

New Near-Real Time Ionospheric Products Based on Real-time EPN Data

N. Bergeot, J.-M. Chevalier

C. Bruyninx, E. Pottiaux, Q. Baire, J. Legrand,
P. Defraigne and W. Aerts

Ionospheric activity

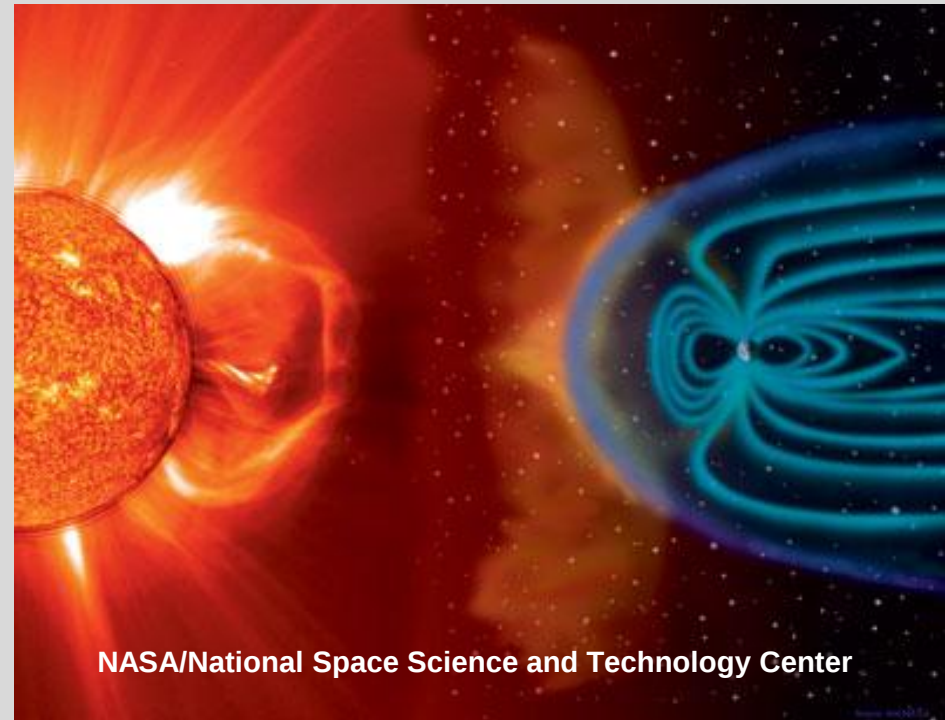
Ionosphere (50-1000km):

- First order of ionospheric state variation: Solar radiation (photoionization)
- Major disturbance in the ionospheric state: CME impact
 - Affects the radio waves propagation with respect to free electrons content
 - Error in GNSS positioning applications
 - Space weather research

Ionosphere and GPS data:

Total Electron Content (TEC)

$$1\text{TECu} = 10^{16}\text{e}^-\cdot\text{m}^{-2}$$



NASA/National Space Science and Technology Center

Ionospheric activity

Ionosphere (50-1000km):

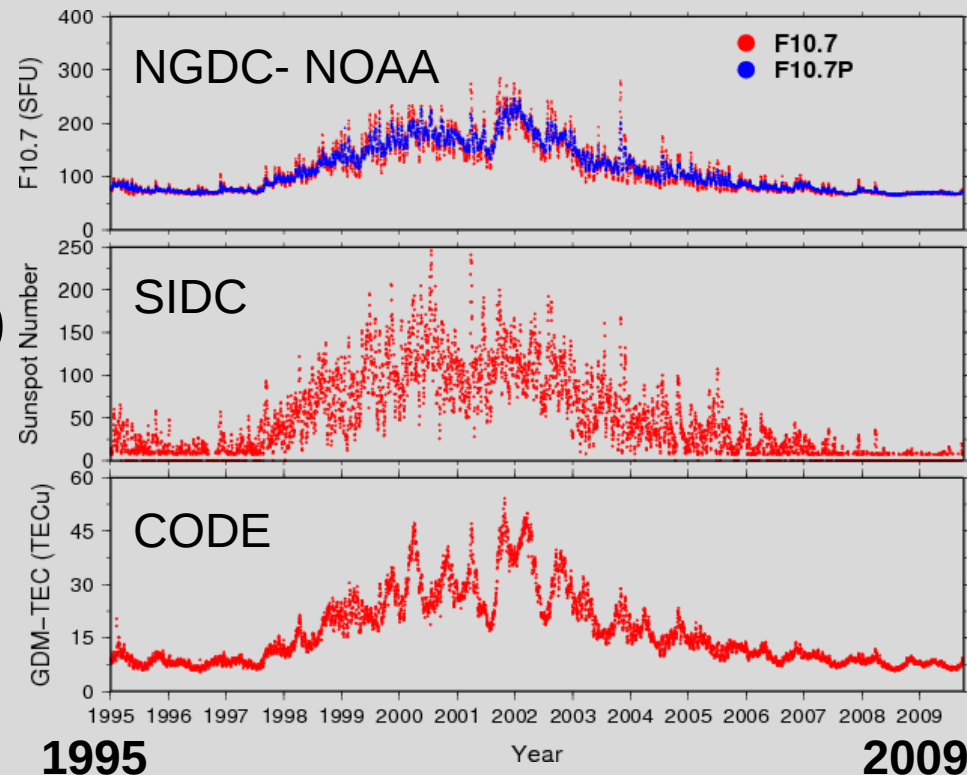
- First order of ionospheric state variation: Solar radiation (photoionization)
- Major disturbance in the ionospheric state: CME impact
 - Affects the radio waves propagation with respect to free electrons content
 - Error in GNSS positioning applications
 - Space weather research

Ionosphere and GPS data:

Total Electron Content (TEC)

$$I = \frac{40.3}{f^2} TEC$$

cm to > 100 m



Ionospheric activity

Ionosphere (50-1000km):

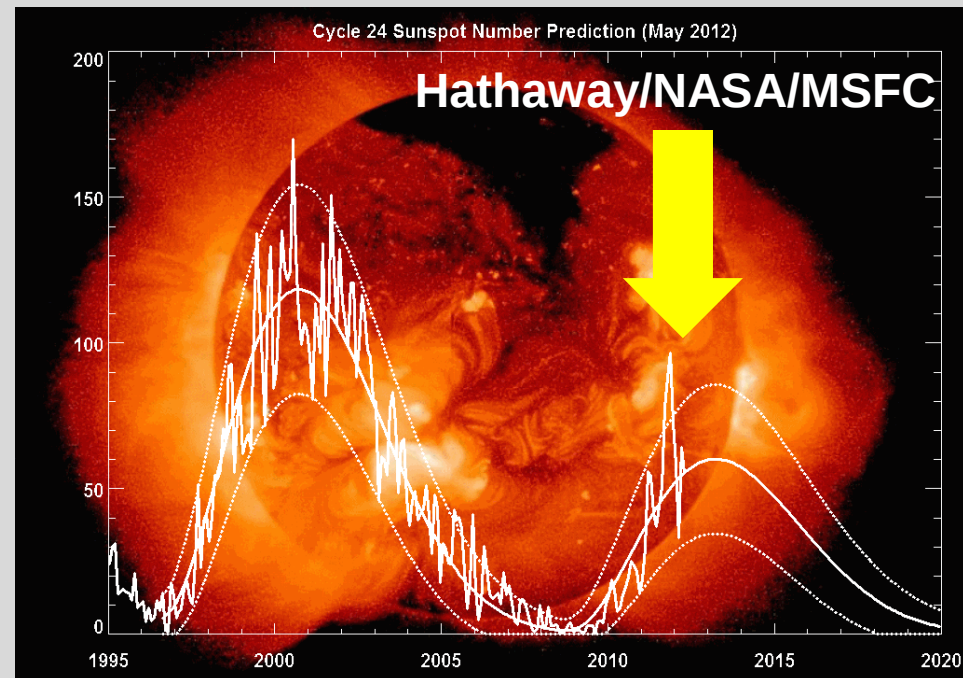
- First order of ionospheric state variation: Solar radiation (photoionization)
- Major disturbance in the ionospheric state: CME impact
 - Affects the radio waves propagation with respect to free electrons content
 - Error in GNSS positioning applications
 - Space weather research

Ionosphere and GPS data:

Total Electron Content (TEC)

$$I = \frac{40.3}{f^2} TEC$$

cm to > 100 m



This presentation

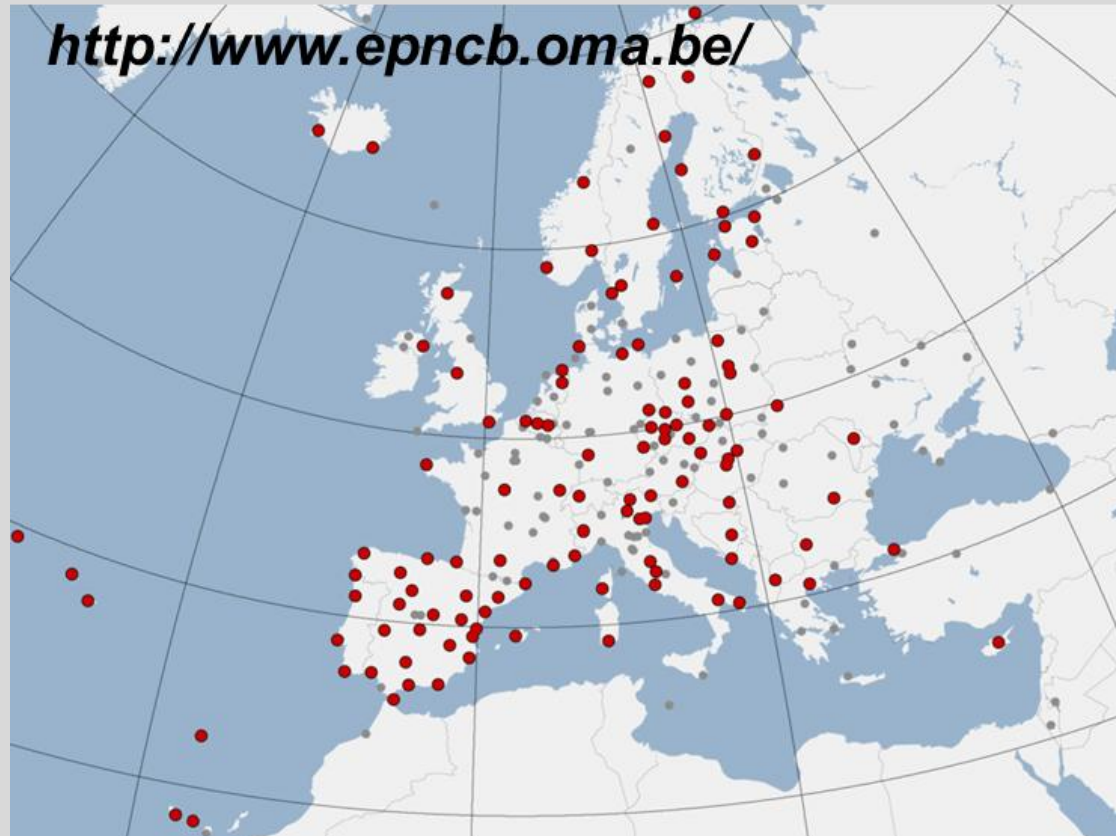
- Development of a method to estimate in Near-real time (NRT) **the ROB TEC** from GPS data over Europe
- Products already online (gnss.be)
- Products under development

**Real-time data from the EUREF Permanent Network (EPN)
provided by the ROB [- BKG] NTRIP broadcaster**

[e.g. Söhne et al. 2010]

European Permanent Network (EPN)

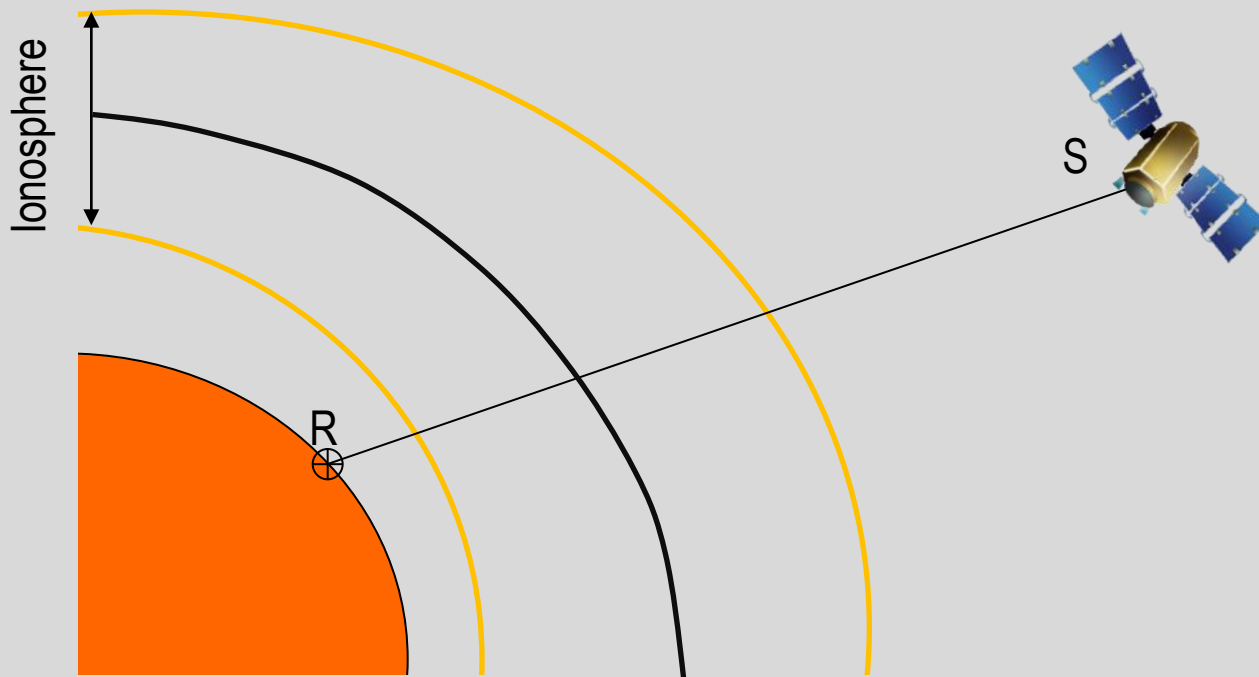
- Continuously observing GNSS stations since 1996
- Presently: ~ 250 stations over Europe
- **NRT : Presently ~ 120 stations**



Ionospheric monitoring from EPN NRT GPS data

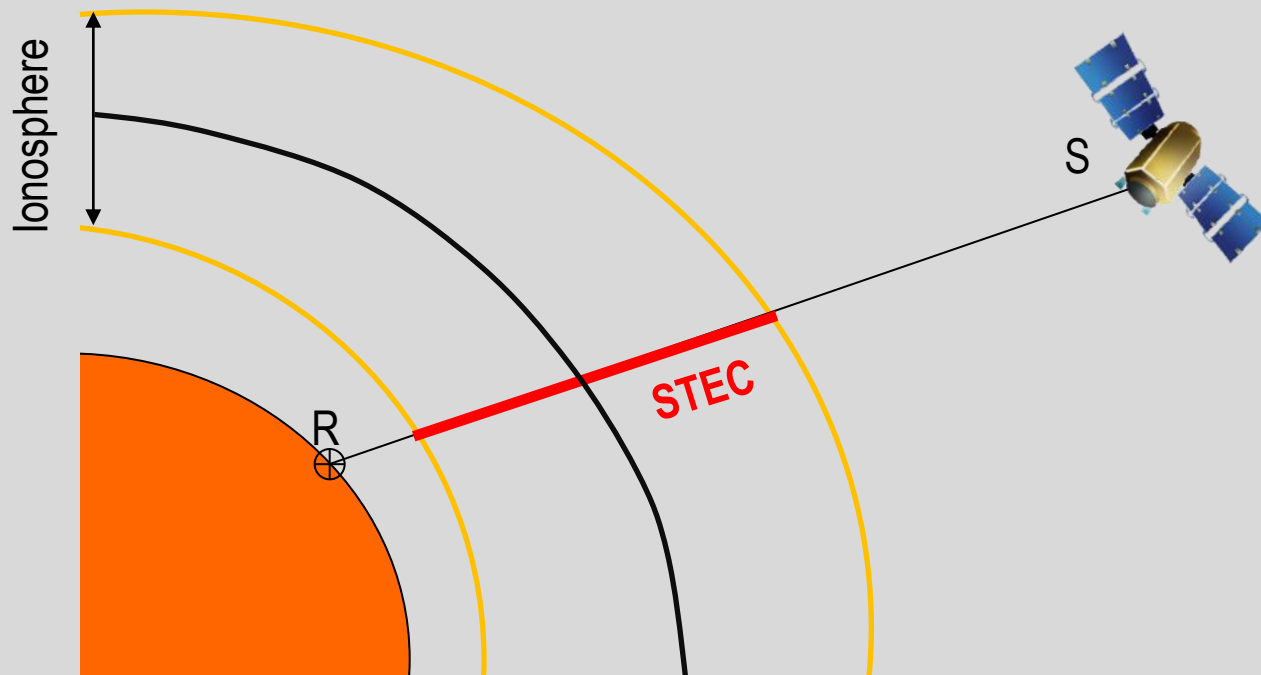
$$P_2 - P_1 + DCB^s + DCB_r = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC$$

Geometry-free linear combination



Ionospheric monitoring from EPN NRT GPS data

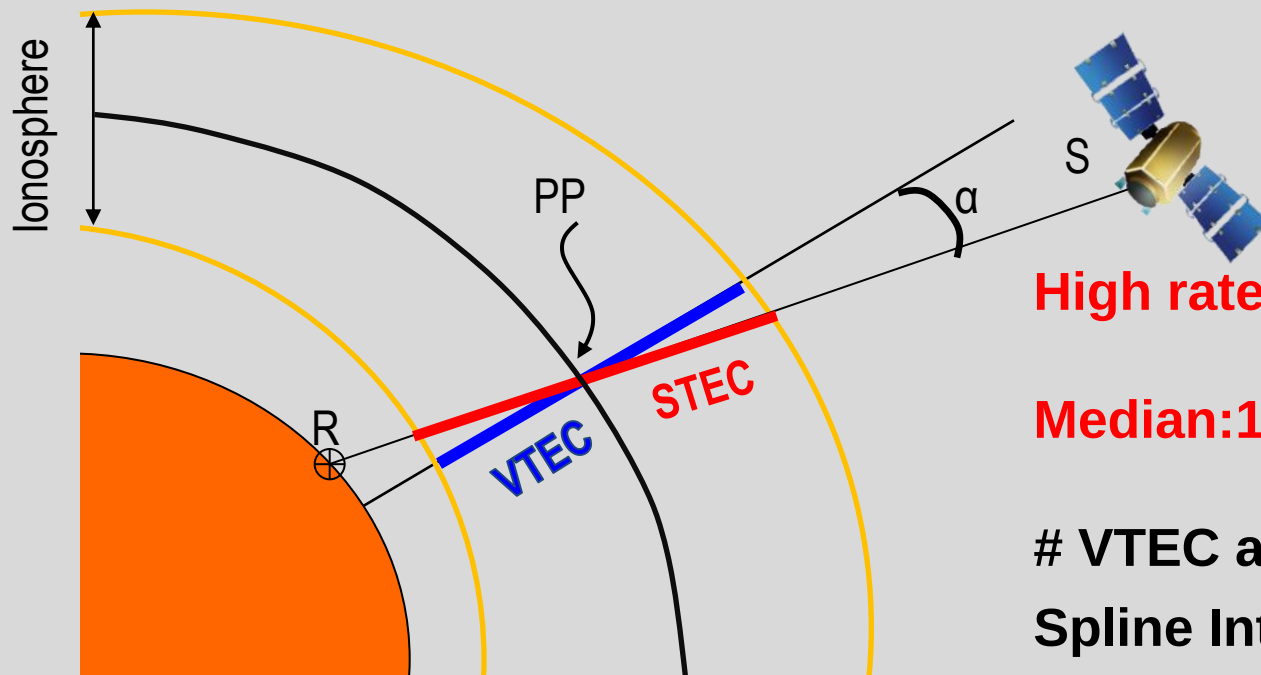
$$\boxed{P_2 - P_1 + DCB^s + DCB_r} = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) \underline{STEC}$$



Ionospheric monitoring from EPN NRT GPS data

$$P_2 - P_1 + DCB^s + DCB_r = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) \underline{STEC}$$

$$\underline{VTEC} = \underline{STEC} \times \cos(\alpha)$$



High rate NRT EPN GPS data

Median: 15min. of VTEC/Rec/Sat

VTEC at PP : 1692 ± 271 .

Spline Interpolation.

VTEC grid : $0.5^\circ \times 0.5^\circ$ - 15 min.

Products available on-line

<http://www.gnss.be>



ROYAL OBSERVATORY OF BELGIUM
GNSS RESEARCH GROUP

ABOUT

- Who we are
- Projects

RESEARCH@ROB

- Antarctica
- Troposphere
- Ionosphere
- Time Transfer
- Atomium

DATA AND PRODUCTS

- EPN Central Bureau
- ROB Network
- Ionospheric Maps
 - Dynamic
 - Static

TUTORIALS

- GPS, GLONASS, GALILEO, ...
- How GNSS Works
- Positioning & Timing
- GNSS Networks
- Coordinate Systems
- Atmosphere
 - Ionosphere
 - Troposphere

LOGIN



IONOSPHERIC MAPS

Contact: iono@oma.be

Last Ionospheric Events

- 22/05/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/04/2012 : Ionospheric activity due to CME impact ([more here](#))
- 16/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 08/02/2012 : Ionospheric activity due to major CME impact ([more here](#))
- 27/02/2012 : Ionospheric activity due to CME impact ([more here](#))
- 22/01/2012 : Ionospheric activity due to major CME impact ([more here](#))

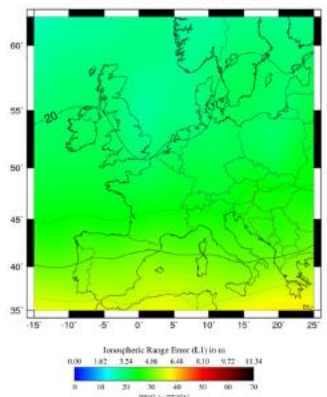
Near-Real Time Products

Vertical Total Electron Content (VTEC) estimated in Near Real-time (NRT) every 15 minutes from EUREF Permanent Network (EPN) GPS data. [More...](#)

- [Dynamic product](#): interactive product which allows viewing VTEC maps at different epochs as a movie. (4-5 sec to load).
- [Static product](#): statistics to compare the ionosphere at a given epoch with respect to the 15 previous days.

Dynamic

VTEC DOY 151 15:15-15:30 UTC

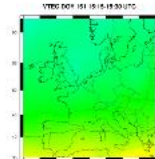


Ionospheric Range Error (R1) in m

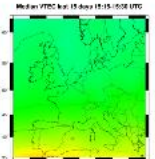
TEC in TECU

Static

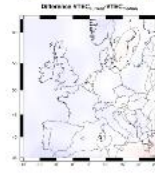
VTEC DOY 151 15:15-15:30 UTC



Median VTEC for 15 days 15:15-15:30 UTC



Comparison of the difference



Statistics of the difference

Mean = 0.4
StdDev = 1.1
Min = 0.0
Max = 1.3

Products available on-line

<http://www.gnss.be>

DATA AND PRODUCTS



ROYAL OBSERVATORY OF BELGIUM
GNSS RESEARCH GROUP

ABOUT

- Who we are
- Projects

RESEARCH@ROB

- Antarctica
- Troposphere
- Ionosphere
- Time Transfer
- Atomium

DATA AND PRODUCTS

- EPN Central Bureau
- ROB Network
- Ionospheric Maps
 - Dynamic
 - Static

TUTORIALS

- GPS, GLONASS, GALILEO, ...
- How GNSS Works
- Positioning & Timing
- GNSS Networks
- Coordinate Systems
- Atmosphere
 - Ionosphere
 - Troposphere

LOGIN



IONOSPHERIC MAPS

Contact: iono@oma.be

Last Ionospheric Events

- 22/05/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/04/2012 : Ionospheric activity due to CME impact ([more here](#))
- 16/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 08/02/2012 : Ionospheric activity due to major CME impact ([more here](#))
- 27/02/2012 : Ionospheric activity due to CME impact ([more here](#))
- 22/01/2012 : Ionospheric activity due to major CME impact ([more here](#))

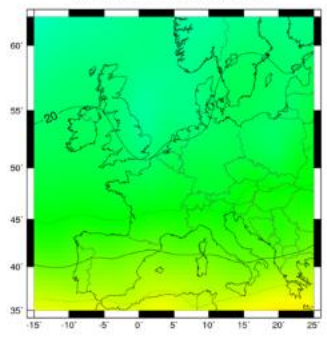
Near-Real Time Products

Vertical Total Electron Content (VTEC) estimated in Near Real-time (NRT) every 15 minutes from EUREF Permanent Network (EPN) GPS data. [More...](#)

- [Dynamic product](#): interactive product which allows viewing VTEC maps at different epochs as a movie. (4-5 sec to load).
- [Static product](#): statistics to compare the ionosphere at a given epoch with respect to the 15 previous days.

Dynamic

VTEC DOY 151 15:15-15:30 UTC



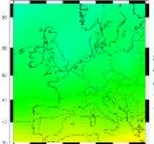
Ionospheric Range Error (R1) in m

0.00 1.62 3.24 4.86 6.48 8.10 9.72 11.34

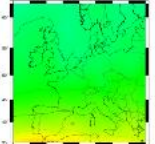
TEC in TECU

Static

VTEC DOY 151 15:15-15:30 UTC



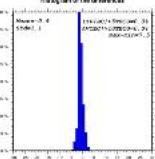
Median VTEC for 15 days 15:15-15:30 UTC



Difference VTEC_{now} - VTEC_{median}



Histogram of the difference



Mean = 0.4
StdDev = 1.1
Min = -1.0
Max = 2.6

Products available on-line

<http://www.gnss.be>

DATA AND PRODUCTS

IONOSPHERIC MAPS

Latency : ~7-10 min.

Time independent maps.



ROYAL OBSERVATORY OF BELGIUM
GNSS RESEARCH GROUP

ABOUT

- Who we are
- Projects

RESEARCH@ROB

- Antarctica
- Troposphere
- Ionosphere
- Time Transfer
- Atomium

DATA AND PRODUCTS

- EPN Central Bureau
- ROB Network
- Ionospheric Maps**
- Dynamic
- Static

TUTORIALS

- GPS, GLONASS, GALILEO, ...
- How GNSS Works
- Positioning & Timing
- GNSS Networks
- Coordinate Systems
- Atmosphere
 - Ionosphere
 - Troposphere

LOGIN



IONOSPHERIC MAPS

Contact: iono@oma.be

Last Ionospheric Events

- 22/05/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/04/2012 : Ionospheric activity due to CME impact ([more here](#))
- 16/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 08/02/2012 : Ionospheric activity due to major CME impact ([more here](#))
- 27/02/2012 : Ionospheric activity due to CME impact ([more here](#))
- 22/01/2012 : Ionospheric activity due to major CME impact ([more here](#))

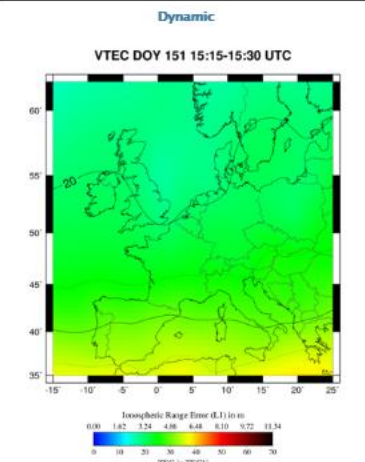
Near-Real Time Products

Vertical Total Electron Content (VTEC) estimated in Near Real-time (NRT) every 15 minutes from EUREF Permanent Network (EPN) GPS data. [More...](#)

- [Dynamic product](#): interactive product which allows viewing VTEC maps at different epochs as a movie. (4-5 sec to load).
- [Static product](#): statistics to compare the ionosphere at a given epoch with respect to the 15 previous days.

Dynamic

VTEC DOY 151 15:15-15:30 UTC

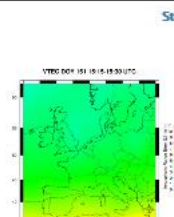


Ionospheric Range Error (R1) in m

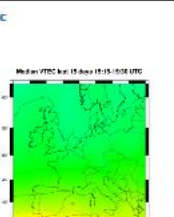
TECU in TECU

Static

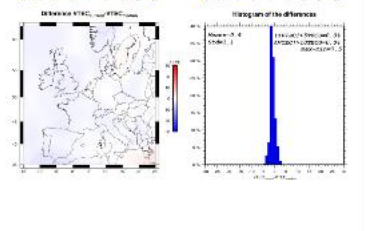
VTEC DOY 151 15:15-15:30 UTC



Median VTEC for 15 days 15:15-15:30 UTC



Histogram of the difference



Mean = 0.4
StdDev = 1.1
Min = -1.0
Max = 2.6

Products available on-line

<http://www.gnss.be>

DATA AND PRODUCTS

- IONOSPHERIC MAPS
- DYNAMIC



ROYAL OBSERVATORY OF BELGIUM
GNSS RESEARCH GROUP

ABOUT

- Who we are
- Projects

RESEARCH@ROB

- Antarctica
- Troposphere
- Ionosphere
- Time Transfer
- Atomium

DATA AND PRODUCTS

- EPN Central Bureau
- ROB Network
- Ionospheric Maps**
- Dynamic
- Static

TUTORIALS

- GPS, GLONASS, GALILEO, ...
- How GNSS Works
- Positioning & Timing
- GNSS Networks
- Coordinate Systems
- Atmosphere
- Ionosphere
- Troposphere

LOGIN



IONOSPHERIC MAPS

Contact: iono@oma.be

Last Ionospheric Events

- 22/05/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/04/2012 : Ionospheric activity due to CME impact ([more here](#))
- 16/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 08/02/2012 : Ionospheric activity due to major CME impact ([more here](#))
- 27/02/2012 : Ionospheric activity due to CME impact ([more here](#))
- 22/01/2012 : Ionospheric activity due to major CME impact ([more here](#))

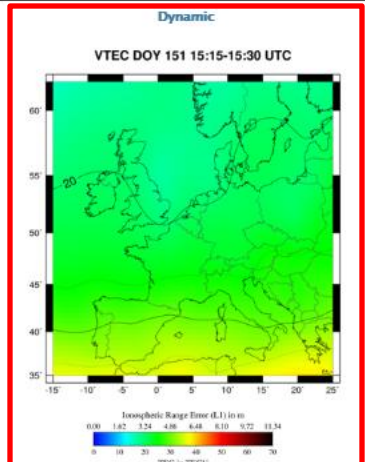
Near-Real Time Products

Vertical Total Electron Content (VTEC) estimated in Near Real-time (NRT) every 15 minutes from EUREF Permanent Network (EPN) GPS data. [More...](#)

- [Dynamic product](#): interactive product which allows viewing VTEC maps at different epochs as a movie. (4-5 sec to load).
- [Static product](#): statistics to compare the ionosphere at a given epoch with respect to the 15 previous days.

Dynamic

VTEC DOY 151 15:15-15:30 UTC



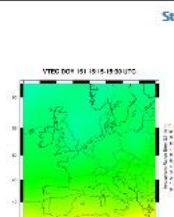
Ionospheric Range Error (R1) in m

0.00 1.62 3.24 4.86 6.48 8.10 9.72 11.34

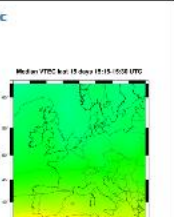
TEC in TECU

Static

VTEC DOY 151 15:15-15:30 UTC



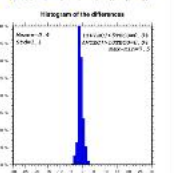
Median VTEC for 15 days 15:15-15:30 UTC



Difference VTEC - median VTEC

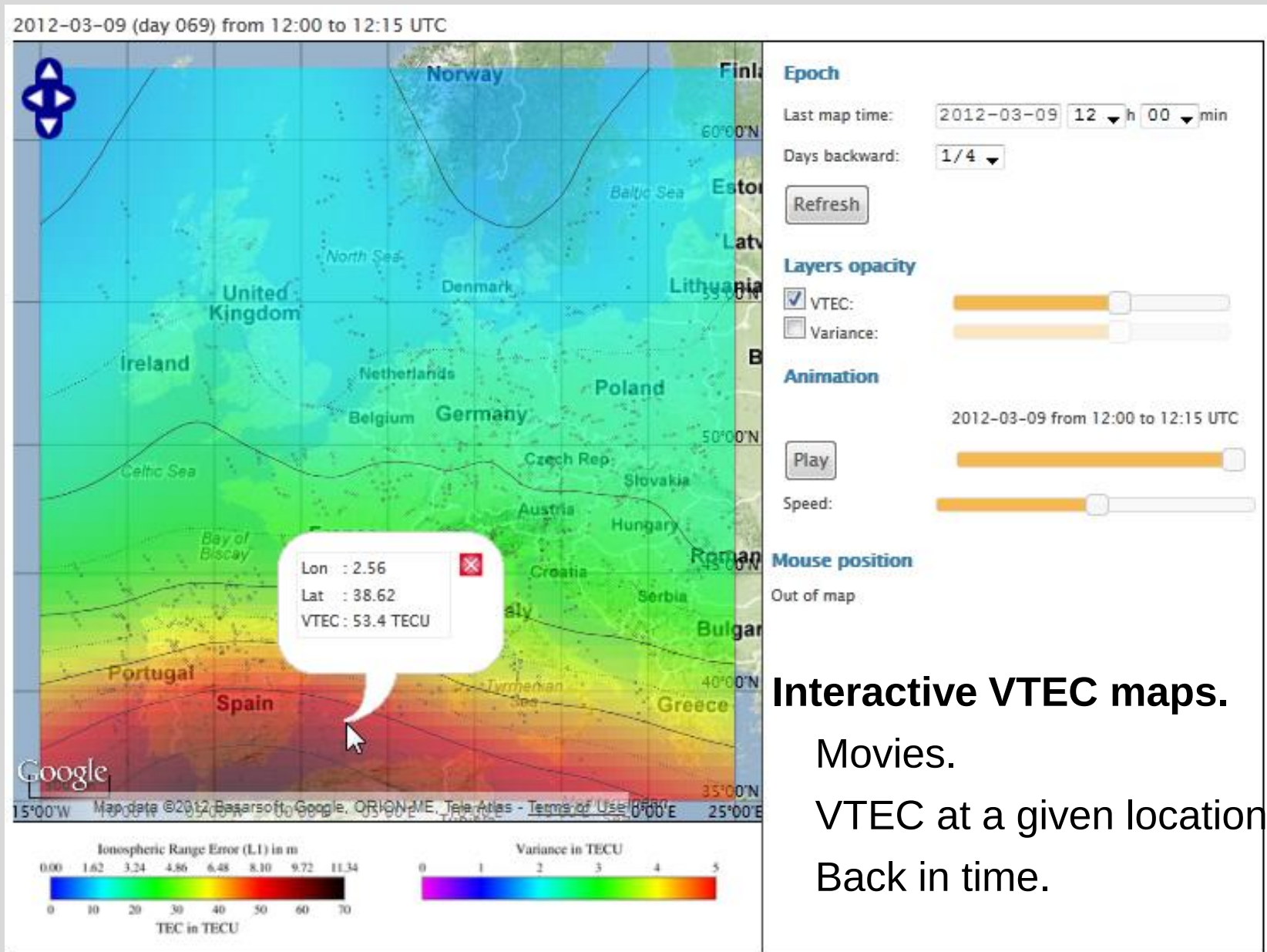


Histogram of the difference



Mean = 0.4
StdDev = 1.1
Min = -1.0
Max = 2.6

Products available on-line



Interactive VTEC maps.
Movies.
VTEC at a given location.
Back in time.

Products available on-line

<http://www.gnss.be>

DATA AND PRODUCTS

- IONOSPHERIC MAPS
 - DYNAMIC
 - STATIC



ROYAL OBSERVATORY OF BELGIUM
GNSS RESEARCH GROUP

ABOUT

- Who we are
- Projects

RESEARCH@ROB

- Antarctica
- Troposphere
- Ionosphere
- Time Transfer
- Atomium

DATA AND PRODUCTS

- EPN Central Bureau
- ROB Network
- Ionospheric Maps**
 - Dynamic
 - Static

TUTORIALS

- GPS, GLONASS, GALILEO, ...
- How GNSS Works
- Positioning & Timing
- GNSS Networks
- Coordinate Systems
- Atmosphere
 - Ionosphere
 - Troposphere

LOGIN



IONOSPHERIC MAPS

Contact: iono@oma.be

Last Ionospheric Events

- 22/05/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/04/2012 : Ionospheric activity due to CME impact ([more here](#))
- 16/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 08/02/2012 : Ionospheric activity due to major CME impact ([more here](#))
- 27/02/2012 : Ionospheric activity due to CME impact ([more here](#))
- 22/01/2012 : Ionospheric activity due to major CME impact ([more here](#))

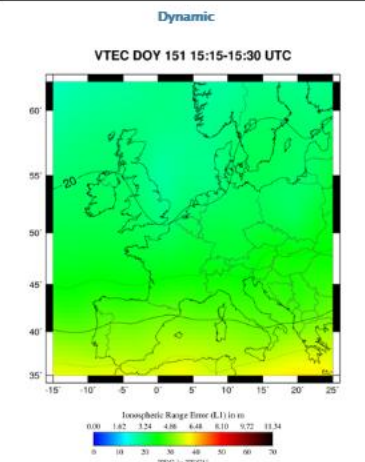
Near-Real Time Products

Vertical Total Electron Content (VTEC) estimated in Near Real-time (NRT) every 15 minutes from EUREF Permanent Network (EPN) GPS data. [More...](#)

- [Dynamic product](#): interactive product which allows viewing VTEC maps at different epochs as a movie. (4-5 sec to load).
- [Static product](#): statistics to compare the ionosphere at a given epoch with respect to the 15 previous days.

Dynamic

VTEC DOY 151 15:15-15:30 UTC



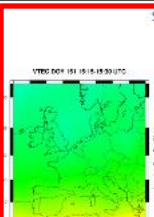
Ionospheric Range Error (R1) in m

0.00 1.62 3.24 4.86 6.48 8.10 9.72 11.34

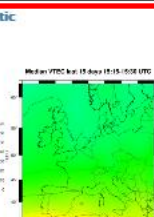
TEC in TECU

Static

VTEC DOY 151 15:15-15:30 UTC



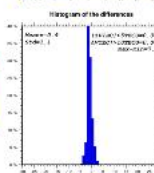
Median VTEC for 15 days 15:15-15:30 UTC



Difference VTEC - median VTEC

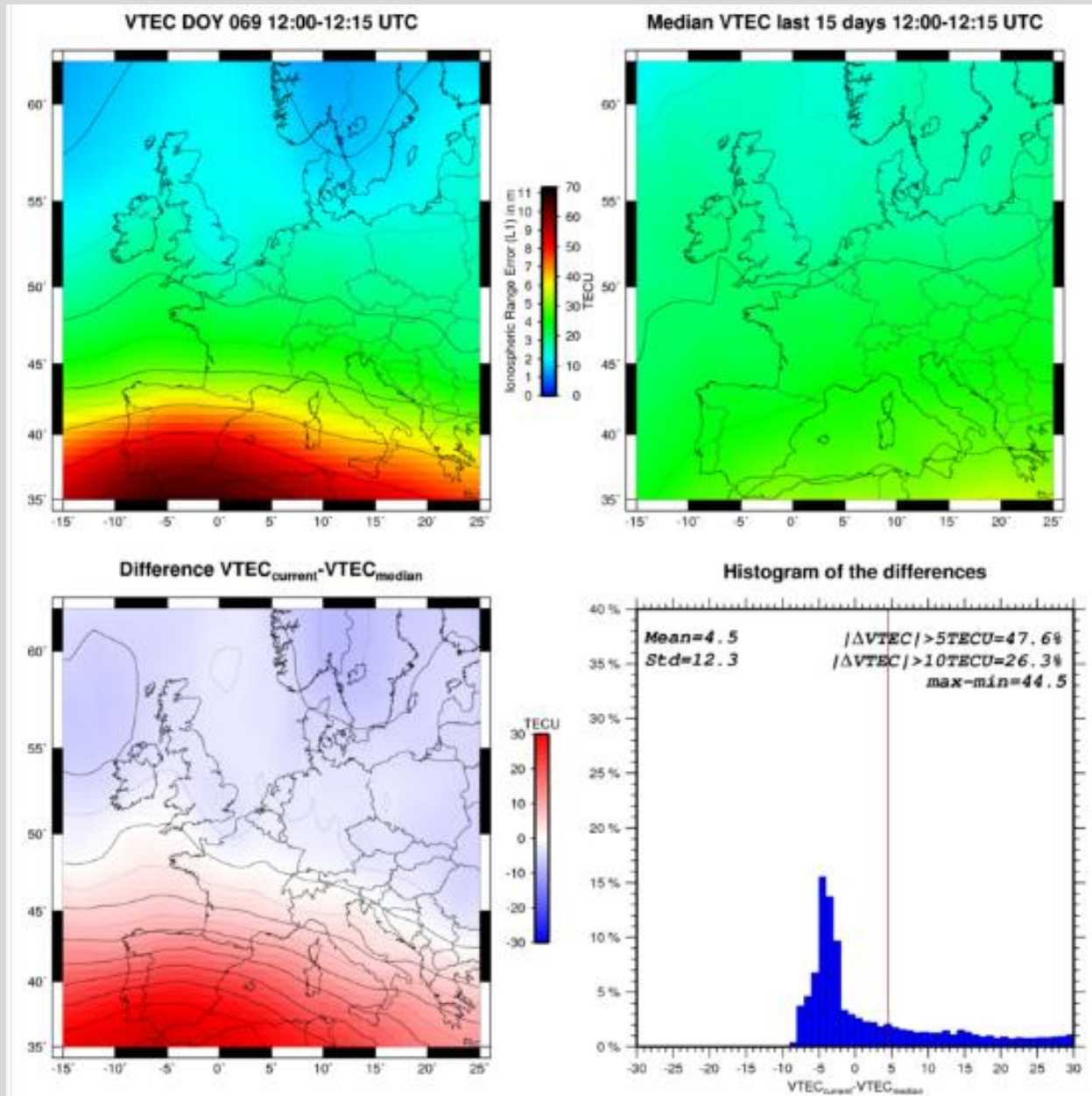


Histogram of the difference



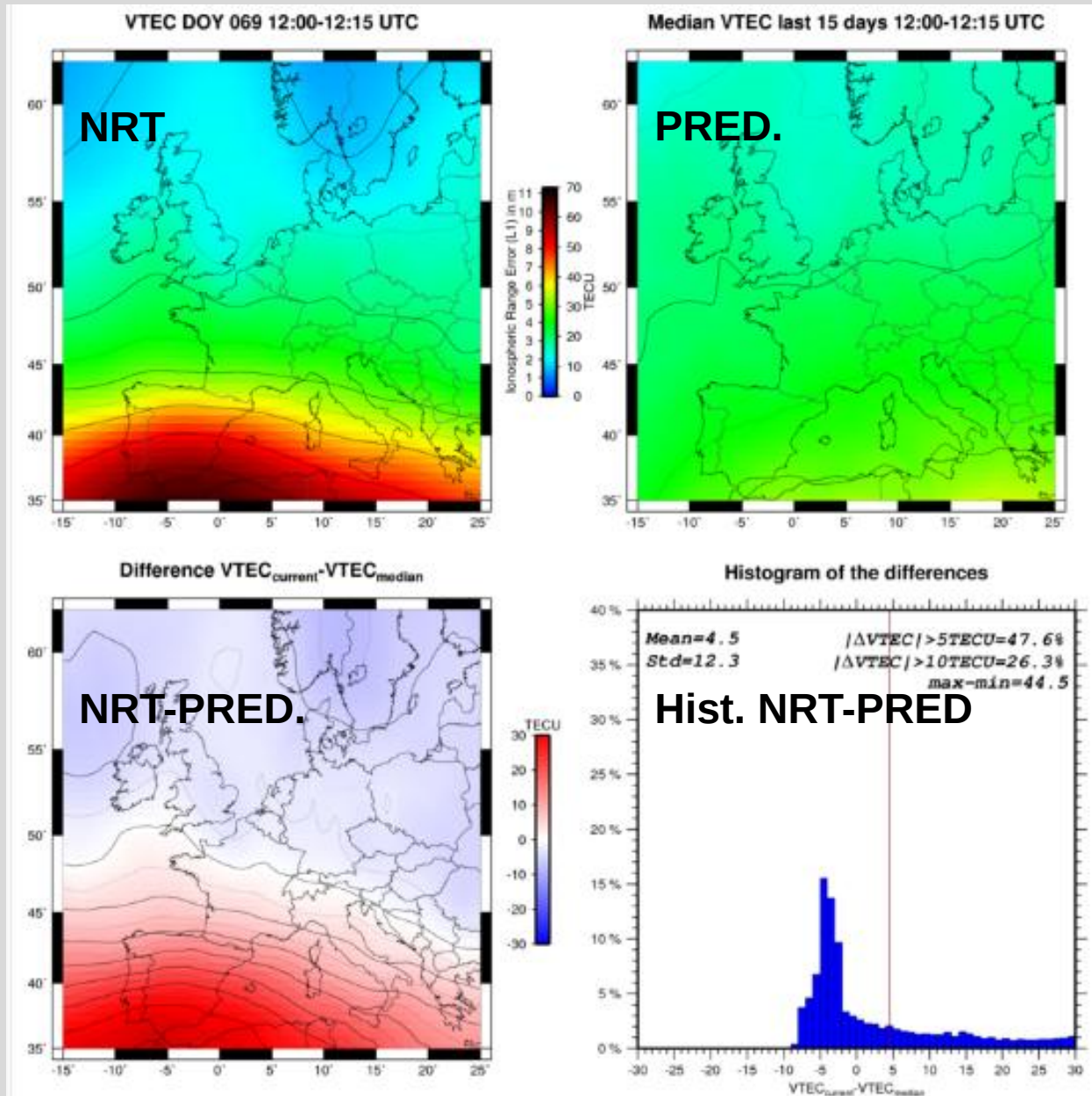
Mean = 0.4
StdDev = 1.1
Min = -1.0
Max = 2.5

Products available on-line



Statistical products.

Products available on-line



Statistical products

Prediction :

Median of the VTEC for the 15 previous days.

Products available on-line

<http://www.gnss.be>

DATA AND PRODUCTS

- IONOSPHERIC MAPS
 - DYNAMIC
 - STATIC
- IONOSPHERIC EVENTS



ROYAL OBSERVATORY OF BELGIUM
GNSS RESEARCH GROUP

ABOUT

- Who we are
- Projects

RESEARCH@ROB

- Antarctica
- Troposphere
- Ionosphere
- Time Transfer
- Atomium

DATA AND PRODUCTS

- EPN Central Bureau
- ROB Network
- Ionospheric Maps**
 - Dynamic
 - Static

TUTORIALS

- GPS, GLONASS, GALILEO, ...
- How GNSS Works
- Positioning & Timing
- GNSS Networks
- Coordinate Systems
- Atmosphere
 - Ionosphere
 - Troposphere

LOGIN



IONOSPHERIC MAPS

Contact: iono@oma.be

Last Ionospheric Events

- 22/05/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/04/2012 : Ionospheric activity due to CME impact ([more here](#))
- 16/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 12/03/2012 : Ionospheric activity due to CME impact ([more here](#))
- 08/02/2012 : Ionospheric activity due to major CME impact ([more here](#))
- 27/02/2012 : Ionospheric activity due to CME impact ([more here](#))
- 22/01/2012 : Ionospheric activity due to major CME impact ([more here](#))

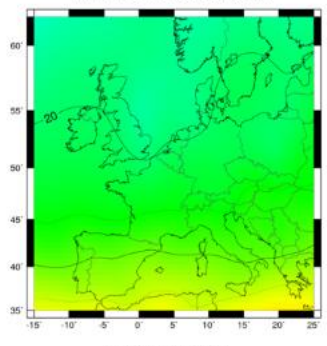
Near-Real Time Products

Vertical Total Electron Content (VTEC) estimated in Near Real-time (NRT) every 15 minutes from EUREP Permanent Network (EPN) GPS data. [More...](#)

- [Dynamic product](#): interactive product which allows viewing VTEC maps at different epochs as a movie. (4-5 sec to load).
- [Static product](#): statistics to compare the ionosphere at a given epoch with respect to the 15 previous days.

Dynamic

VTEC DOY 151 15:15-15:30 UTC

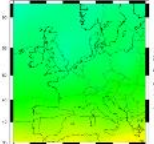


Ionospheric Range Error (R1) in m

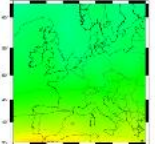
TECU in TECU

Static

VTEC DOY 151 15:15-15:30 UTC



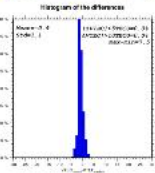
Median VTEC for 15 days 15:15-15:30 UTC



Subtraction VTEC - median VTEC



Histogram of the difference



Mean = 0.4
StdDev = 1.1
Min = -1.0
Max = 2.6

Products available on-line

IONOSPHERIC EVENT 08-03-2012

Contact: iono@oma.be

A first major solar flare occurred the 05/03/2012, followed by two other major flares the 07/03/2012 at 00:24 UTC and 01:14 UTC (source www.sidc.be). As a consequence, the Earth's ionosphere above Europe was disturbed during 4 periods :

- (1) 07/03/2012 from 05:30UTC to 21:30UTC (peak at noon),
- (2) 08/03/2012 from 07:00UTC to 10:30UTC,
- (3) 08/03/2012 from 13:00UTC to 21:00UTC,
- (4) 09/03/2012 from 07:00 UTC to 19:30UTC.

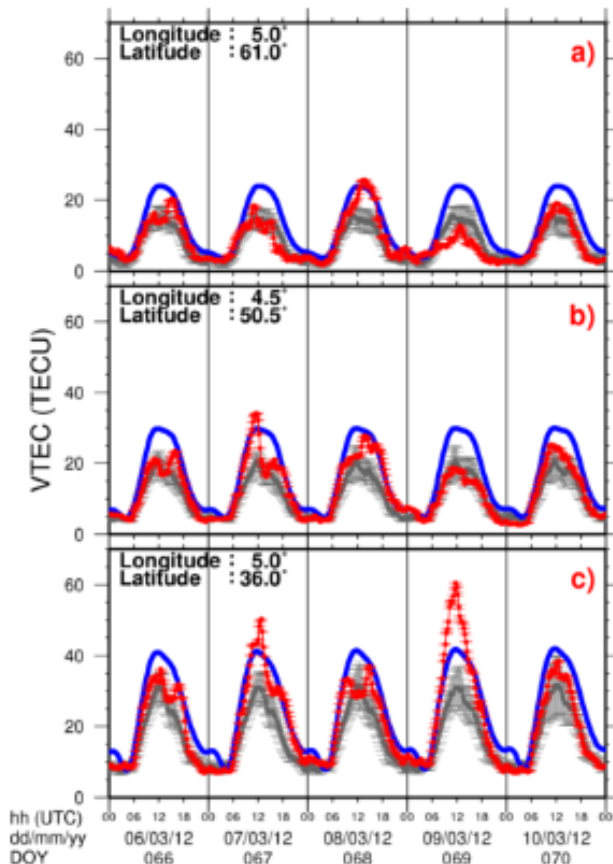


Figure 1: VTEC time series

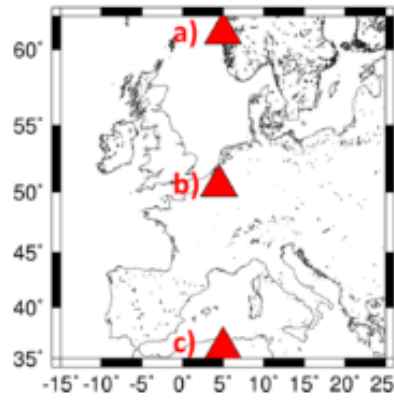


Figure 2: Map of the 3 locations

Figure 1 shows the time evolution of the [Vertical Total Electron Content](#) (VTEC) time series (*in red*) extracted from the near-real time 15-min VTEC maps at 3 different locations (see Figure 2):

- a) Northern part of the map (top)
- b) Brussels (middle)
- c) Southern part of the map (bottom)

Also shown, the model based on the median from the 15 previous days (*in grey*), and the IRI 2011 [Bilitza et al. 2011] model (*in blue*).

More informations:

- the 15 min VTEC maps during these events: [here](#)
- comparison with the median of the last 15 days (07/02

Time-series extracted from
the NRT maps

Prediction

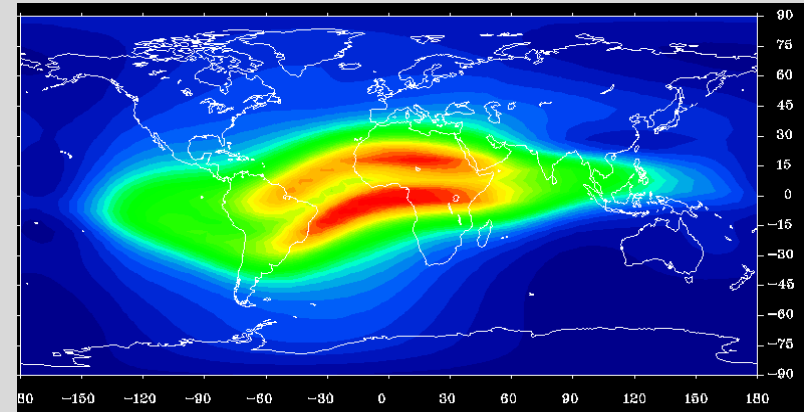
Observations

IRI 2012 [Bilitza et al. 2011]

Comparison with other ionospheric models

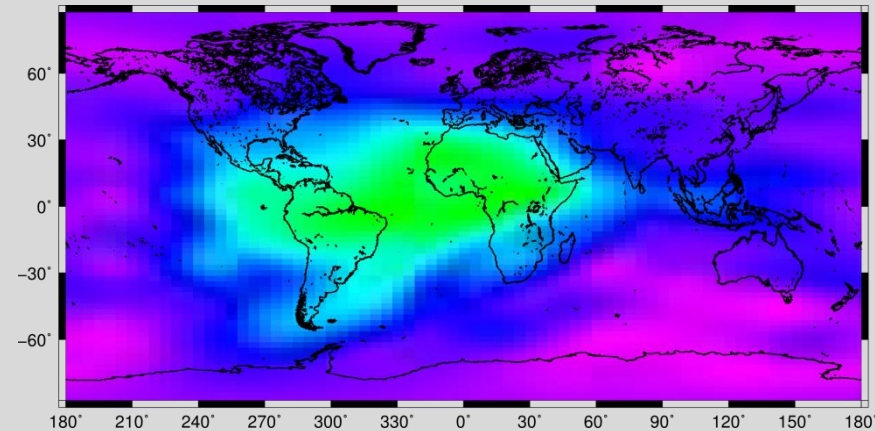
International Reference Ionosphere
NASA model iri.gsfc.nasa.gov
IRI 2012 [Bilitza et al. 2011]

Empirical climatological ionospheric model



CODE Final GIMs - IONEX
Bern <ftp.unibe.ch>
[Schaer et al. 1998]

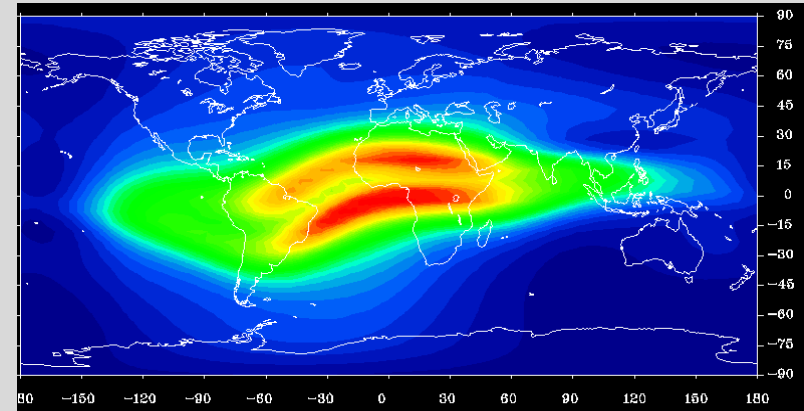
Post-processing of GNSS data (5-6 days)
~280 GNSS stations (GPS+GLONASS)
2.5°x5° - 2h
Spher. Harmonics. ($n, m=15$)



Comparison with other ionospheric models

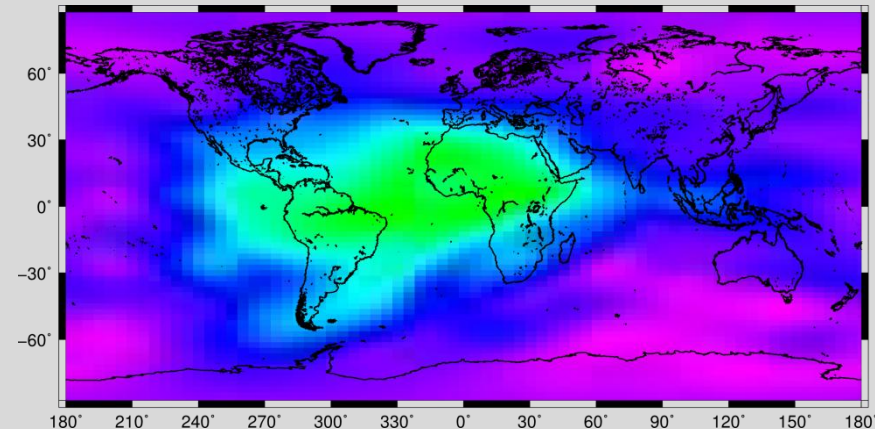
International Reference Ionosphere
NASA model iri.gsfc.nasa.gov
IRI 2012 [Bilitza et al. 2011]

IRI
Very smooth

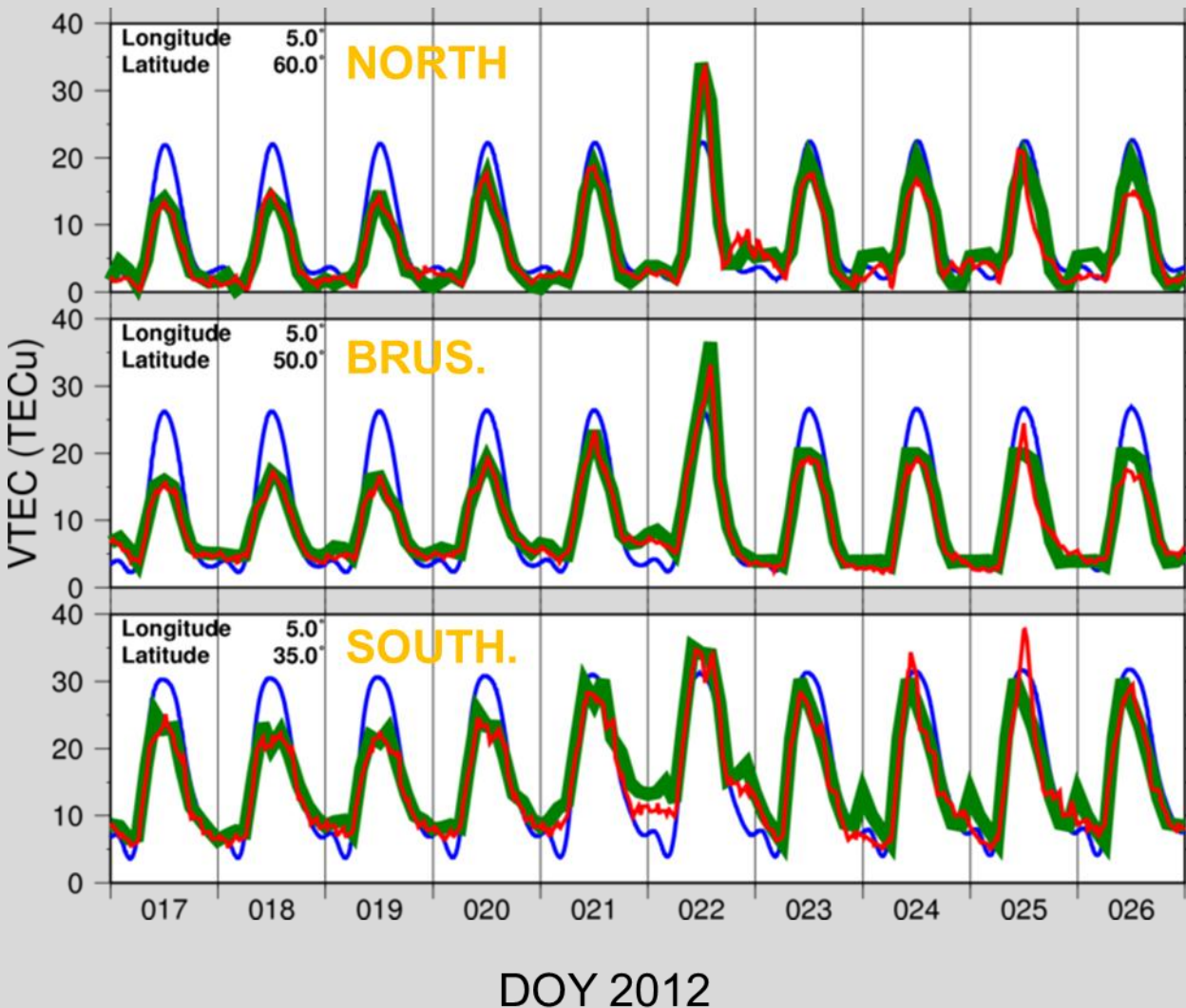


CODE Final GIMs - IONEX
Bern <ftp.unibe.ch>
[Schaer et al. 1998]

CODG
Slightly smooth



Comparison with other ionospheric models



$VTEC_{ROB} - VTEC_{CODG}$

North : 0.0 ± 1.3 TECu

Brus. : 0.2 ± 0.8 TECu

South : -0.9 ± 1.5 TECu

$VTEC_{ROB} - VTEC_{IRI}$

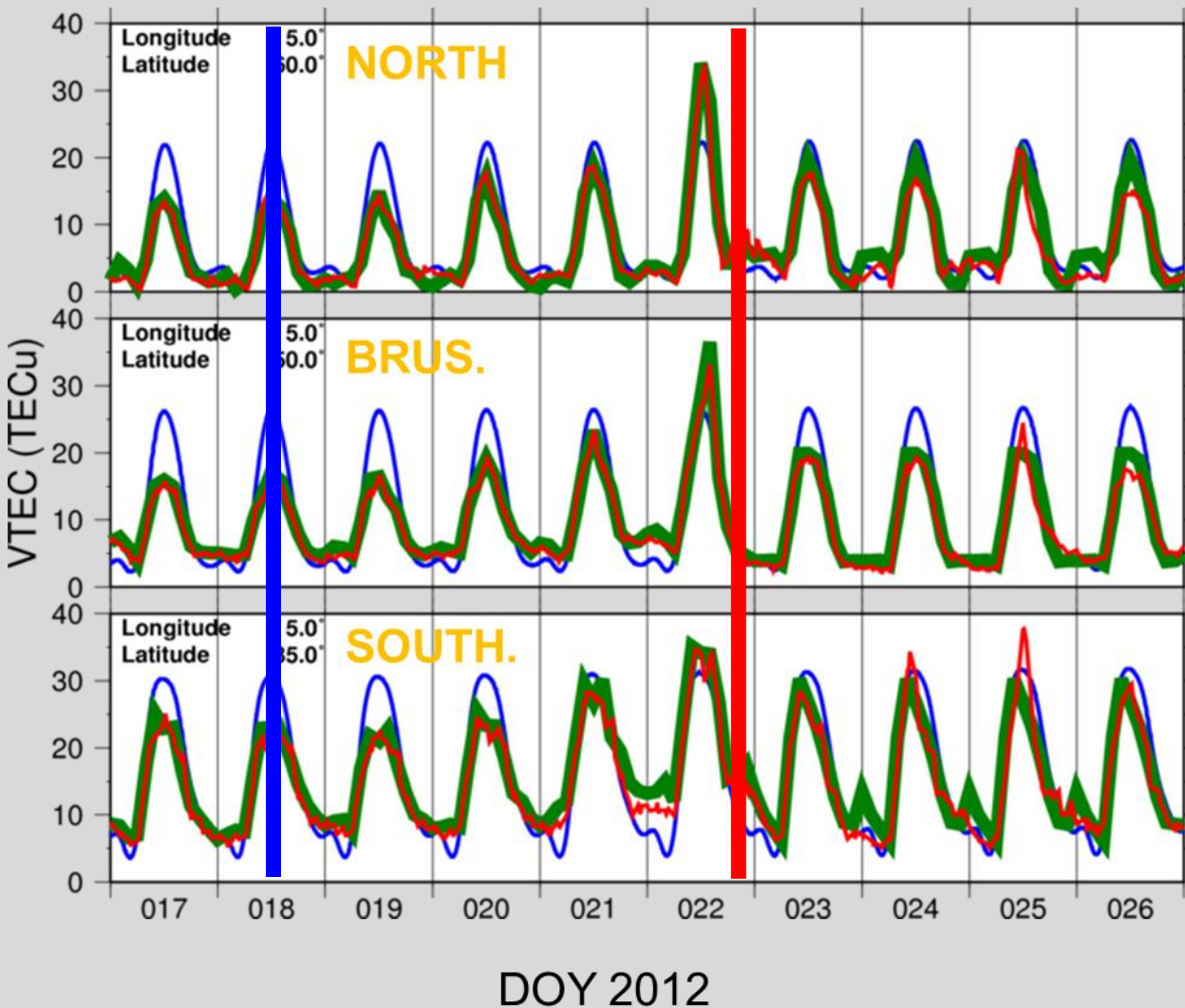
12:00 UTC

North : -6.4 ± 3.9 TECu

Brus. : -9.5 ± 3.2 TECu

South : -5.6 ± 4.2 TECu

Comparison with other ionospheric models



$$\text{VTEC}_{\text{ROB}} - \text{VTEC}_{\text{CODG}}$$

North : 0.0 ± 1.3 TECu

Brus. : 0.2 ± 0.8 TECu

South : -0.9 ± 1.5 TECu

$$\text{VTEC}_{\text{ROB}} - \text{VTEC}_{\text{IRI}}$$

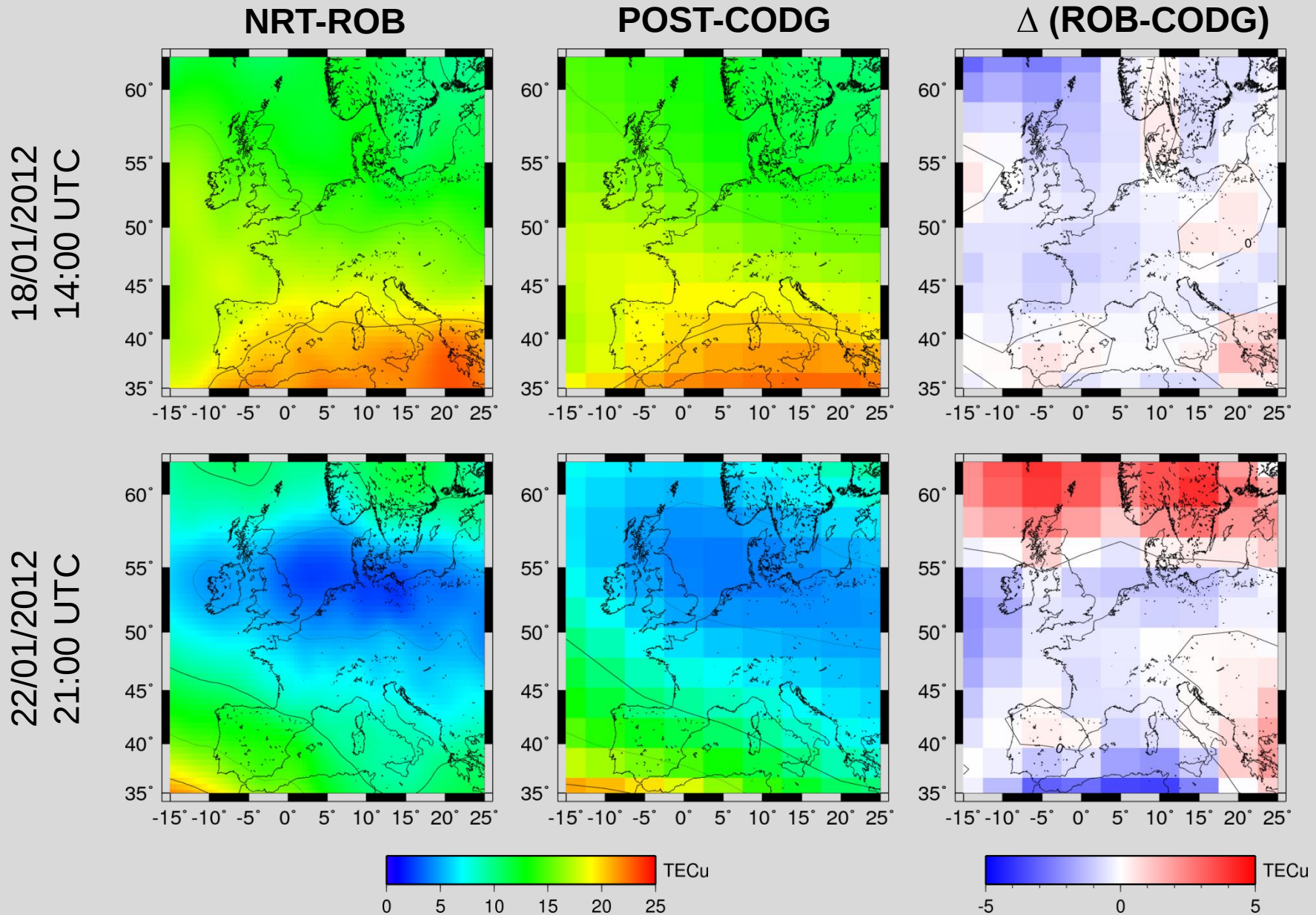
12:00 UTC

North : -6.4 ± 3.9 TECu

Brus. : -9.5 ± 3.2 TECu

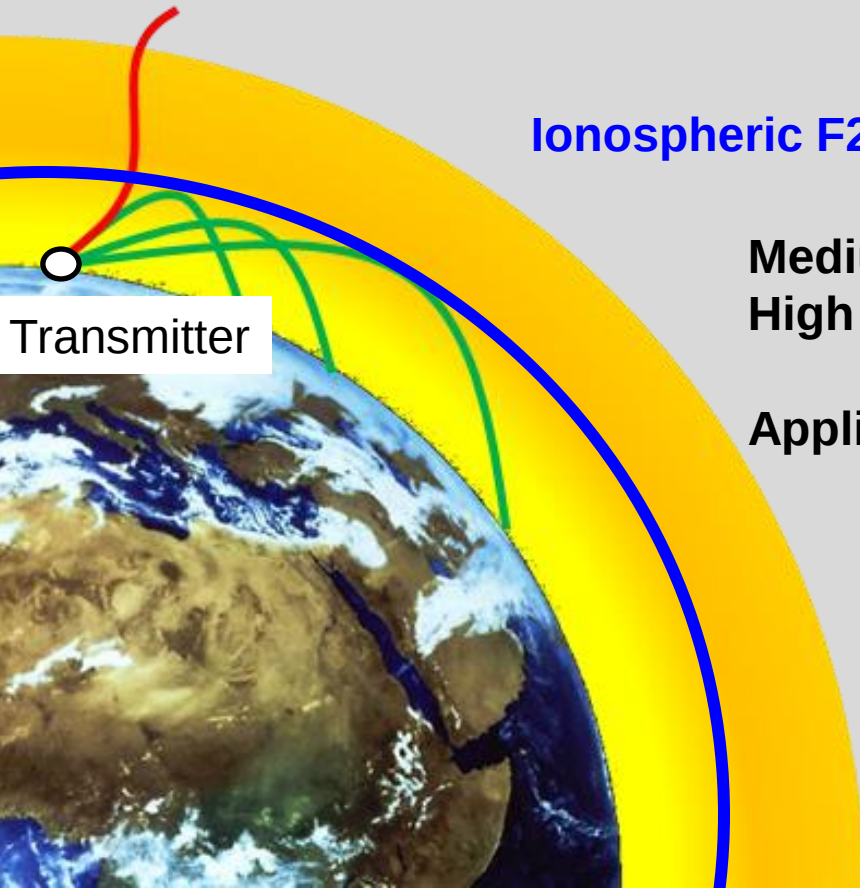
South : -5.6 ± 4.2 TECu

Comparison with other ionospheric models



Products
under
development

F2 Critical frequency = f_oF2



Ionospheric F2 layer ~ 300-400 km.

Medium Frequency (0.3-3MHz)

High Frequency (3-30MHz)

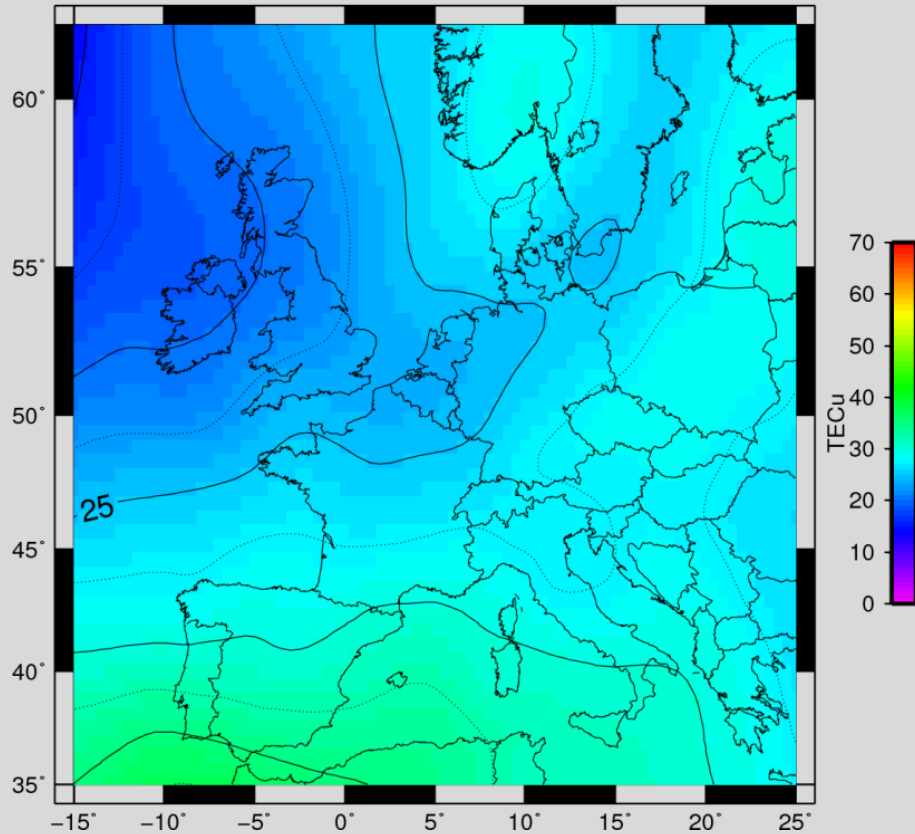
Applications : Aviation, amateur radio

< f_oF2 = Reflexion

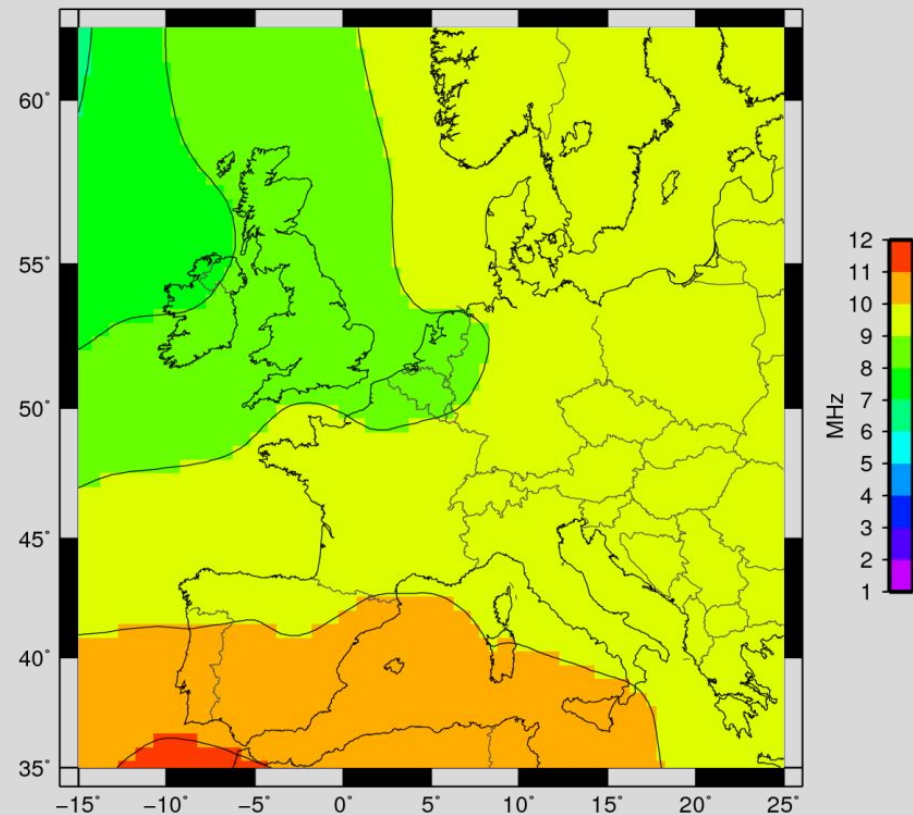
> f_oF2 = Refraction

F2 Critical frequency = foF2

NRT-VTEC ROB maps

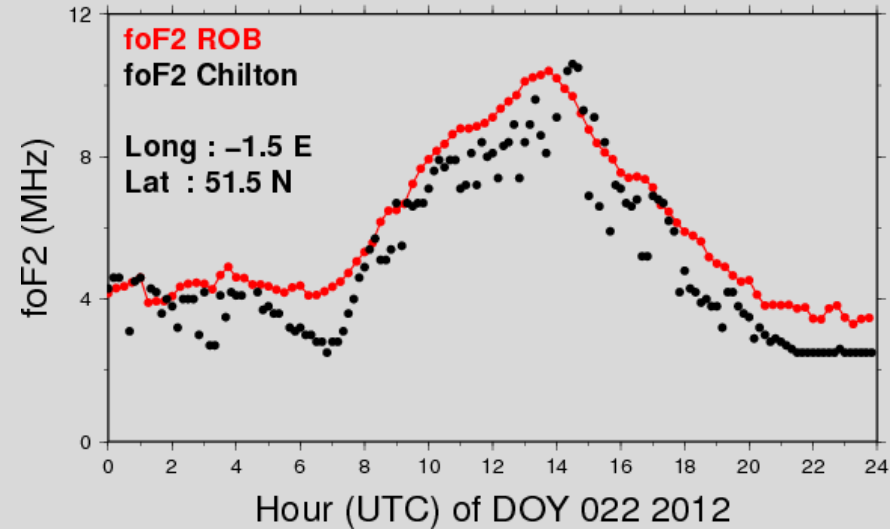
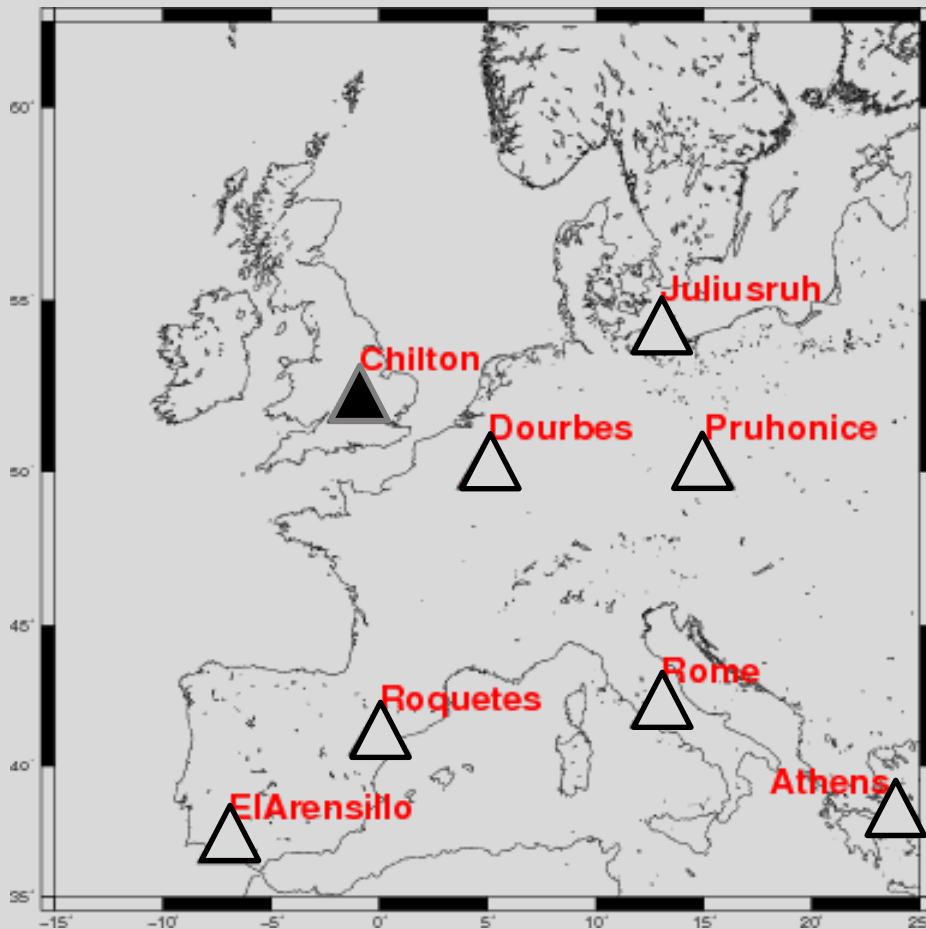


NRT-foF2 ROB maps



NRT – FoF2 each 15min. on a 0.5°x0.5° grid

F2 Critical frequency = foF2



Differences with Chilton ionosonde

31 days in Jan. 2012

Each 15 min

REL. Δ : 13 ± 17 %

ABS. Δ : 0.6 ± 0.5 MHz

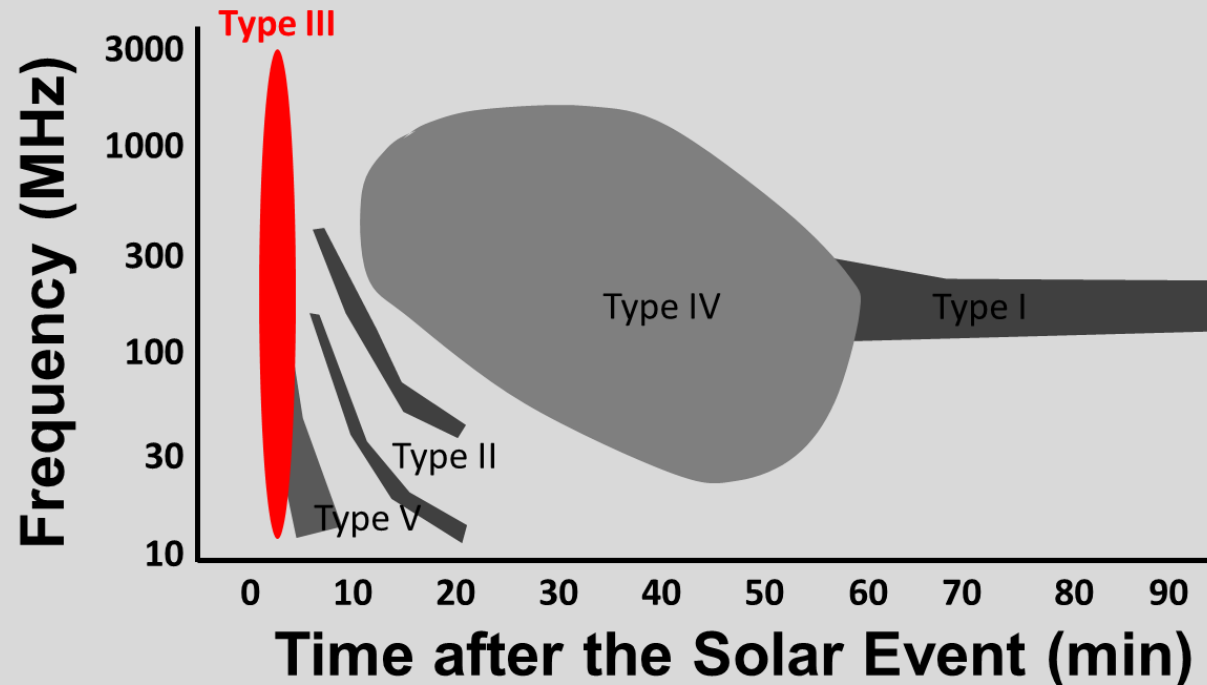
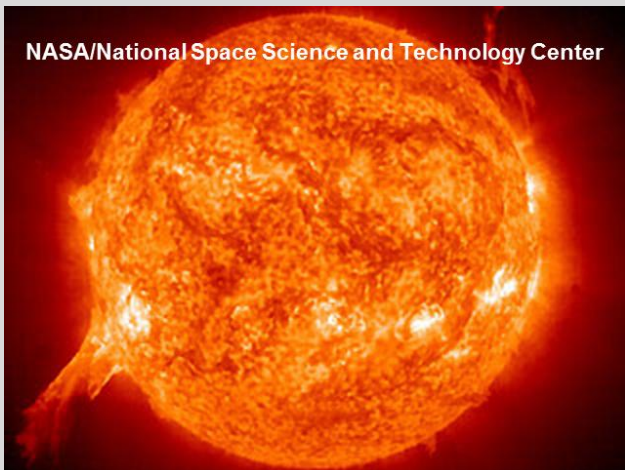
Useful for MF and HF reflexion

Study of the GPS Signal/Noise

L1 and L2 Signal to Noise Ratio (SNR) = S1 S2 observables RINEX observations files

S1/S2 in dB-Hz for the two GPS frequency.

- L1= 1575.42 MHz
- L2= 1227.60 MHz

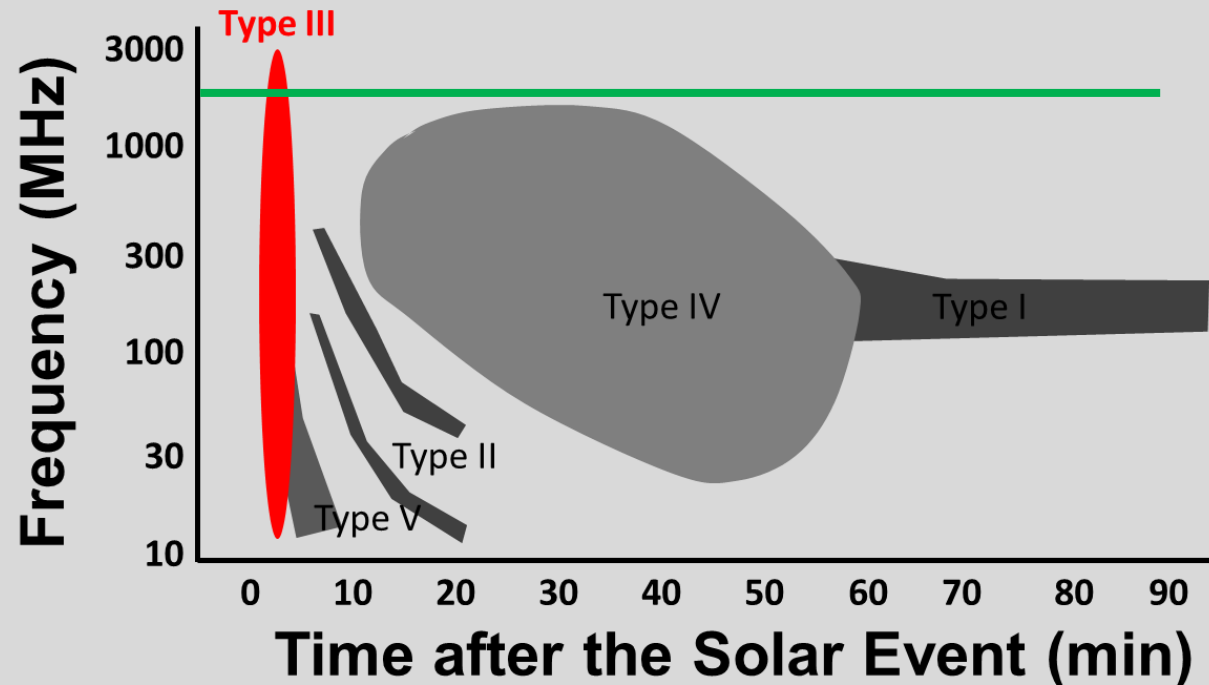
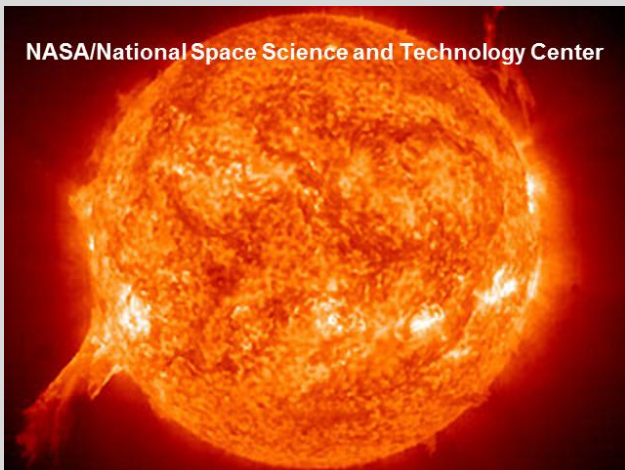


Study of the GPS Signal/Noise

L1 and L2 Signal to Noise Ratio (SNR) = S1 S2 observables RINEX observations files

S1/S2 in dB-Hz for the two GPS frequency.

- L1= 1575.42 MHz
- L2= 1227.60 MHz

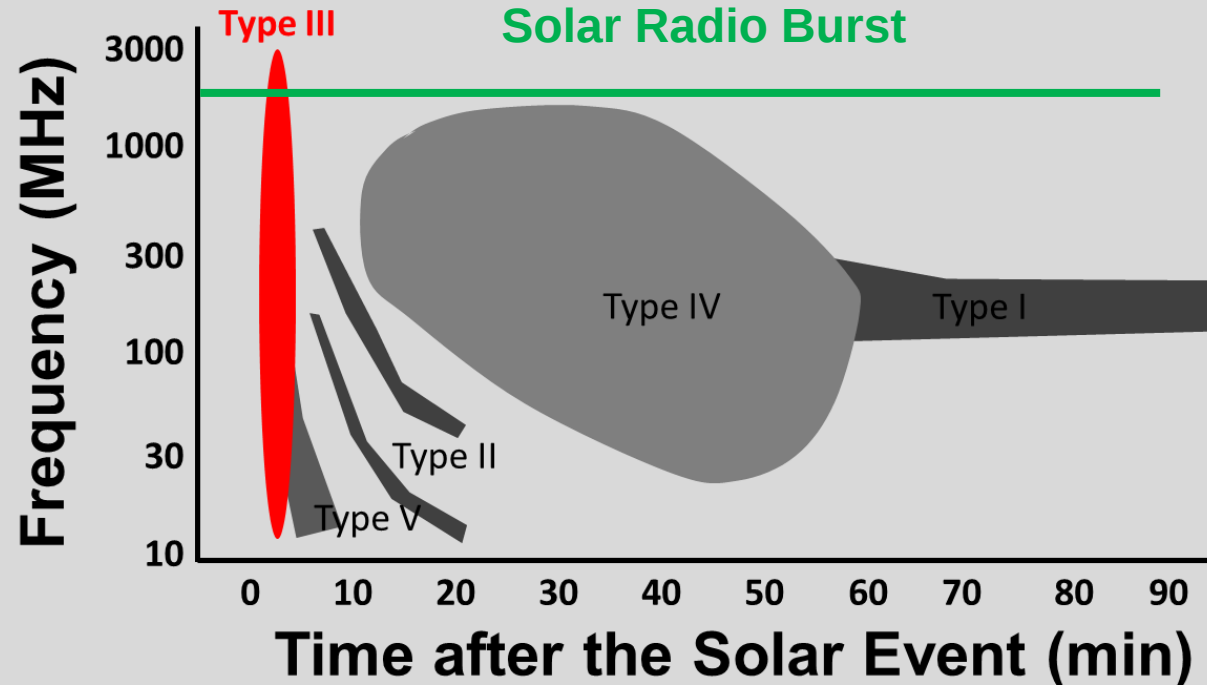
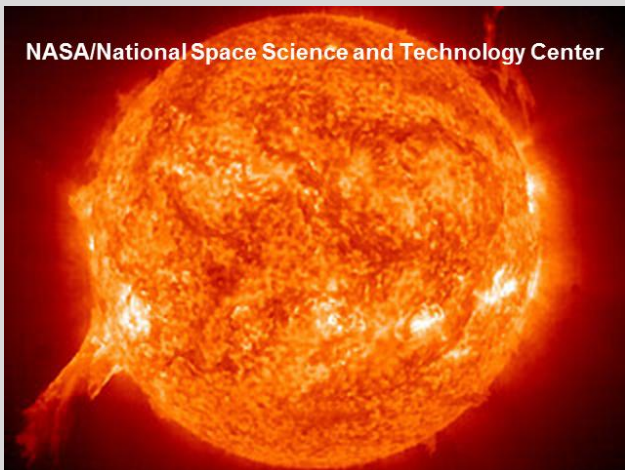


Study of the GPS Signal/Noise

L1 and L2 Signal to Noise Ratio (SNR) = S1 S2 observables RINEX observations files

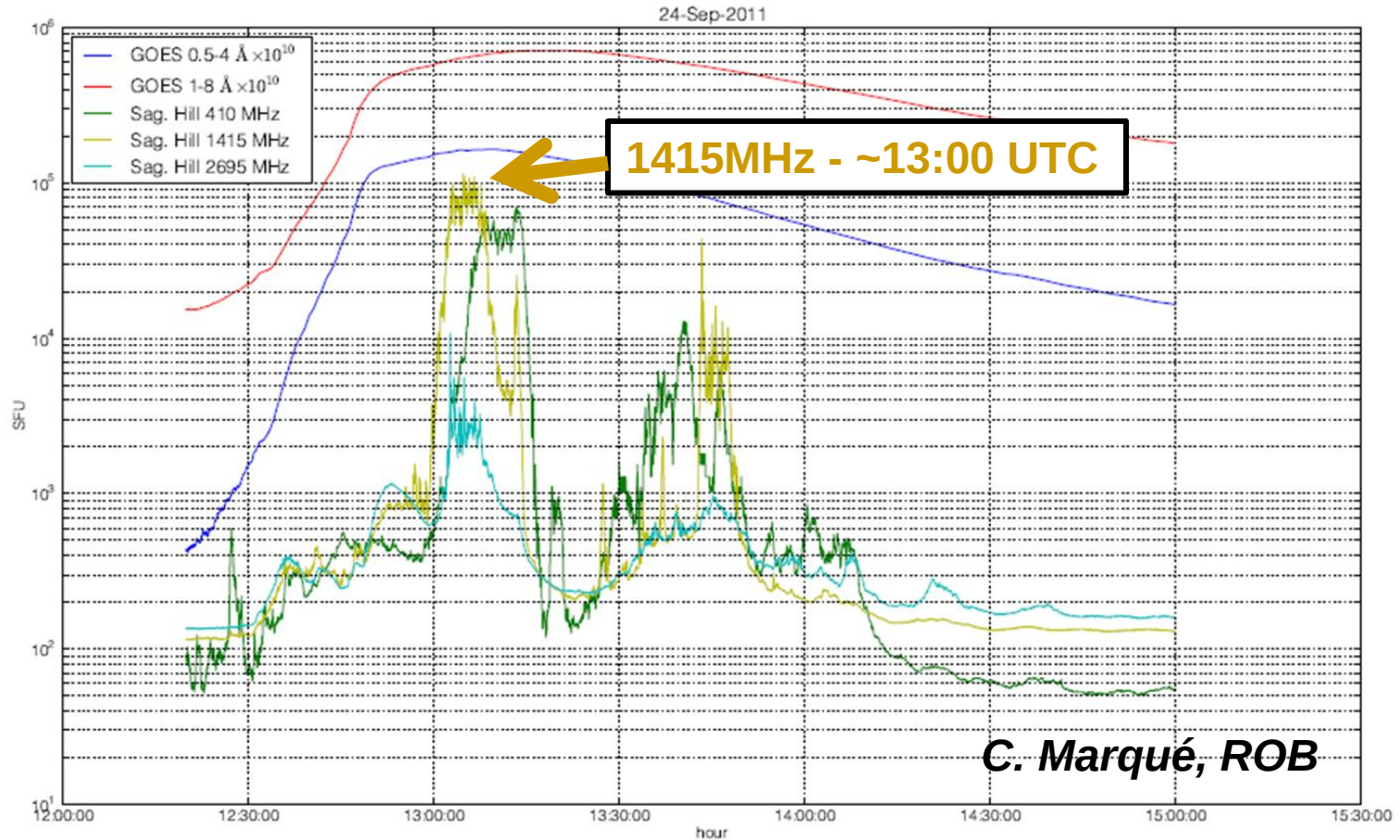
S1/S2 in dB-Hz for the two GPS frequency.

- L1= 1575.42 MHz
- L2= 1227.60 MHz

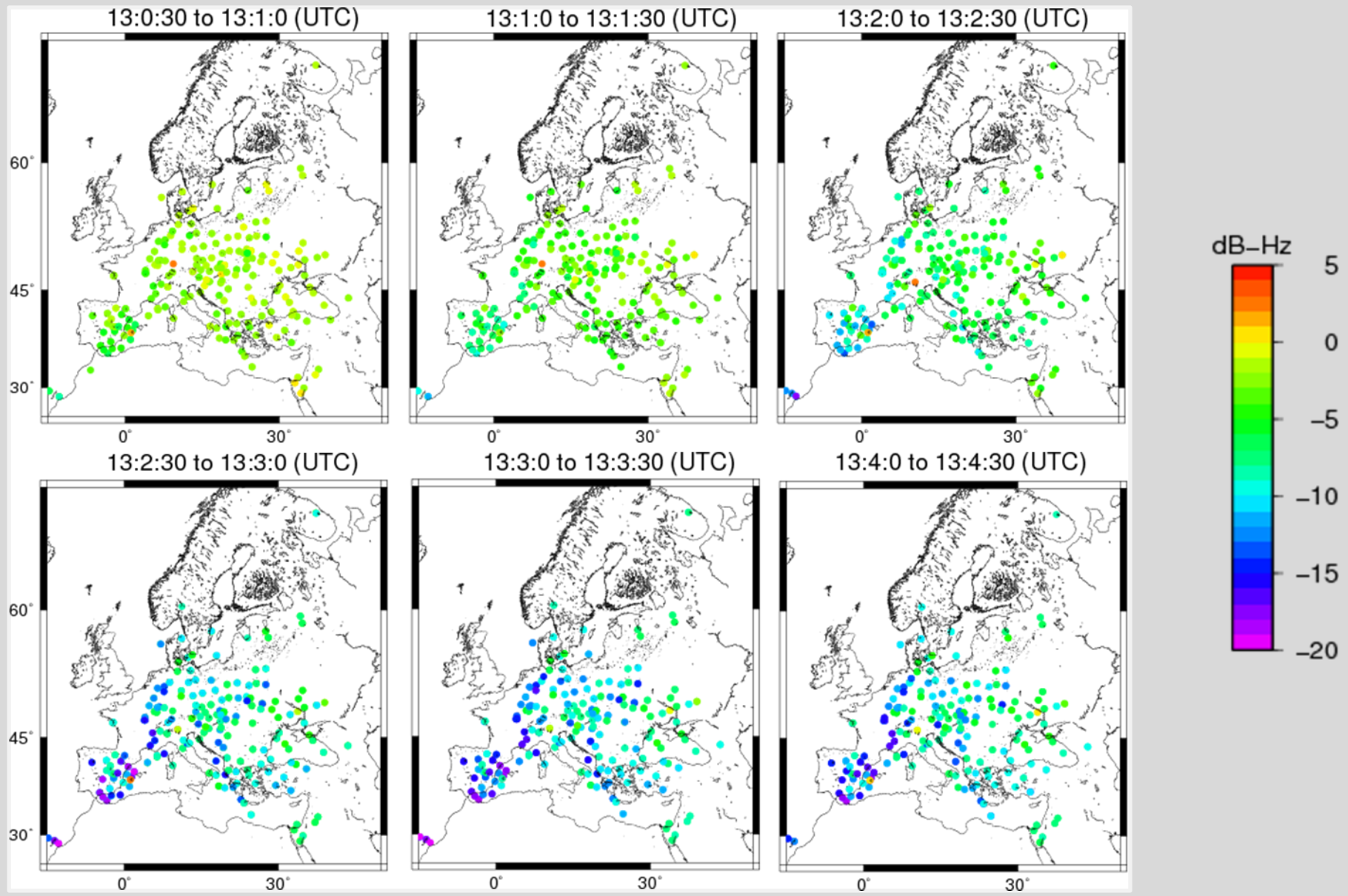


Study of the GPS Signal/Noise

Frequencies emitted by the Sun 24-09-2011



Study of the GPS Signal/Noise



Conclusions and perspectives

- NRT-VTEC ROB maps each 15min. ($0.5^{\circ} \times 0.5^{\circ}$). Latency 7-10 min.
- Use of EPN NRT GPS data from ROB [& BKG] NTRIP Broadcaster.
- Products available on gnss.be

Densification of NRT GPS stations in Northern Part of Europe.

- Products under development (S/N, foF2).

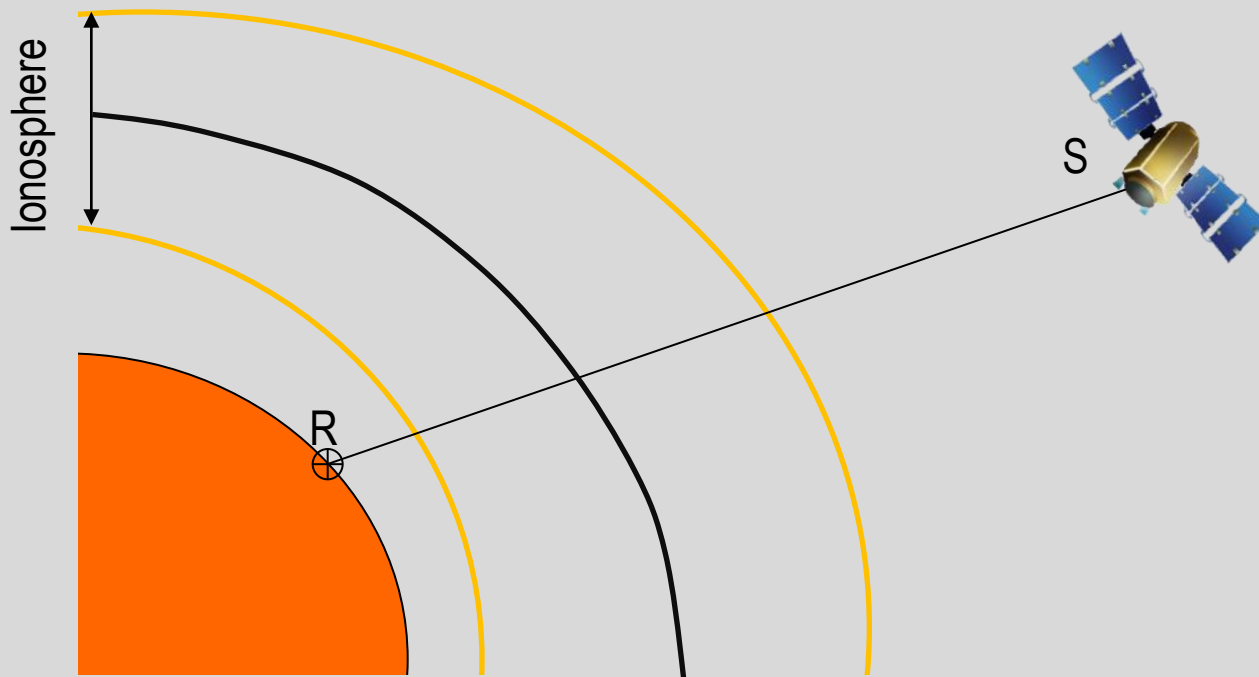
ROB NRT **IONEX** will be also provided.

iono@gnss.be

Ionospheric monitoring from EPN NRT GPS data

$$\boxed{P_2 - P_1} + DCB^s + DCB_r = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC$$

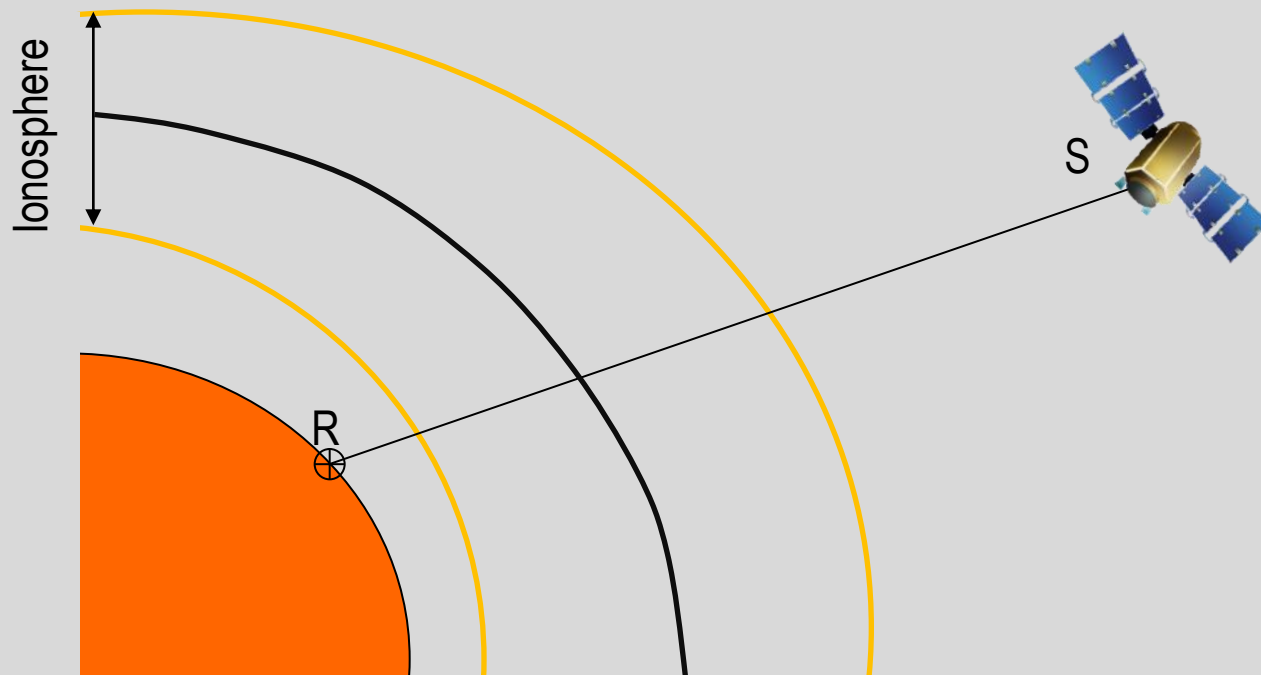
Zero-difference phase-smoothed (P_1 and P_2) code observations



Ionospheric monitoring from EPN NRT GPS data

$$\boxed{P_2 - P_1} + \boxed{DCB^s} + DCB_r = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC$$

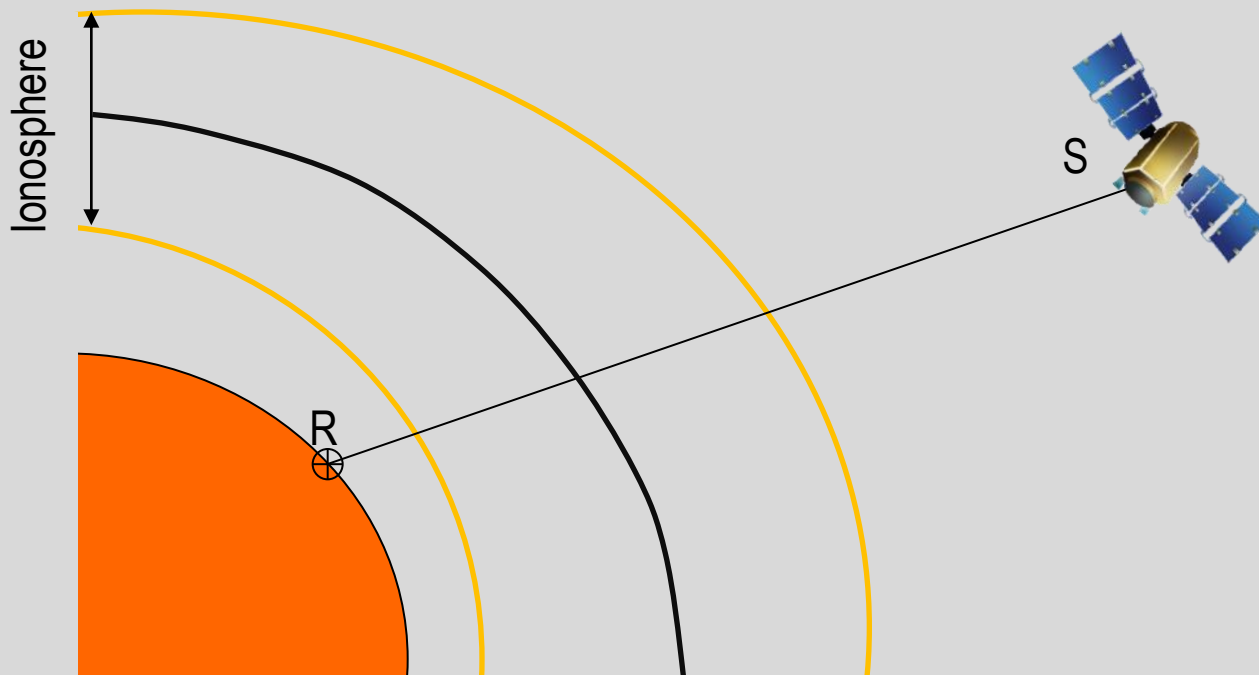
DCB^s : estimation from CODE analysis centre [Schaer et al. 1998]
Rapid IONEX (IONosphere map EXchange).



Ionospheric monitoring from EPN NRT GPS data

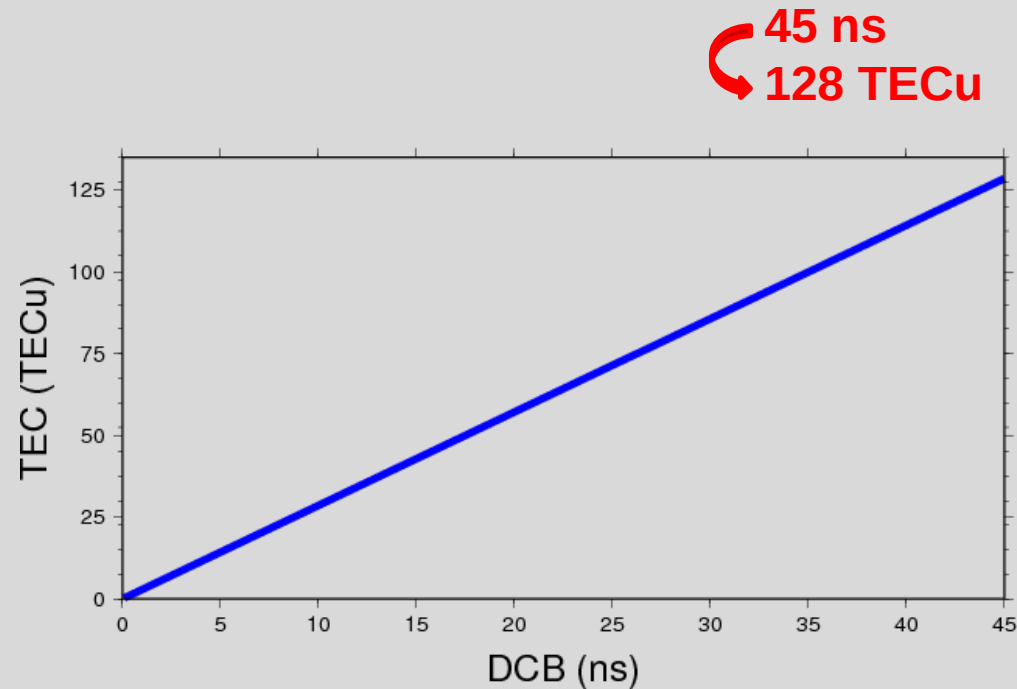
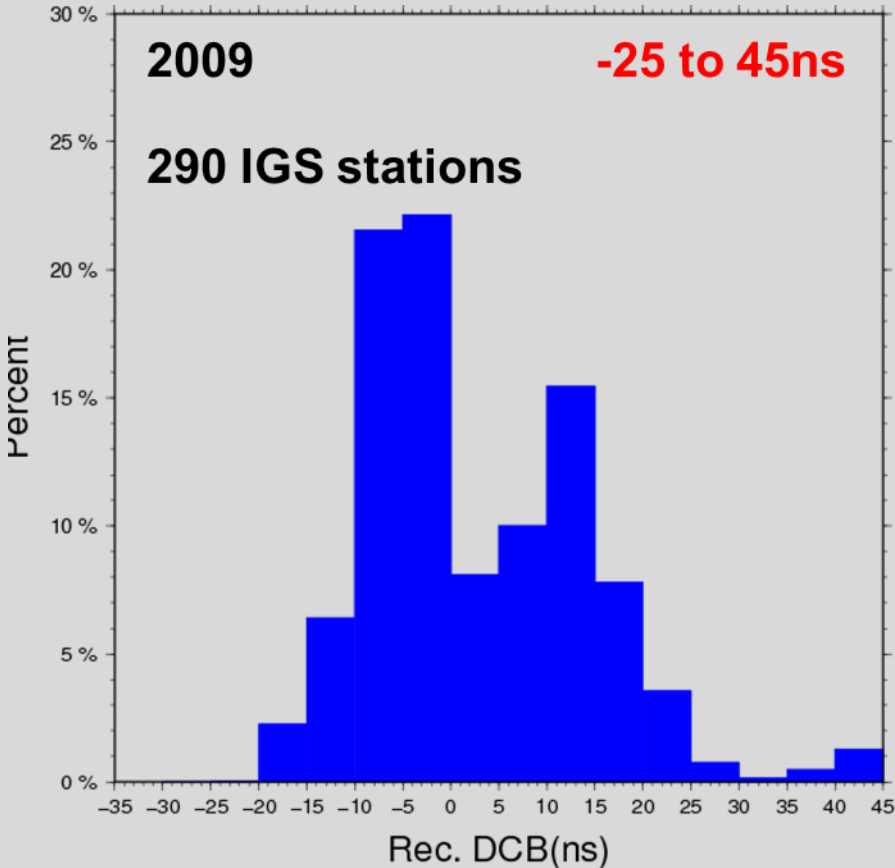
$$\boxed{P_2 - P_1} + \boxed{DCB^s} + \boxed{DCB_r} = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC$$

DCB_r : estimation using *a priori* ionospheric models (Rapid IONEX)



Receiver Differential Code Biases

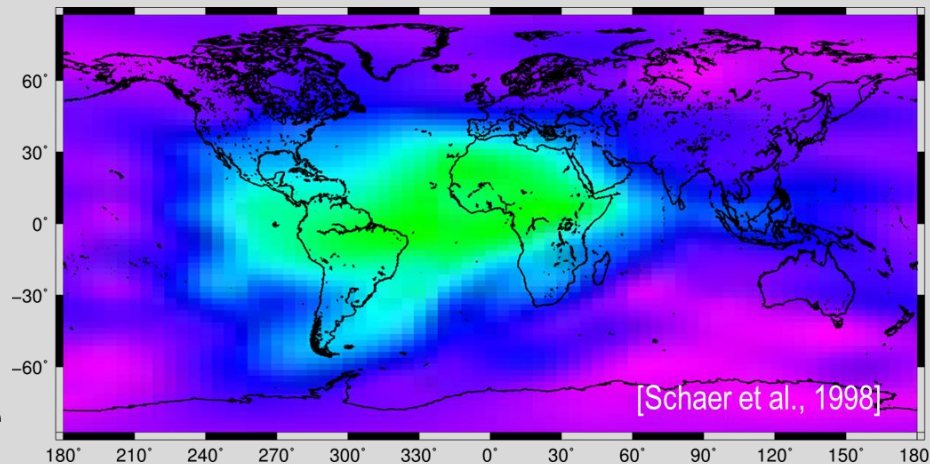
$$P_2 - P_1 + DCB^s + \boxed{DCB_r} = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC$$



Receiver Differential Code Biases use in NRT

$$P_2 - P_1 + DCB^s + DCB_r = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC$$

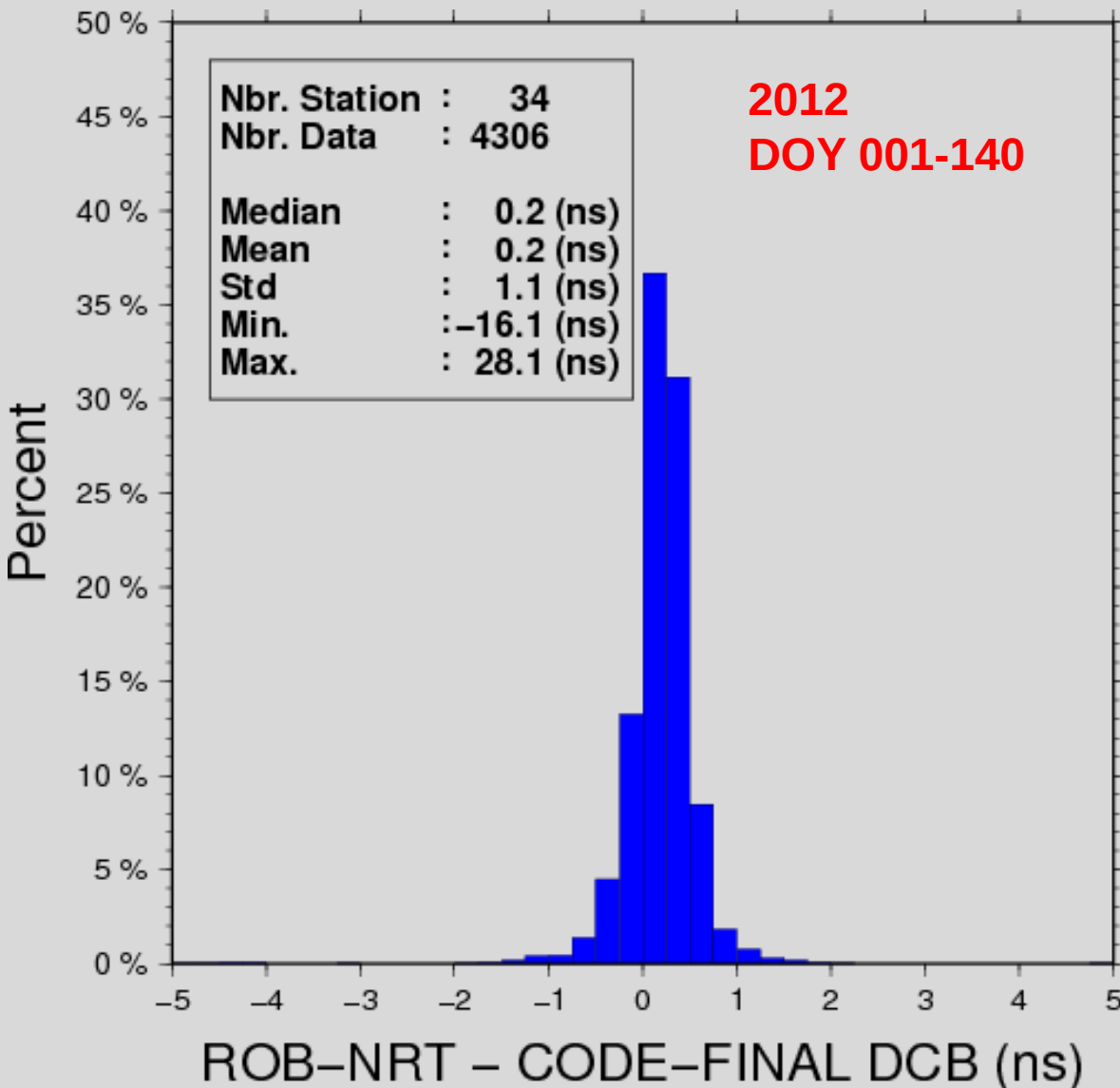
- ❑ Global Ionospheric Maps (GIM) of VTEC (5°x2.5°x2h, 2-9 TECu)
- ❑ CODE rapid products (~ 24h)
- ❑ ~120 globally distributed stations
- ❑ GLONASS and GPS constellations
- ❑ Linear interpolation in space and time



$DCB_r(j) =$

$MEDIAN [DCB_r(j-2), DCB_r(j-3), DCB_r(j-4), DCB_r(j-5), DCB_r(j-6)]$

Receiver Differential Code Biases



Comparison with CODE
Final product (~5-6 days).

34 stations from the IGS.

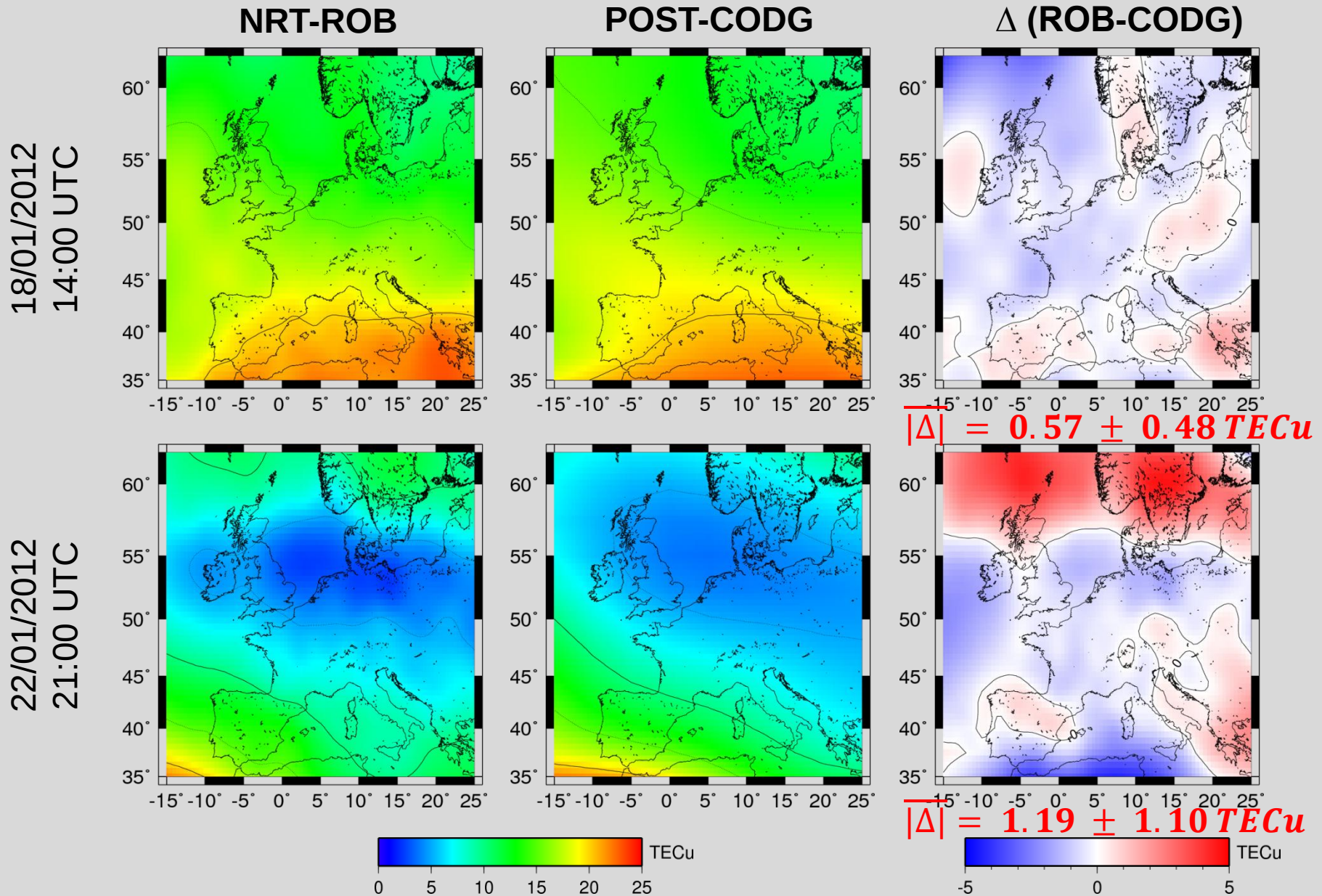
0.3 ns ~ 1 TECu (60%)

0.7 ns ~ 2 TECu (94%)

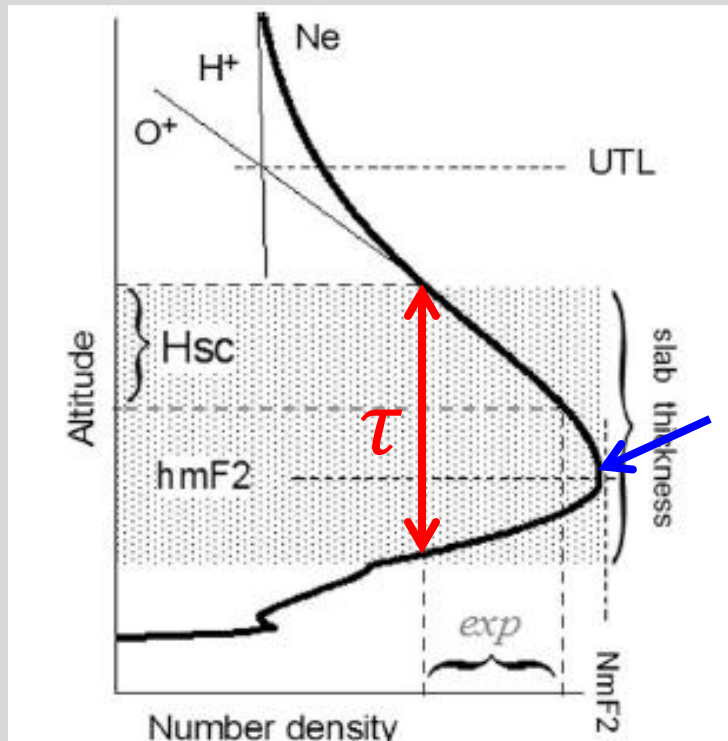
Biases = 0.2 ns (~0.5 TECu)

**Lower than the precision of
the TEC estimation
(2-3 TECu)**

Comparison with other ionospheric models



F2 Critical frequency = foF2



From Stankov et Warnant, 2009

Davies, 1990:

$$\tau = \frac{VTEC}{NmF2}$$

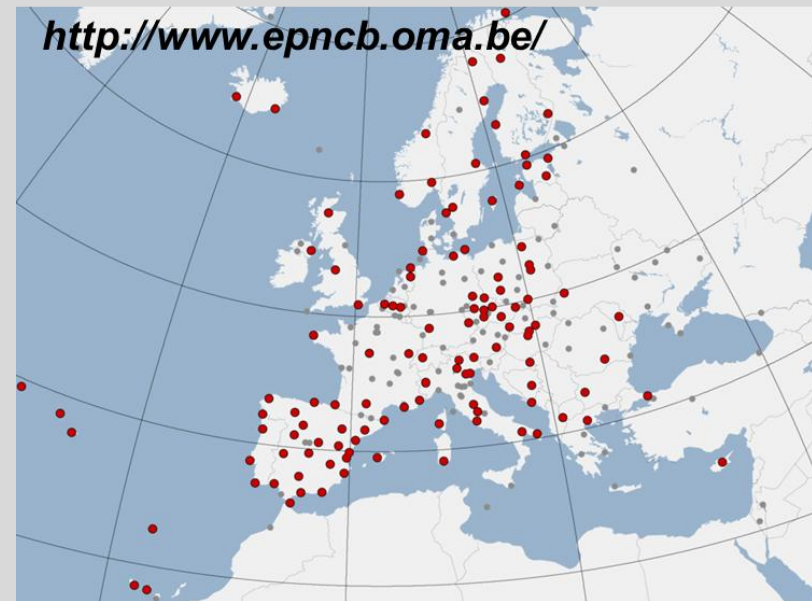
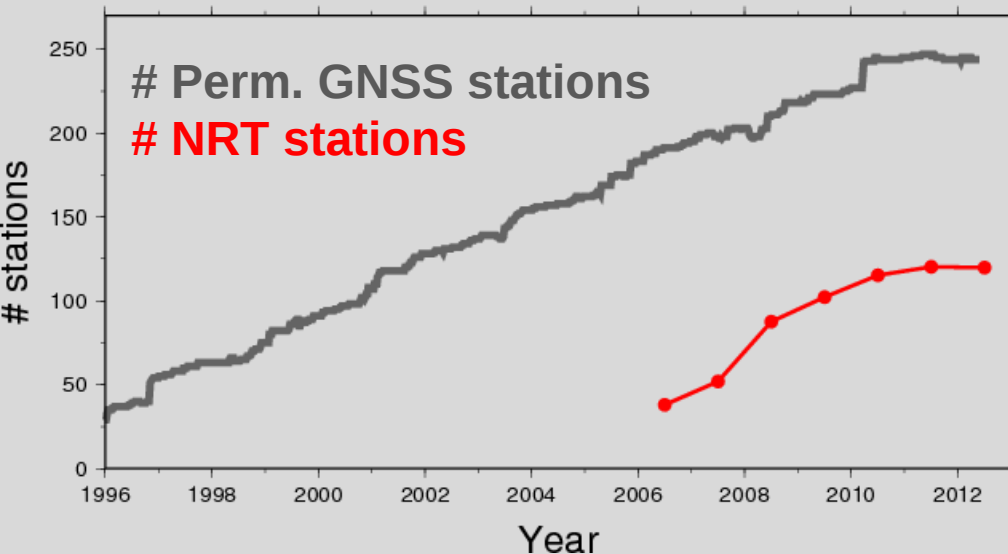
*NmF2
Scaled IRI 2012*

$$\tau = \frac{VTEC}{foF2^2 \times 1.24 \times 10^{-6}}$$

- foF2 : F2 critical frequency in MHz
- τ : Ionospheric slab thickness in m
- VTEC : Vertical Total Electron Content in e⁻/m²
- NmF2 : Maximum electronic concentration in e⁻/m³

European Permanent Network (EPN)

- Continuously observing GNSS stations since 1996
- Presently: ~ 250 stations over Europe
- **NRT : Presently ~ 120 stations**



EPN (European Permanent Network)