SPACE WEATHER INTRODUCTORY COURSE

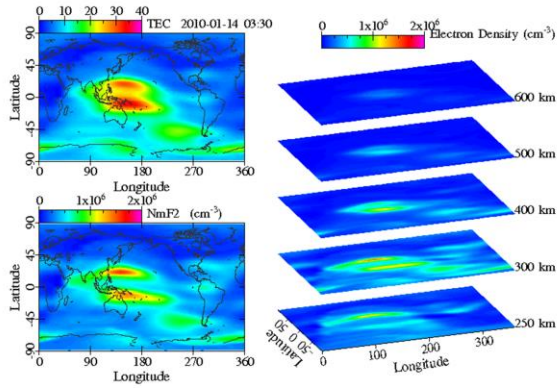
Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

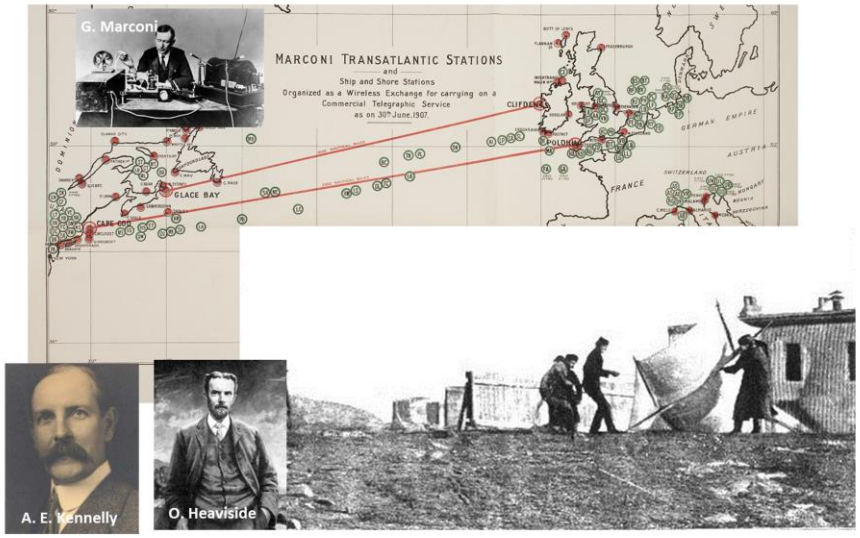
May 2017



Earth environment - Ionosphere

Dr Nicolas Bergeot, Dr Jean-Marie Chevalier

1901 : First Trans-Atlantic communication
1902 : Reflecting layer in altitude



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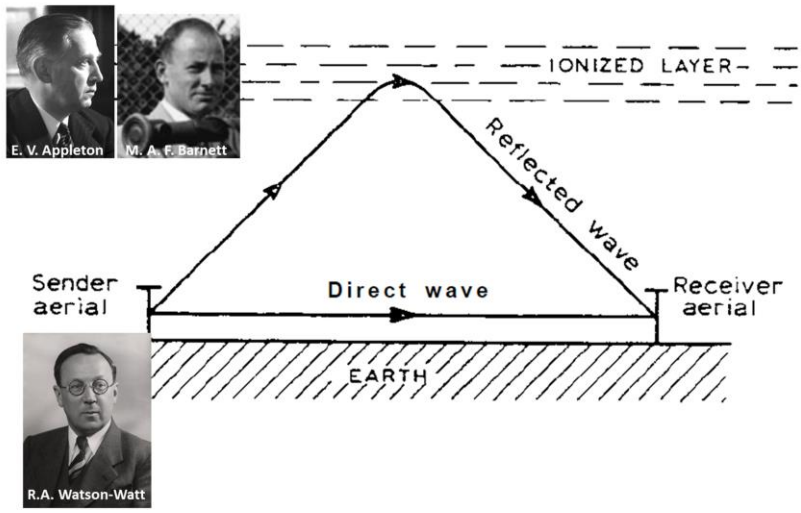
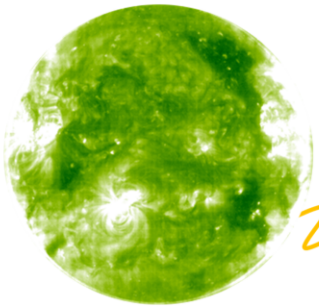
1925 : Ionized layer in the upper atmosphere
1926 : The term ionosphere appears



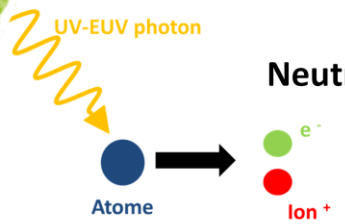
1931 : Theory of on the ionization of the upper atmosphere by electromagnetic waves emitted from the Sun.



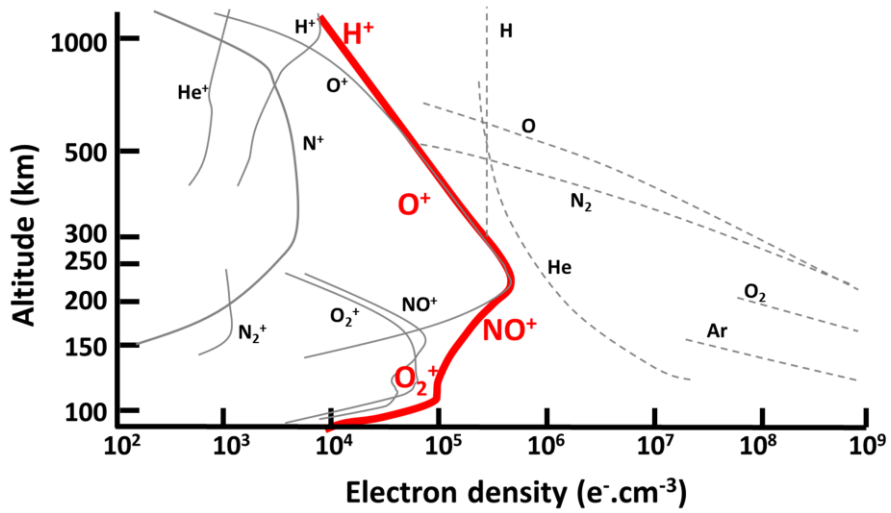
Ionosphere

||

Neutral ionized plasma



$O + h\nu \rightarrow O^{+} + e^{-}$



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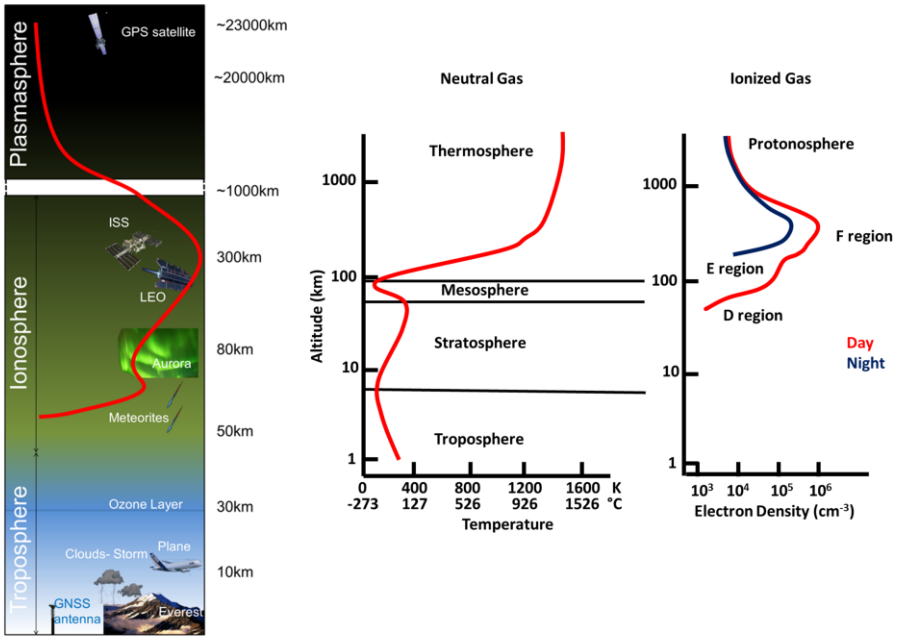
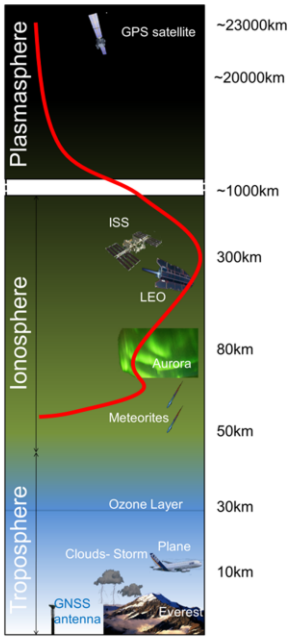
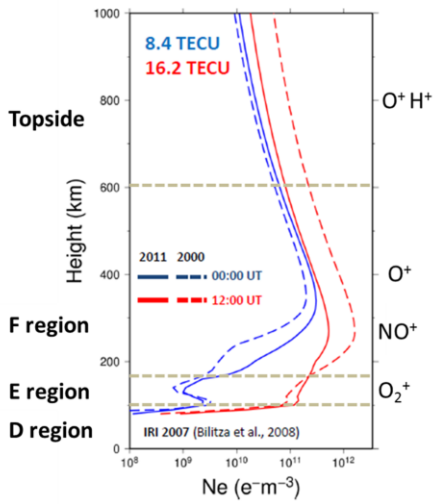


SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI

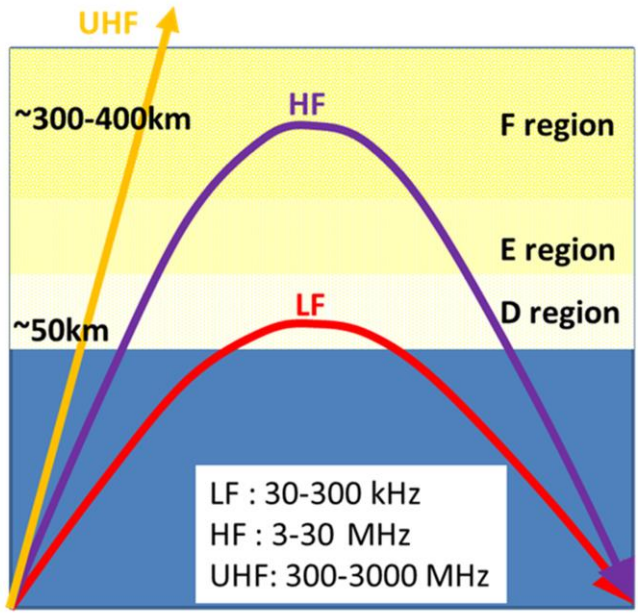


Total Electron Content (TEC)

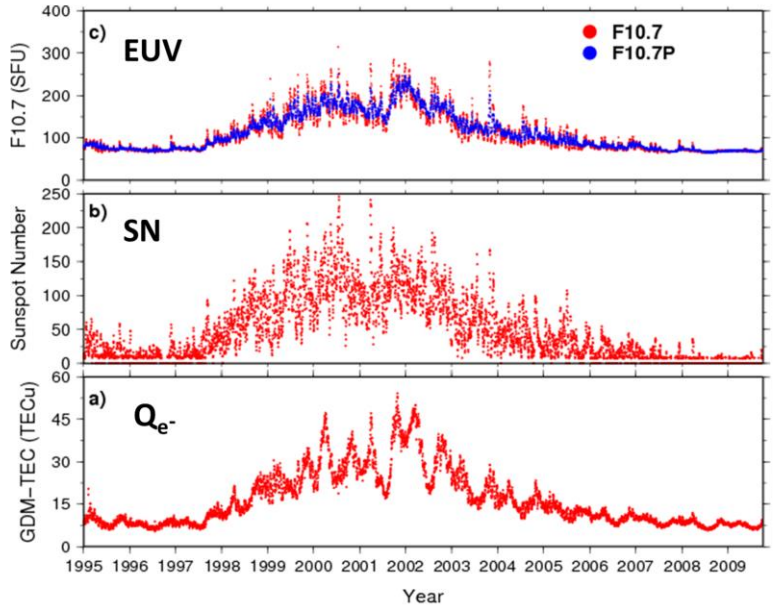
1TECu = $10^{16} e^{-}.m^{-2}$



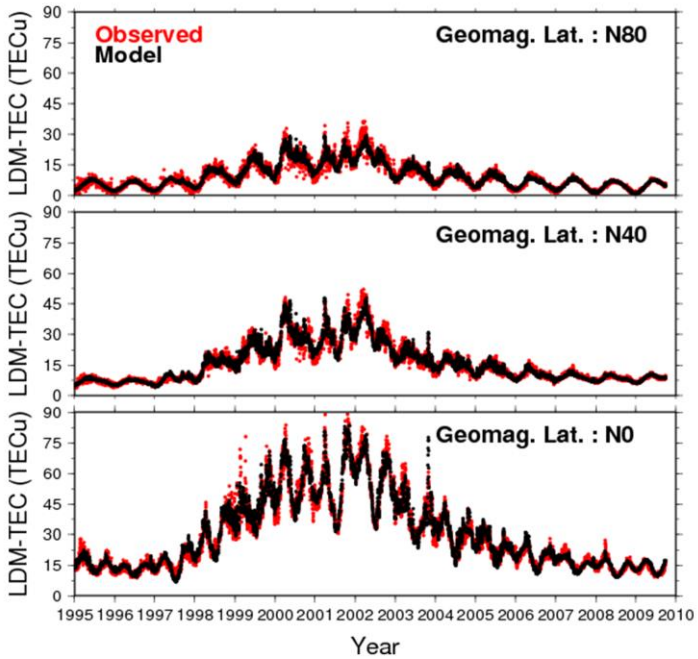
SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI



SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI



SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI



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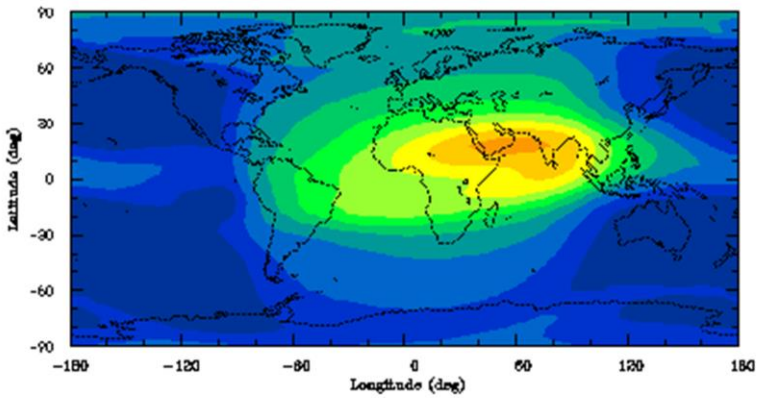
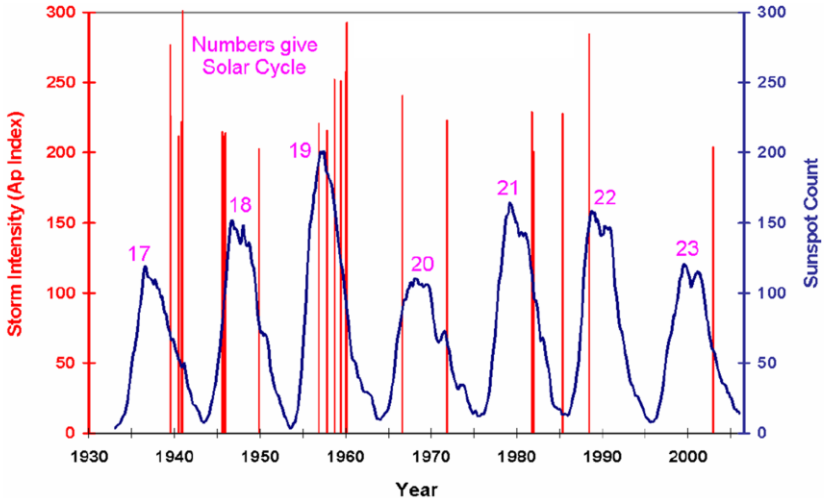
UT = 12h 00m


90
60
30
0
-30
-60
-90
Latitude (deg)
-180
-120
-60
0
60
120
180
Longitude (deg)



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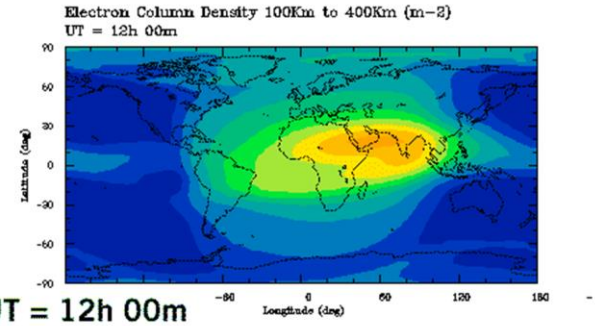
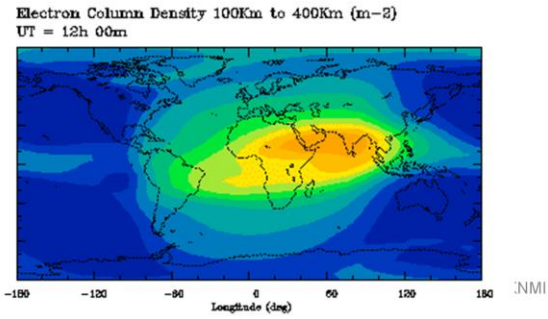
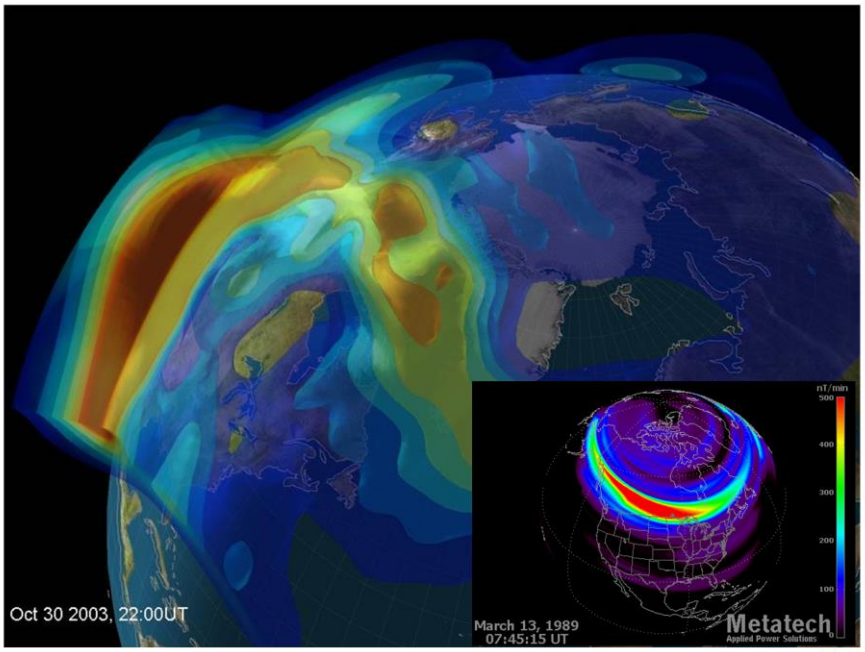
Quiet Ionosphere UT = 12h 00m



Ionospheric Storm UT = 12h 00m





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GNSS

=

Global Navigation Satellite Systems

GPS	32 /31 satellites
Galileo	10 (+2+4+~~2~~)/30 satellites
GLONASS	24/24 satellites

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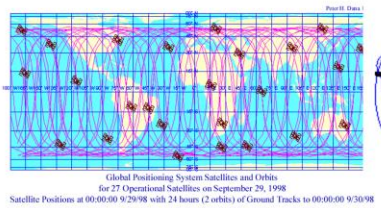
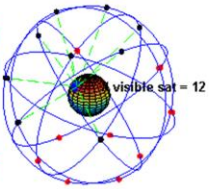
GNSS : Global Navigation Satellite System

Global systems MEO:

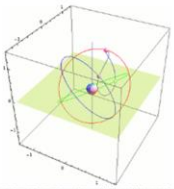
- GPS (US)
- Galileo (EU)
- GLONASS (RU)
- Beidou (CH)





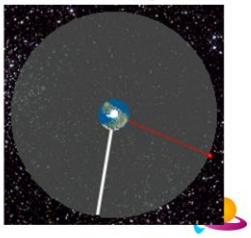
Regional systems GEO + IGSO:

- QZSS (JP)
- IRNSS (IN)



Augmentation systems (SBAS) GEO:

- WAAS (US)
- EGNOS (EU)
- MSAS (JP)
- GAGAN (IN)



MEO: Medium Earth Orbiter – 20 000 km

GEO-IGSO: Geostationary Orbit – 36 000km

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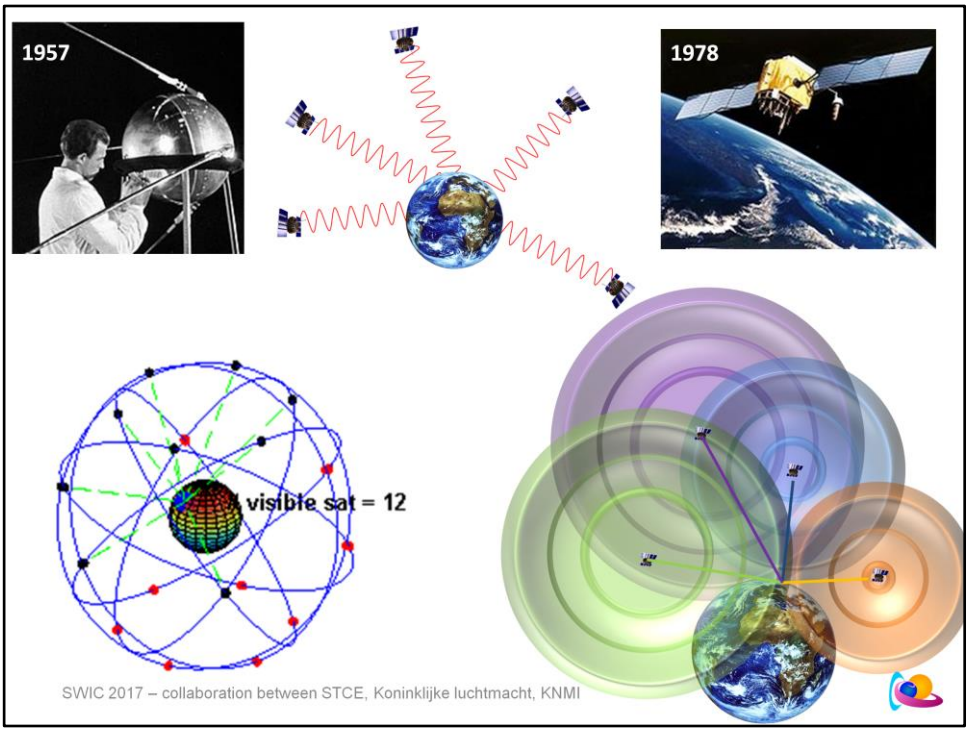
1957
1978
visible sat = 12
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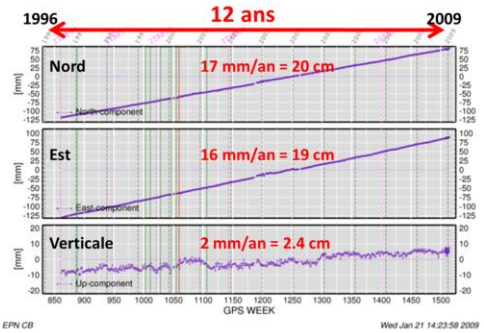

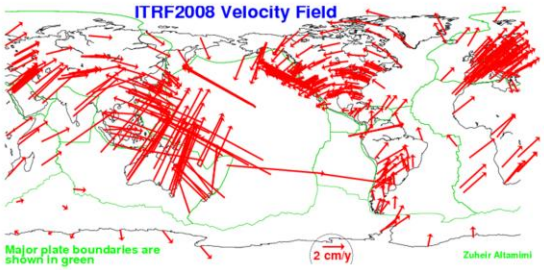

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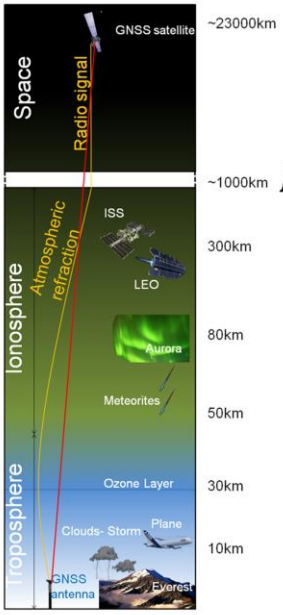

Troposphere

2-3m

$$D_{Tropo} = Q_{N_2,O_2,Ar} + Q_{H_2O}$$

Ionosphere

50cm-100m to loss of signal

$$D_{Iono} = \frac{1}{f^2} \times Q_{e^-}$$

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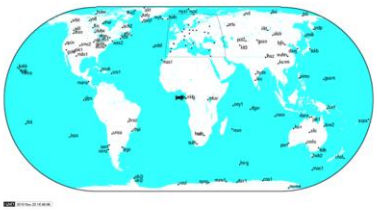

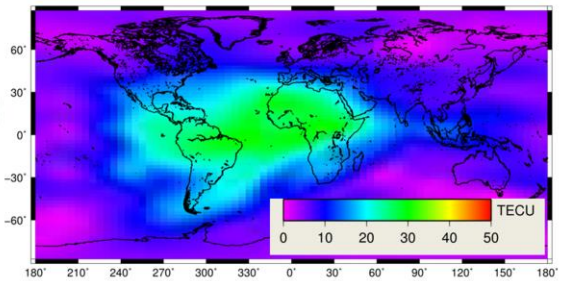

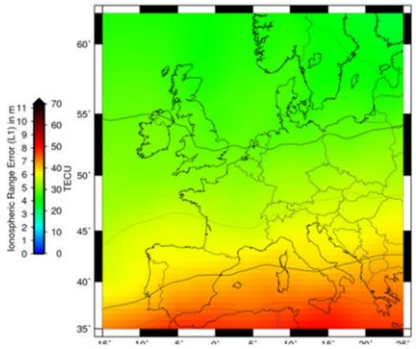

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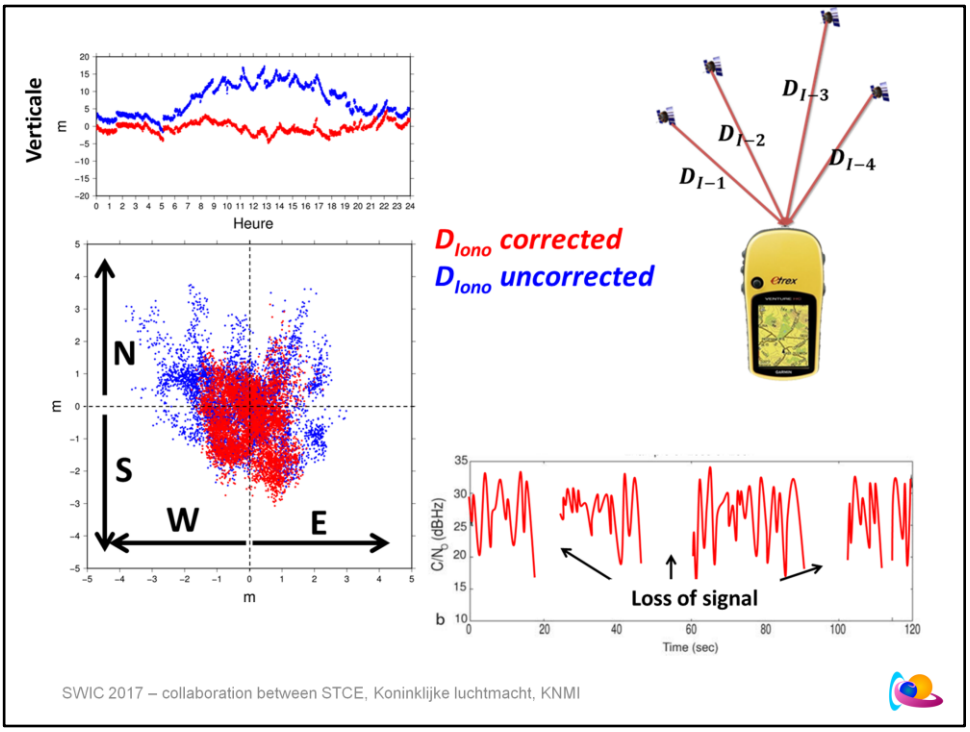
Verticale
m
Heure
N
S
W
E
m
D_{Iono} corrected
D_{Iono} uncorrected
D_{I-1}
D_{I-2}
D_{I-3}
D_{I-4}
C/N0 (dBHz)
Loss of signal
Time (sec)
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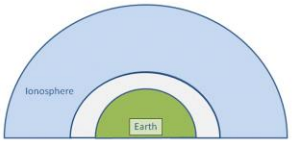
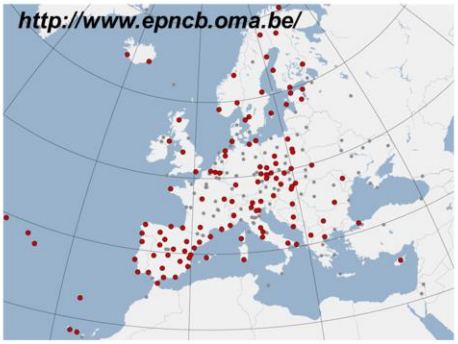
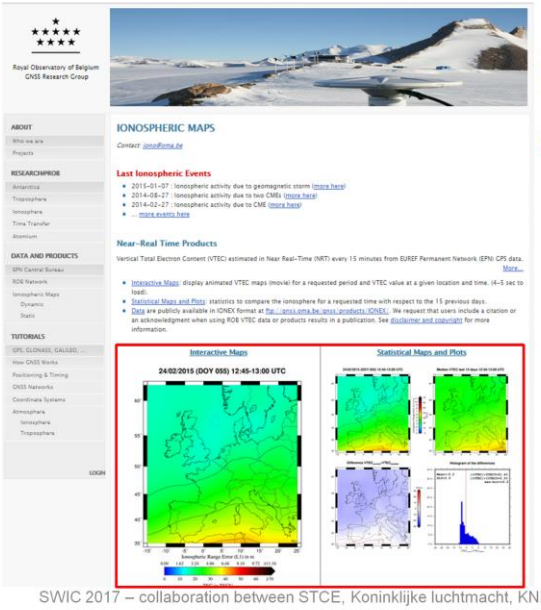
GNSS – Space Weather

- Continuously observing GNSS stations since 1996
- Presently: ~ 320 stations over Europe
- **RT : Presently ~ 140 stations**





Products available on-line



http://www.gnss.be

DATA AND PRODUCTS

- **IONOSPHERIC MAPS**
  - **DYNAMIC**
  - **STATIC**

NRT – TEC maps

Every 15min.

0.5°x0.5° grid

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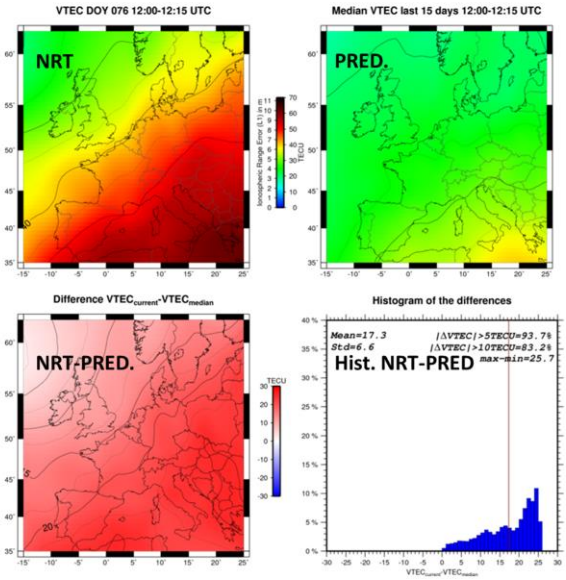
Products available on-line



March 17th 2013 event

Statistical products

Prediction :

Median of the VTEC for the 15 previous days.

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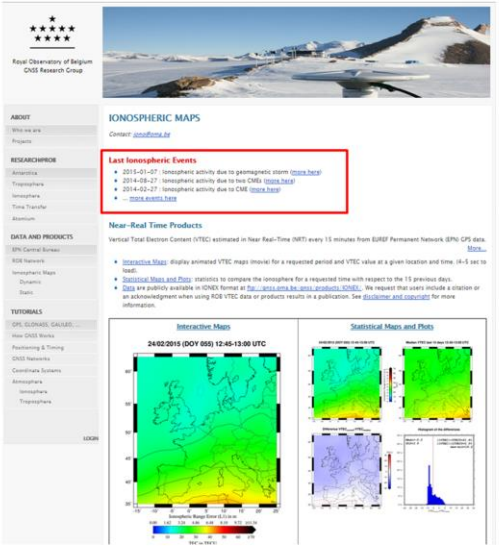
Products available on-line

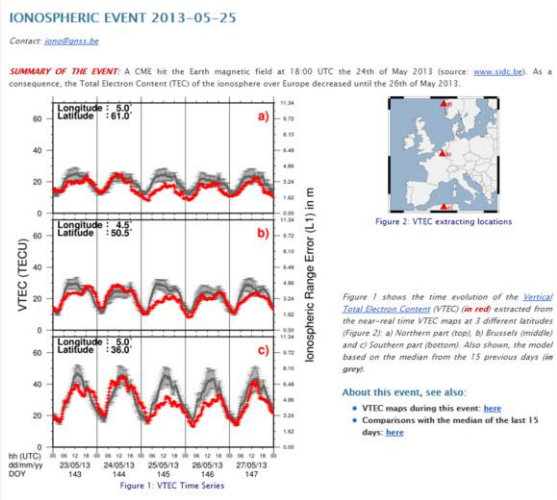


http://www.gnss.be

DATA AND PRODUCTS

- IONOSPHERIC MAPS
  - DYNAMIC
  - STATIC
- **IONOSPHERIC EVENTS**

Products available on-line



IONOSPHERIC EVENT 2013-05-25

Contact: iono@gnss.be

SUMMARY OF THE EVENT: A CME hit the Earth magnetic field at 18:00 UTC the 24th of May 2013 (source: www.sidc.be). As a consequence, the Total Electron Content (TEC) of the ionosphere over Europe decreased until the 26th of May 2013.

Figure 1: VTEC Time Series

Figure 2: VTEC extracting locations

*Figure 1 shows the time evolution of the Vertical Total Electron Content (VTEC) (**in red**) extracted from the near-real time VTEC maps at 3 different latitudes (Figure 2): a) Northern part (top), b) Brussels (middle) and c) Southern part (bottom). Also shown, the model based on the median from the 15 previous days (**in grey**).*

About this event, see also:

- **VTEC maps during this event: here**
- **Comparisons with the median of the last 15 days: here**

Time-series extracted from the NRT maps

Prediction

Observations

2012–2017 (43 events)

70% CMEs
20% geomagnetic activity (??)
10% unidentified phenomena

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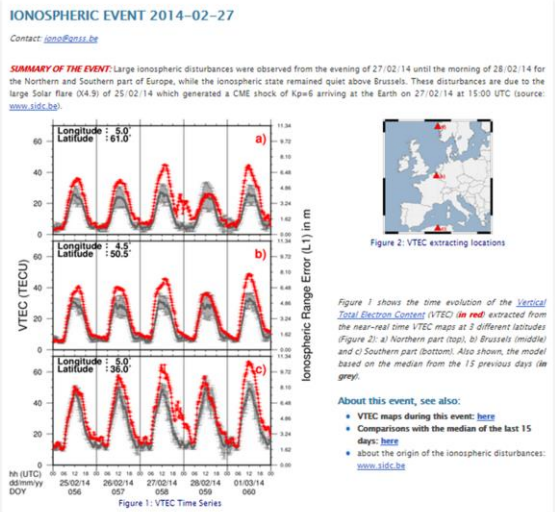
Products available on-line



IONOSPHERIC EVENT 2014-02-27

Contact: iono@gnss.be

SUMMARY OF THE EVENT: Large ionospheric disturbances were observed from the evening of 27/02/14 until the morning of 28/02/14 for the Northern and Southern part of Europe, while the ionospheric state remained quiet above Brussels. These disturbances are due to the large Solar flare (X4.9) of 25/02/14 which generated a CME shock of Kp=6 arriving at the Earth on 27/02/14 at 15:00 UTC (source: www.sidc.be).

Figure 1: VTEC Time Series

*Figure 1 shows the time evolution of the Vertical Total Electron Content (VTEC) (**in red**) extracted from the near-real time VTEC maps at 3 different latitudes (Figure 2): a) Northern part (top), b) Brussels (middle) and c) Southern part (bottom). Also shown, the model based on the median from the 15 previous days (**in grey**).*

About this event, see also:

- **VTEC maps during this event: here**
- **Comparisons with the median of the last 15 days: here**
- about the origin of the ionospheric disturbances: www.sidc.be

Time-series extracted from the NRT maps

Prediction

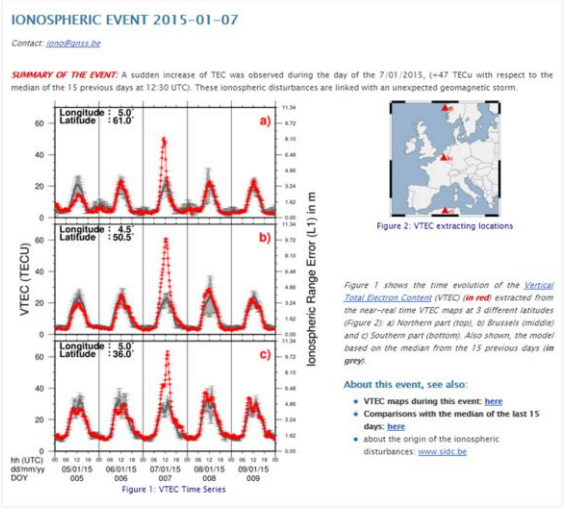
Observations

2012–2017 (43 events)

70% CMEs
20% geomagnetic activity (??)
10% unidentified phenomena

SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI

Products available on-line



IONOSPHERIC EVENT 2015-01-07

Contact: iono@gnss.be

SUMMARY OF THE EVENT: A sudden increase of TEC was observed during the day of the 7/01/2015, (+47 TECu with respect to the median of the 15 previous days at 12:30 UTC). These ionospheric disturbances are linked with an unexpected geomagnetic storm.

Figure 1: VTEC Time Series

Figure 2: VTEC extracting locations

*Figure 1 shows the time evolution of the Vertical Total Electron Content (VTEC) **(in red)** extracted from the near-real time VTEC maps at 3 different latitudes (Figure 2): a) Northern part (top), b) Brussels (middle) and c) Southern part (bottom). Also shown, the model based on the median from the 15 previous days (in grey).*

About this event, see also:

- **VTEC maps during this event: here**
- **Comparisons with the median of the last 15 days: here**
- about the origin of the ionospheric disturbances: www.sidc.be

Time-series extracted from the NRT maps

Prediction

Observations

2012–2017 (43 events)

70% CMEs
20% geomagnetic activity (??)
10% unidentified phenomena

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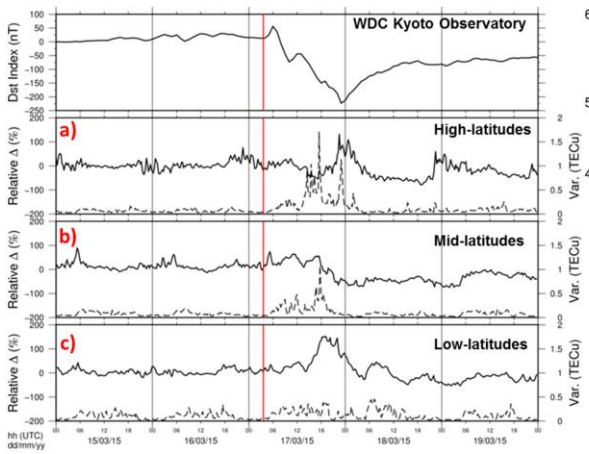
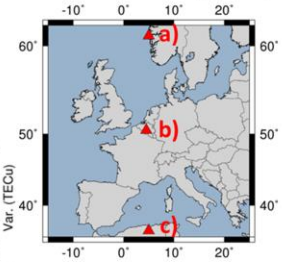
Saint Patrick storm

March 17, 2015 - Onset 05:00 UTC – Dst = -223 nT – Geom. Storm (Kp=7)





$$\frac{\mathrm{vTEC_{NRT}} - \widetilde{\mathrm{vTEC}}_{\mathrm{15\ prev\ days}}}{\widetilde{\mathrm{vTEC}}_{\mathrm{15\ prev\ days}}}$$

— Relative vTEC (%)

--- Variability

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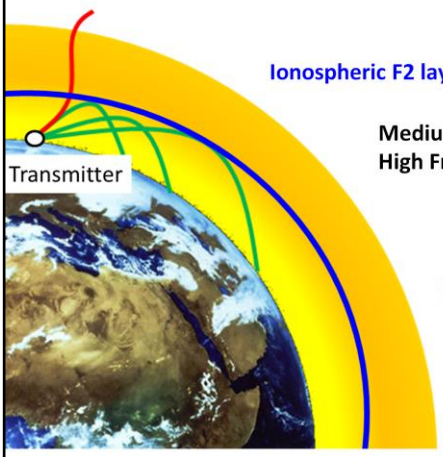
F2 Critical frequency = foF2



< foF2 = Reflexion

> foF2 = Refraction

FOF_2 – SLAB THICKNESS

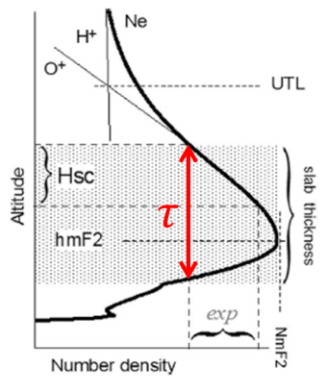


Fig. 1. Schematic view of the vertical electron density profile with key characteristics such as the peak density (NmF2), peak height (hmF2), upper ion transition level (UTL), scale height (Hsc) and slab thickness (τ).

From Stankov et Warnant, 2009

Davies, 1990

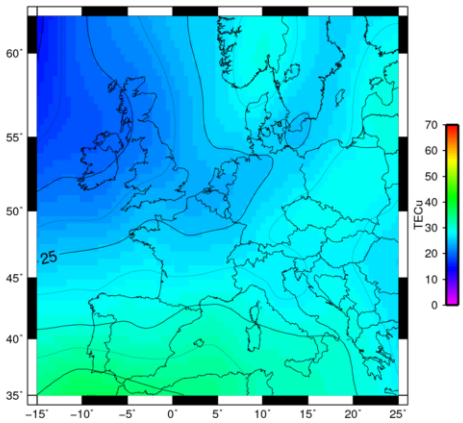
$$\tau = \frac{VTEC}{foF2^2 \times 1.24 \times 10^{-6}}$$

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

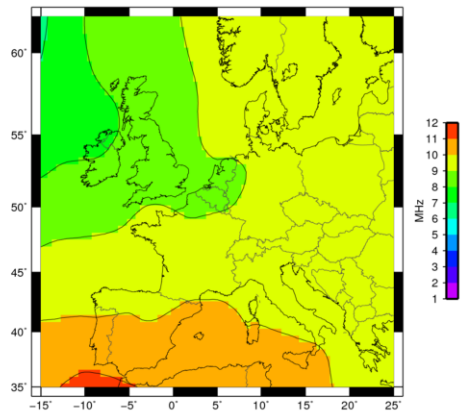
foF2 : F2 critical frequency in MHz
τ : Ionospheric slab thickness in m
VTEC : Vertical Total Electron Content in e/m2
NmF2 : Maximum electronic concentration in e/m3

F2 Critical frequency = foF2

NRT-VTEC ROB maps



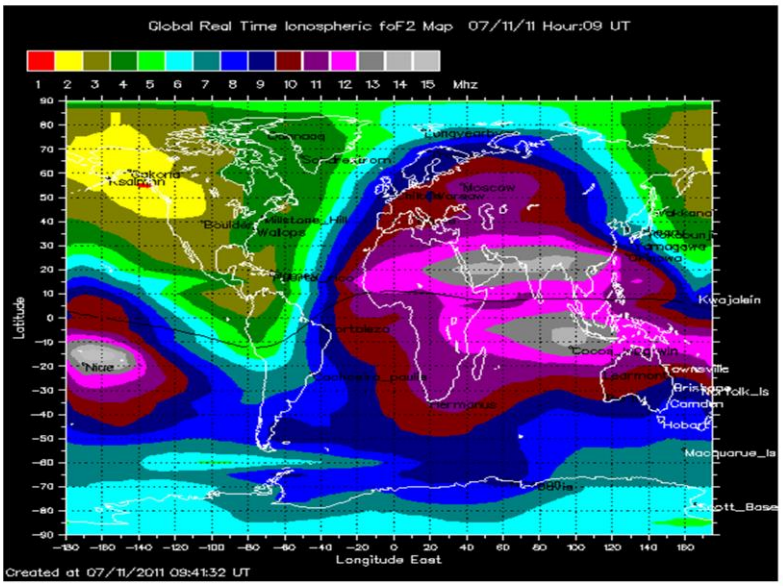
NRT-foF2 ROB maps



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

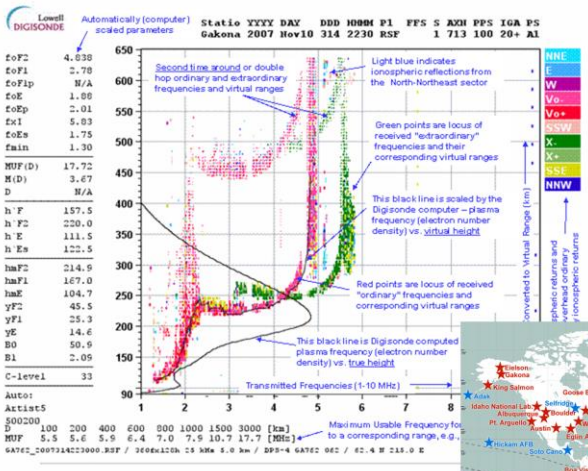
SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI

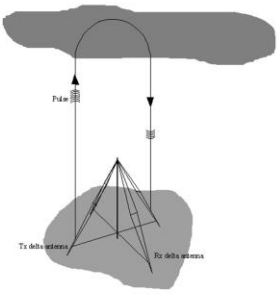
Fof_2 Critical Frequency



SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI

IONOSONDE

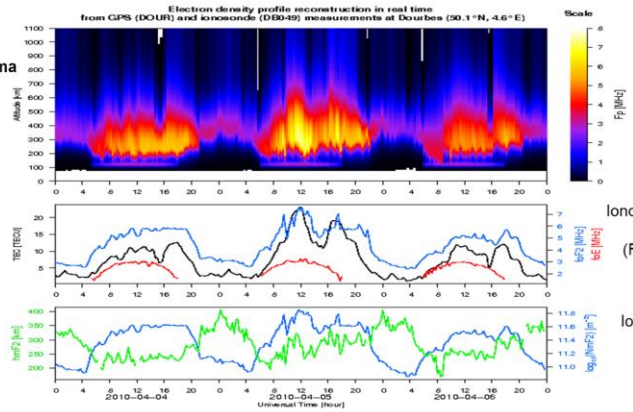




SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI

IONOSONDE

Ionosphere Plasma Frequency



Ionosphere Total Electron Content (TEC)

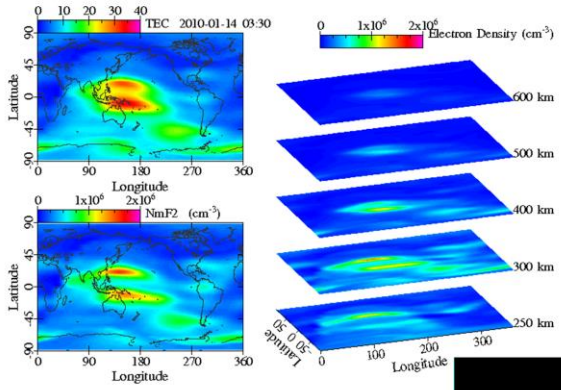
Ionosphere Critical Frequencies (F2 layer - foF2 , E layer - foE)

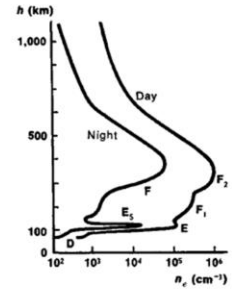
Ionosphere peak density altitude (hmF2)

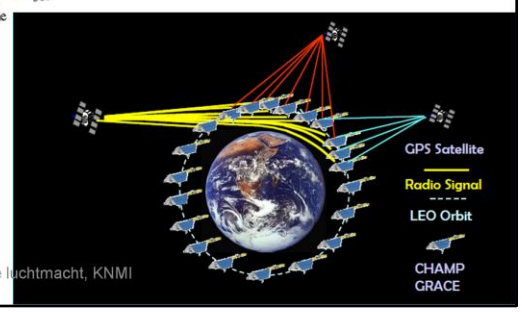
Ionosphere Peak Density (NmF2)

@Dourbes-RMI

RADIO OCCULTATION

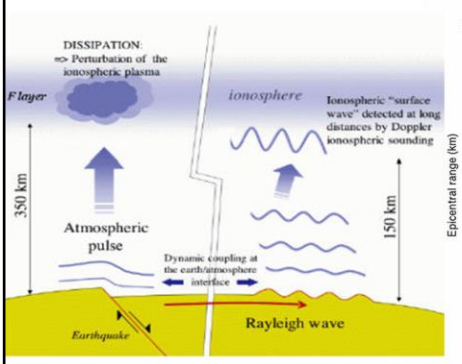


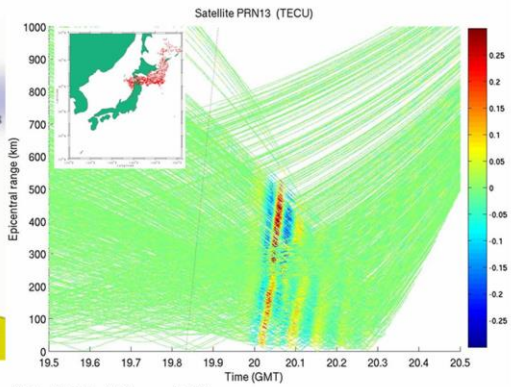




SWIC 2017 – collaboration between STCE, Koninklijke luchtmacht, KNMI

EARTHQUAKES

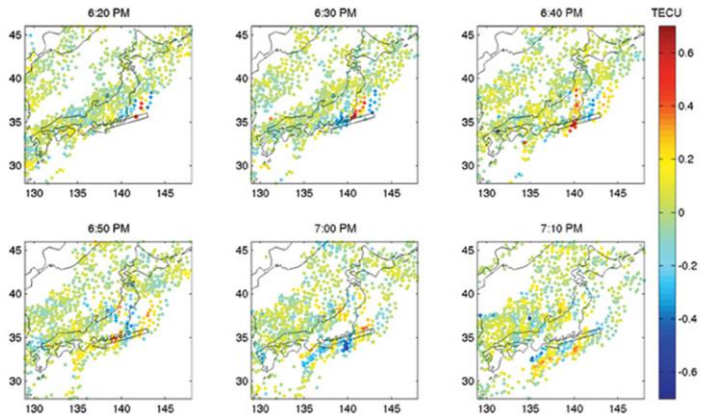




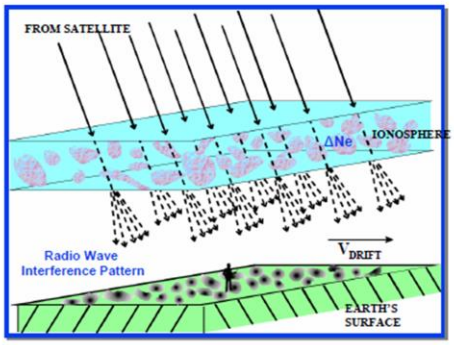
Tokachi-Oki earthquake of September 26, 2003 (Mw = 8.0).
Waves propagating at 3.5 km/s from the epicenter

DÉTECTION DE TSUNAMI

The observed signal for the June 23, 2001, tsunami (initiated offshore Peru). Total electron content variations are plotted at the ionosphere pierce points. A wave-like disturbance is seen propagating toward the coast of Honshu, the main island of Japan.

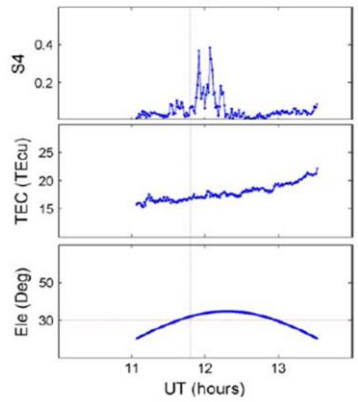


SCINTILLATION



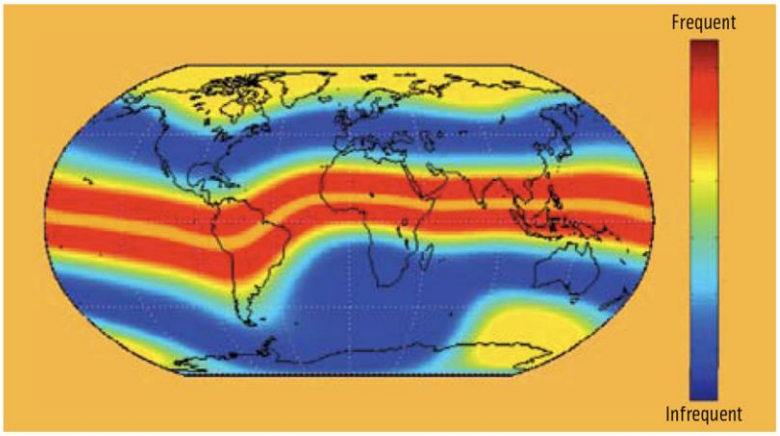
Écart type normalisé des fluctuations de l'intensité *I* du signal reçu:

$$S_4 = \frac{\sqrt{\overline{I^2} - \overline{I}^2}}{\overline{I}}$$



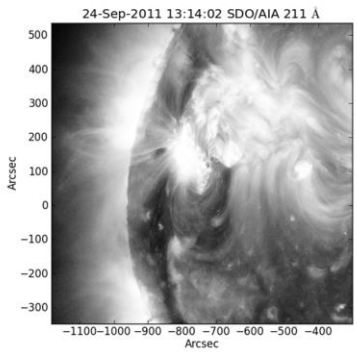
Irrégularités 200-300m
Ondes radio < 3 GHz

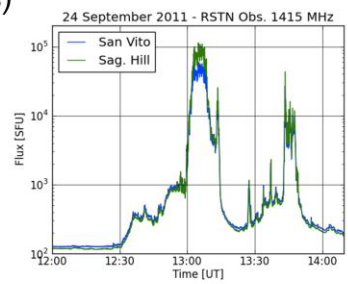
Scintillation



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)





The SRB power is measured in solar flux units (1 SFU = 10^{-22} W.m^{-2}.Hz^{-1}) at different frequencies [250 MHz; 34 GHz]

SOLAR RADIO BURSTS

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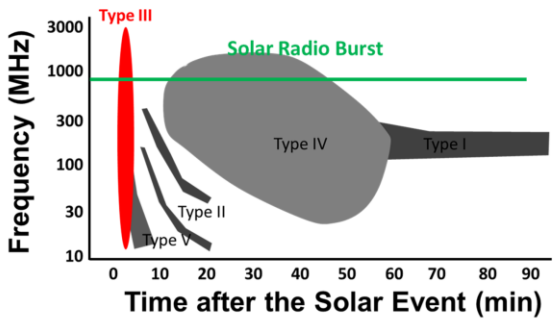
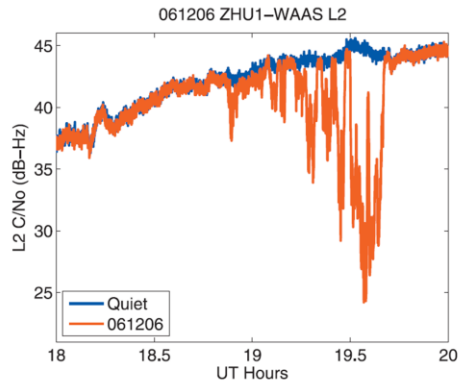
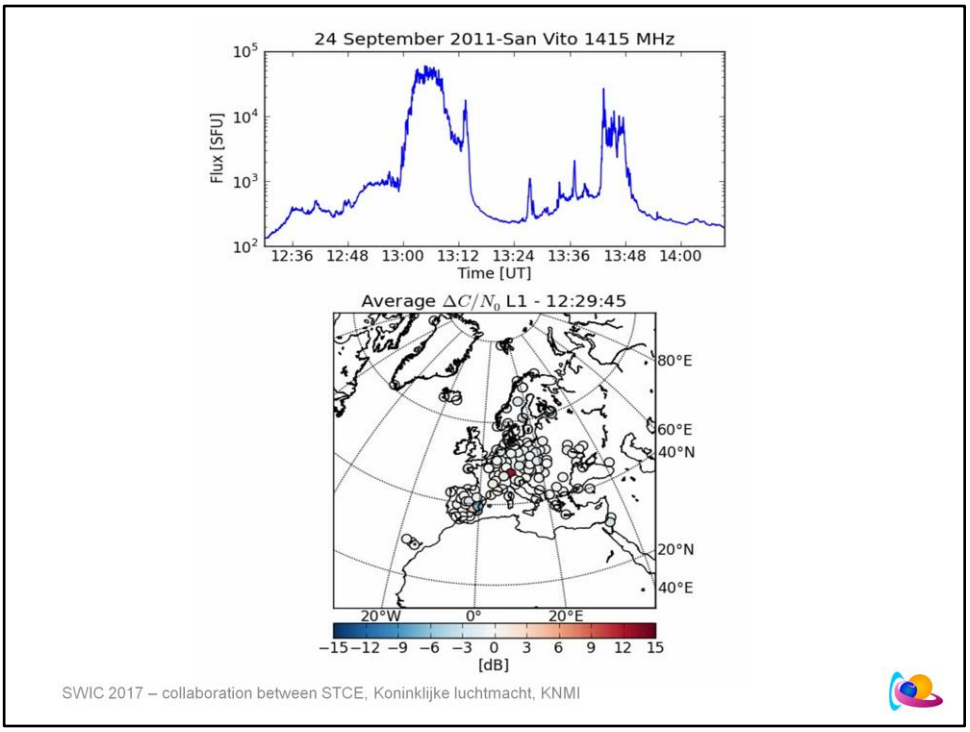


IMPACT ON GNSS SIGNAL RECEPTION

- GNSS signals:
  - L1 [1550 ; 1610] MHz
  - L2 [1170 ; 1300] MHz
  - Right Hand Circular Polarized (RHCP)
  - Low power (~-160dBW)
    → vulnerable to Radio Frequency Interferences
- SRBs increase the noise level of GNSS ground stations
- **Carrier-to-Noise density (C/N_0)** [35; 55] dB-Hz

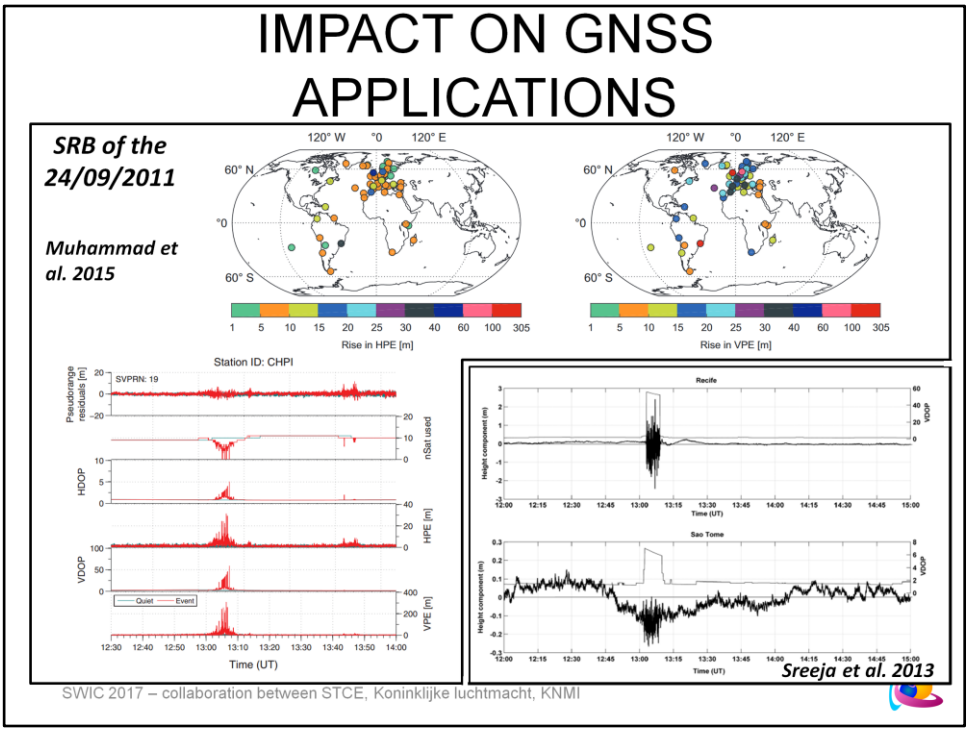


Cerruti et al. 2006



212 stations

QUIET
MIN -7.03
MAX 7.00
MEAN 0.00
MEDIAN -0.01
STD 0.50
SRB
44787
MIN -7.14
MAX 7.21
MEAN 0.00
MEDIAN 0.06
STD 1.98



GNSS receivers do not distinguish the GNSS signal through the solar radio interferences.

Positioning error due to the loss of lock of individual satellites

FIGURE 1: PPP height component and Vertical Dilution of Precison (VDOP) at Recife, Brazil (top) and Sao Tome, Africa (bottom)
Stations located at the equator
-11dB.Hz on L1
-22dB.Hz on L2 at Cap Verde

Figure 2: C/N_0 fades of -25dB.Hz on L1 and -30dB.Hz on L2

NEAR-REAL TIME DETECTION IN EUROPE

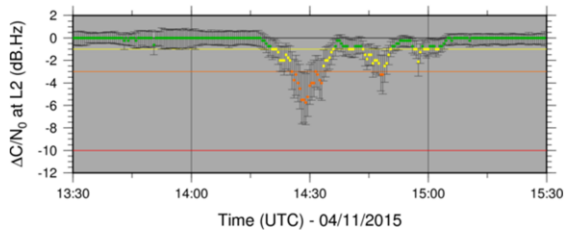
Reported on **www.gnss.be**

In collaboration with the **Humain Radioastronomy Station** http://sidc.be/humain/index.php

SOLAR RADIO BURST EVENT 2015-11-04

Contact: iono@gnss.be

SUMMARY OF THE EVENT: The signal reception of the GNSS L2 frequency was affected by a solar radio burst on 4th November 2015 between 14:20 and 15:02 (UTC). The maximum peak was observed at 14:29 UTC with a median fade of -5.8±2.2 dB-Hz over all EPN stations and a maximum fade of -10 dB-Hz.



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