



From user's perspective

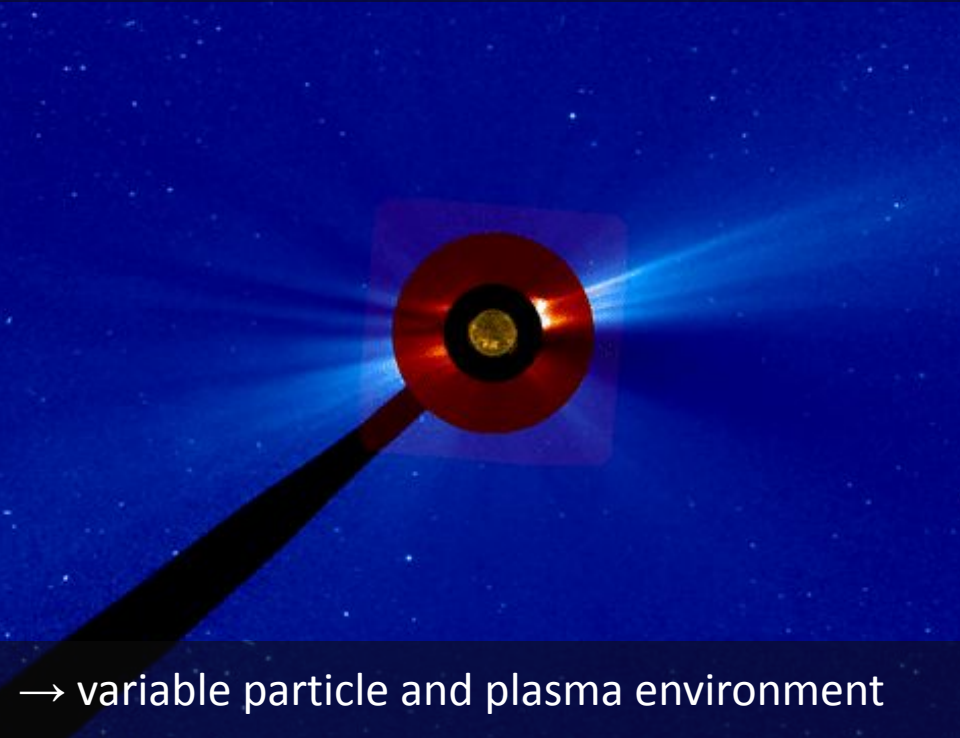
Michaela Brchnelova
m.brchnelova@mindef.nl



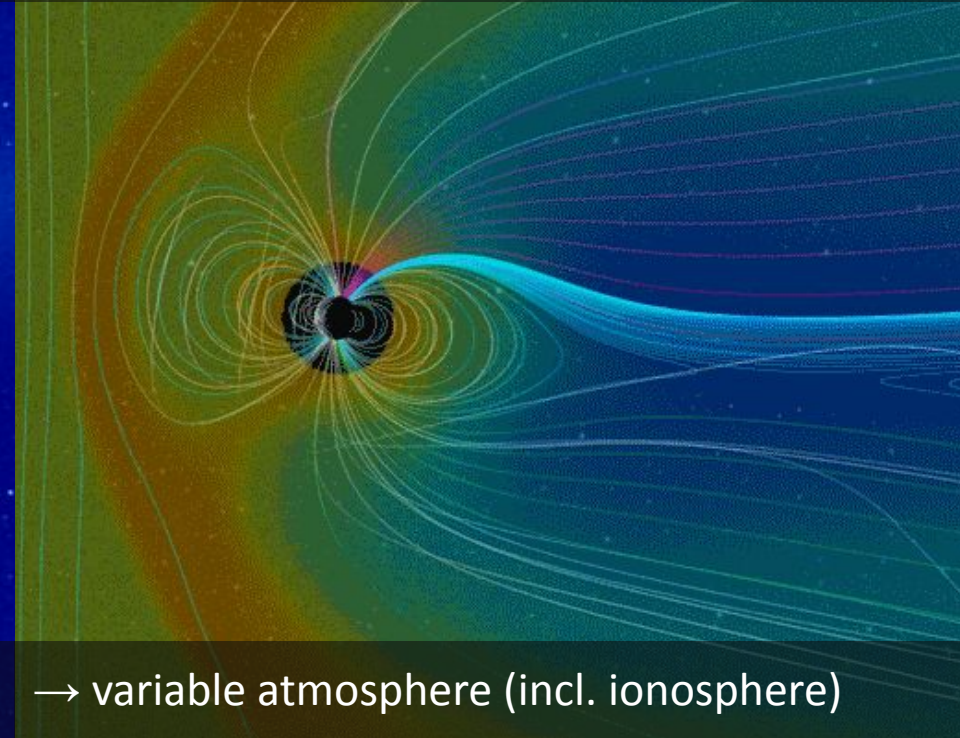
Introduction



→ variable electromagnetic radiation



→ variable geomagnetic field



→ variable particle and plasma environment

→ variable atmosphere (incl. ionosphere)

T14:29:33.342

solar physics

plasma physics

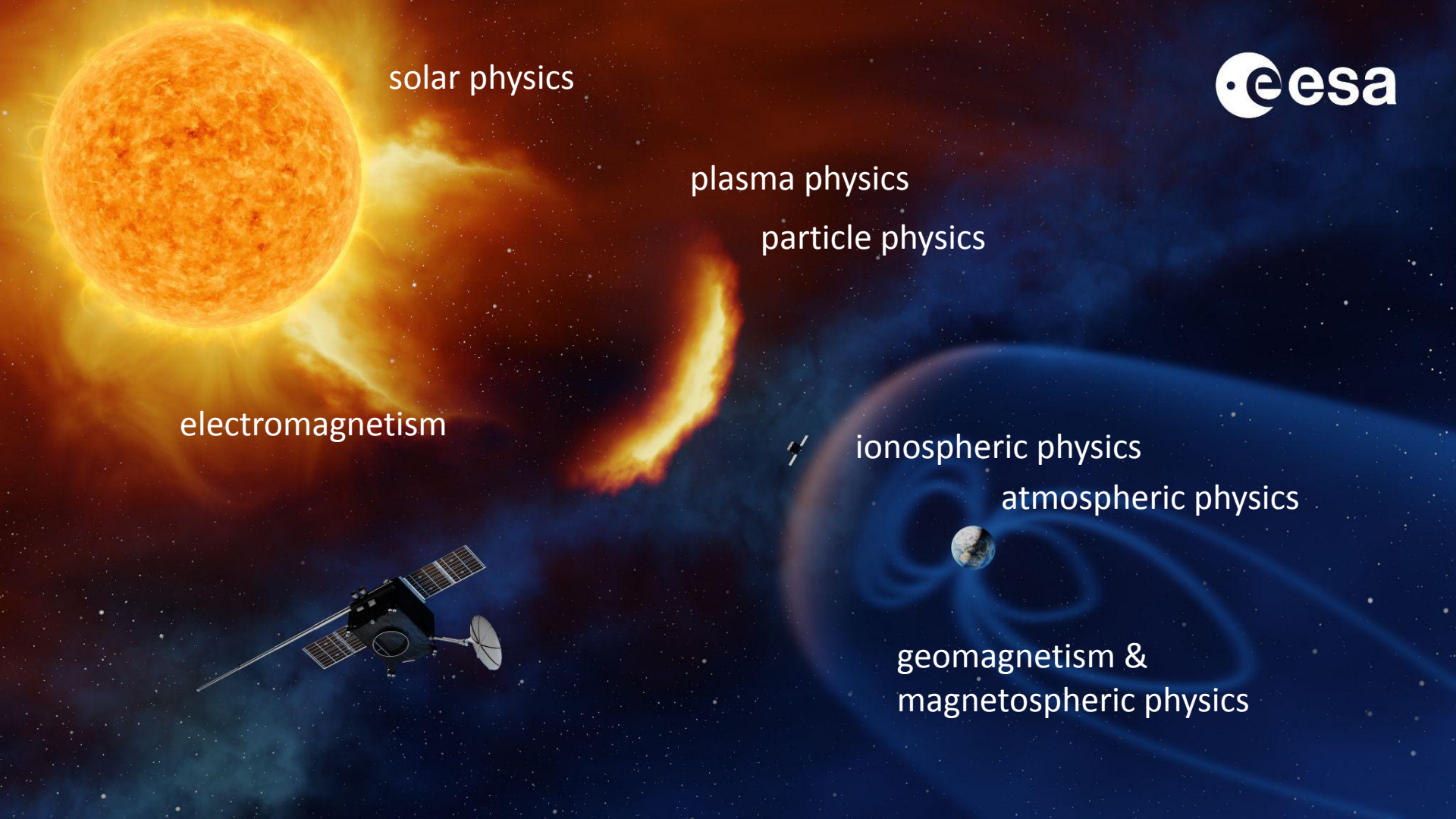
particle physics

electromagnetism

ionospheric physics

atmospheric physics

geomagnetism &
magnetospheric physics



crew radiation

[ESA]

satellite damage

SOLAR ENERGETIC PROTONS

SOLAR FLARE RADIATION

SOLAR CELL DEGRADATION

SINGLE EVENT UPSET

satellite drag

ENERGETIC RADIATION BELT PARTICLES

ENHANCED IONOSPHERIC CURRENTS AND DISTURBANCES

ionospheric link disturbances
comm & nav

NAVIGATION ERRORS

CREW AND PASSENGERS RADIATION

SIGNAL SCINTILLATION

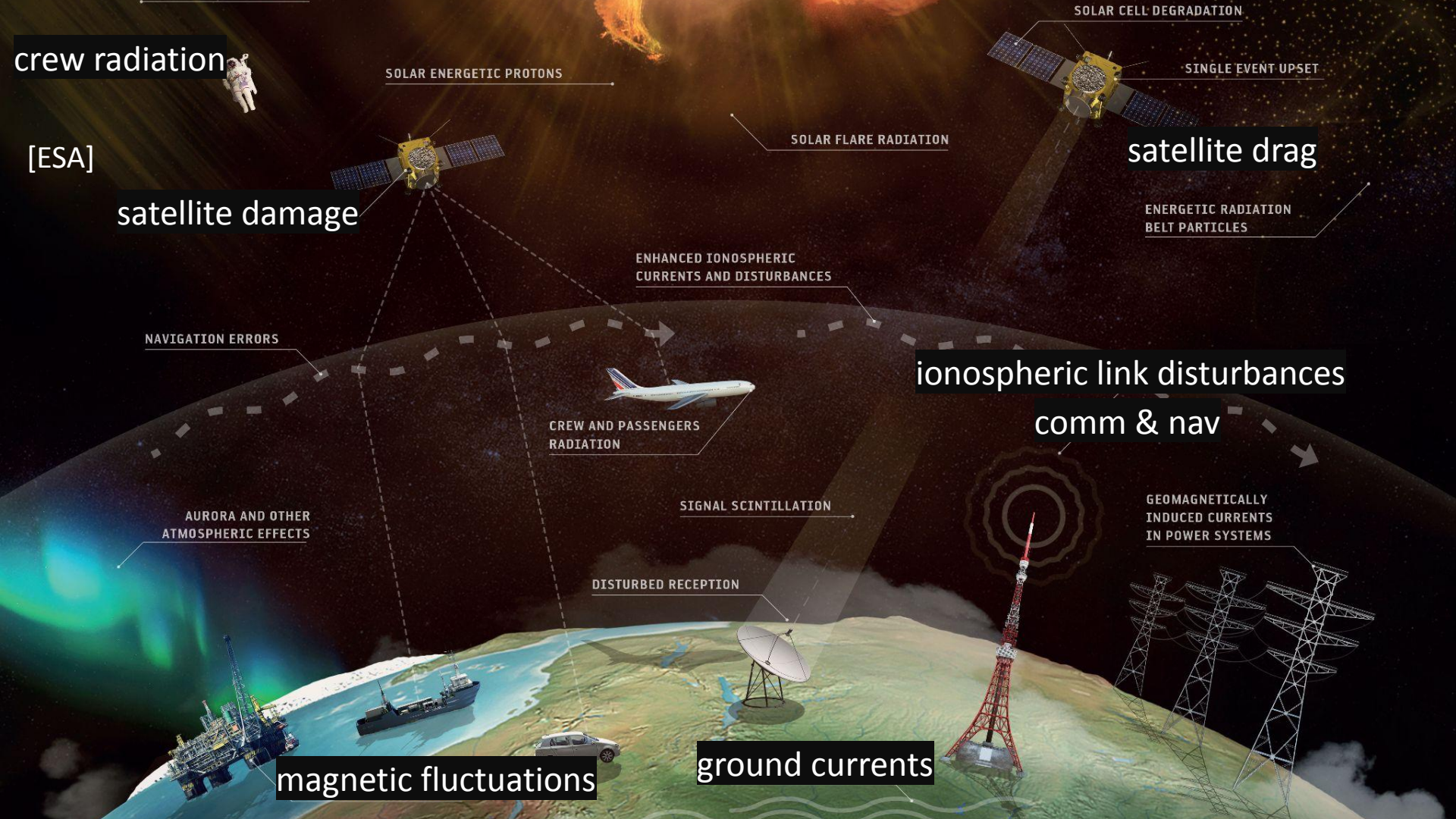
GEOMAGNETICALLY INDUCED CURRENTS IN POWER SYSTEMS

AURORA AND OTHER ATMOSPHERIC EFFECTS

DISTURBED RECEPTION

magnetic fluctuations

ground currents

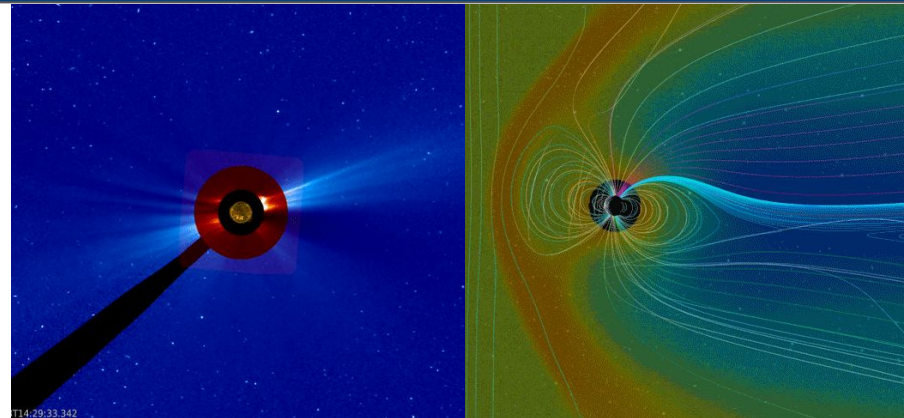




Defence vulnerabilities

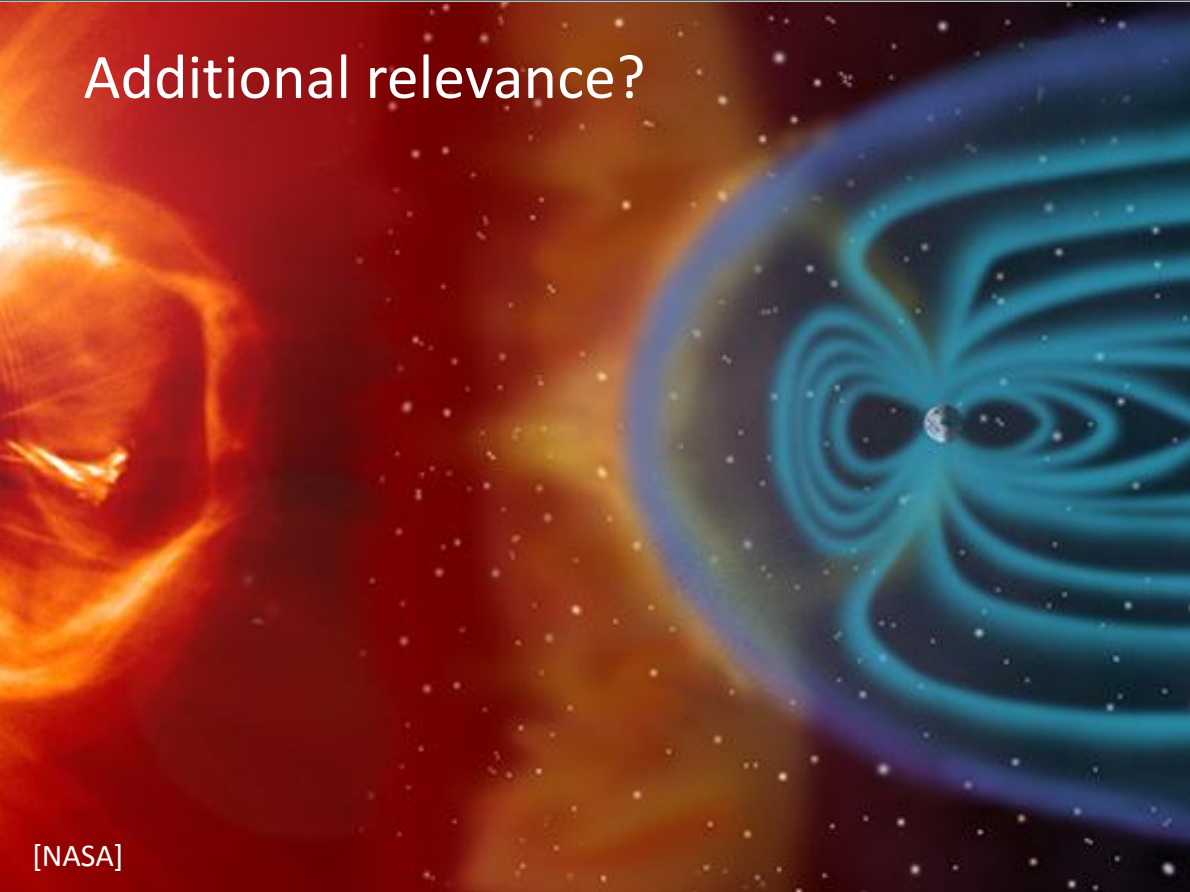
- if it:
 - flies in space/ upper atmosphere (or needs assets that do)
 - uses/ detects radio signals
 - communicates through the ionosphere
 - requires magnetic measurements
 - is sensitive to electric currents in the grounds

- system response often depends on parameters we do not know exactly





Additional relevance?



[NASA]





“Risk”



Space weather (SW) effects risks

- when evaluating SW risks, looking at the probability alone is often not enough:

risk = probability x cost

- cost may be political, military, societal, financial, etc.
- the resulting risks are organisation- and platform-dependent, e.g., on the procedures in place, the protocols and the system diversity/ redundancy
→ **up to the user to decide! But with the “probability” part, we can help**





Reception VHF advertisements

- ~ 40 MHz advertisement originated from Israel, how to stop this?
- VHF line-of-sight (LOS) only: ionosphere normally only reflects up to ~ 30 MHz
- What causes ionospheric disturbances?
 - solar flares → none strong detected that day
 - proton storms → not in polar regions + no proton storms detected that day
 - geomagnetic storms → none strong that day/ days prior
- check ionospheric total electron content maps → no extraordinary patterns
- check ionogram data of nearby stations → strong E-layer normally not there
→ **reception and noise due to a sporadic E-layer**



Reception VHF advertisements

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- check

- check

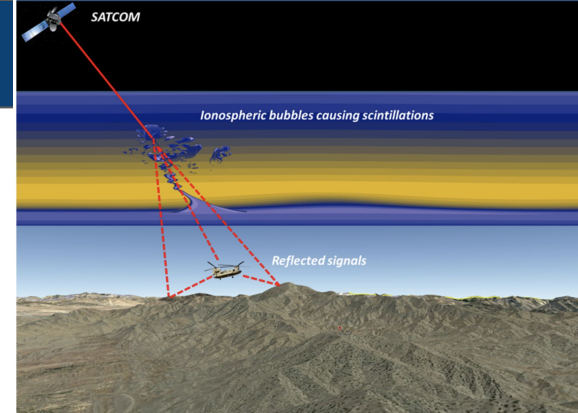
→ not a problem during an exercise

→ **but what would happen during an actual mission?**

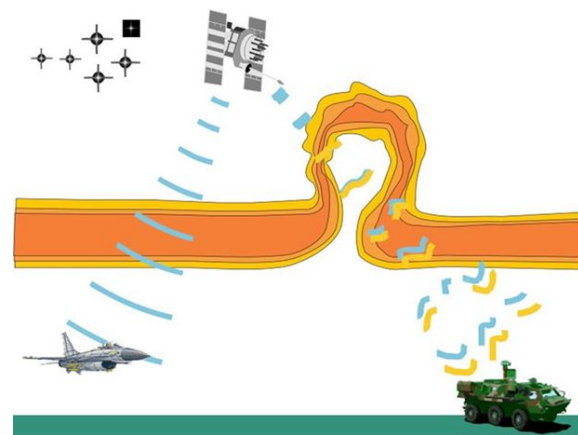


2002 The Battle of Takur Ghar (Afghanistan)

- plasma bubbles post-midnight might occur due to increased geomagnetic activity of $K_p > 3$: the battle of Takur Ghar: $K_p = 4$, 0300 LT March 4, 2002
- 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

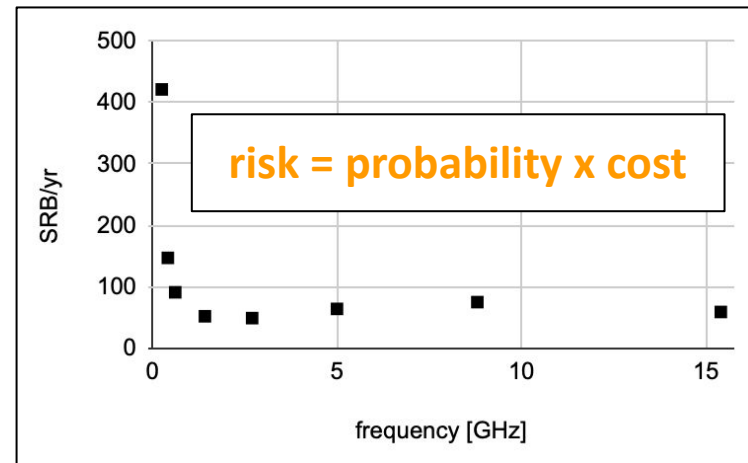


Credit: U.S. Air Force Research Laboratory (AFRL)
https://www.nasa.gov/mission_pages/cindi/five-years.html



Questions to be asked (and answered)

- is this **really** a problem?
 - how often does this happen?
 - which systems are affected and how much?
 - what are the consequences in operations?
- if so, is there something we can do about it?
 - operational settings adjustment?
 - better design of existing systems?
 - increasing redundancy?
 - improving awareness?
 - fast-tracking/ delaying operations?



own work based on Giersch et al. 2017



SWx vulnerability examples:

- HF radio (radar)
- UHF & VHF radio (radar)
- VLF radio
- SATCOM, GNSS
- MAD/ magnetic navigation
- power systems
- SATOPS:
 - atmosphere
 - particle environment
 - COM loss



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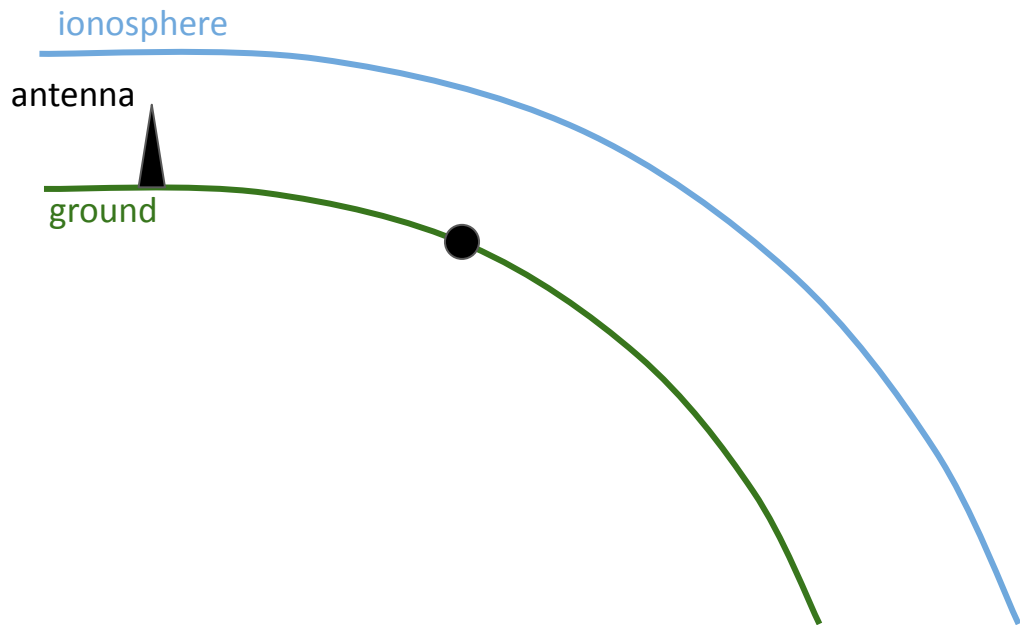
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HF radio

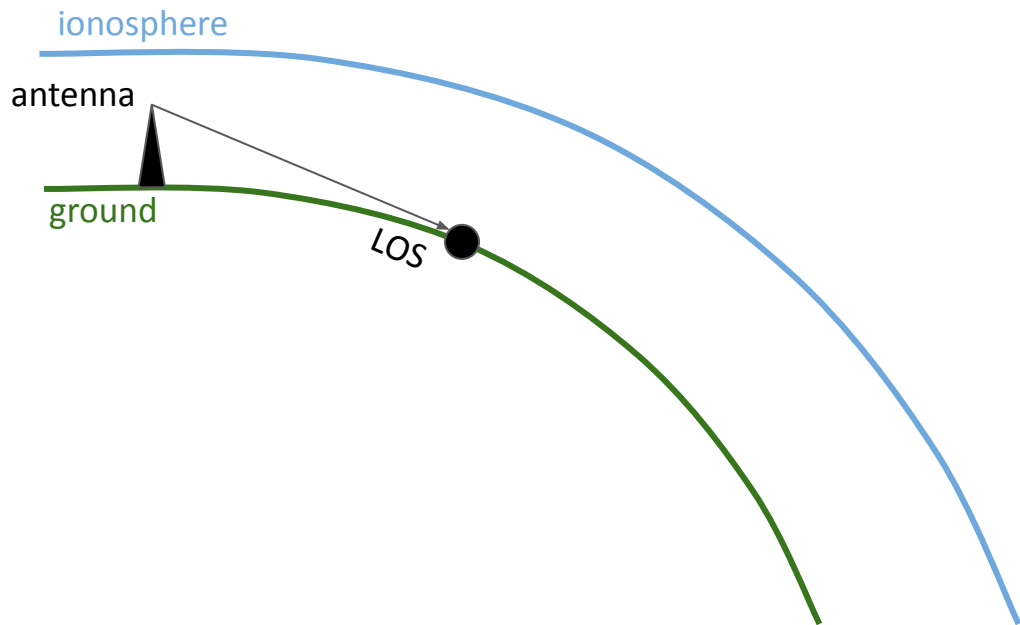


How do we communicate? Why is the ionosphere important?



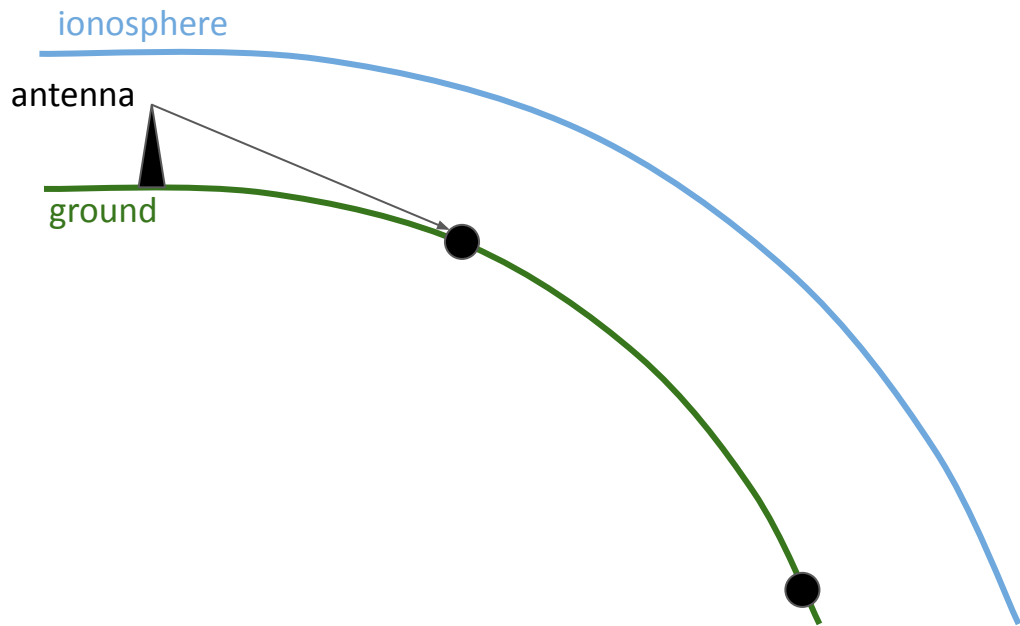


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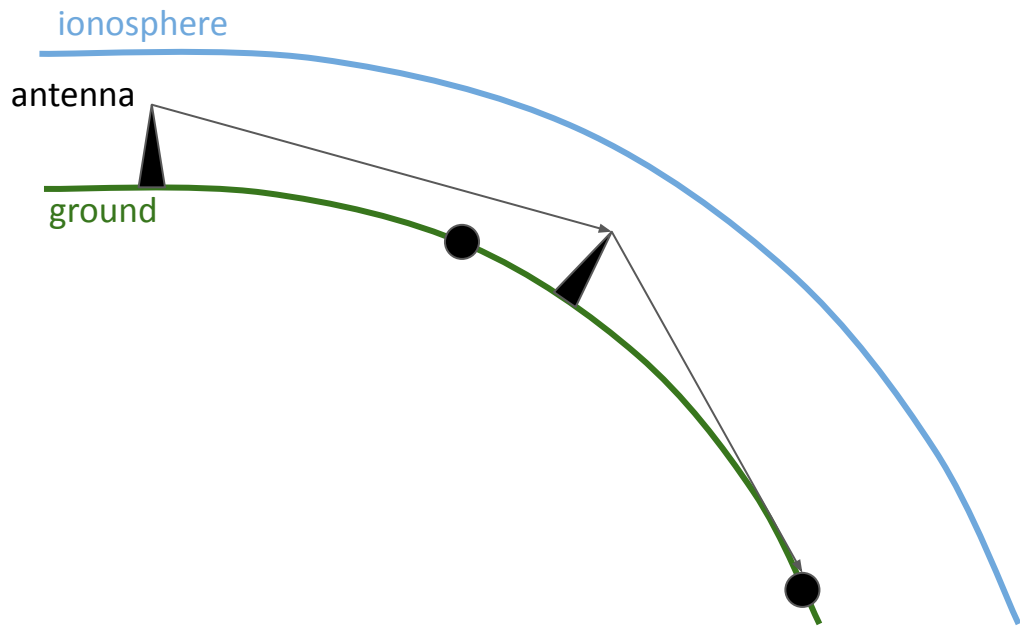


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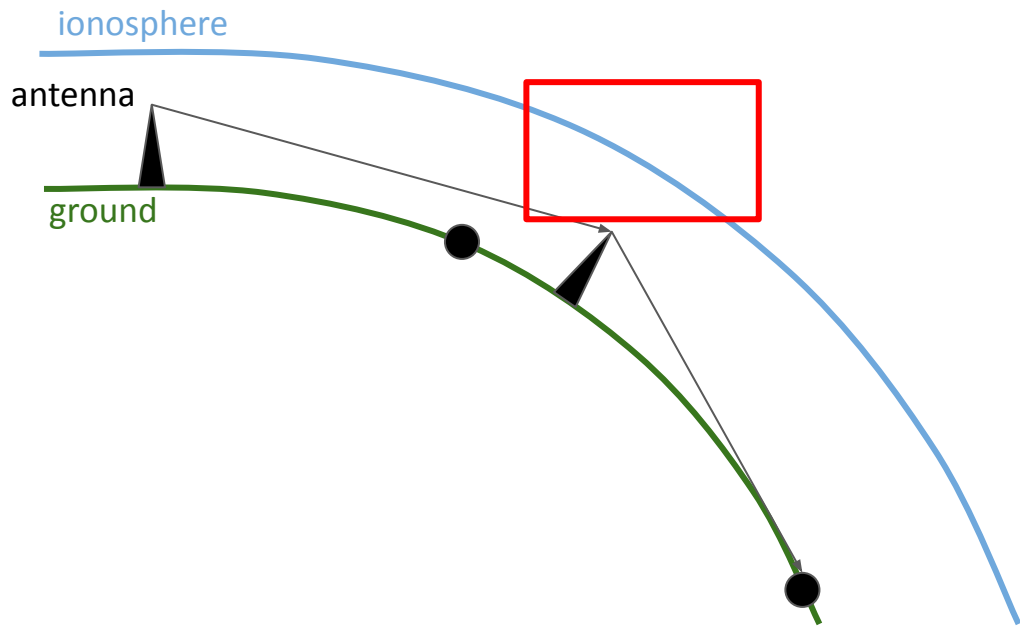


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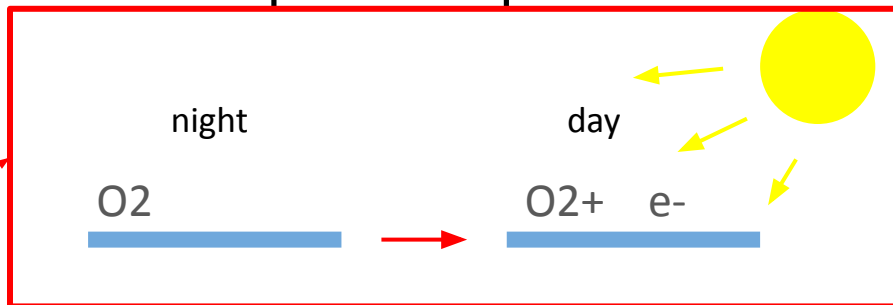
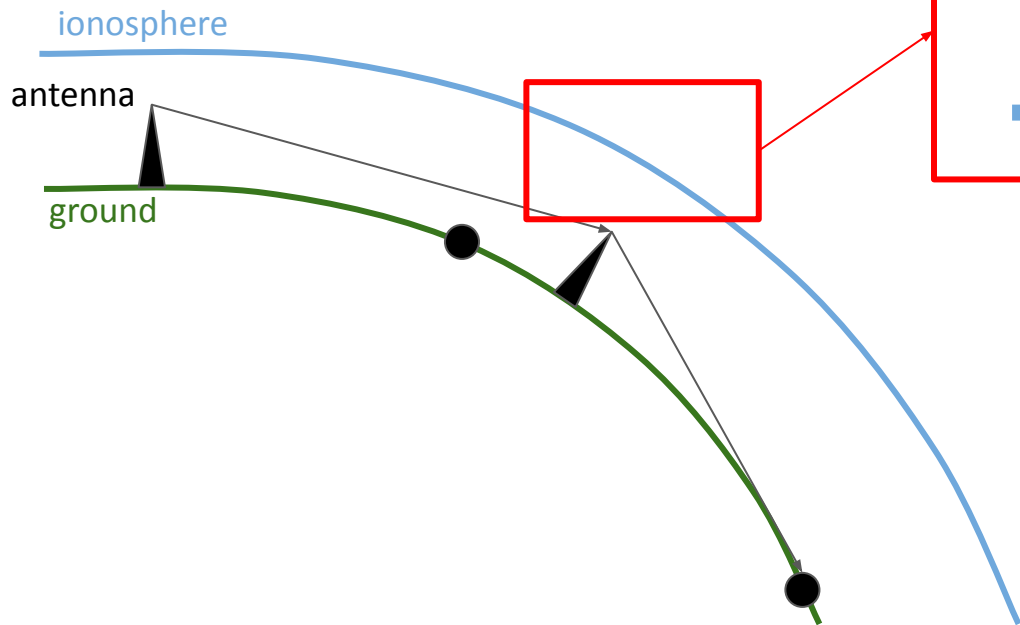


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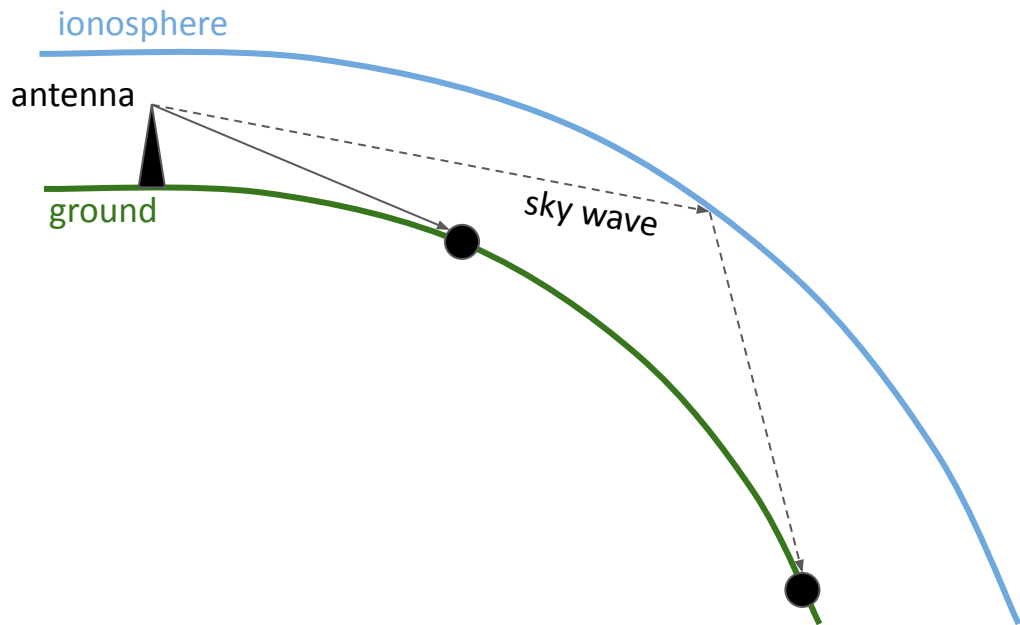


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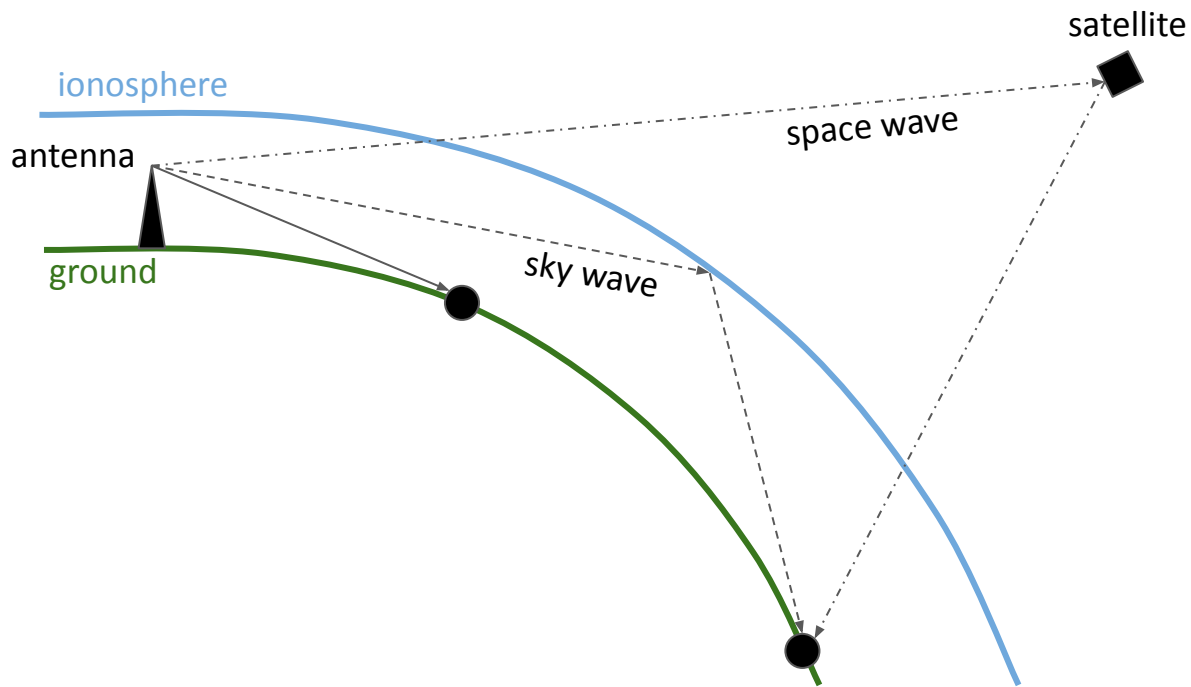


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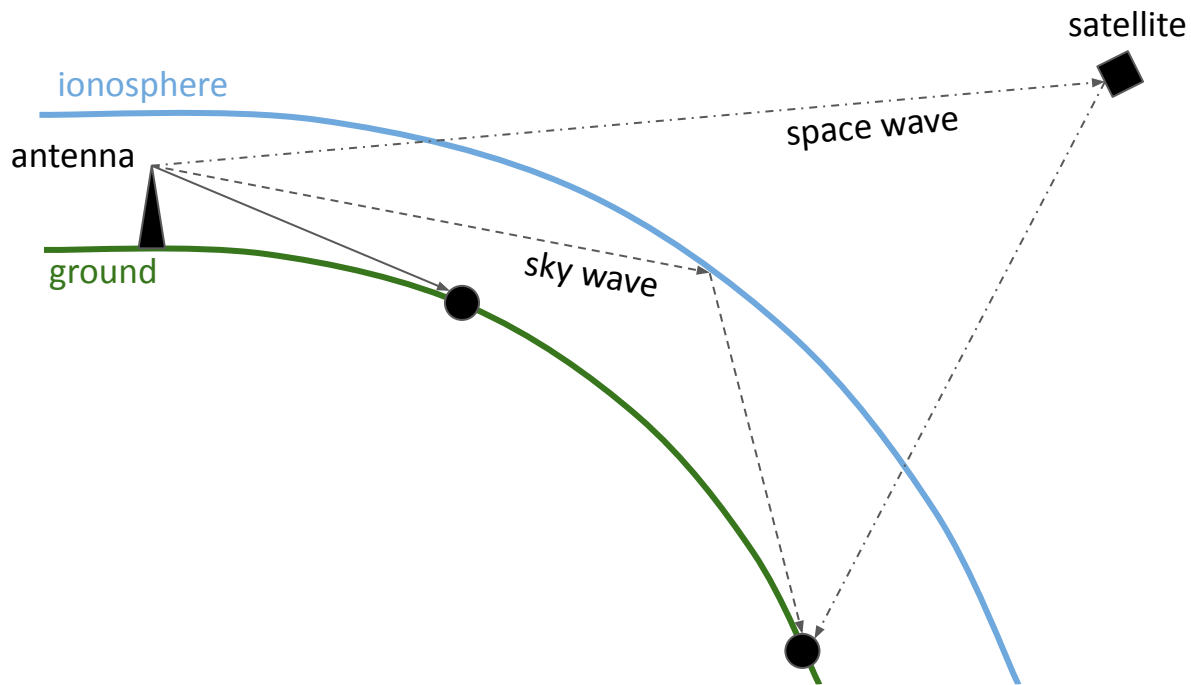


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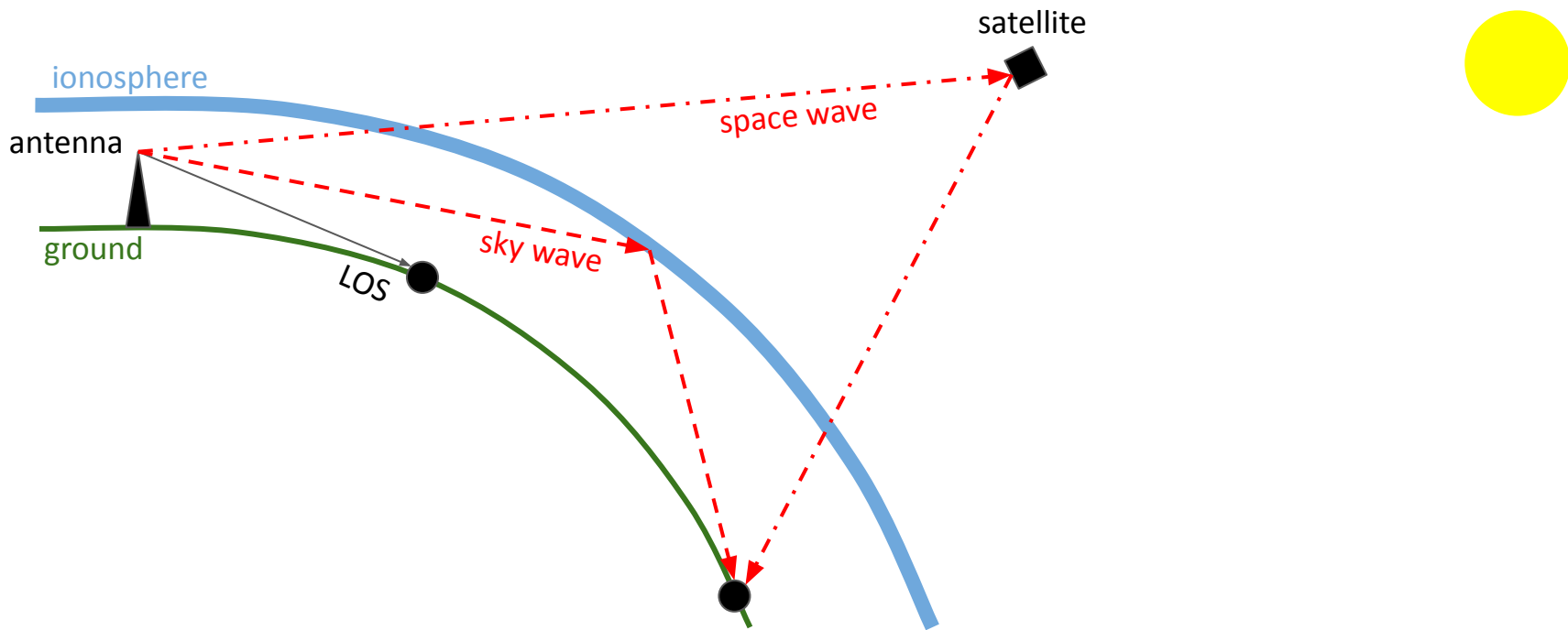
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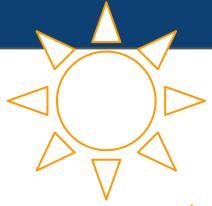


- HF more and more important due to anti-sat weapons and satcom jamming (Ukr)



How do we communicate? Why is the ionosphere important?





0.1 - 0.8 nm

160 - 500 km

F/F2 layer

$f_D < f_{\text{signal}}$

$f_{\text{MIN}} \propto \rho(e)$

50 - 90 km

D layer

absorption on the path

normal: $f_{F/F2} > f_D \rightarrow f_D < f_{\text{signal}} < f_{F/F2}$



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160 - 500 km

E/F2 layer

- similar extra effects in the poles due to **auroral absorption** (magnetospheric electrons) and **polar cap absorption** (solar energetic particles)
- **post-storm depression** lowers the maximum usable frequency

f_{MIN}

f_oF_2

50 - 90 km

D layer

$f_D > f_{signal}$

normal: $f_{F/F2} > f_D \rightarrow f_D < f_{signal} < f_{F/F2}$



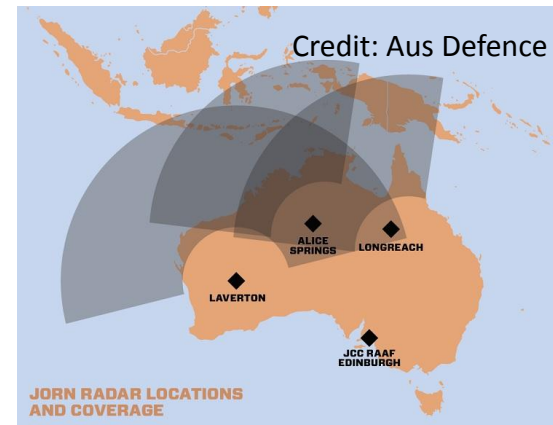
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Credit: Harris



Credit: Aus Defence





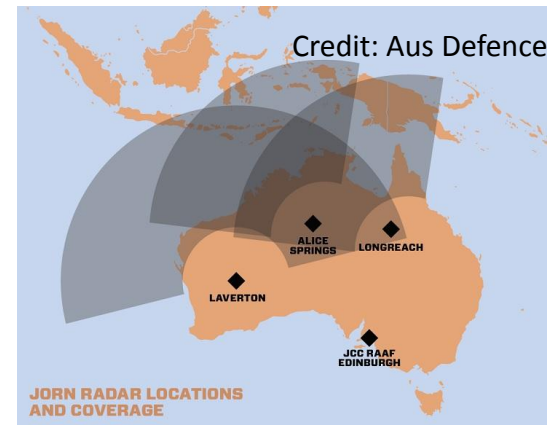
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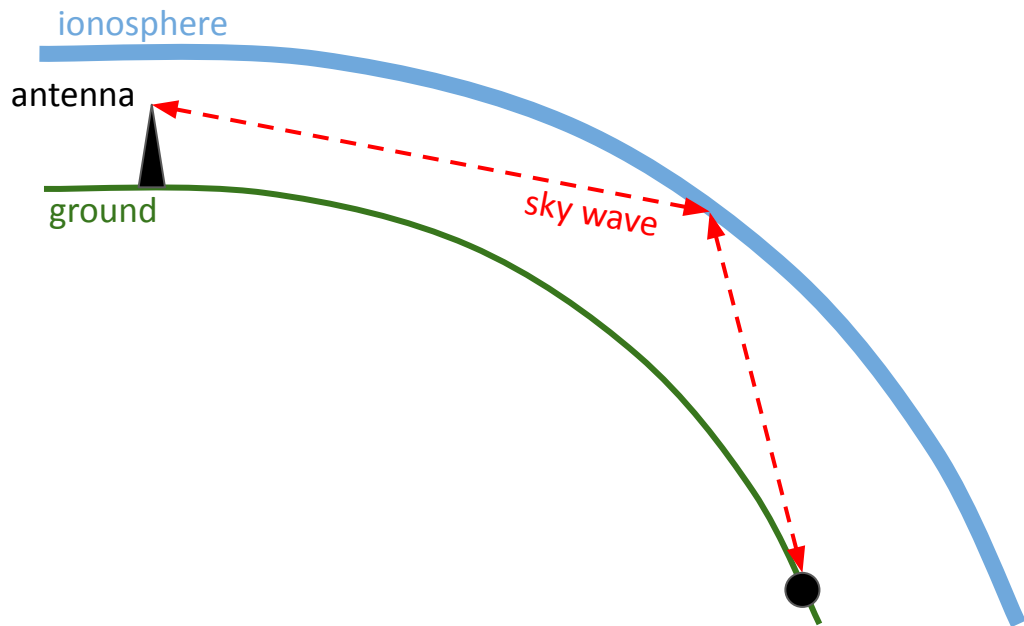
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Radio/ radar differences

- signal travels the path twice → more interference with the ionosphere!





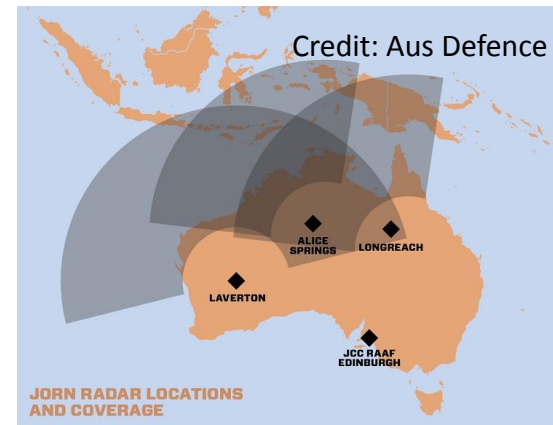
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HF radio: what do operators want?

- how much of a problem is this really?
- what do these mean for operations? Are there mitigation strategies?
- how much exactly is the fade-out / δ MUF due to the different absorption events?
 - real and vertical HF signals differ!
 - can we predict post-storm depression better?
 - can we predict auroral absorption better, e.g. as a function of Kp?



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HF: How much of a problem is this really?

Event	Moderate events in solar maximum [h]			Moderate events in solar minimum [h]		
	0 - 10 MHz	10 - 20 MHz	20 - 30 MHz	0 - 10 MHz	10 - 20 MHz	20 - 30 MHz
SWF	> 300	50 - 300	5 - 50	> 200	30 - 200	3 - 30
AA	> 30		10 - 30	> 20		5 - 20
PCA	≫ 100	> 100	50 - 100	≫ 50	> 50	10 - 50
PSD	N/A	100 - 200		N/A	10 - 100	

Event	Severe events in solar maximum [h]			Severe events in solar minimum [h]		
	0 - 10 MHz	10 - 20 MHz	20 - 30 MHz	0 - 10 MHz	10 - 20 MHz	20 - 30 MHz
SWF	> 5	0 - 5	0 - 5	> 3	0 - 3	0 - 3
AA	0 - 30	0 - 10	0 - 10	0 - 20	0 - 5	0 - 5
PCA	≫ 50	> 50	10 - 50	≫ 20	> 20	5 - 20
PSD	N/A	10 - 100		N/A	10 - 50	



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PCA	≫ 50	> 50	10 - 50	≫ 20	> 20	5 - 20
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- needs further “translation”, contains statistics & recommendation

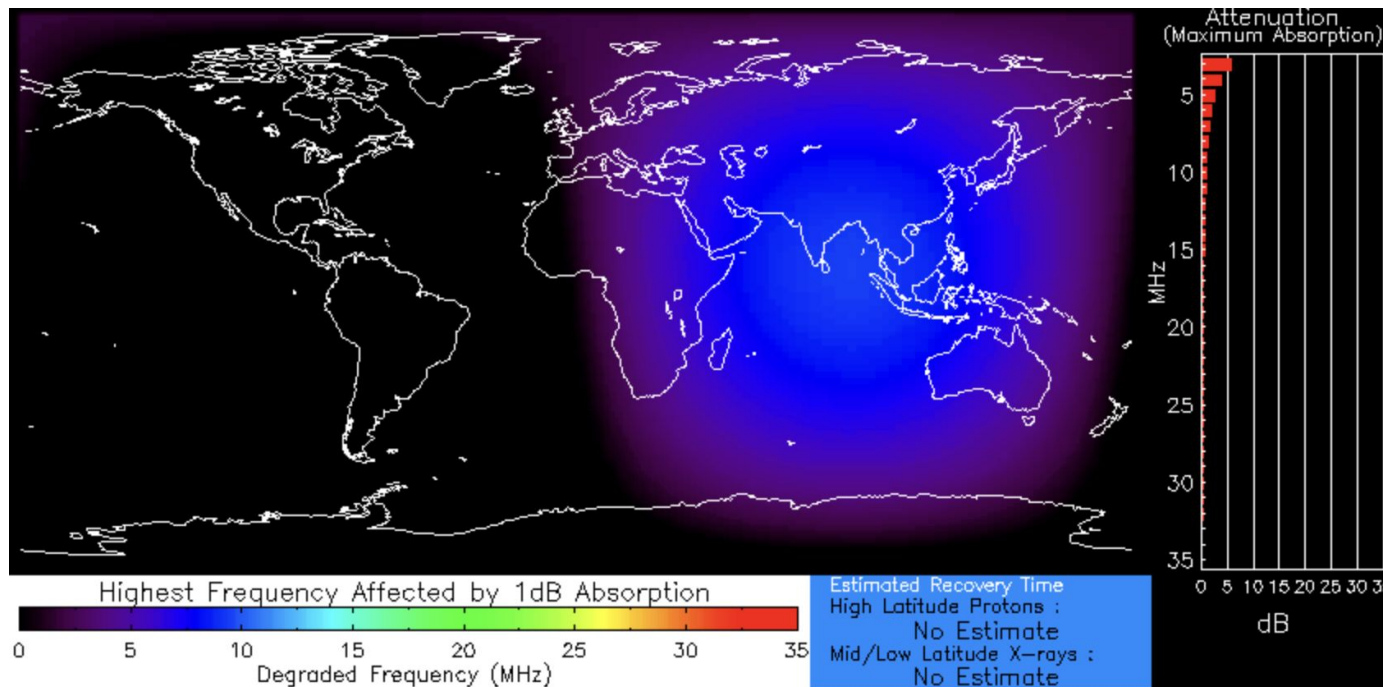


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K. Cornelis: Monitoring predictions of D-rap of NOAA

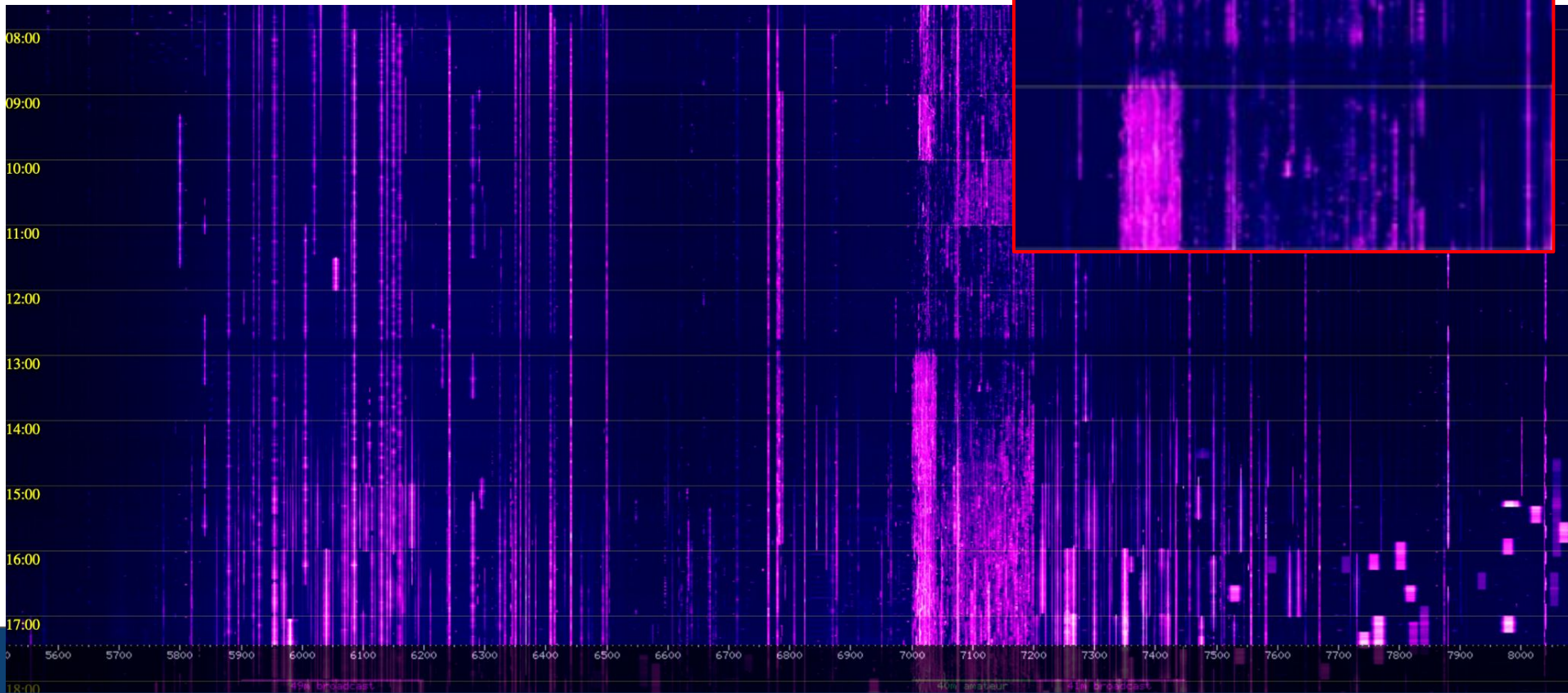


Elevated X-ray flux
Product Valid At : 2025-04-08 06:08 UTC

Normal Proton Background
NOAA/SWPC Boulder, CO USA



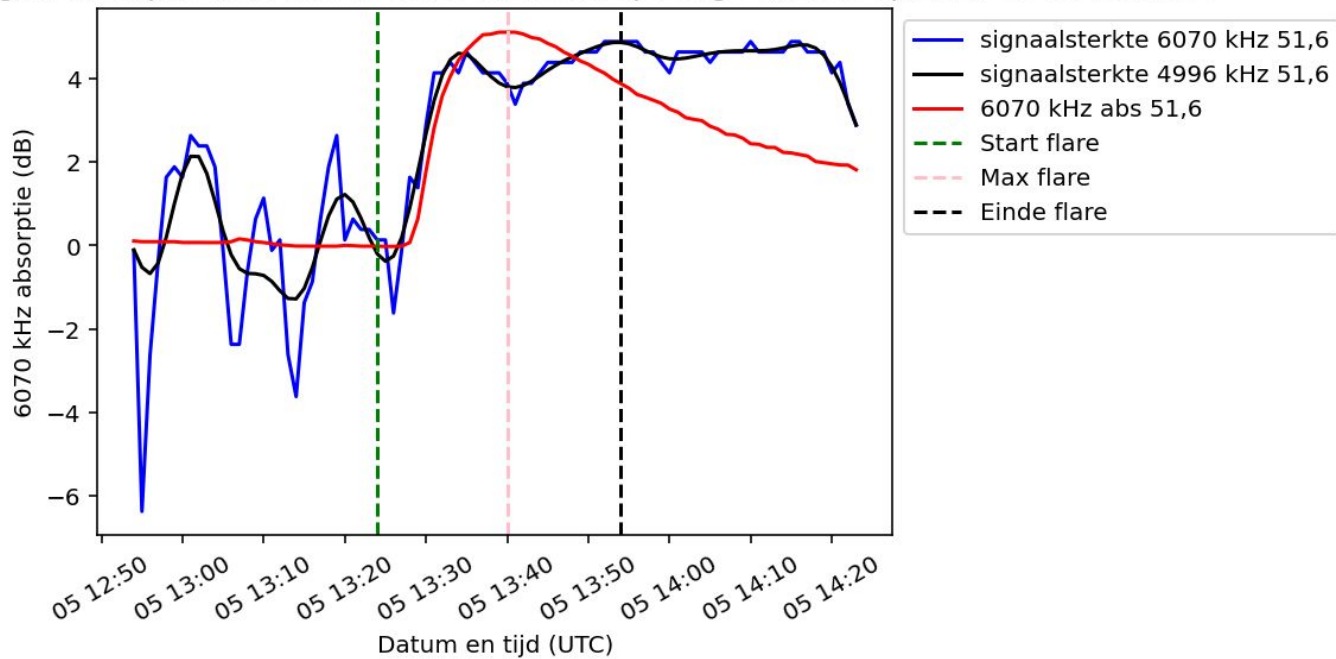
K. Cornelis: ... with the radio data from Twer





K. Cornelis: Radio data from Twente → accuracy of D-rap

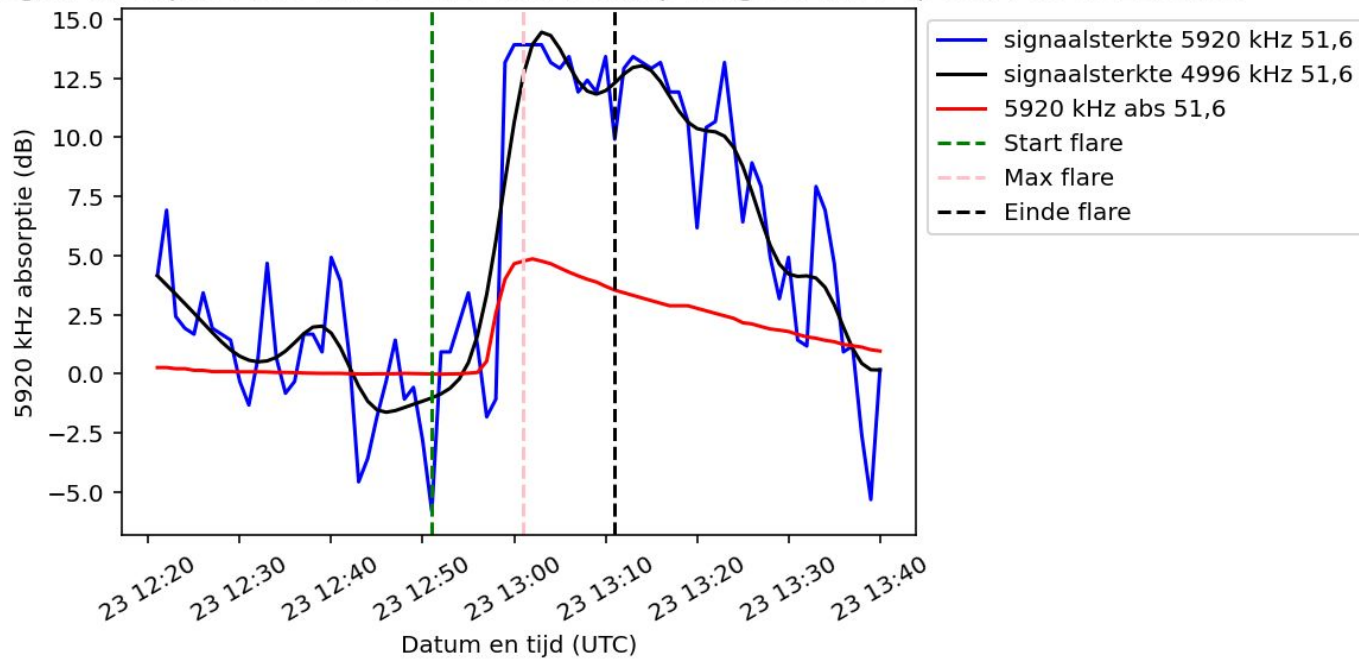
Voorspelde D-region absorptie X1.7 van de 6070 kHz band op Long 51, Lat 6 op 2024-08-05 13:40:00





K. Cornelis: Radio data from Twente → accuracy of D-rap

Voorspelde D-region absorptie M9.3 van de 5920 kHz band op Long 51, Lat 6 op 2024-06-23 13:01:00





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HF radio: forecasting

- forecasting via other space weather indicators

Event	Forecasting index	Resolution	Moderate limits	Severe limits
SWF	Solar flares/ R-scale	Daily	M1+ / R1	X1+ / R3+
AA	K_p	3-hourly	8+	9+
PCA	Energetic protons / S-scale	Daily	10+ pfu / S1+	1000+ pfu / S3+
PSD	K_p	3-hourly	6+	6+

- a daily resolution is not enough as even strong flares only last 0.5 - 2 hours → without knowing when it occurs, impact cannot be predicted
- especially AA and PSD forecasts are insufficient → association with K_p (from what I could find) Fiori et al. 2020 + Fiori et al. 2022



UHF & VHF radio

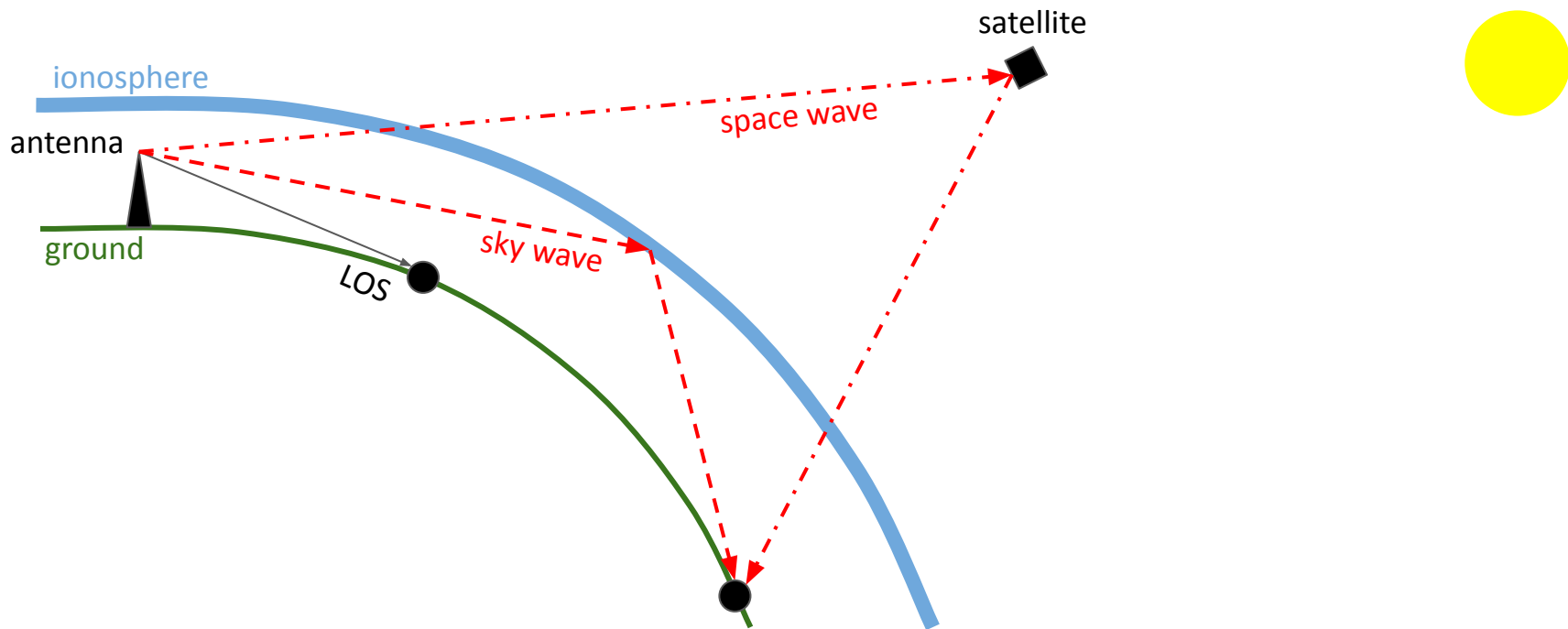


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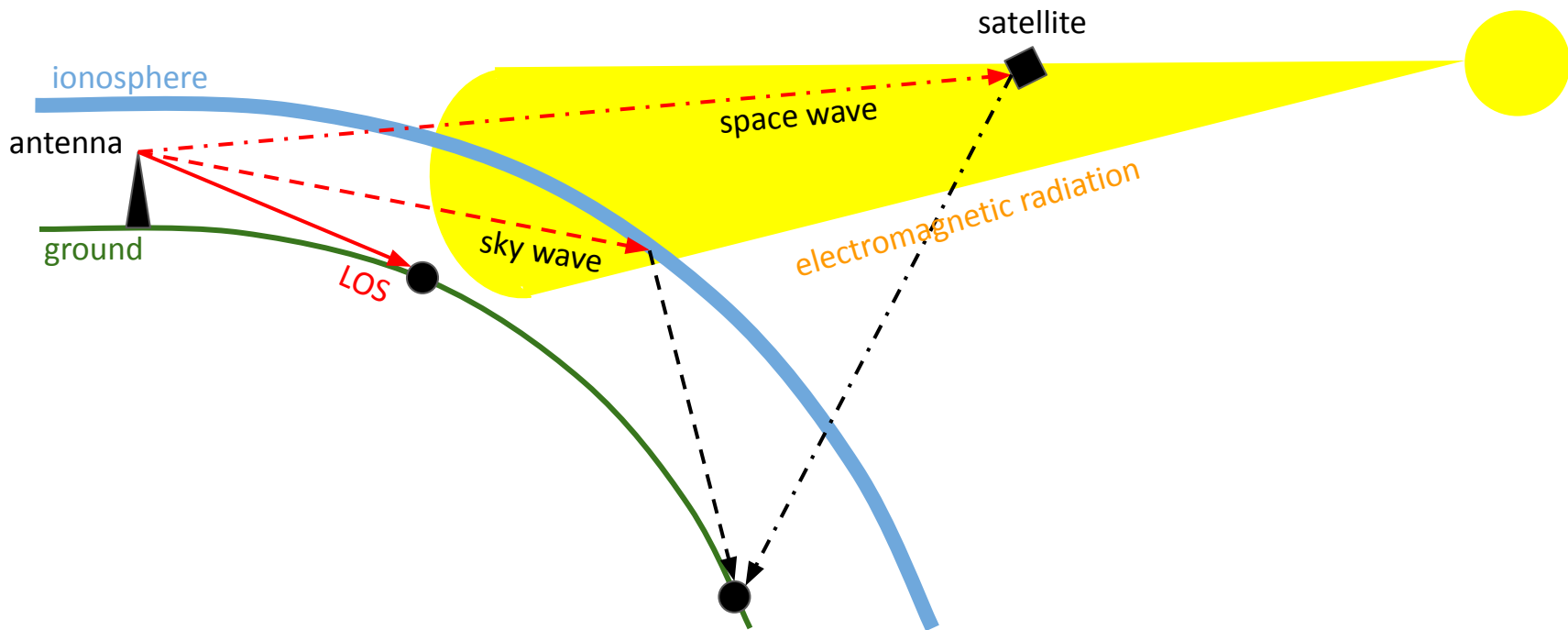


How do we communicate? Why is the ionosphere important?





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Credit: Naval Technology



Credit: T. Baba





VHF & UHF radios: what do operators want?

- how much of a problem is this really? → SW risk
- what do these mean for operations? Are there mitigation strategies?
- what can measurements on just one/ more frequency channel tell us about space weather?
- can we predict which frequencies will be affected and when?



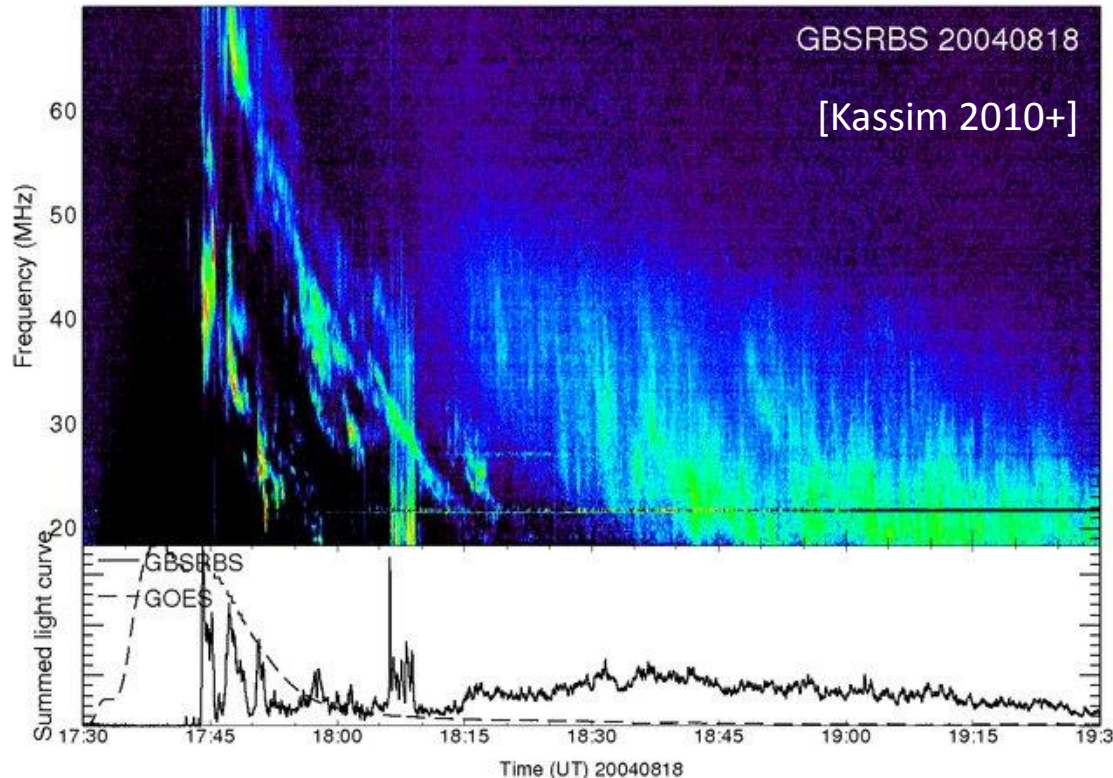
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Ravenswaaij: operationally-useful statistics of SRBs vs X-ray

- statistics exist: similar research considered all kinds of SRB and also very weak flares → strong flares only
- per channel, how often/ does a radio signal come: how early/ how late?
- is there any correspondence in the signal profiles?





VHF & UHF radios: what do operators want?

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UHF & VHF radio: what do operators want?

Probably not.



Other effects

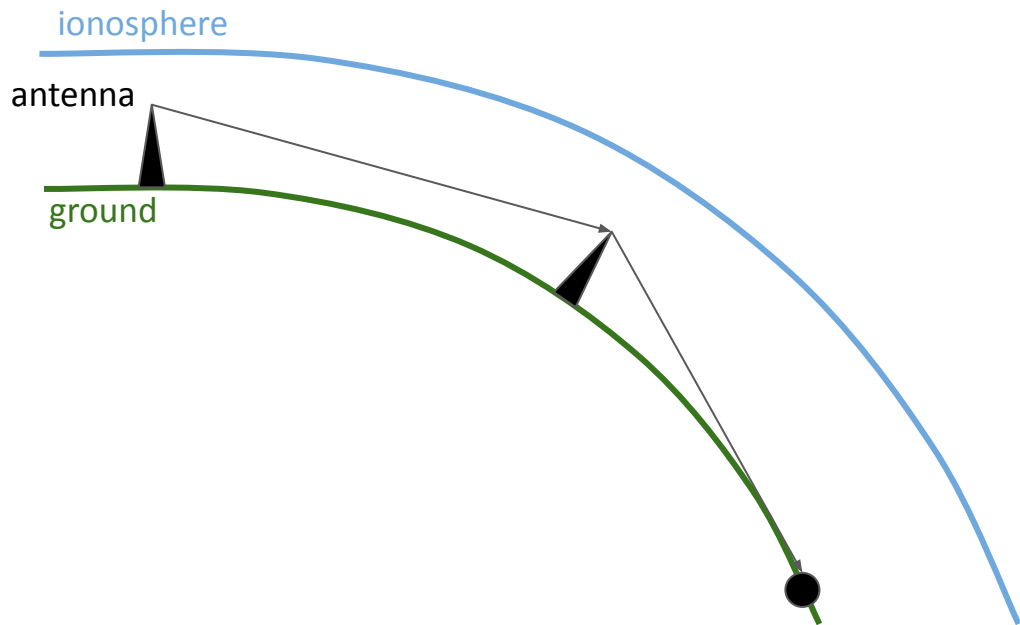


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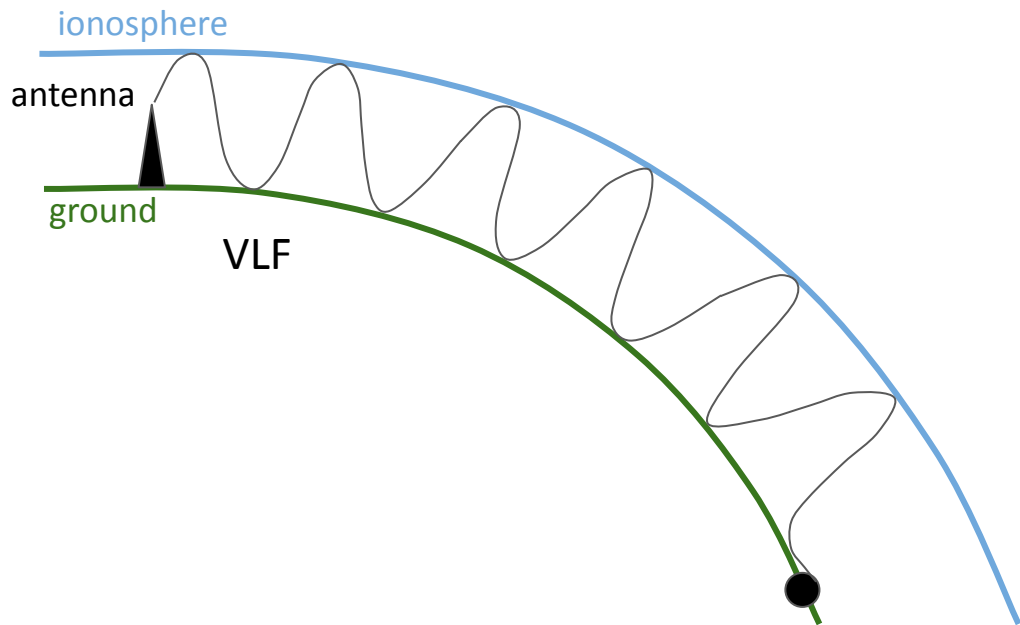


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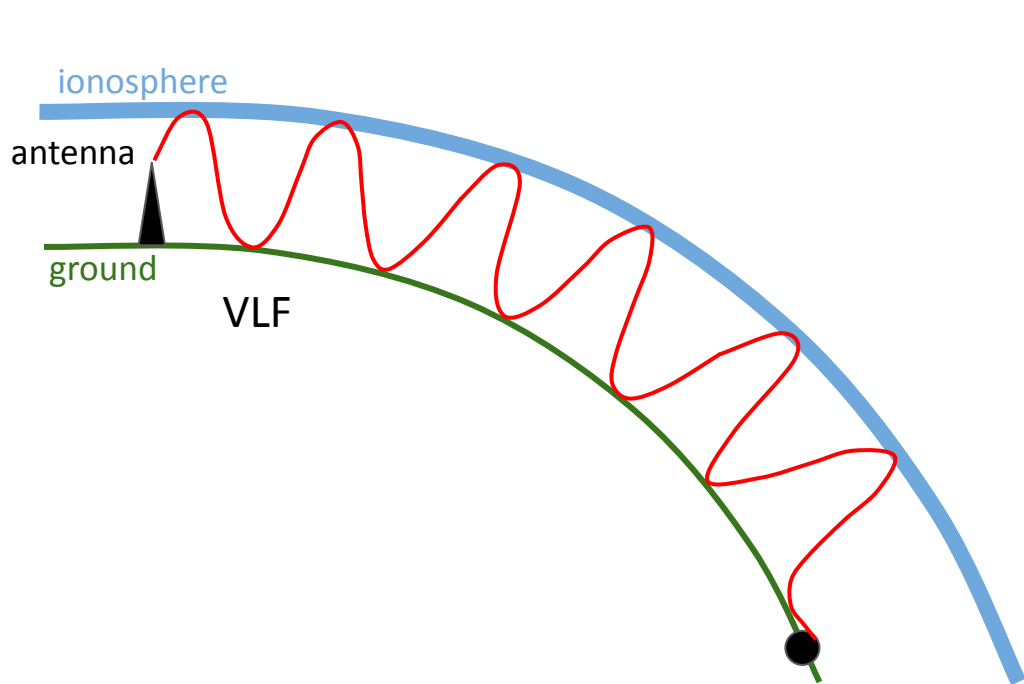


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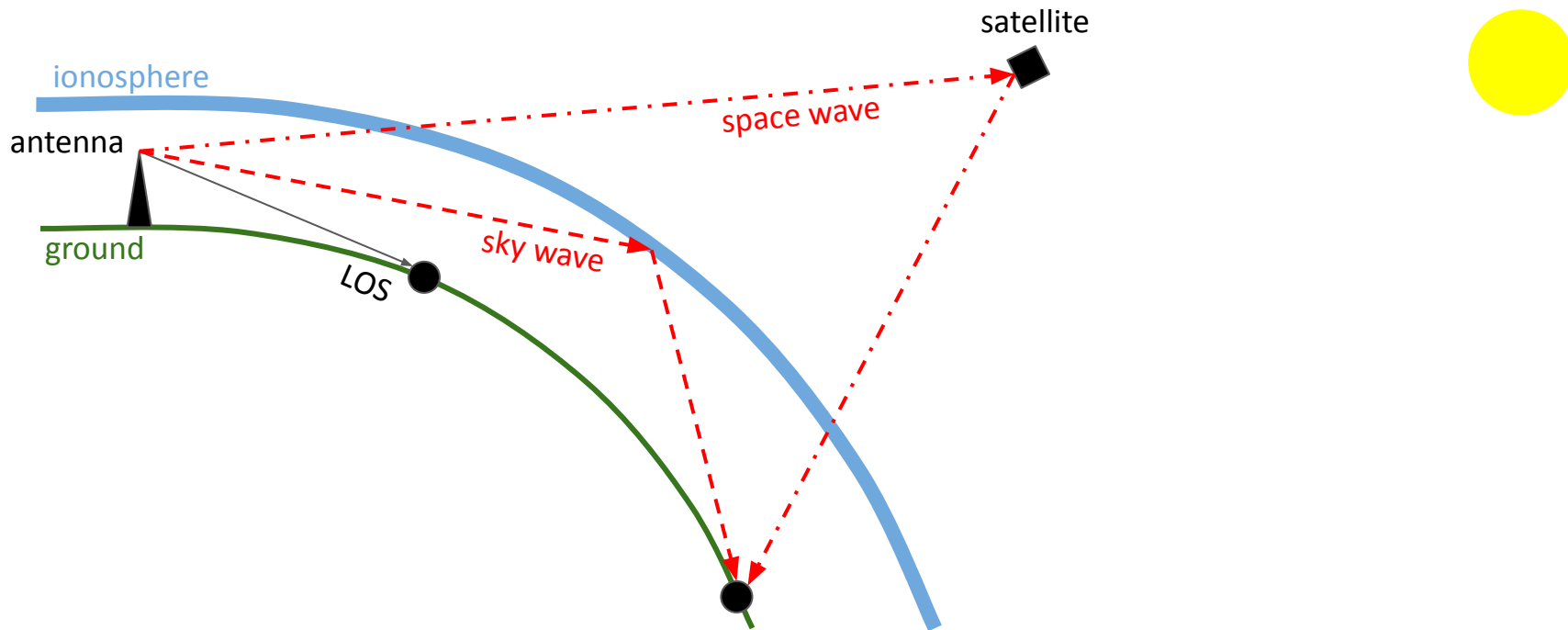


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Credit: AeroVironment



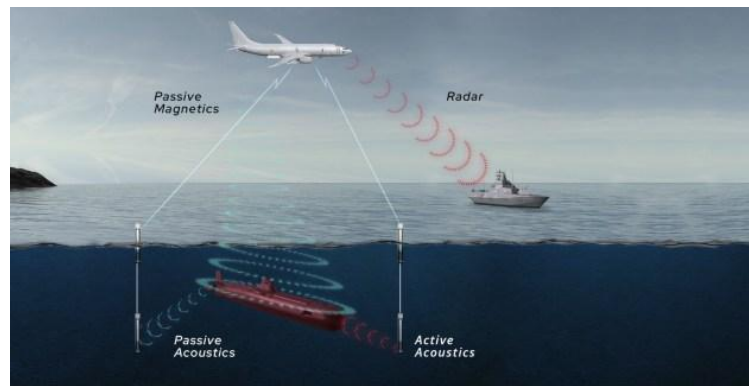
Credit: Naval Technology





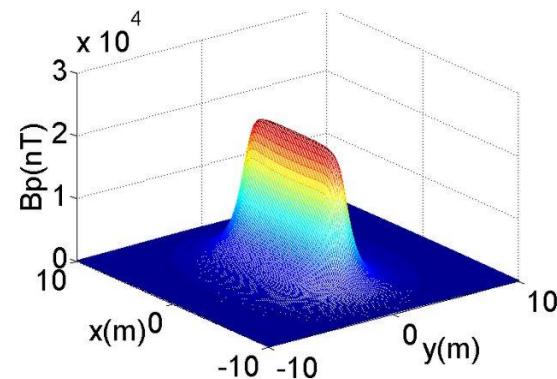
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- **MAD: accuracy issues → low range of detection**
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Credit: Australiandefence.com

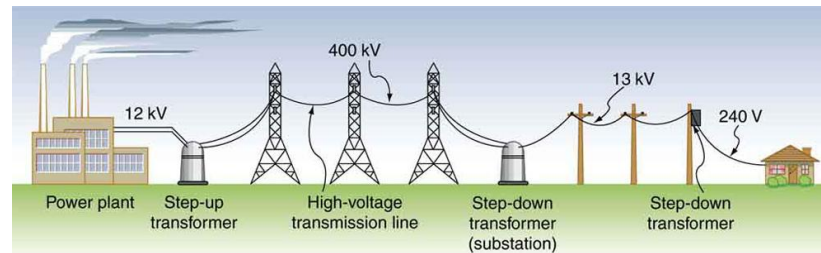
Credit: Guo et al. 2012





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- SATCOM, GNSS: scintillation, delay → loss of lock
- MAD: accuracy issues → low range of detection
- **power systems: limited loads → failures**
- SATOPS:
 - atmosphere
 - particle environment
 - COM loss



Credit: Lumen





SWx vulnerability examples:

- HF radio (radar): frequency limits → fade-outs
- UHF & VHF radio (radar): noise → blackouts
- VLF radio: noise → fade-outs
- SATCOM, GNSS: scintillation, delay → loss of lock
- MAD: accuracy issues → low range of detection
- power systems: limited loads → failures
- **SATOPS:**
 - **atmosphere: increased fuel usage → reentry**
 - **particle environment: excessive charging → failure**
 - **COM loss: OPS issues → collision risk**

Credit: ISISpace





Other types of challenges



Operator awareness?

- “technical failures” that later disappear
- too much extra “noise”
- some are resolved within minutes, some for hours/ days
- essential to know what these look like in different systems but:
 - operator awareness largely lacking
 - insufficient applied SWx research to know if SW-related
- need to better engage operators and improve their awareness

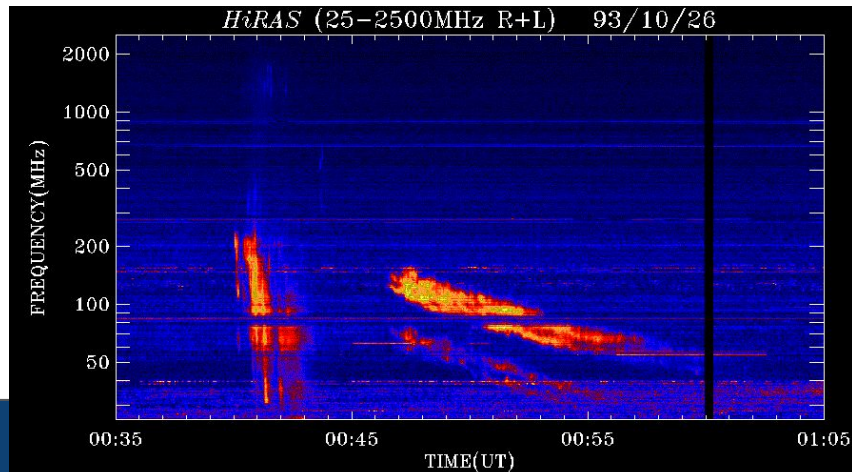
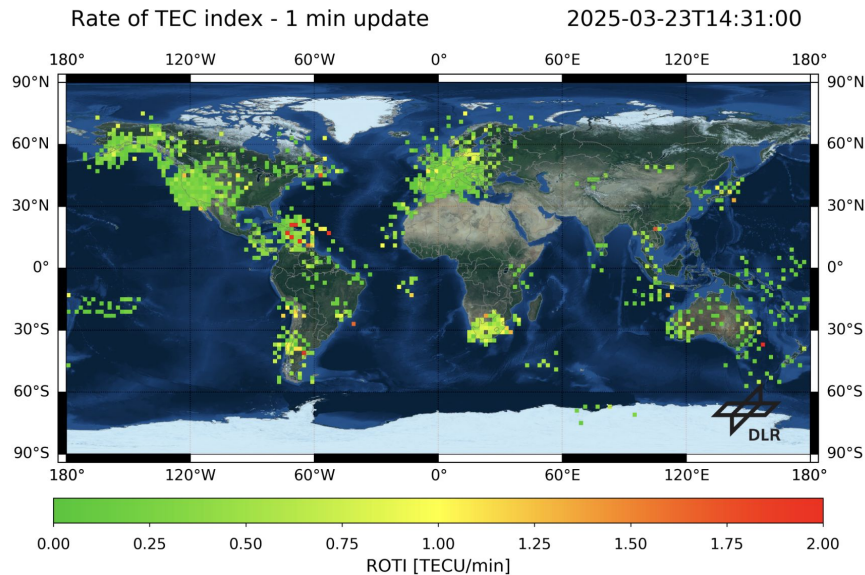


Credits: Lockheed Martin



Examples of SWx vulnerabilities

- HF-radio system for long-distance comms:
 - ... but needs time-synchronisation from GPS/ GNSS
- UHF radio with several channels on a drone
 - ... with all the channels within 20 MHz from each other





Strategic SWx challenges

- US dependencies in our infrastructures:
 - interplanetary magnetic field data at L1
 - solar magnetogram measurements
 - (near) real-time X-ray & EUV measurements
 - modelling of D-layer ionospheric absorption
 - atmospheric models (what does ESA use?) ...
- now free & open access, but what if indeed NOAA/ SWPC goes under DHS? Or a large portion of its employees are fired?

→ **need to improve the quality and exploitation of European services**



Credits: NOAA



Thank you for your attention

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