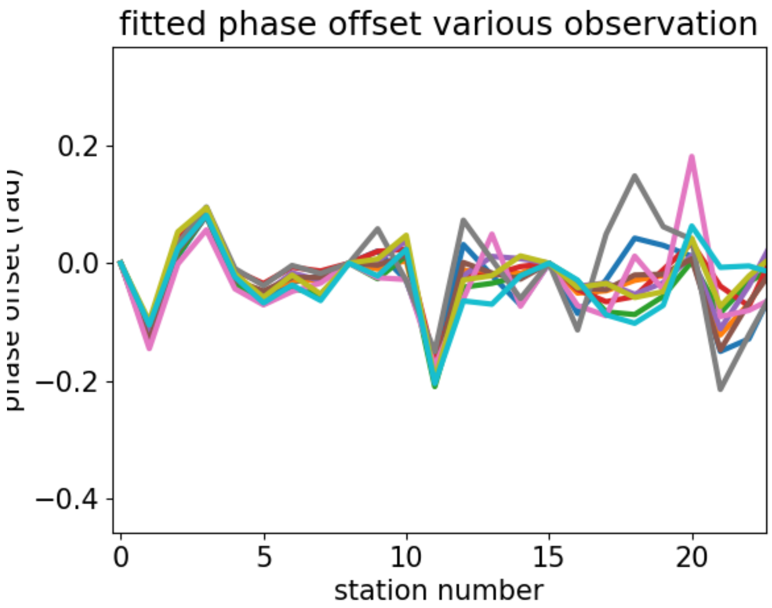


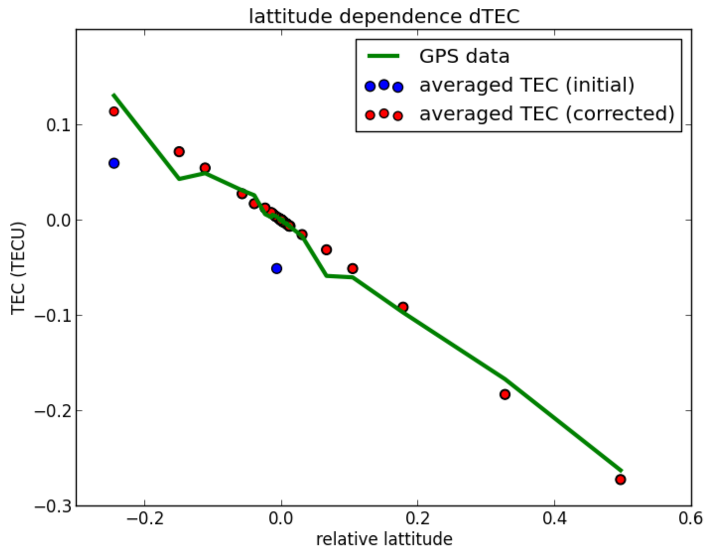
dTEC systematic uncertainty phase offset

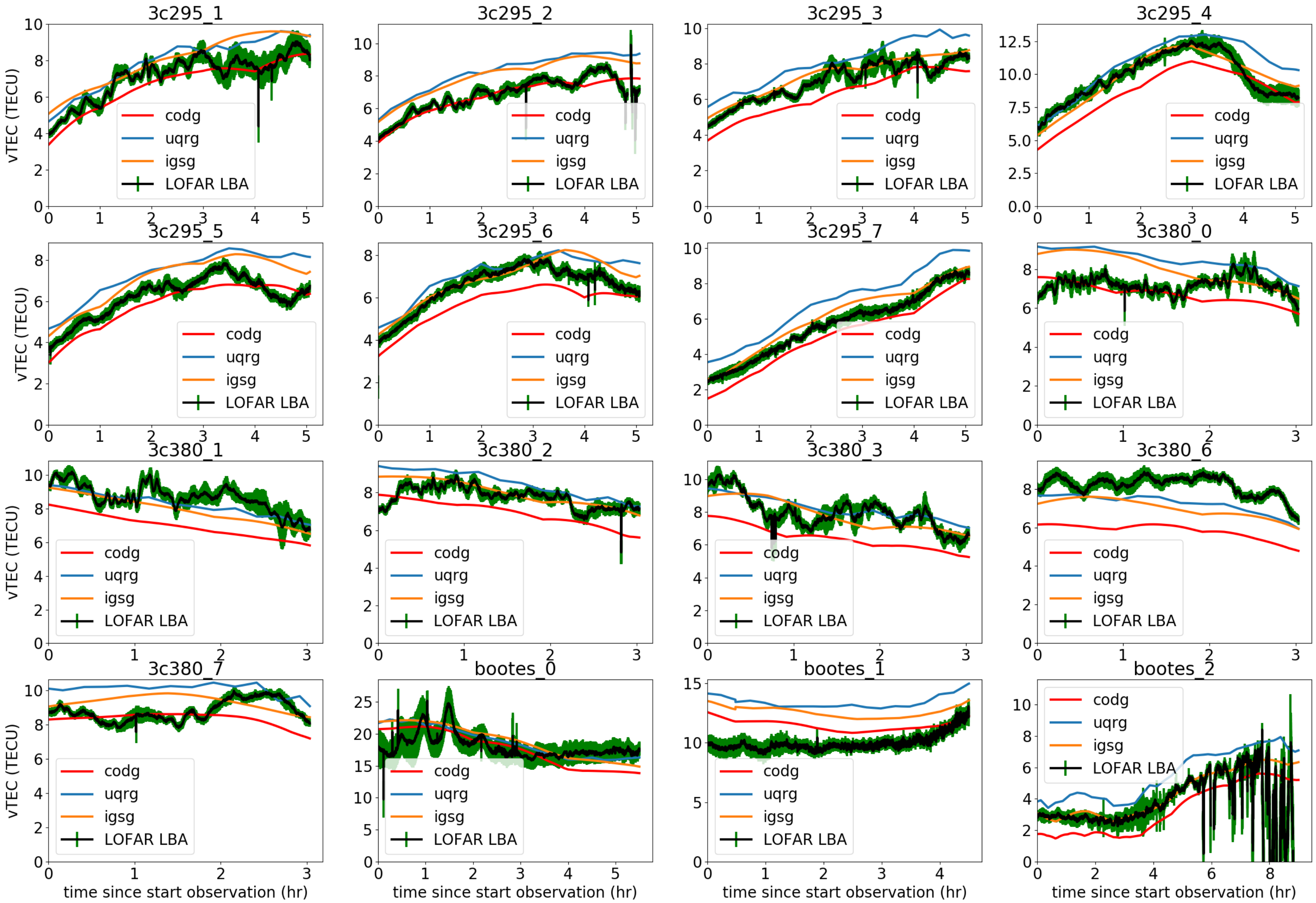
$$\Delta\phi(\nu) = A \cdot 2\pi\nu + B \cdot 8.4479745 \cdot 10^9 / \nu$$

A constant (t,ν) phase offset will result in a constant dTEC offset if not taken into account
Fit using spatial constraint on average dTEC
Works reasonable for CS, not for RS

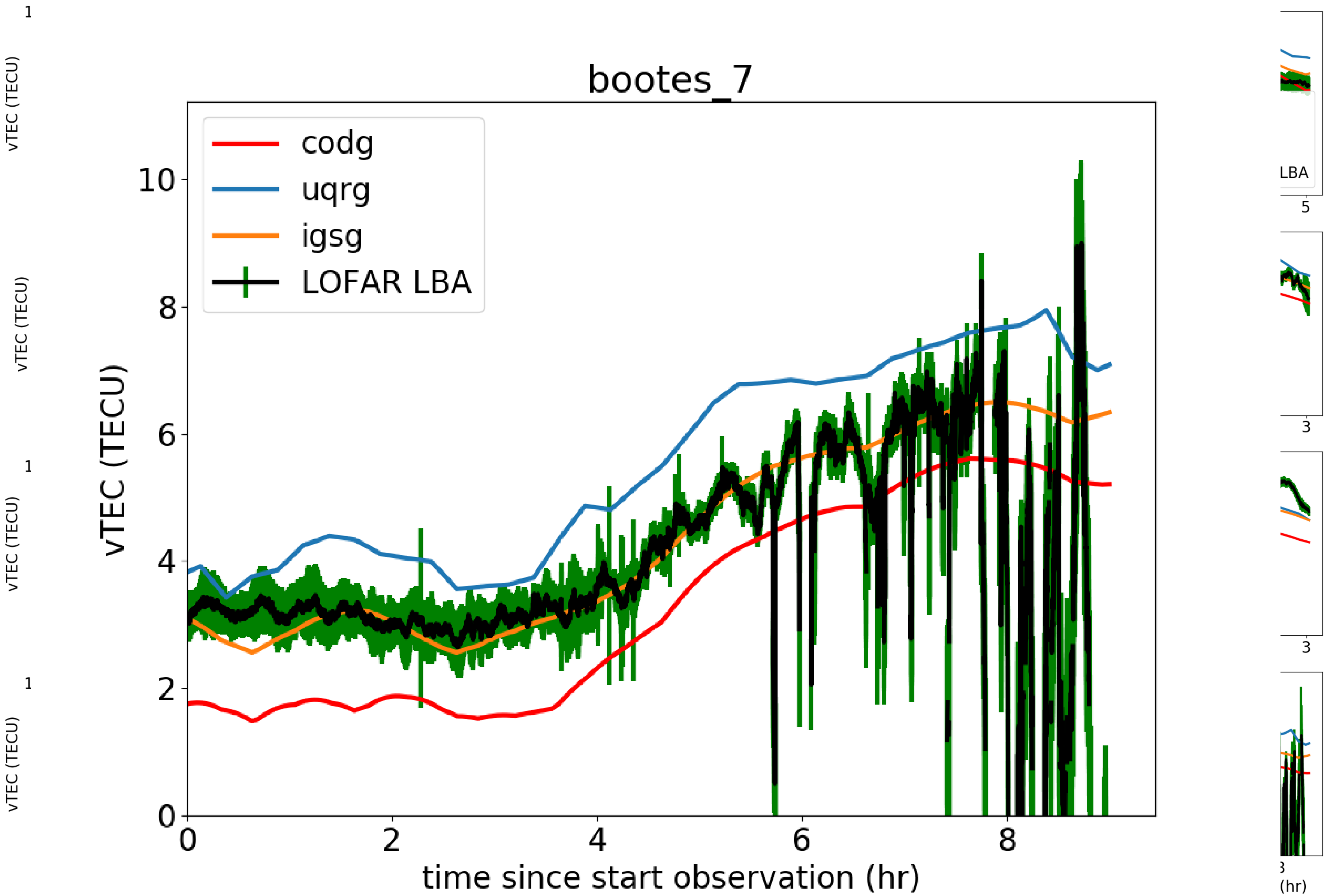




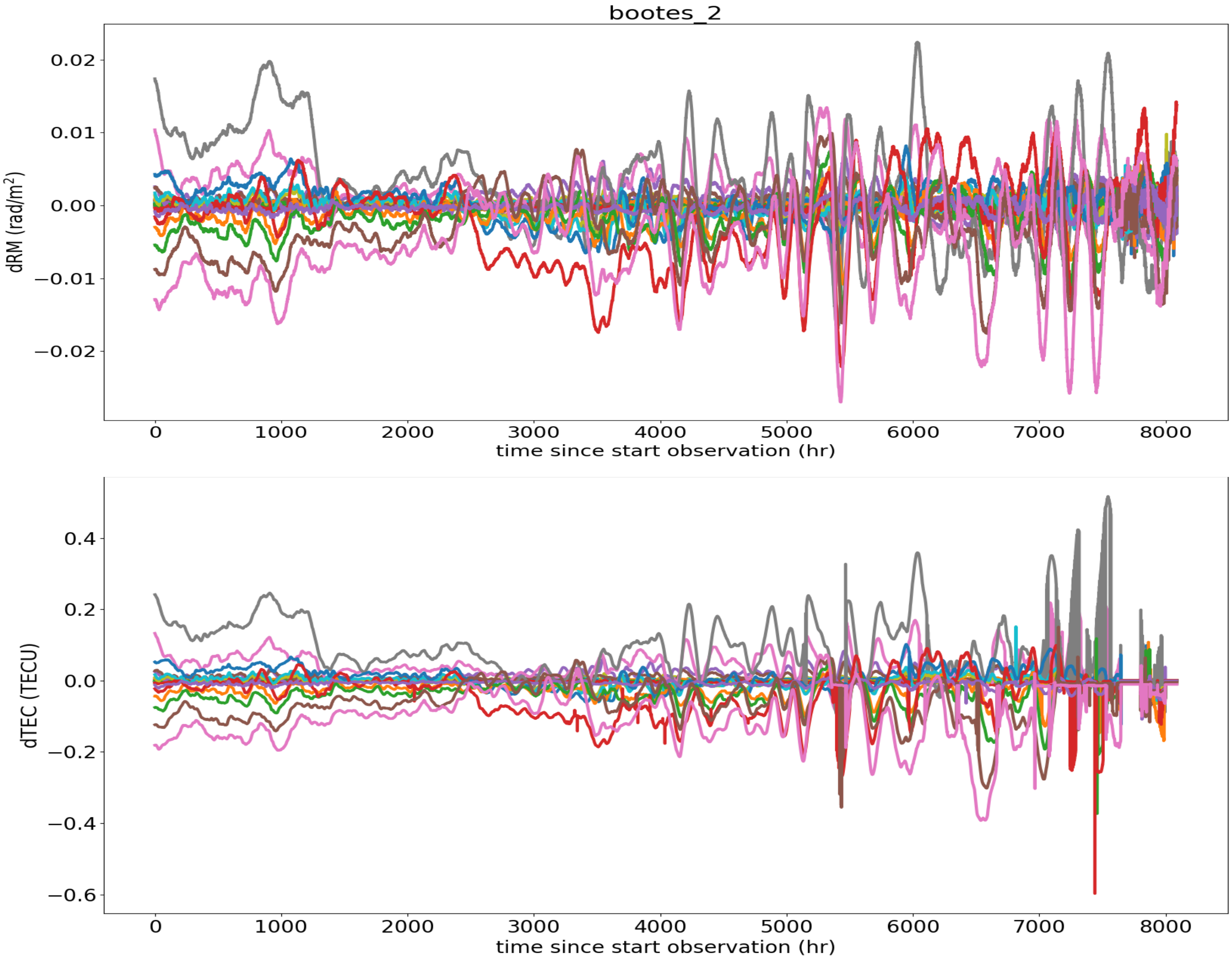




3c295_1
3c295_2
3c295_3
3c295_4
3c295_5
3c295_6
3c295_7
3c380_0
3c380_1
3c380_2
3c380_3
3c380_6
3c380_7
bootes_0
bootes_1
bootes_2
vTEC (TECU)
time since start observation (hr)
codg
uqrg
igsg
LOFAR LBA

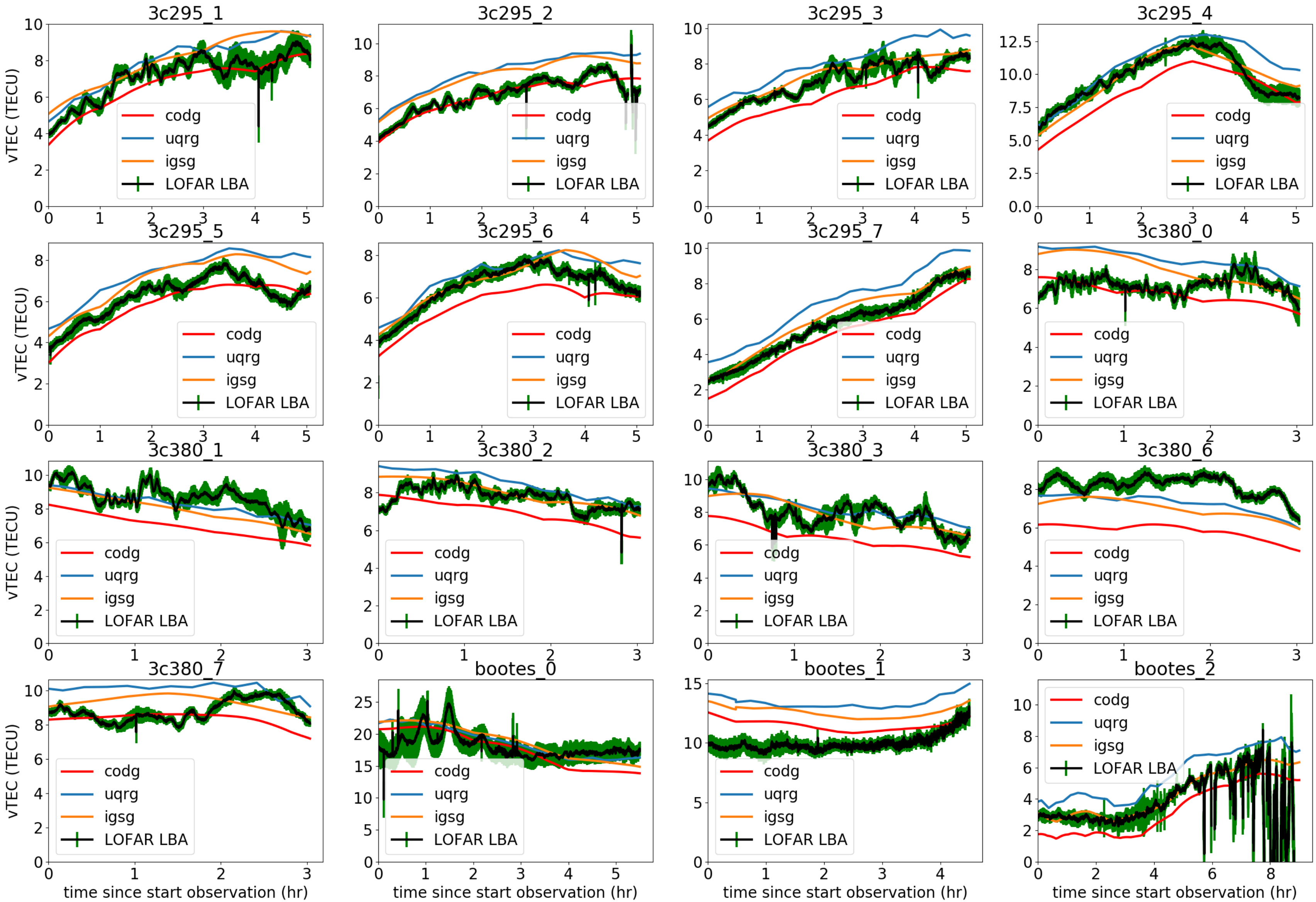


bootes_7
codg
uqrg
igsg
LOFAR LBA
vTEC (TECU)
time since start observation (hr)
0
2
4
6
8
10

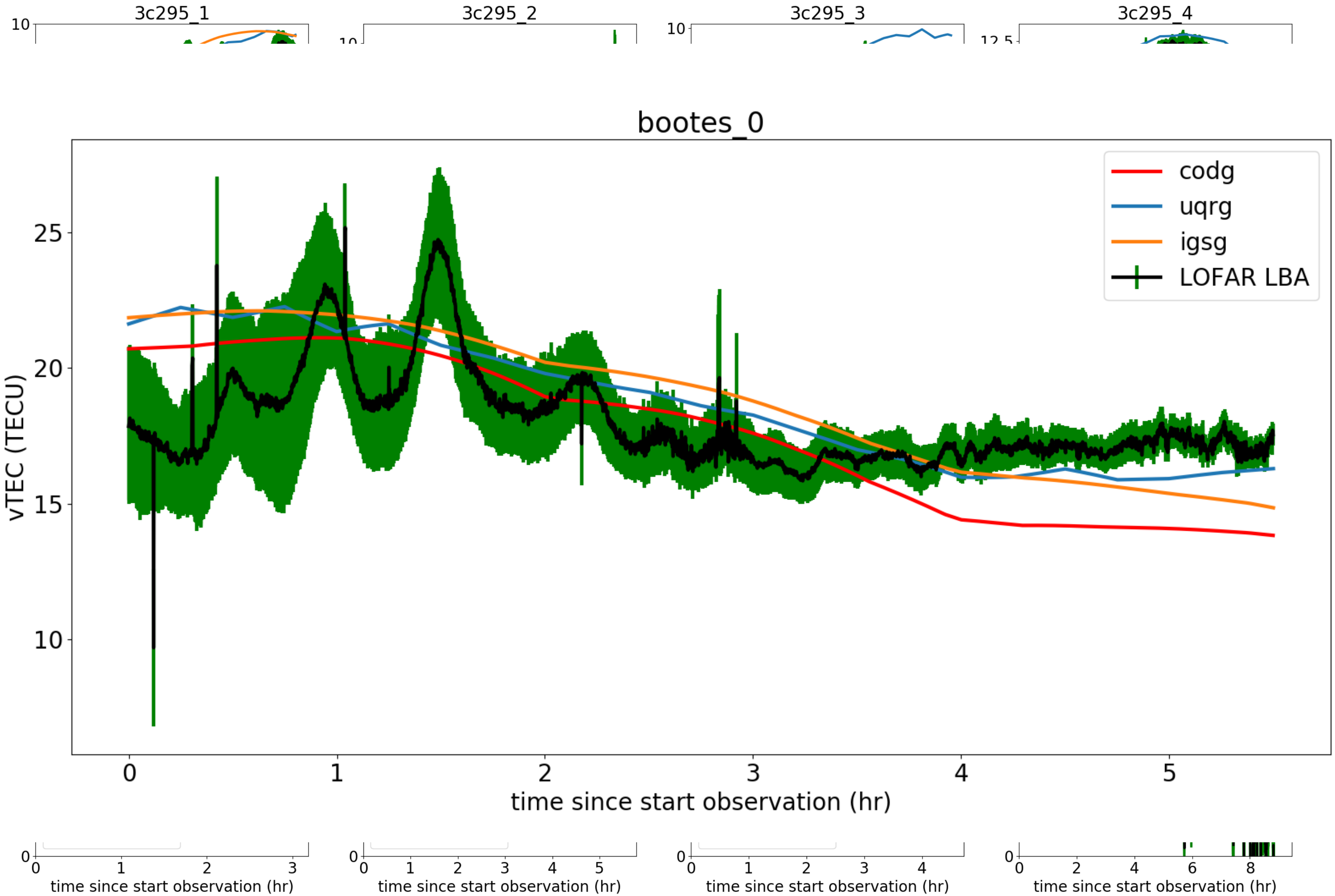

bootes_2
0.02
0.01
0.00
−0.01
−0.02
dRM (rad/m^2)
0
1000
2000
3000
4000
5000
6000
7000
8000
time since start observation (hr)
0.4
0.2
0.0
−0.2
−0.4
−0.6
dTEC (TECU)
0
1000
2000
3000
4000
5000
6000
7000
8000
time since start observation (hr)

dRM

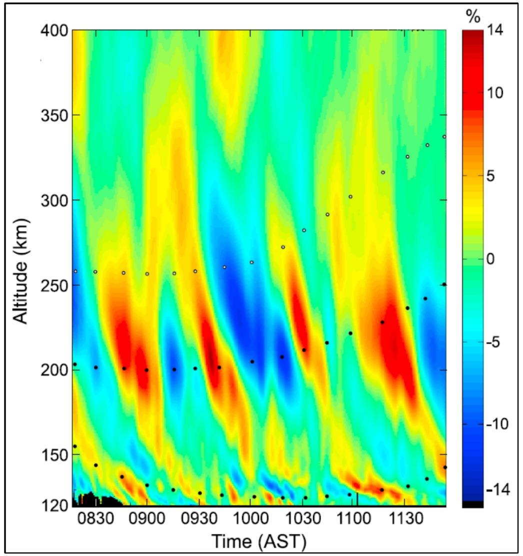
dTEC



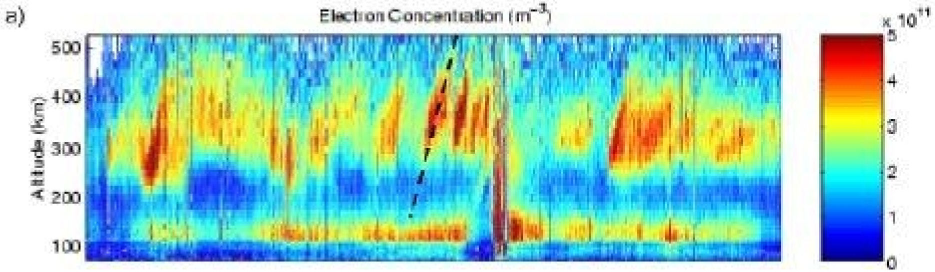
3c295_1
3c295_2
3c295_3
3c295_4
3c295_5
3c295_6
3c295_7
3c380_0
3c380_1
3c380_2
3c380_3
3c380_6
3c380_7
bootes_0
bootes_1
bootes_2
vTEC (TECU)
time since start observation (hr)
codg
uqrg
igsg
LOFAR LBA



3c295_1
3c295_2
3c295_3
3c295_4
bootes_0
codg
uqrg
igsg
LOFAR LBA
vTEC (TECU)
time since start observation (hr)
time since start observation (hr)
time since start observation (hr)
time since start observation (hr)
time since start observation (hr)



Waves



EISCAT data
Ford et al 2006

Method tends to overestimate sTEC variations in turbulent conditions (waves):

WMM model does not include local variations

Waves could locally change the nominal bulk altitude (~10-100km)

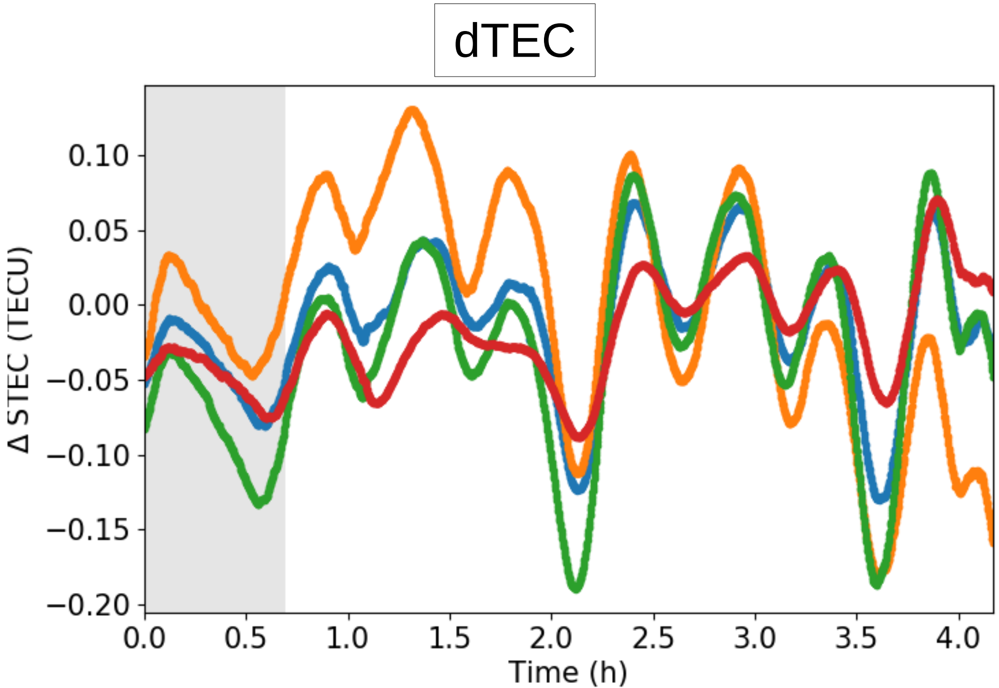
Thinscreen model not sufficient

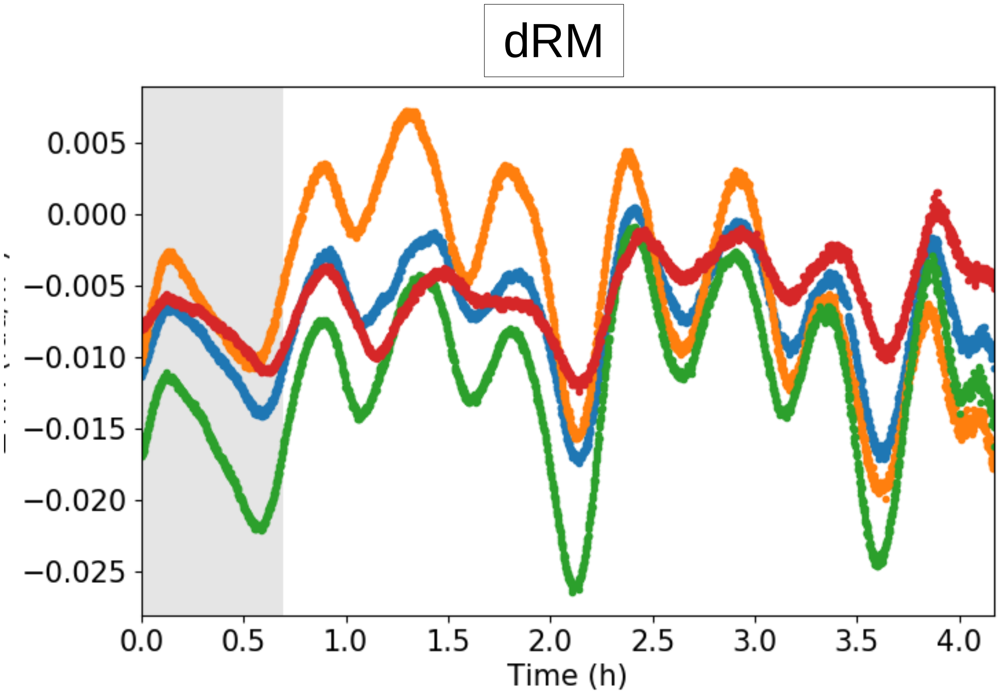
Vertical shifts

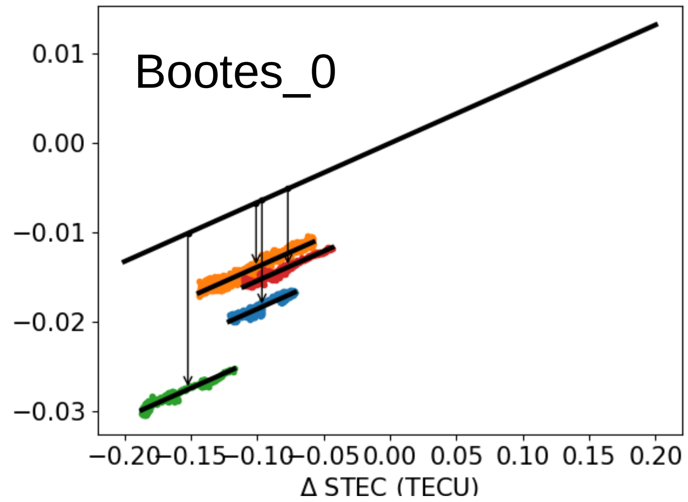
Reversing the argument:
B-field estimation from linear dependence

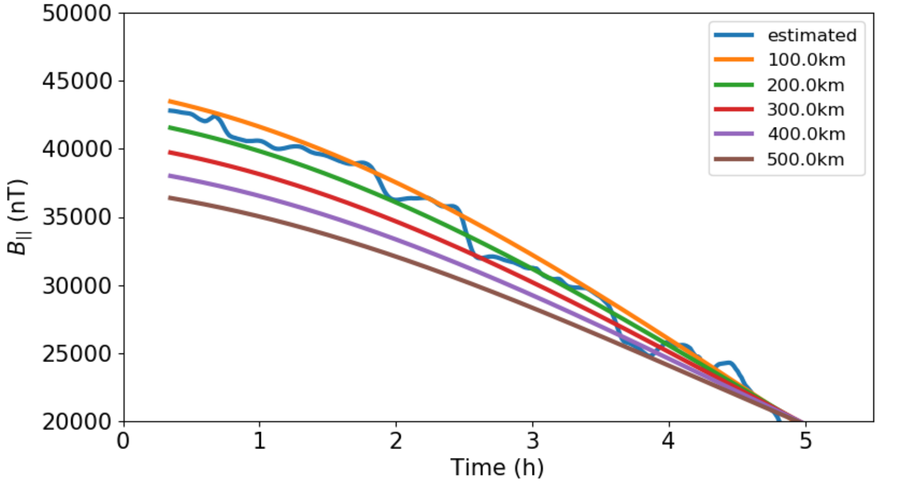
$$\Delta \mathrm{RM}_{ij} = a \Delta \mathrm{STEC}_{ij} + b \mathrm{STEC}_i$$

$$a = C \cdot B_{||i}, \quad b = -C \cdot \Delta B_{||ij}$$





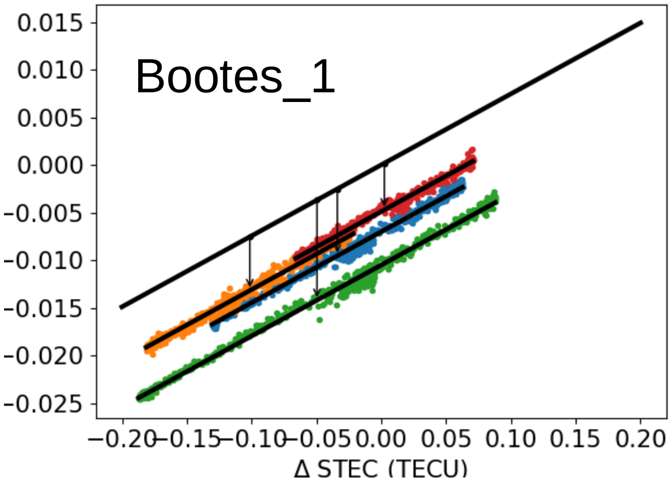


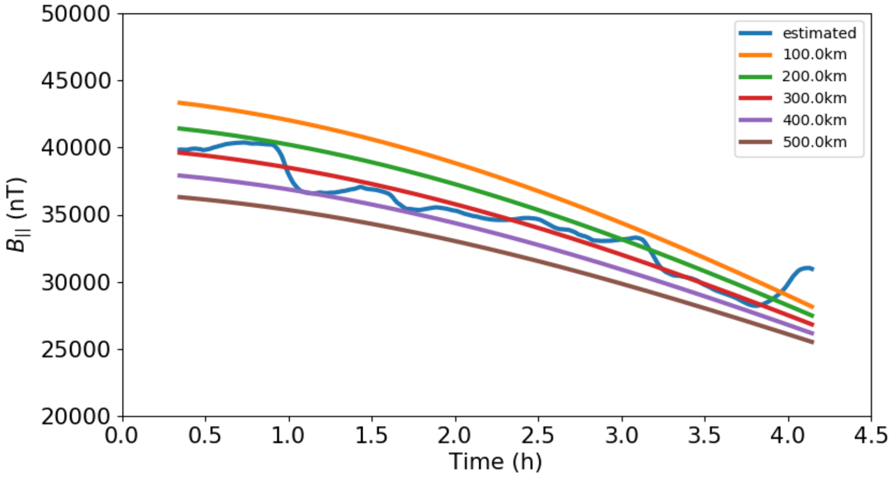


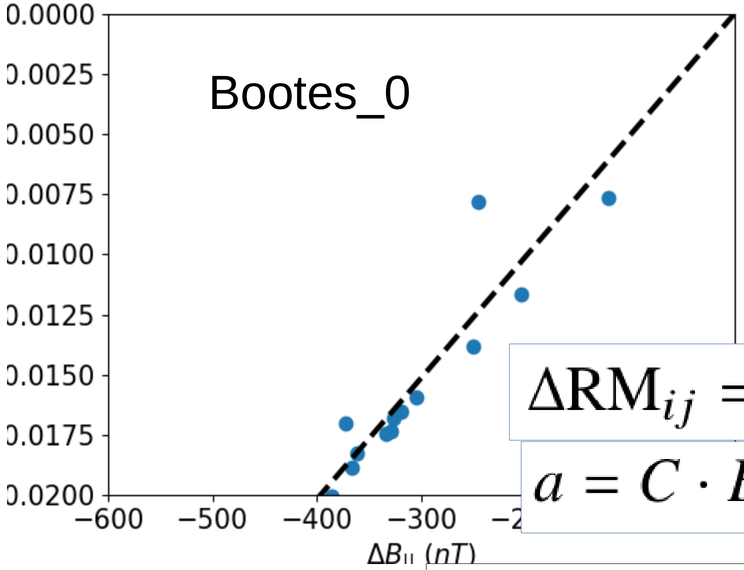
Estimated B||
from slope

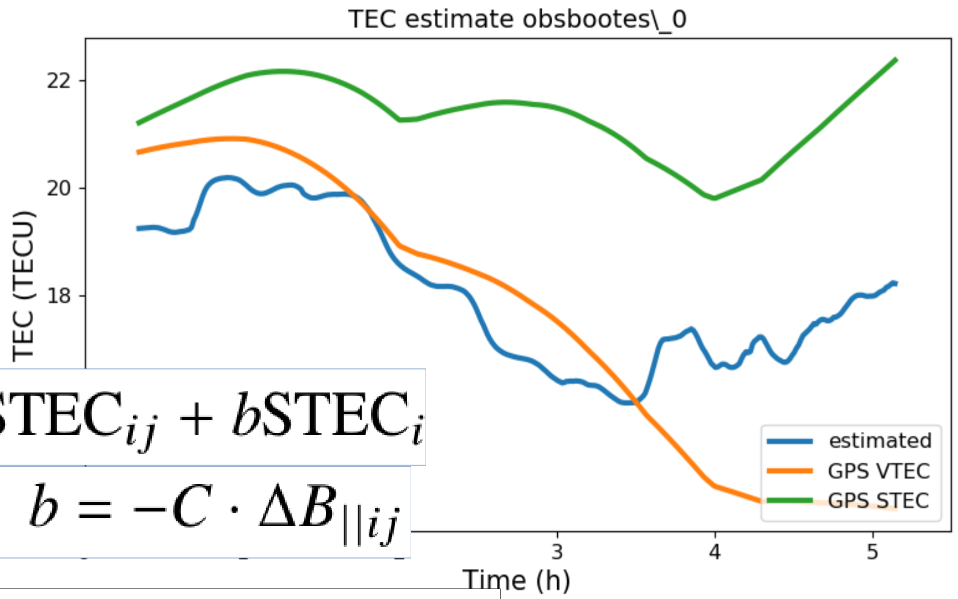
Sliding window

ΔRM vs ΔSTEC





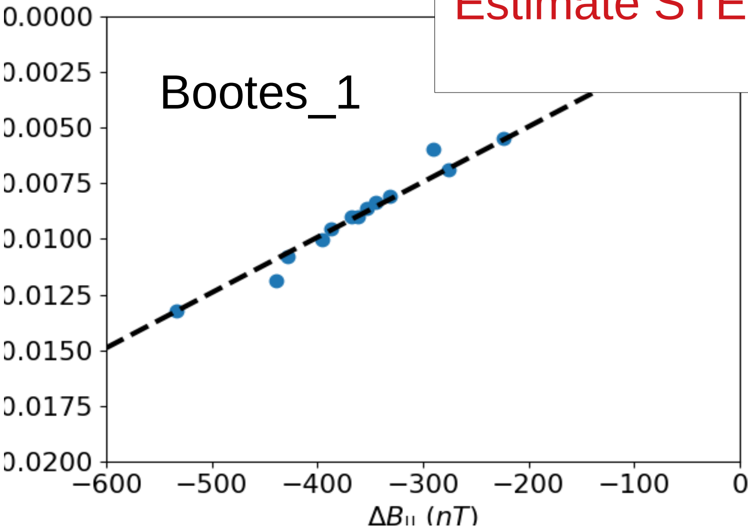


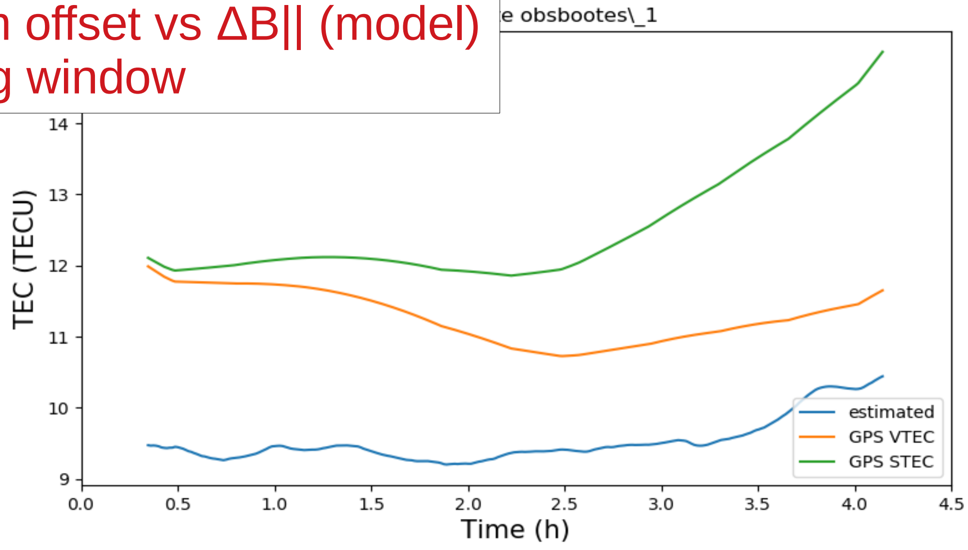


$$\Delta \mathrm{RM}_{ij} = a\Delta \mathrm{STEC}_{ij} + b\mathrm{STEC}_i$$

$$a = C \cdot B_{||i}, \quad b = -C \cdot \Delta B_{||ij}$$

Estimate STEC from offset vs ΔB|| (model)
Sliding window





Conclusion

- In principle measurements with similar accuracy as IONEX data possible
- Systematic uncertainties not fully understood yet:
  - Altitude/Profile dependence
  - dTEC offsets
  - Magnetic Field Model
- Too large amplitudes especially in the case of waves -> related to altitude shifts?
- absolute sTEC measurements in LOS: useful for polarization RM corrections

OUTLOOK:

- HBA data
- International Baselines
- Paper (Mevius, vdTol, de Gasperin et al) in preparation

Overview of Space Weather activities with LOFAR