SWx on military operations

Understanding, prevention, mitigation

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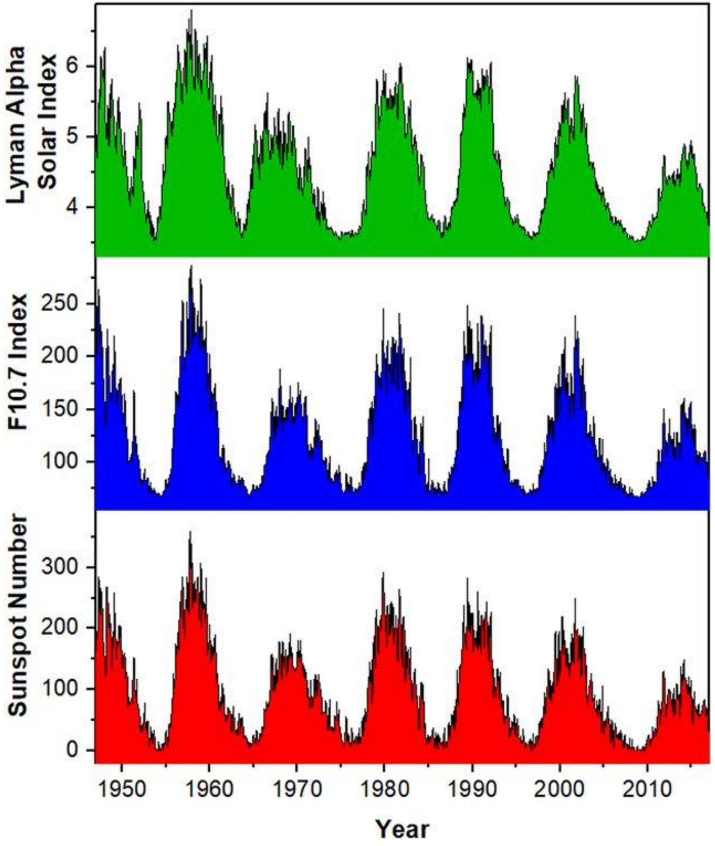
Content

1. Some definitions

Space weather indices

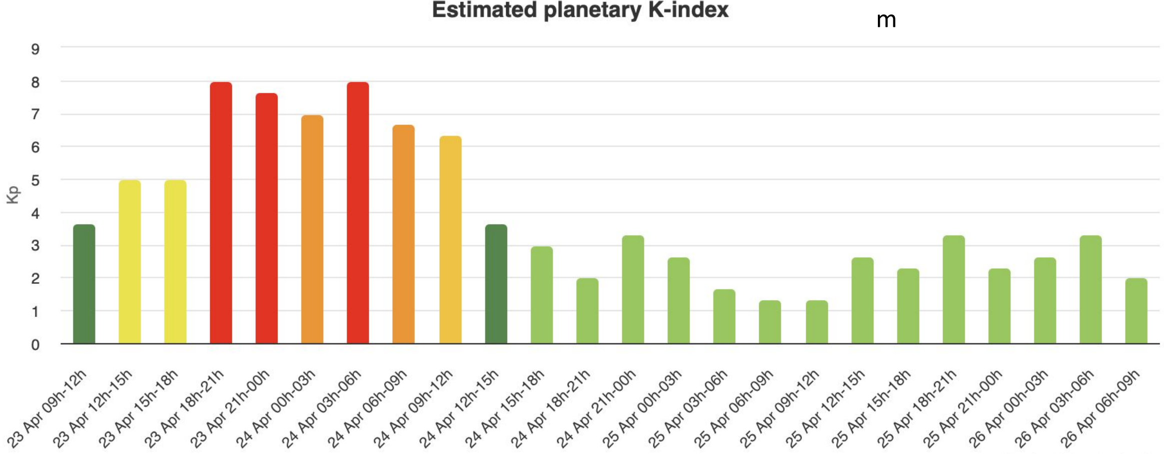
- **F10.7 index** (solar radio flux at 10.7cm) ⟶ excellent indicator of solar activity

Singh et al. 2019



Space weather indices

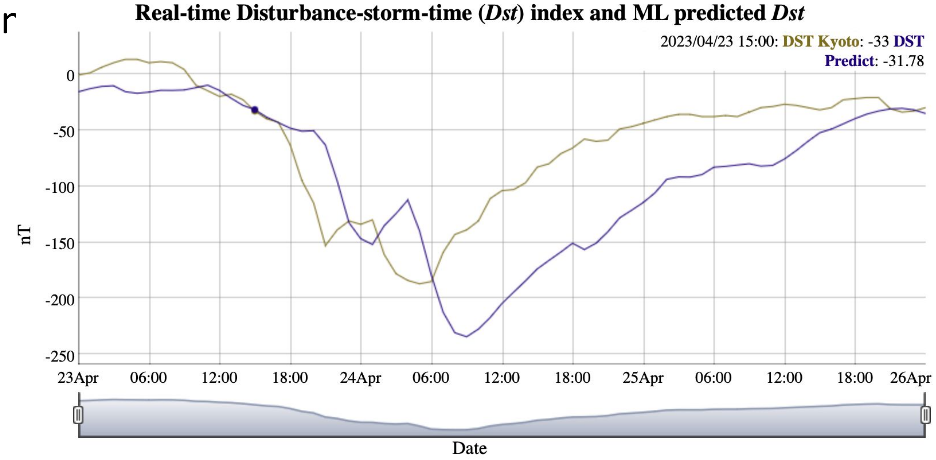
- F10.7 index (solar radio flux at 10.7cm)
- **Planetary K-index** (Kp) → disturbances in the horizontal component of Earth’s B-field, 0-9, from 3 hour intervals and 13 mid-latitude stations



spaceweatheronline.com

Space weather indices

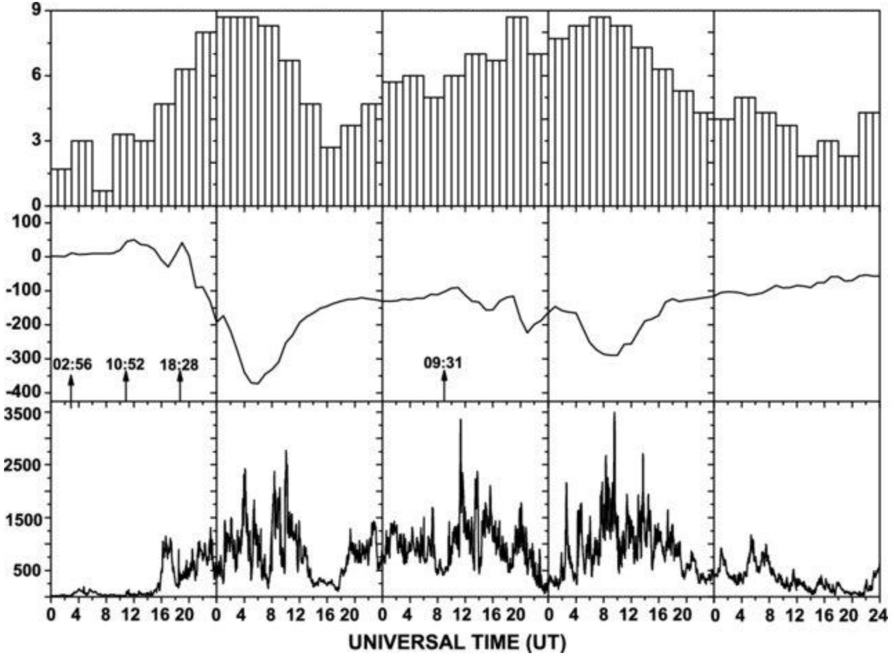
- F10.7 index (solar radio flux at 10.7cm)
- **Planetary K-index** (Kp) → disturbances in the horizontal component of Earth’s B-field, 0-9, from 3 hour intervals and 13 mid-latitude stations
- **Disturbance storm-time index (Dst)** → field variations in the horizontal component of the Earth’s magnetic field measuring the strer near-equatorial stations



Space weather indices

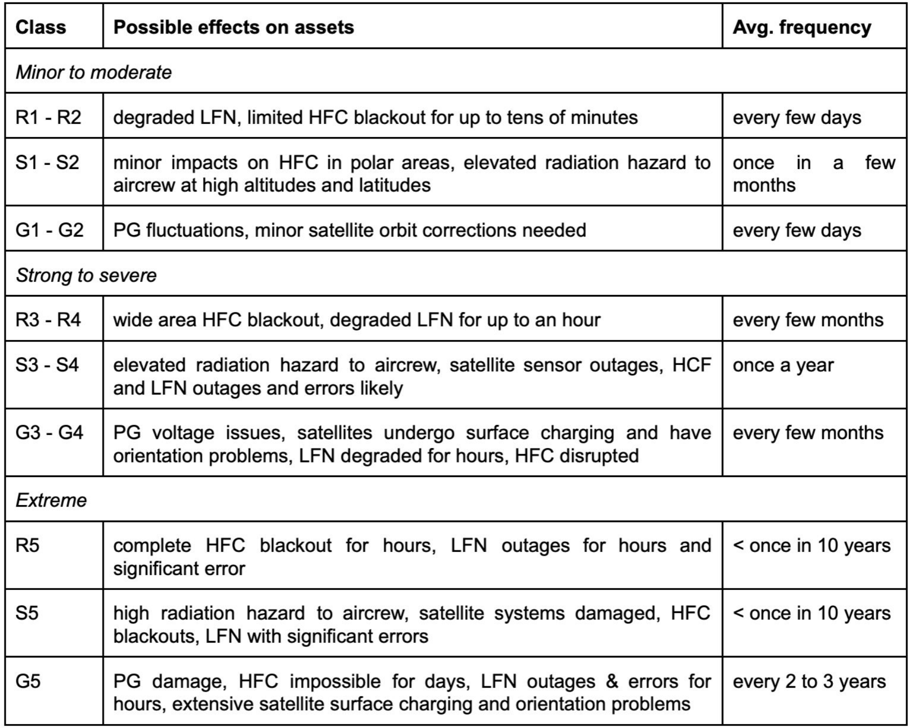
- F10.7 index (solar radio flux at 10.7cm)
- Planetary K-index (Kp)
- Disturbance storm-time index (Dst)
- **Auroral Electrojet index (AE)** ⟶ total deviation from the quiet day horizontal B field around the auroral oval, giving a measure of auroral zone activity, instantaneous basis, measures in high northern latitude stations

Sahai et al. 2009



Classification of space weather events

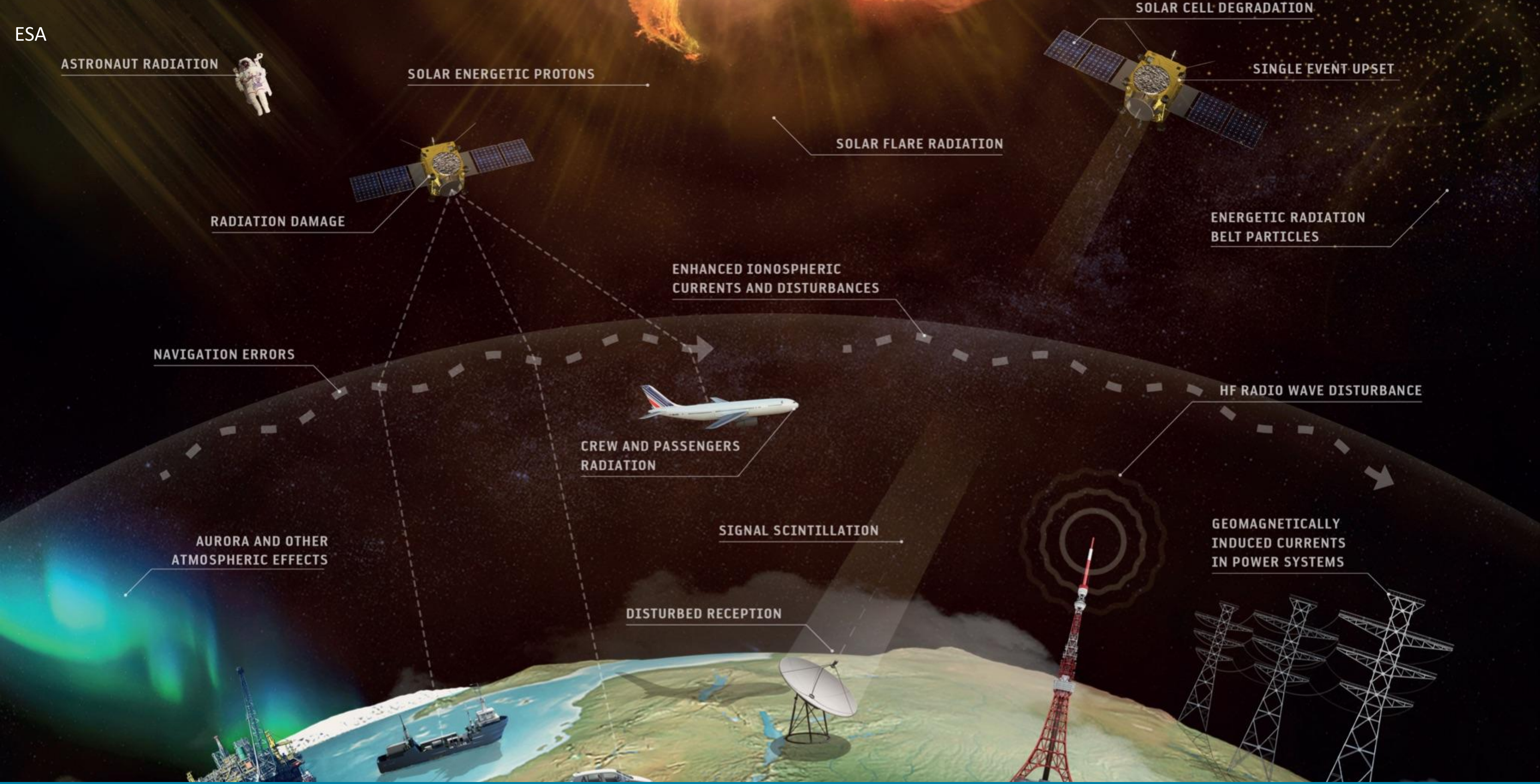
- **geomagnetic storms** (solar wind disturbance)
  - with intensity levels G1 to G5 (Kp 5 to Kp 9)
- **radiation storms** (charged particle fluxes)
  - with intensity levels S1 to S5 (flux of >10 MeV particles 10 - 10e5*)
- **radio blackouts** (solar flares)
  - with intensity levels R1 to R5 (M1, M5, X1, X10, X20)



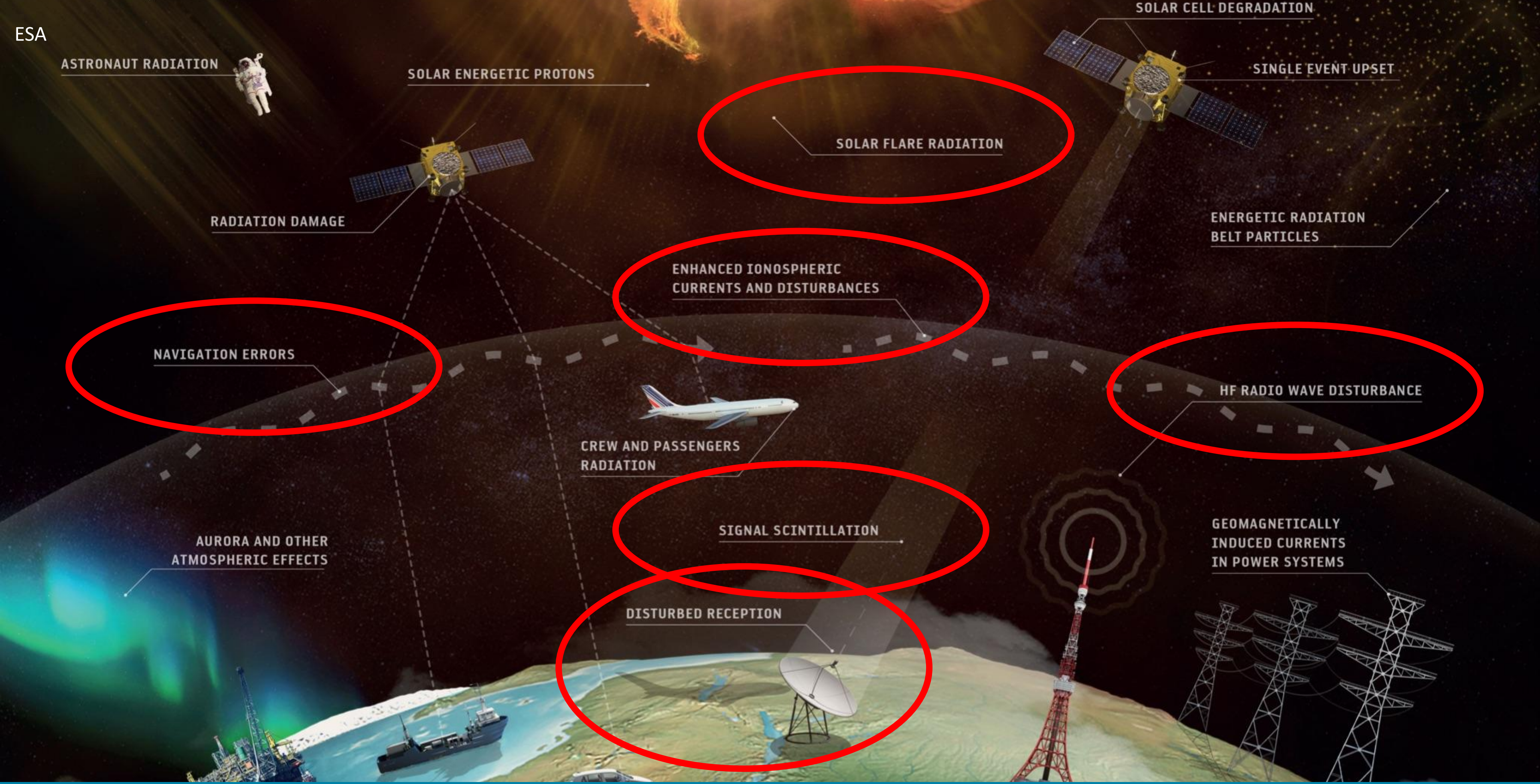
Class	Possible effects on assets	Avg. frequency
Minor to moderate		
R1 - R2	degraded LFN, limited HFC blackout for up to tens of minutes	every few days
S1 - S2	minor impacts on HFC in polar areas, elevated radiation hazard to aircrew at high altitudes and latitudes	once in a few months
G1 - G2	PG fluctuations, minor satellite orbit corrections needed	every few days
Strong to severe		
R3 - R4	wide area HFC blackout, degraded LFN for up to an hour	every few months
S3 - S4	elevated radiation hazard to aircrew, satellite sensor outages, HCF and LFN outages and errors likely	once a year
G3 - G4	PG voltage issues, satellites undergo surface charging and have orientation problems, LFN degraded for hours, HFC disrupted	every few months
Extreme		
R5	complete HFC blackout for hours, LFN outages for hours and significant error	< once in 10 years
S5	high radiation hazard to aircrew, satellite systems damaged, HFC blackouts, LFN with significant errors	< once in 10 years
G5	PG damage, HFC impossible for days, LFN outages & errors for hours, extensive satellite surface charging and orientation problems	every 2 to 3 years

* particle/cm2/s/ster

ESA


SOLAR CELL DEGRADATION
ASTRONAUT RADIATION
SOLAR ENERGETIC PROTONS
SINGLE EVENT UPSET
SOLAR FLARE RADIATION
RADIATION DAMAGE
ENERGETIC RADIATION BELT PARTICLES
ENHANCED IONOSPHERIC CURRENTS AND DISTURBANCES
NAVIGATION ERRORS
HF RADIO WAVE DISTURBANCE
CREW AND PASSENGERS RADIATION
GEOMAGNETICALLY INDUCED CURRENTS IN POWER SYSTEMS
SIGNAL SCINTILLATION
AURORA AND OTHER ATMOSPHERIC EFFECTS
DISTURBED RECEPTION

2. (Radio) communications effects



ESA

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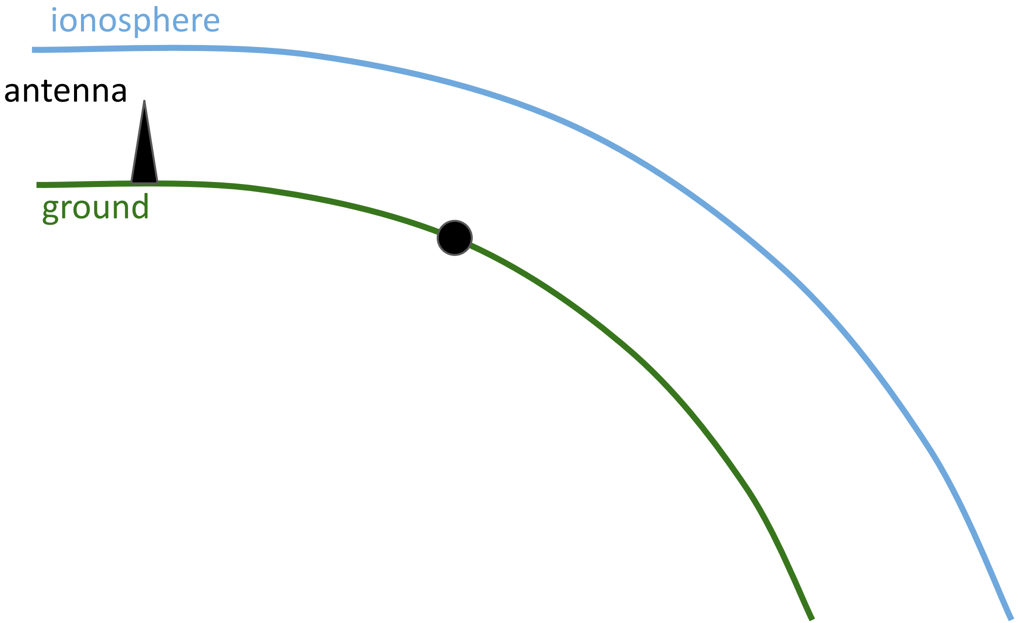
How do we communicate? Why is the ionosphere important?



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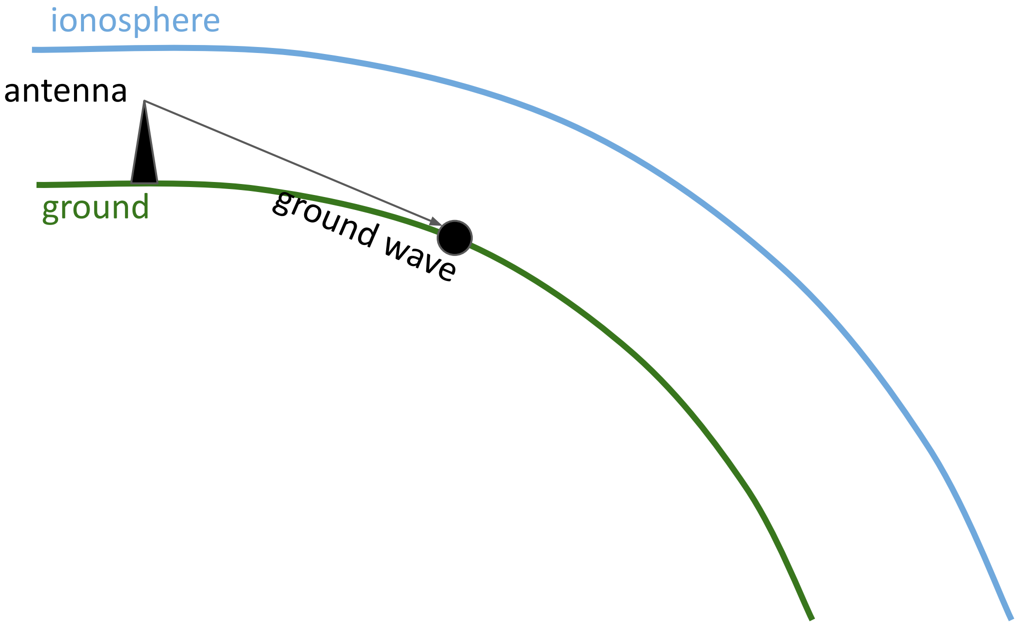

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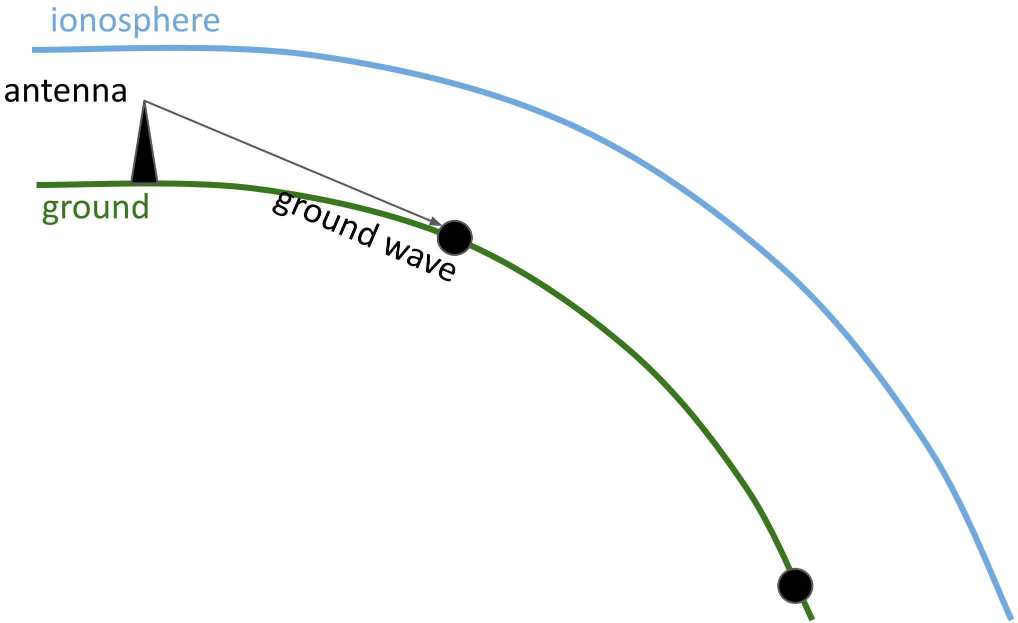

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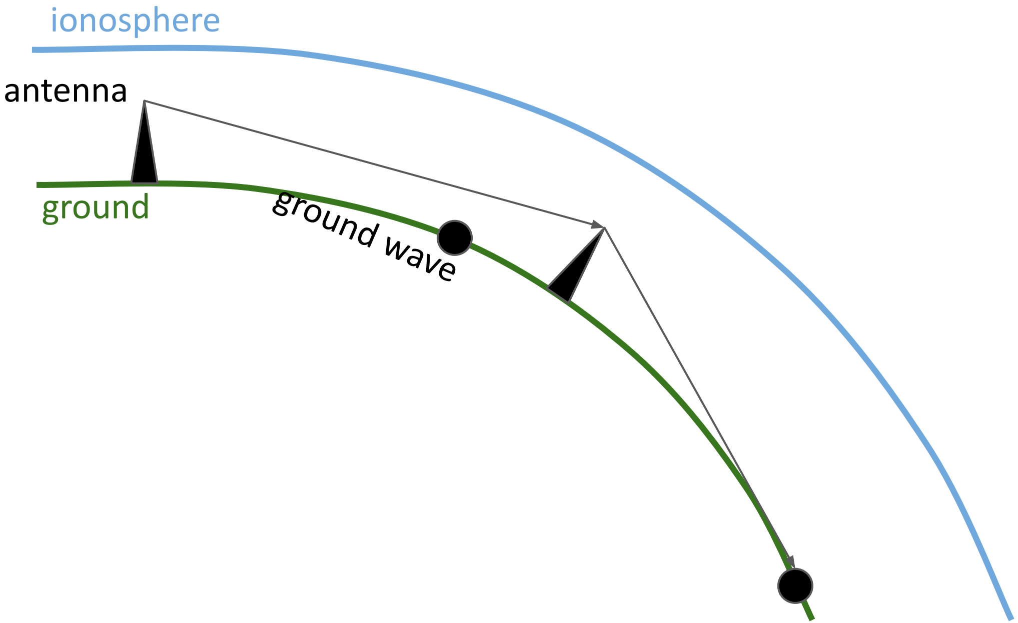

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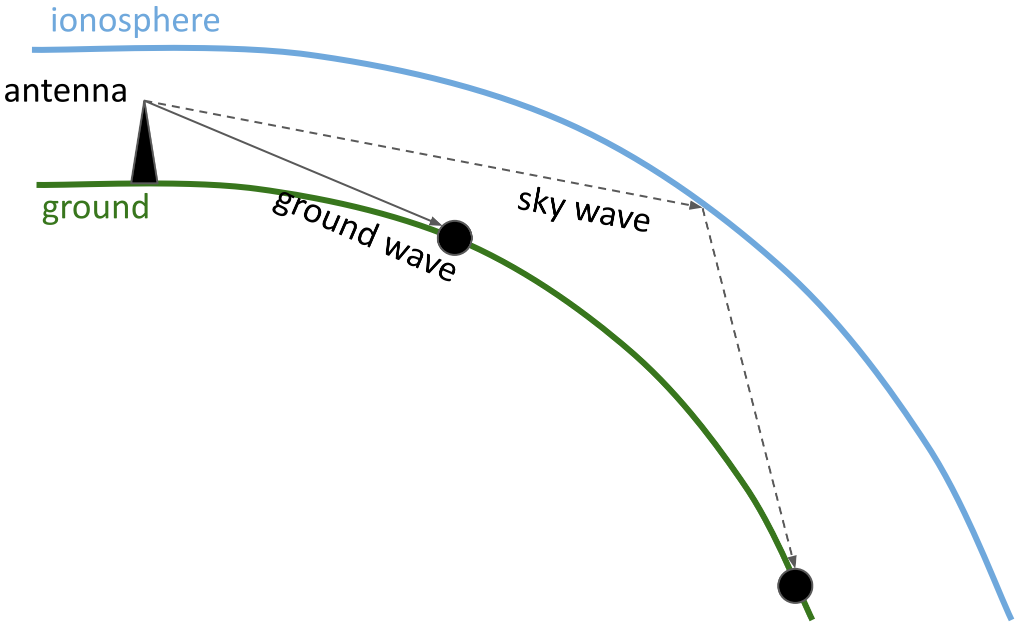

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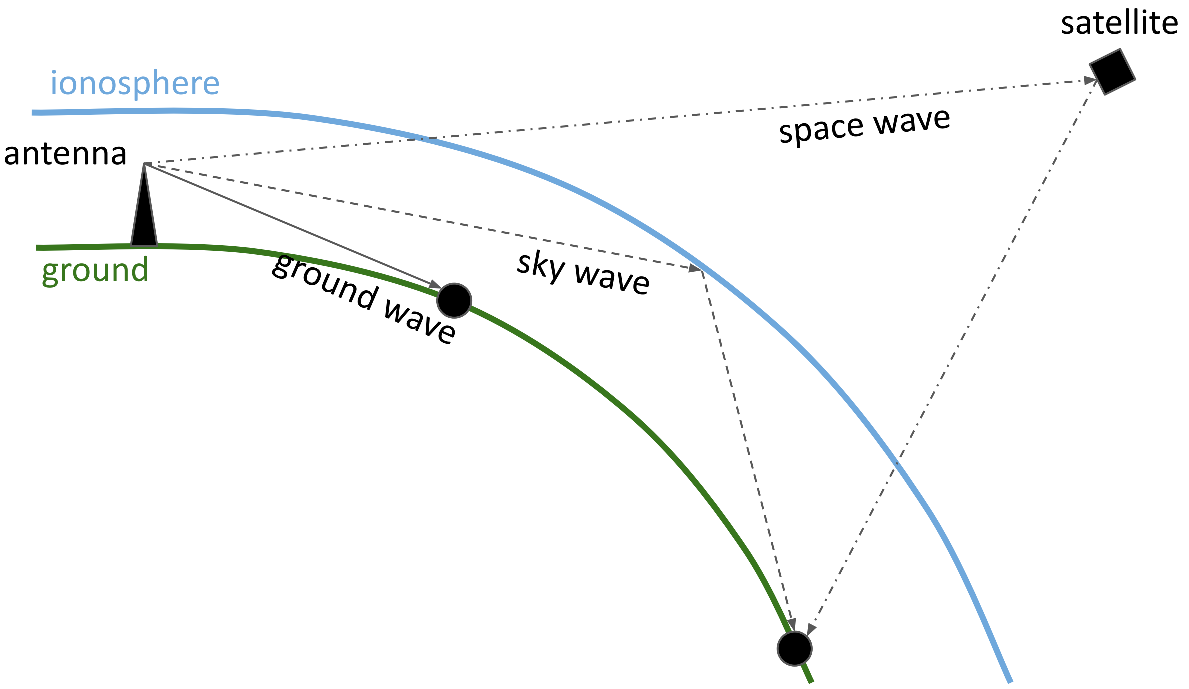

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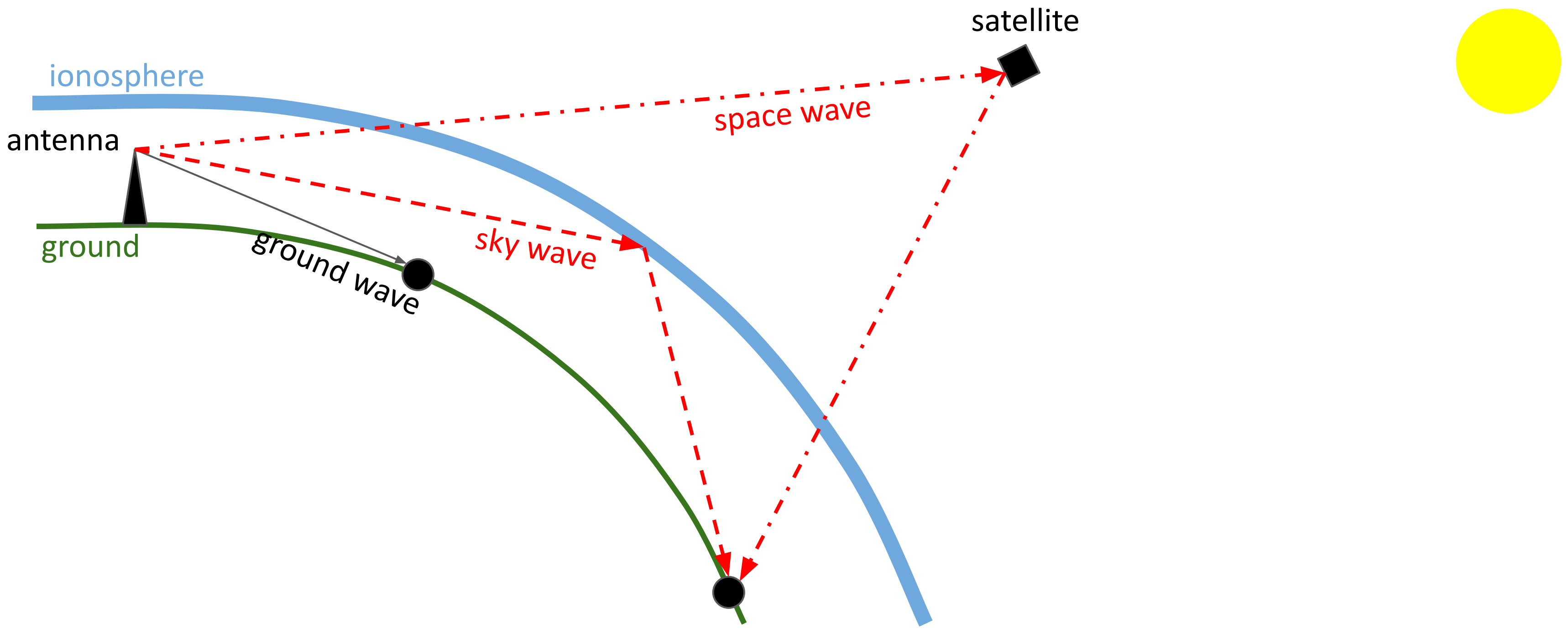

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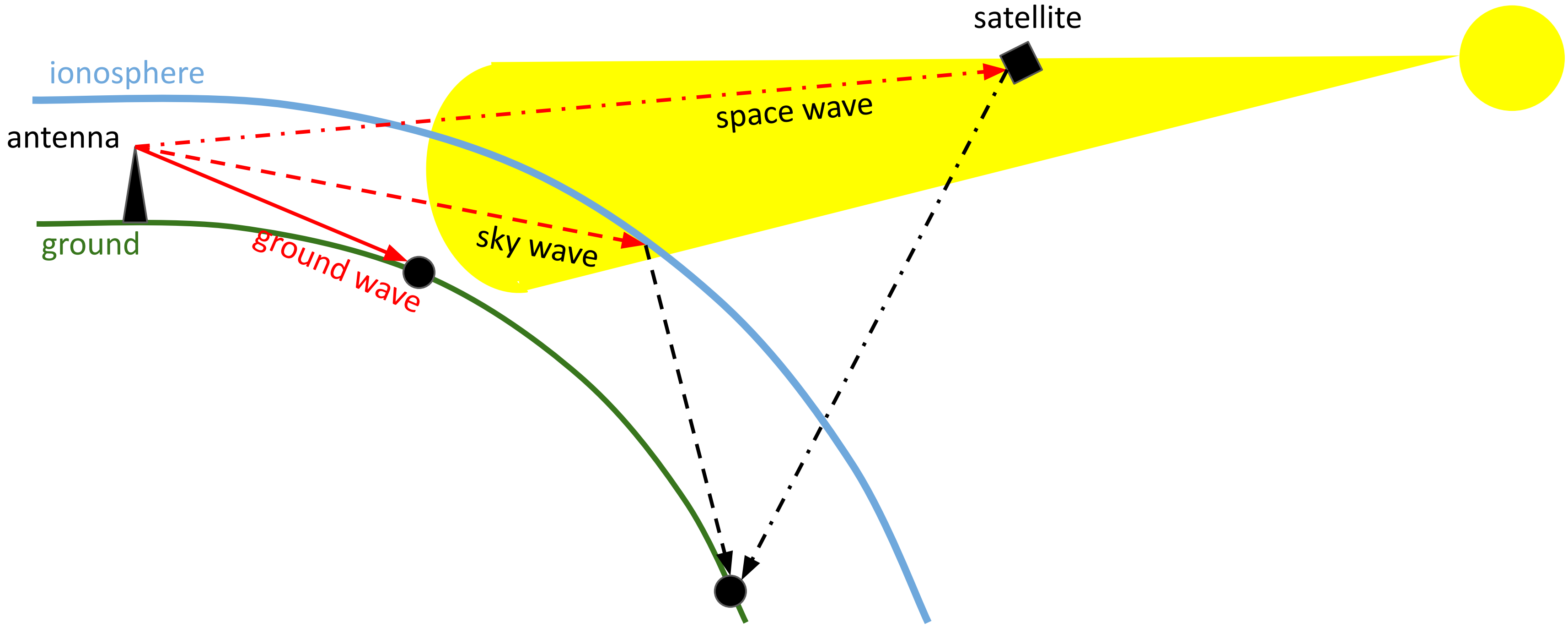

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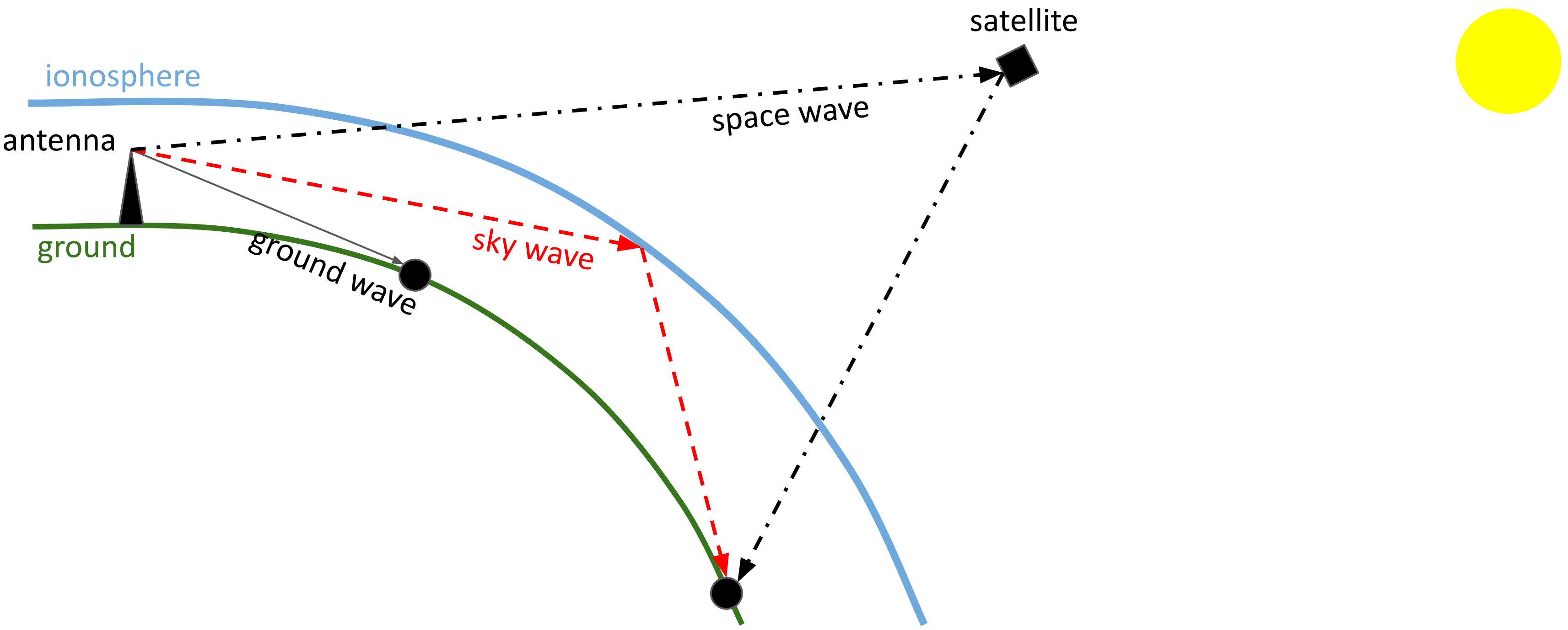
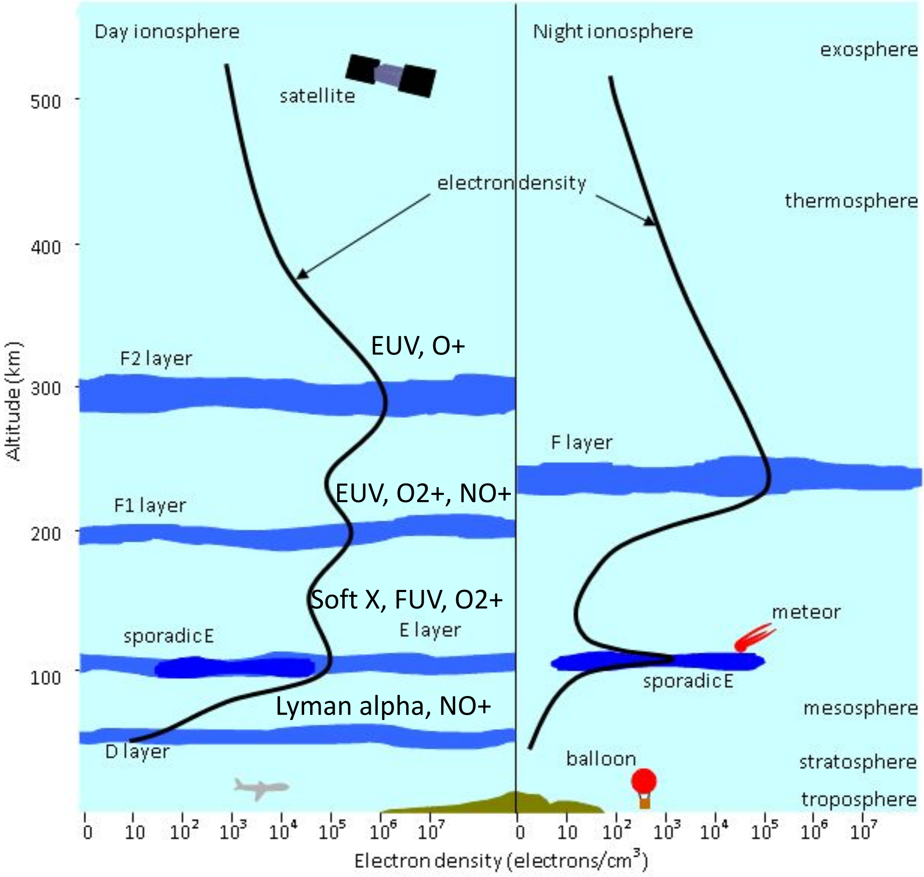


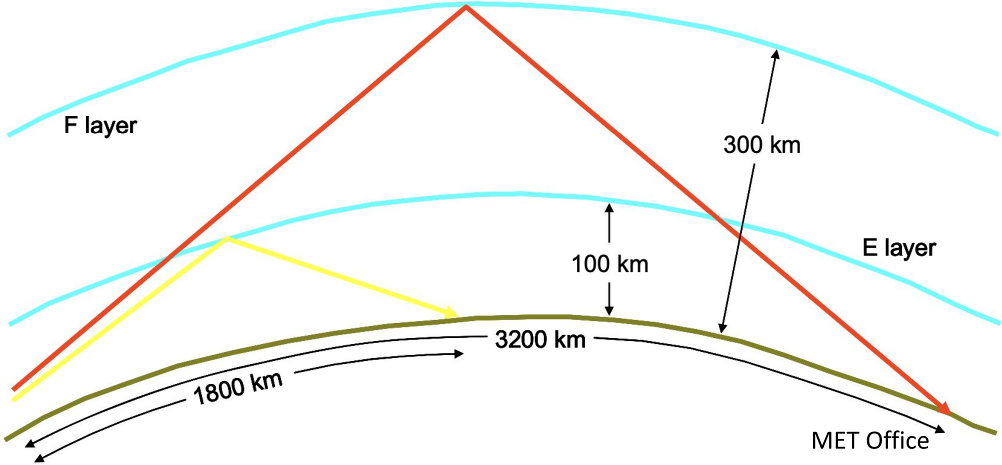
Ionospheric composition

- HF RW hitting free e- in the ionosphere cause them to vibrate and re-radiate the energy back down at the same frequency → free e- cause refraction and reflection of RW
- where this happens depends on the free e- density profile
- the region of highest e- density determines the highest freq. capable of being reflected

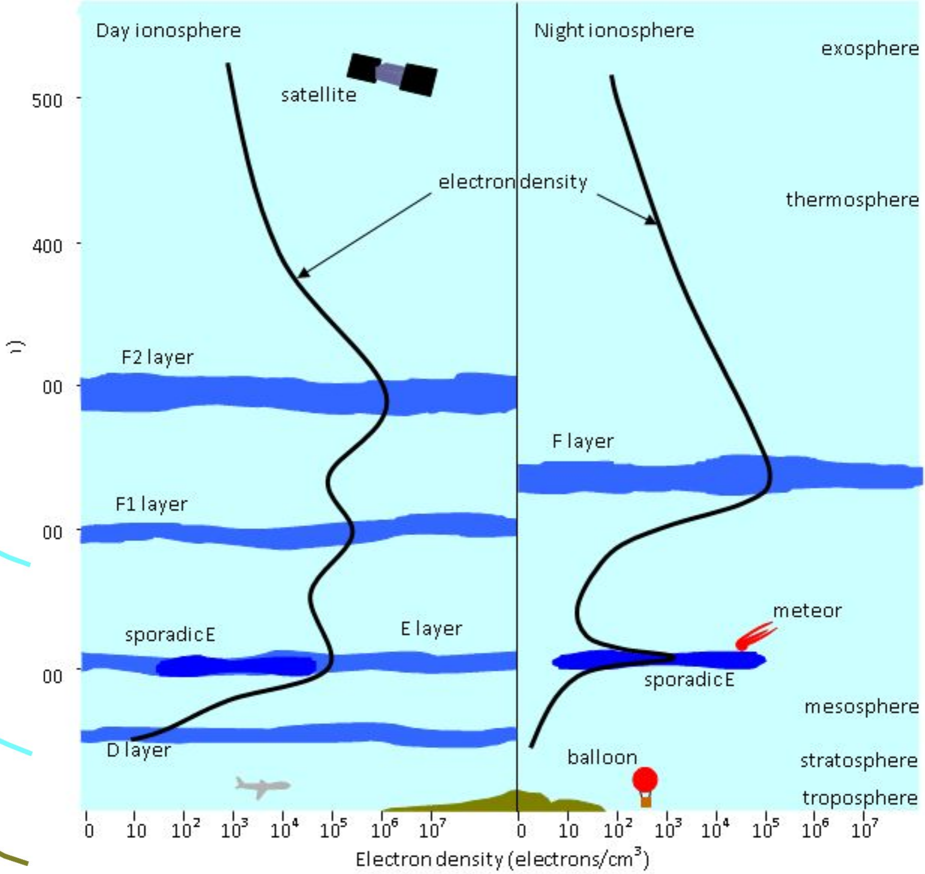


Ionospheric composition

- use of E and F layers instead of LOS increases our range from 100km to 200km (LOS) to 1500km (E) to 3500km (F)



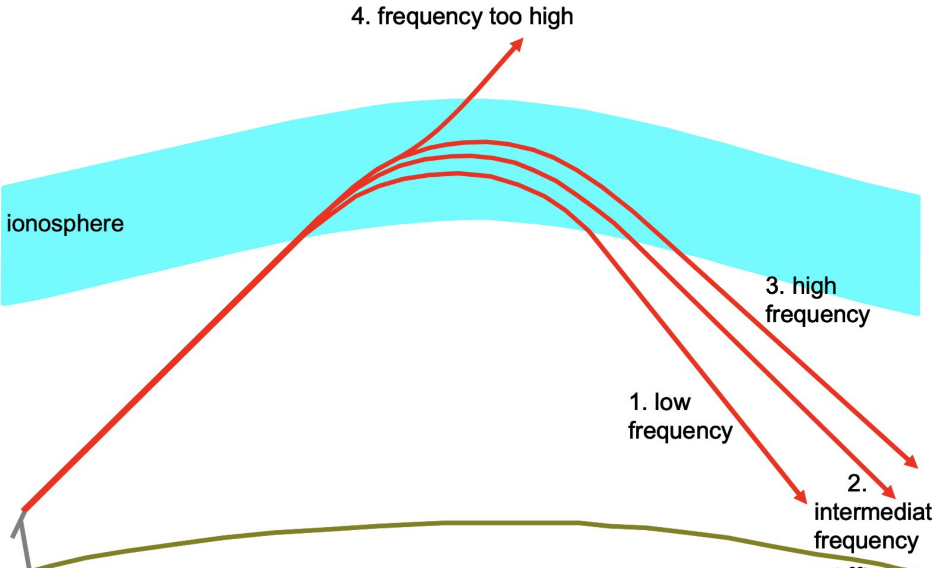
MET Office



MET Office

Ionospheric composition

- if the frequency is too high, the signal is lost to space



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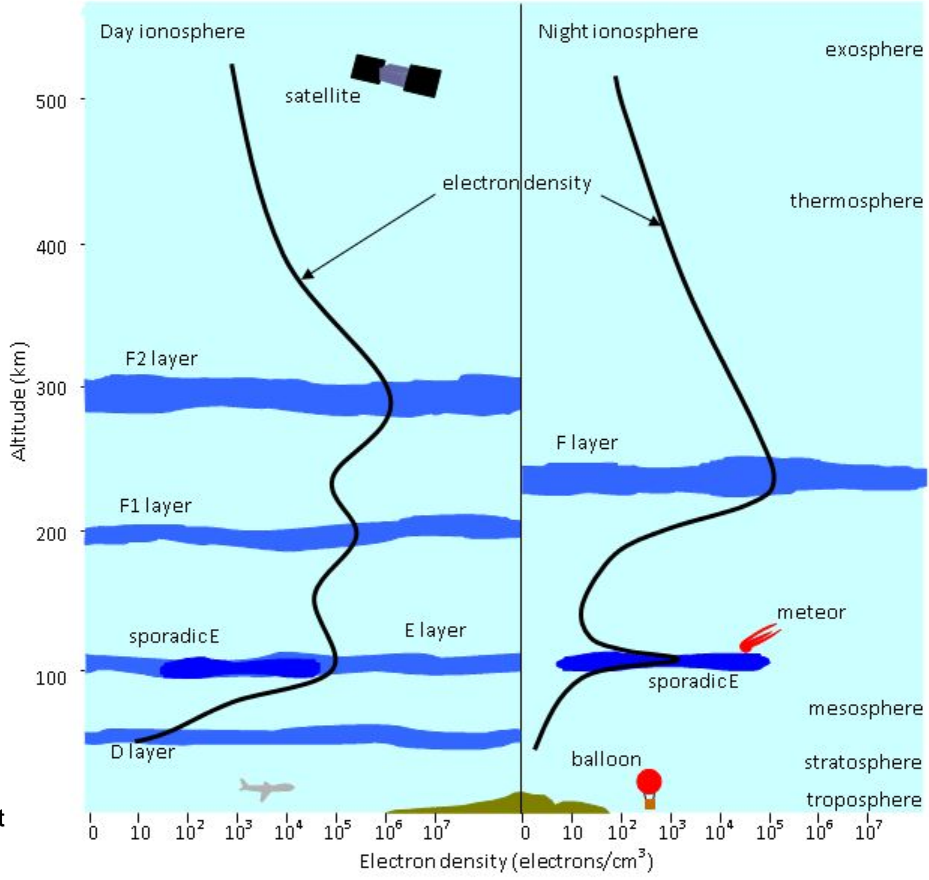
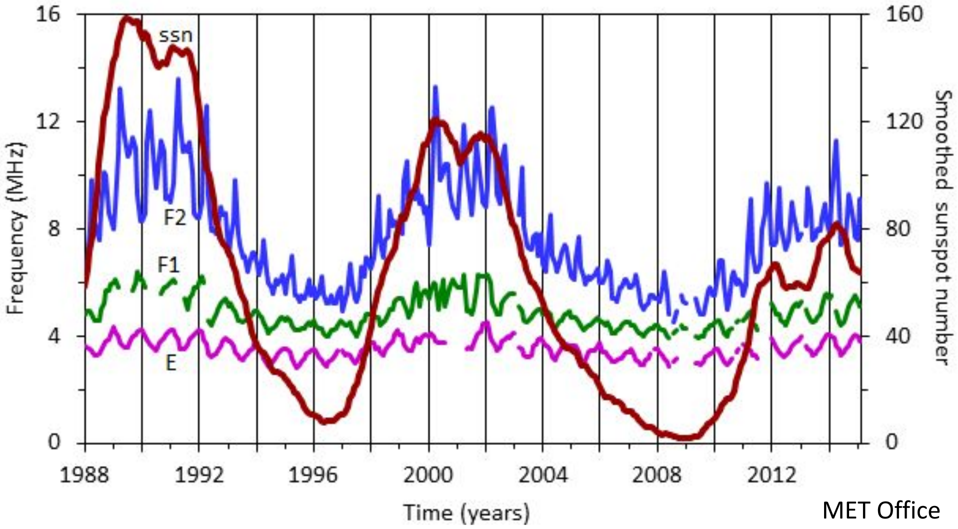


Ionospheric communication challenges

1. Ionospheric plasma frequency changes → affects usable frequency range
2. Ionisation of lower layers → short-wave fade-outs (inability to communicate)
3. Travelling ionospheric disturbances → defocusing of signals
4. Plasma bubbles → signal scintillation and degradation

Problem 1: plasma freq. change

- the usable HF RW freq. is also directly dependent on the solar activity:



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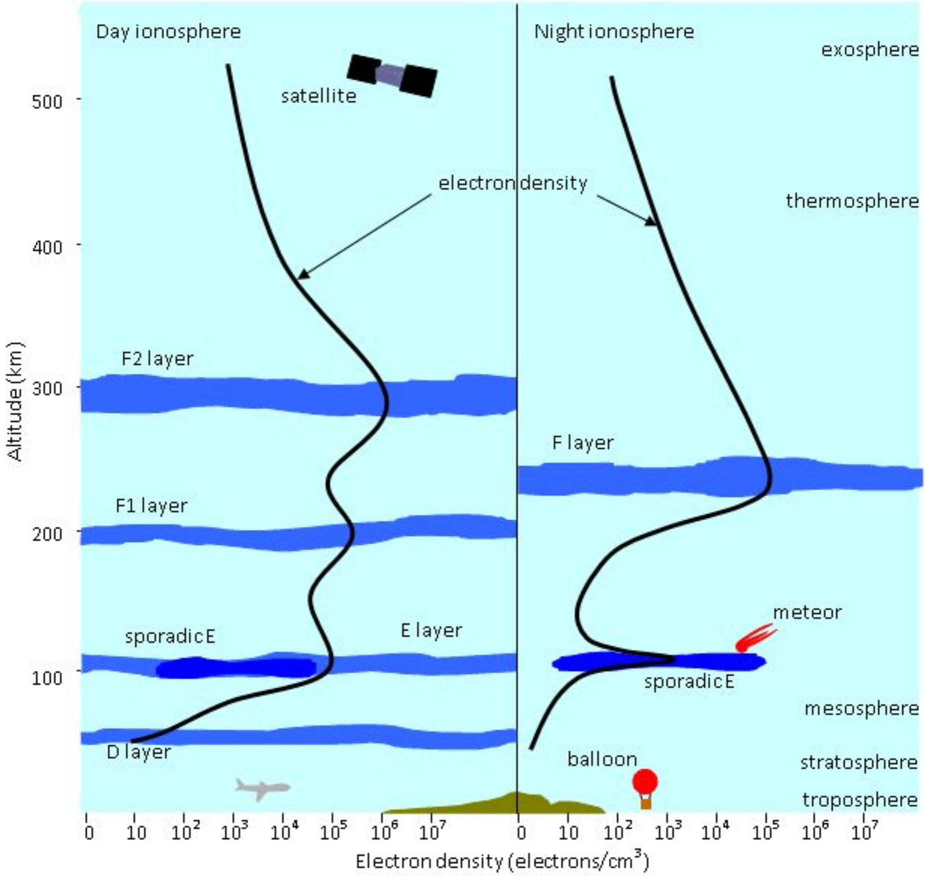

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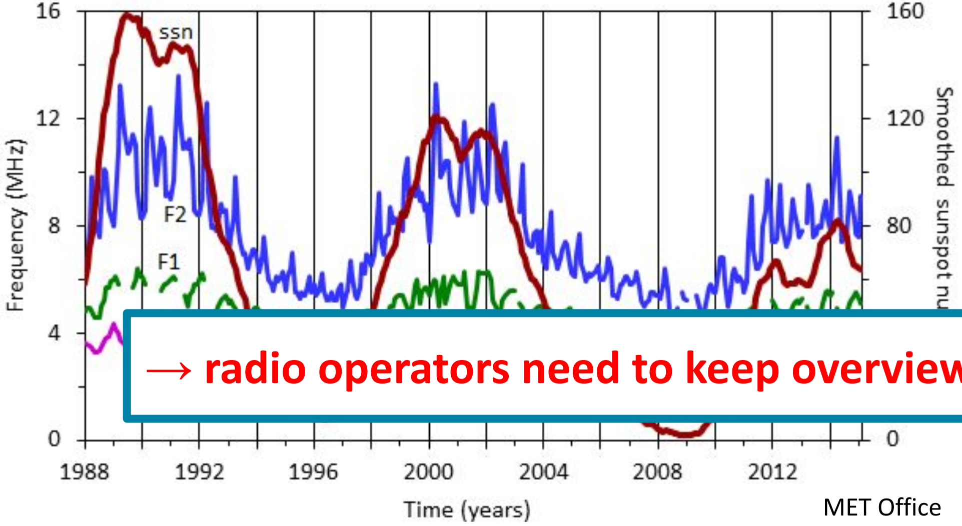

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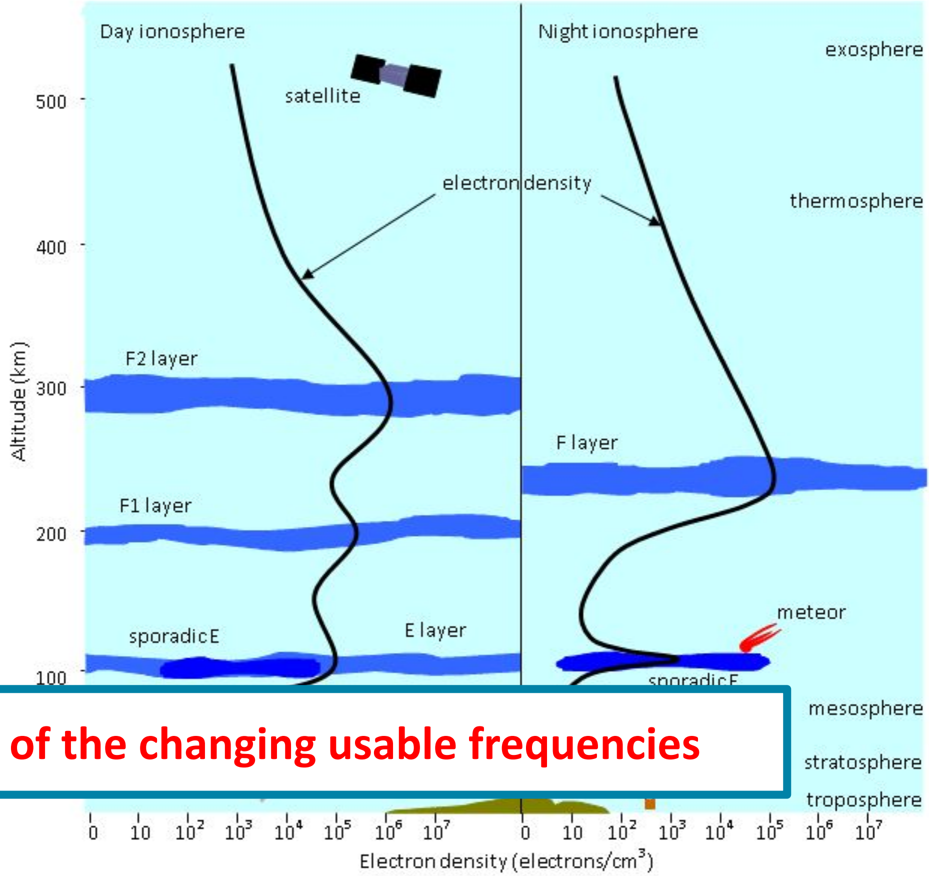
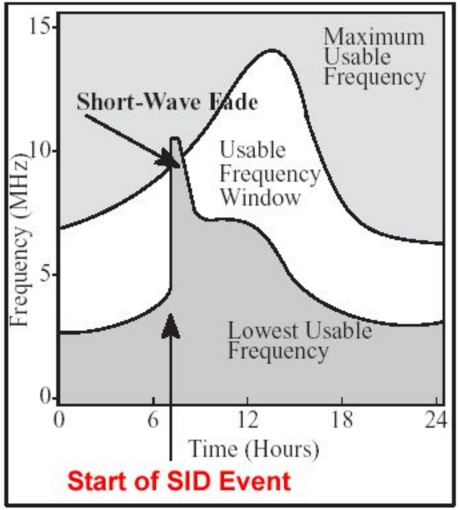


→ radio operators need to keep overview of the changing usable frequencies

Problem 2: ionisation of lower layers

- During solar flares, the D layer can get ionised, causing absorption of HF RW
- after a flare: “**short wave fade-outs**” or “**sudden ionospheric disturbances**” at lower frequencies
- 10 minutes up to several hours/ days

NOAA



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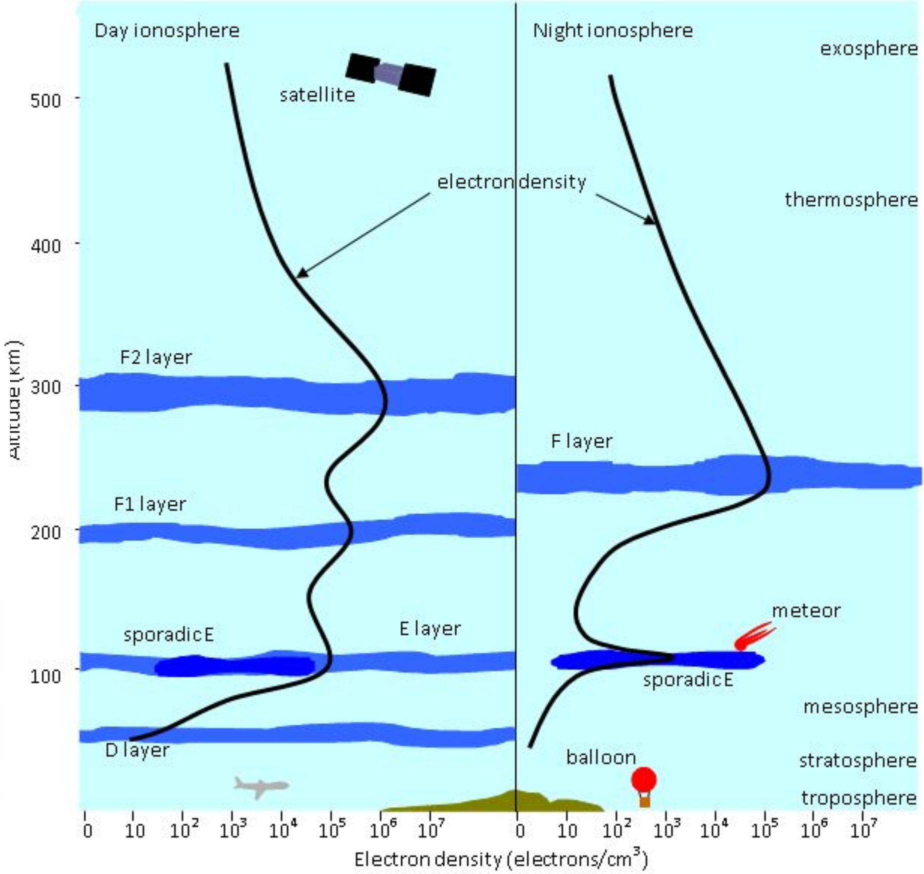
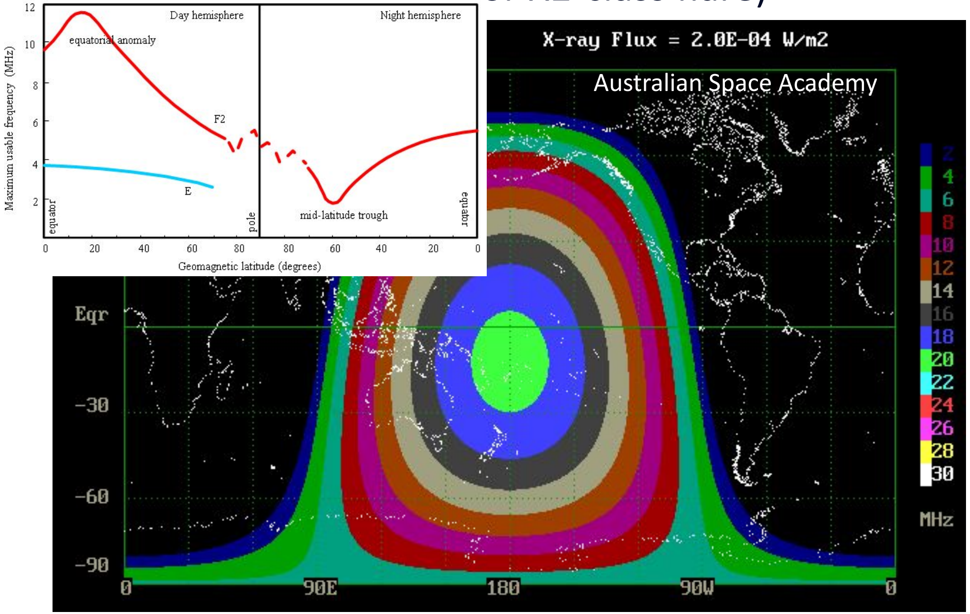
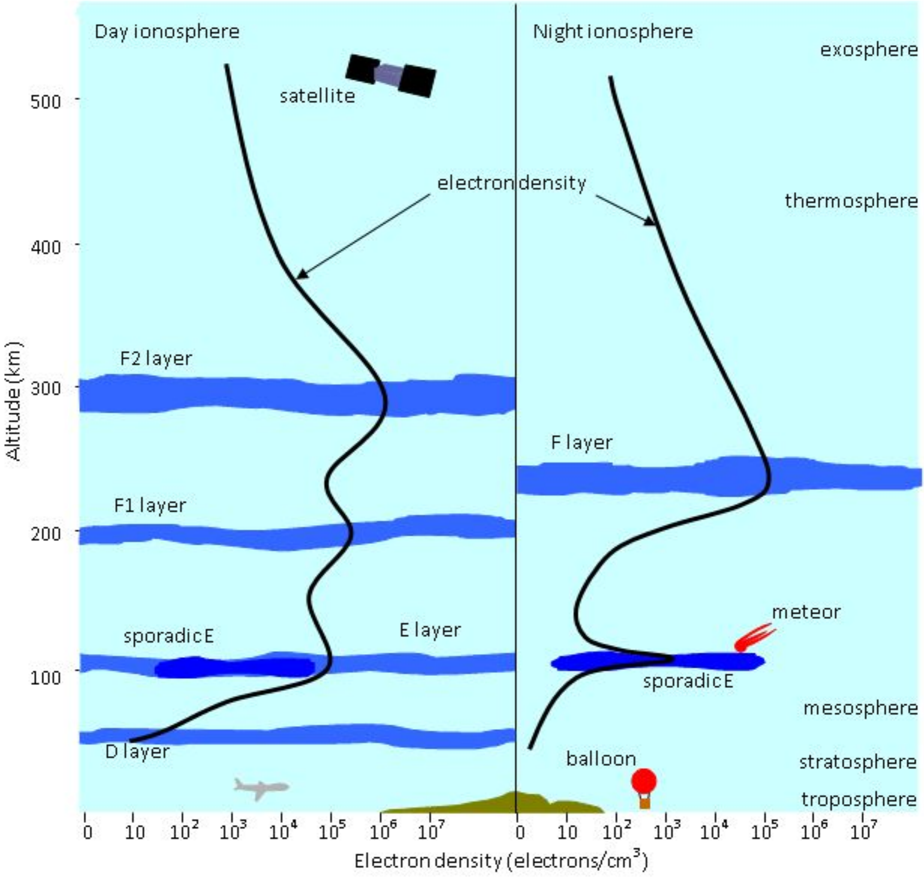


Problem 2: ionisation of lower layers

- affects the lowest usable frequency on the daylit side (below for X2-class flare)



Australian Space Academy



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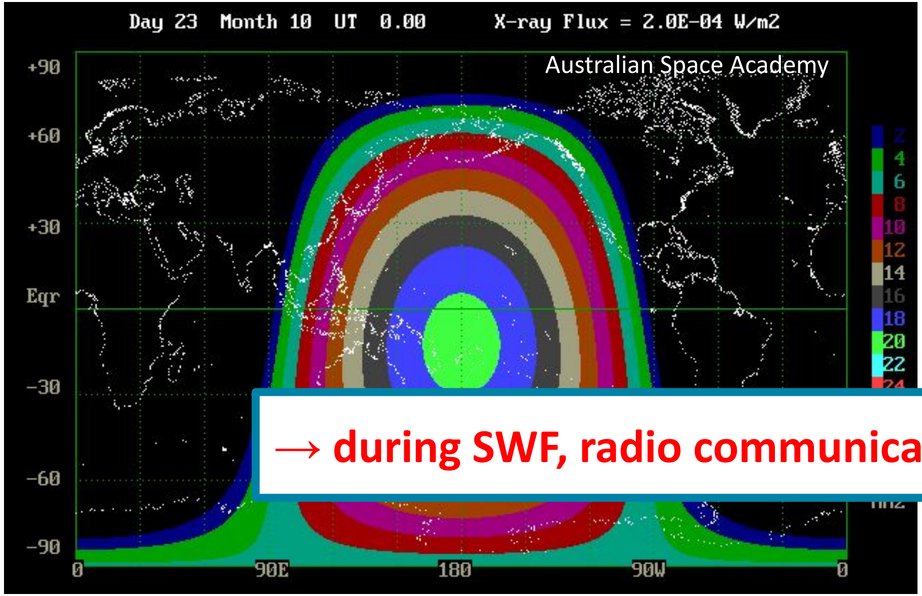

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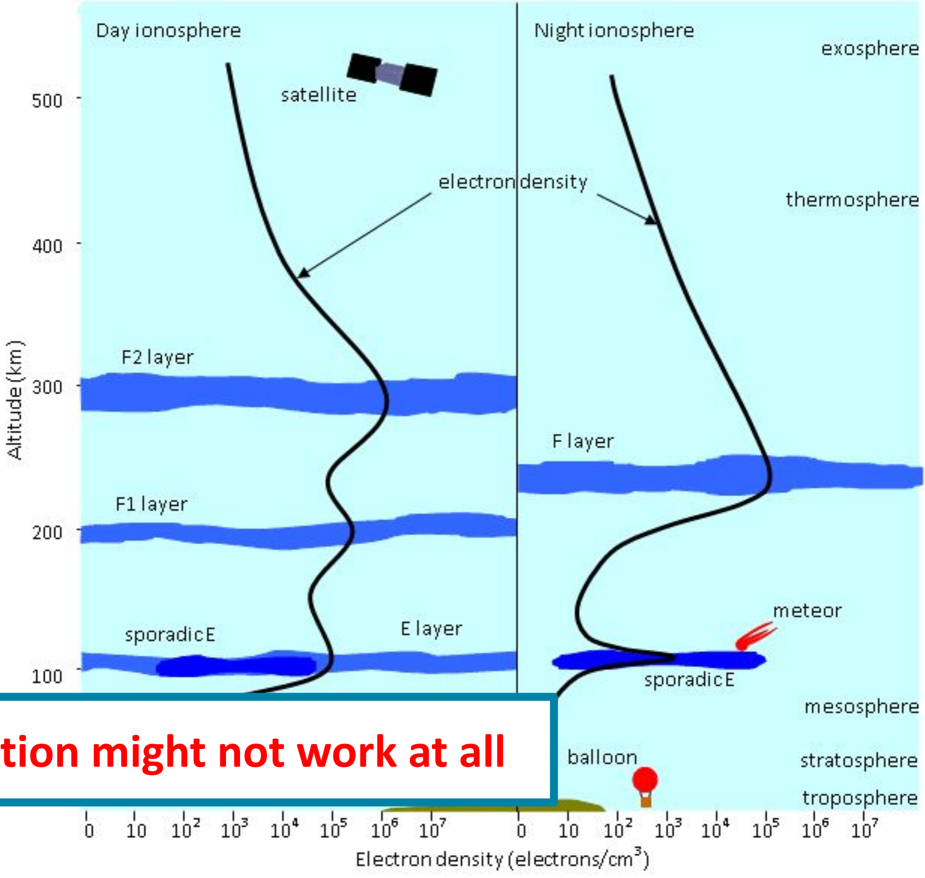
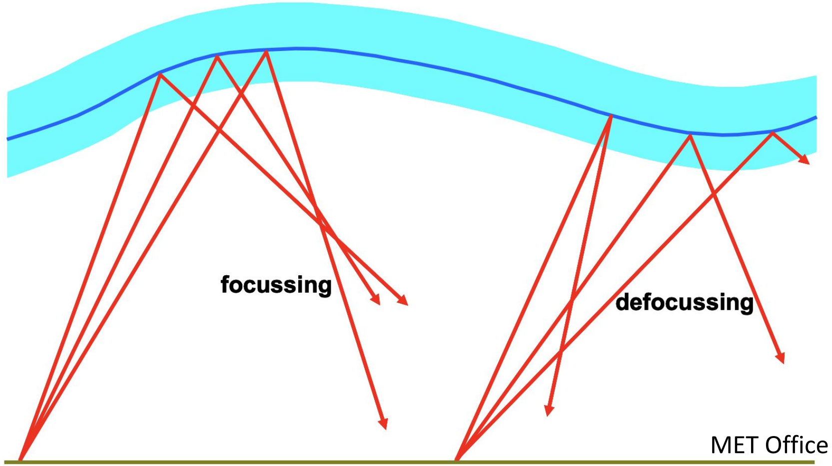


→ during SWF, radio communication might not work at all

Problem 3: TID

- **travelling ionospheric disturbances**: may be created in auroral regions also due to geomagnetic activity and propagate (see e.g. Tsagouri et al. 2023)



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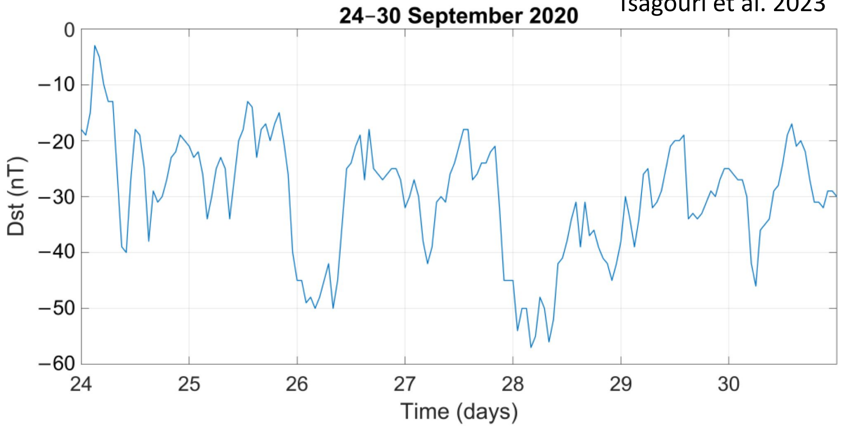
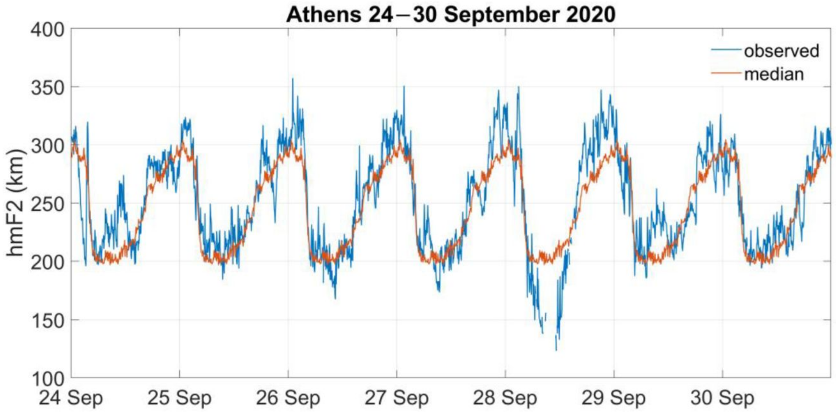


Tsagouri et al. 2023



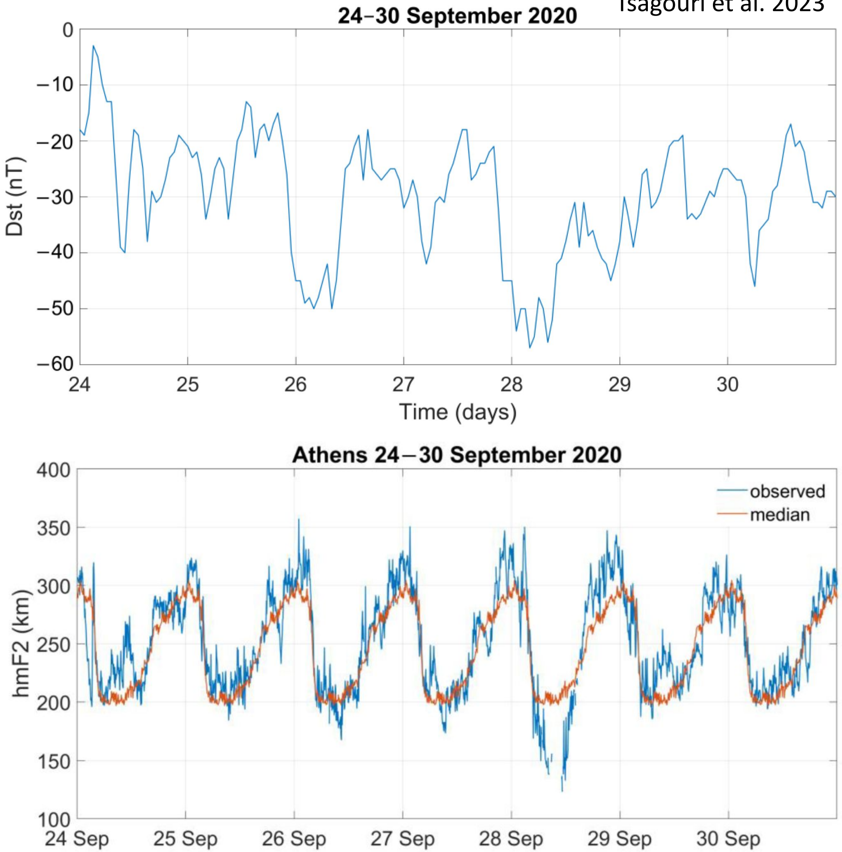
Problem 3: TID

- can impose a doppler shift on the HF frequencies

- short-scale TIDs affect the performance of high-accuracy navigation systems, a nuisance for any system using trans-ionospheric propagation

- the principal mechanism limits the performance of target detection algorithms for geolocation systems (as the associated range/azimuth deflections spread the target return)

Tsagouri et al. 2023



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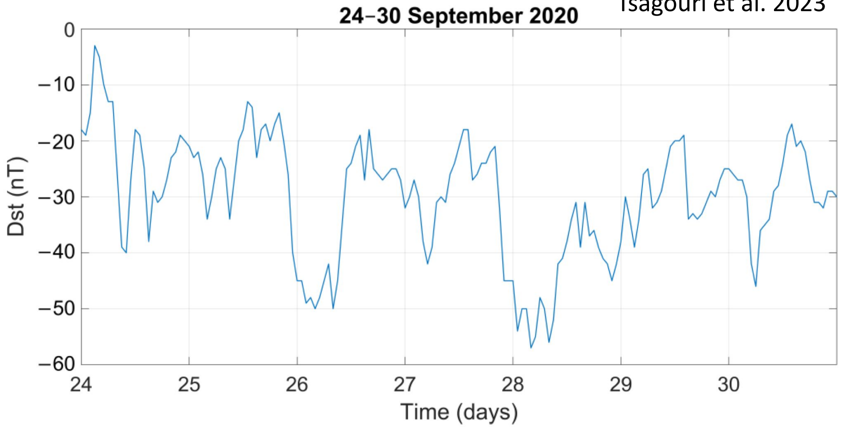
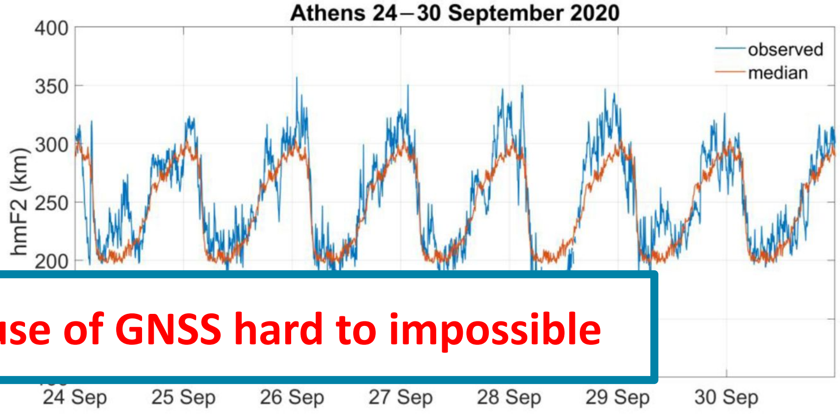
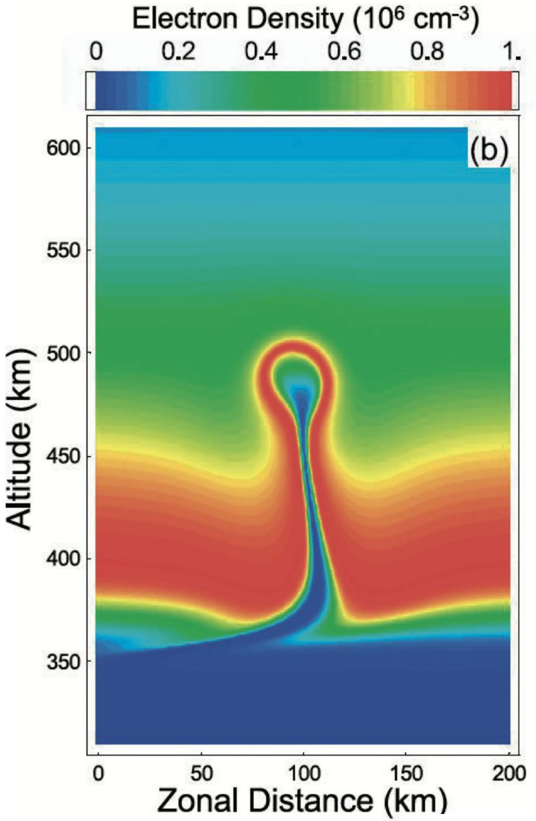




→ TIDs may make target acquisition and use of GNSS hard to impossible

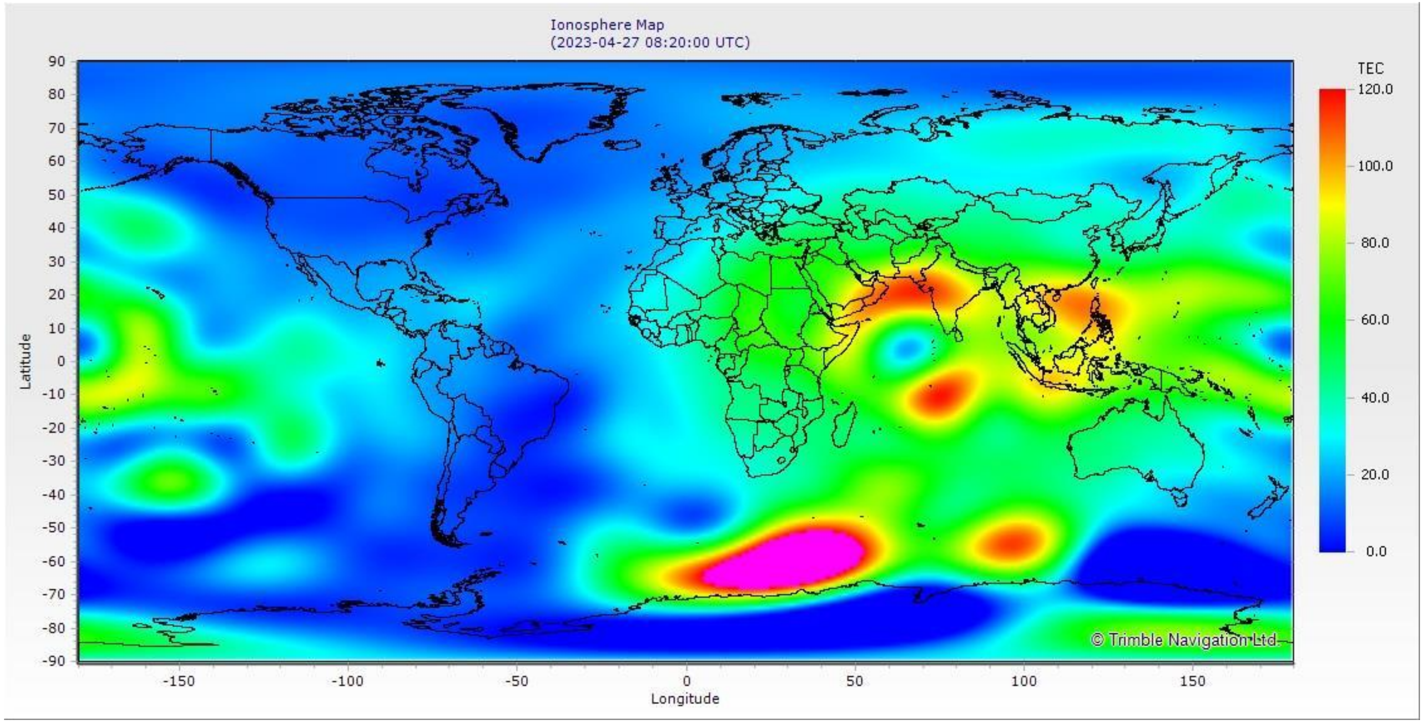
Problem 4: plasma bubble, irregularities

- **plasma bubble:** generally after sunset, but might also happen later at night, **spread-F**
- 50-200km (EW) x > 3000km (NS) due to:
    - lack of ionising radiation (loss of free e-)
    - R-T instabilities creating further irregularities



Bernhardt et al. 2007

Total electron count (TEC) (current info here)

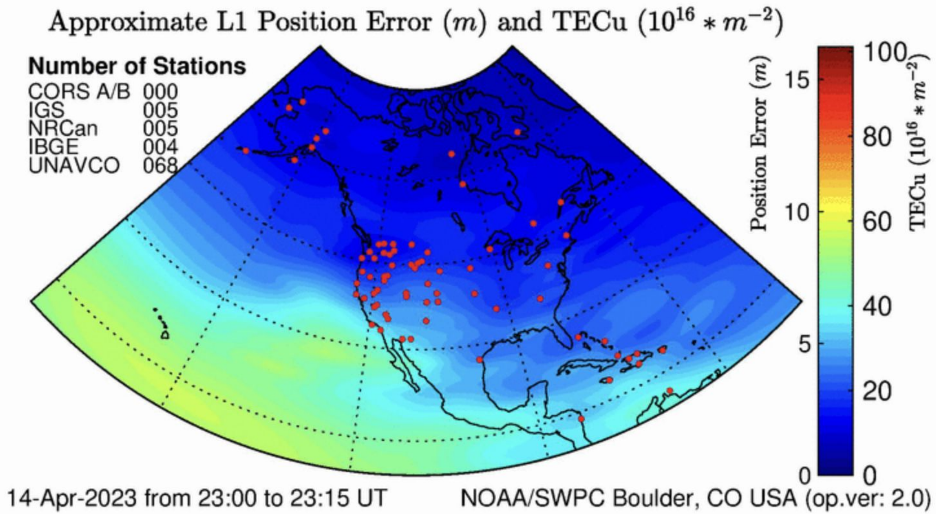


Problem 4: plasma bubble, irregularities

- for space communications & navigation signals, TEC increases path length difference due to refraction → TEC proportionally increases the GPS error (100% increase in TEC doubles the error)

- TEC used as a proxy for position error

- actual information here



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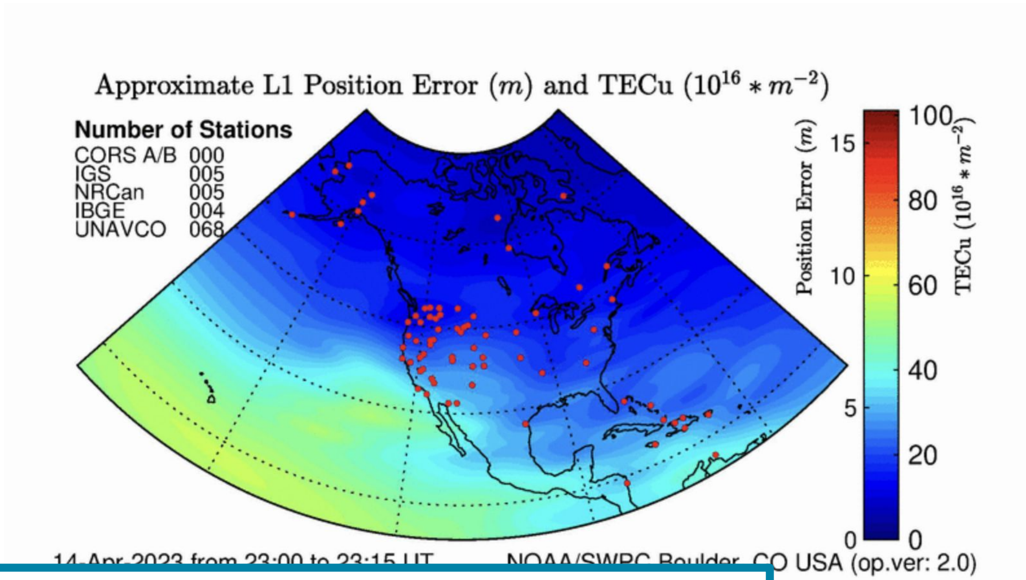

→ if TEC is too high, GNSS services might be unreliable/ unusable

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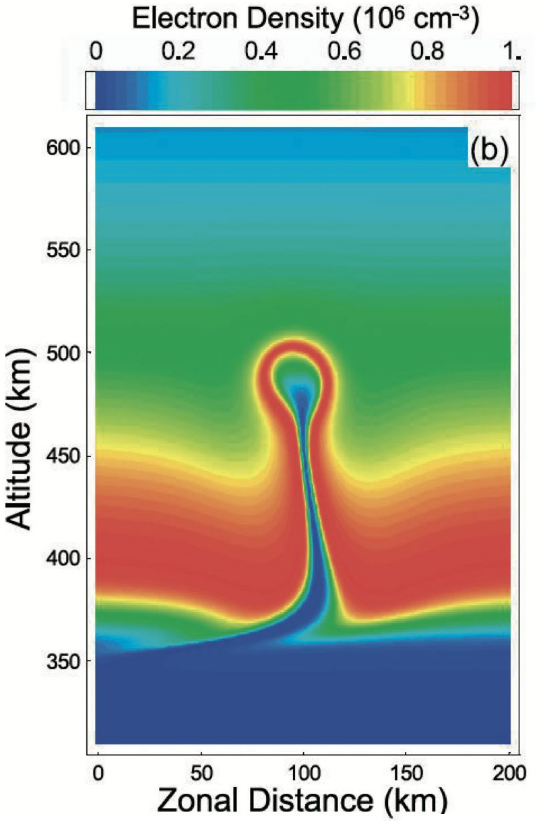
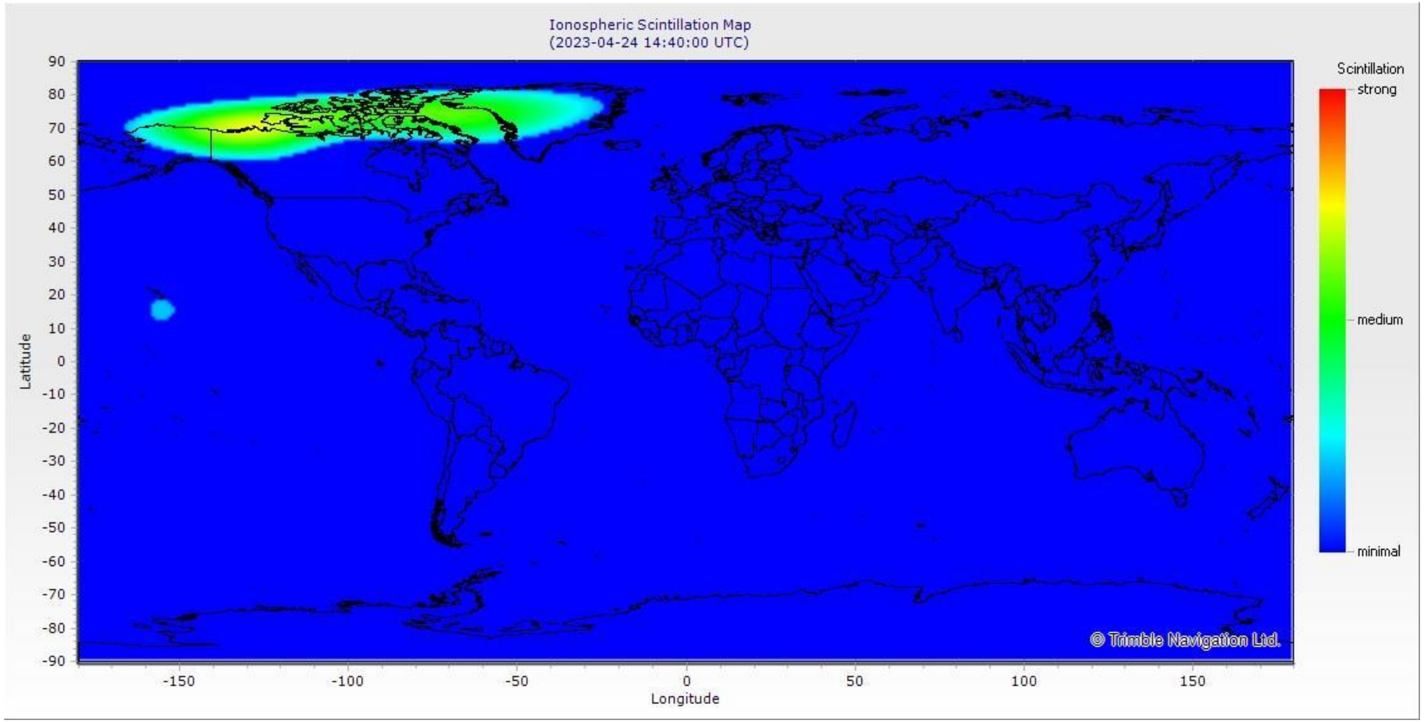
- 50-200km (EW) x > 3000km (NS) due to:
    - lack of ionising radiation (loss of free e-)
    - R-T instabilities creating further irregularities
- ionosphere reshaped after sunset full of irregularities
- this can cause signal **scintillation**



Bernhardt et al. 2007

Ionospheric scintillation (current info here)



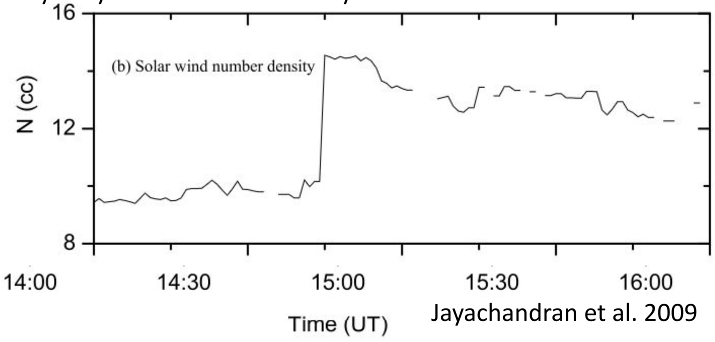
Problem 4: plasma bubble, irregularities

- scintillations due to spatial/ temporal irregularities result in positioning errors, difficult to forecast

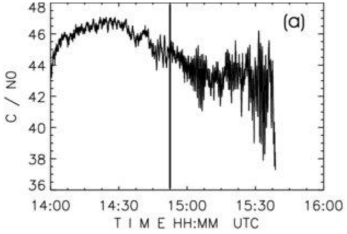
- errors also due to e.g. plasma bubbles but also “magnetospheric impact events” that can be caused by dense solar wind (Konik et al., 1994)

- if signal to noise ratio < 10 → **loss of lock**

- monitored by the ionospheric scintillation monitor



Jayachandran et al. 2009



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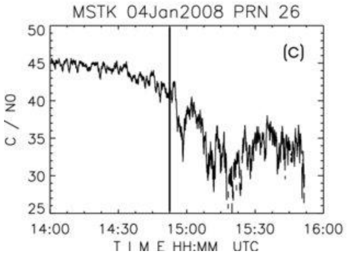

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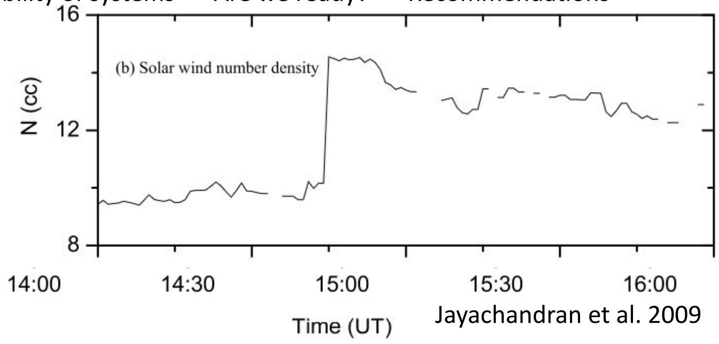

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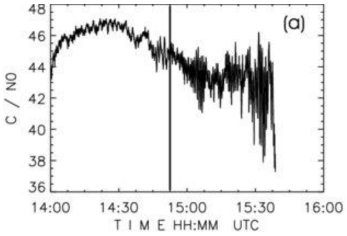

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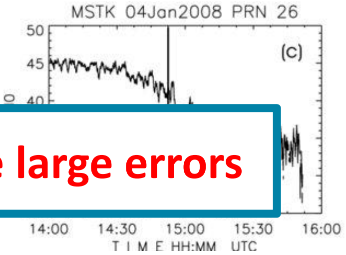

→ if scintillation is too strong, GNSS might be unable to lock or have large errors

Examples

- all these effects (TEC, scintillation, SWF, TIDs etc.) largely associated with solar activity

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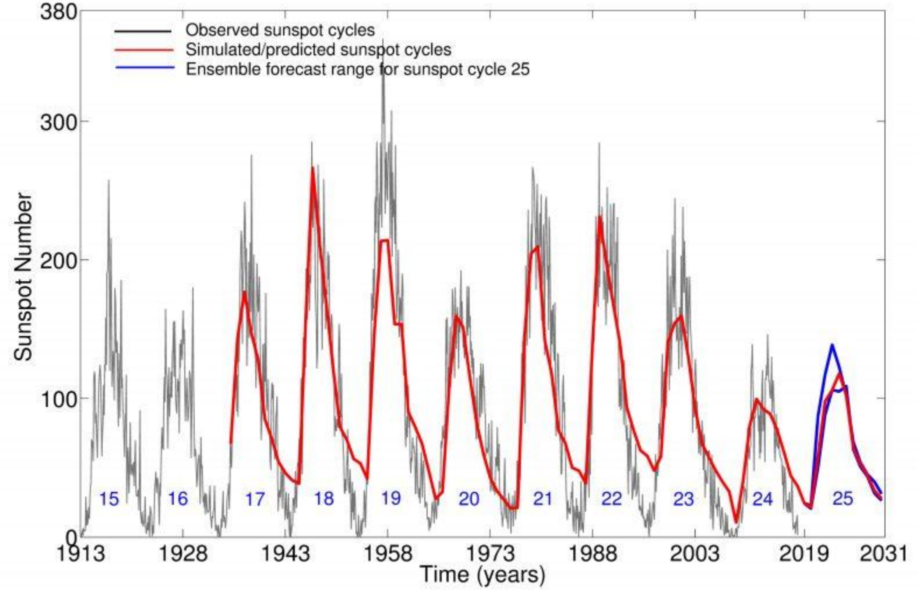


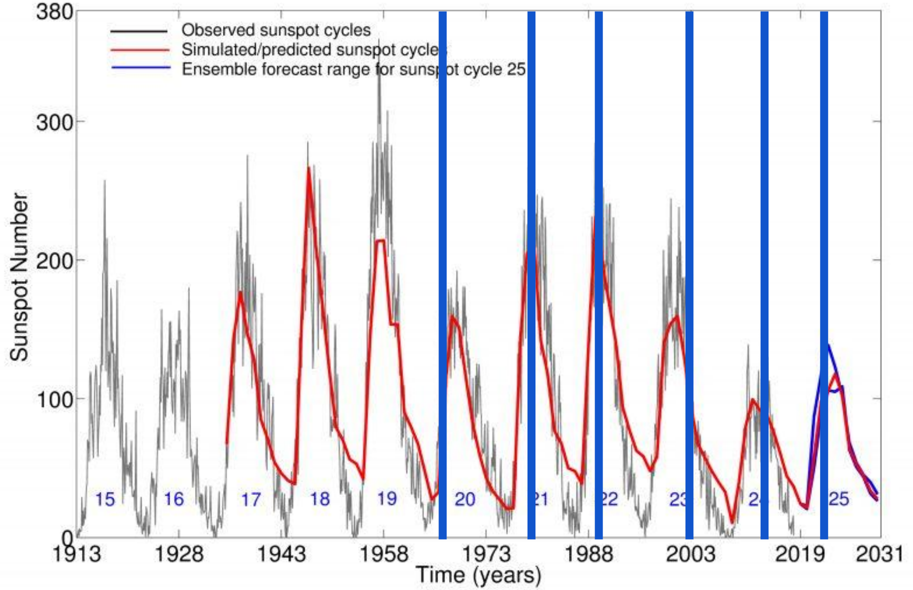
Examples

- all these effects (TEC, scintillation, SWF, TIDs etc.) largely associated with solar activity

- the solar cycle is roughly 11 years long with periods of minima and maxima

- in this presentation mostly:
  notable events in 1967, 1979, 1989, 2003 (Halloween storms), 2015, 2022

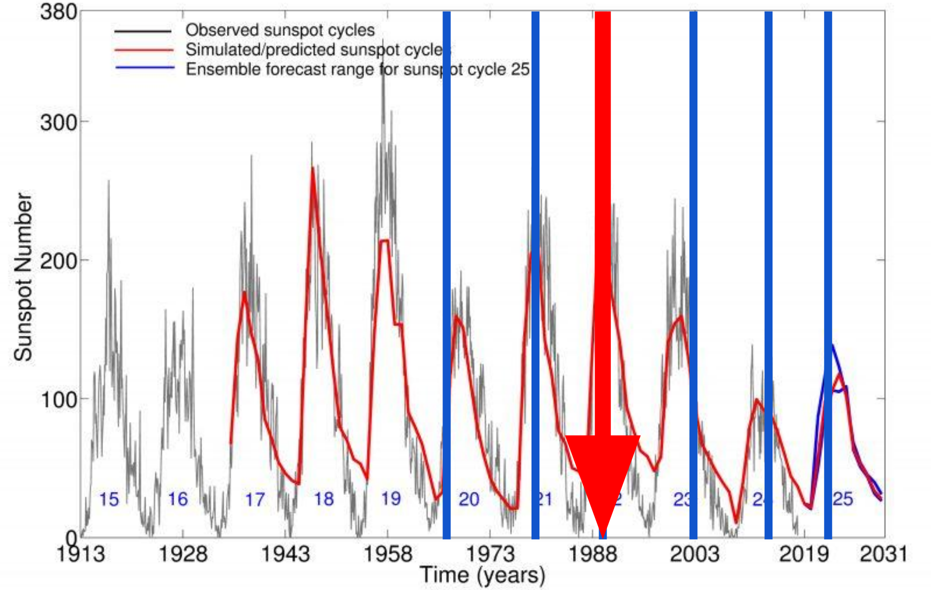
CESSI



1989 HF radio disruption during UNTAG

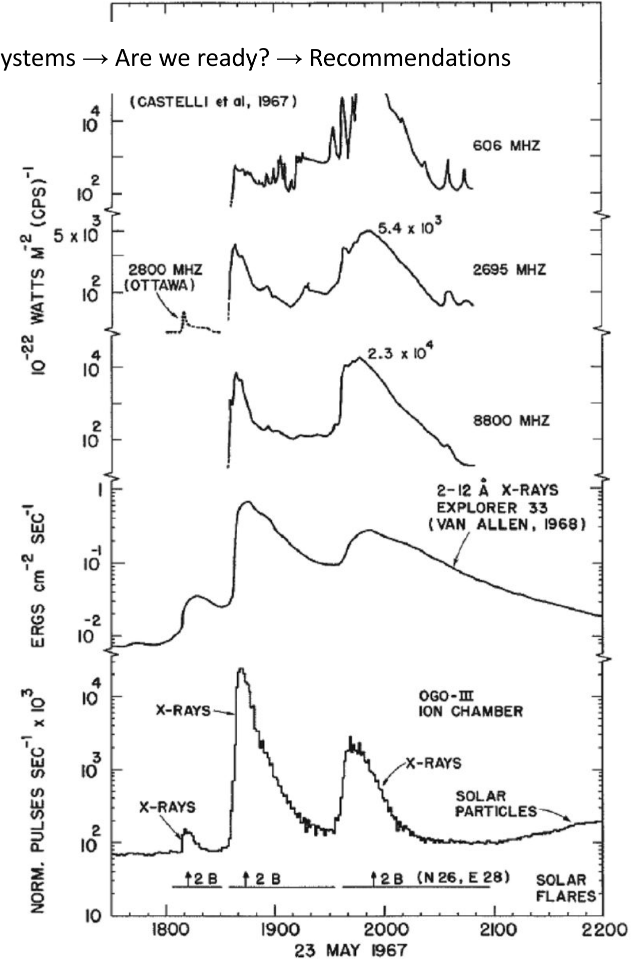
- In March 1989, the Australian Army joined the UN Peacekeeping Force in Namibia (Australian contribution to UNTAG)
  - experienced significant HF RC problems shortly after its deployment
  - HF RC very difficult during the first two months

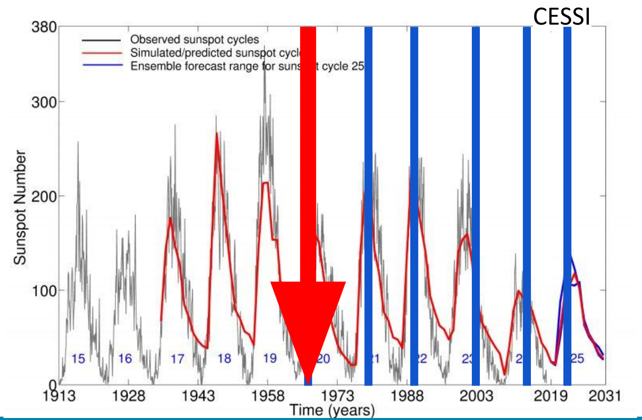
CESSI

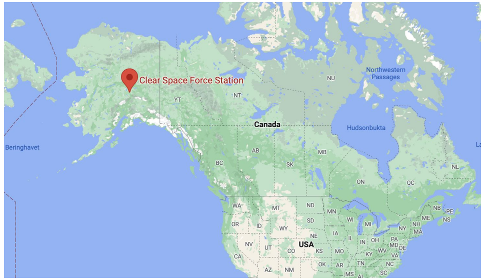


1967 Disruption of BMEWS

- in May 1967, an X6.5 solar flare followed by a CME triggered by the McMath active region
    - flare resulting in disruption of early warning radars
- the US thought it was Russia and were “ready to launch”
- Kp = 9, Dst = -287nT (May 23)







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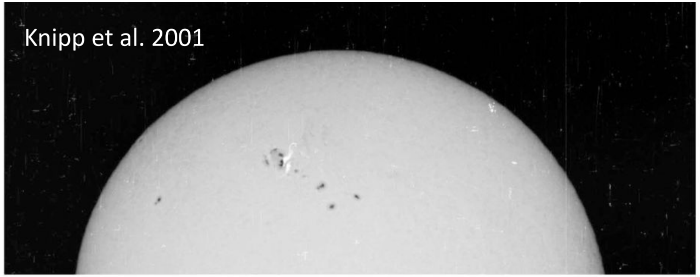
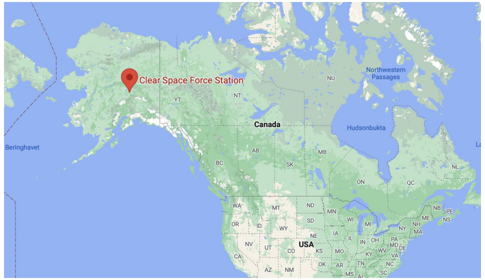
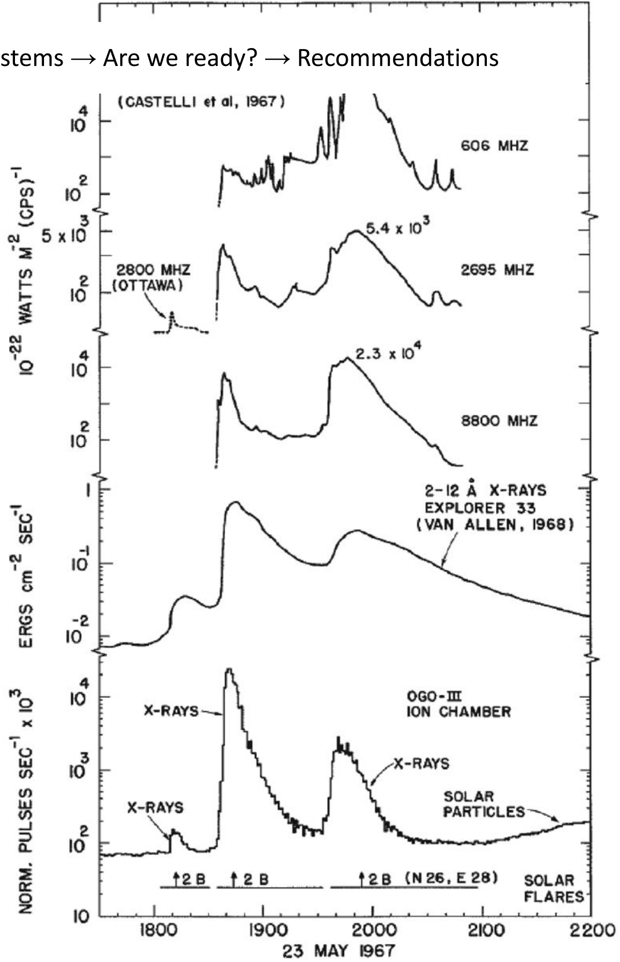

Knipp et al. 2001





ROYAL HIGHER INSTITUTE 150-year think tank for DEFENCE

cpa

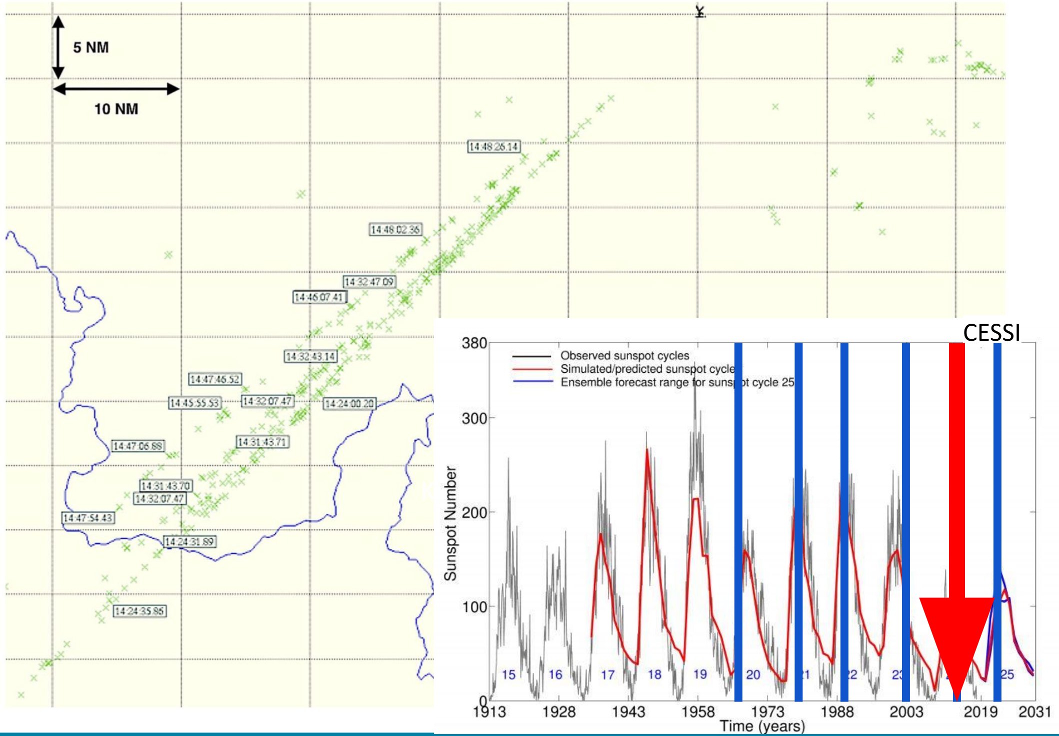
KU LEUVEN

2015 Black out of Swedish air-traffic control systems

Marqué et al. 2018

- November 4, 2015, an M3.7 solar flare responsible for disruption of secondary air traffic radars (1030 to 1090 MHz), showing "ghost echoes" in straight lines in the direction of the Sun

- no significant disruption of primary ATC radars (2700 to 2900 MHz) → the frequency is important!



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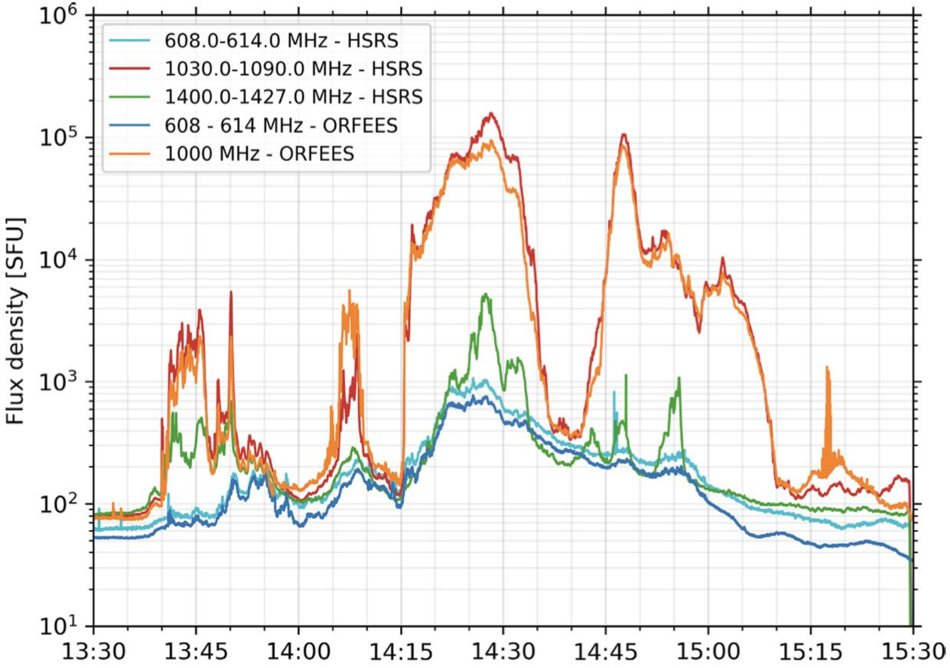

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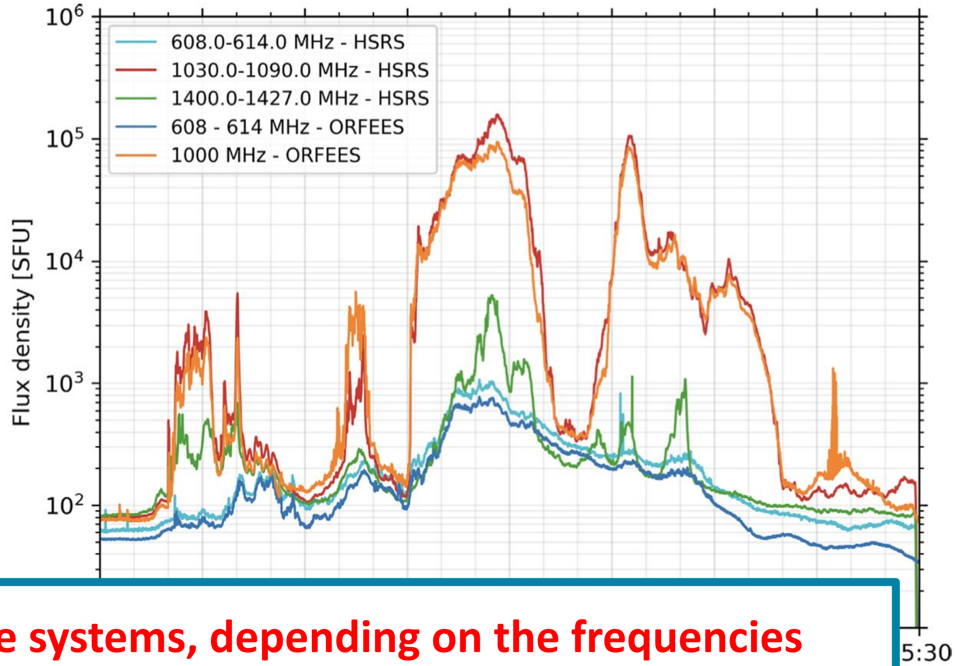
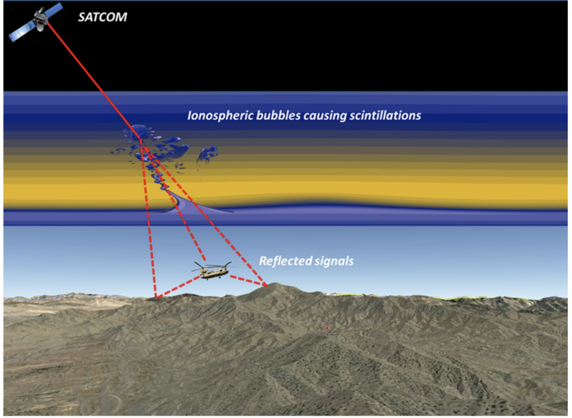


→ a SW event might affect only some systems, depending on the frequencies

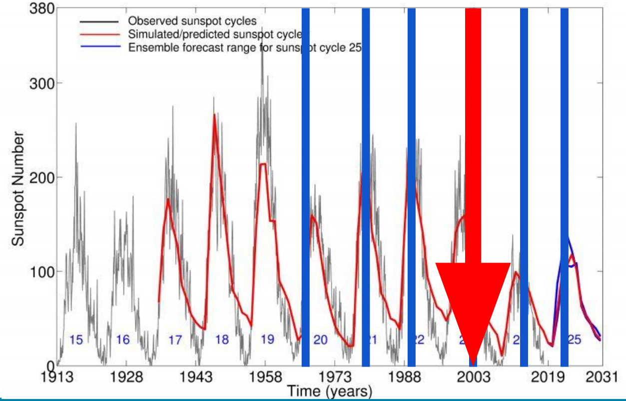
2002 The Battle of Takur Ghar (Afghanistan)

- plasma bubbles post-midnight might occur due to increased geomagnetic activity of Kp > 3 (Huang et al. 2005): the battle of Takur Ghar: Kp = 4, 0300 LT March 4, 2002 (solar maximum)
- during the battle, Chinook helicopters from the QRF were called to help Navy SEAL units, landing at Takur Ghar (Afghanistan)
- in the meantime, the area became "hot", but the helicopters never received the repeated warnings avoid the area → the Chinook crashed and seven people died



Sketch prepared by ROB/GNSS (Dr Nicolas Bergeot) with NICT/AERI – Dr Yokoyama's model as base http://aer.nict.go.jp/en/people/spe_yokoyama.html

CESSI



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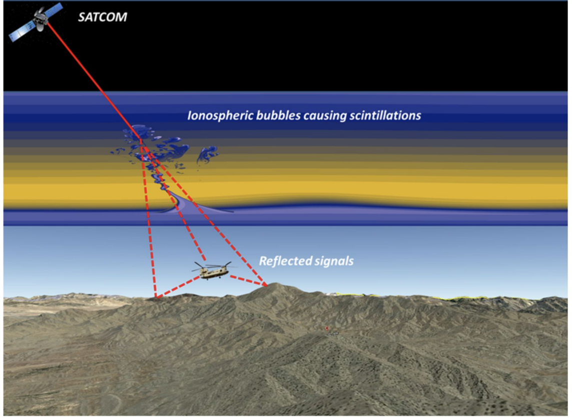

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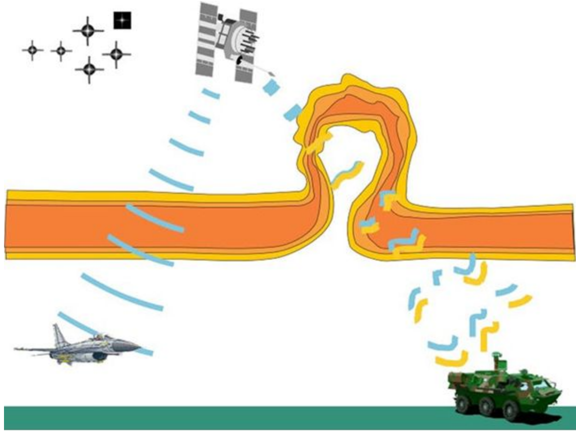


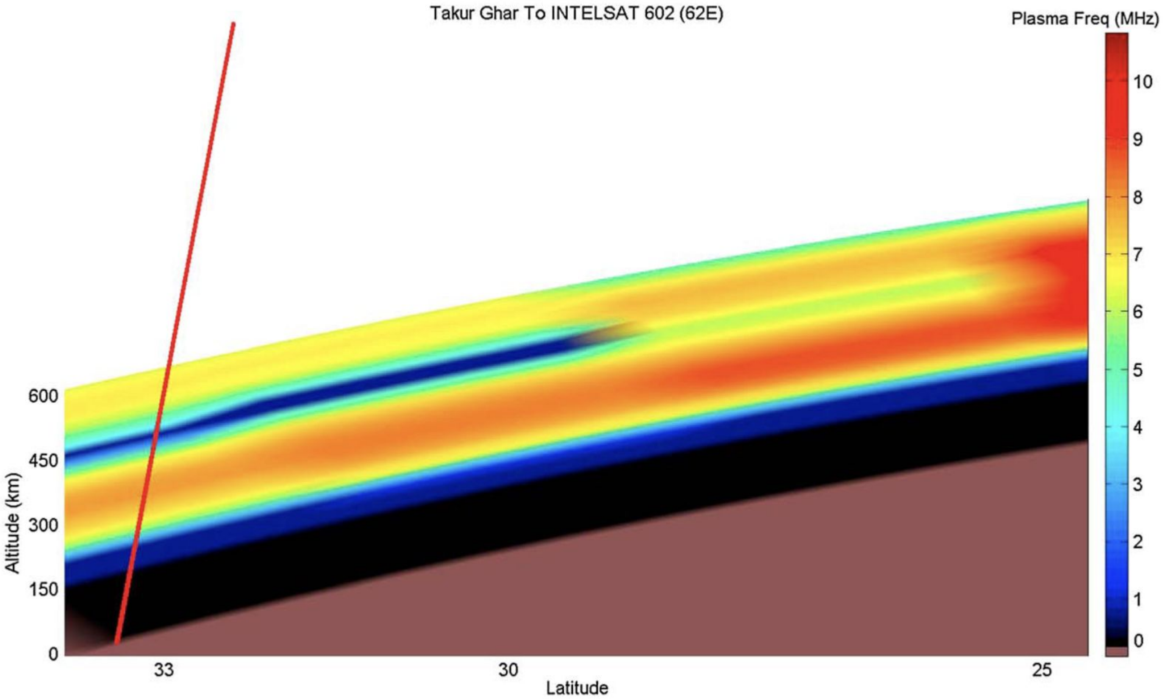
Credit: U.S. Air Force Research Laboratory (AFRL)
https://www.nasa.gov/mission_pages/cindi/five-years.html

2002 The Battle of Takur Ghar (Afghanistan)

- GUVI UV data - electron density reconstruction show clear electron depletion regions consistent with plasma bubbles (Kelly et al. 2014)

  → it is likely that plasma bubbles was what caused the loss of lives and the failure of the operation

Kelly et al. 2014



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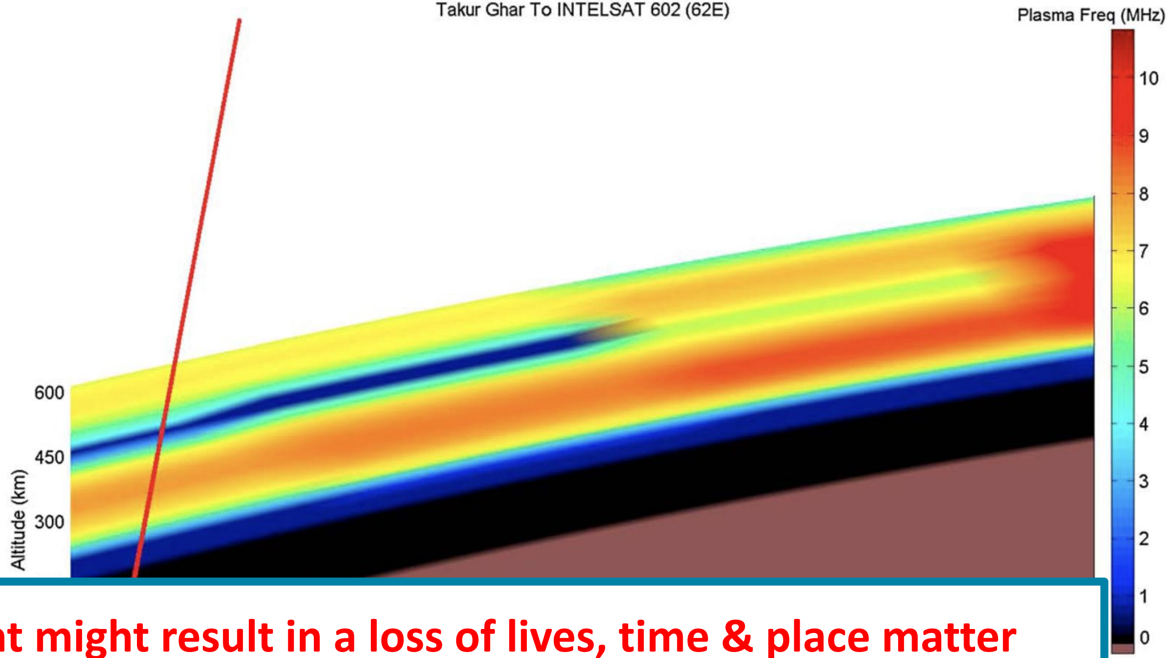


→ even a weaker SW event might result in a loss of lives, time & place matter

Communication SWx overview (VLF to HF)

Long-distance comm. (submarines): VLF to LF

- during/ after events, signal strength can be degraded for a day or two
- sudden changes in ionospheric density can produce brief phase anomalies

Long-distance comm. (A/C, ships or remote land-based units): MF to HF

- X-rays emitted by solar flares can produce shortwave fadeouts & blocking up to a few hours.
- ionospheric storms also affect HF communication by decreasing the maximum useable frequency, or degrading their quality, for up to a few days.
- long-term changes in the solar UV throughout the solar cycle and during seasonal variations → predictable changes in the range of frequencies available for HF comm., however, the variations occurring during individual geomagnetic storms are difficult to forecast.

Communication SWx overview (VHF to UHF)

LOS comm. (between mobile units, including ship-to-shore and air-to-ground): VHF to UHF

- solar radio bursts associated with solar flares can briefly interfere with VHF and UHF signals in the sunlit hemisphere of the Earth, when the sun is low on the horizon
- mobile phone comm. can be impacted by these bursts in the same way (operates within UHF)

Land-based fixed LOS communication links using microwave L-band

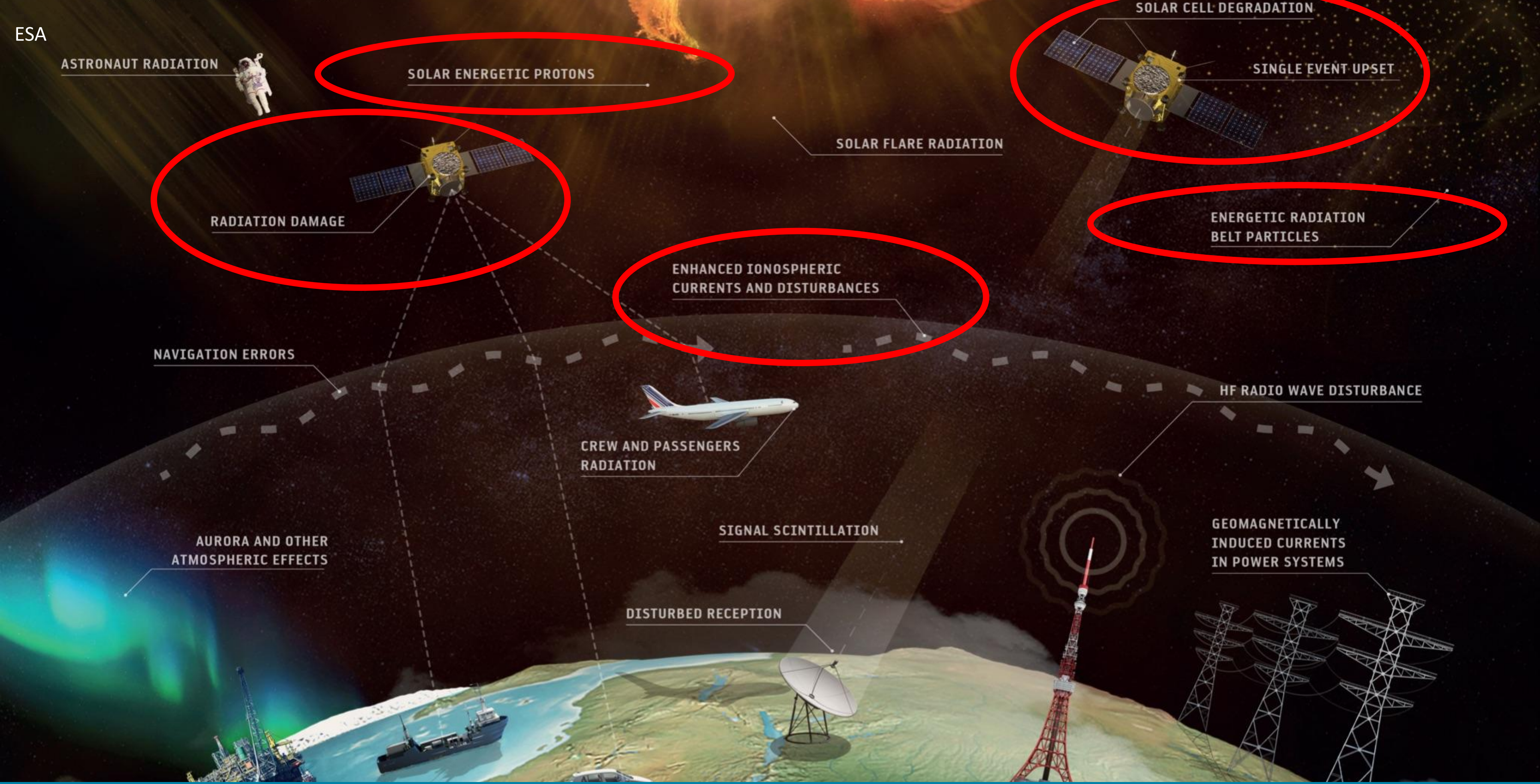
- solar radio bursts can briefly interfere with L-band communication links

Mobile phone networks

- 4G and 5G networks use GPS synchronisation to avoid interference between cell coverage → signal interference if GPS signal disrupted (more GPS used by 5G → more susceptible)

3. Spacecraft effects

ESA


ASTRONAUT RADIATION
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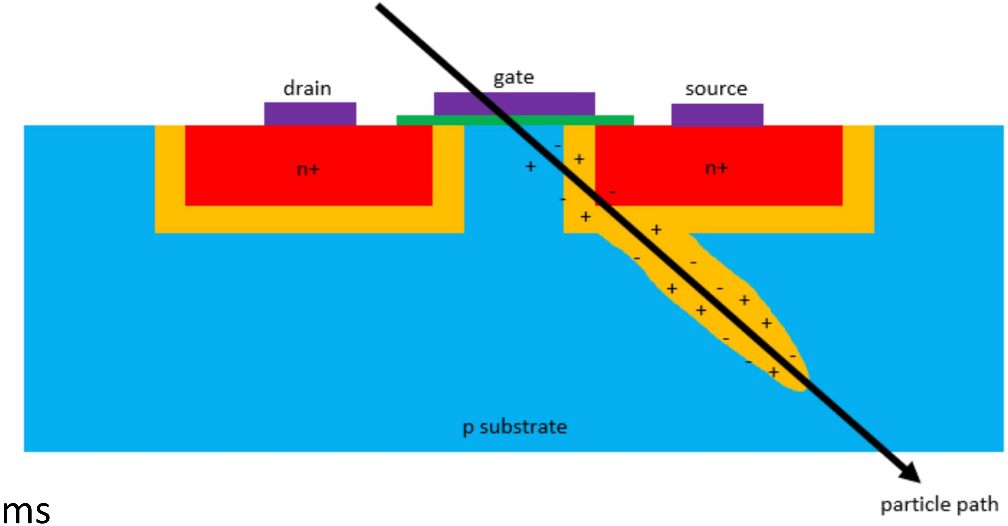
GEOMAGNETICALLY INDUCED CURRENTS IN POWER SYSTEMS
AURORA AND OTHER ATMOSPHERIC EFFECTS
DISTURBED RECEPTION

Spacecraft effects

- S/C exposed to SW first-handedly
- several effects:
  - **single event effects**

Single event effects

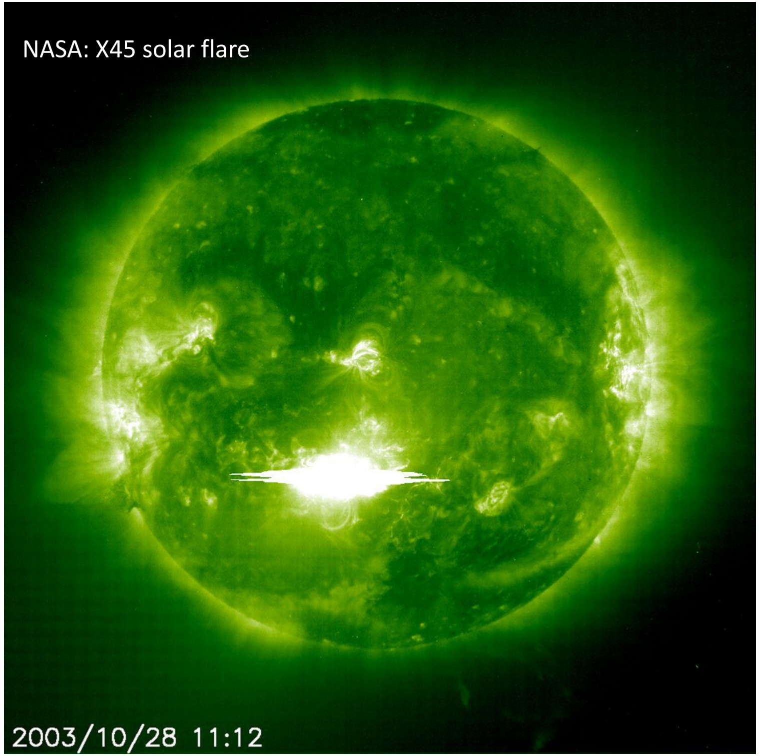
engineeringpilot.com



- S/C exposed to SW first-handedly
- several effects:
  - single event effects (SEE)
  - usually due to n0 (difficult to shield) or p+
  - the high energy n0/p+ impacts the semiconductor material atoms
    - creates electron-hole pairs which can lead to local charge depletion
    - depending how/ where this happens exactly, several types of SEE

Single event effects

- Halloween 2003 storms, October 29 2003, G5
- Goddard's SS Mission Operations Team: 59% of NASA's Earth and space science satellites were affected
    - data outages
    - reboots
    - unwanted thruster firings
- According to USAF operators: over half a satellites lost, up to 3 days to reestablish contact


NASA: X45 solar flare

2003/10/28 11:12

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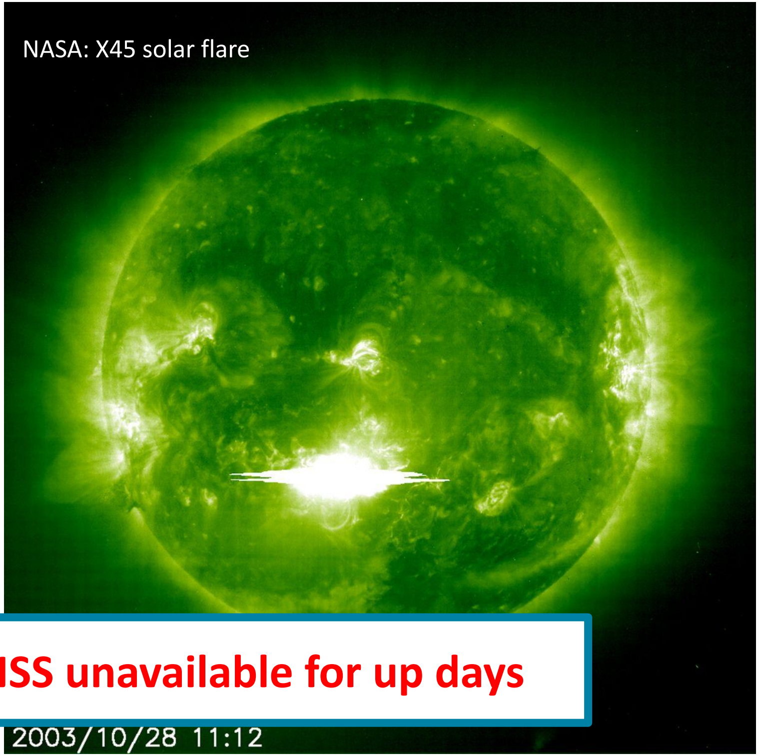

NASA: X45 solar flare

2003/10/28 11:12

→ SEEs can make SATCOM services/ GNSS unavailable for up days

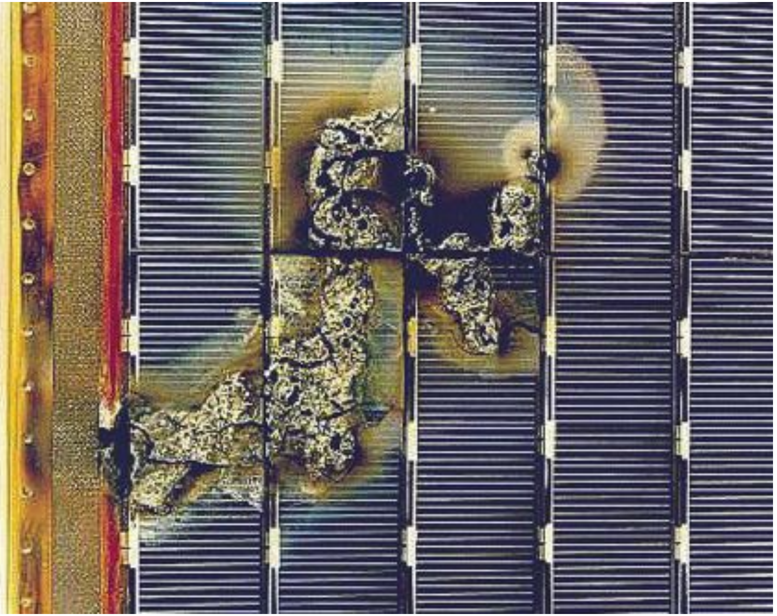
Spacecraft effects

- S/C exposed to SW first-handedly
- several effects:
  - single event effects
  - **satellite charging**

Spacecraft charging

- surface charging due to hot e- forming above auroras (LEO) or due to solar flux (GEO)
- e.g. Galaxy 15 telecomm. sat lost for 8 months in April 2010, the ADEOS-II (570M USD) in a high inclination LEO lost its power system completely in October 2003
- damage to materials, electronics, PVAs, interference with measurements sometimes complete loss of power & control

ESA: EURECA sat PVA discharge damage



Spacecraft effects

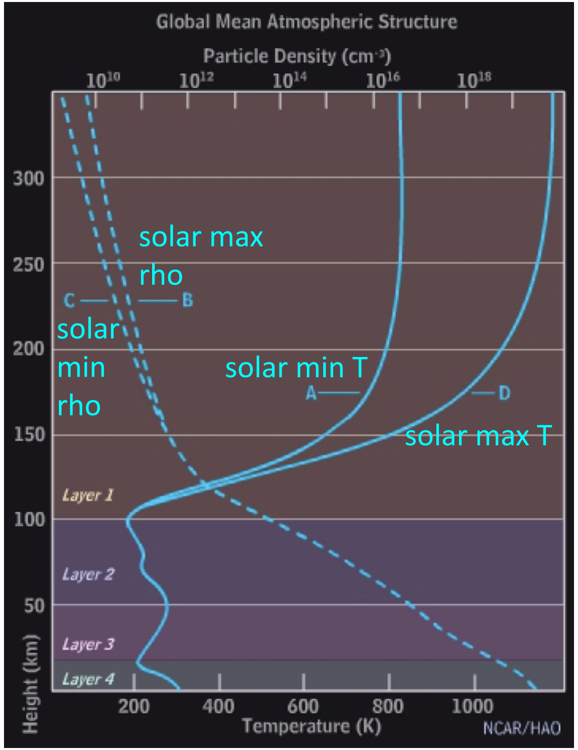
- S/C exposed to SW first-handedly
- several effects:
    - single event effects
    - satellite charging
    - **drag increase**

Spacecraft drag increase

- the atmosphere warms up and expands:
  - absorption of EUV (10 -200nm)
  - Joule heating (increased electrical currents)
  - particle precipitation

- most drag models use 10.7cm radio flux as a proxy for UV flux and Kp/ Ap for short term atmospheric heating:
  - if 10.7 flux > 250 standard solar flux and Kp > 6

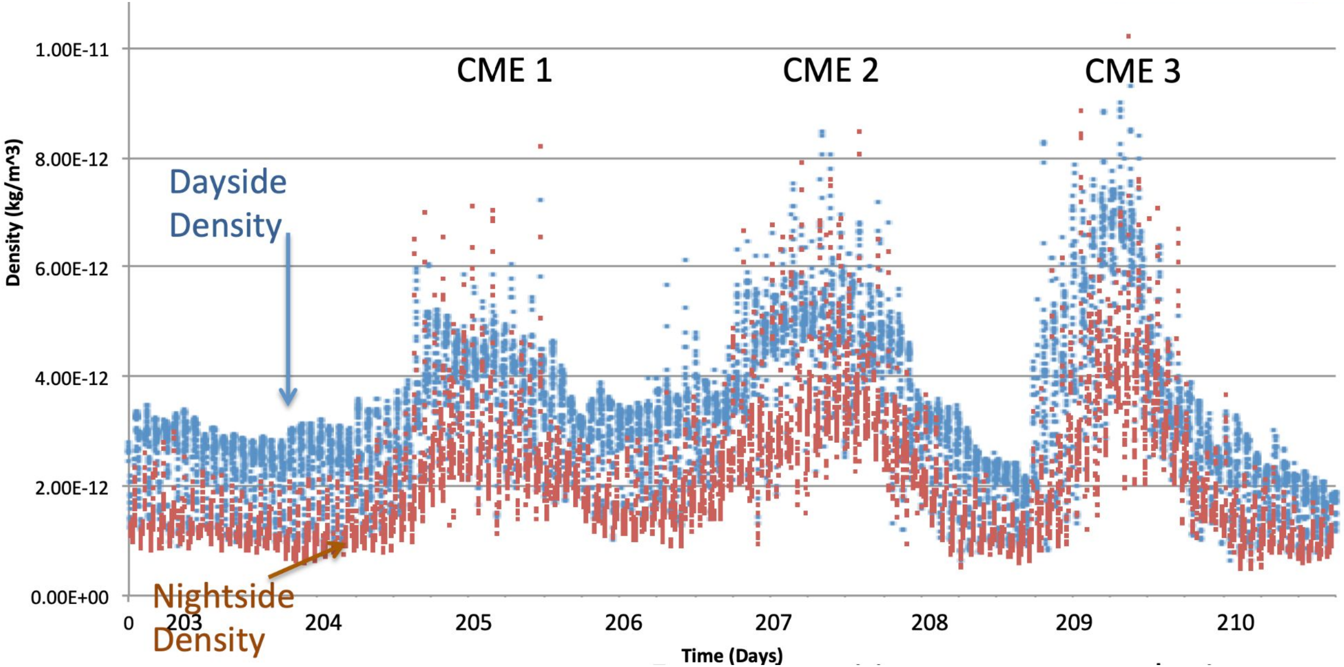
- 13-14 March 1989, a LEO sat recorded to lose 30km of altitude



Spacecraft drag increase

- density increase both on dayside and nightside
- 5x to even 10x the undisturbed profile
- drag scales proportionally to density

Knipp 2013

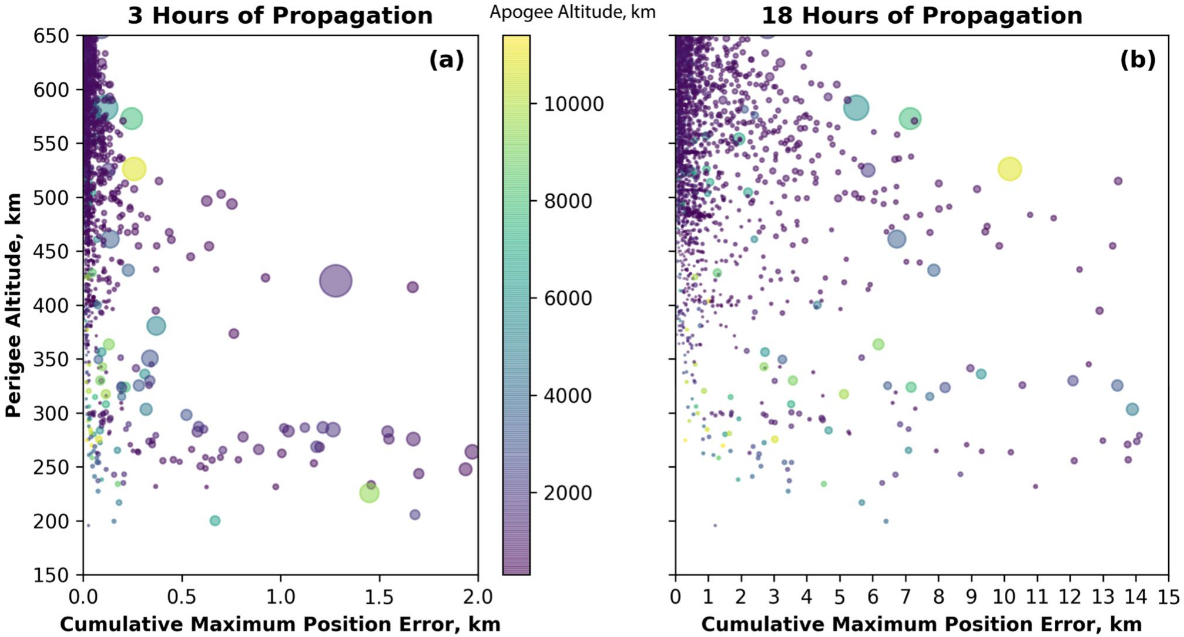


Spacecraft drag increase

- Berger et al. 2020: a simulation of cumulative position errors of 2653 LEO objects in the USAF catalogue as a result of a G2 (Kp 6) storm due to increased atmospheric drag

- geomagnetic storms move all LEO objects to new locations → collision risk

Berger et al. 2020



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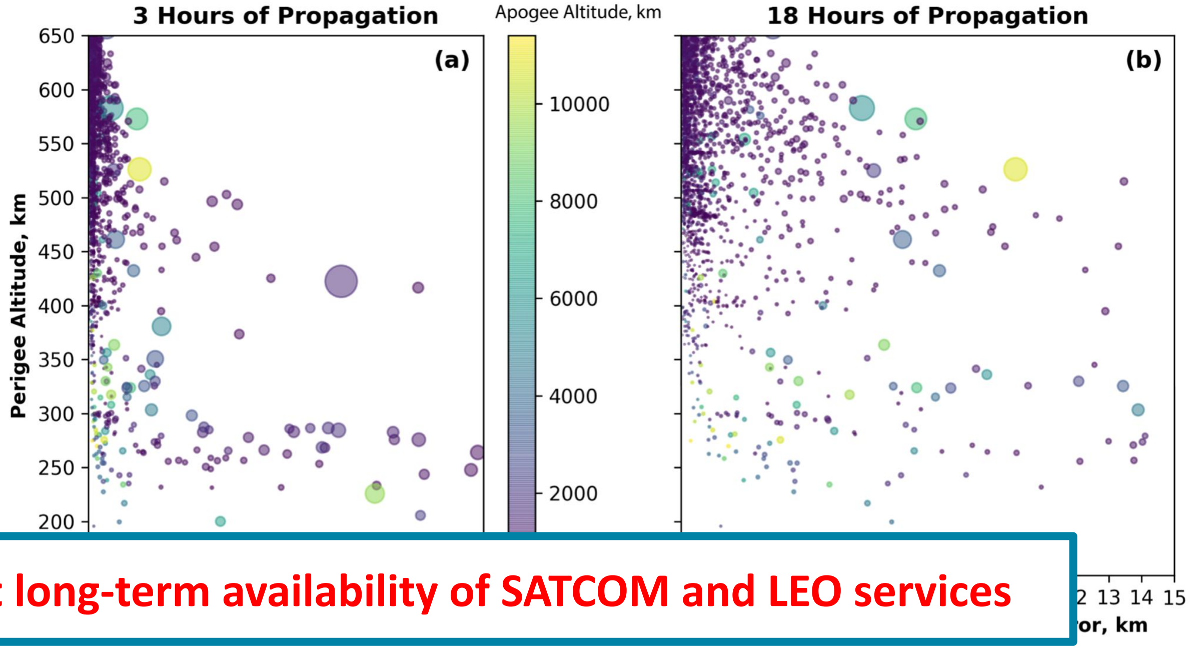


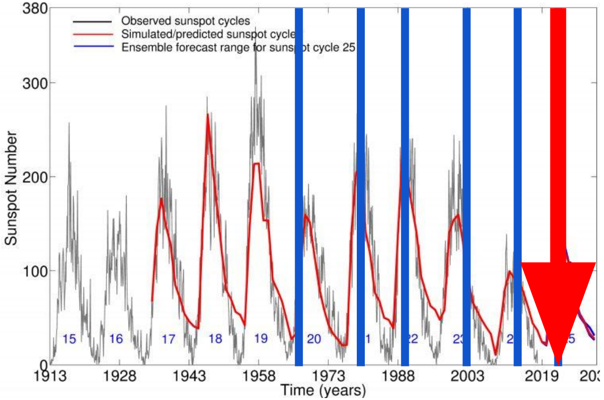
→ drag increase will affect long-term availability of SATCOM and LEO services

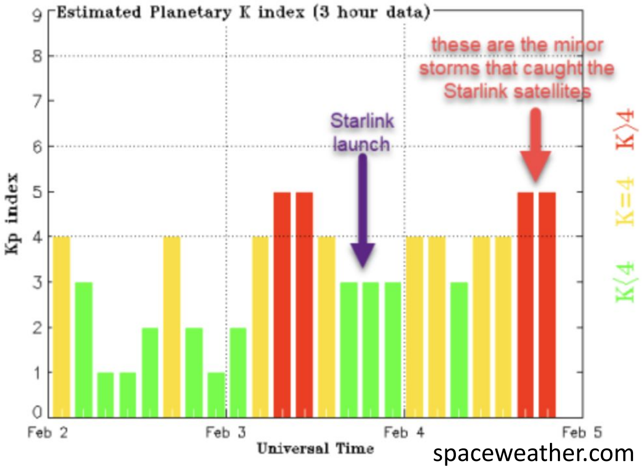
2022 Starlink sats burn up in the atmosphere

- 2 days before launch a minor G1, then Earth passed in the CME’s wake → created another G1
- *"The Starlink team commanded the satellites into a safe-mode where they would fly edge-on to minimize drag…[] … Preliminary analysis show the **increased drag at the low altitudes** prevented the satellites from leaving safe-mode to begin orbit raising maneuvers, and up to 40 of the satellites will re-enter or already have re-entered the Earth’s atmosphere."*

SpaceX loses 40 satellites to geomagnetic storm a day after launch

9 February 2022

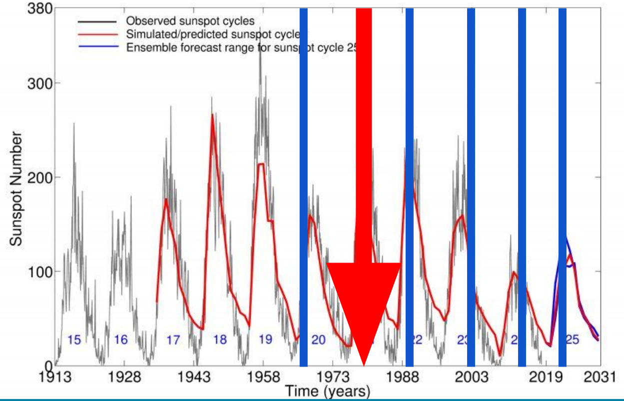




spaceweather.com

1979 Skylab's premature re-entry

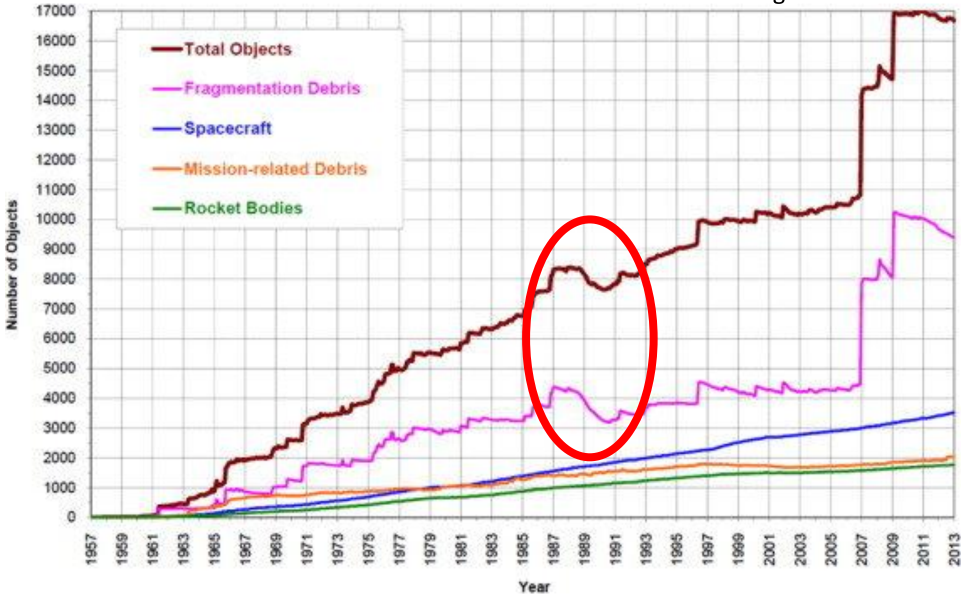
- Skylab was the first US space station (launched 1973)
- originally planned for de-orbit in 1982
- premature re-entry in 1979 because of higher-than-expected solar activity
- millions of dollars invested to save the station, but the attempts still failed



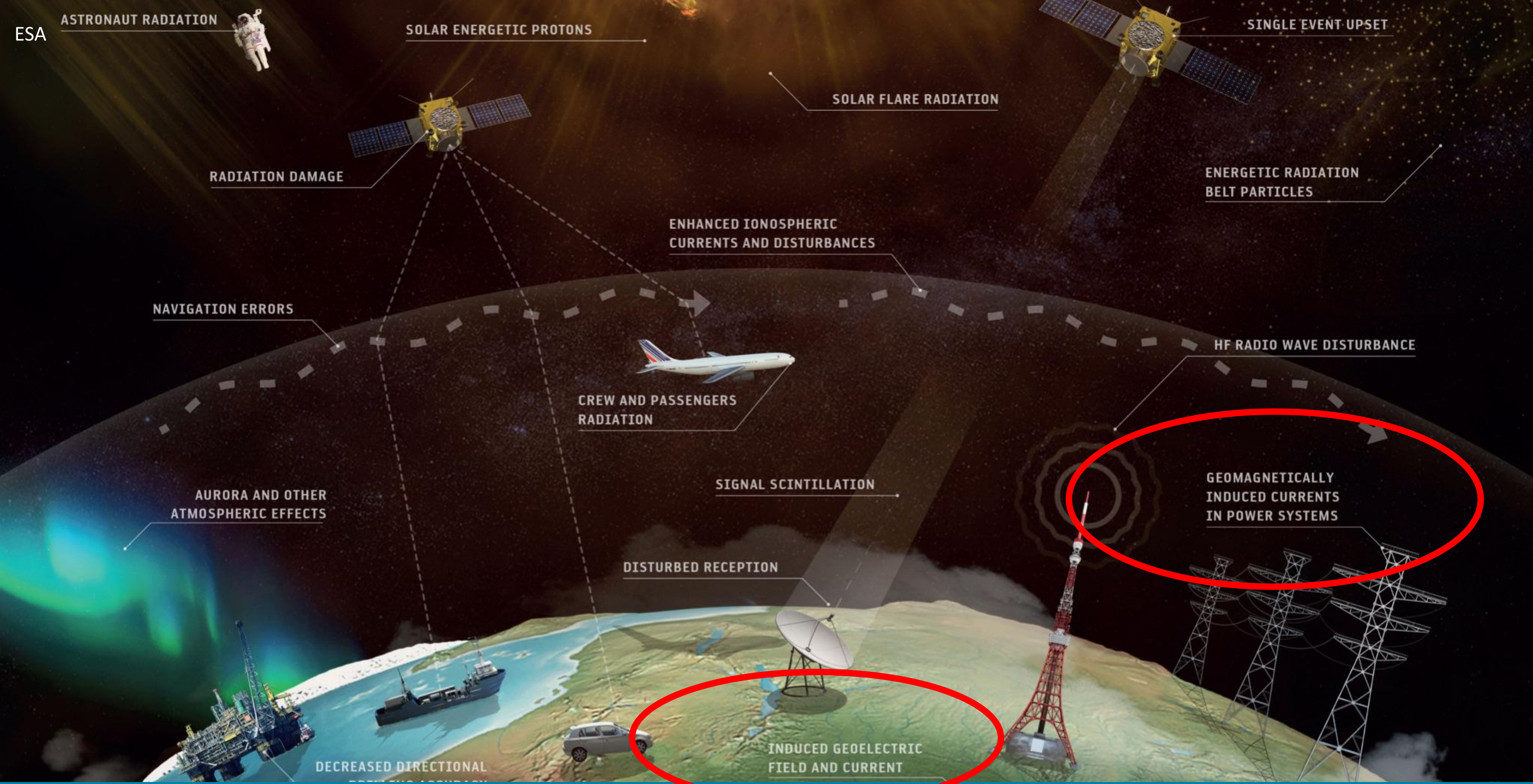
Spacecraft drag increase

- monthly number of objects in the Earth orbit cataloged by the US Space Surveillance Network

Englert et al. 2014



4. Power grid effects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ESA

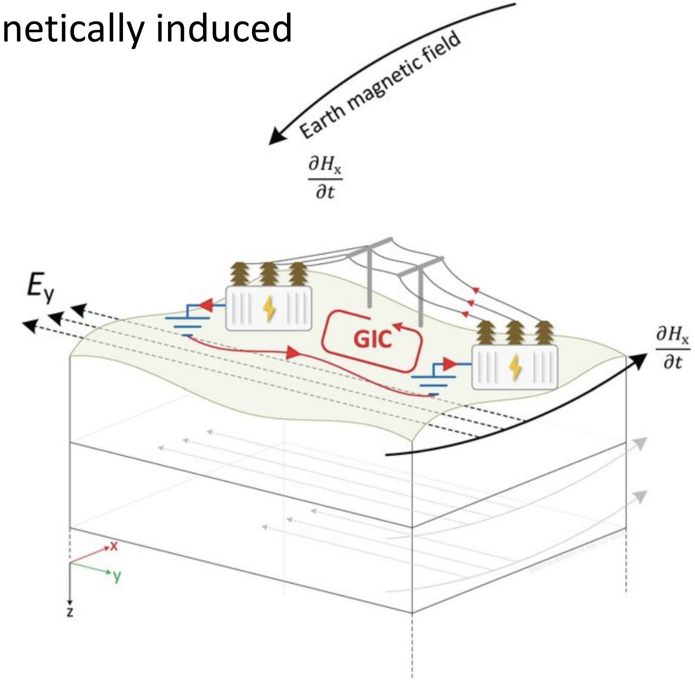
Power grids

Albert et al. 2022

- long-distance high-voltage systems sensitive to geomagnetically induced currents (GIC)

- a time varying magnetic field → telluric currents (in the conducting ground) → secondary magnetic field → Faraday's law of induction → electric field on the surface: GIC

- electric power transmission networks, oil and gas pipelines, telecommunication cables, railway circuits, other large-scale conductors



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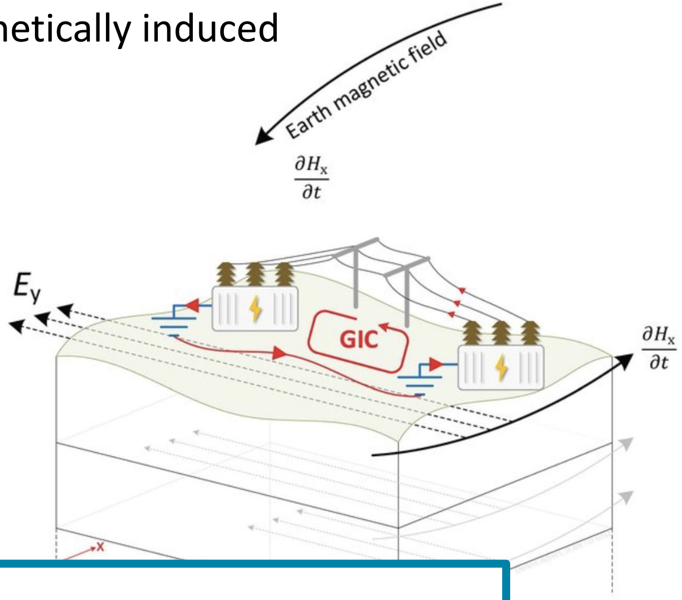
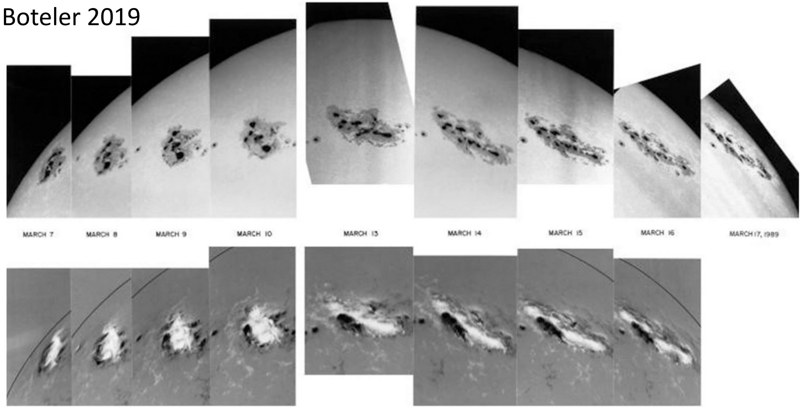


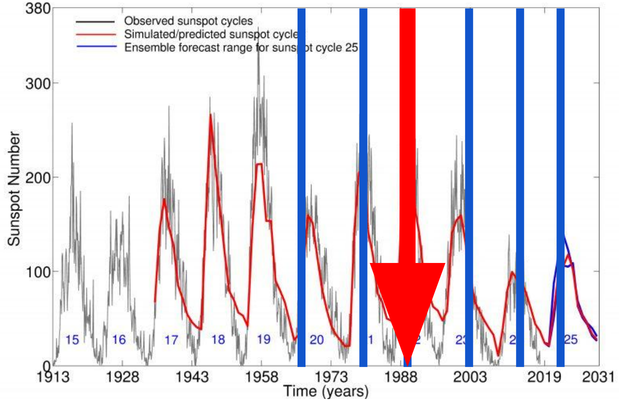
→ blackouts due to GICs might result in a complete power outage

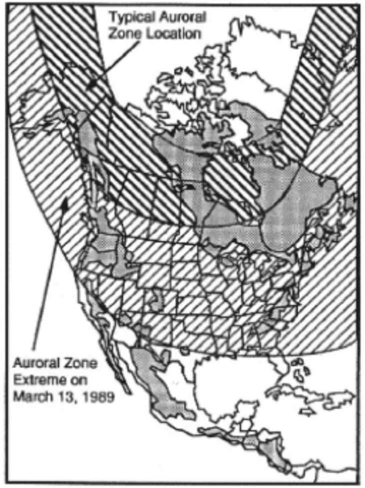
1989 Quebec blackout

- March 13, 1989, 2:45 LT, -589 nT
- within ~ 1.5 minutes the entire network collapsed, after 9 hours: 17 % of the load still out of service
- 6M people without electricity

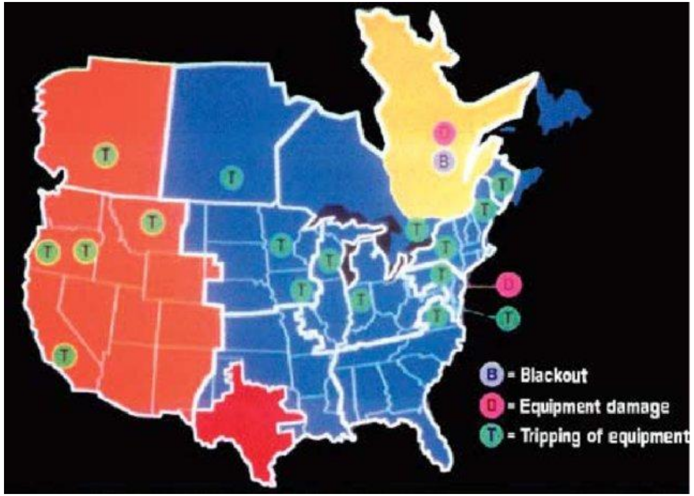
Boteler 2019







Electric Power Research Institute, Inc.



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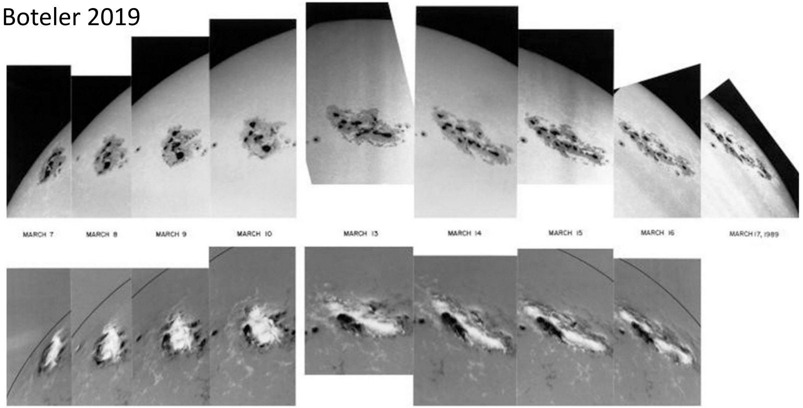
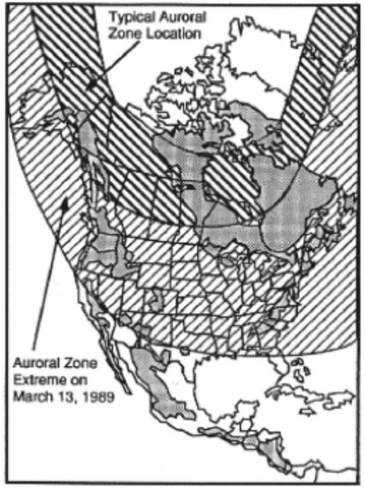
- 6M people without electricity for several hours
- costs to Hydro-Québec:
  - direct damage to equipment 6.5M CAD
  - total costs 13.2M CAD


Boteler 2019



spaceweatherarchive.com

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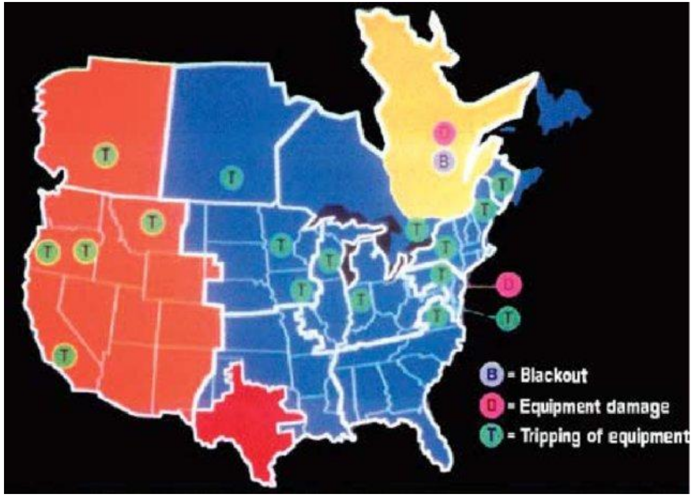
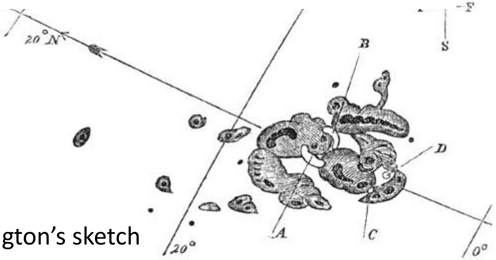


Other blackouts

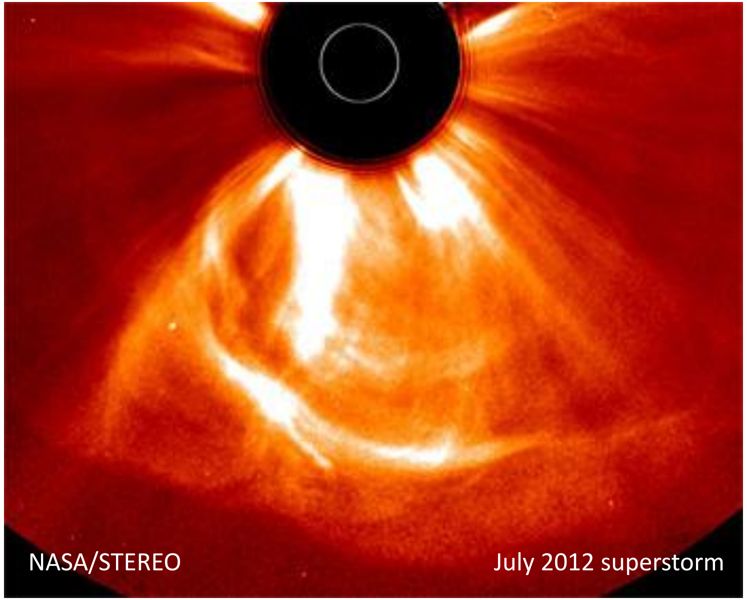


Carrington's sketch

- Malmo, October 30, 2003 (G5), about 50k customers without electricity for 20-50 min

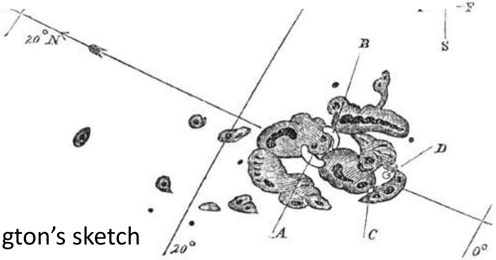
- 1859 Carrington event September 1, 0.80 to 1.75 µT
    - failed telegraph communications, "shocking operators and setting papers ablaze"

    - In Boston, could communicate only when they unplugged batteries: atmosphere so charged due to the auroral current was sufficient to transmit messages to Portland


NASA/STEREO

July 2012 superstorm

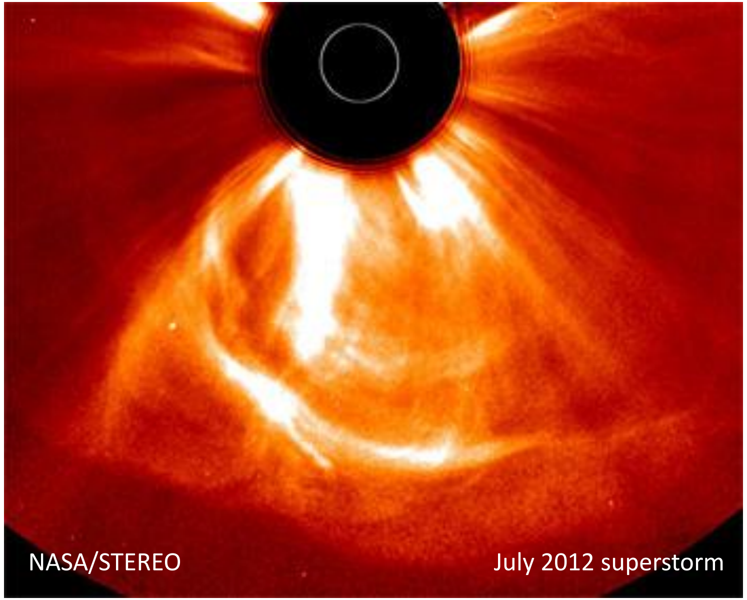
Other blackouts



Carrington's sketch

- Malmo, October 30, 2003 (G5), about 50k customers without electricity for 20-50 min

- July 23, 2012 "superstorm" that missed the Earth:
  - the National Space Science Center of the Chinese Academy of Sciences in Beijing estimated:
    - trillions of dollars of damage
    - 4-10 years recovery time


NASA/STEREO

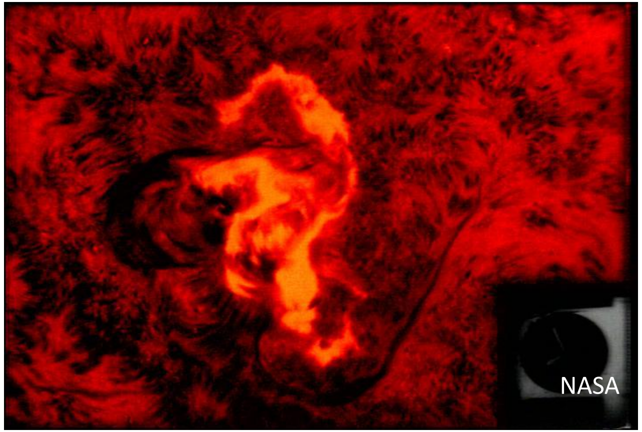
July 2012 superstorm

August 1972 mine explosions in Vietnam

- 2 and 4 August 1972, day-time radio blackouts, X-ray emissions lasting 16 hours

- USAF’s Vela nuclear detonation detection satellites mistook that an explosion occurred, but the monitoring personnel identified the real source

- detonation of a ‘large number’ of sea mines dropped in North Vietnam coastal waters
  - magnetic sensors in the mines triggered, originally meant to detect passing metal ships


NASA

5. Special considerations

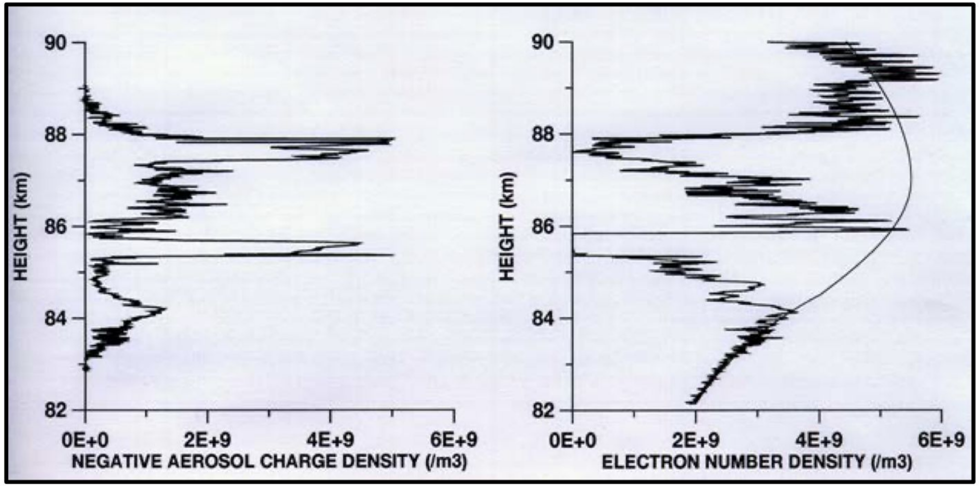
Special considerations: Polar regions

- polar regions latitudes: frequent disruptions of signals
    - **Polar Mesosphere Summer Echoes: PMSE**
    - **Noctilucent Clouds: NC**

- due to large aerosol particles affecting electron density profiles

- can affect signal transmission to and from satellites

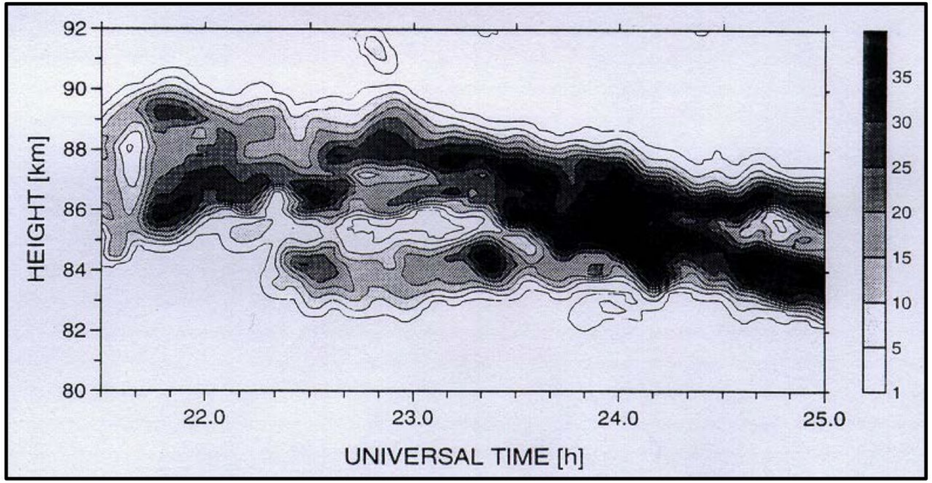
FFI.no



Special considerations: Polar regions

FFI.no

- polar regions latitudes: frequent disruptions of signals
  - **Polar Mesosphere Summer Echoes: PMSE**
  - **Noctilucent Clouds: NC**
- PMSE: 30 - 300MHz frequency
- top shows NC
- right shows PMSE at 50MHz radar measured in Andøya



Special considerations: Polar regions

FFI.no

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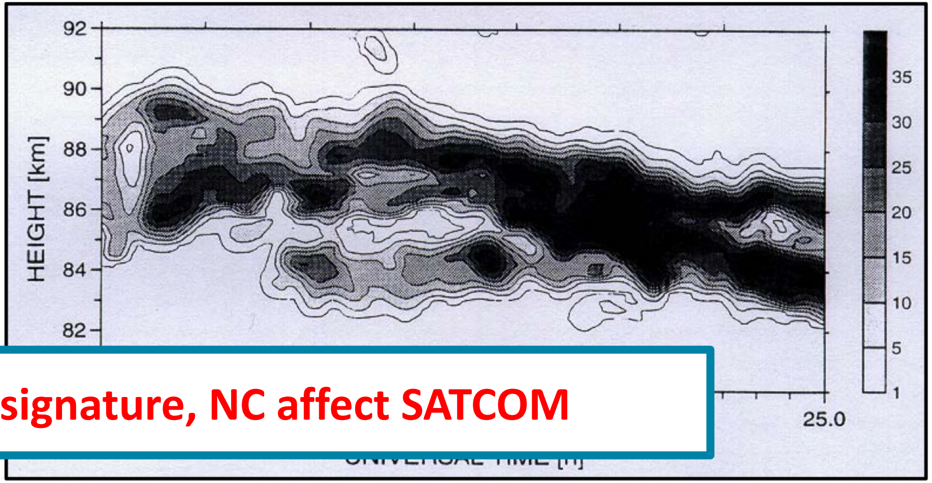


→ PMSE might show up as radar signature, NC affect SATCOM

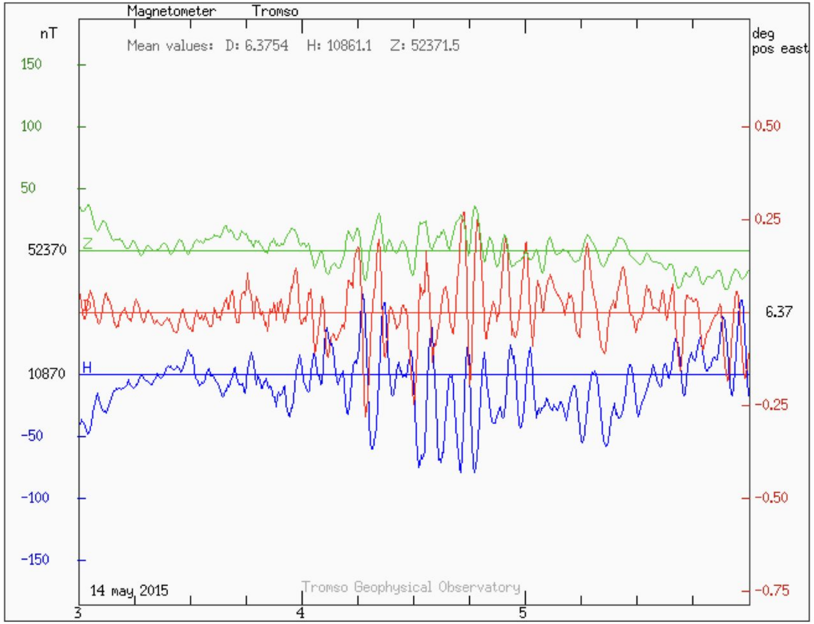
Special considerations: Polar regions

- polar regions latitudes: **magnetic micro-pulses**
- occur with CMEs, current fluctuations

- because of their frequency (<1Hz) they might resemble both over-/ underwater vehicles when passing magnetometers

- unlike vehicles, micro-pulses affect the sensors everywhere the same, whereas for a passing vehicle → a motion signature

FFI.no



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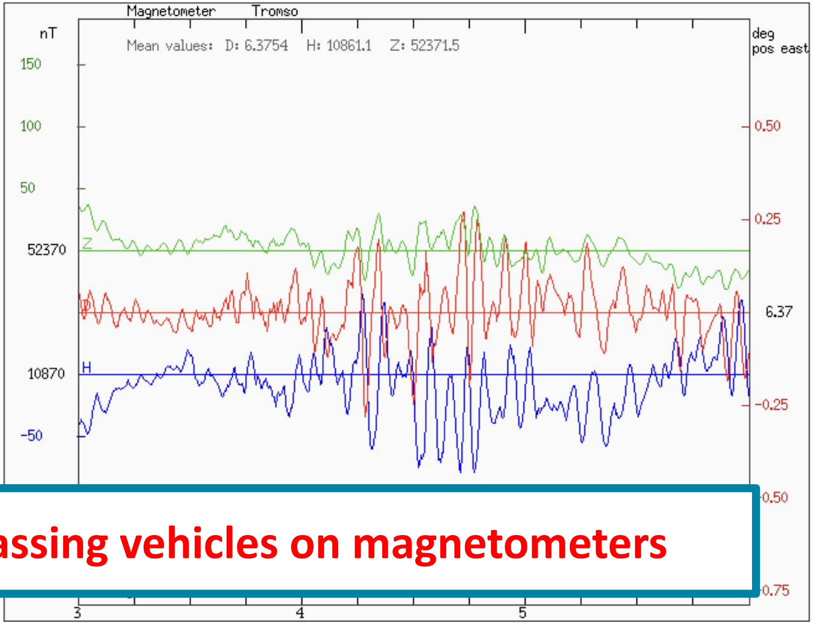
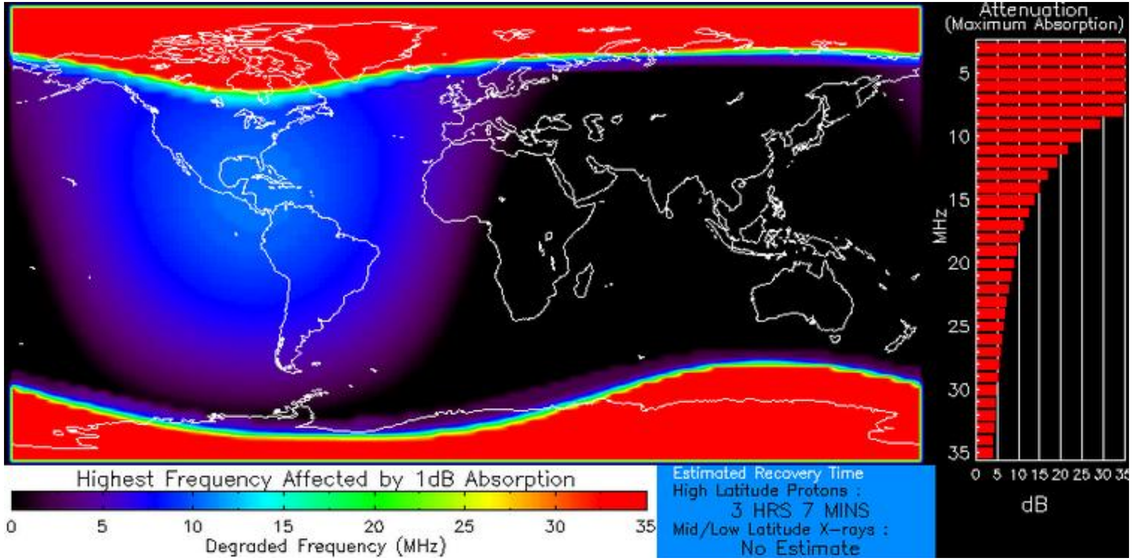


→ magnetic micro-pulses might show up as passing vehicles on magnetometers

Special considerations: Polar regions

- polar regions latitudes: **polar cap absorption:** high energy protons from the Sun, leading to a massive ionisation in the D-layer
- disrupt or completely block frequencies of 2-30MHz
- scintillation at VHF and UHF
- known since 1956 (made HF impossible), wide in Antarctica in 1967

Spaceweather.com, SWPC

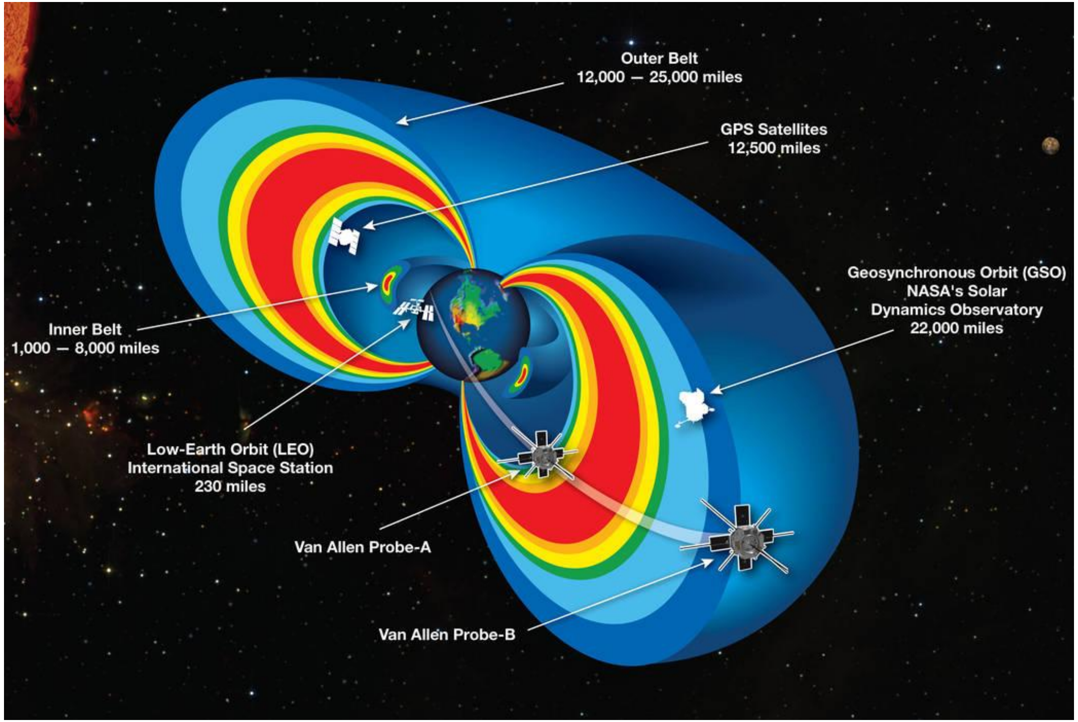


Special considerations: Radiation belts

- trapped (also solar wind) particles in the magnetosphere → Van Allen radiation belts around Earth
    - intersection MEO and GEO orbits
    - heightened radiation exposure

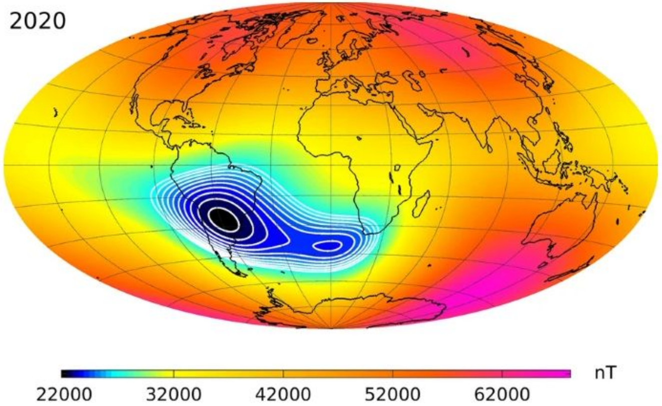
- higher E particles in the inner belt, lower E particles in the outer

NASA



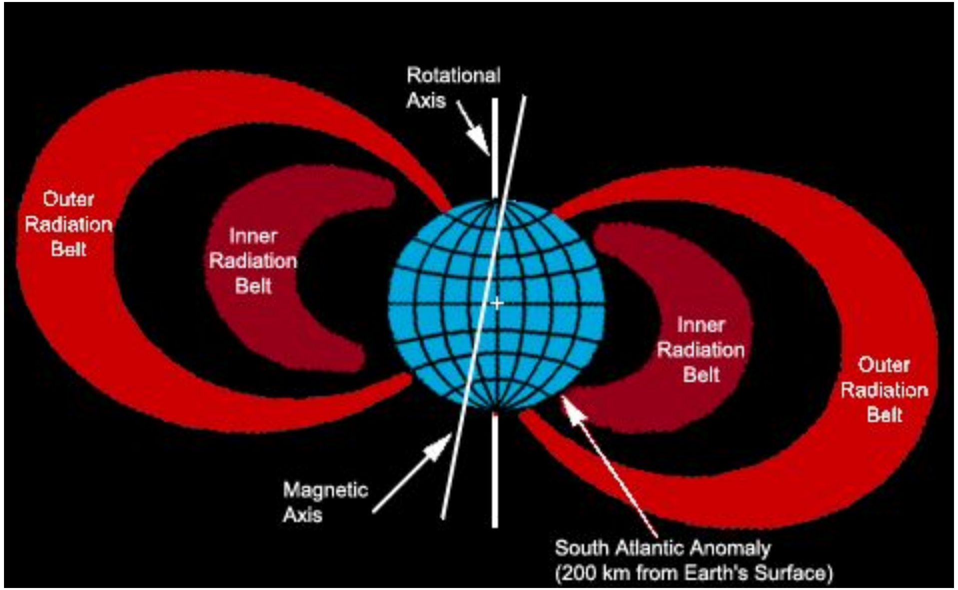
Special considerations: the South Atlantic Anomaly

- the belts are symmetric around the magnetic axis → asymmetric around the rotational axis → the inner belt comes only 200km of Earth surface in the South Atlantic Anomaly → more



ESA

NASA



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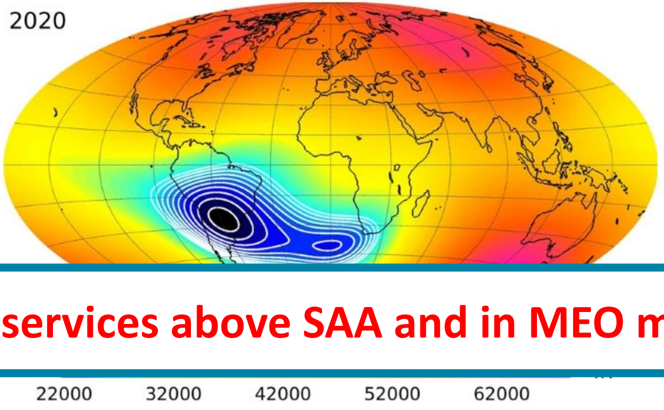

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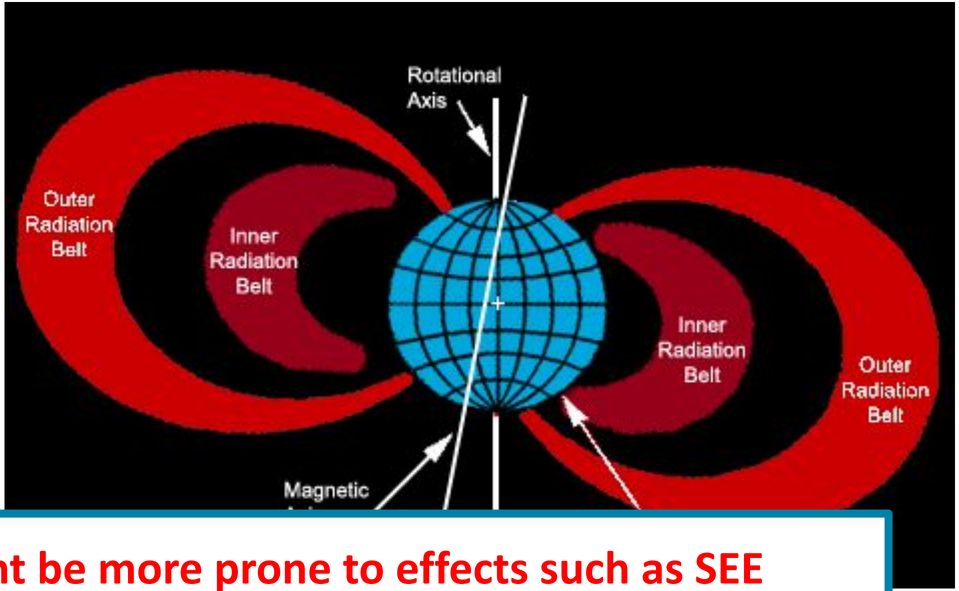


→ services above SAA and in MEO might be more prone to effects such as SEE

6. Vulnerability of military systems

Determining vulnerability of a military system: F35 example

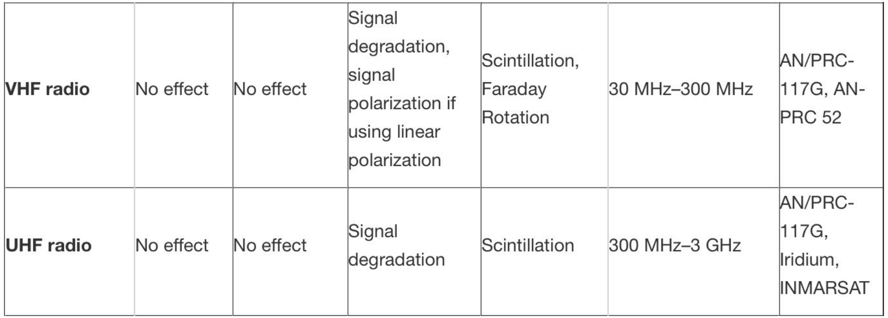
- Northrop Grumman AN/APG-81 active electronically scanned array radar: X band, 8 - 12 GHz (SHF)

- BAE Systems AN/ASQ-239 Barracuda electronic warfare system: S band to K band, 2 - 20 GHz (SHF)

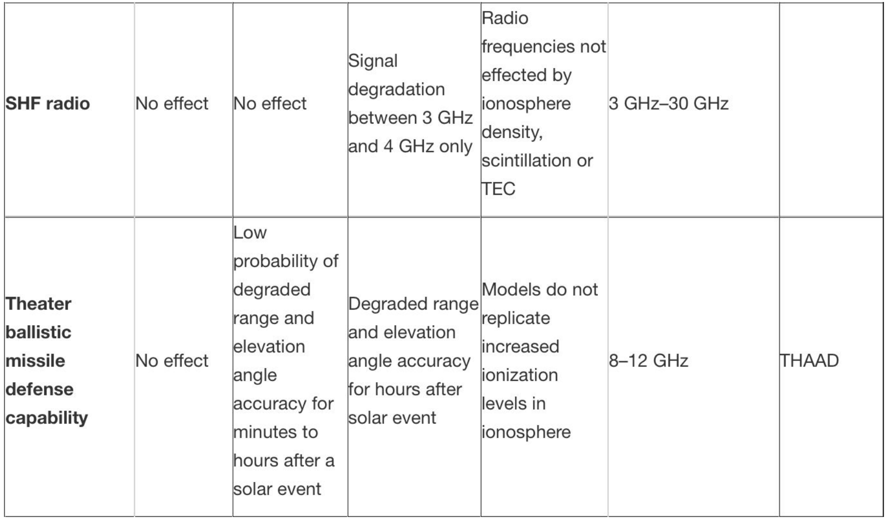
- Northrop Grumman AN/ASQ-242 Integrated CNI suite: VHF to UHF

Effects at mid-latitudes

Source: LTC(R) Gregory Sharpe and MAJ Kenneth Rich (ALSSA Center)



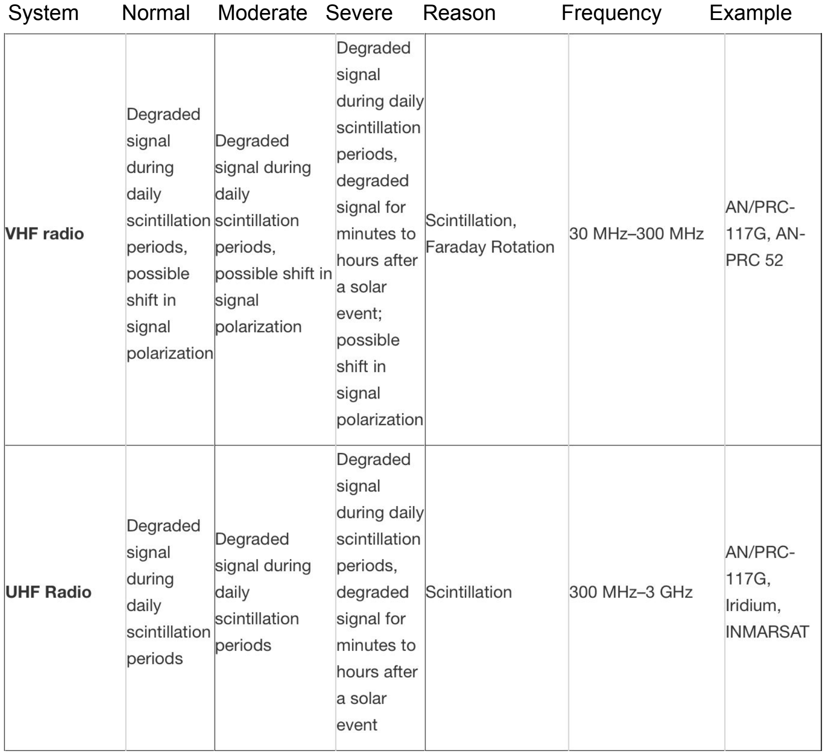
System	Normal	Moderate	Severe	Reason	Frequency	Example
VHF radio	No effect	No effect	Signal degradation, signal polarization if using linear polarization	Scintillation, Faraday Rotation	30 MHz–300 MHz	AN/PRC-117G, AN-PRC 52
UHF radio	No effect	No effect	Signal degradation	Scintillation	300 MHz–3 GHz	AN/PRC-117G, Iridium, INMARSAT



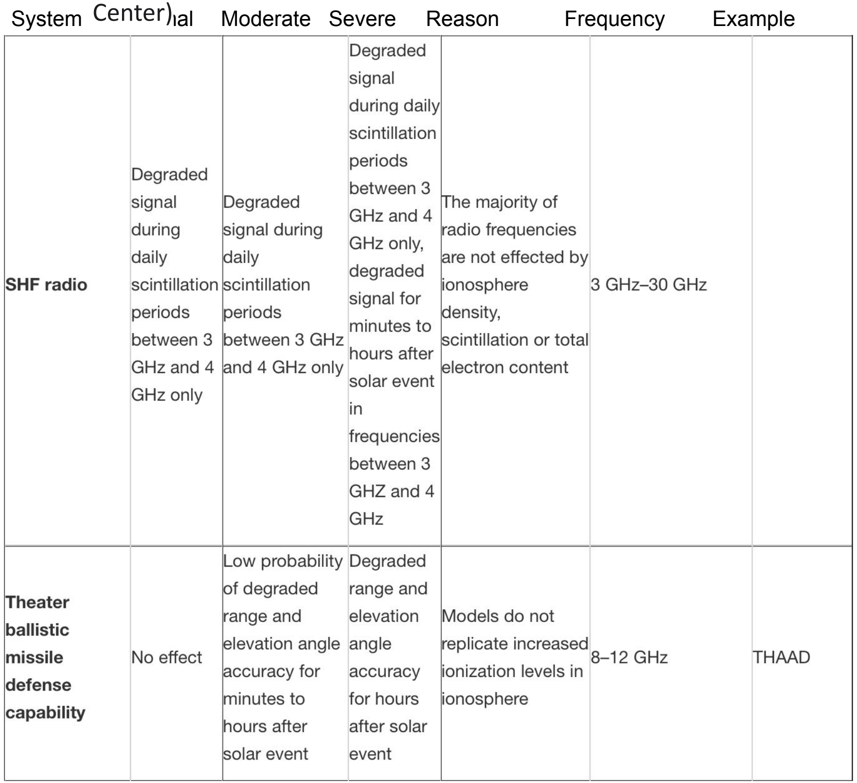
System	Normal	Moderate	Severe	Reason	Frequency	Example
SHF radio	No effect	No effect	Signal degradation between 3 GHz and 4 GHz only	Radio frequencies not effected by ionosphere density, scintillation or TEC	3 GHz–30 GHz	
Theater ballistic missile defense capability	No effect	Low probability of degraded range and elevation angle accuracy for minutes to hours after a solar event	Degraded range and elevation angle accuracy for hours after solar event	Models do not replicate increased ionization levels in ionosphere	8–12 GHz	THAAD

Effects at polar-latitudes

Source: LTC(R) Gregory Sharpe and MAJ Kenneth Rich (ALSSA Center)



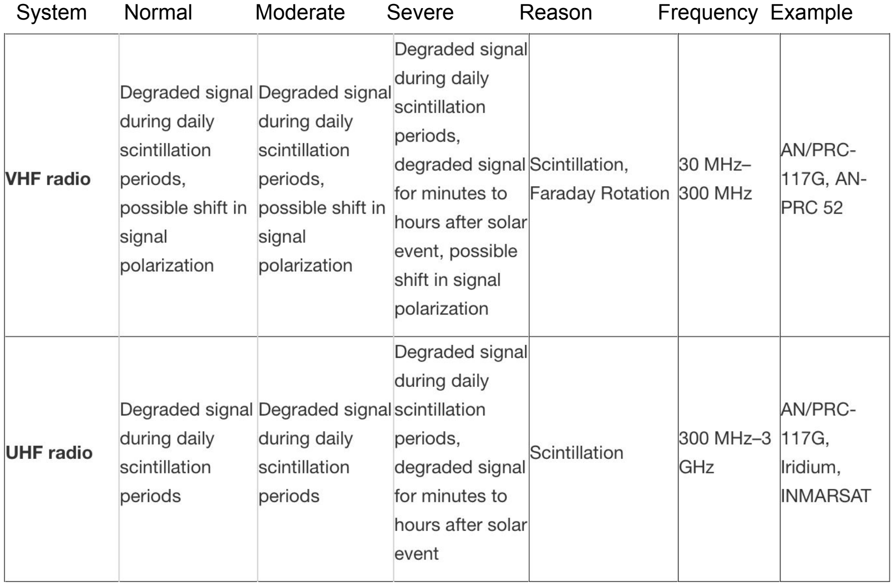
System	Normal	Moderate	Severe	Reason	Frequency	Example
VHF radio	Degraded signal during daily scintillation periods, possible shift in signal polarization	Degraded signal during daily scintillation periods, possible shift in signal polarization	Degraded signal during daily scintillation periods, degraded signal for minutes to hours after a solar event; possible shift in signal polarization	Scintillation, Faraday Rotation	30 MHz–300 MHz	AN/PRC-117G, AN-PRC 52
UHF Radio	Degraded signal during daily scintillation periods	Degraded signal during daily scintillation periods	Degraded signal during daily scintillation periods, degraded signal for minutes to hours after a solar event	Scintillation	300 MHz–3 GHz	AN/PRC-117G, Iridium, INMARSAT



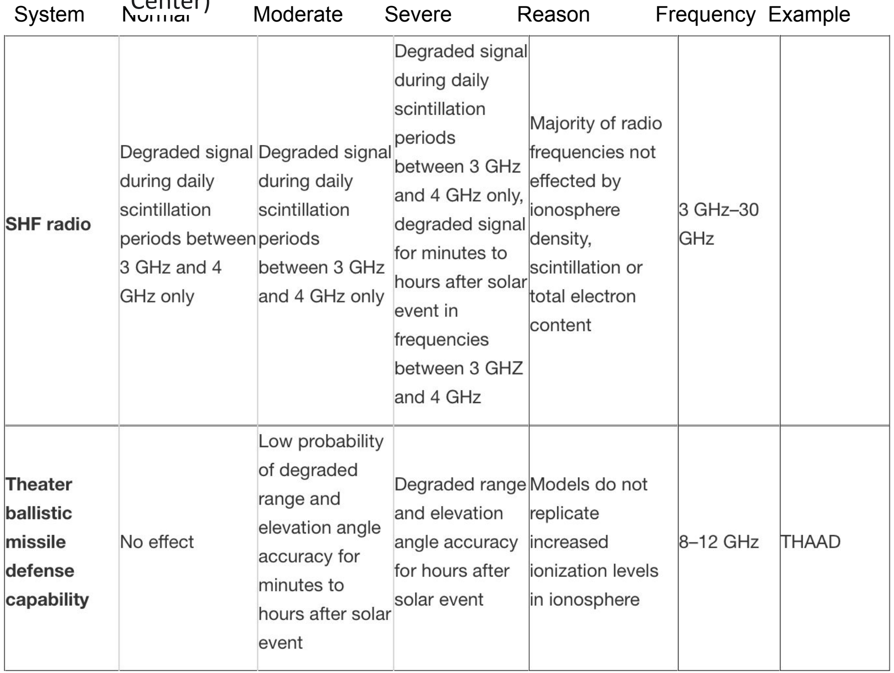
System	al	Moderate	Severe	Reason	Frequency	Example
SHF radio	Degraded signal during daily scintillation periods between 3 GHz and 4 GHz only	Degraded signal during daily scintillation periods between 3 GHz and 4 GHz only	Degraded signal during daily scintillation periods between 3 GHz and 4 GHz only, degraded signal for minutes to hours after solar event in frequencies between 3 GHZ and 4 GHz	The majority of radio frequencies are not effected by ionosphere density, scintillation or total electron content	3 GHz–30 GHz	
Theater ballistic missile defense capability	No effect	Low probability of degraded range and elevation angle accuracy for minutes to hours after solar event	Degraded range and elevation angle accuracy for hours after solar event	Models do not replicate increased ionization levels in ionosphere	8–12 GHz	THAAD

Effects at equatorial-latitudes

Source: LTC(R) Gregory Sharpe and MAJ Kenneth Rich (ALSSA Center)



System	Normal	Moderate	Severe	Reason	Frequency	Example
VHF radio	Degraded signal during daily scintillation periods, possible shift in signal polarization	Degraded signal during daily scintillation periods, possible shift in signal polarization	Degraded signal during daily scintillation periods, degraded signal for minutes to hours after solar event, possible shift in signal polarization	Scintillation, Faraday Rotation	30 MHz–300 MHz	AN/PRC-117G, AN-PRC 52
UHF radio	Degraded signal during daily scintillation periods	Degraded signal during daily scintillation periods	Degraded signal during daily scintillation periods, degraded signal for minutes to hours after solar event	Scintillation	300 MHz–3 GHz	AN/PRC-117G, Iridium, INMARSAT



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SHF radio	Degraded signal during daily scintillation periods between 3 GHz and 4 GHz only	Degraded signal during daily scintillation periods between 3 GHz and 4 GHz only	Degraded signal during daily scintillation periods between 3 GHz and 4 GHz only, degraded signal for minutes to hours after solar event in frequencies between 3 GHZ and 4 GHz	Majority of radio frequencies not effected by ionosphere density, scintillation or total electron content	3 GHz–30 GHz	
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Determining vulnerability of a military system: F35 example

- Northrop Grumman AN/APG-81 active electronically scanned array radar: X band, 8 - 12 GHz (SHF)
    - range and accuracy might degrade with moderate to severe storms

- BAE Systems AN/ASQ-239 Barracuda electronic warfare system: S band to K band, 2 - 20 GHz (SHF)
    - in mid-latitude regions such as Belgium, these frequencies are generally not affected by SWx
    - in polar and equatorial regions, these bands might respond to strong ionospheric scintillation

- Northrop Grumman AN/ASQ-242 Integrated CNI suite: VHF to UHF
    - at polar and equatorial latitudes might be sensitive to strong scintillation
    - VHF might also degrade for minutes to hours after strong geomagnetic events

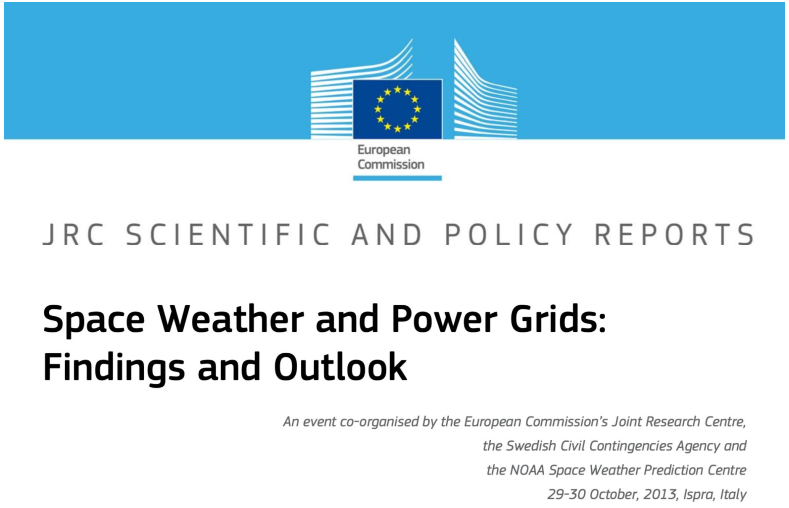
7. Are we ready?

Are we ready yet?

- ongoing training of Space, Air Traffic and Defence operators (e.g. by ROB)
- the European Space Weather Office in construction
- PECASUS space weather advisory for airliners

- UK & USA power grids should be resilient:
  how about the north sea wind power hub?

- are critical infrastructures & technologies
  protected? Stakeholders will not disclose



European Commission

JRC SCIENTIFIC AND POLICY REPORTS

Space Weather and Power Grids: Findings and Outlook

An event co-organised by the European Commission's Joint Research Centre,
the Swedish Civil Contingencies Agency and
the NOAA Space Weather Prediction Centre
29-30 October, 2013, Ispra, Italy

Are we ready yet?

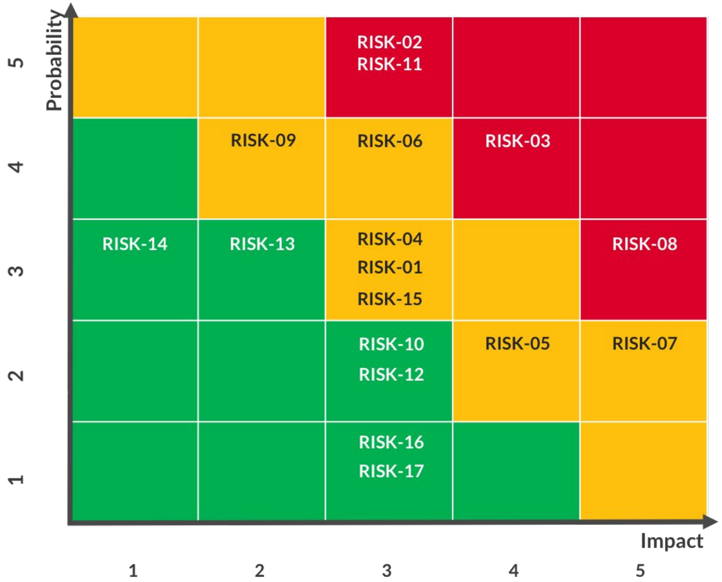
- space weather effects can be expensive

- PITHIA-NRF report (assuming a Carrington-like event):
  - LEO 10-100 satellites deorbit, 4 to 200 billion EUR
  - GEO services outage 1 to 14 days, 200 million to 2.6 billion EUR
  - A/C flight re-routing & canceling, 1 billion EUR

Are we ready yet?

- current forecasting software: low reliability

- low frequency of Carrington-like events:
    - cost/ reliability trade-off
    - insufficient statistics



	1	2	3	4	5
5			RISK-02 RISK-11		
4		RISK-09	RISK-06	RISK-03	
3	RISK-14	RISK-13	RISK-04 RISK-01 RISK-15		RISK-08
2			RISK-10 RISK-12	RISK-05	RISK-07
1			RISK-16 RISK-17		

- difficult to certainly determine the origin of damage and estimate the actual economic costs of space weather, also due to business interests

- communication gaps: training of operators

8. Recommendations

Power system protection

- SWx have to be taken into account when designing the system

- several possible prevention & mitigation strategies:
  - installing GIC blocking elements
  - using transformers capable of handling temporarily higher currents
  - operating grids at reduced loading during loading

- most importantly, all critical infrastructure should have a backup power generator

Current Belgian Defence strategy

I. Developing tailored SWx products in collaboration with partner SWx centres

II. Training Defence personnel

III. Opening additional positions for SWx coordination and support

IV. Military accident investigation with SWx expertise

Short-term SWx preparedness

I. Delaying/ fast-tracking operations if an event is expected

II. Aviation operations might need adjustments to trajectories to prevent excessive radiation

III. Switching to higher/ lower frequencies* for communications or using multiple bands at the same time for redundancy

IV. Satellite ISR can be replaced by airborne ISR

V. When interpreting sensor and equipment data, keep SWx in mind

*switching to lower HF radio frequencies during ionospheric depressions and high HF radio frequencies during solar flares

Long-term SWx preparedness

I. Perform risk-assessment on critical military systems (vulnerability to SWx)

II. Backing up all critical systems with diesel/ solar/ wind/ other power generators

III. Ensuring that critical communication systems have sufficient diversity in them

IV. Systems with GNSS time-synchronization designed to also operate with holdover technology

V. Challenging service providers to determine the level of survivability of their systems

VI. Where GNSS data is critical, using EGNOS or similar to monitor the level of error

What can we do better on the research side?

- Europe must perfect the R2O2R philosophy
- developers of SWx software are frequently PhDs and PostDocs at universities → they must know what is at stake and what is needed
- at the same time, the customers must keep providing useful feedback to the developers

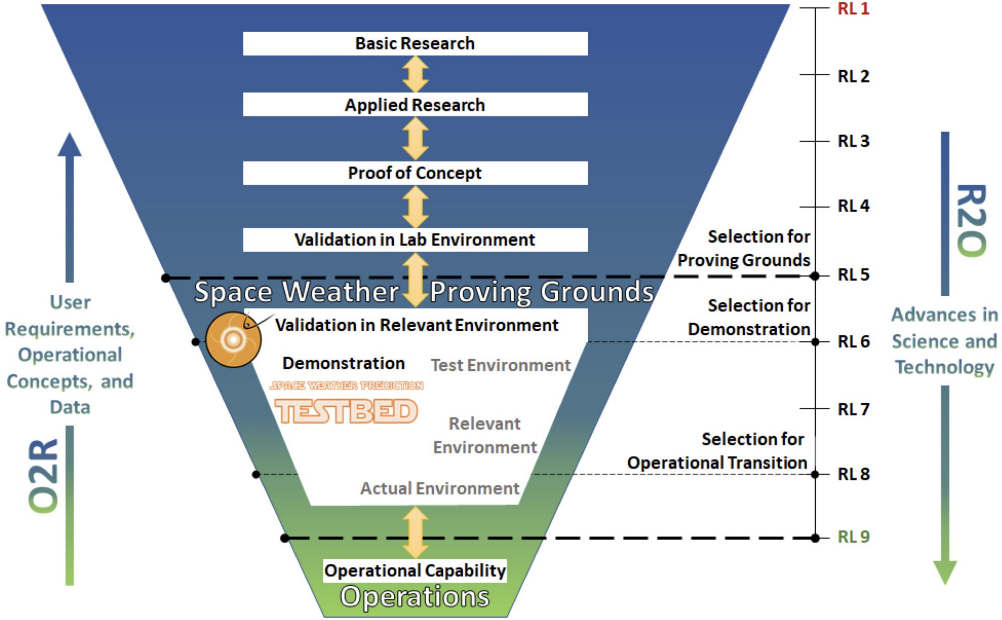
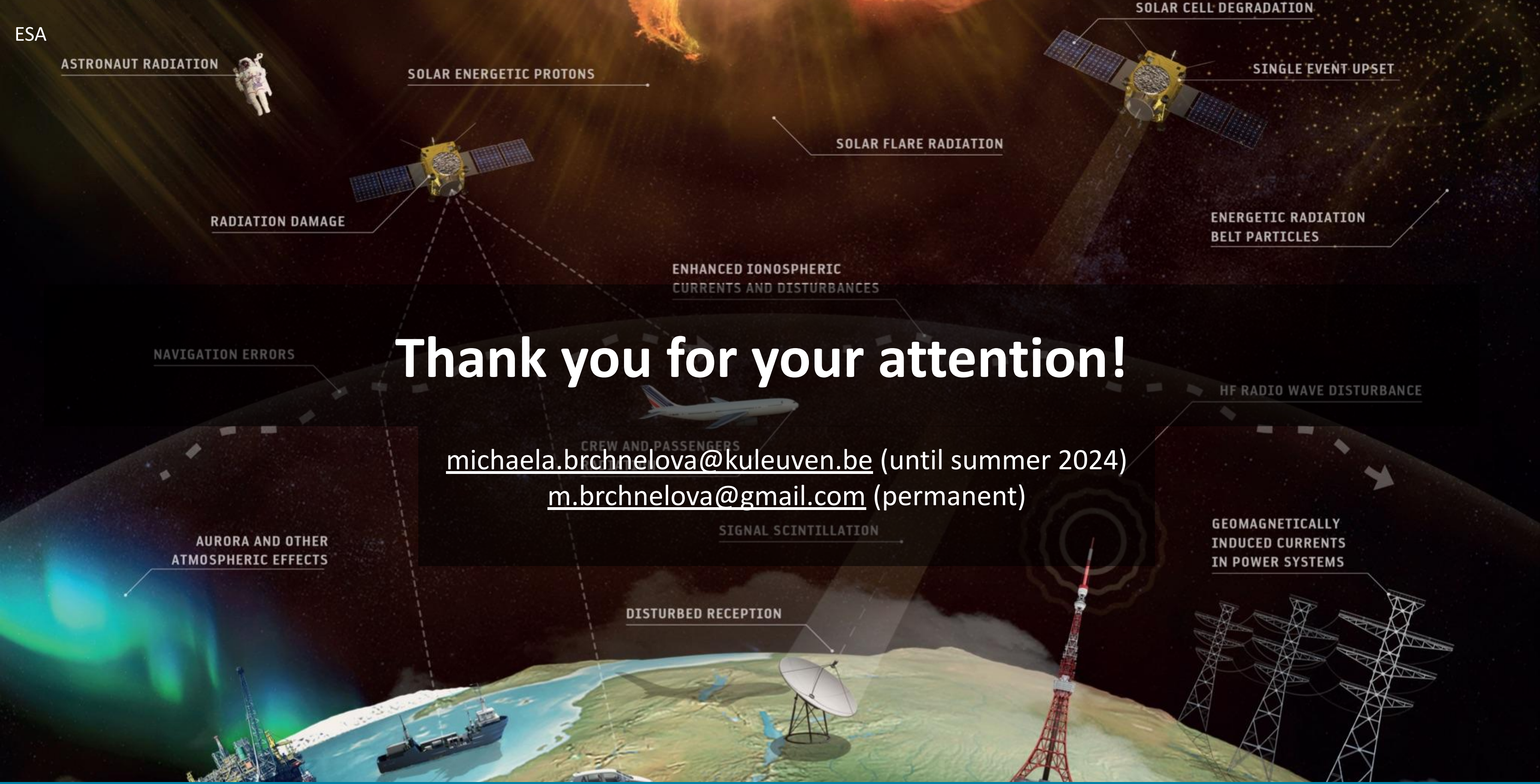


Figure 1: Research to Operations to Research Process (NOAA Example)

Conclusions

- SW events have cost a lot of money and likely even claimed lives in the past
- stronger SW events can be more destructive, but even weaker ones can affect operations depending on the time, place & affected frequencies
- awareness of SW effects and forecasts of the personnel is key for ensuring both smooth operations and data interpretation & analysis
- elements of operations & infrastructure that can be sensitive to SW should be identified and, if possible, backed up appropriately or made more robust



ESA

Thank you for your attention!

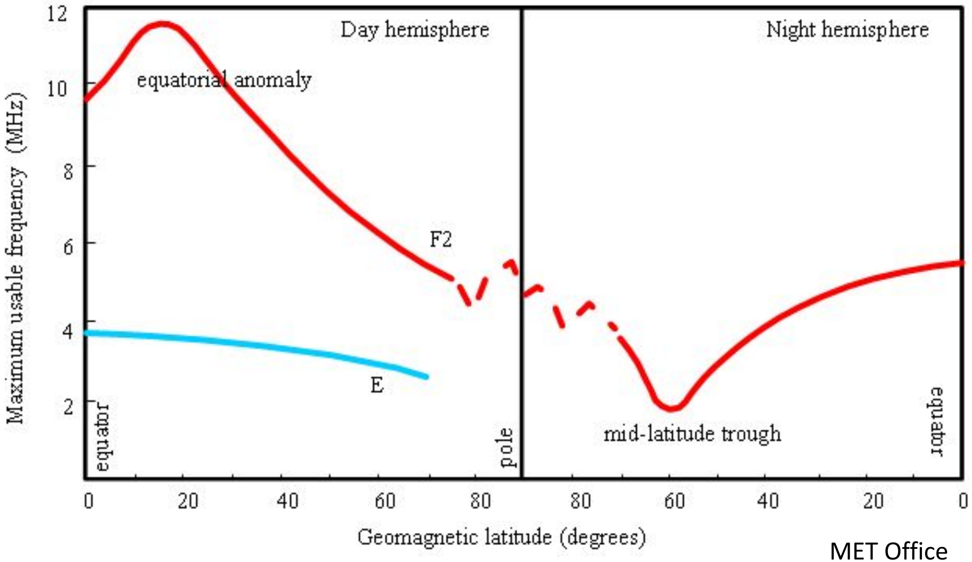
michaela.brchnelova@kuleuven.be (until summer 2024)
m.brchnelova@gmail.com (permanent)

Appendix & details

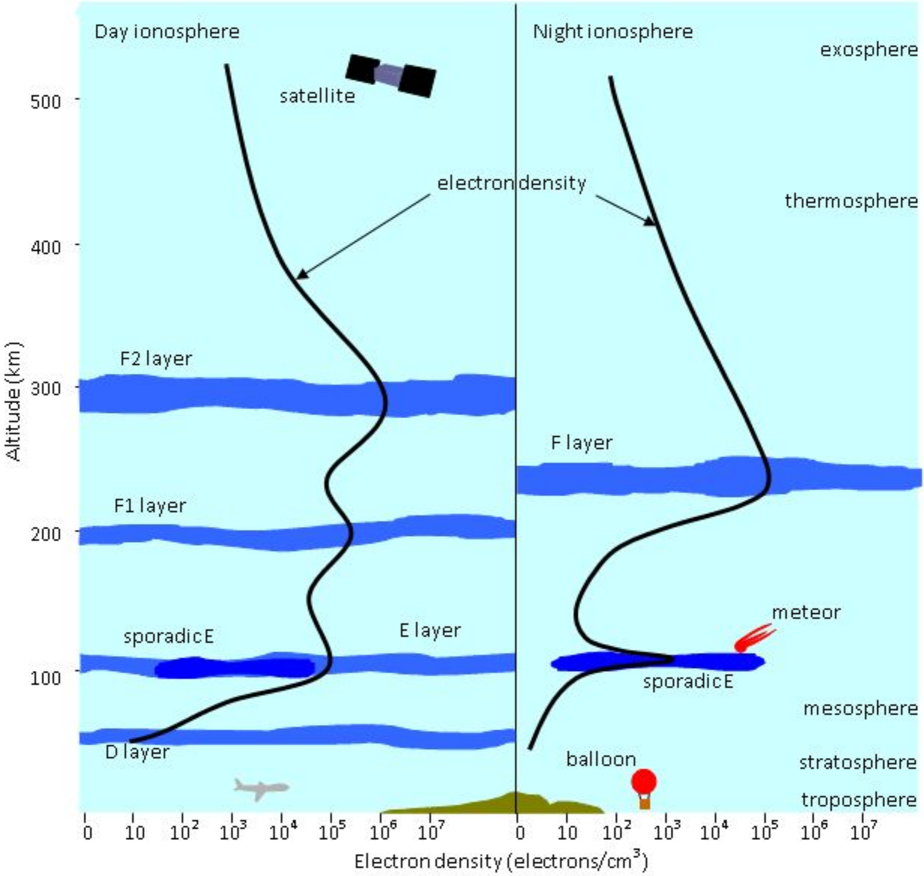
Ionospheric composition

- the properties of the e- profiles depend on latitude → affects the usable HF RW freq.

MUF is documented for each day of the year



MET Office



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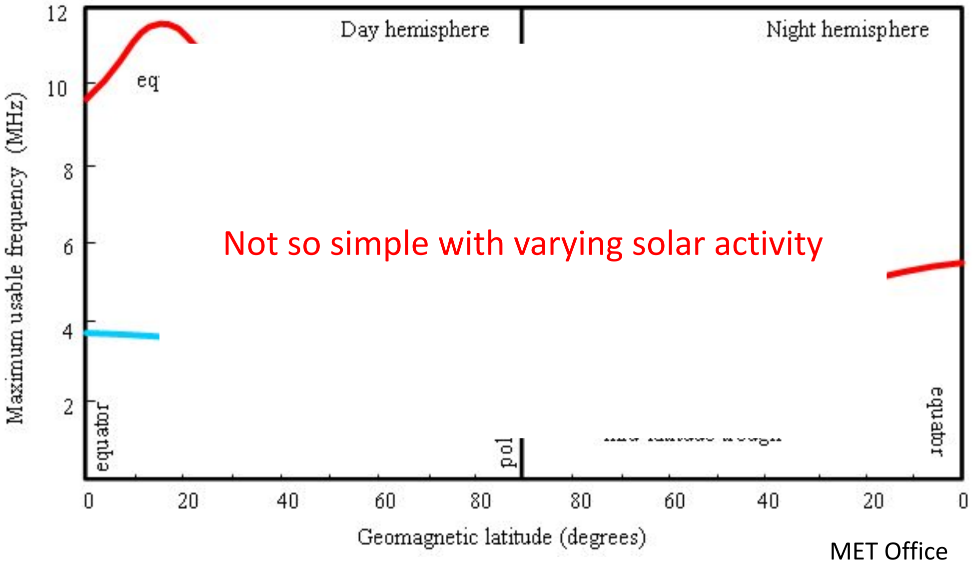
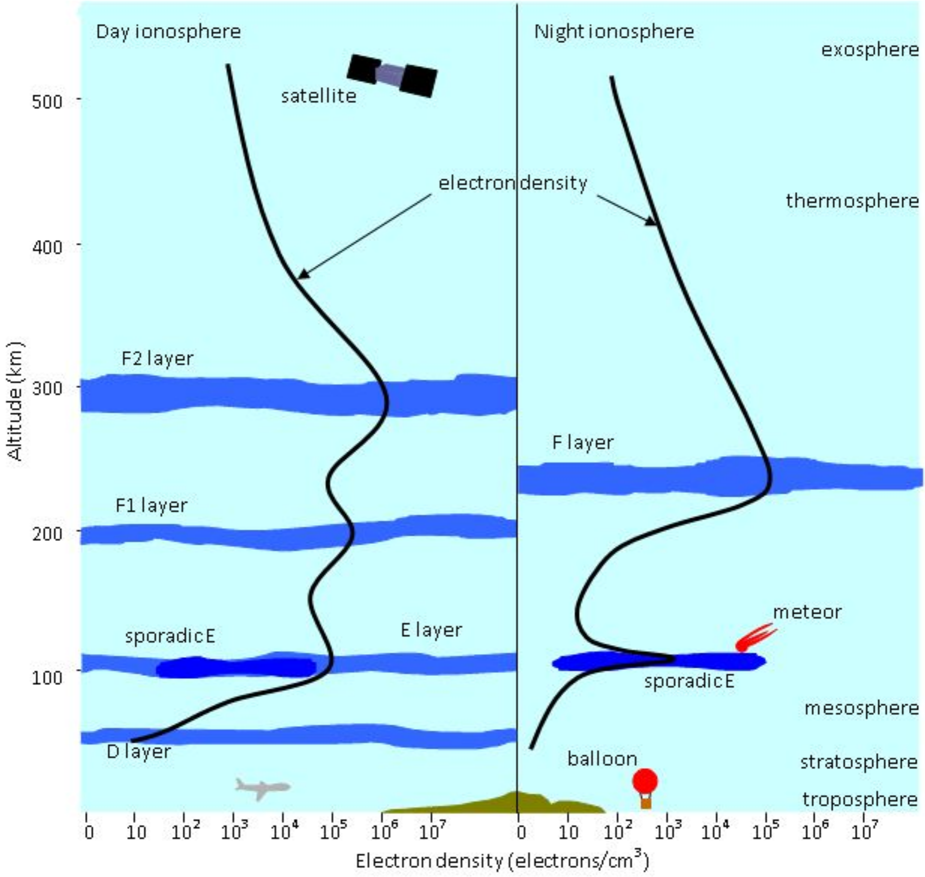


Not so simple with varying solar activity

MET Office



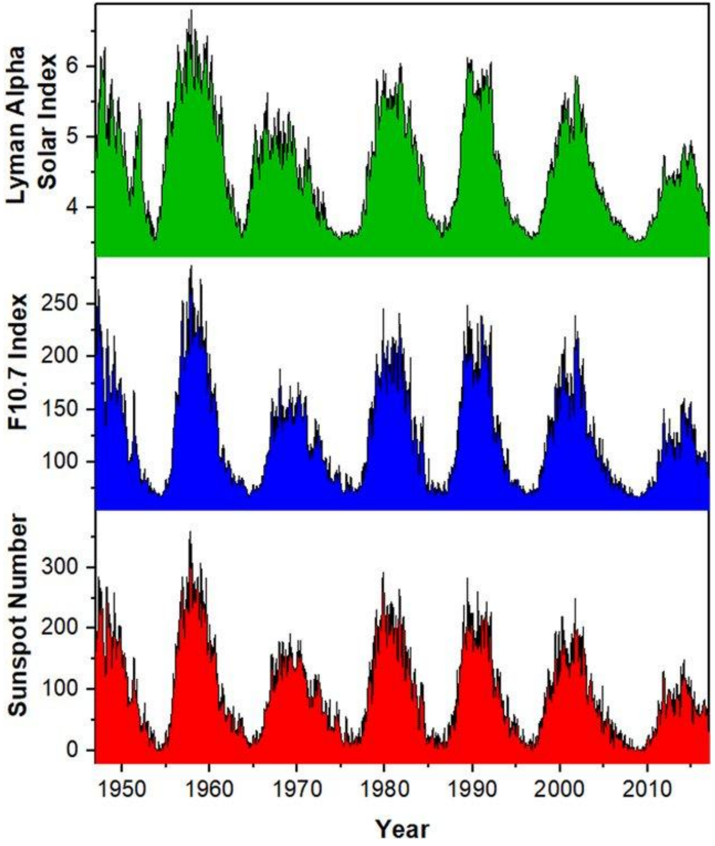
Radio frequencies

- ELF/SLF: submarines, but psychological issues, 3Hz - 300Hz
- ULF: submarines, communication with mines, 300Hz - 3kHz
- VLF: navigation & time signals (ground, sea, air), 3kHz - 30kHz
- LF: navigation & time signals (ground, sea, air), long AM, 30kHz - 300kHz
- MF: AM broadcasting, telegraphy, MRI, 300kHz - 3MHz
- HF: over-the-horizon communication, CTI, citizen band radio, 3MHz - 30MHz
- VHF: FM broadcasting, TV broadcasting, mobile comm., 30MHz - 300MHz
- UHF: TV broadcasting, remote control systems, satellite signals, 300MHz - 3GHz
- SHF: WLAN, radio astronomy, modern radars, satellite signals, 3GHz - 30GHz
- EHF: radio astronomy, MW remote sensing, satellite signals, 30GHz - 300GHz

Singh et al. 2019

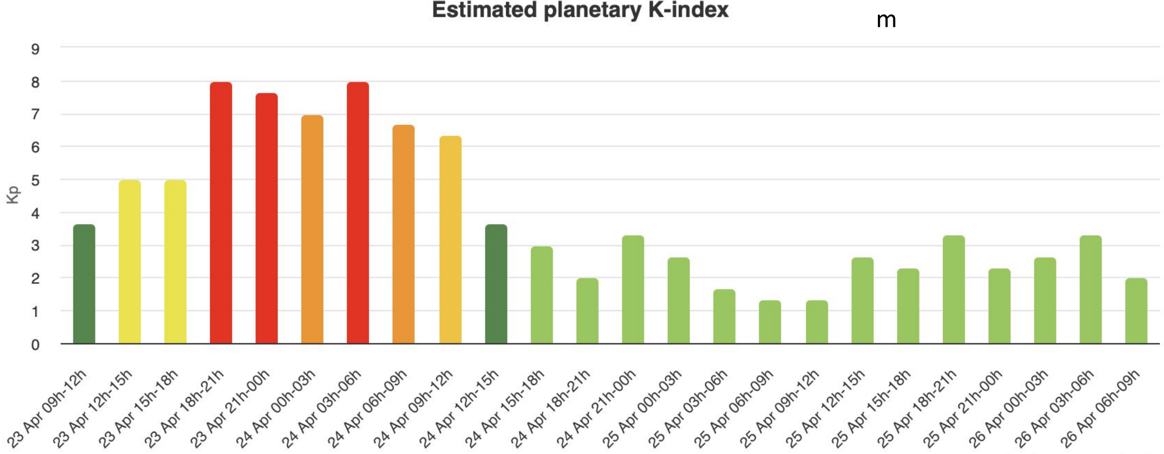
Space weather indices

- **F10.7 index** (solar radio flux at 10.7cm) → excellent indicator of solar activity
  - from high chromosphere/ lower corona
  - corresponds with the sunspot number and UV irradiance
  - can be observed from the ground



Space weather indices

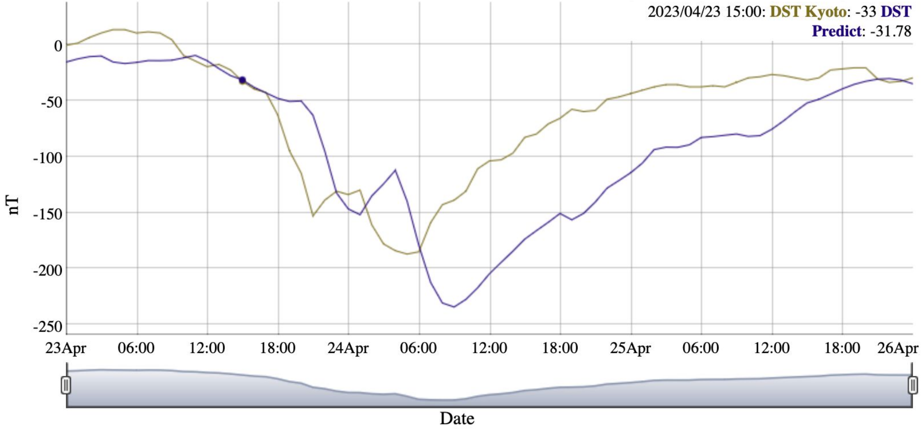
- F10.7 index (solar radio flux at 10.7cm)
- **Planetary K-index** (Kp) → disturbances in the horizontal component of Earth’s B-field, 0-9
  - derived from maximum fluctuations in the horizontal component during 3 hours intervals from 13 different mid-latitude measuring stations
  - scale quasi-logarithmic
  - if daily average: A index



spaceweatheronline.com

Space weather indices

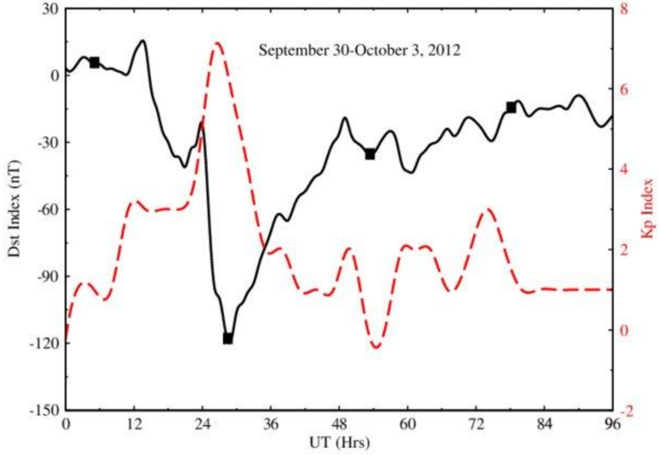
- F10.7 index (solar radio flux at 10.7cm)
- Planetary K-index (Kp)
- **Disturbance storm-time index (Dst)** → field variations in the horizontal component of the Earth’s magnetic field measuring the strength of the ring current created by the drifts of charged particles
    - measured hourly
    - from 4-5 near-equatorial stations
    - storm if under approx 50nT



Real-time Disturbance-storm-time (*Dst*) index and ML predicted *Dst*

Space weather indices

- F10.7 index (solar radio flux at 10.7cm)
- Planetary K-index (Kp)
- **Disturbance storm-time index (Dst)** → field variations in the horizontal component of the Earth's magnetic field measuring the strength of the ring current created by the drifts of charged particles
  - measured hourly
  - from 4-5 near-equatorial stations
  - storm if under approx 50nT
  - correlation with Kp

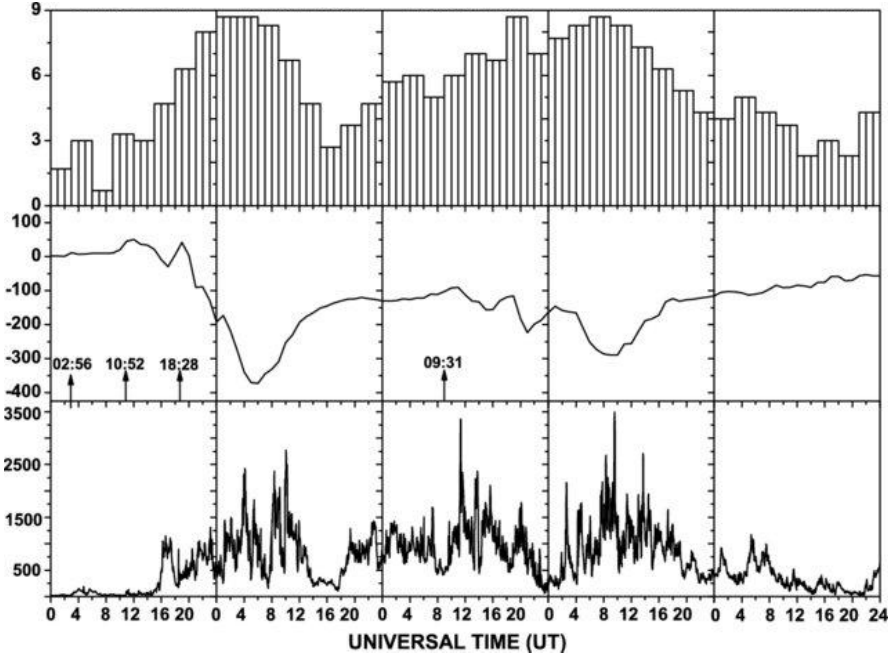


Singh et al. 2016

Space weather indices

- F10.7 index (solar radio flux at 10.7cm)
- Planetary K-index (Kp)
- Disturbance storm-time index (Dst)
- **Auroral Electrojet index (AE)** → total deviation from the quiet day horizontal B field around the auroral oval, giving a measure of auroral zone magnetic activity
    - instantaneous basis
    - measures in high northern latitude stations (auroral)
    - correlates with Kp and Dst

Sahai et al. 2009



Loss of satellite availability

- to protect a satellite electronics → might be placed into “safe mode”
- then the satellite will not be functional for the ground force or any other users
- the Regional Satellite Communications Support Center (RSSC) or equivalent should notify the end users of pending safe mode operations
- the remaining SATCOM assets will be re-prioritised
- non-priority links might have to continue without SATCOM until solar activity lessens
- If ISR satellite is required but unavailable, the collection managers might need to request additional airborne ISR capability or wait until the solar activity lessens

Quebec blackout of 1989

- a table of effects and affected systems during the 1989 13-14 March geomagnetic storm:

Boteler 2019

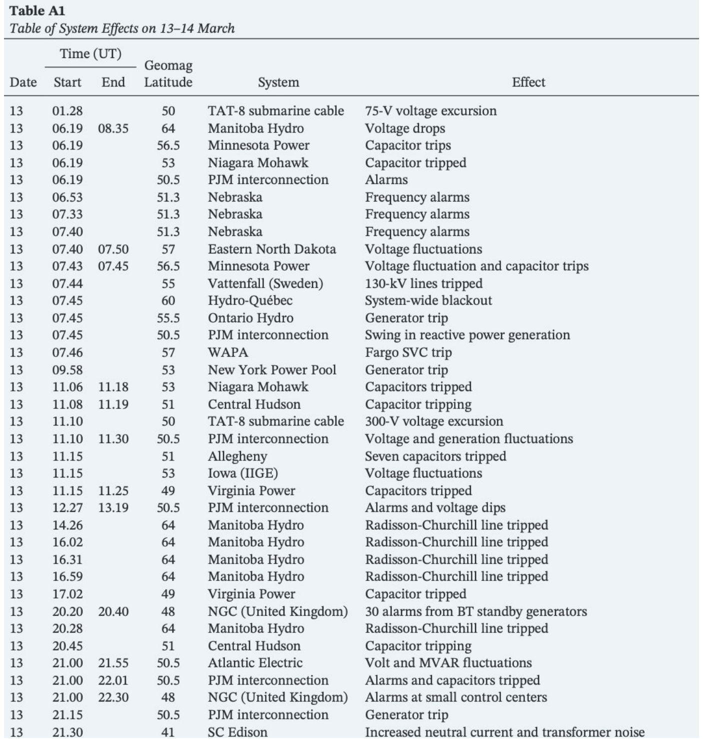


Table A1

Table of System Effects on 13–14 March

Date	Time (UT)		Geomag Latitude	System	Effect
	Start	End			
13	01.28		50	TAT-8 submarine cable	75-V voltage excursion
13	06.19	08.35	64	Manitoba Hydro	Voltage drops
13	06.19		56.5	Minnesota Power	Capacitor trips
13	06.19		53	Niagara Mohawk	Capacitor tripped
13	06.19		50.5	PJM interconnection	Alarms
13	06.53		51.3	Nebraska	Frequency alarms
13	07.33		51.3	Nebraska	Frequency alarms
13	07.40		51.3	Nebraska	Frequency alarms
13	07.40	07.50	57	Eastern North Dakota	Voltage fluctuations
13	07.43	07.45	56.5	Minnesota Power	Voltage fluctuation and capacitor trips
13	07.44		55	Vattenfall (Sweden)	130-kV lines tripped
13	07.45		60	Hydro-Québec	System-wide blackout
13	07.45		55.5	Ontario Hydro	Generator trip
13	07.45		50.5	PJM interconnection	Swing in reactive power generation
13	07.46		57	WAPA	Fargo SVC trip
13	09.58		53	New York Power Pool	Generator trip
13	11.06	11.18	53	Niagara Mohawk	Capacitors tripped
13	11.08	11.19	51	Central Hudson	Capacitor tripping
13	11.10		50	TAT-8 submarine cable	300-V voltage excursion
13	11.10	11.30	50.5	PJM interconnection	Voltage and generation fluctuations
13	11.15		51	Allegheny	Seven capacitors tripped
13	11.15		53	Iowa (IIGE)	Voltage fluctuations
13	11.15	11.25	49	Virginia Power	Capacitors tripped
13	12.27	13.19	50.5	PJM interconnection	Alarms and voltage dips
13	14.26		64	Manitoba Hydro	Radisson-Churchill line tripped
13	16.02		64	Manitoba Hydro	Radisson-Churchill line tripped
13	16.31		64	Manitoba Hydro	Radisson-Churchill line tripped
13	16.59		64	Manitoba Hydro	Radisson-Churchill line tripped
13	17.02		49	Virginia Power	Capacitor tripped
13	20.20	20.40	48	NGC (United Kingdom)	30 alarms from BT standby generators
13	20.28		64	Manitoba Hydro	Radisson-Churchill line tripped
13	20.45		51	Central Hudson	Capacitor tripping
13	21.00	21.55	50.5	Atlantic Electric	Volt and MVAR fluctuations
13	21.00	22.01	50.5	PJM interconnection	Alarms and capacitors tripped
13	21.00	22.30	48	NGC (United Kingdom)	Alarms at small control centers
13	21.15		50.5	PJM interconnection	Generator trip
13	21.30		41	SC Edison	Increased neutral current and transformer noise

Date	Time (UT)		Geomag Latitude	System	Effect
	Start	End			
13	21.34		48	NGC (United Kingdom)	Transformer at Norwich Main switched out
13	21.40	21.48	48	NGC (United Kingdom)	150 alarms from BT standby generators
13	21.43		55	Vattenfall (Sweden)	130-kV line tripped
13	21.44		55	Vattenfall (Sweden)	Increased reactive power: max 540 MVAr
13	21.45		50	TAT-8 submarine cable	450-V voltage excursion
13	21.45	01.00	55	Wisconsin Power and Light	Voltage problems, regulators hunting
13	21.51	22.11	53	Niagara Mohawk	Capacitors tripped
13	21.55		56.5	Minnesota Power	Voltage fluctuations
13	21.58		55	WAPA	Miles City line trip
13	21.58		57	BC Hydro	4% voltage fluctuation
13	21.58		51	BPA	Capacitor tripping
13	21.58		55.5	Ontario Hydro	Demand fluctuates by 200 MW
13	21.58		55.8	West Kootney Power	Alarms
13	22.00		53	Iowa (IIGE)	Voltage fluctuations
13	22.00		56.5	UPA, Elk River, Mn	Voltage fluctuations
13	22.00		51	Long Island Lt Co	Voltage fluctuations
13	22.01		55.5	Ontario Hydro	Overvoltage alarm
13	22.01	22.23	49	Virginia Power	Capacitor tripped
13	22.08		56.5	UPA, Elk River, Mn	Capacitor switching
13	22.09		55	WAPA	Miles City line trip
13	22.09		55.7	WAPA	Bole, Montana, transformer trip
13	22.09		57	WAPA	Fargo SVC trip
13	22.20		56.5	UPA, Elk River, Mn	Voltage swing
13	22.20	22.30	57	Eastern North Dakota	Voltage fluctuations
13	22.40		55	Vattenfall (Sweden)	Oscillating reactive power
13	22.42		50.5	PJM interconnection	Alarm
13	23.27	23.29	49	Virginia Power	Capacitor tripped
13	23.30		51.4	Philadelphia	Voltage fluctuations
13	23.32		53	NEPOOL	Capacitor tripped
14	00.10		49	Virginia Power	Capacitor tripped
14	01.00	01.30	53	NEPOOL	Widespread voltage and MVAR swings
14	01.00	02.00	51	Long Island Lt Co	Voltage fluctuations
14	01.11		53	Niagara Mohawk	Capacitor tripped
14	01.11	01.18	49	Virginia Power	Capacitor tripped
14	01.14		53	New York Power Pool	Voltage drop
14	01.14	01.32	50.5	PJM interconnection	Alarms and capacitors tripped
14	01.16		55.5	Ontario Hydro	Belleville capacitor tripped
14	01.16		55.5	Ontario Hydro	Phase imbalance at Bruce
14	01.19		55	Wisconsin Electric Power	Alarms
14	01.20		55.5	Ontario Hydro	Chats Falls generator power fluctuations
14	01.20		51	Allegheny	Transformer heating
14	01.20		50.5	Atlantic Electric	Volt and MVAR fluctuations
14	01.20	01.22	56.5	UPA, Elk River, Mn	Alarms and line trip
14	01.20	01.40	57	Eastern North Dakota	Voltage fluctuations
14	01.24	01.54	56.5	Minnesota (CPA)	Voltage fluctuations, high-voltage alarms, capacitors on and off
14	01.27		48	NGC (United Kingdom)	Transformer at Norwich Main switched out
14	01.30		50	TAT-8 submarine cable	700-V voltage excursion
14	01.52		48	NGC (United Kingdom)	Transformer at Indian Queens switched out
14	04.00	05.00	51.4	Philadelphia	Voltage fluctuations