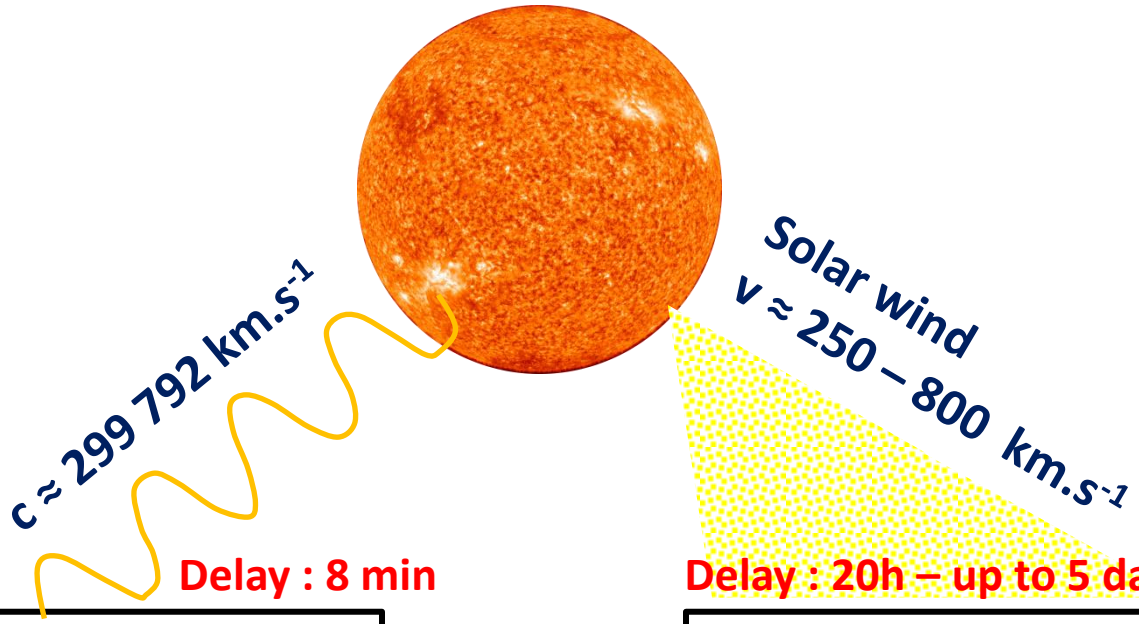
Solar-Terrestrial Center of Excellence

Royal Observatory of Belgium

Near Real-Time Monitoring of the Solar Activity Impact on European Region from the EPN Data

J.-M. Chevalier and N. Bergeot

The Sun, Source of Space Weather



Electromagnetic <u>Radiations</u>

EUV X-rays Radio Waves

Energetic Electrically charged <u>Particles</u>

Inter-planetary Magnetic Field

Protons & Electrons

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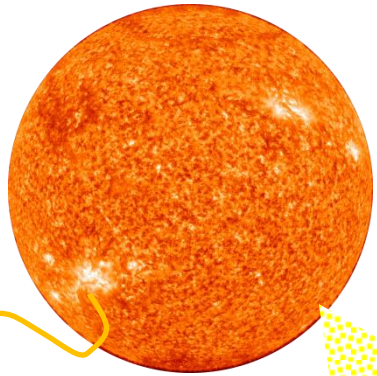

$c \approx 299\,792\ km.s^{-1}$

Delay : 8 min

Solar wind
$v \approx 250 - 800\ km.s^{-1}$

Delay : 20h – up to 5 days

Electromagnetic Radiations

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Emissions

Effects

Photo-ionisation

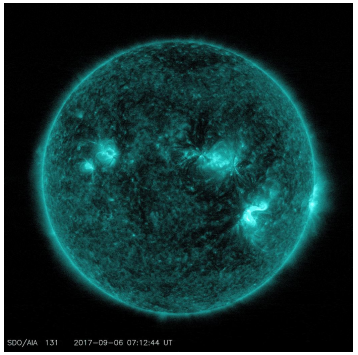
Ionospheric Ne Δ

Ionospheric content

Radio signal delay

GNSS

Introduction — The Sun, Source of Space Weather



NASA

Solar Flare

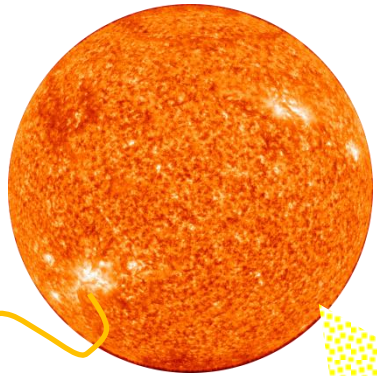


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Photo-ionisation	Solar Radio Burst
Effects	
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Radio signal delay- ↘ Signal reception	**Signal reception fade (↗noise)**
	GNSS

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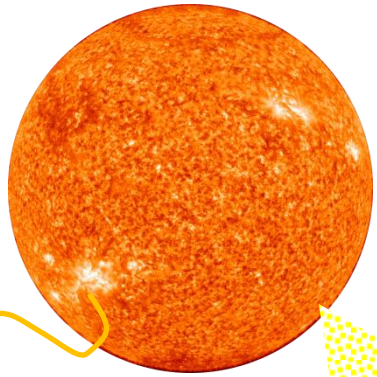
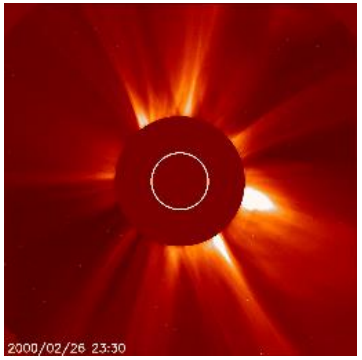


Solar Flare

Coronal Mass Ejection



ESA/NASA SOHO

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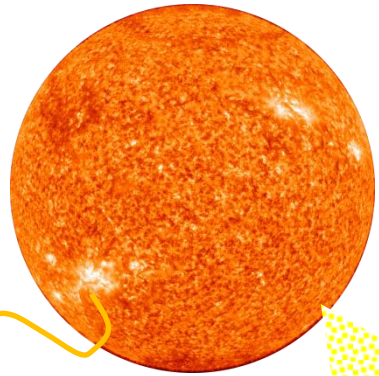
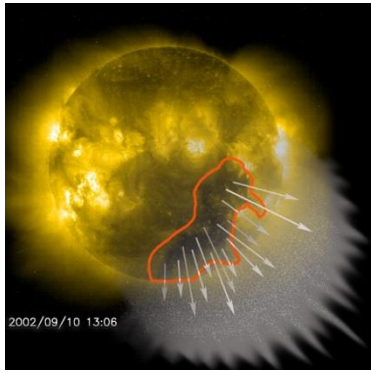
The Sun, Source of Space Weather

Solar Flare

Coronal Mass Ejection

Coronal Hole





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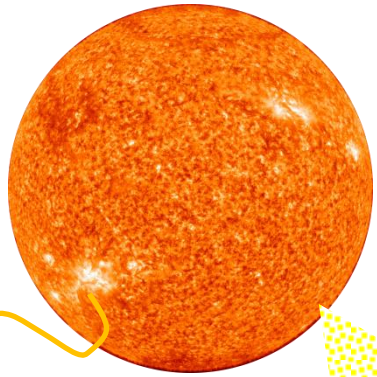

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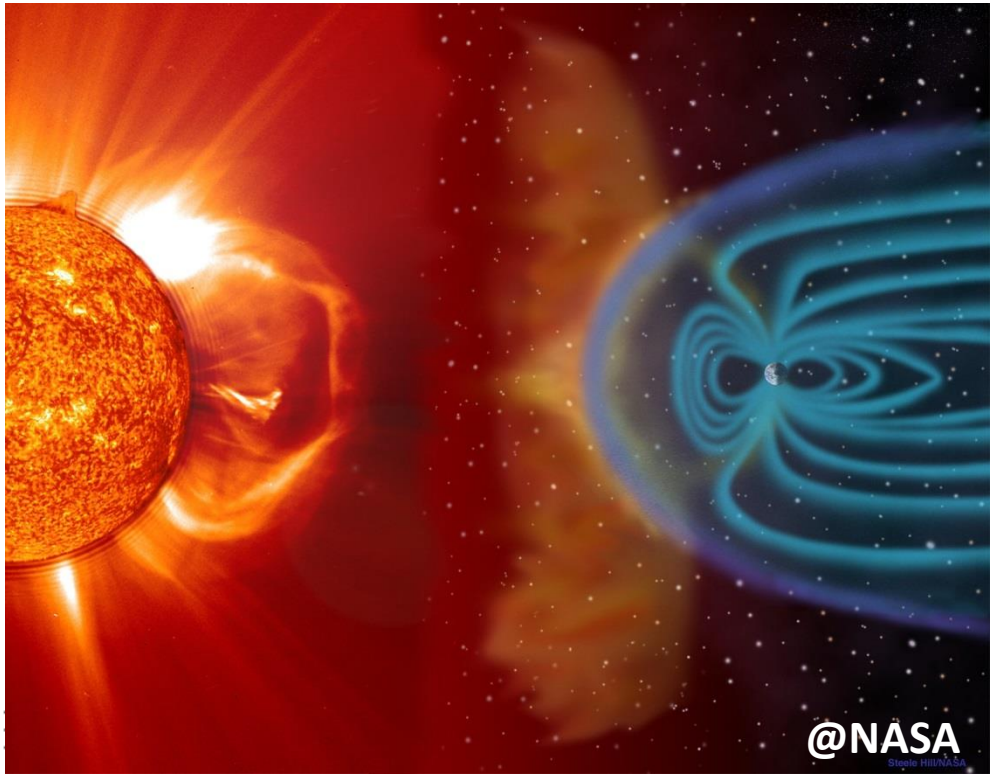
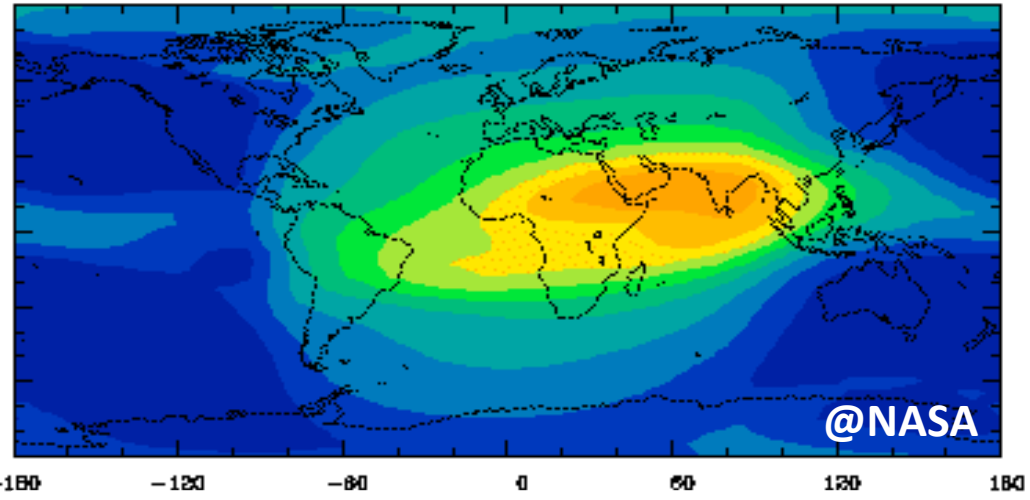
Ionosphere

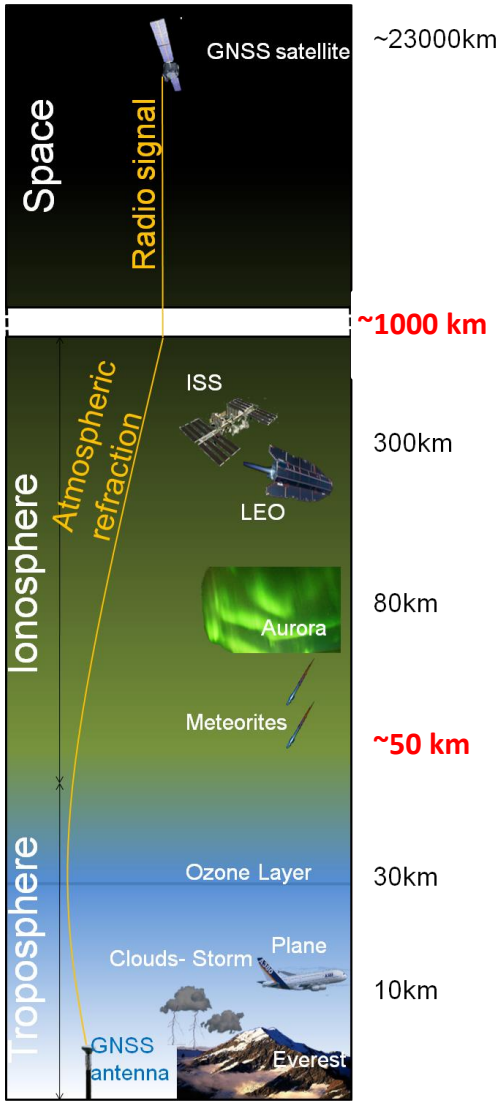


Ionised media

Plasma:

e- = ion+





Ionosphere vs GNSS

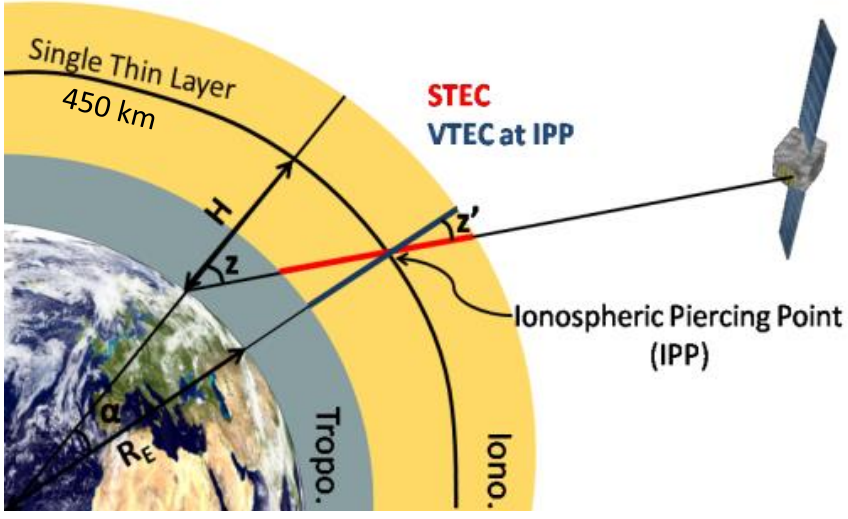
Electrically charged media affects the radio-wave propagation (depending on the frequency)

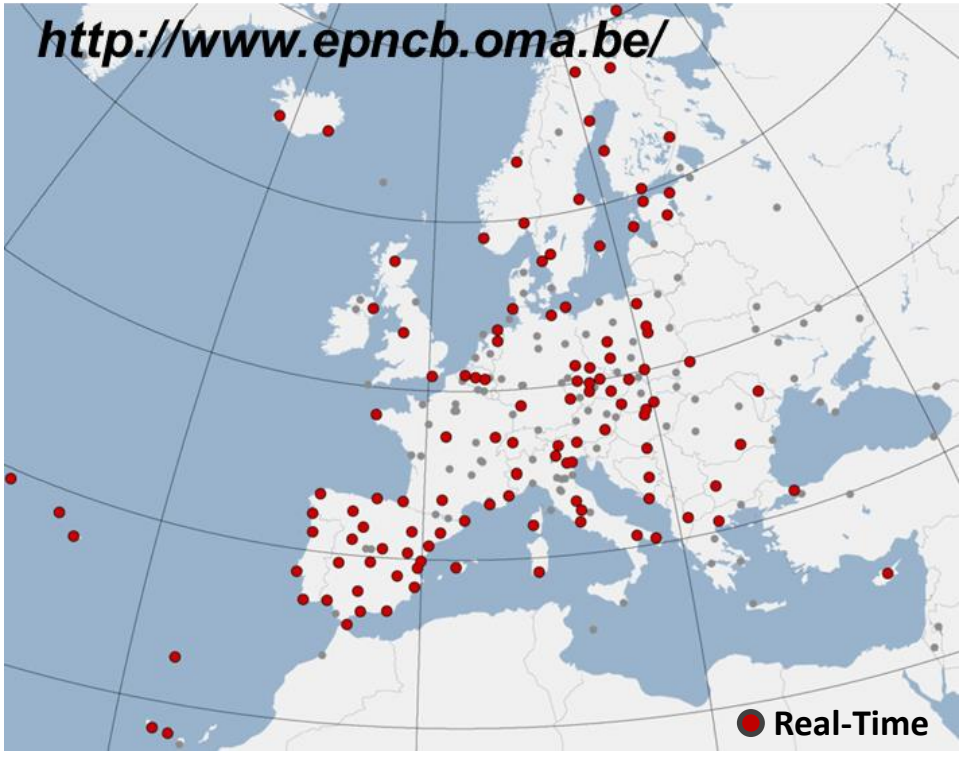
=> ionospheric delay $I_{1,2}$

Pseudorange $$P_{1,2} = \rho_{1,2} - c\Delta t_{rec} + c\Delta t_{sat} + I_{1,2} + Tr + \delta^P_{1,2} + \epsilon^P_{1,2}$$

Ionospheric delay $$I_{1,2} = 40.3 \frac{STEC}{{f_{1,2}}^2}$$

Slant Total Electron Content $$STEC = \int_R^S N_e dl$$





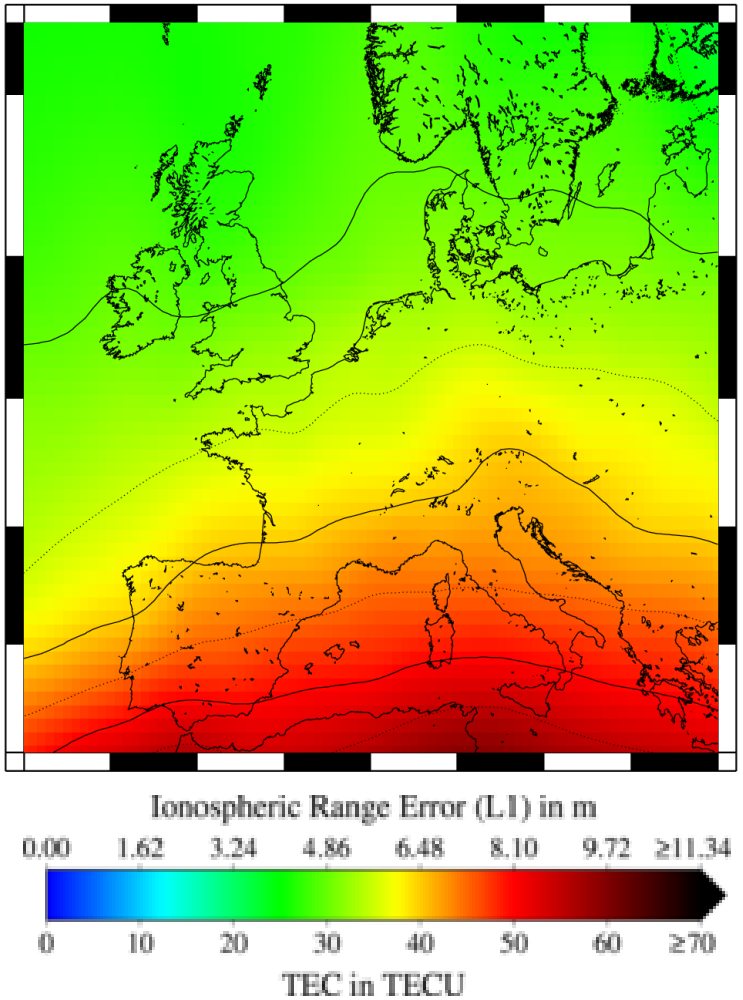
ROB-IONO Software

SWSC Journal of Space Weather and Space Climate

Bergeot N., et al. (2014) J. Space Weather Space Clim.

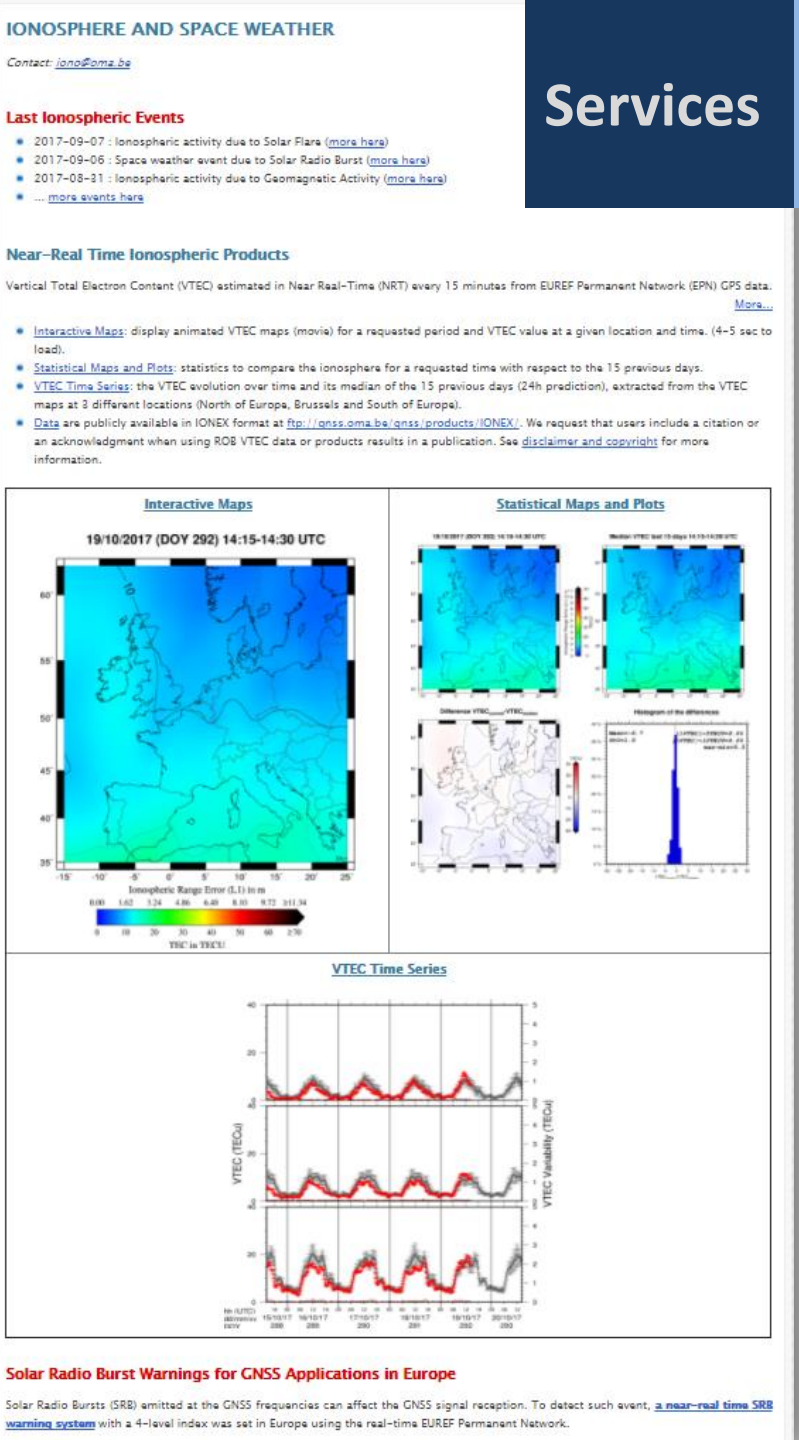
- Input data: real-time data from the EPN (~150 stations)
- Near real-time TEC maps over Europe + variability
  - since 2012

Sampling rate	: 15 min
Grid extent	: Long W15° / E25°
	: Lat N35° / N62°
Grid resolution	: 0.5°x0.5°
Latency	: ~3 minutes



Services

Monitoring based on Real-Time EPN Data



IONOSPHERE AND SPACE WEATHER

Contact: iono@oma.be

Last Ionospheric Events

- 2017-09-07 : Ionospheric activity due to Solar Flare (more here)
- 2017-09-06 : Space weather event due to Solar Radio Burst (more here)
- 2017-08-31 : Ionospheric activity due to Geomagnetic Activity (more here)
- ... more events here

Near-Real Time Ionospheric Products

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

- Interactive Maps: display animated VTEC maps (movie) for a requested period and VTEC value at a given location and time. (4-5 sec to load).
- Statistical Maps and Plots: statistics to compare the ionosphere for a requested time with respect to the 15 previous days.
- VTEC Time Series: the VTEC evolution over time and its median of the 15 previous days (24h prediction), extracted from the VTEC maps at 3 different locations (North of Europe, Brussels and South of Europe).
- Data are publicly available in IONEX format at ftp://gnss.oma.be/gnss/products/IONEX/. We request that users include a citation or an acknowledgment when using ROB VTEC data or products results in a publication. See disclaimer and copyright for more information.

Interactive Maps

19/10/2017 (DOY 292) 14:15-14:30 UTC

Statistical Maps and Plots

VTEC Time Series

Solar Radio Burst Warnings for GNSS Applications in Europe

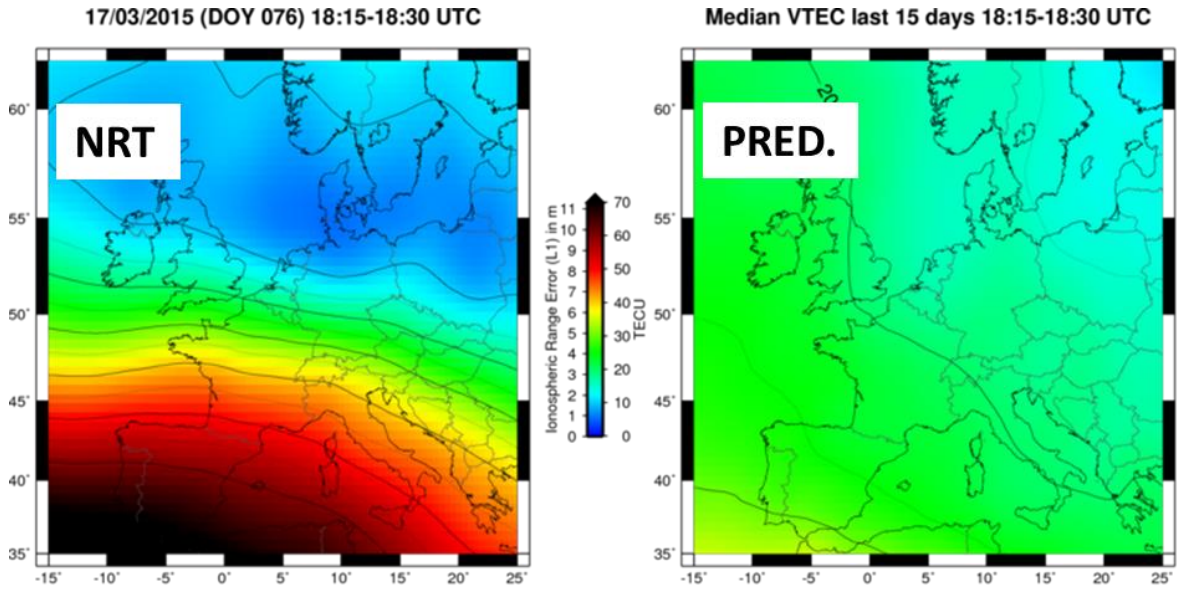
Solar Radio Bursts (SRB) emitted at the GNSS frequencies can affect the GNSS signal reception. To detect such event, a near-real time SRB warning system with a 4-level index was set in Europe using the real-time EUREF Permanent Network.

www.gnss.be

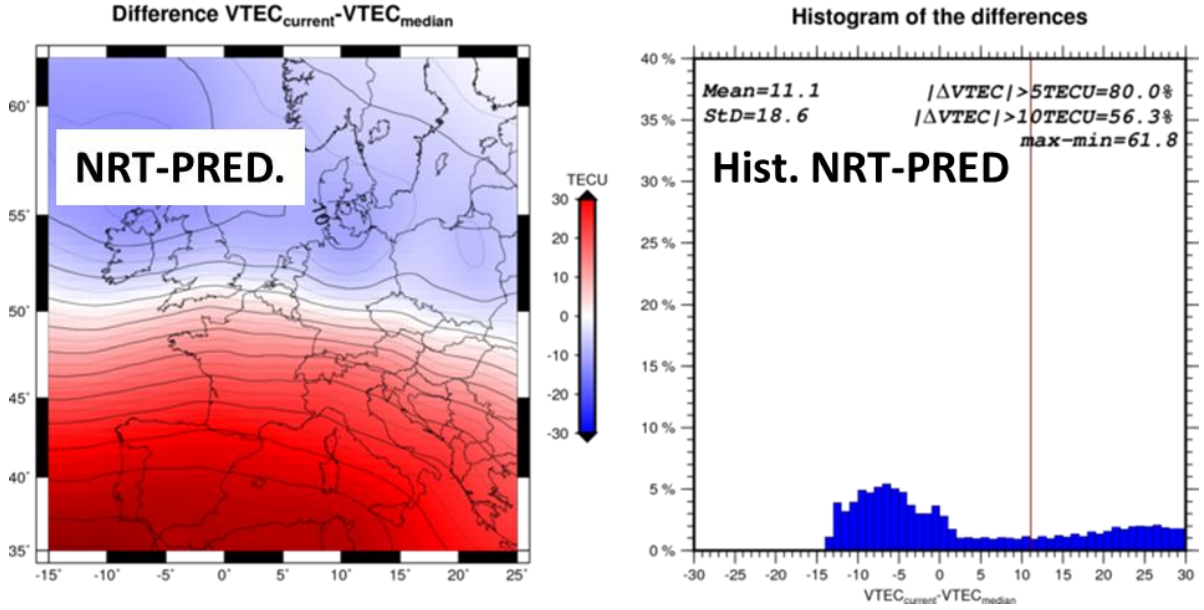
1) **Ionospheric Total Electron Content (TEC)**
   - Interactive TEC maps
   - Statistical TEC maps
   - TEC Time Series at 3 locations (North-Brussels-South)
   - TEC Data (IONEX) ftp://gnss.oma.be/gnss/products/IONEX/
   - Event Description

2) **Solar Radio Burst (SRB)**
   - Warning System
   - Event Description

Statistical TEC Maps



Normal ionospheric TEC behaviour : median of the VTEC for the 15 previous days

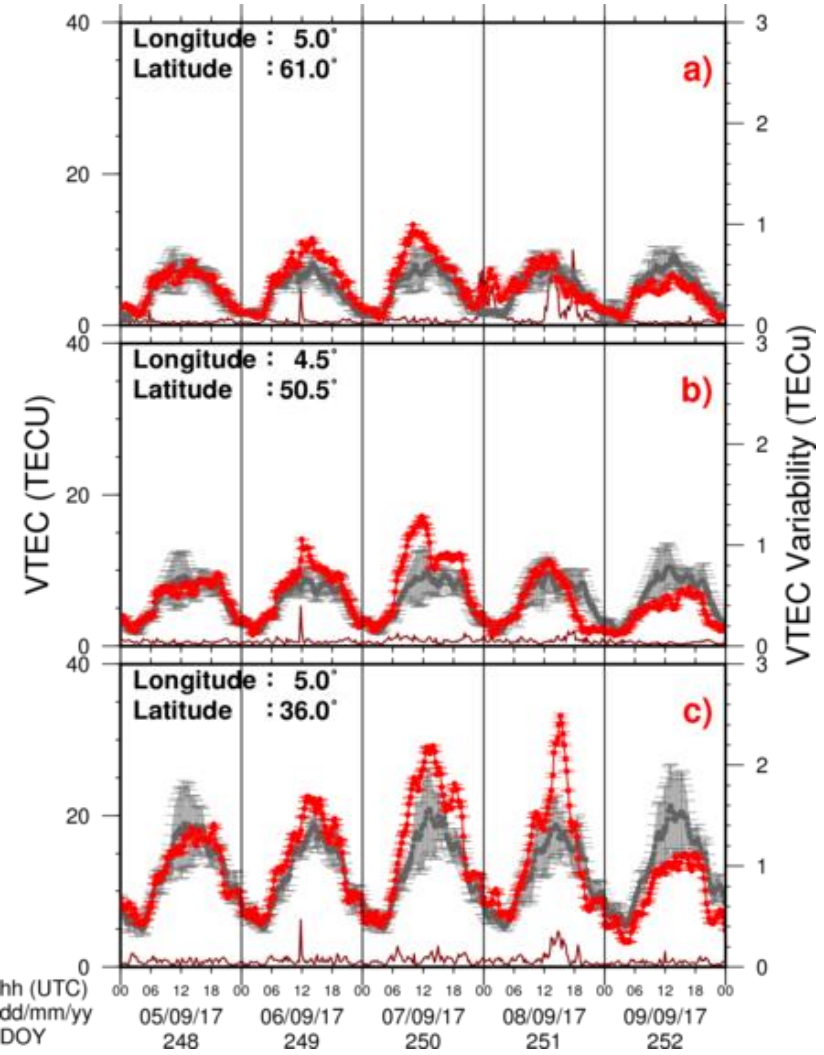


Saint Patrick storm
March 17th 2015 event

http://www.gnss.be/Atmospheric_Maps/static_ionospheric_maps.php

Ionospheric Event Description

SUMMARY OF THE EVENT: A solar flare occurred the 6/09/2017 generating a sudden small increase of TEC at noon with higher variability of TEC. The next days, the arrival of the CME generated disturbances in the North during night-time of the 7/09/2017 and at the end of the day 07/09/2017. An increase of TEC was also observed in the South the 07 and 08/09/2017. A depletion of TEC followed the following day 09/09/2017



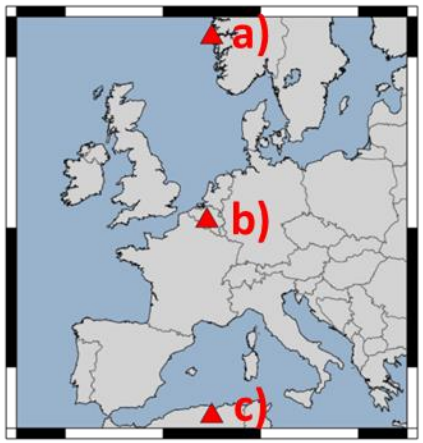
TEC extracted from the NRT maps

TEC current

15-days median TEC

TEC Variability

+ Links to interactive and statistical maps, and origin of the event sidc.oma.be



2012–2017 (43 events)

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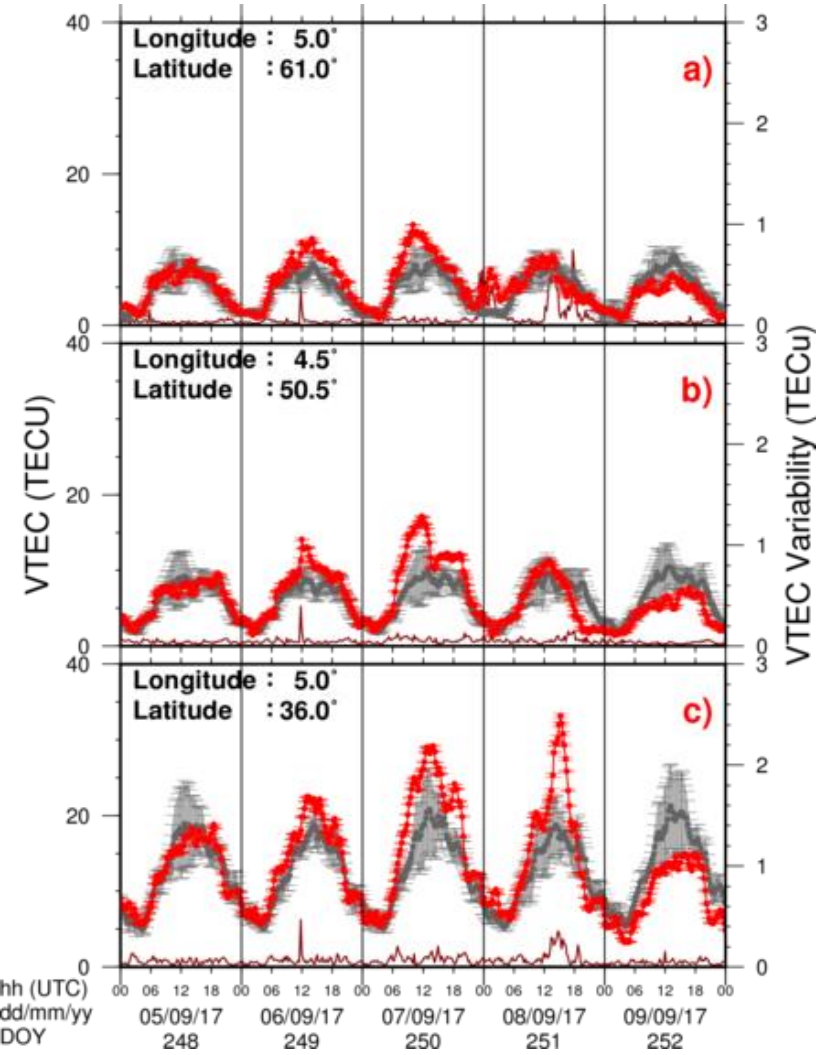
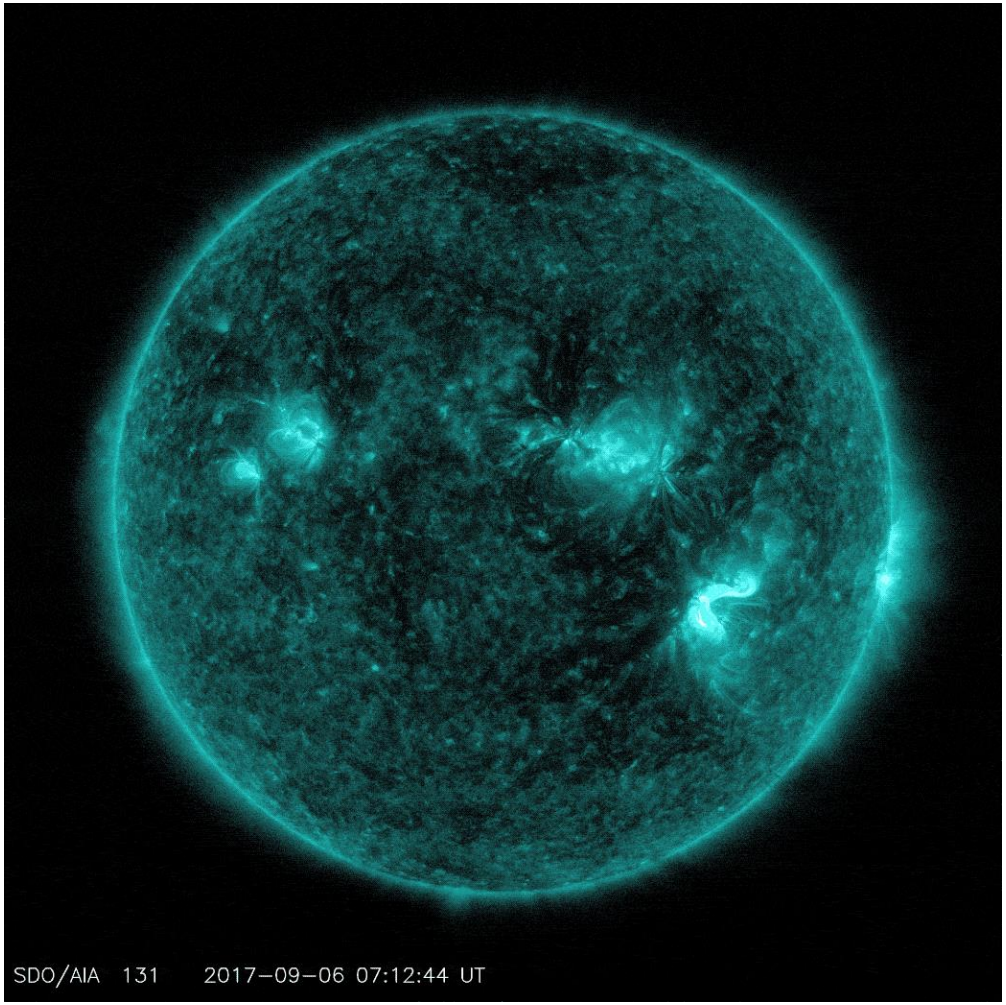
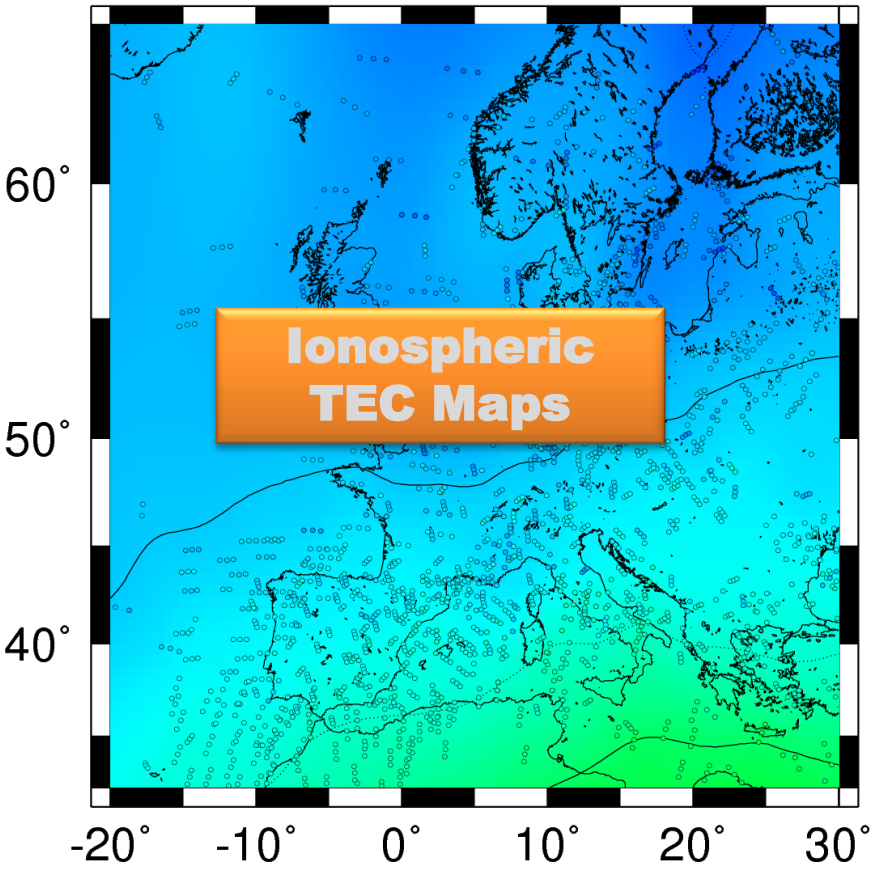




Research and Scientific Applications



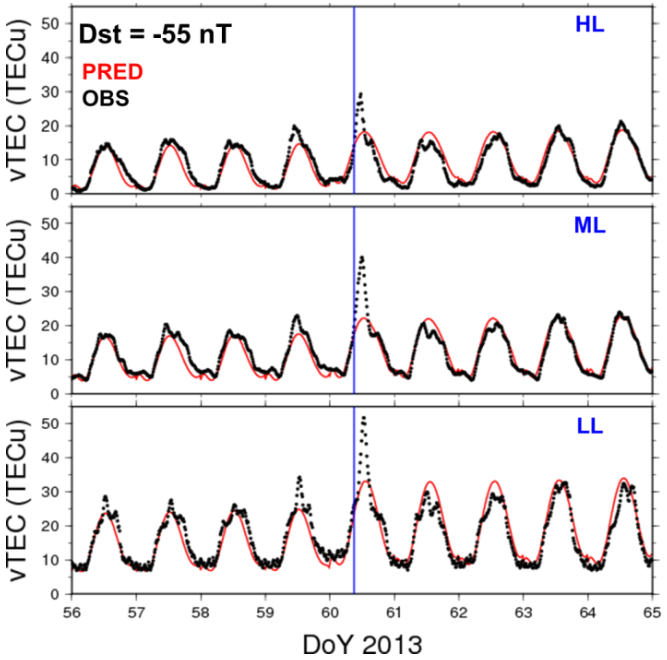
Climatology of the Ionosphere

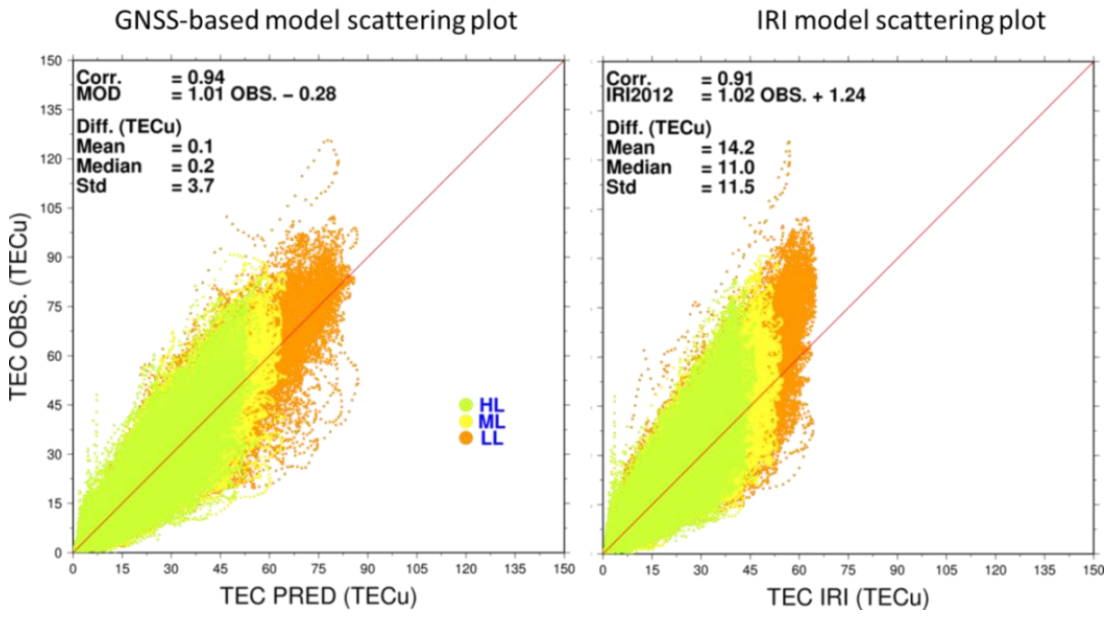
Empirical Model, least-square adjustment with :

- 8th order polynomial function with monthly coefficients between the TEC and F10.7P
- Discretization with respect to the solar activity phases

Bergeot et al. 2015, EGU

Ionospheric TEC Maps





Climatology of the Ionosphere

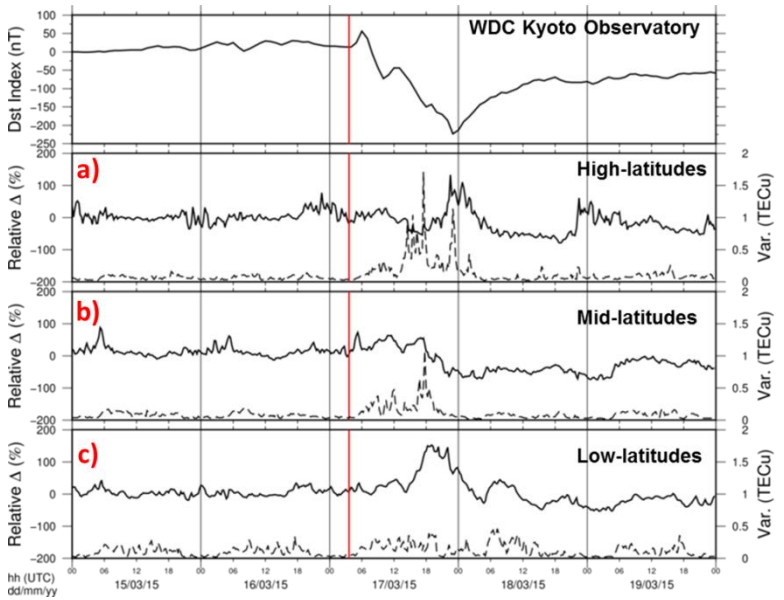
IAG – Real-Time Ionospheric Monitoring Working Group

Comparison of current Ionospheric Models:

March 17, 2015 - St Patrick Storm

Ionospheric TEC Maps

Garcia-Rigo et al. 2017, EGU



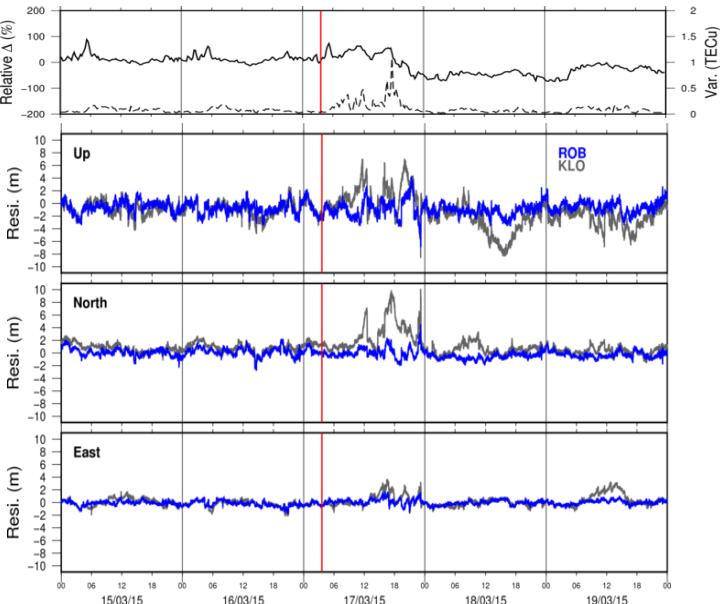
Research and Scientific Applications

Climatology of the Ionosphere

IAG – Real-Time Ionospheric Monitoring Working Group

Improving GNSS single frequency positioning

Position of the GNSS station at Brussels during 2015 March Storm (*W. Huang and P. Defraigne*)



Bergeot et al. 2015, URSI

Ionospheric TEC Maps

Correction using Klobuchar ionospheric model

East	10	± 80 cm
North	100	± 140 cm
Up	120	± 210 cm

Correction using ROB-TEC products

East	6	± 40 cm
North	9	± 66 cm
Up	76	± 150 cm

Research and Scientific Applications

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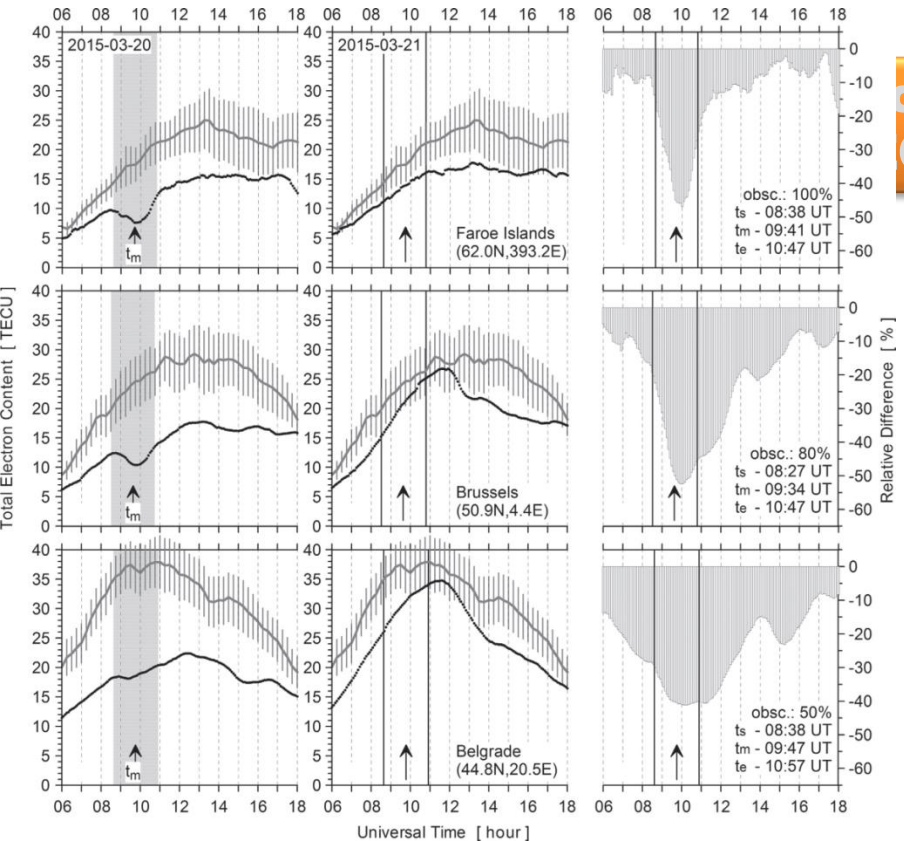
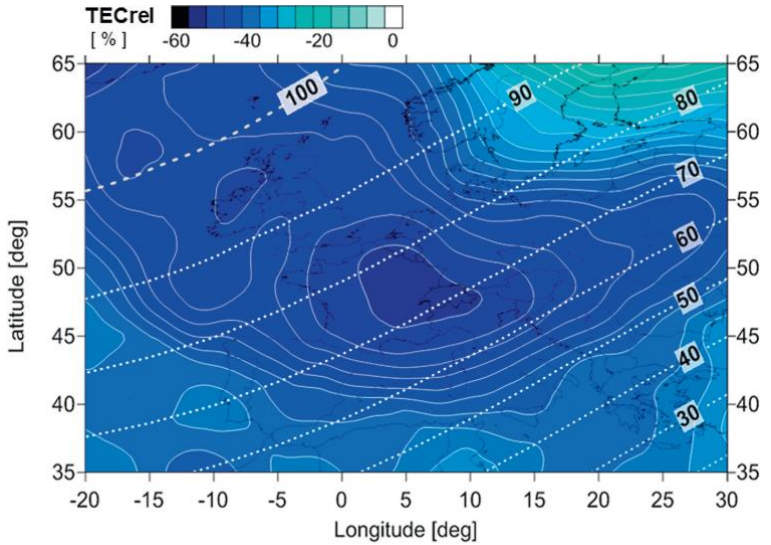
Solar Eclipse 20th Mar. 2015 RT and post



ospheric C Maps

Stankov et al. 2017, SWSC Journ.



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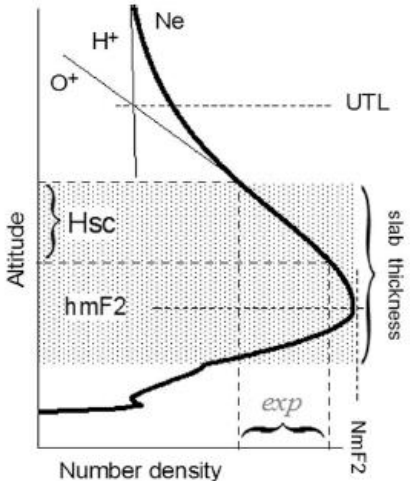
3D Ionosphere Nowcasting and Forecasting for ESA Space Situational Awareness

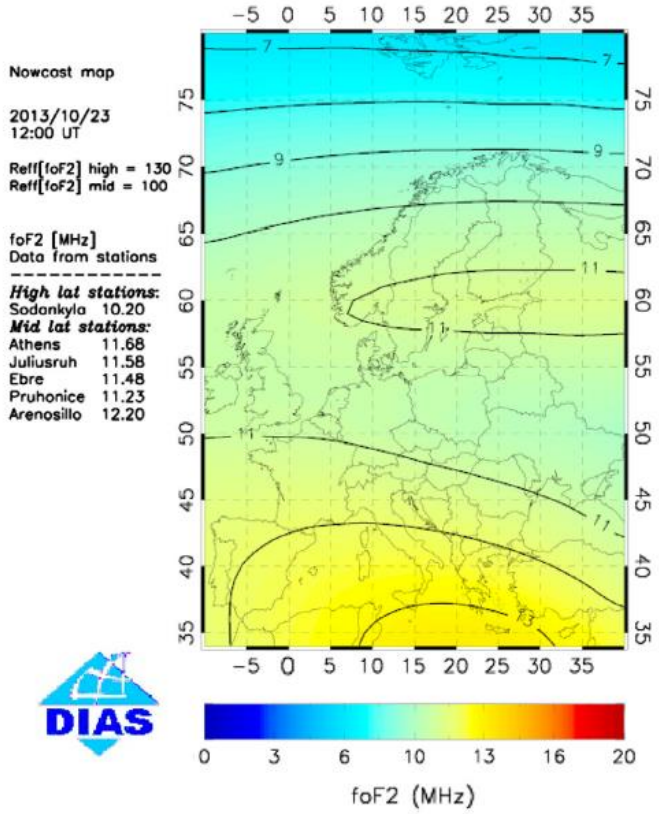
Ionospheric TEC Maps

with Digisonde Network Data

National observatory of Athens

ESA





Belehaki et al. 2015, SWSC Journ.

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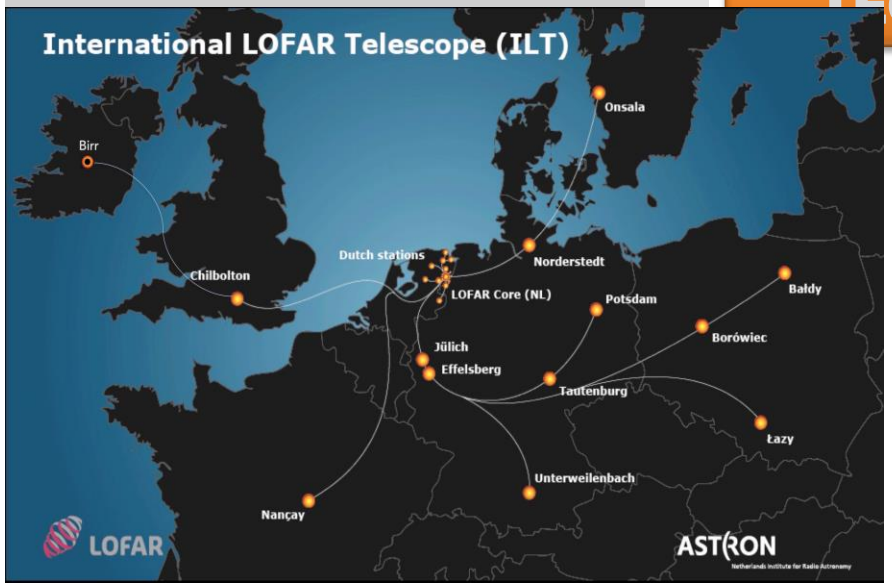

Calibration of LOFAR radio telescope

Sotomayor-Beltran et al. 2013 Astronomy & Astrophysics

Use of ROB-TEC maps to remove the time-variable ionospheric Faraday rotation contribution

Research and Scientific Applications

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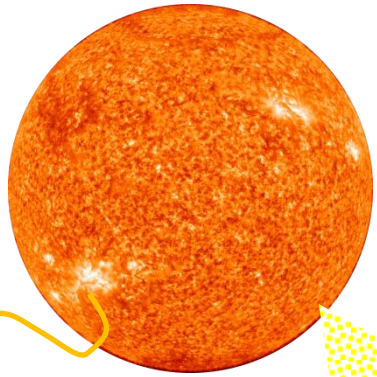

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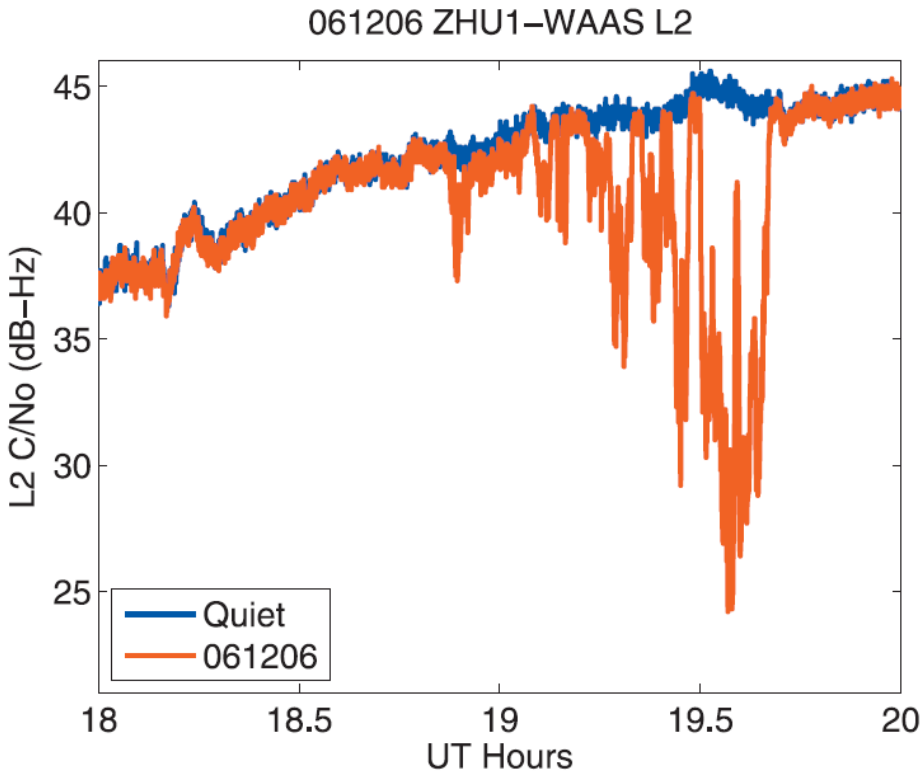
Radio signal delay- ↘ Signal reception	**Signal reception fade (↗noise)**	**GNSS**	**Radio signal delay - ↘ Signal reception**

Solar Radio Bursts

- The Sun emits in radio over a wide frequency range (from few kHz to GHz)
- Solar Radio Bursts (**SRB**) are intense radio emissions (durations from 10s to few hours)

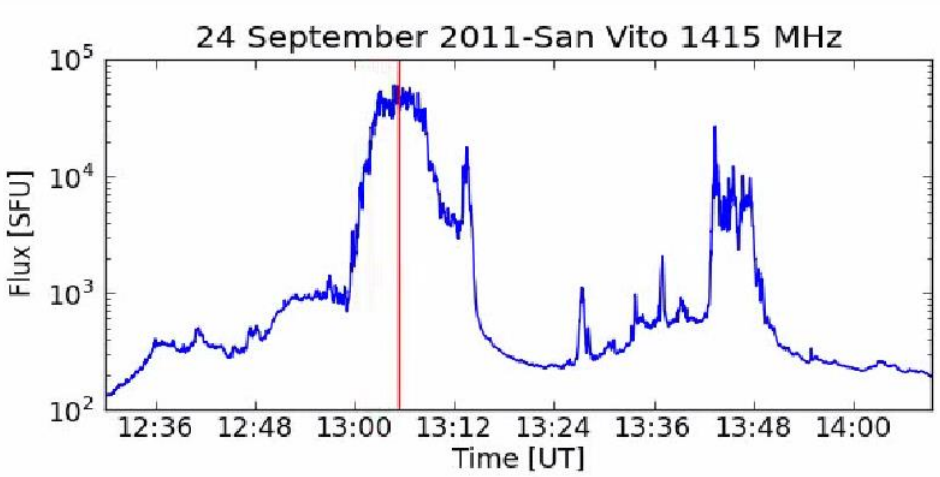
- SRBs increase the noise level of GNSS ground stations

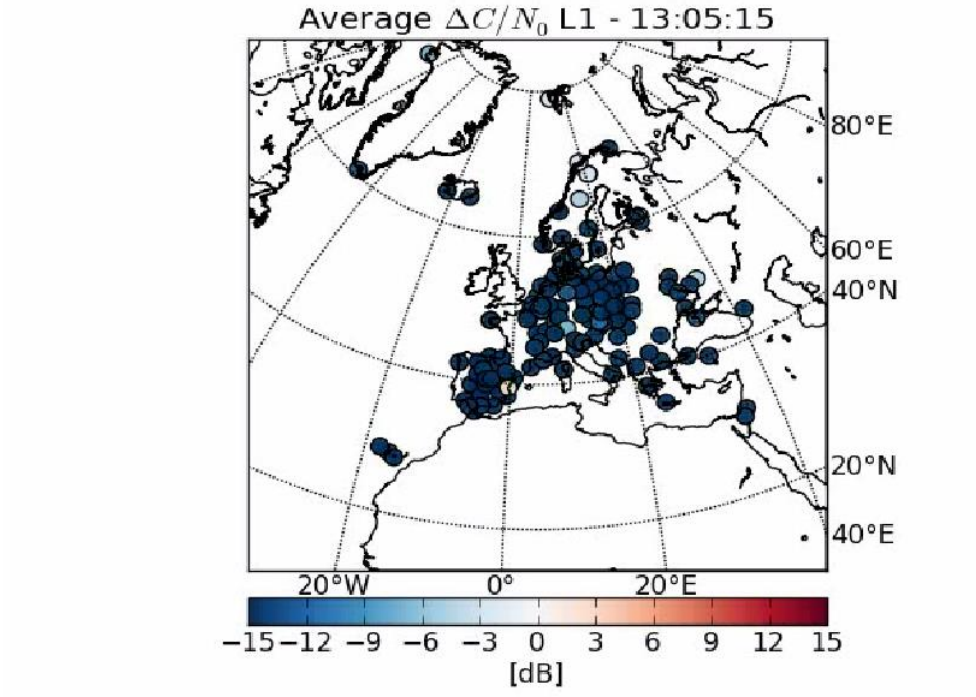
- **Carrier-to-Noise density (C/N_0)** [35; 55] dB-Hz



Cerruti et al. 2006

SRB Impact on GNSS Signal Reception





EPN data for SRB monitoring

RT monitoring of the abnormal fade of GNSS signal reception due to SRB at the 2 GNSS frequency bands L1 and L2

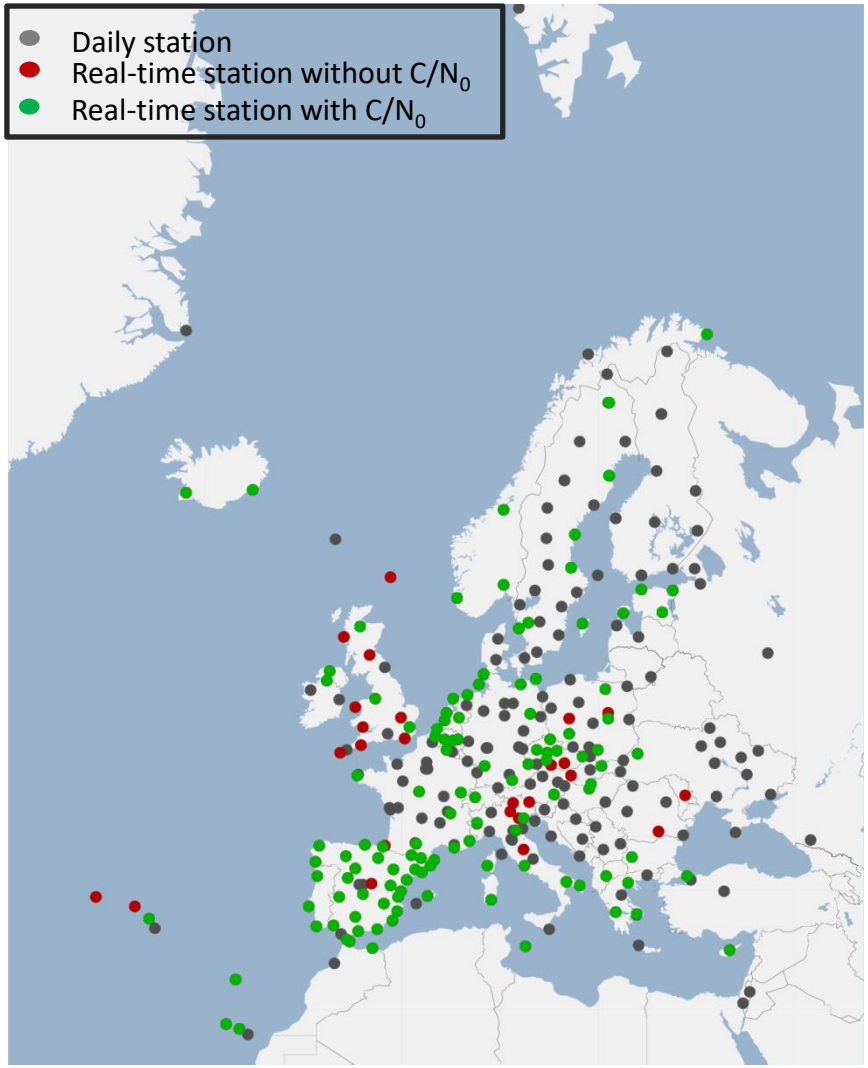
Chevalier et al., URSI GASS 2017

C/N_0 (dB-Hz) extracted from RINEX files (S1-S2)

- But no standardized unit

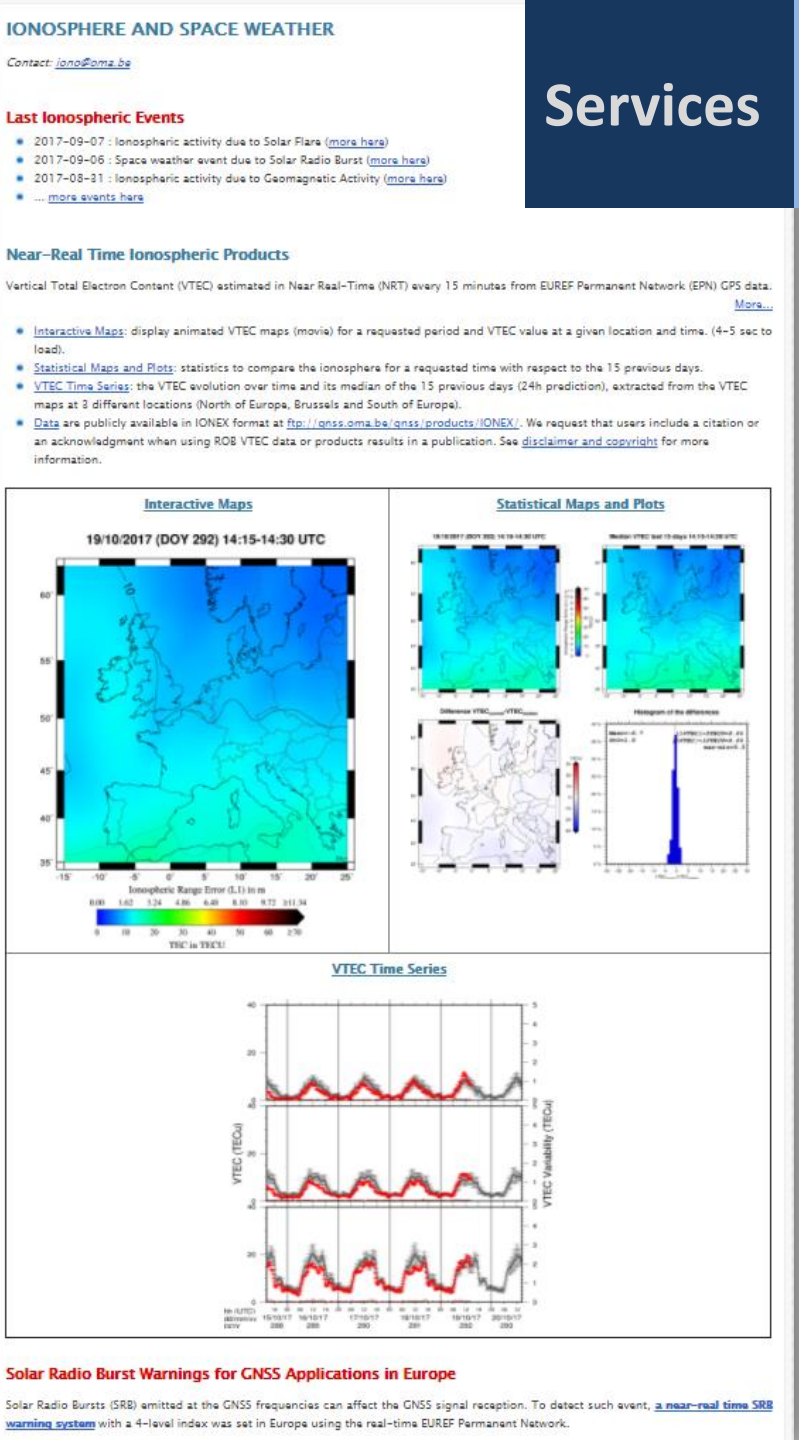
⇒ **Please provide C/N_0 instead of Signal to Noise Ratio (SNR) (manufacturer/receiver dependent)**

Level	GNSS $\Delta C/N_0$ Fade	Effect
Quiet	>-1dB-Hz	none
Moderate	-1 dB-Hz	SRB detected but should not impact GNSS applications
Strong	-3 dB-Hz	Potential impact on GNSS applications
Severe	-10 dB-Hz	Potential failure of the GNSS receivers



Services

Monitoring based on Real-Time EPN Data



IONOSPHERE AND SPACE WEATHER

Contact: iono@oma.be

Last Ionospheric Events

- 2017-09-07 : Ionospheric activity due to Solar Flare (more here)
- 2017-09-06 : Space weather event due to Solar Radio Burst (more here)
- 2017-08-31 : Ionospheric activity due to Geomagnetic Activity (more here)
- ... more events here

Near-Real Time Ionospheric Products

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

- Interactive Maps: display animated VTEC maps (movie) for a requested period and VTEC value at a given location and time. (4-5 sec to load).
- Statistical Maps and Plots: statistics to compare the ionosphere for a requested time with respect to the 15 previous days.
- VTEC Time Series: the VTEC evolution over time and its median of the 15 previous days (24h prediction), extracted from the VTEC maps at 3 diffarent locations (North of Europe, Brussels and South of Europe).
- Data are publicly available in IONEX format at ftp://gnss.oma.be/gnss/products/IONEX/. We request that users include a citation or an acknowledgment when using ROB VTEC data or products results in a publication. See disclaimer and copyright for more information.

Interactive Maps

19/10/2017 (DOY 292) 14:15-14:30 UTC

Statistical Maps and Plots

VTEC Time Series

Solar Radio Burst Warnings for GNSS Applications in Europe

Solar Radio Bursts (SRB) emitted at the GNSS frequencies can affect the GNSS signal reception. To detect such event, a near-real time SRB warning system with a 4-level index was set in Europe using the real-time EUREF Permanent Network.

www.gnss.be

1) Ionospheric Total Electron Content (TEC)

- Interactive TEC maps
- Statistical TEC maps
- TEC Time Series at 3 locations (North-Brussels-South)
- TEC Data (IONEX) ftp://gnss.oma.be/gnss/products/IONEX/
- Event Description

2) Solar Radio Burst (SRB)

- Warning System
- Event Description

SRB Warning System: 4th Nov. 2015 Event

www.gnss.be

SRB WARNING SYSTEM FOR GNSS APPLICATIONS IN EUROPE

Contact: *iono@oma.be*
To receive real-time alert emails, please contact us to be added to the mailing list.

Last update : 2015-11-04 14:29:30	L1	L2
Last 15min		
Last 24h		
Last week		

Events of the last 30 days:

Frequency	Date of the maximum fade	Maximum fade (in dB/Hz)	Beginning of the event (fade<-1dB/Hz)	End of the event (fade>-1dB/Hz)
L2	2015-11-04 14:29:00	-5.75±2.26	2015-11-04 14:22:00	On-Going

To detect Solar Radio Burst (SRB) affecting the GNSS signal reception in Europe, the carrier to noise density (C/N0) of the real-time EPN GPS network are monitored in near-real time (updated every 15 minutes). The intensity of the SRB impacts on GNSS applications are indexed at 4 levels:

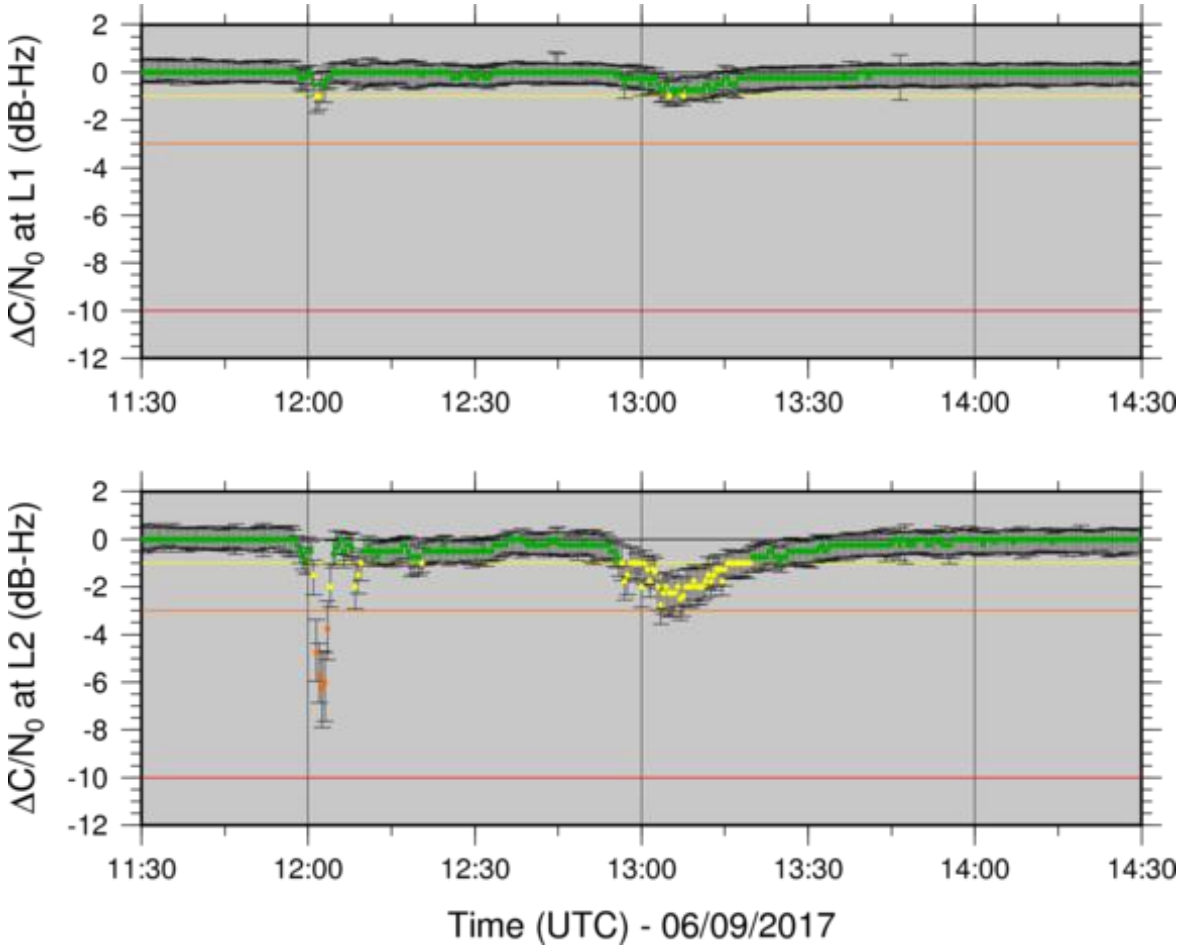
- *quiet*
- *moderate* : SRB detected but should not impact GNSS applications,
- *strong* : potential impact on GNSS applications,
- *severe* : potential failure of the GNSS receivers.

Previous SRB Events at the GNSS frequencies

- 2015-11-04 : Space weather event due to Solar Radio Burst (more here)

Event description: SRB 6th Sep. 2017

SUMMARY OF THE EVENT: The solar radio bursts of the 06/09/2017 impacted the GPS signal reception at both frequencies L1 and L2. On L1, two fades above 1dB-Hz were detected at 12h01 and 12h05. On L2, a first fade above 3dB-Hz which could potentially affect the GNSS application, occurred for 3 min with a maximum of -6.25±1.6dB-Hz at 12h02. It was followed by a second lower fade above 1dB-Hz at 13h03. For additional information about the burst on a larger frequency spectrum see at SIDC Humain Radioastronomy Station.



SUMMARY

Space Weather Monitoring based on EPN

- **IONOSPHERE**
  - TEC maps (+TEC variability) over Europe since 2012 in near-real time (0.5°x0.5° grids, 15 min.)
  - Visualisation of the ionospheric activity : www.gnss.be
  - Data: ftp://gnss.oma.be
  - Scientific applications : Climatology of the Ionosphere, GNSS single frequency positioning(…)

- **SOLAR RADIO BURST**
  - GNSS signal reception is monitored in real-time
  - SRB Warning System
  - Register at the email alert : iono@oma.be

SUMMARY

Thank you

Back-up slides

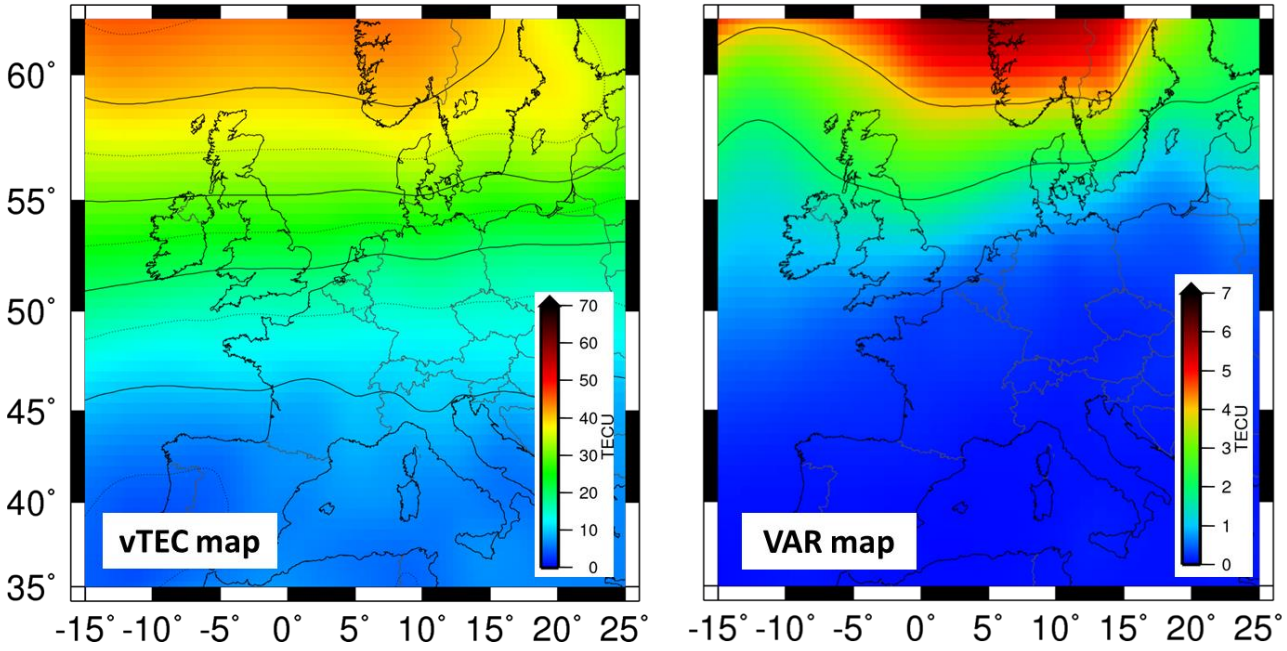
ROB-IONO software

SWSC Journal of Space Weather and Space Climate

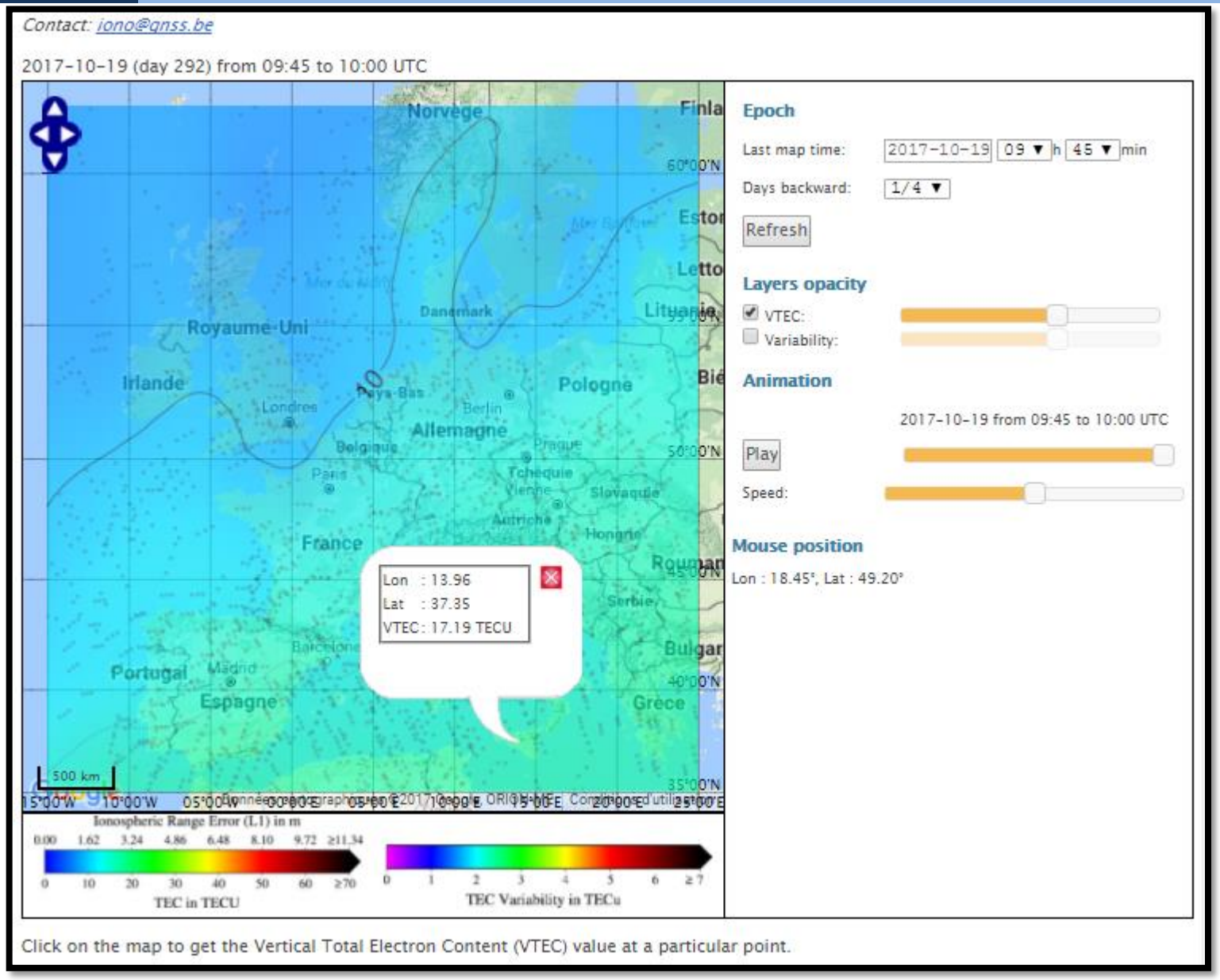
Bergeot N., et al. (2014) J. Space Weather Space Climate

- Post processing – all available GPS+GLONASS data
- Time independent, tested and validated during quiet time and, minor and major events

HALLOWEEN STORM 2003
(22:15-22:30 UTC)



Interactive VTEC maps



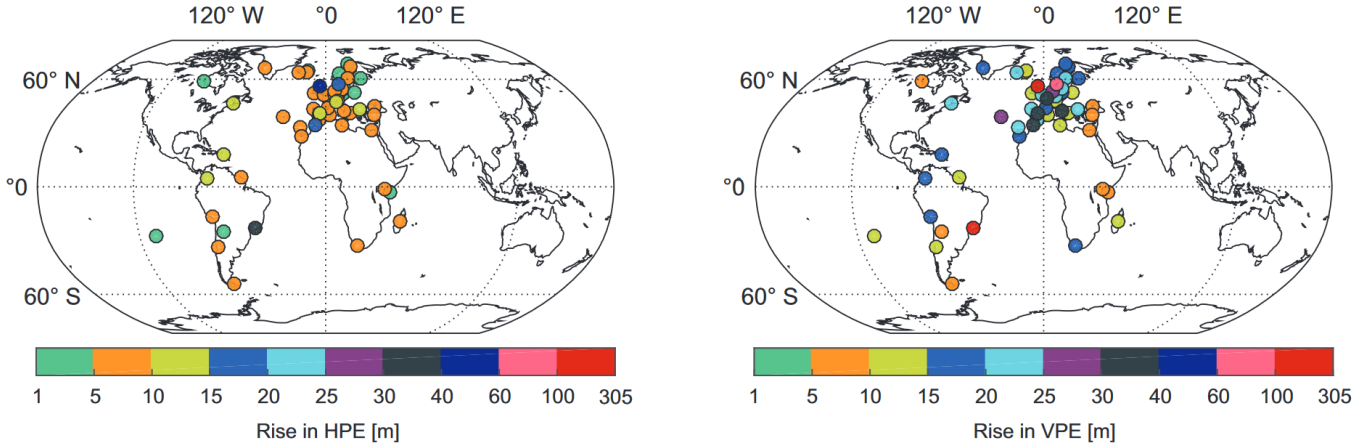
http://www.gnss.be/Atmospheric_Maps/dynamic_ionospheric_maps.php

SRB Impact on GNSS applications

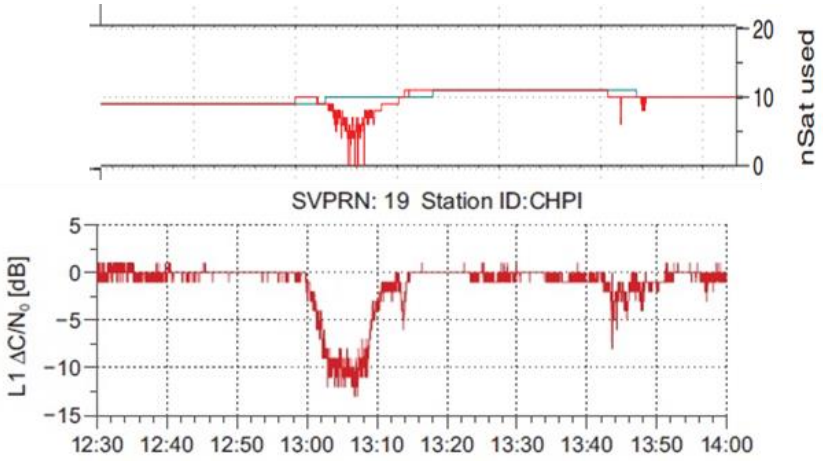
SRB of the 24/09/2011

Muhammad et al. 2015

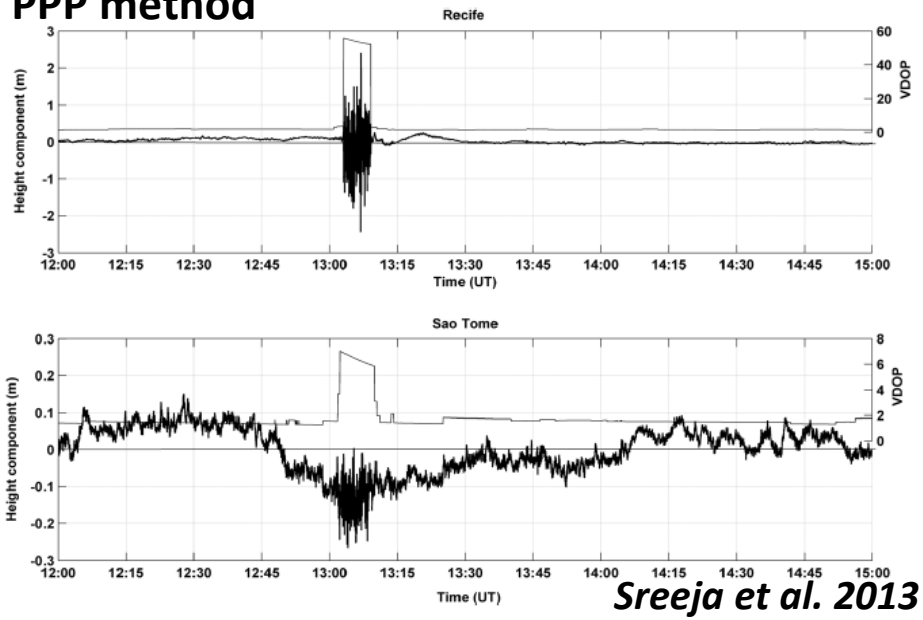
Rise in error = Positioning error during SRB – Positioning error on a quiet day



Sao Paulo, Brazil



PPP method



Sreeja et al. 2013