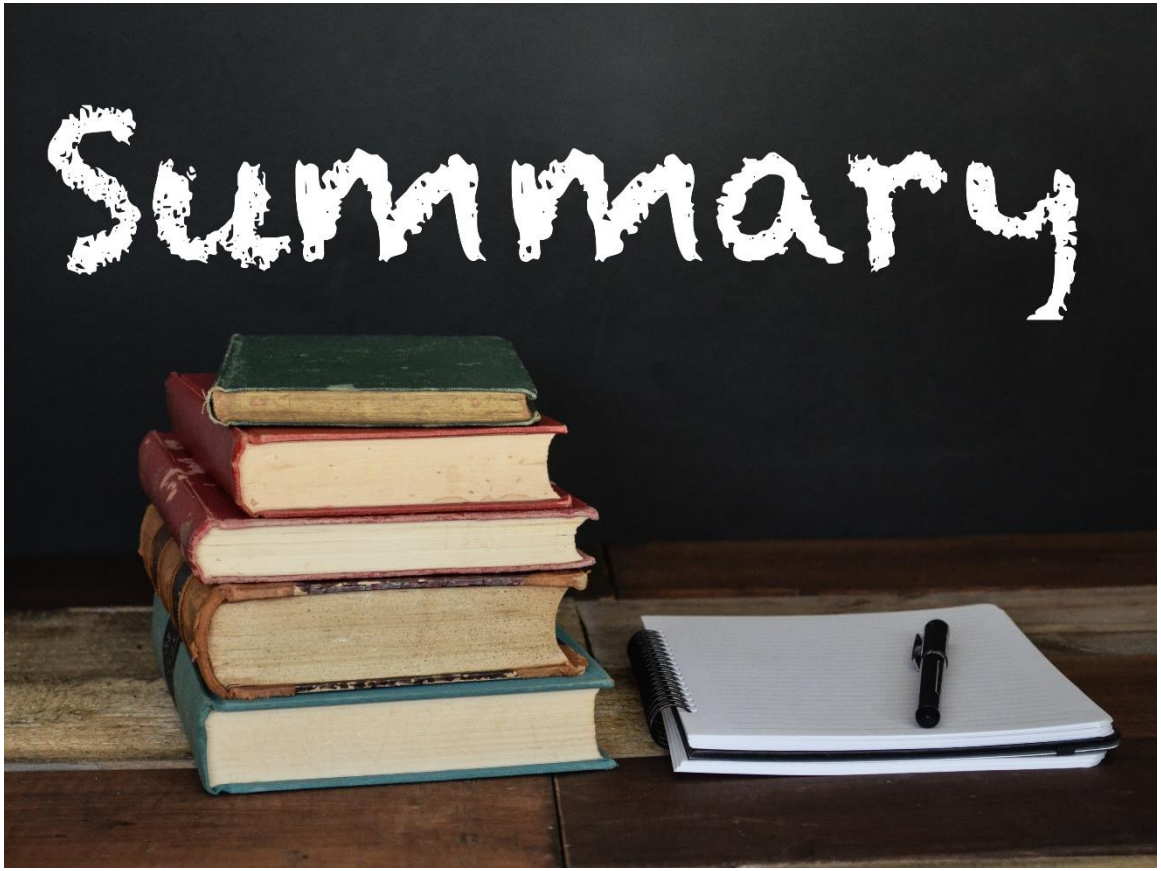
SPACE WEATHER INTRODUCTORY COURSE

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

- Thermosphere-Ionosphere
  - Eelco Doornbos
- SWx effects
- SWx from pilots view
  - Klaus Sievers
- Solar radio bursts – effects on aviation
  - Christophe Marqué

- SWx of the day

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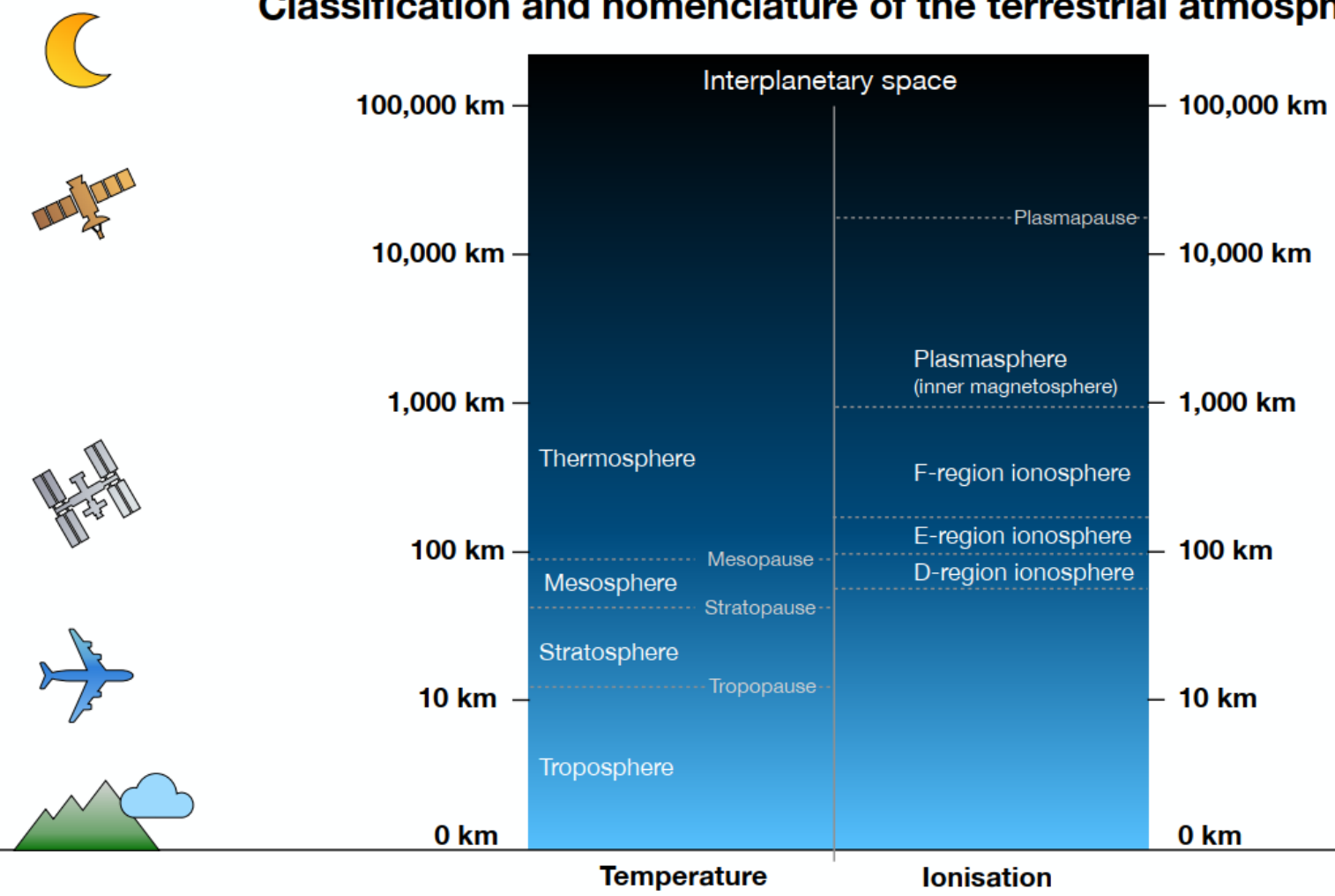
SWx in the thermosphere-ionosphere

Eelco Doornbos (KNMI)

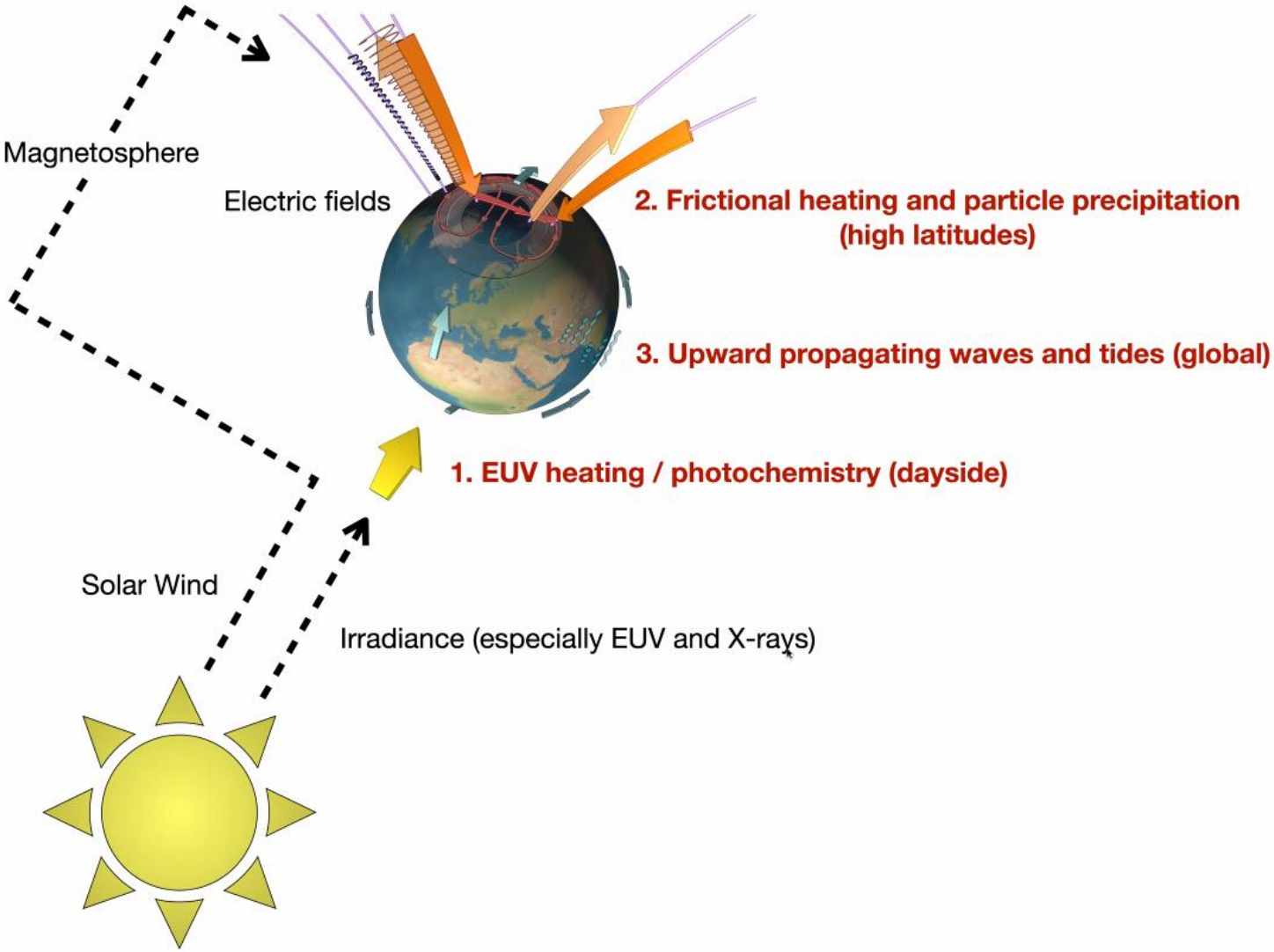
Classification and nomenclature of the terrestrial atmosphere



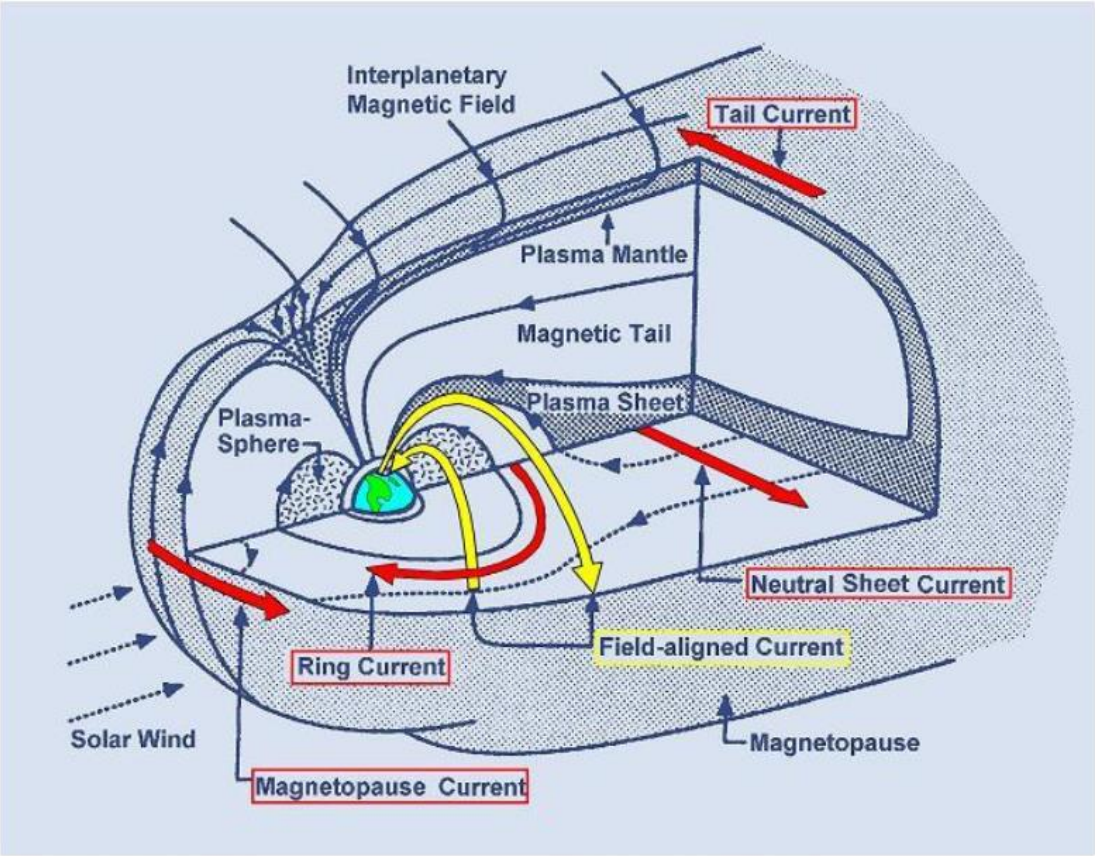
Based on G.W. Prölss, Physics of the Earth's Space Environment, Figure 2.13

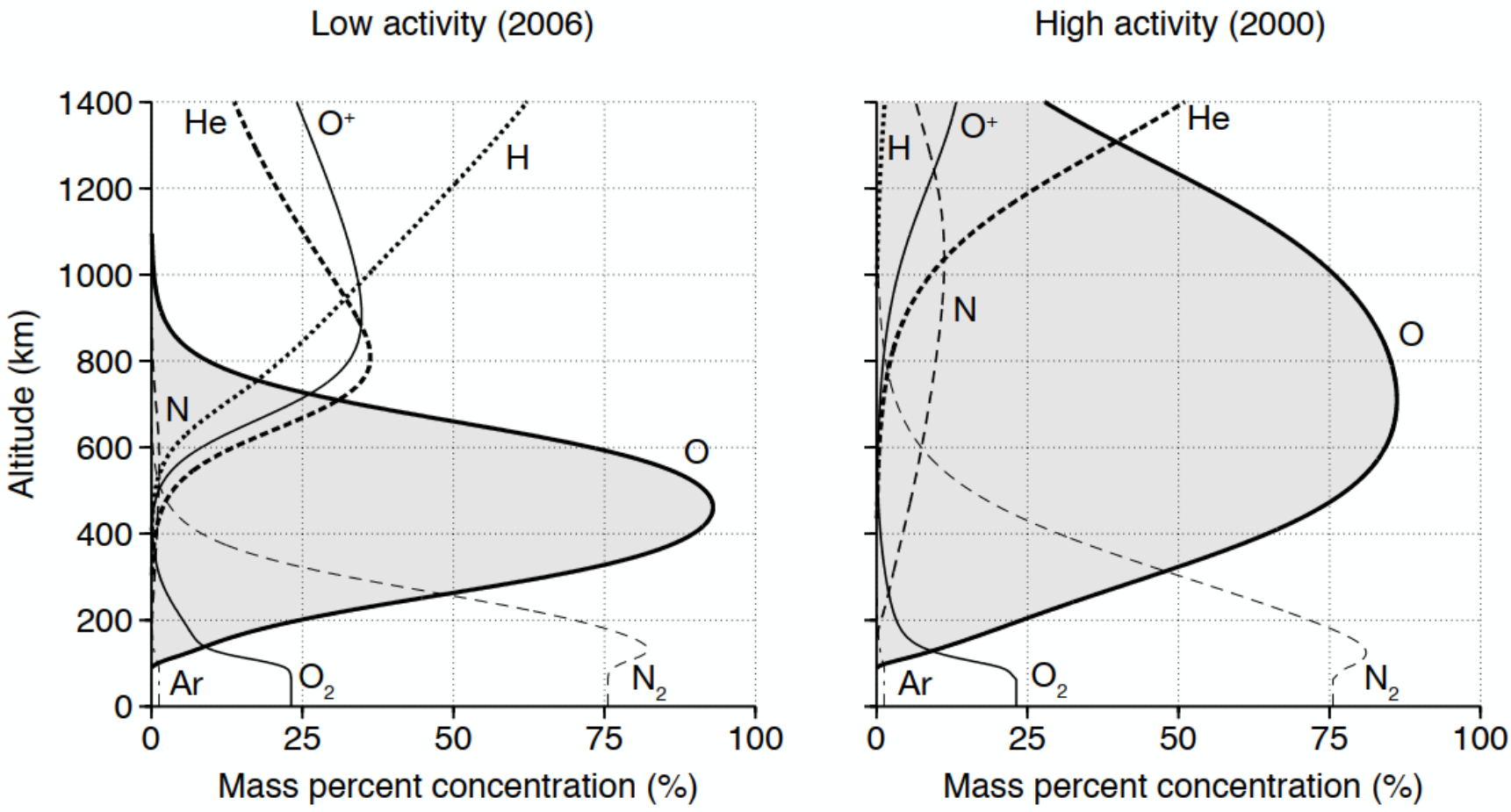
Ionospheric regions

- 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 (%)

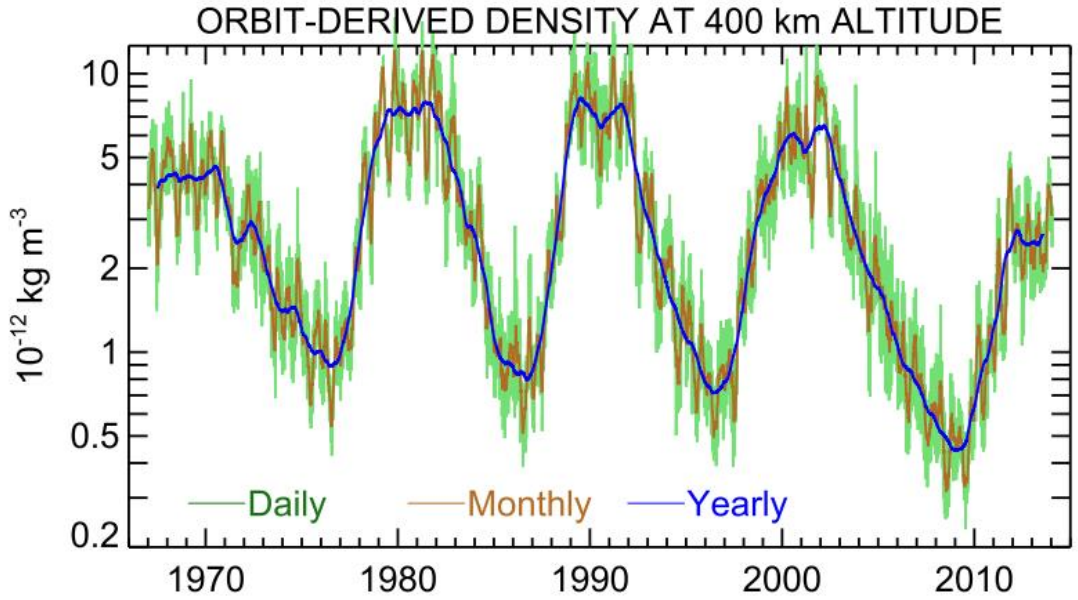
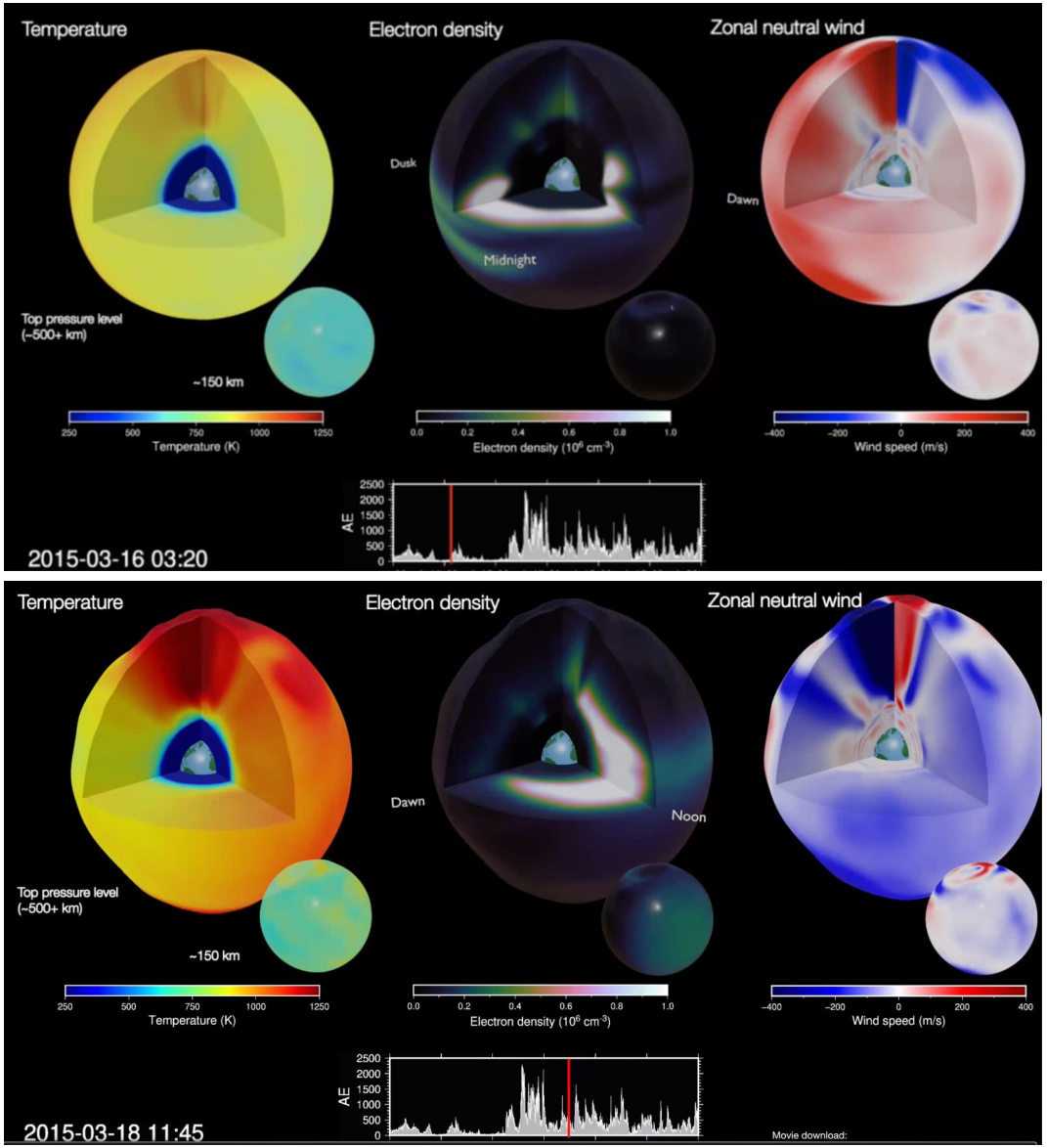
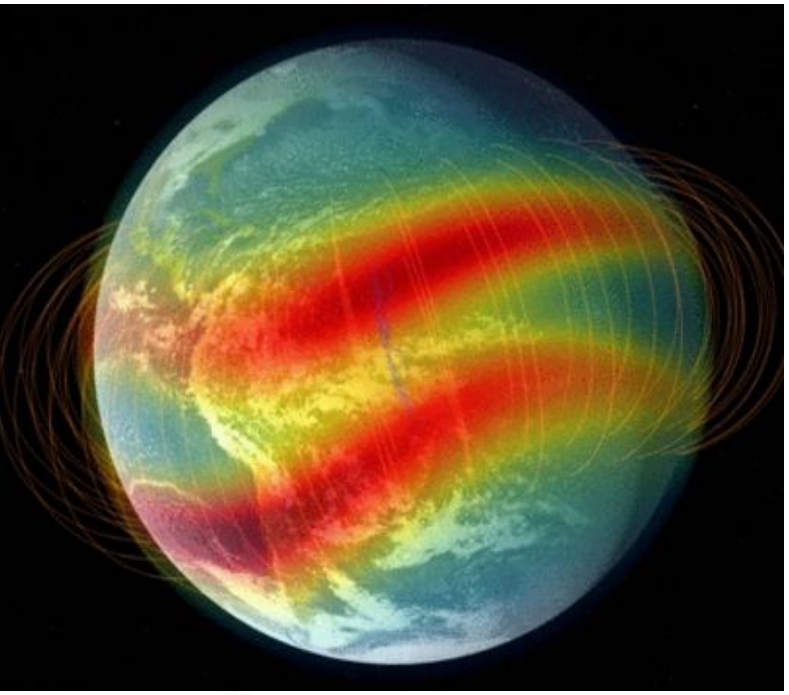
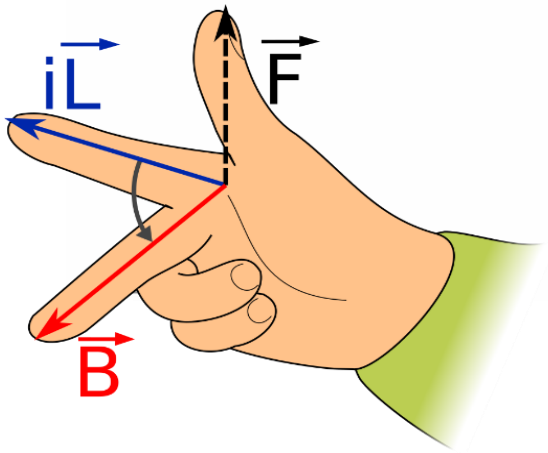


Fig. 1. 1967–2013 global average thermospheric mass density at an altitude of 400 km, derived from orbit data (Emmert, 2009, 2015) and plotted on a log scale. Shown are daily values (green), monthly running averages (orange), and yearly running averages (blue). (For interpretation of the references to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


Temperature
Electron density
Zonal neutral wind
Dusk
Midnight
Dawn
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
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
2015-03-18 11:45
Movie download:





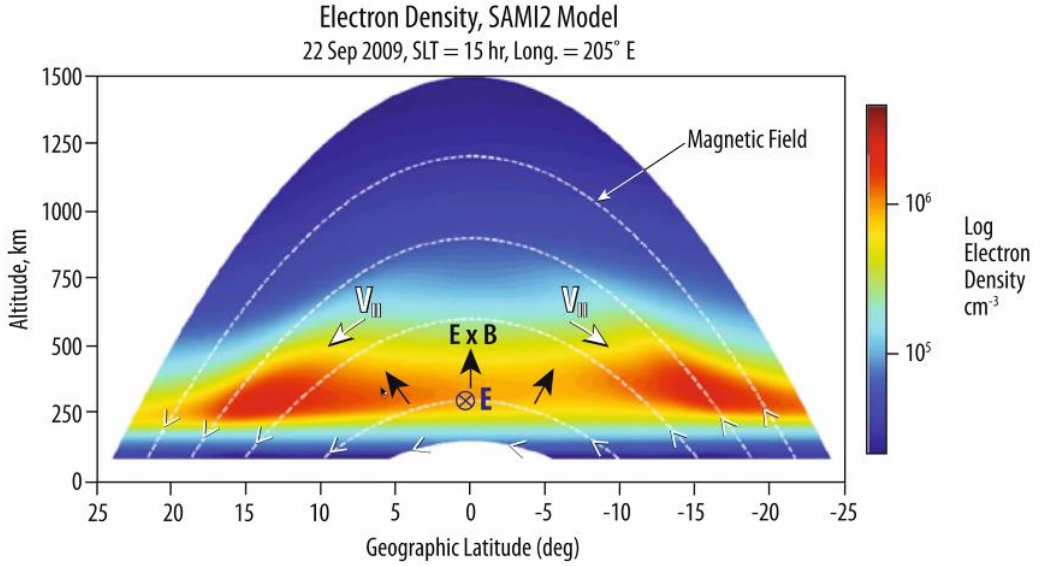
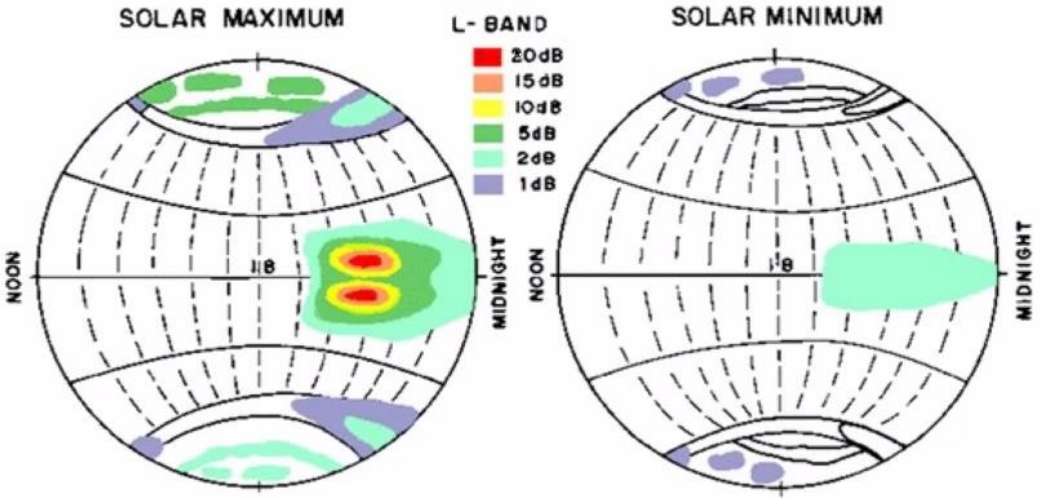
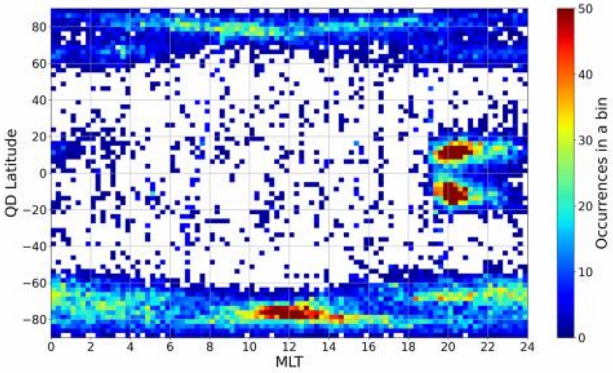


Fig. 19 SAMI2 model calculations versus latitude and altitude of the plasma density for 1500 SLT at 205° East. The upward **E** × **B** drift at the magnetic equator is driven by the eastward electric field, and there is subsequent flow downward along the magnetic field lines

Ionospheric scintillation



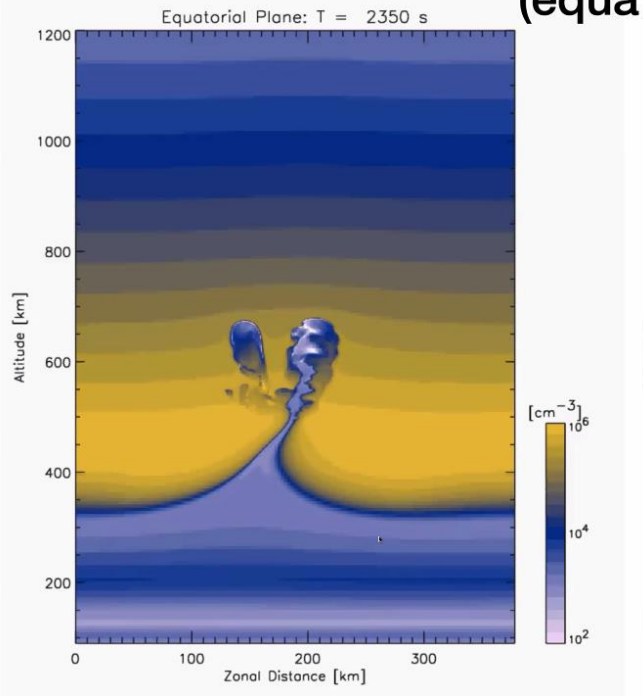
Global variation of amplitude scintillation fades at L band (after Basu et al. 1988a, b, colored by A.W. Wernik)

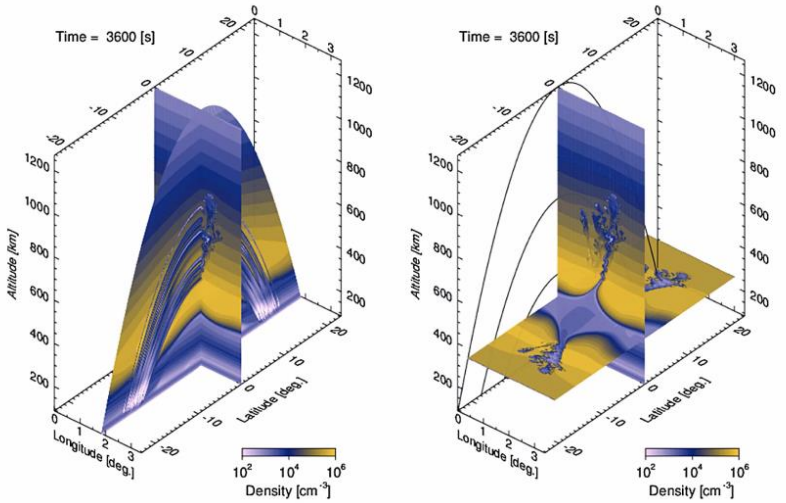


Distribution of GPS Loss of Lock events affecting Swarm A, B and C from Dec 2013-Dec 2020.

Pezzopane et al., 2021

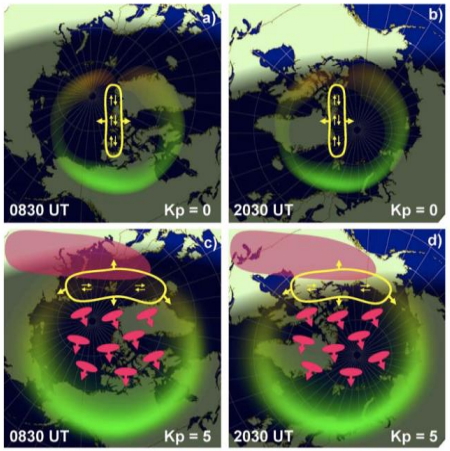
Scintillation mechanism 2: equatorial plasma bubbles (equatorial spread-F)





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

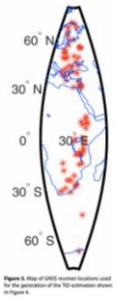
Scintillation mechanism 1: Polar cap patches



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



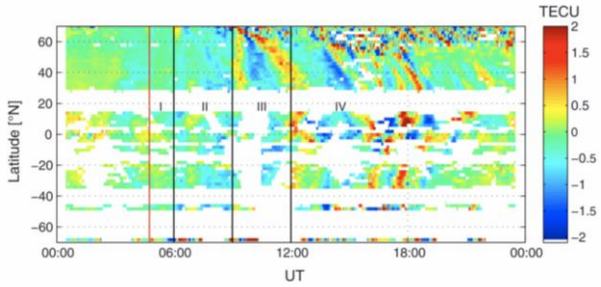


Figure 4. Illustration of TID amplitudes generated from GNSS data along the European-African sector with about 30°E center longitude during the 17 March 2015 storm. The red line indicates storm onset at 04:45 UT, and the solid black lines show the shift between the different phases of storm.

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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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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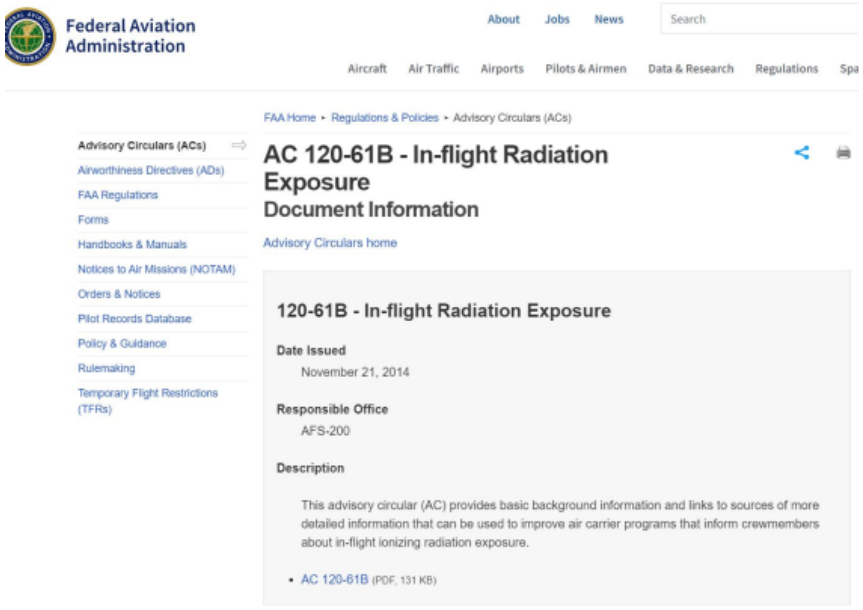
KSAW

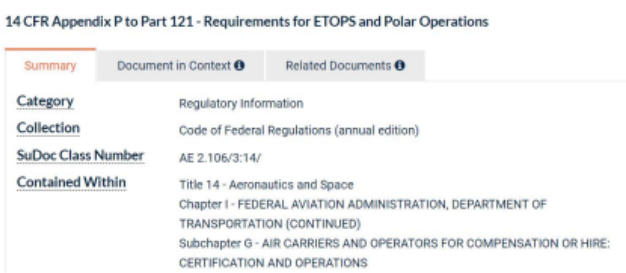
➢ Rules

➢ FAA requires radiation dose information, not accounting, for all

➢ and a radiation exposure mitigation plan for polar flights



https://www.govinfo.gov/app/details/CFR-2016-title14-vol3/CFR-2016-title14-vol3-part121-appP



(....) Section III.
Approvals for operations whose airplane routes are planned to traverse either the North Polar or South Polar Areas. (...)
(6) A training plan for operations in these areas.
(7) A plan for mitigating crew exposure to radiation during solar flare activity.
(8) A plan for providing at least two cold weather anti-exposure suits in the aircraft (...)

KSAW

➢ Rules

➢ Europe: Crew radiation protection requirements according to the general Euratom Basic Safety Standards

➢ airlines have to conduct accounting for radiation dose

Council Directive 2013/59/Euratom (new BSS)

ISSN 1977-0677
doi:10.3000/19770677.L_2014.013.eng

Official Journal **L 13**

of the European Union

English edition — Legislation — **Volume 57**, **17 January 2014**

Contents — *II Non-legislative acts* — page

DIRECTIVES

* **Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom** 1

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02013L0059-20140117&from=EN
https://osha.europa.eu/en/legislation/directives/directive-2013-59-euratom-protection-against-ionising-radiation

Summary

Maximum radiation dose for exposed workers shall be 100 mSv / 5 years, and 50 mSv in any single year. For pregnant women there is a maximum dose of 1 mSv during the remainder of the pregnancy.

If more than 1 mSv / year is expected, dose assessment is required.

Workers have to be informed about the risk their work involves.

PLUS: national legislation, which may set occupational exposure limits at other values for crew, like 6 mSv/year.

KSAW

➢ ICAO SWx advisories

- ➢ SWx advisories are issued on a rotating schedule by the four global SWx Centres SWPC, PECASUS, CRC and ACFJ
- ➢ South Africa is associated with PECASUS for now

A.Naidu, BOM , https://www.icao.int/APAC/Meetings/2021%20METATM%20Seminar%20and%20METR%20WG10/SP11_AI.2_AUS_SpaceWeather.pdf

KSAW

➢ ICAO SWx advisories in flight operations

➢ EU / EASA §§§

COMMISSION IMPLEMENTING REGULATION (EU) 2021/1338

of 11 August 2021

amending Implementing Regulation (EU) 2017/373 as regards reporting requirements and reporting channels between organisations, and requirements for meteorological services

(.....)

On 7 March 2018 and on 9 March 2020, the International Civil Aviation Organization (ICAO) adopted Amendment 78 and Amendment 79, respectively, to Annex 3 to the Convention on International Civil Aviation, signed on 7 December 1944 in Chicago ('the Chicago Convention') aiming, among other things, to enhance and improve harmonisation as regards the exchange of meteorological observations and reports (aerodrome routine meteorological reports (METAR)/aerodrome special meteorological reports (SPECI)), aerodrome forecasts (TAF), information concerning en-route weather phenomena which may affect the safety of aircraft operations (SIGMET), information concerning en-route weather phenomena which may affect the safety of low-level aircraft operations (AIRMET), volcanic ash and tropical cyclone advisory information, space weather advisory information, etc., in a system-wide information management (SWIM)-compliant environment. Those amendments are applicable in the ICAO Contracting States as of 8 November 201
format, the date of application of which is aligned
reporting format ('GRF') for runway surface condit
should be reflected in Implementing Regulatio
requirements for meteorological service providers

(.....

This Regulation shall enter into force on the twentieth day following that of its publication in the *Official Journal of the European Union*.

Point 32 of Annex IV and Annex V shall apply from 12 August 2021.

This Regulation shall be binding in its entirety and directly applicable in all Member States.

Done at Brussels, 11 August 2021.

For the Commission
The President
Ursula VON DER LEYEN

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1338&from=EN

KSAW

- ICAO SWx advisories in flight operations
- ADVISORY: **GNSS SEV.** Go or no-go ? That´s the question !

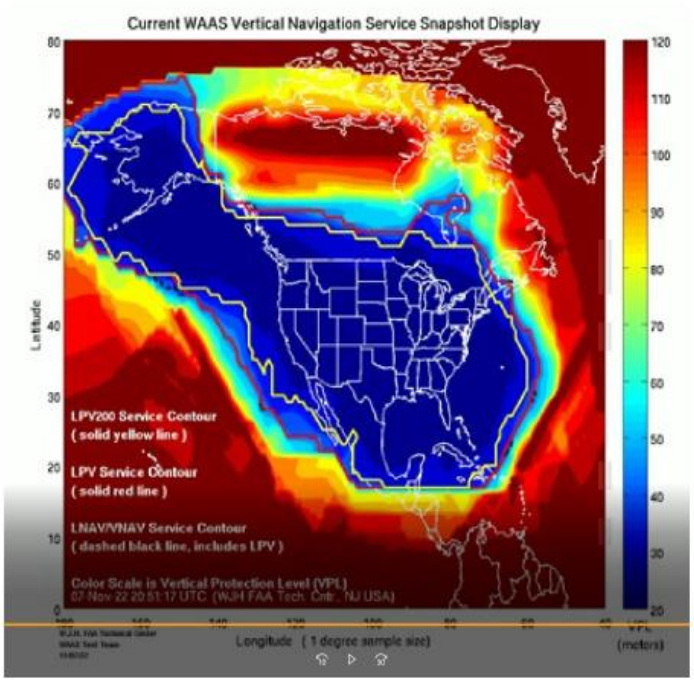
2022-11-07 15:36:00

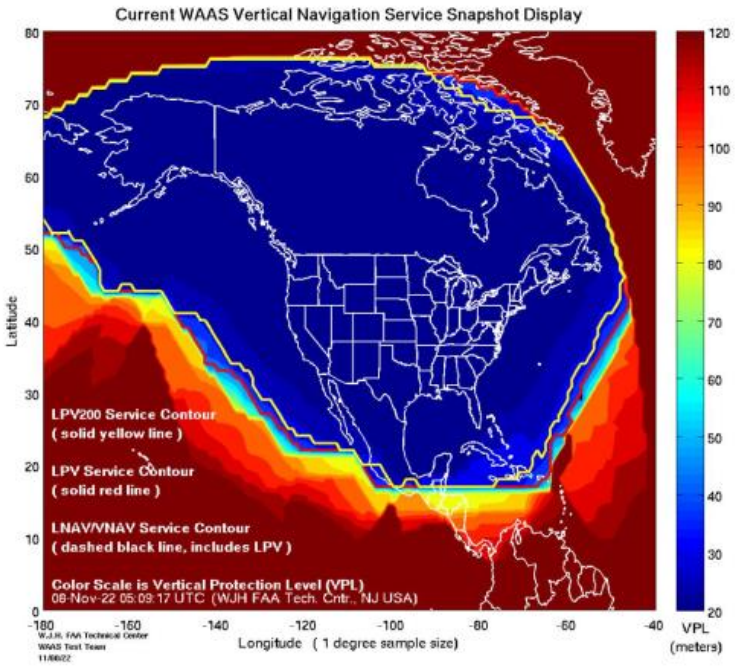
```
FNXX01 EFKL 071535
     SWX ADVISORY
     DTG:              20221107/1536Z
     SWXC:             PECASUS
     ADVISORY NR:      2022/57
     NR RPLC:          2022/56
     SWX EFFECT:       GNSS SEV
     OBS SWX:          07/1517Z HNH HSH W105 - E135
     FCST SWX +6 HR:   07/2200Z NOT AVBL
     FCST SWX +12 HR:  08/0400Z NOT AVBL
     FCST SWX +18 HR:  08/1000Z NOT AVBL
     FCST SWX +24 HR:  08/1600Z NOT AVBL
     RMK:              SPACE WEATHER EVENT (IONOSPHERIC
     DISTURBANCE) IN PROGRESS. IMPACT ON GNSS PERFORMANCE
     POSSIBLY LEADING TO LOSS OF GNSS SIGNALS AND/OR DEGRADATION
     OF TIMING AND POSITIONING PERFORMANCE.
     NXT ADVISORY:     WILL BE ISSUED BY 20221107/2117Z=
```

07 Nov 2022

KSAW

- ICAO SWx advisories in flight operations
- ADVISORY: **GNSS SEV.** Go or no-go ? That´s the question !





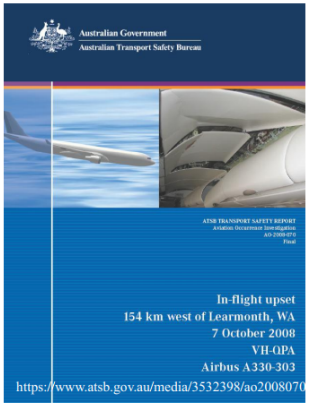
07 Nov 22 20:51 z >>>>>>>>>>>>>>>>>>> 08 Nov 22 05:09z

https://www.nstb.tc.faa.gov/

KSAW

➢ Space Weather impacting Aviation - Examples : Radiation

➢ Airplane electronics gave wrong command: **sudden descent**



Summary of the occurrence

(.....)
At 0442:27, the aircraft suddenly pitched nose down. (...) Although the pitch-down command lasted less than 2 seconds, the resulting forces were sufficient for almost all the unrestrained occupants to be thrown to the aircraft's ceiling. **At least 110 of the 303 passengers and nine of the 12 crew members were injured;** 12 of the occupants were seriously injured and another 39 received hospital medical treatment. (...)

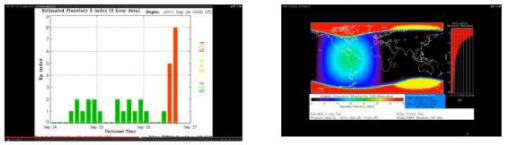
2010

KSAW

➢ Space Weather impacting Aviation - Examples: Navigation

➢ GPS augmentation system unreliable due to solar flare.

Sept. 26 / 27, 2011: WAAS CAT 1 approaches u/s



SWPC: Issue Time: 2011 Sep 26 1708 UTC
WARNING: Geomagnetic K-index of 7 or greater expected
Valid From: 2011 Sep 26 1715 UTC Valid To: 2011 Sep 26 2100 UTC
Warning Condition: Onset NOAA Scale: G3 or greater - Strong to Extreme

Air Traffic Control System Command Center (´´Network Manager´´) :

ATCSCC ADVZY 059 DCC 09/XX/2011 WAAS FYI
DUE TO SOLAR FLARE ACTIVITY; WAAS SIGNALS ARE DEEMED UNRELIABLE:
AS A RESULT; RNP CAT 1 ARRIVAL PROCEDURES WITHIN THE U.S. ARE ALSO
DEEMED UNRELIABLE. 261930 – 271059 11/09/XX 20:30 DCCOPS

Source of graphics: https://www.swpc.noaa.gov/

Summary

The Wide Area Augmentation System, a GPS enhancement, was **deemed unreliable** due to impacts of a solar flare.

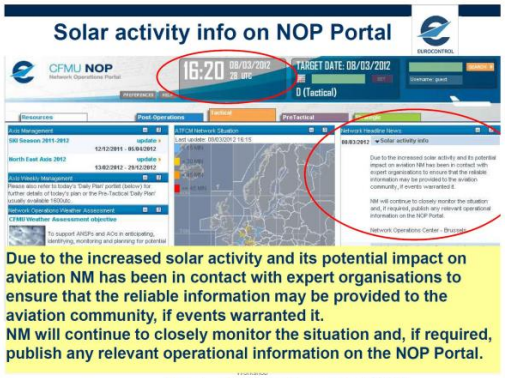
Note: the compatible European system is called EGNOS. WAAS, EGNOS and similar systems allow reliable approaches to relatively low altitudes at nearly all airports.

2011

KSAW

➢ Space Weather impacting Aviation - Examples : Eurocontrol

➢ Flight routes are changed due SWx, impacting **air traffic management.**



Courtesy Z. Sivcev, Eurocontrol (2013)

Summary

UNITED and DELTA Airlines did not fly on Polar Routes due to radiation as well as short wave radio communi-cations concerns.

The US Space-Weather Prediction Center had noted a G3 geomagnetic storm combined with a S3 radiation storm.

Link to NOAA scales
https://www.swpc.noaa.gov/noaa-scales-explanation

2012

KSAW

➢ Space Weather impacting Aviation - Examples : *Everything*

➢ During an active period in 2017, multiple impacts occurred at the same time. They affected aviation, too !

USAF survey for Sept. 2018 found:

> 06 Sept. ....: Radar interference issues reported

> 10 Sept. ....: HF Comm issues in the Caribbean and SE Asia

> 10 Sept. ....: SATCOM issues noted over Florida

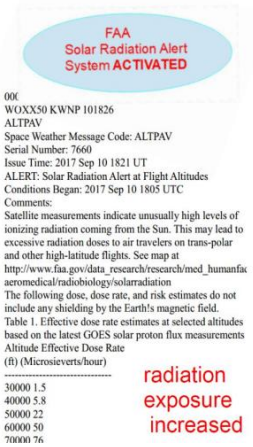
> 11-14 Sept.: High latitude communication issues / protons

> 04-11 Sept.: Sat anomalies in 4 NATO satellites,
1 USN Satcom, 2 HEO Sat

> 12-18 Sept.: 4 LEO, 1 HEO, 1 MEO and 3 GEO anomalies:
Total: 16 satellite anomalies

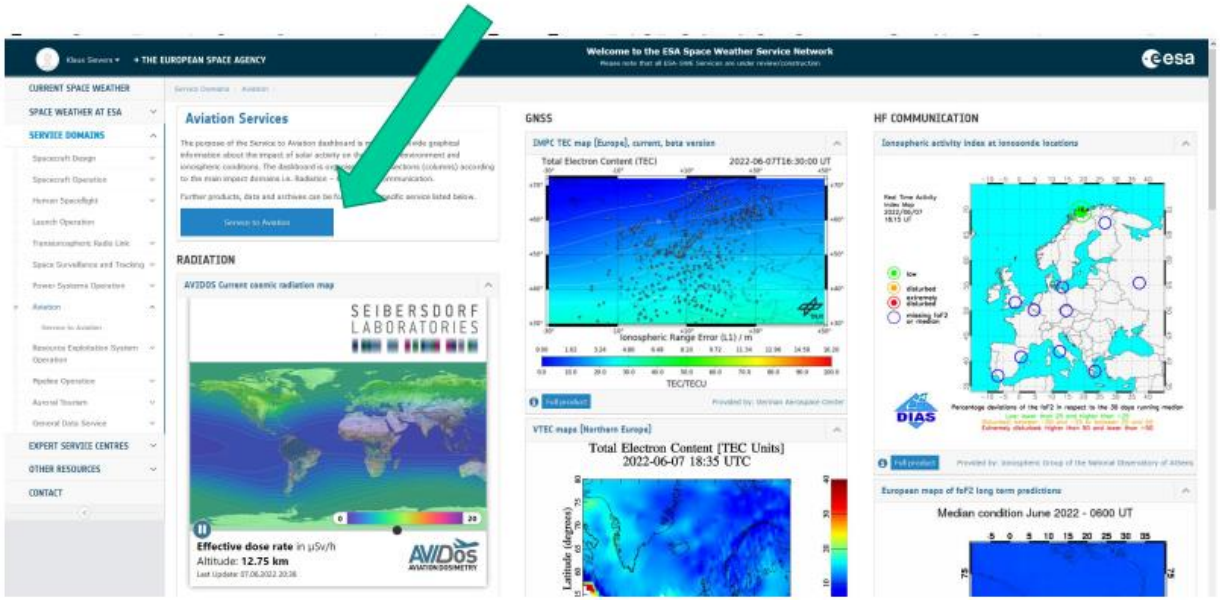
USAF CPT B.Ross, NOAA Annual Meeting 2018
https://www.swpc.noaa.gov/sites/default/files/images/u4/05%20Ca

2017



KSAW

- SWx information from ESA
- Comprehensive information - science oriented
- Registration required. Log-in available the next day
- Consult the Service to Aviation section for more information



https://swe.ssa.esa.int/nso_air_dashboard

KSAW

➢ ICAO SWx advisories in flight operations

➢ Detailed guidance on handling of SWx advisories in real life is in the process of beeing published or mandated by FAA , EASA and other Authorities

After a long process, a winding road to success, provisions for Space Weather Advisories were introduced, effective from November 2018. One year later, in November 2019, three Global Space Weather Centers have become operational and provide Space Weather (SWx) Advisories. On the 28th of September 2020 ICAO released their first-ever Space-Weather Advisory (see Links and Resources # 6).

The Space-WX Advisories using the existing channels, similar to SIGMET. The advisories are thereby transmitted directly to aircraft operators and flight crew throughout the flight as standard meteorological information (see here).

The advisories provide the most up to date information possible on any solar events and cover these three categories:
a) Shortwave Communications
b) GNSS
c) Increased solar radiation.

RELATED CONTENT

https://www.eurocockpit.be/news/icao-space-wx-advisories-instructions-be-included-ops-manual

SWIC Summary Day 3 - Contents

- Thermosphere-Ionosphere
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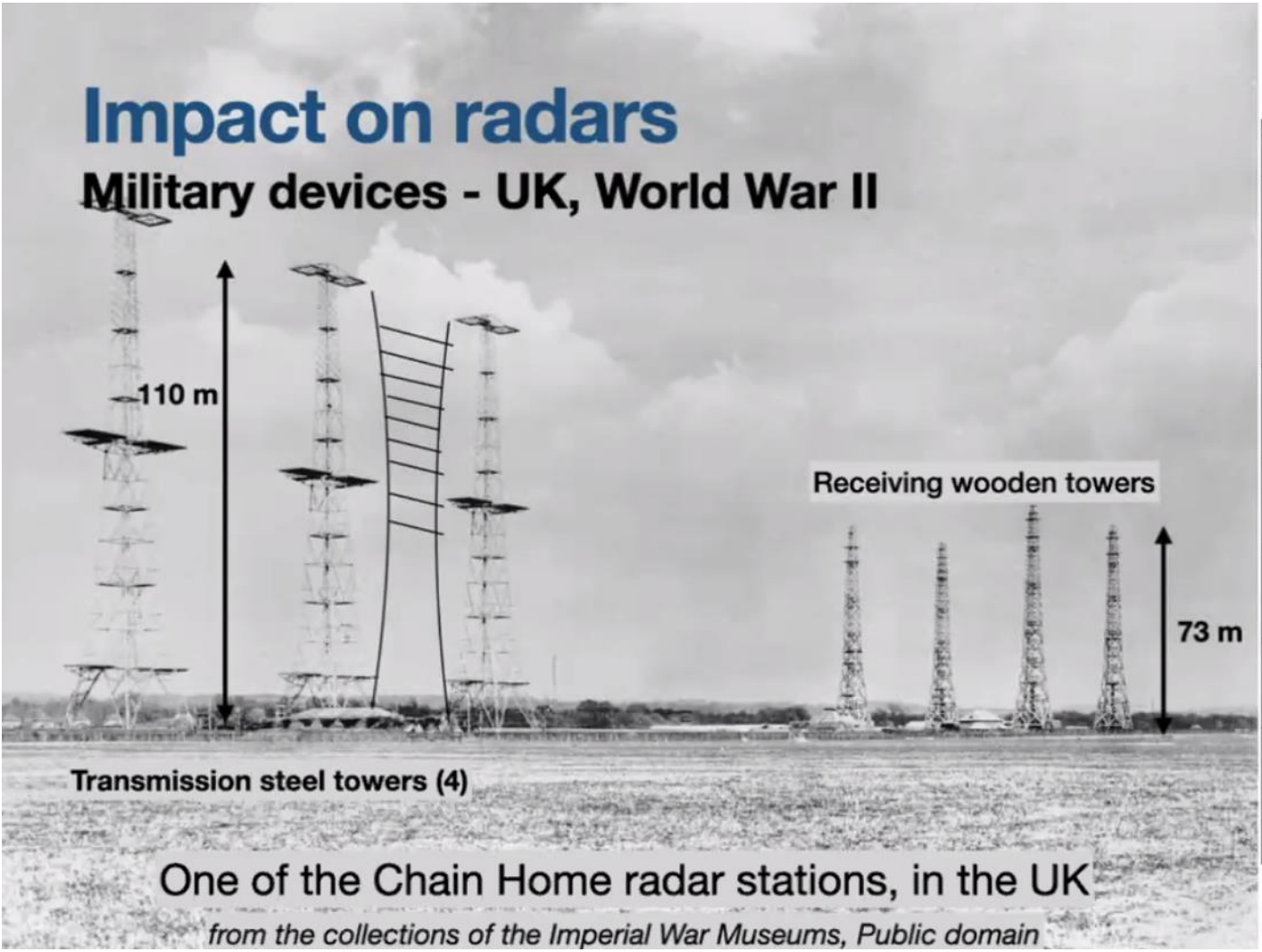
  - Klaus Sievers
- Solar radio bursts – effects on aviation
  - Christophe Marqué

- SWx of the day

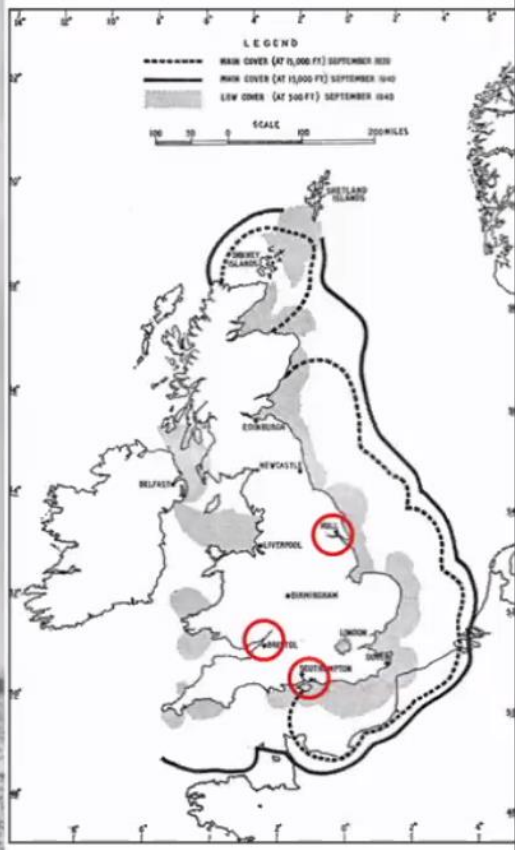
Impact on radars

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



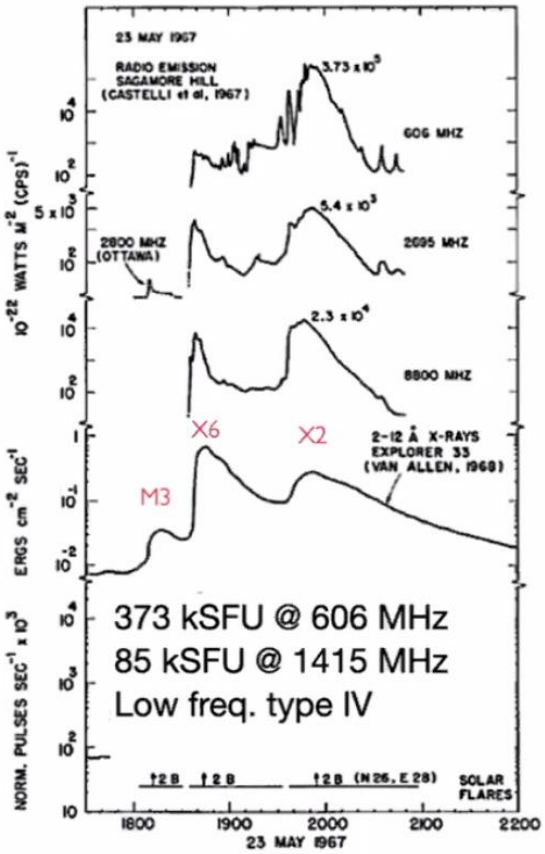
WIKIPEDIA

Impact on radars

Military devices - Cold war

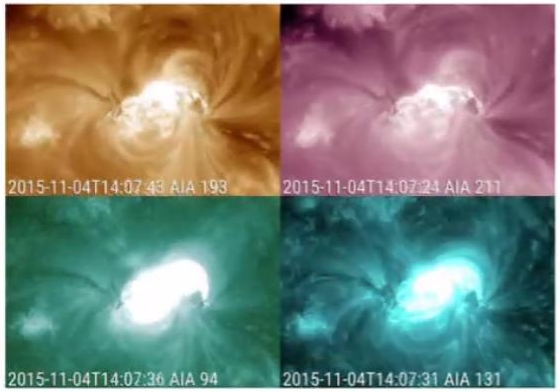
Jamming of Ballistic Missile Early Warning System (BMEWS) radars at 440 MHz

"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."

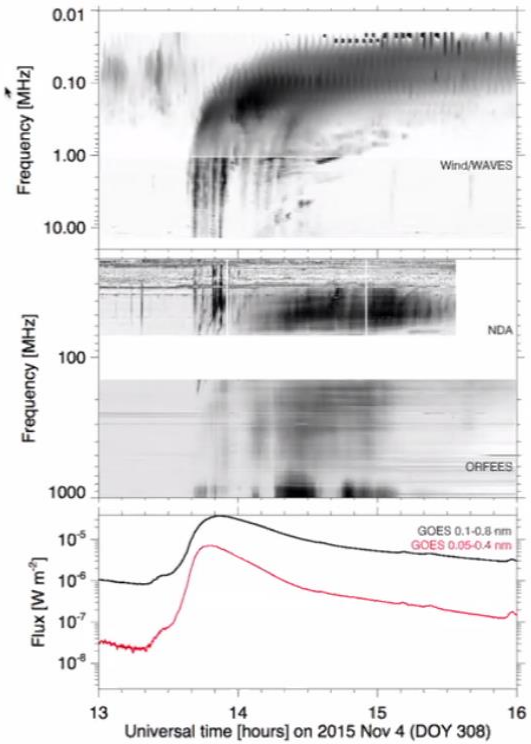


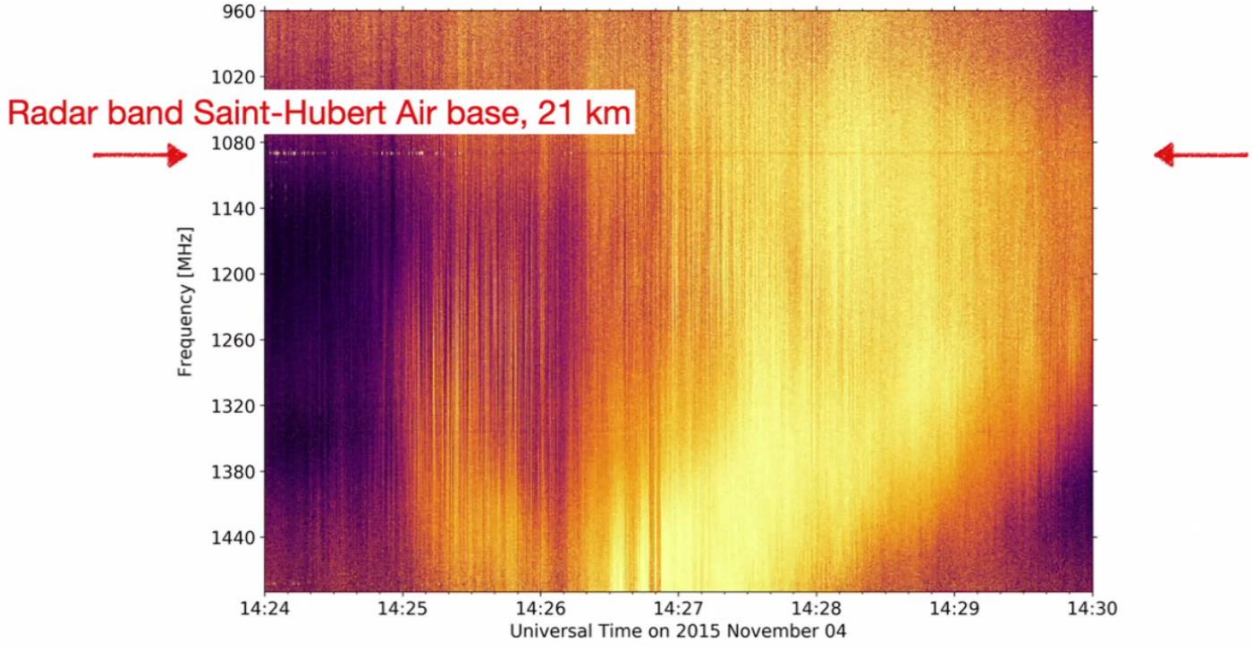
Knipp et al. 2016

Solar event



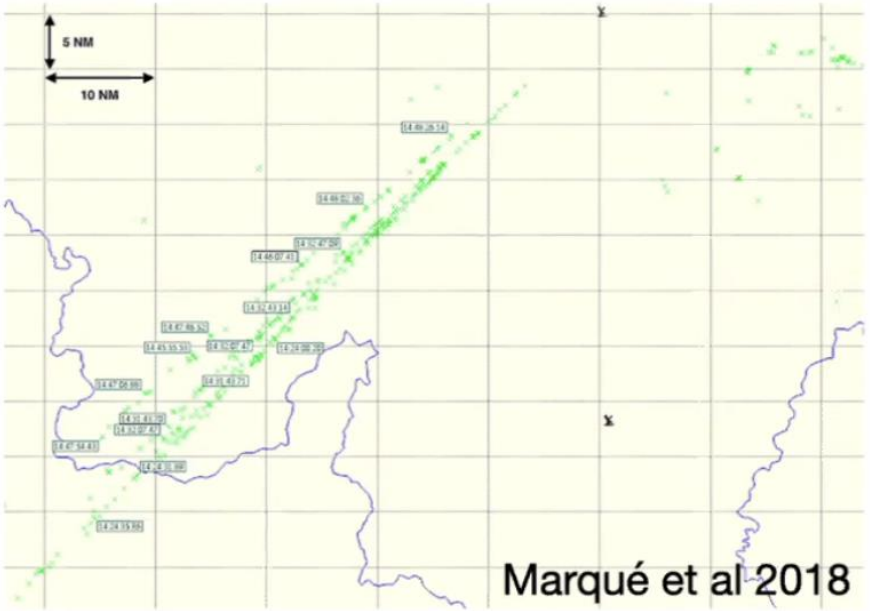
M3.7 flare peaking @1352 UT
NOAA AR 2243





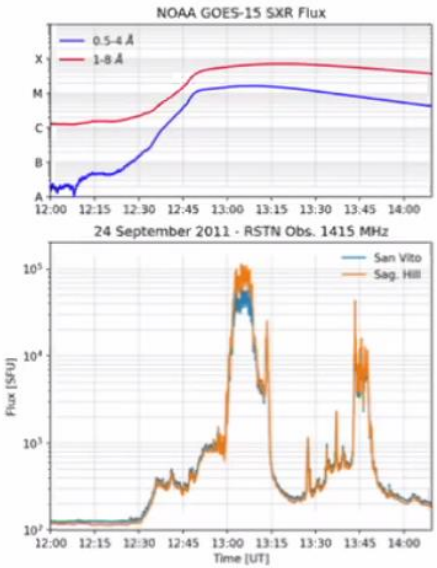
A European wide disruption

- 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



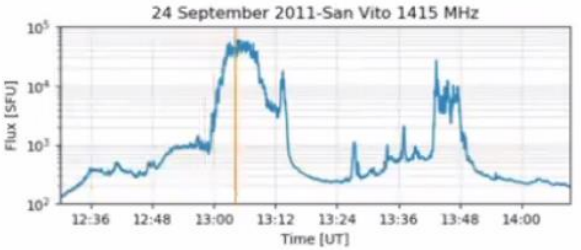
Other services

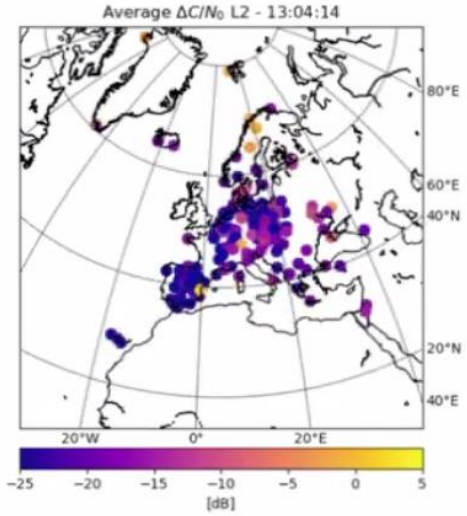
GNSS



- M7.1 flare, max @ 13:20 UT
- AR 11302, Ekc, $\beta\gamma$
- ★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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SWx of the day

- 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