SPACE WEATHER INTRODUCTORY COURSE

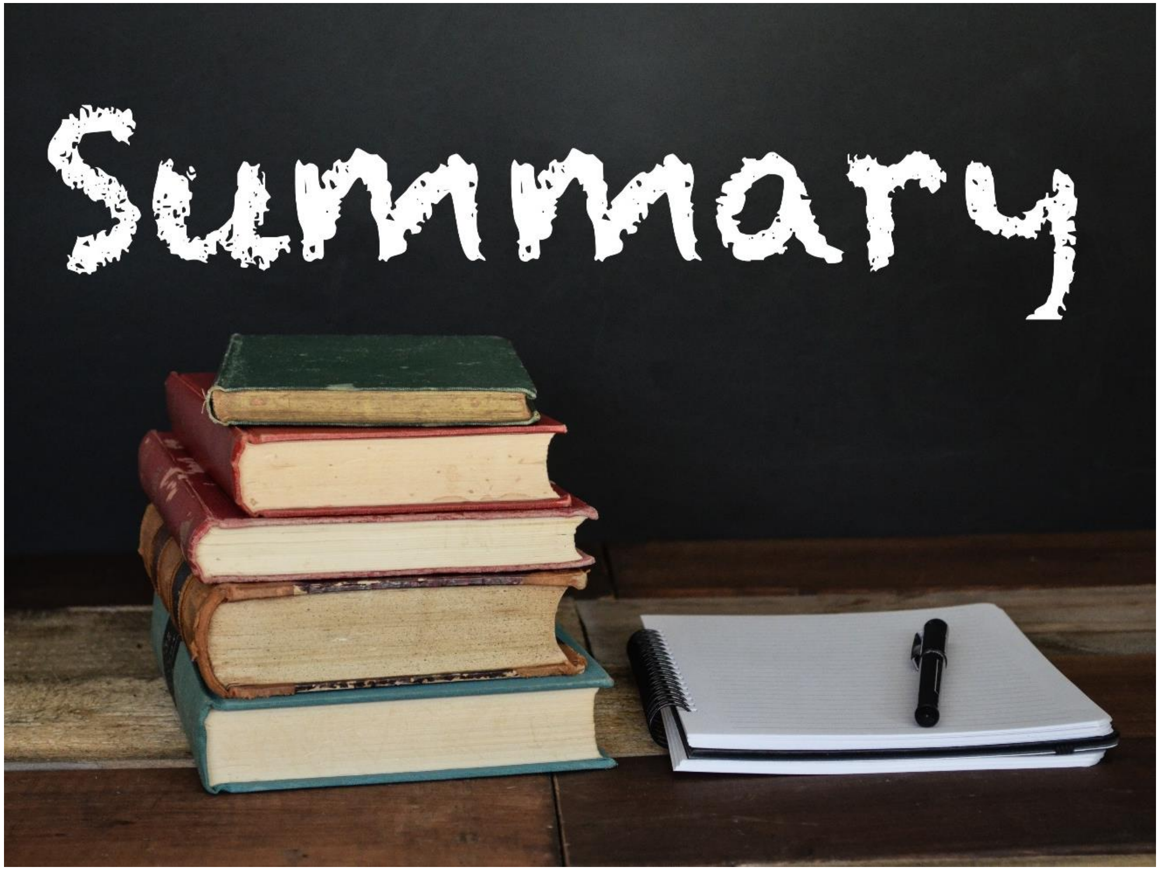
SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



SWIC – Summary Day 3 + SWx of the day

Jan Janssens

SWIC Summary Day 3 - Contents

- SWx effects
- SWx products
- SWx in the thermosphere-ionosphere
  - Eelco Doornbos
- Solar radio bursts – effects on aviation
  - Christophe Marqué

- SWx of the day

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Summary SWx effects (1/2)

- **Solar flares**
  - NOAA scale (R)
  - From EUV & X-ray radiation
    - Solar flare effect
      - “magnetic crochet”
      - => Effects from ICMEs
  - Shortwave fadeout
    - “Radio Blackout”
    - => PECASUS
  - From radio emission
    - GNSS disturbances
    - Radar disturbances

- **Proton events**
  - NOAA scale (S)
  - Polar Cap Absorption (PCA)
    - => PECASUS
  - Radiation
    - Astronauts, Polar flights
    - => PECASUS
  - Satellites
    - Star trackers
    - Single Event Effects (SEE)
    - Solar arrays
  - Ground Level Enhancement (GLE)

Summary SWx effects (2/2)

- **ICMEs**
  - NOAA scale (G)
  - From magnetic field
    - Satellites
      - Magnetopause crossings
    - High-Precision industry
    - GCR: Forbush decrease
  - From particles
    - Satellites
      - Drag
      - Charging effects
        - » Electrostatic Discharges (ESD)
      - Satellite-based Comms/Nav applications (GNSS)
        - » => PECASUS
    - HF Communication (aviation)
      - => PECASUS
    - Geomagnetically Induced Currents (GIC)
    - Aurora

- **Coronal Holes**
  - NOAA scale (G)
    - Impacts similar but less severe than with (strong) ICMEs
    - Especially during the declining phase of Solar Cycle
    - SNAP (Spring - Autumn +)
  - Satellites
    - Deep di-electric charging

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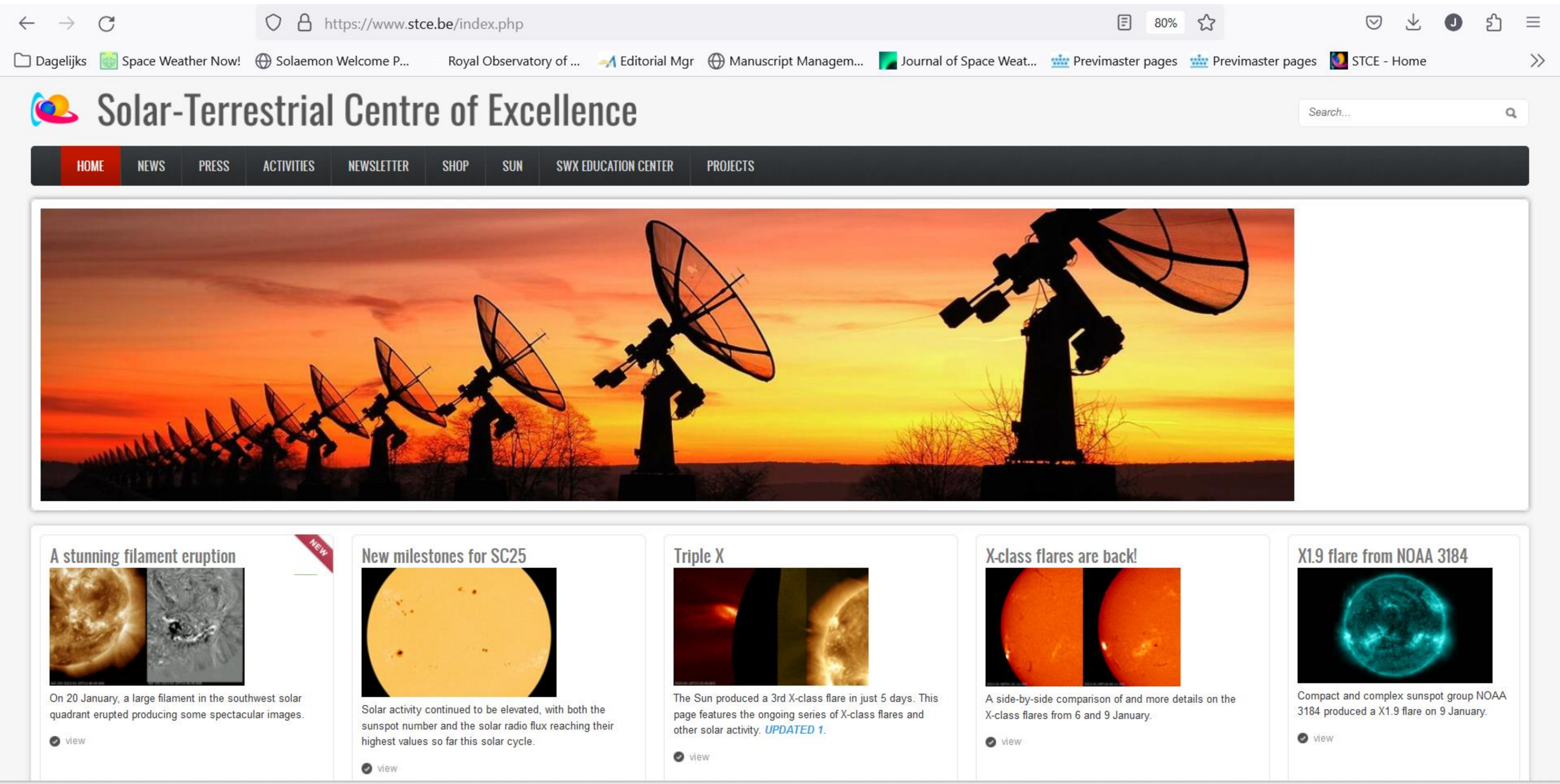
STCE website

https://www.stce.be/



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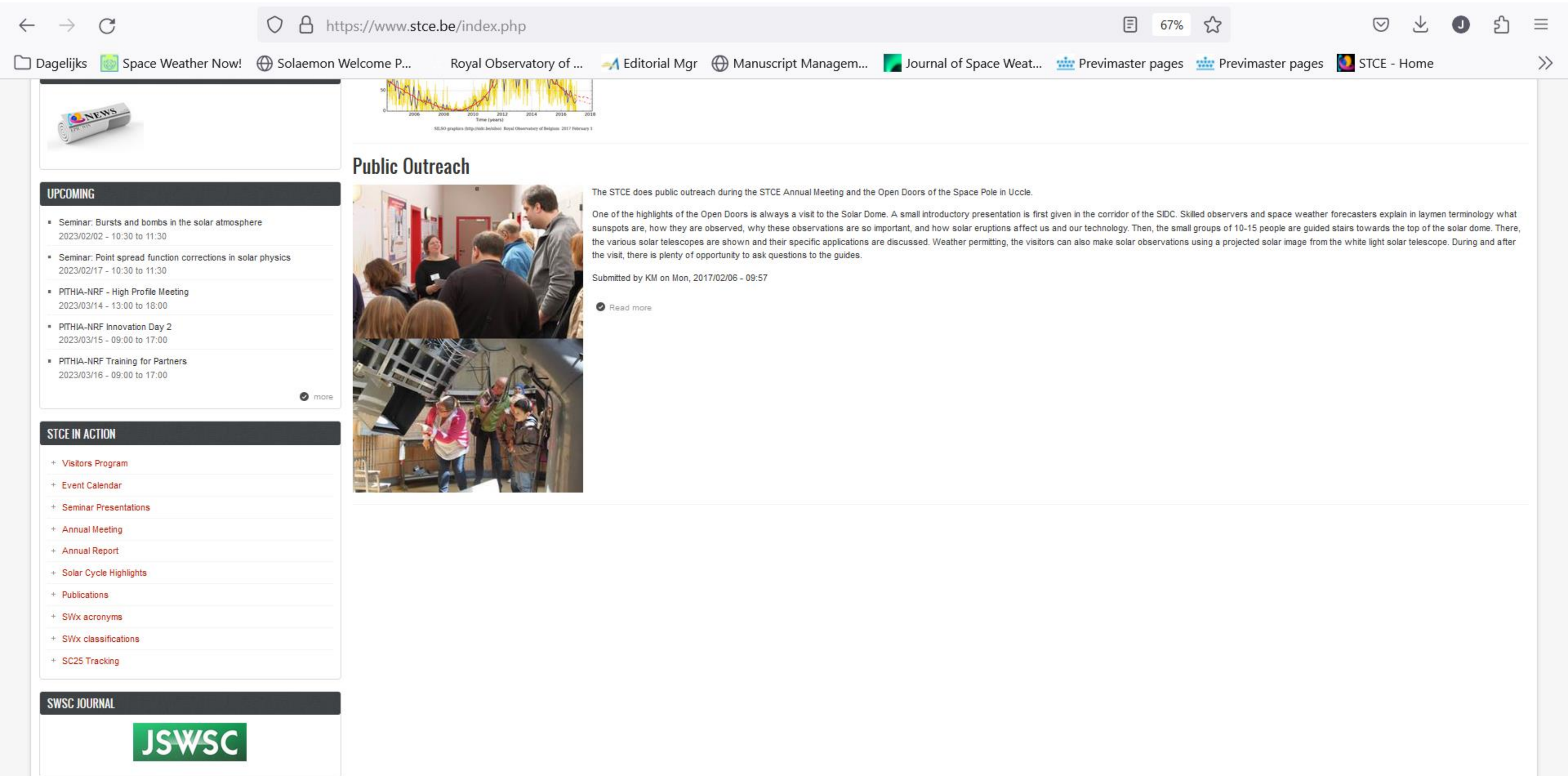
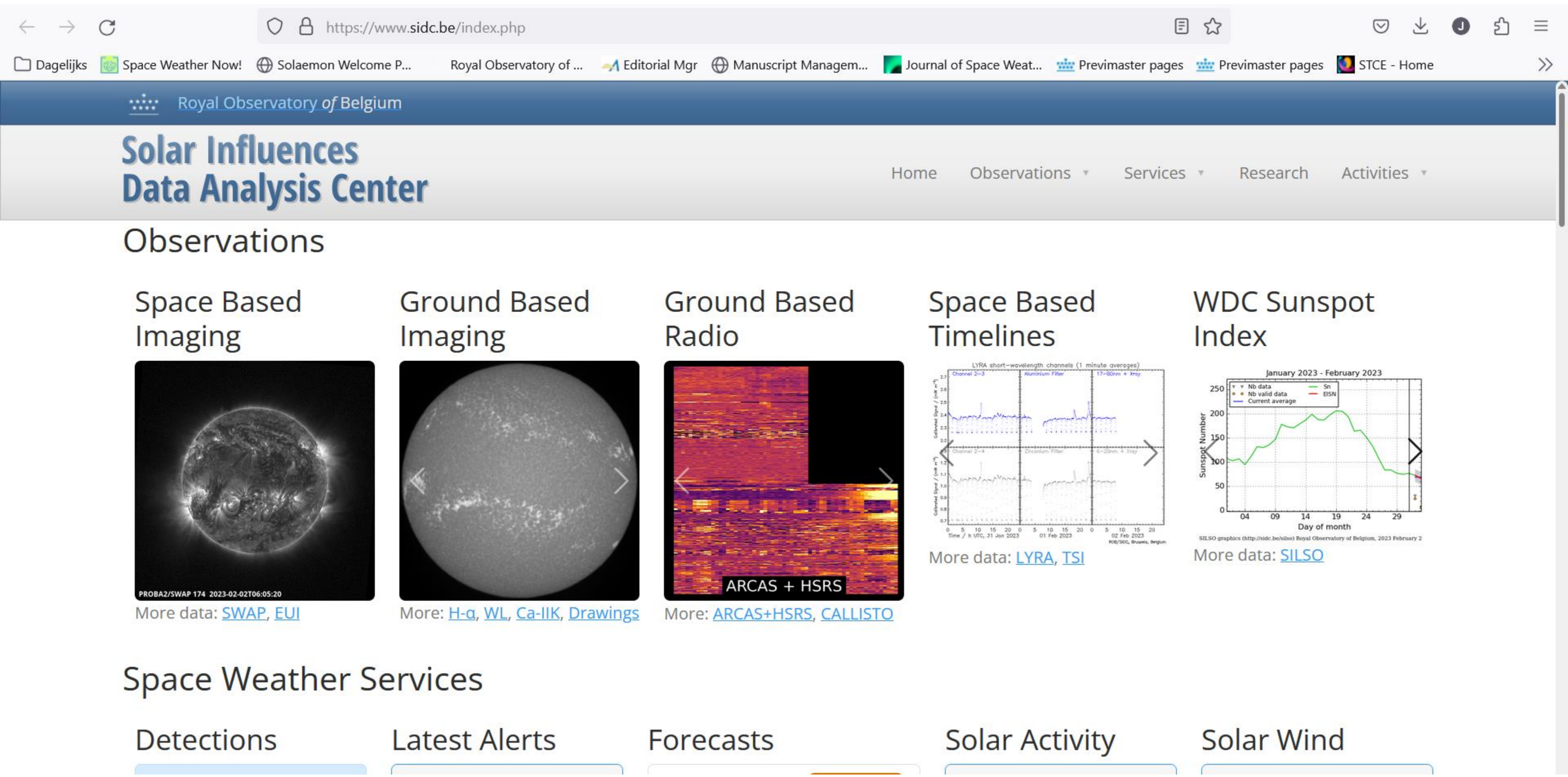


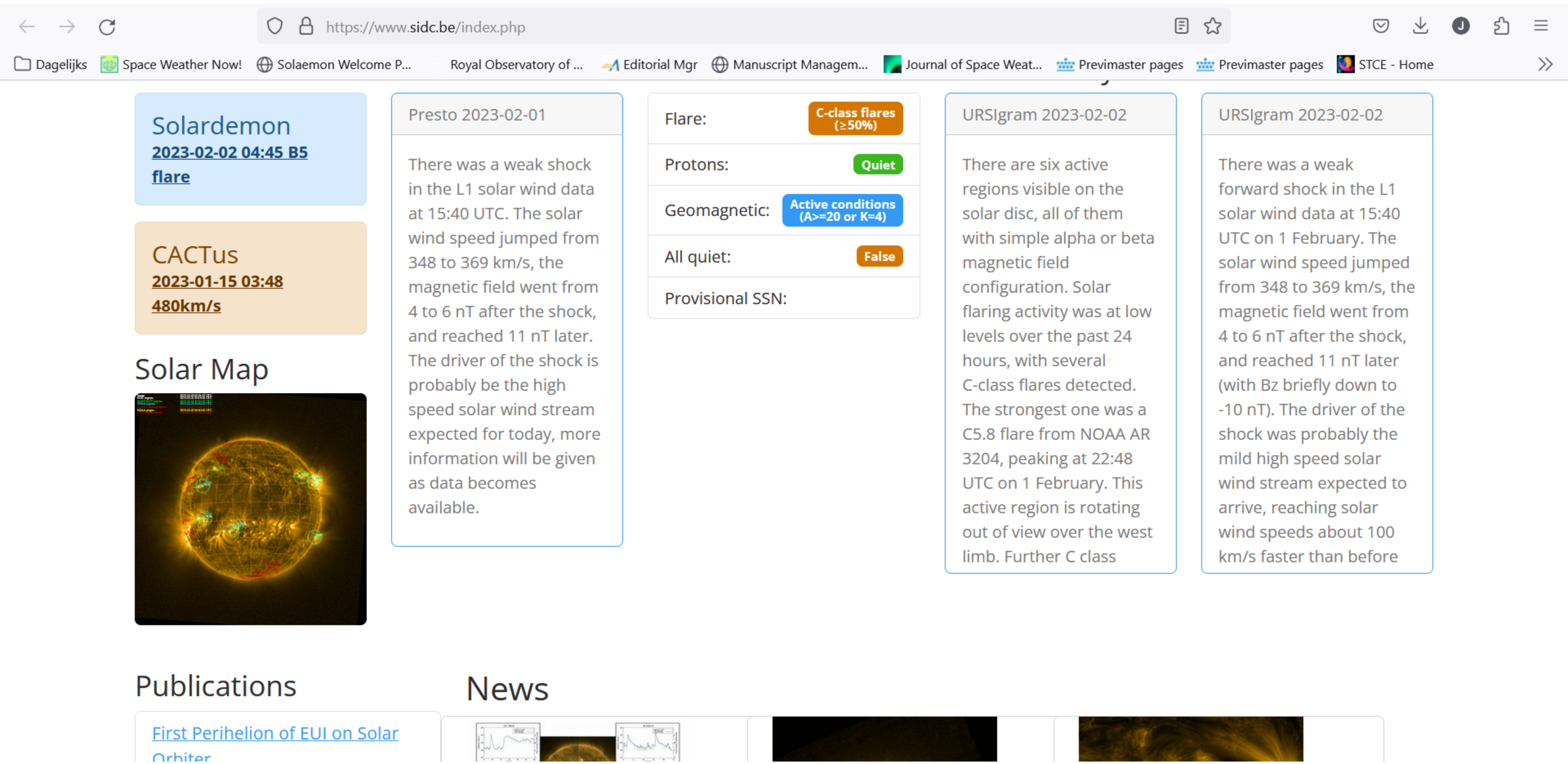
SIDC website

https://www.sidc.be/



SIDC website

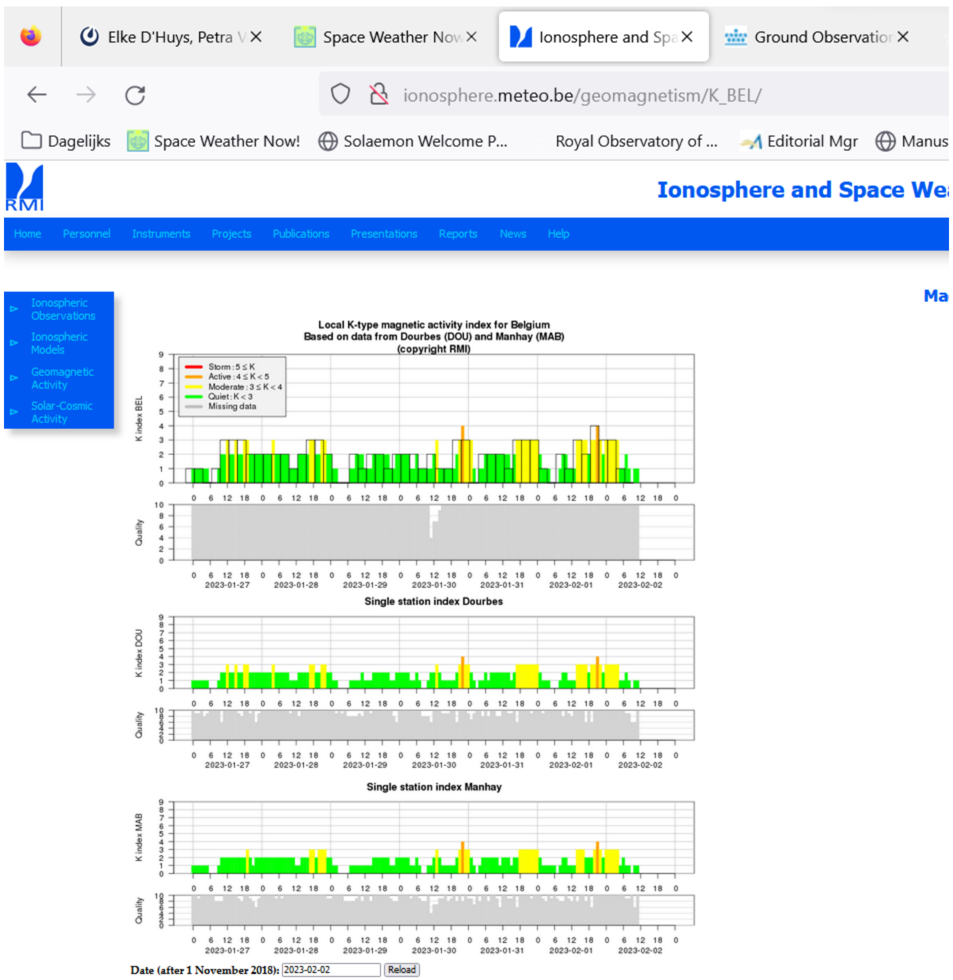
https://www.sidc.be/



Dourbes

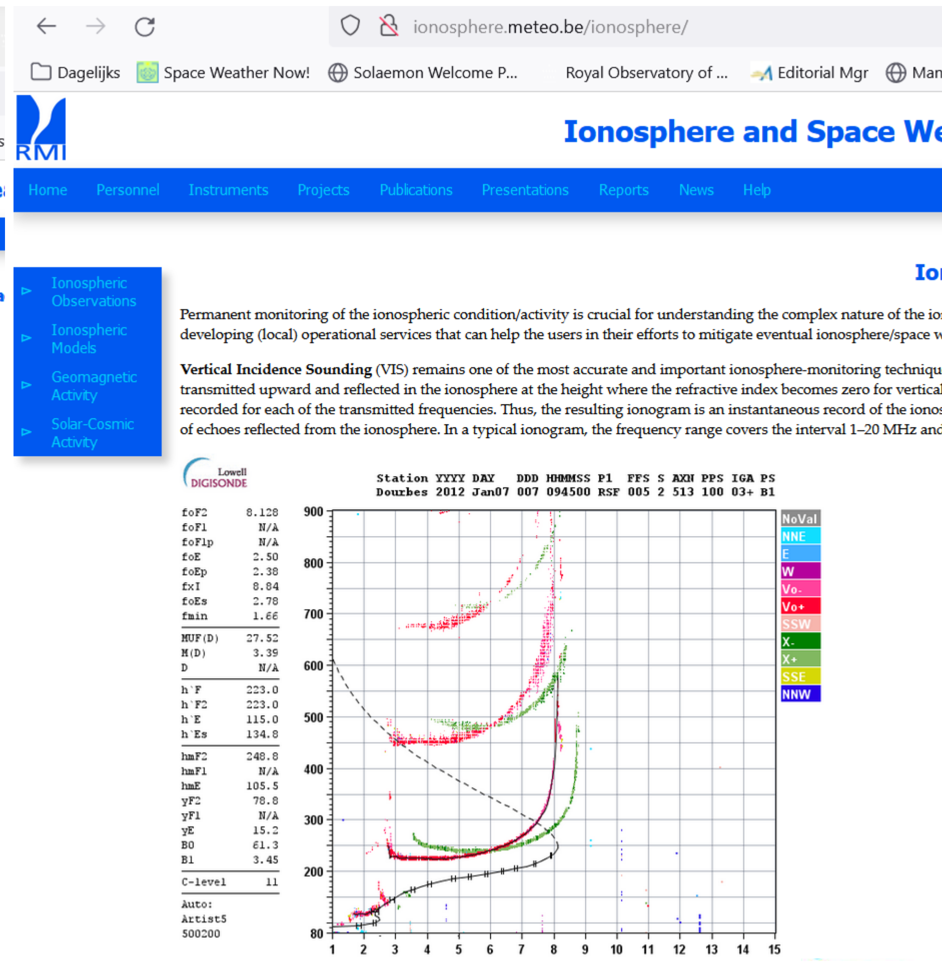
Geomagnetic

http://ionosphere.meteo.be/geomagnetism/K_BEL/



Ionosphere

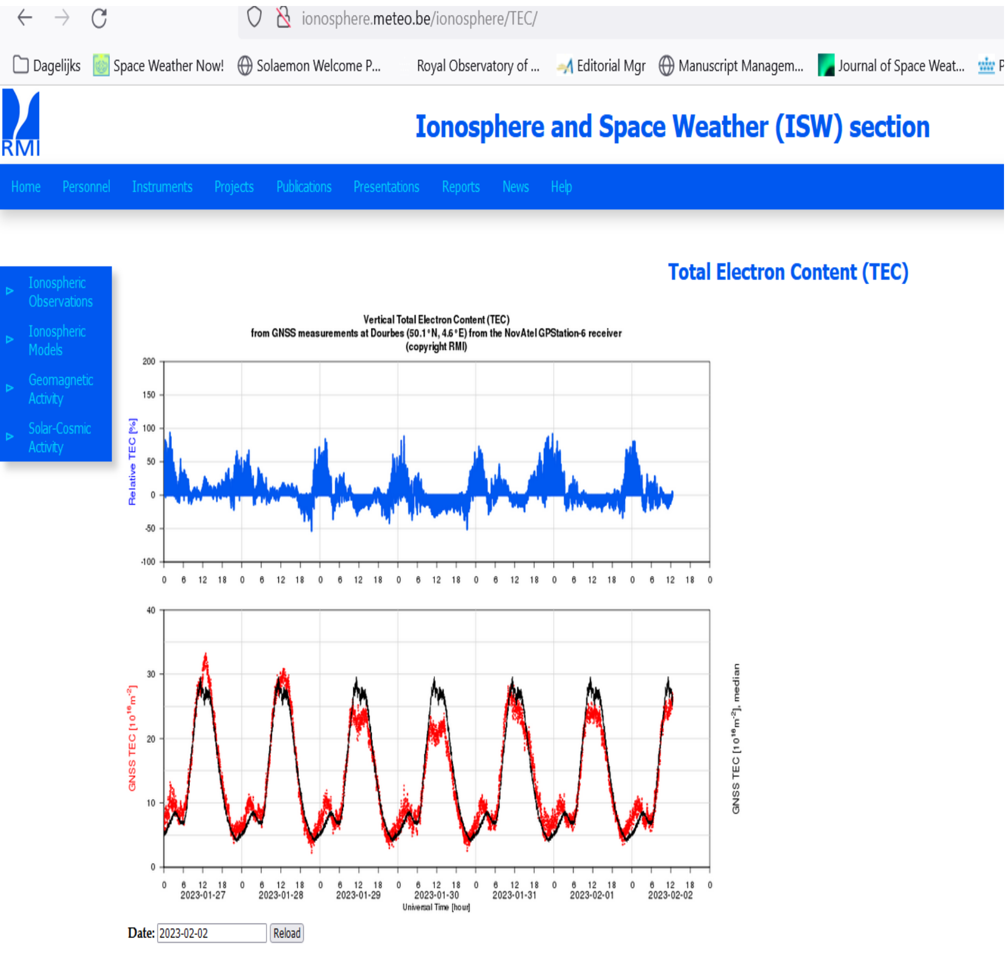
http://ionosphere.meteo.be/ionosphere/



GNSS

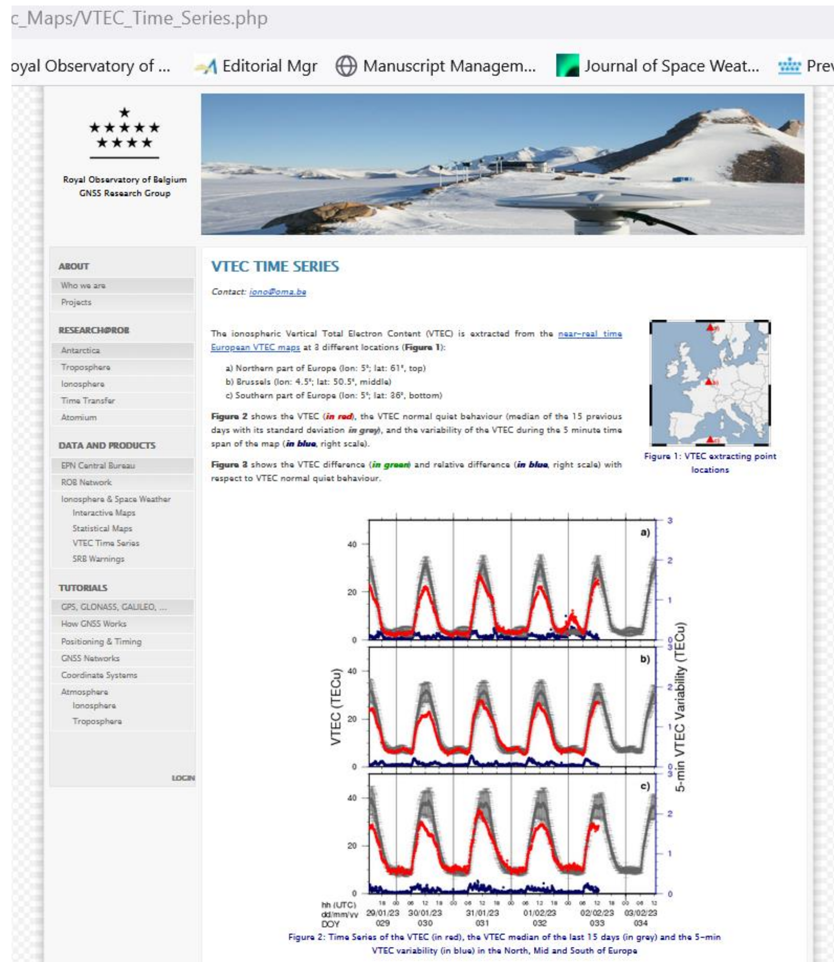
Dourbes (RMI)

http://ionosphere.meteo.be/ionosphere/TEC/



Uccle (ROB)

http://gnss.be/Atmospheric_Maps/ionospheric_maps.php



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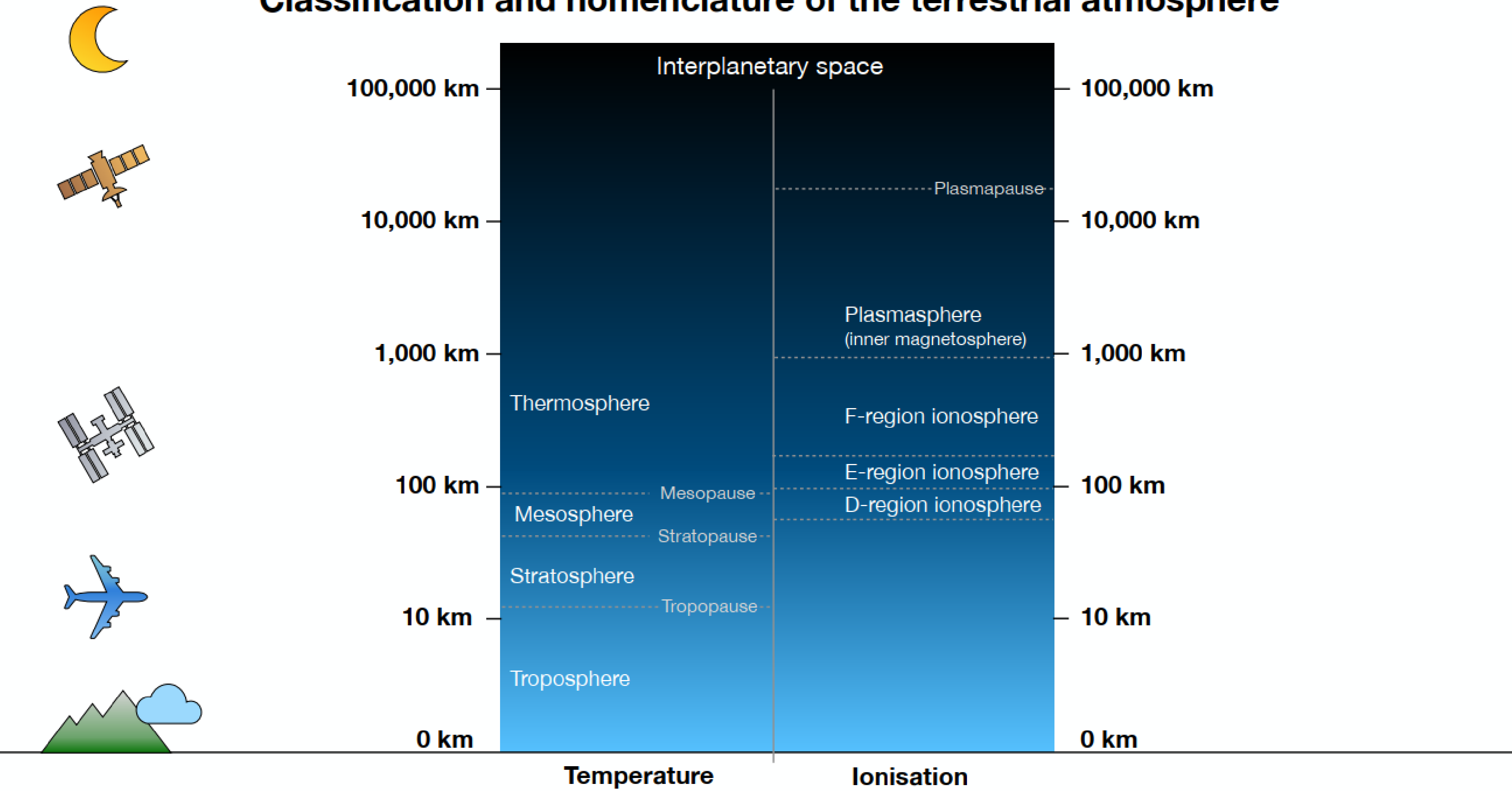
SWx in the thermosphere-ionosphere

Eelco Doornbos (KNMI)

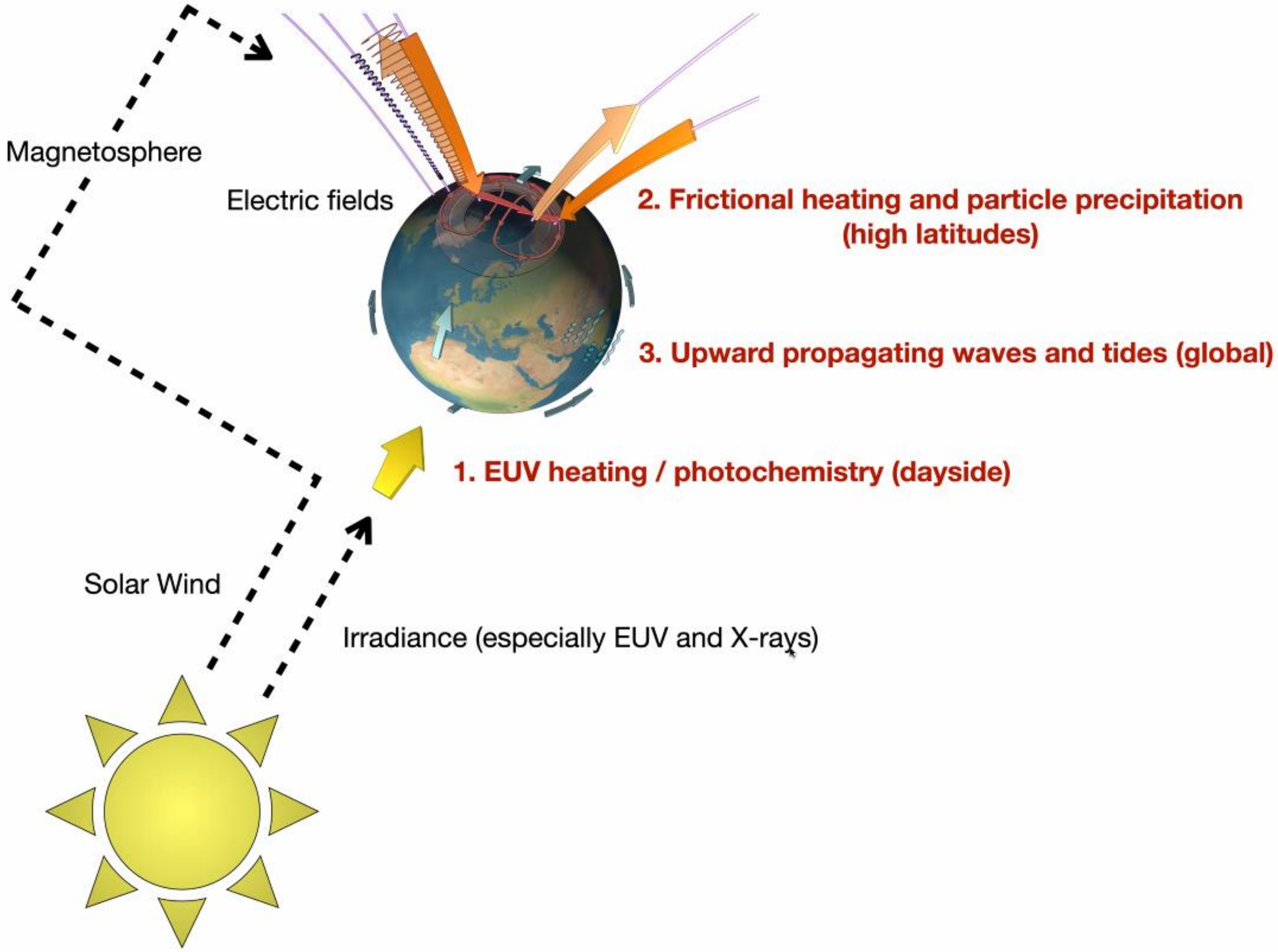
Classification and nomenclature of the terrestrial atmosphere



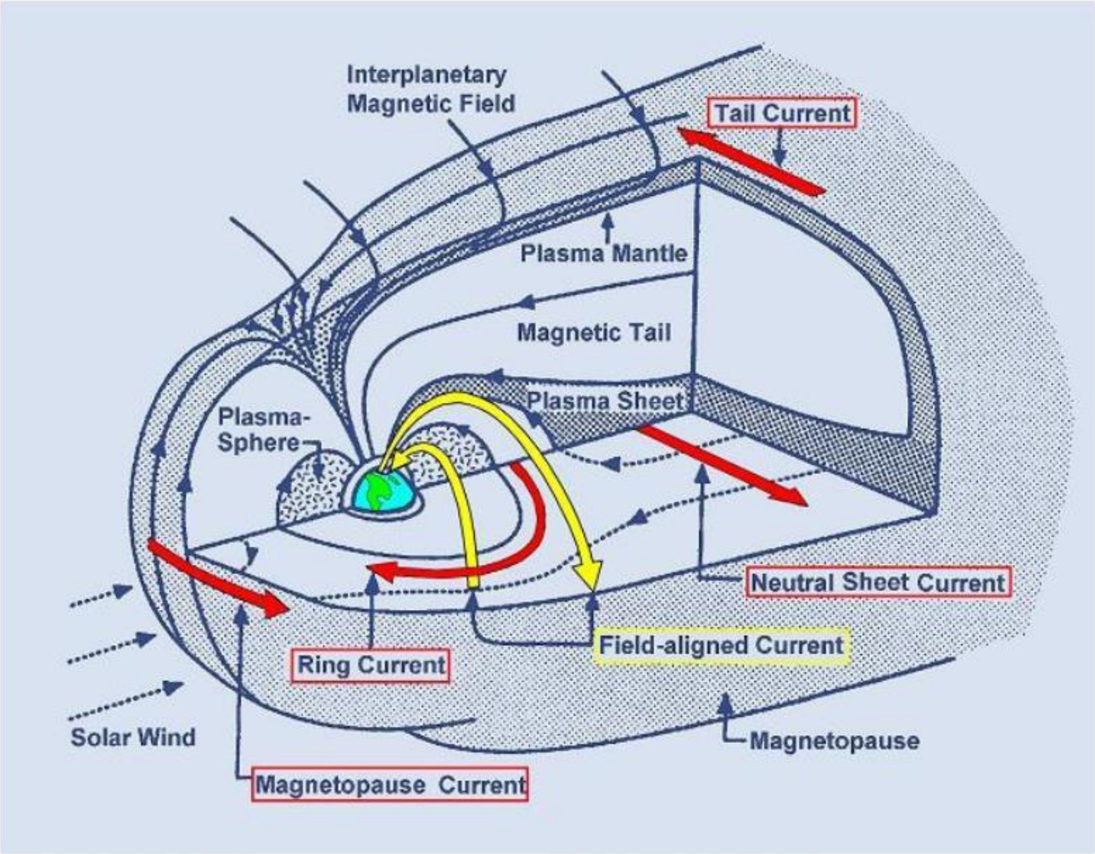
Based on G.W. Prölss, Physics of the Earth's Space Environment, Figure 2.13

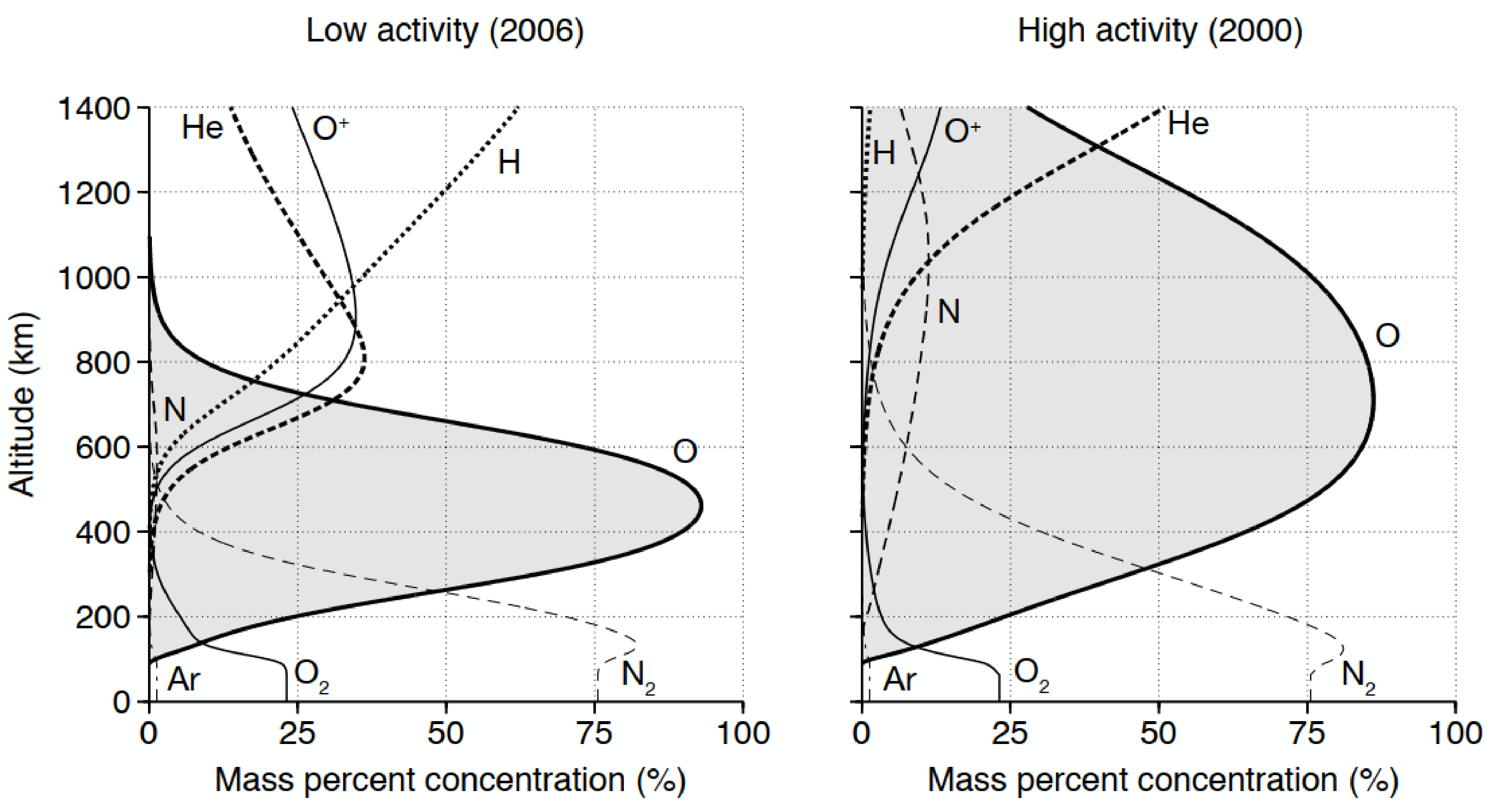
Ionospheric regions

- D-region (~80-100 km): rapid ionisation during X-ray flares leading to absorption of HF radio signals
- E-region (~100-150 km): systems of currents of charged particles from the magnetosphere close here at high latitudes, leading to impacts in power grids due to geomagnetically induced currents
- F-region (>150 km, peak at ~250-500 km): highest electron densities, scintillation of radio signals in regions of steep gradients

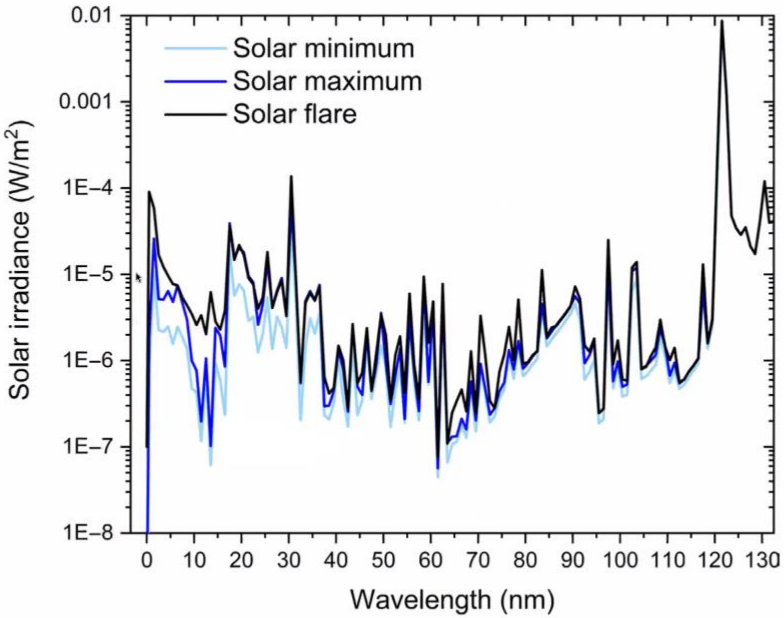

Magnetosphere
Electric fields
2. Frictional heating and particle precipitation (high latitudes)
3. Upward propagating waves and tides (global)
1. EUV heating / photochemistry (dayside)
Solar Wind
Irradiance (especially EUV and X-rays)

Magnetospheric currents





Low activity (2006)
High activity (2000)
Altitude (km)
1400
1200
1000
800
600
400
200
0
He
O+
H
N
O
Ar
O2
N2
0
25
50
75
100
Mass percent concentration (%)



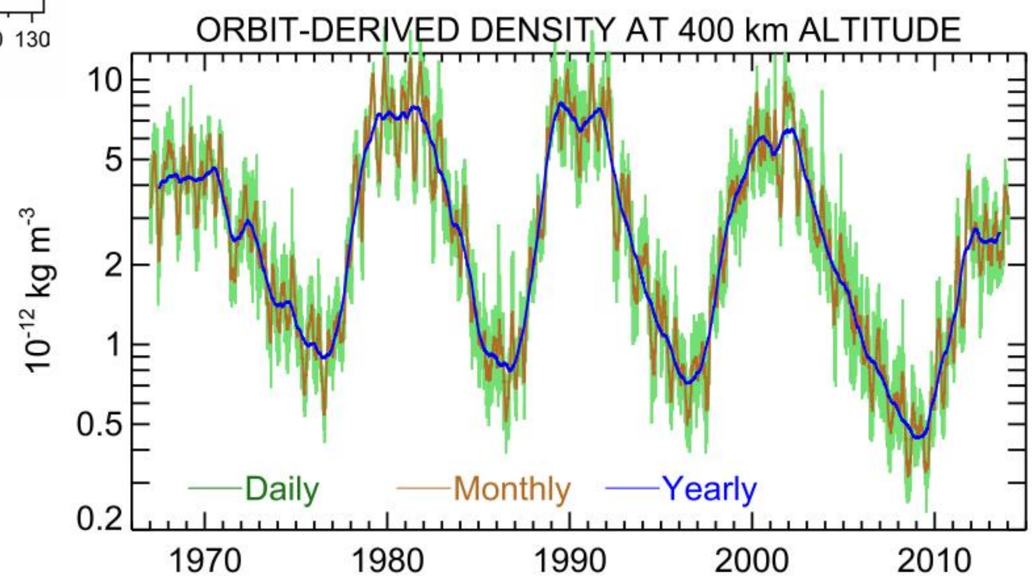
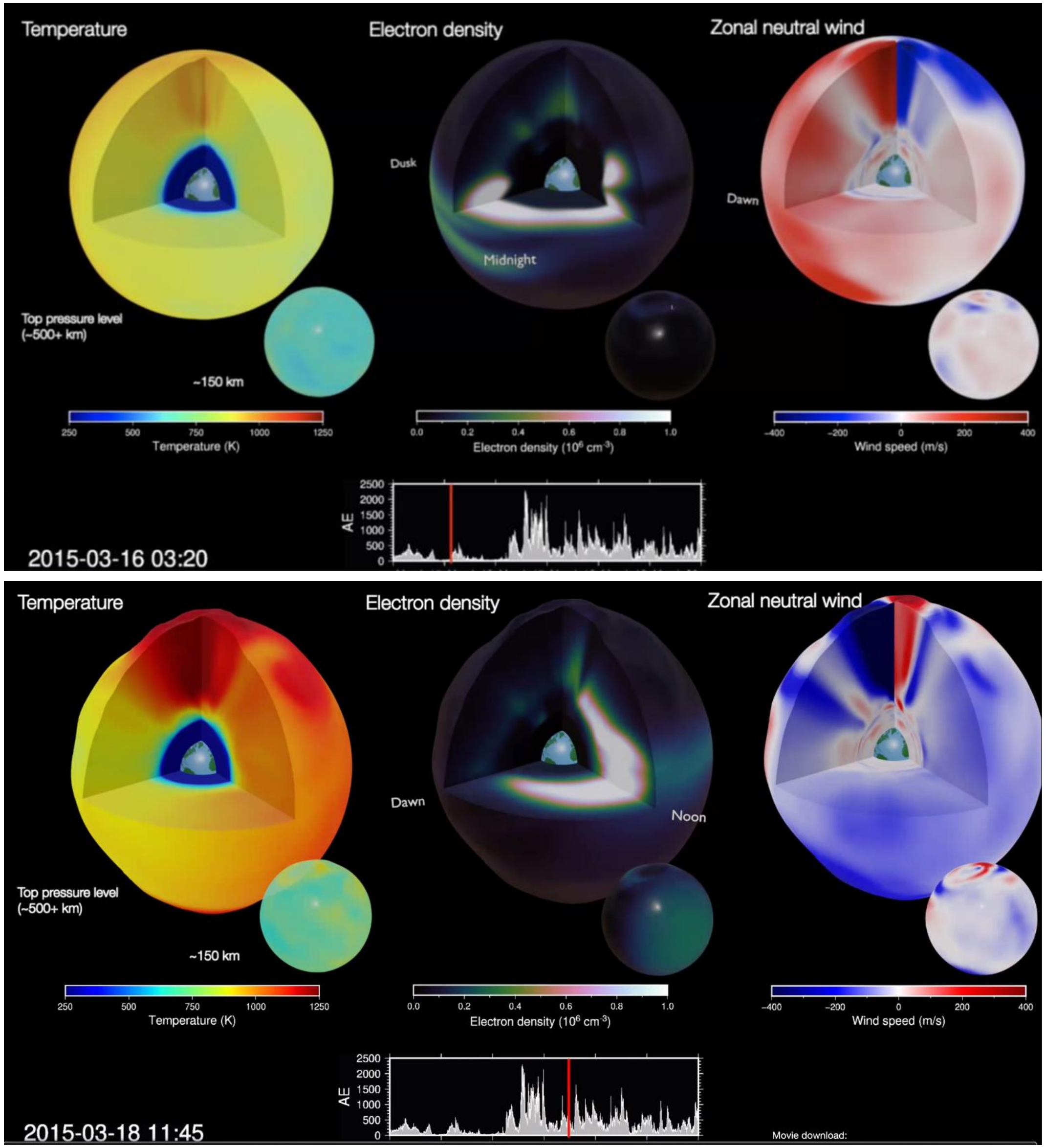
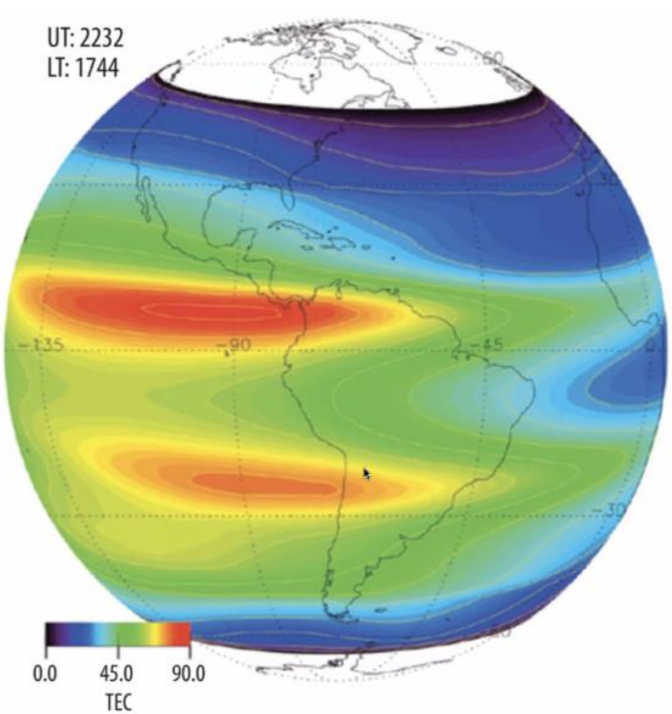
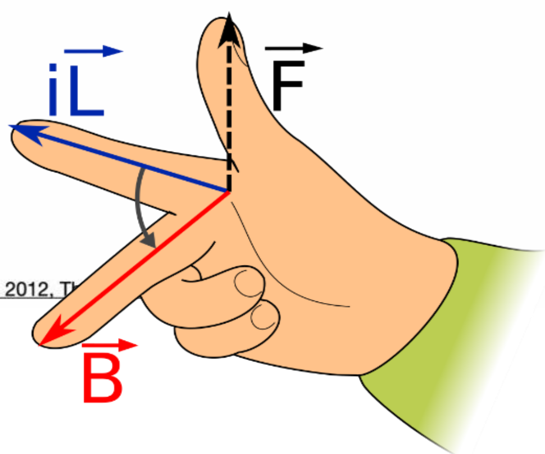


Fig. 1. 1967–2013 global average thermospheric mass density at an altitude of 400 km, derived from orbit data (Emmert, 2009, 2015) and plotted on a log scale. Shown are daily values (green), monthly running averages (orange), and yearly running averages (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)


Temperature
Electron density
Zonal neutral wind
Dusk
Dawn
Midnight
Top pressure level
(~500+ km)
~150 km
250
500
750
1000
1250
Temperature (K)
0.0
0.2
0.4
0.6
0.8
1.0
Electron density (10^6 cm^{-3})
-400
-200
0
200
400
Wind speed (m/s)
AE
2500
2000
1500
1000
500
0
2015-03-16 03:20
Temperature
Electron density
Zonal neutral wind
Dawn
Noon
Top pressure level
(~500+ km)
~150 km
Temperature (K)
Electron density (10^6 cm^{-3})
Wind speed (m/s)
AE
2015-03-18 11:45
Movie download:



Pfaff, 2012, Th



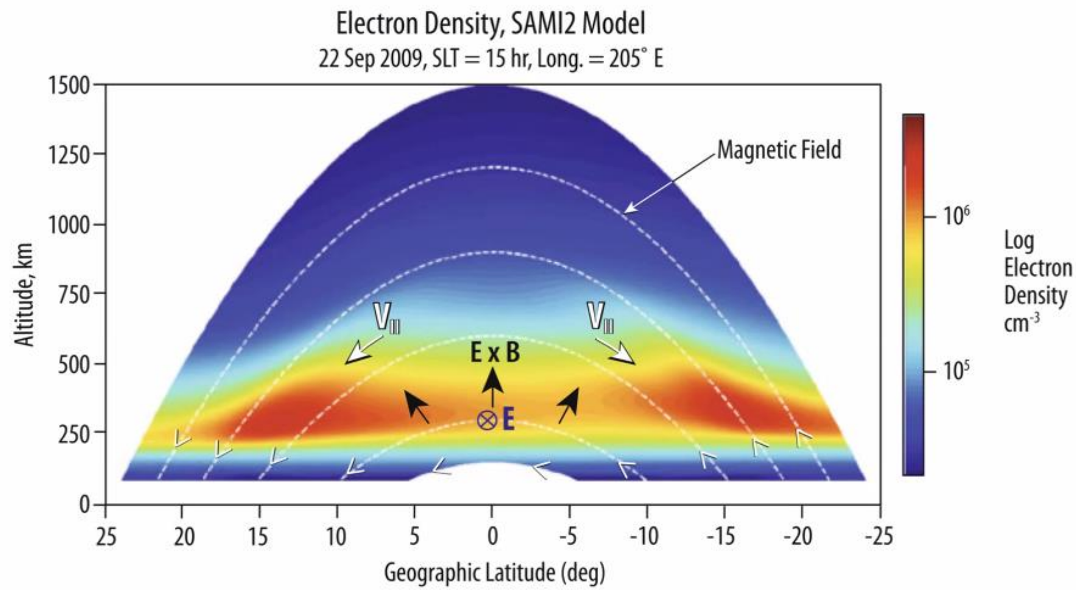
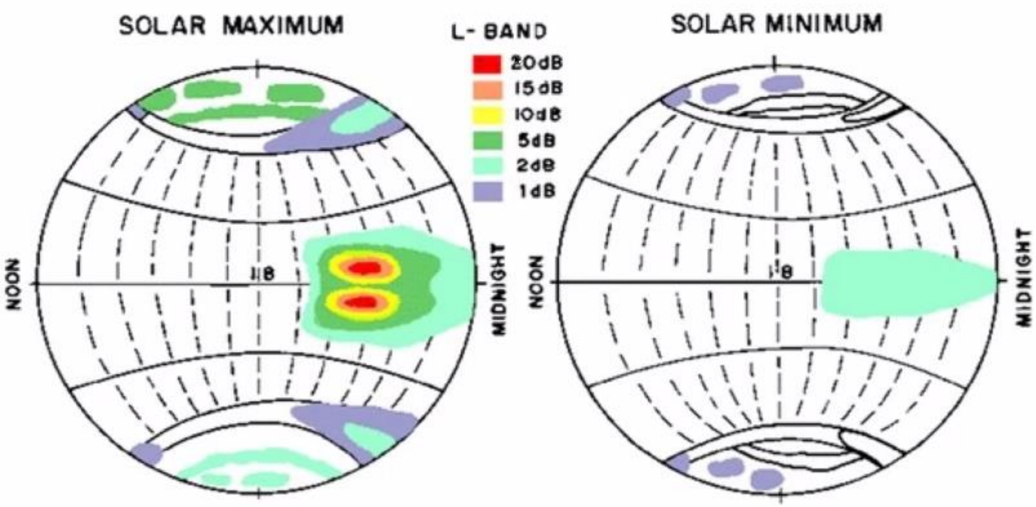
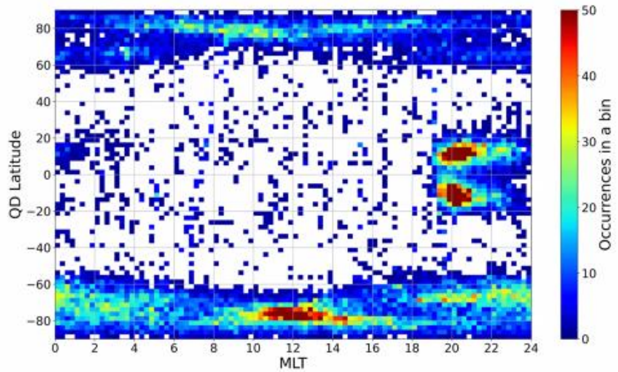


Fig. 19 SAMI2 model calculations versus latitude and altitude of the plasma density for 1500 SLT at 205° East. The upward **E** × **B** drift at the magnetic equator is driven by the eastward electric field, and there is subsequent flow downward along the magnetic field lines

Ionospheric scintillation



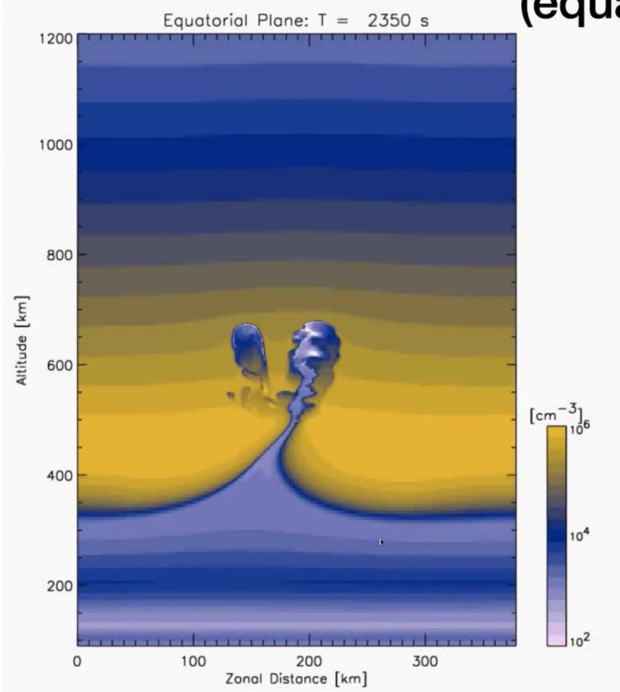
Global variation of amplitude scintillation fades at L band (after Basu et al. 1988a, b, colored by A.W. Wernik)

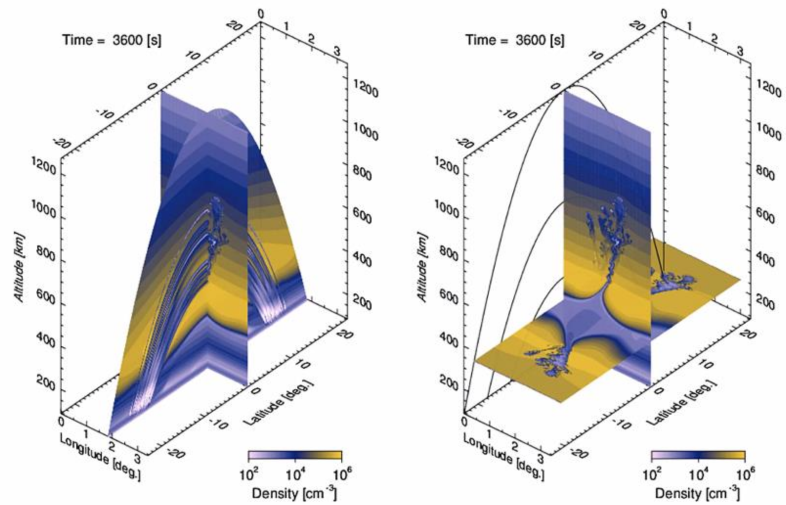


Distribution of GPS Loss of Lock events affecting Swarm A, B and C from Dec 2013-Dec 2020.

Pezzopane et al., 2021

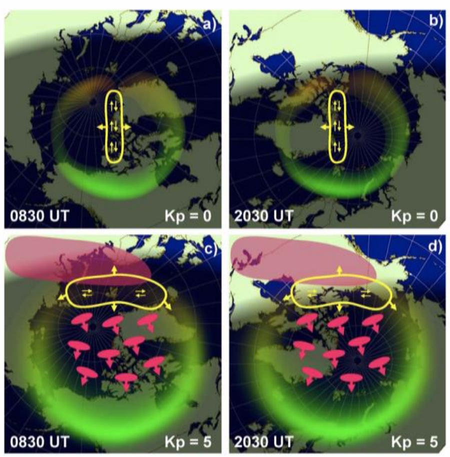
Scintillation mechanism 2: equatorial plasma bubbles (equatorial spread-F)





Nonlinear growth, bifurcation, and pinching of equatorial plasma bubble simulated by three-dimensional high-resolution bubble model

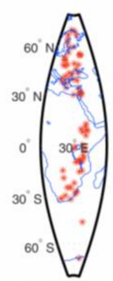
Scintillation mechanism 1: Polar cap patches



A schematic illustration of active space weather regions in the polar cap ionosphere when IMF BZ is north (top row, Kp = 0), and IMF BZ is south (bottom row, Kp = 5). The active regions for creation of polar cap patches/plasma irregularities are shown in yellow color and move under the influence of IMF as indicated with yellow arrows. For IMF BZ north the active region is caused by flow shears near transpolar arcs in the central polar cap, and space weather problems are only expected far north of Svalbard both day (panel a, 0830 UT) and night (panel b, 2030 UT). For IMF BZ south the tongue of ionization (pink) extends into the dayside auroral oval, where magnetic reconnection chops it into polar cap patches (pink) that begin to drift across the polar cap. In the production region there are flow channels and strong flow shears that initiate the growth of ionospheric irregularities. Svalbard will be directly under the production region at daytime (panel c, 0830 UT), and at night Svalbard will see patches arriving from the polar cap (panel d, 2030 UT).

et al., 2013 Space weather challenges of the polar cap ionosphere

Mechanism 3: Traveling ionospheric disturbances during a geomagnetic storm



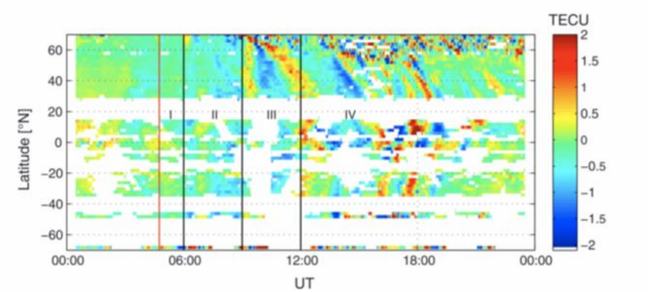


Figure 4. Illustration of TID amplitudes generated from GNSS data along the European-African sector with about 30°E center longitude during the 17 March 2015 storm. The red line indicates storm onset at 04:45 UT, and the solid black lines show the shift between the different phases of storm.

Summary

- The thermosphere-ionosphere is the upper part of the Earth's atmosphere.
- It is weakly ionised, so it consists of both neutral particles (thermosphere) and ions and electrons (ionosphere).
- The combined thermosphere-ionosphere system is strongly driven by three distinct energy sources: solar EUV irradiation (dayside), interaction with the magnetosphere (auroral latitudes) and interaction with the lower atmosphere (global).
- The impacts of these two systems are very different (thermosphere: satellite drag, ionosphere: radio signals, currents). But there are strong interactions.
- Important ionospheric impacts are related to small-scale irregularities related to strong gradients (equatorial plasma bubbles, polar cap patches and traveling disturbances).

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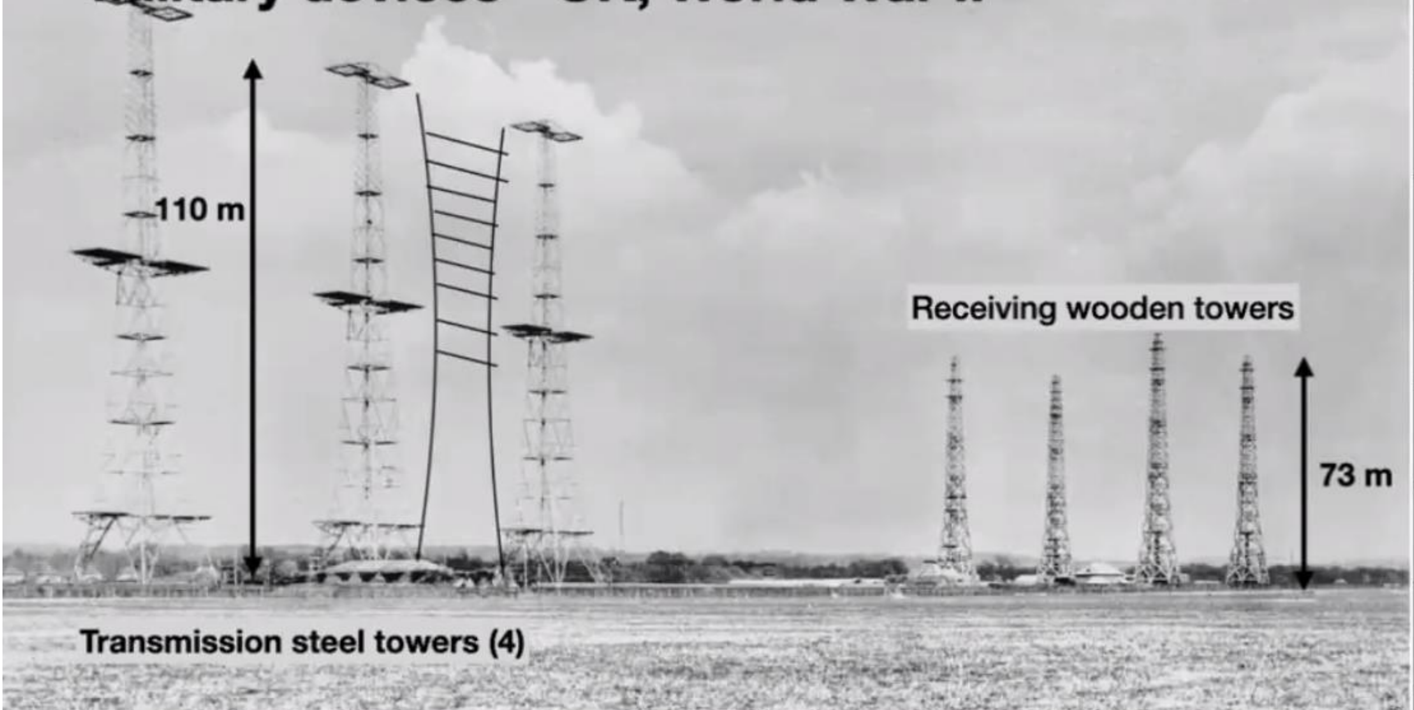
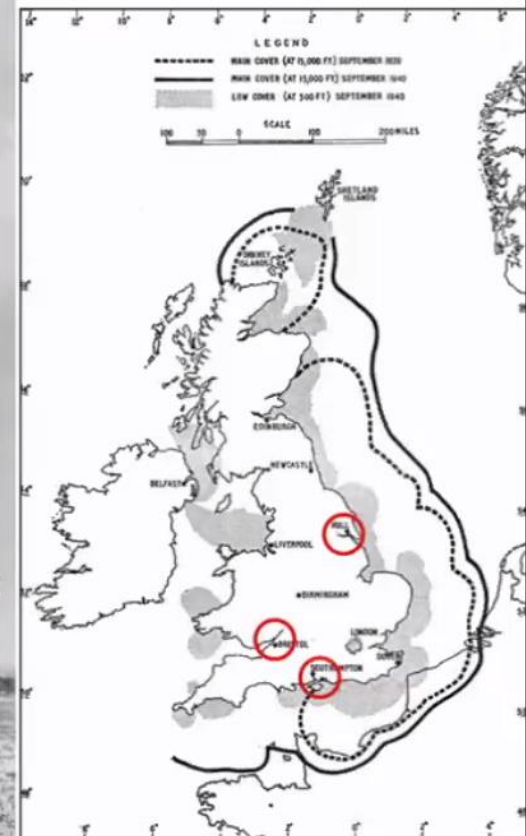
Impact on radars

Military devices - UK, World War II



One of the Chain Home radar stations, in the UK

from the collections of the Imperial War Museums, Public domain



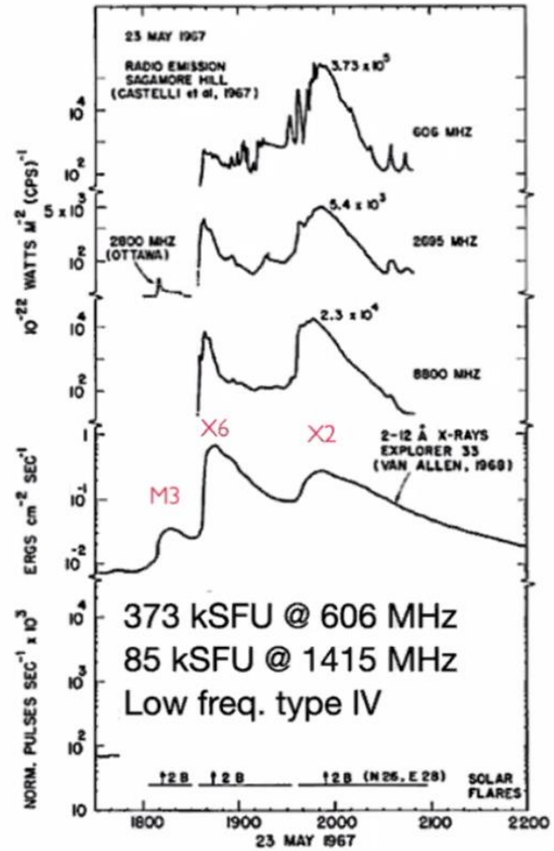
WIKIPEDIA

Impact on radars

Military devices - Cold war

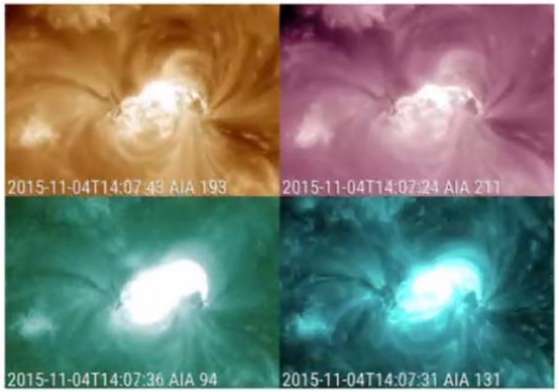
Jamming of Ballistic Missile Early Warning System (BMEWS) radars at 440 MHz

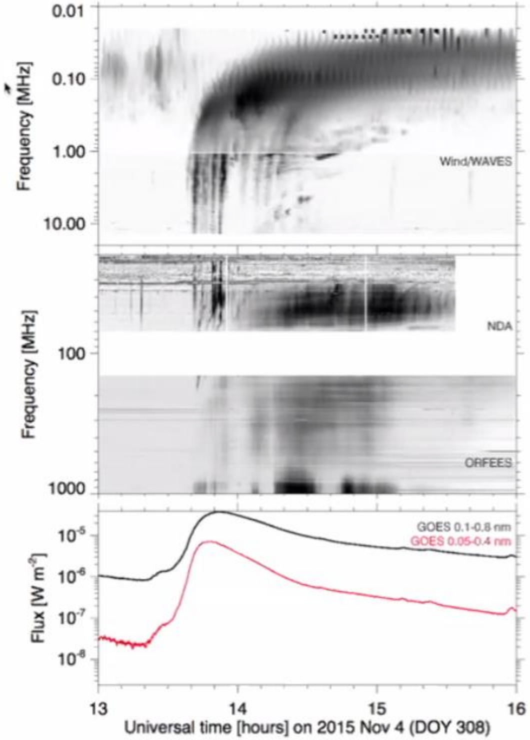
"Cold War military commanders viewed full scale jamming of surveillance sensors as a potential act of war. (...) the online memorial tributes to Col C. K. Anderson, (...) clearly credit him and his NORAD solar forecasting staff (...) with providing the information that eventually calmed nerves and allowed aircraft engines to cool as they returned to normal alert stance."



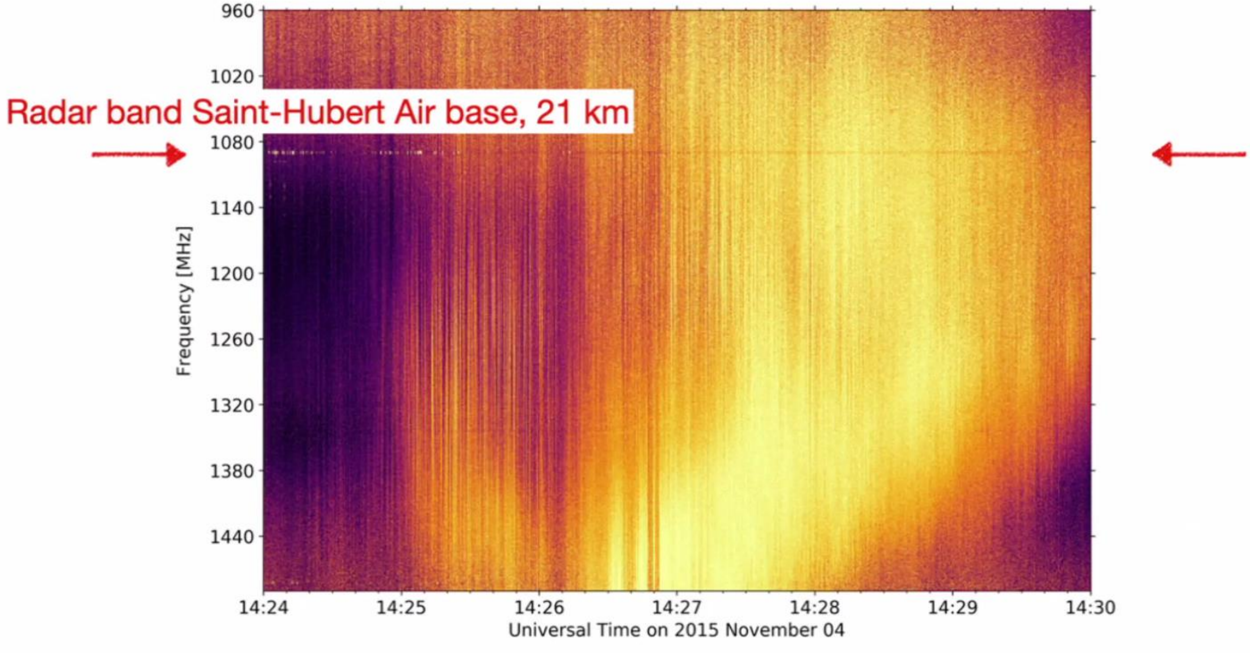
Knipp et al. 2016

Solar event



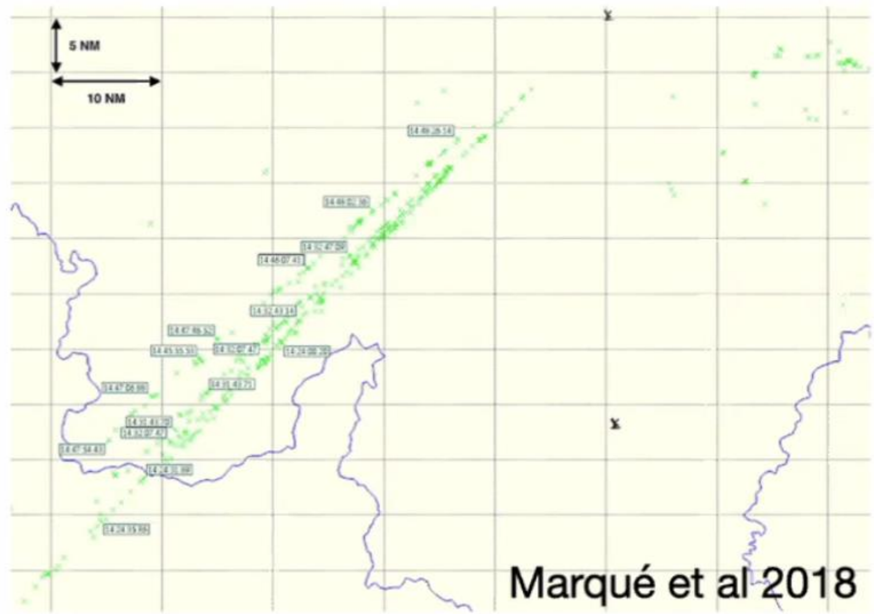


M3.7 flare peaking @1352 UT
NOAA AR 2243



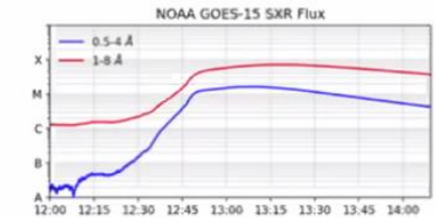
A European wide disruption

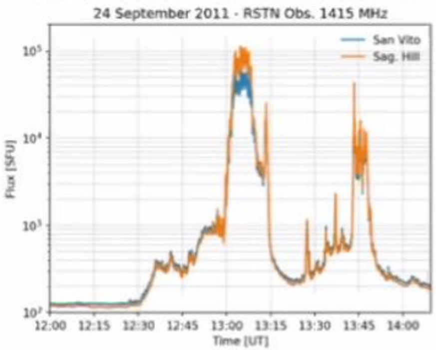
- Sweden: ATC radars suffered severe disturbances 14:20 UT - 16:00 UT
- Sweden: Partial closure of air space for an hour
- Minor disturbances in Norway, Belgium



Other services

GNSS





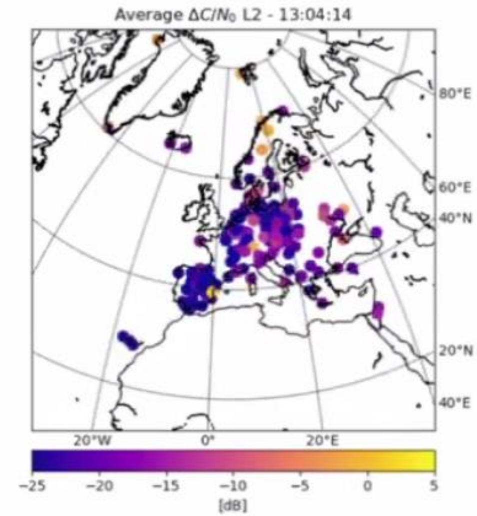
- M7.1 flare, max @ 13:20 UT
- AR 11302, Ekc, βγ

★110000 SFU @13:02 UT [Sag. Hill]

★60000 SFU [San Vito]

- Dm type IV burst (Bleien, Ondrejov)

C/N0 degradation



http://gnss.be/

In conclusion

- The November 4 2015 event one of the strongest radio events of cycle 24
- Impact on ATC radars depends on radar type and technologies
- Impact on ground based GNSS stations (no report from aviation industry)
- Type IV bursts can be delayed by almost an hour with respect to the X ray flare
- Flux density can vary by several order of magnitudes in narrow bands

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- SIDC URSIgram: https://www.sidc.be/index.php
- Solar flares:
  - GOES x-ray: https://www.swpc.noaa.gov/products/goes-x-ray-flux
  - Solar Demon: https://www.sidc.be/solardemon/flares.php
  - Humain Radio bursts: https://www.sidc.be/humain/humain_spectra_realtime.php
- GOES proton: https://www.swpc.noaa.gov/products/goes-proton-flux
- Sunspots:
  - SILSO: https://www.sidc.be/silso/eisnplot
  - SolarMonitor: https://solarmonitor.org/index.php
- Radio flux: https://www.spaceweather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-5-flux-en.php
- CMEs:
  - CACTus: https://www.sidc.be/cactus/out/latestCMEs.html
  - SOHO: https://soho.nascom.nasa.gov/data/Theater/
  - STEREO: https://stereo-ssc.nascom.nasa.gov/cgi-bin/images
- Solar Wind:
  - DSCOVR: https://www.swpc.noaa.gov/products/real-time-solar-wind
- Geomagnetism:
  - NOAA Kp: https://www.swpc.noaa.gov/products/planetary-k-index
  - K Dourbes (K_BEL): http://ionosphere.meteo.be/geomagnetism/ground_K_dourbes/ (http://ionosphere.meteo.be/geomagnetism/K_BEL/)
  - Dst: http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html
- GOES electrons: https://www.swpc.noaa.gov/products/goes-electron-flux
- GNSS (TEC, ionospheric maps): http://gnss.be/ ; http://ionosphere.meteo.be/ionosphere/TEC/