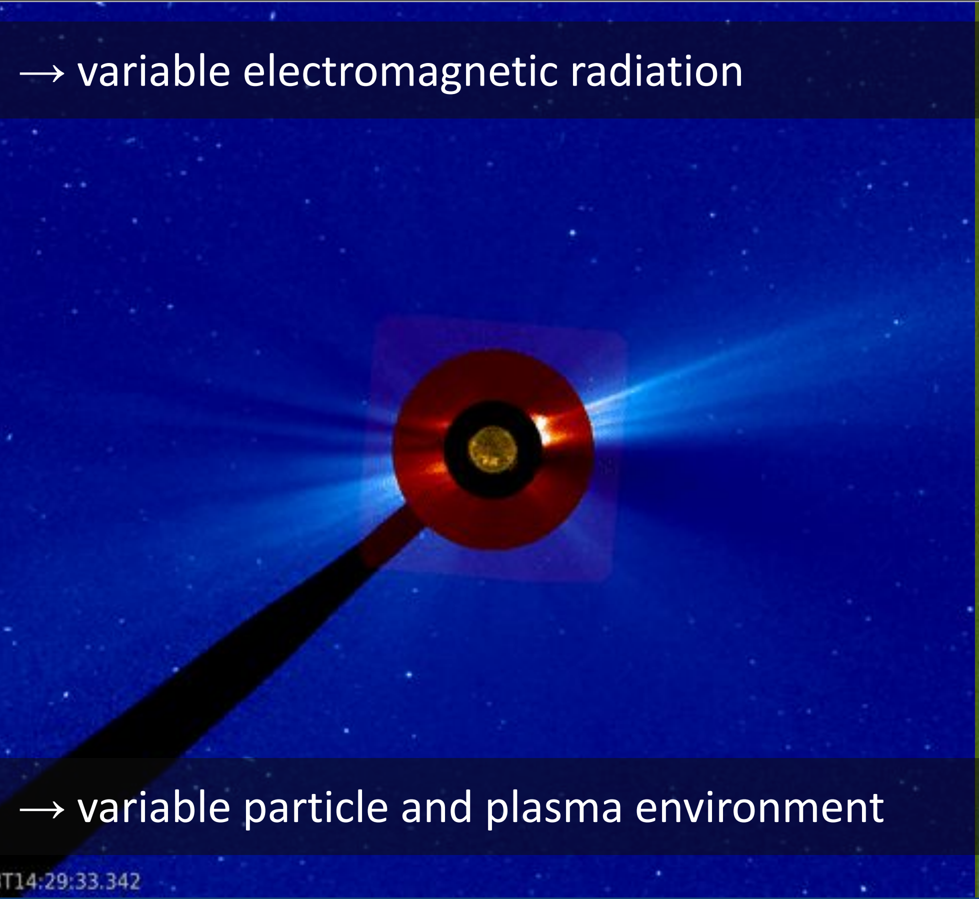
From user's perspective

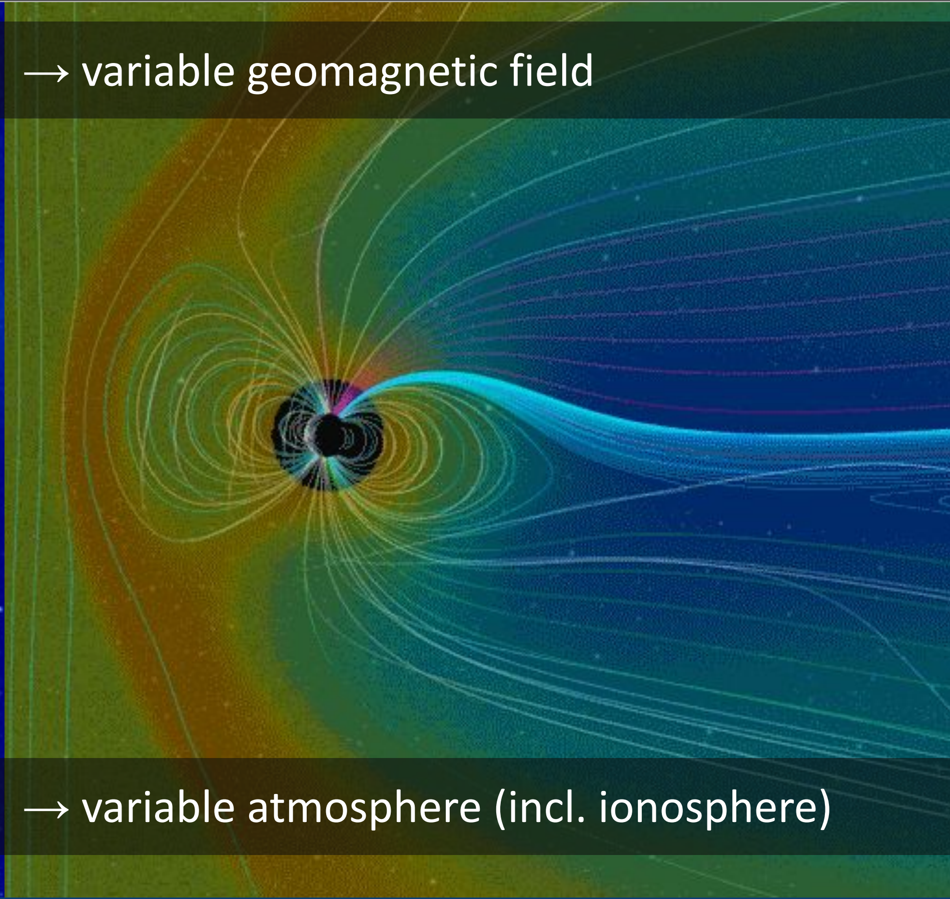
Michaela Brchnelova
m.brchnelova@mindef.nl

Introduction

→ variable electromagnetic radiation

→ variable geomagnetic field

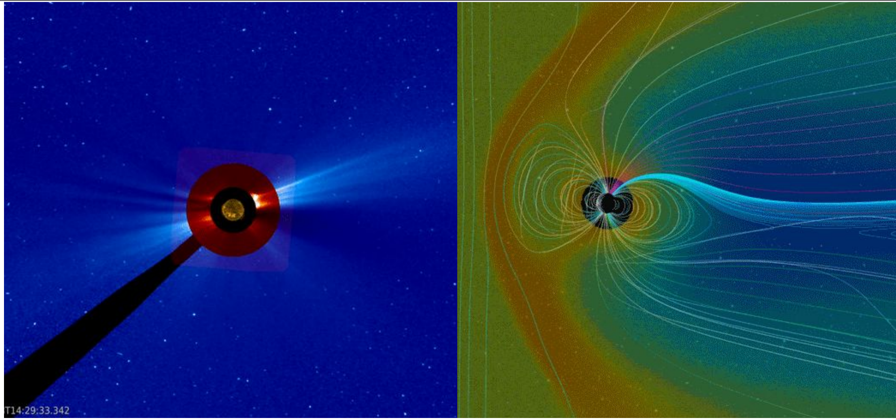




→ variable particle and plasma environment

→ variable atmosphere (incl. ionosphere)

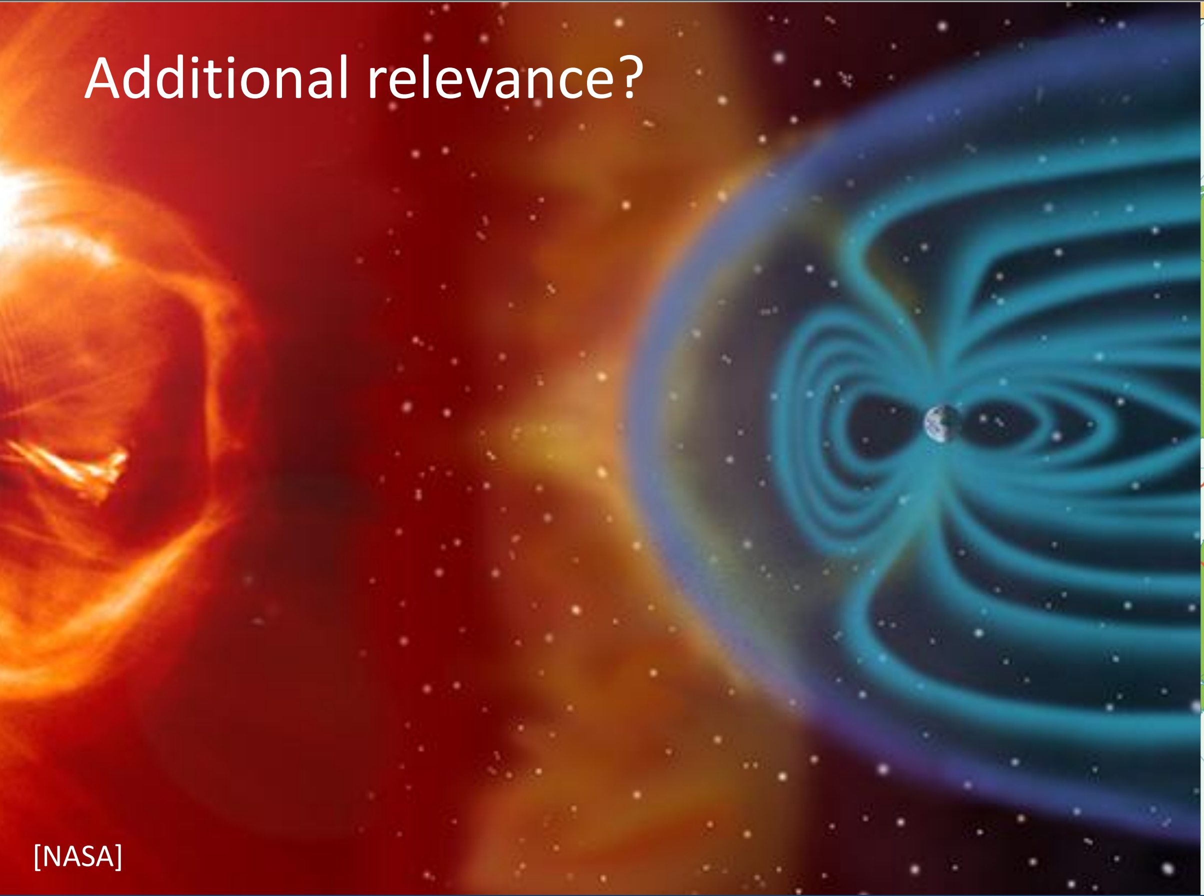
Defence vulnerabilities

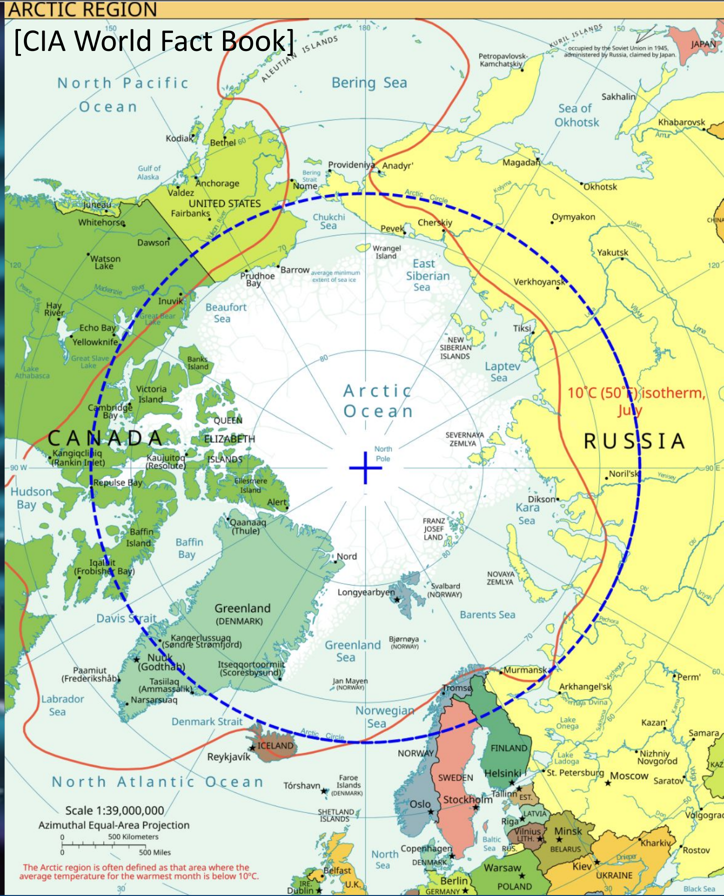


- if it:
  - flies in space/ upper atmosphere (or needs assets that do)
  - uses/ detects radio signals
  - communicates through the ionosphere
  - requires magnetic measurements
  - is sensitive to electric currents in the grounds

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

Additional relevance?


[NASA]



[CIA World Fact Book]

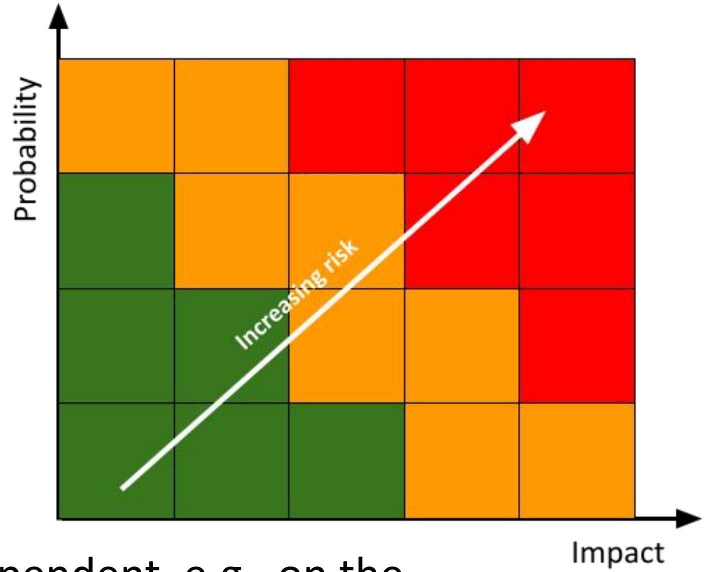
“Risk”

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

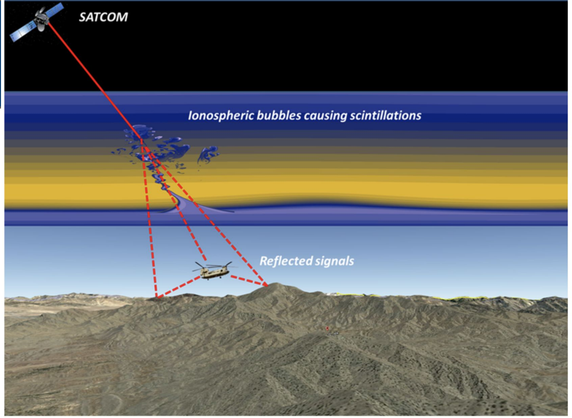
  → **reception and noise due to a sporadic E-layer**

2002 The Battle of Takur Ghar (Afghanistan)

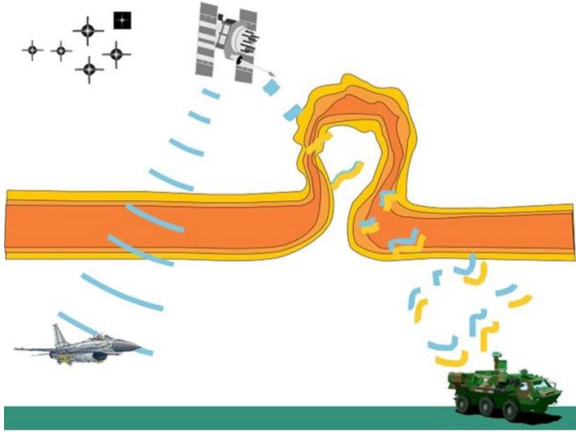
- plasma bubbles post-midnight might occur due to increased geomagnetic activity of Kp > 3: the battle of Takur Ghar: Kp = 4, 0300 LT March 4, 2002

- 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



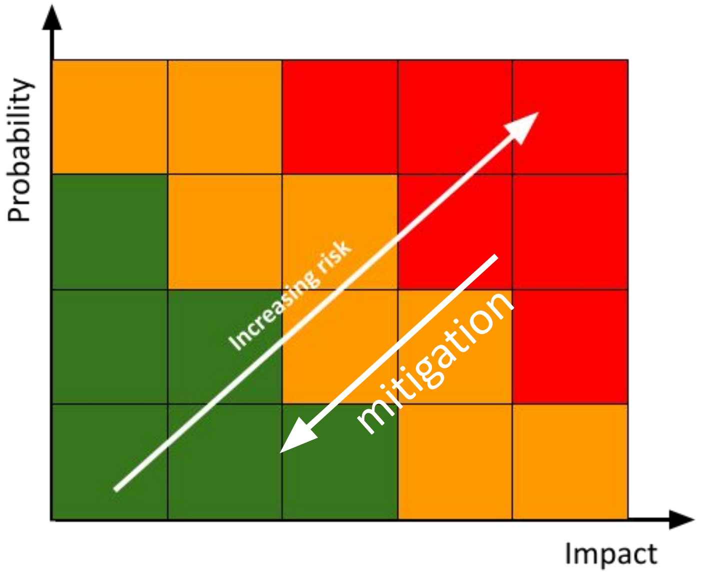
Credit: U.S. Air Force Research Laboratory (AFRL)
https://www.nasa.gov/mission_pages/cindi/five-years.html

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?

risk = probability x cost



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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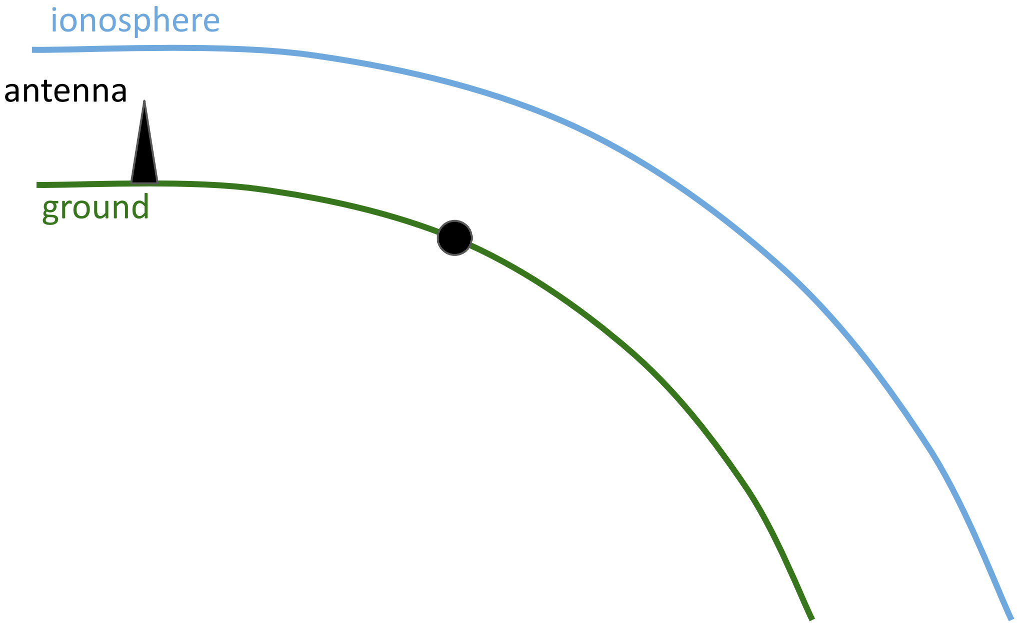
HF radio

How do we communicate? Why is the ionosphere important?



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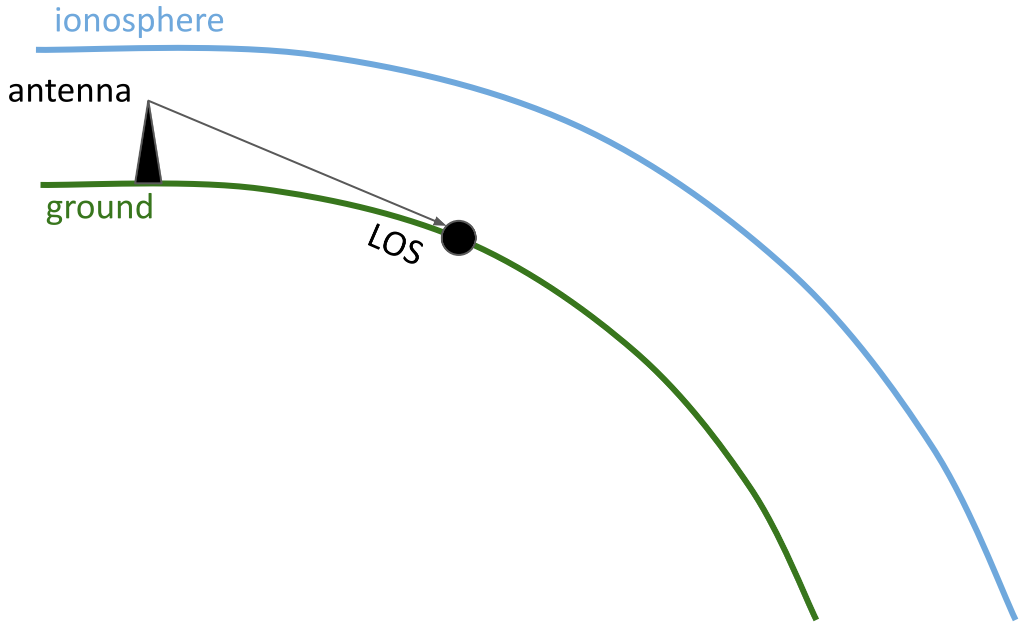

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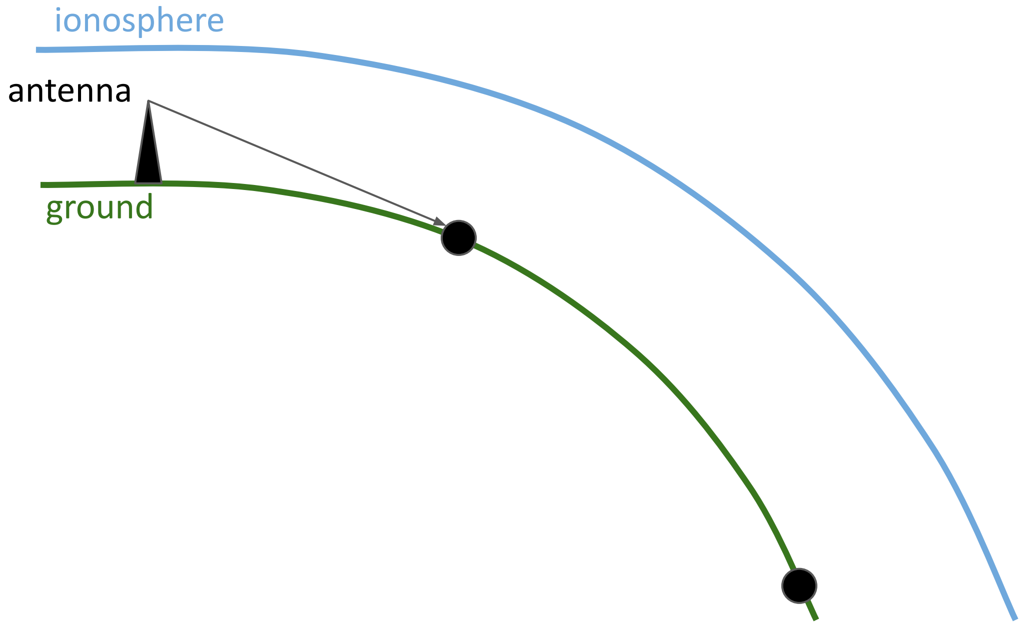

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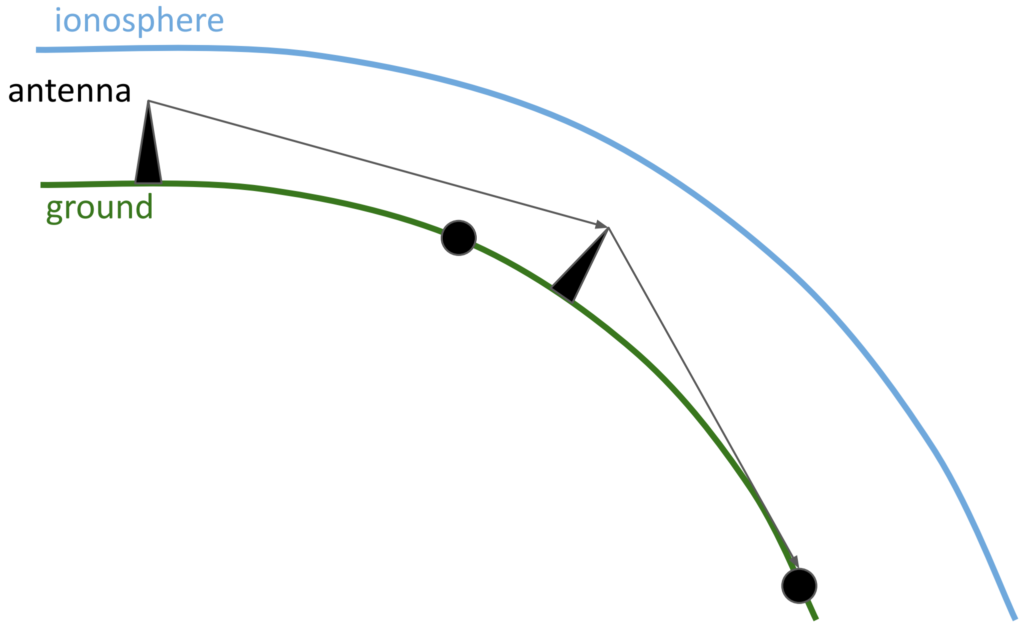

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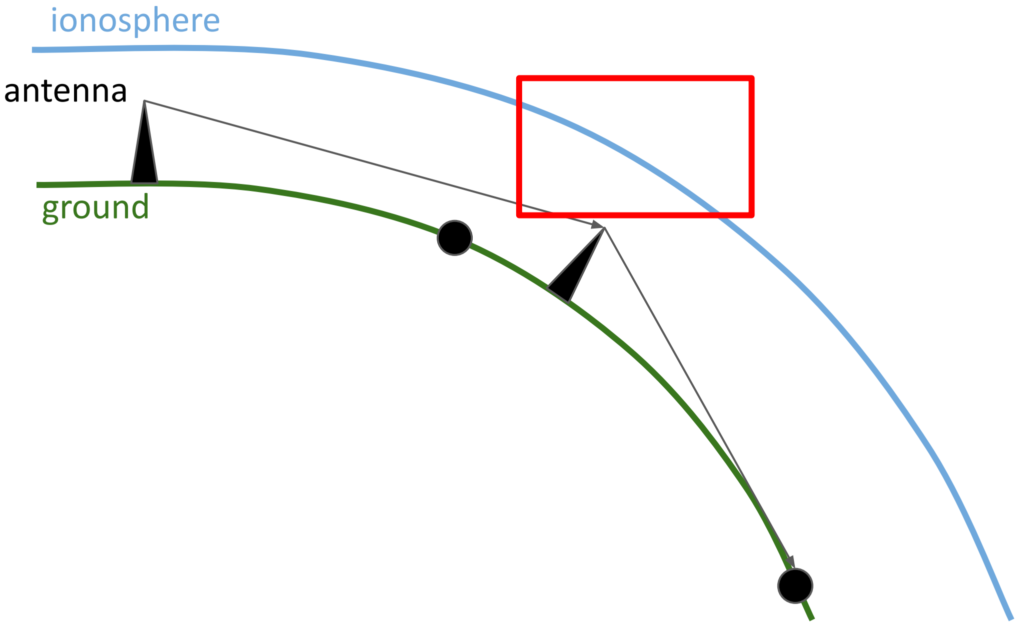

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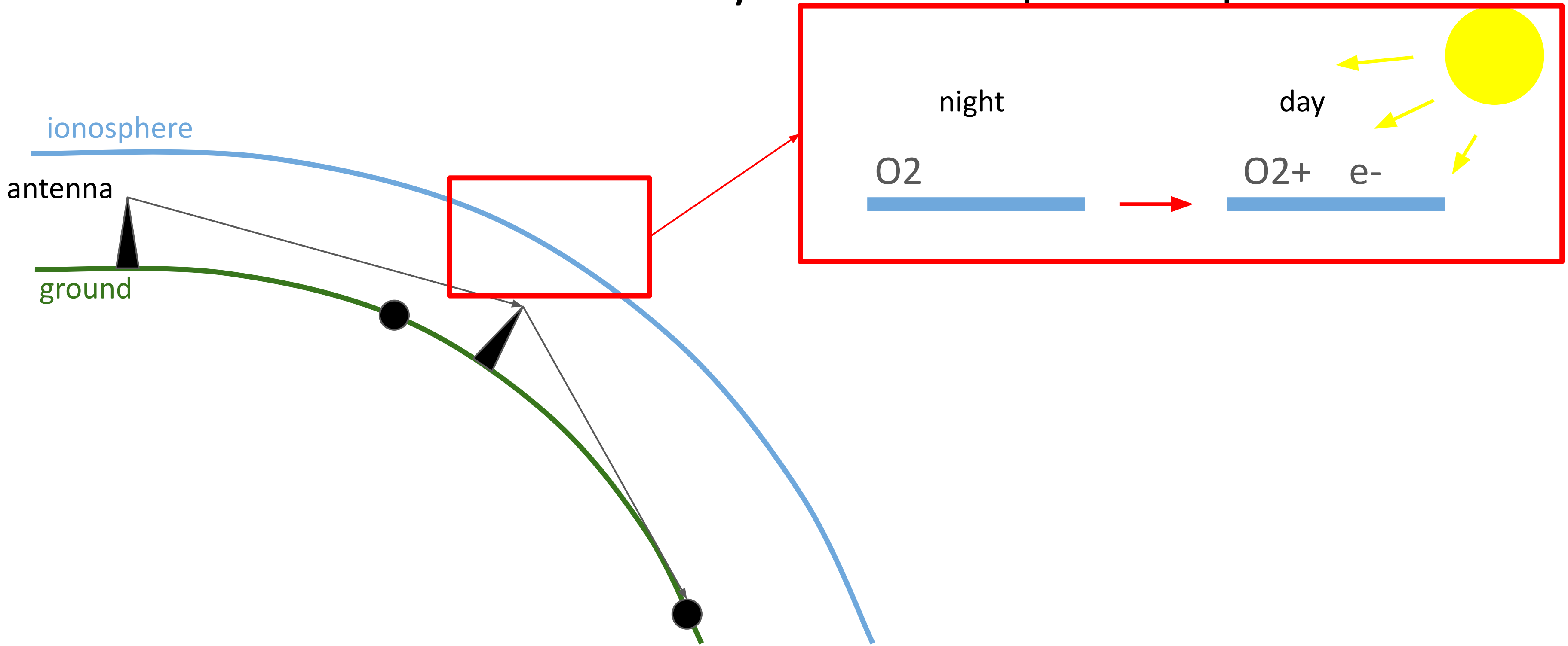

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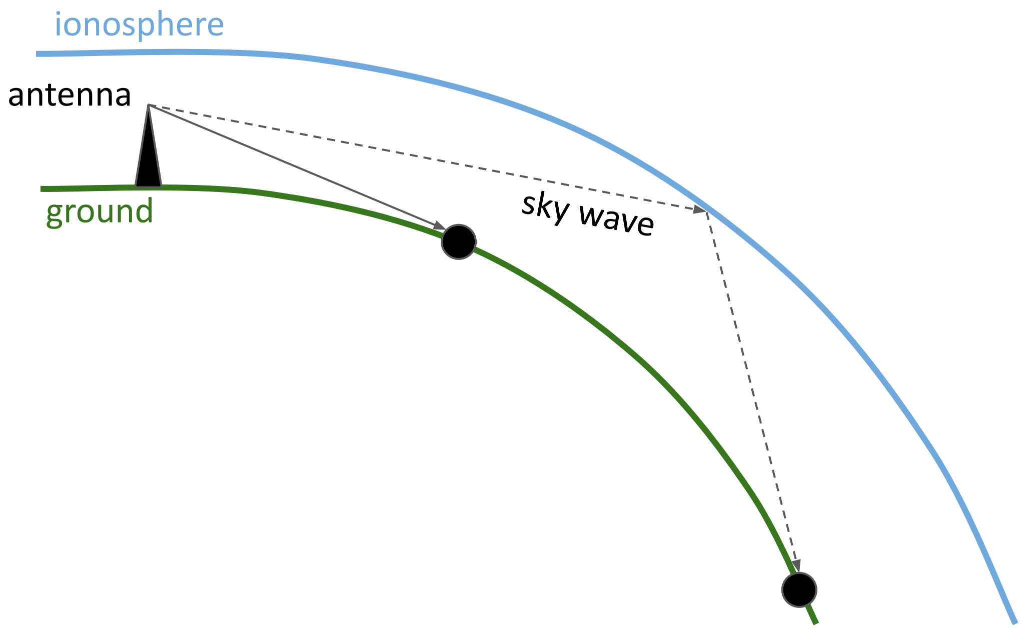

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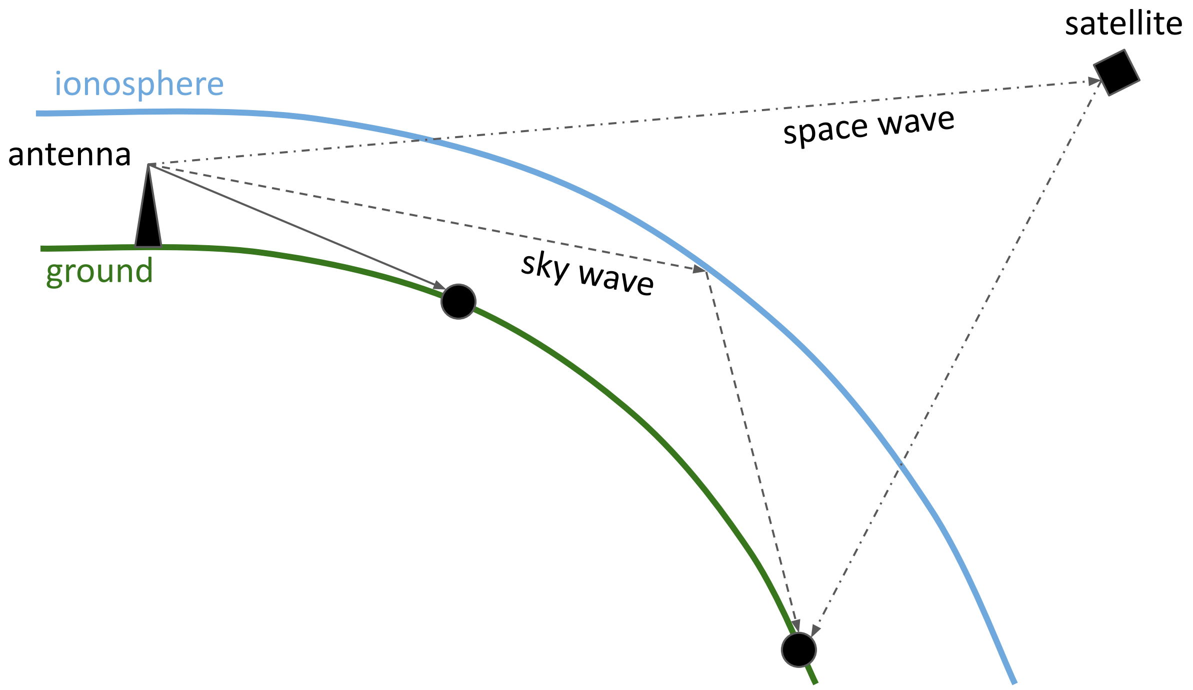

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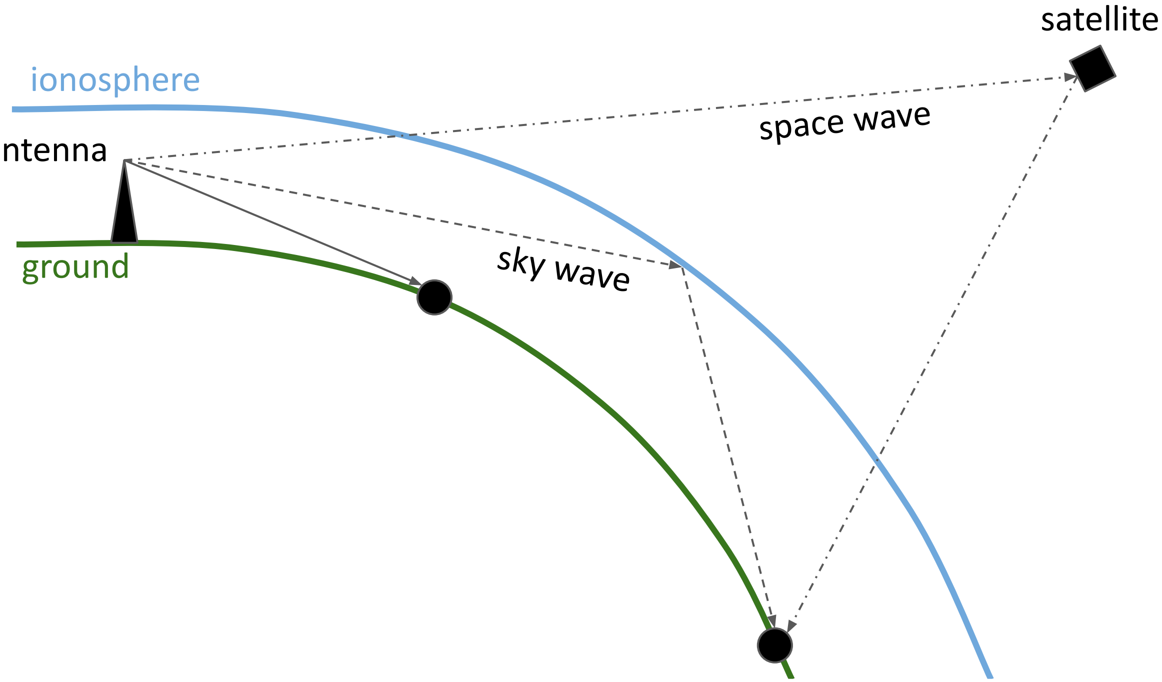

- HF more and more important due to anti-sat weapons and satcom jamming (Ukr)

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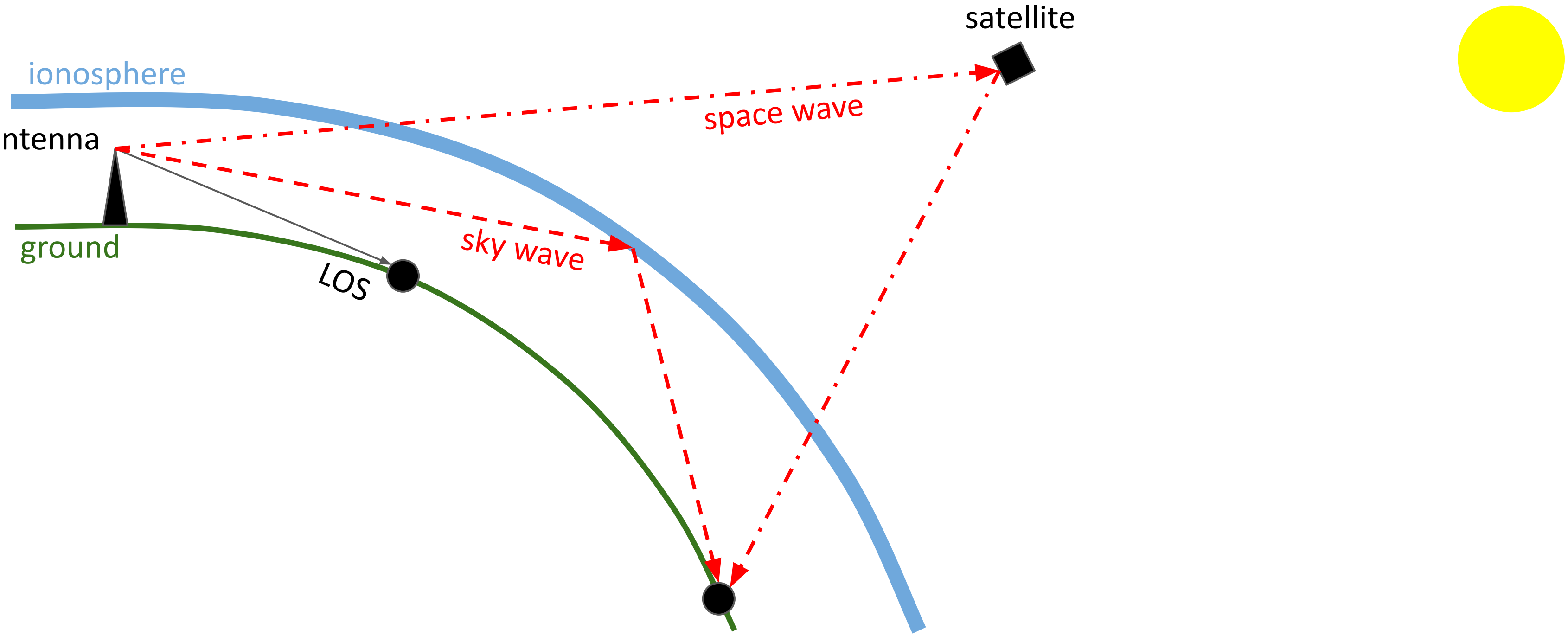

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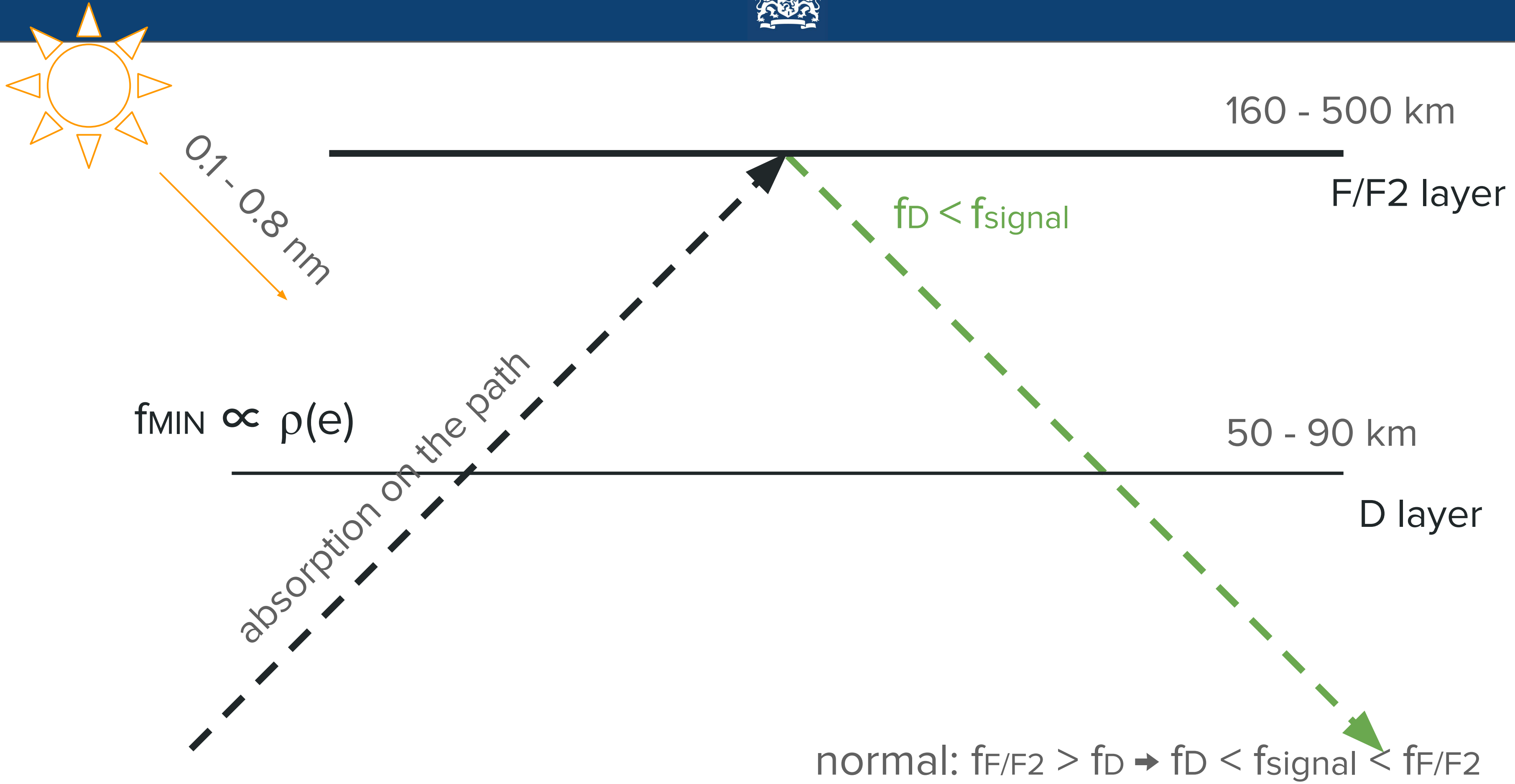
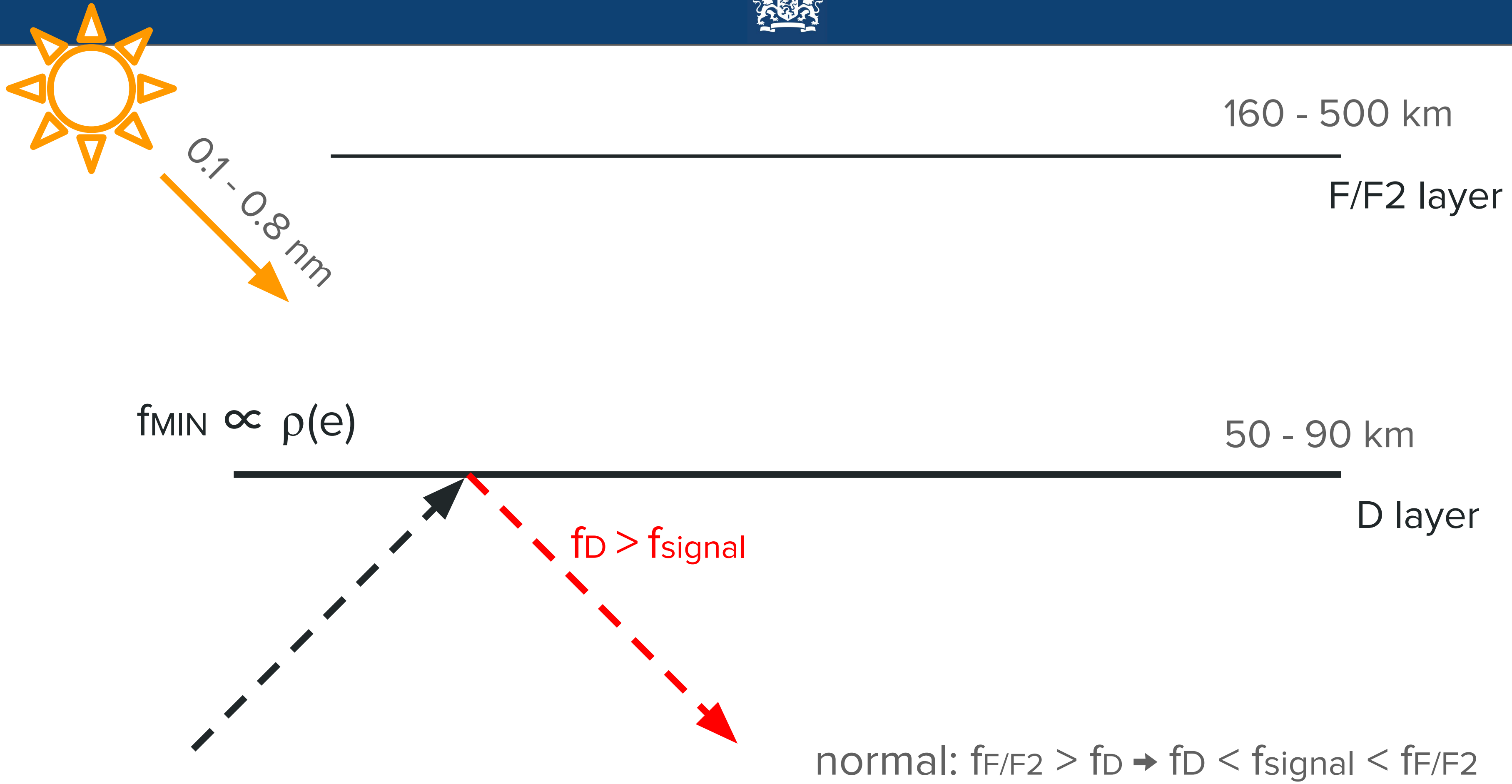

0.1 - 0.8 nm
160 - 500 km
F/F2 layer
$f_D < f_{signal}$
$f_{MIN} \propto \rho(e)$
absorption on the path
50 - 90 km
D layer
normal: $f_{F/F2} > f_D \rightarrow f_D < f_{signal} < f_{F/F2}$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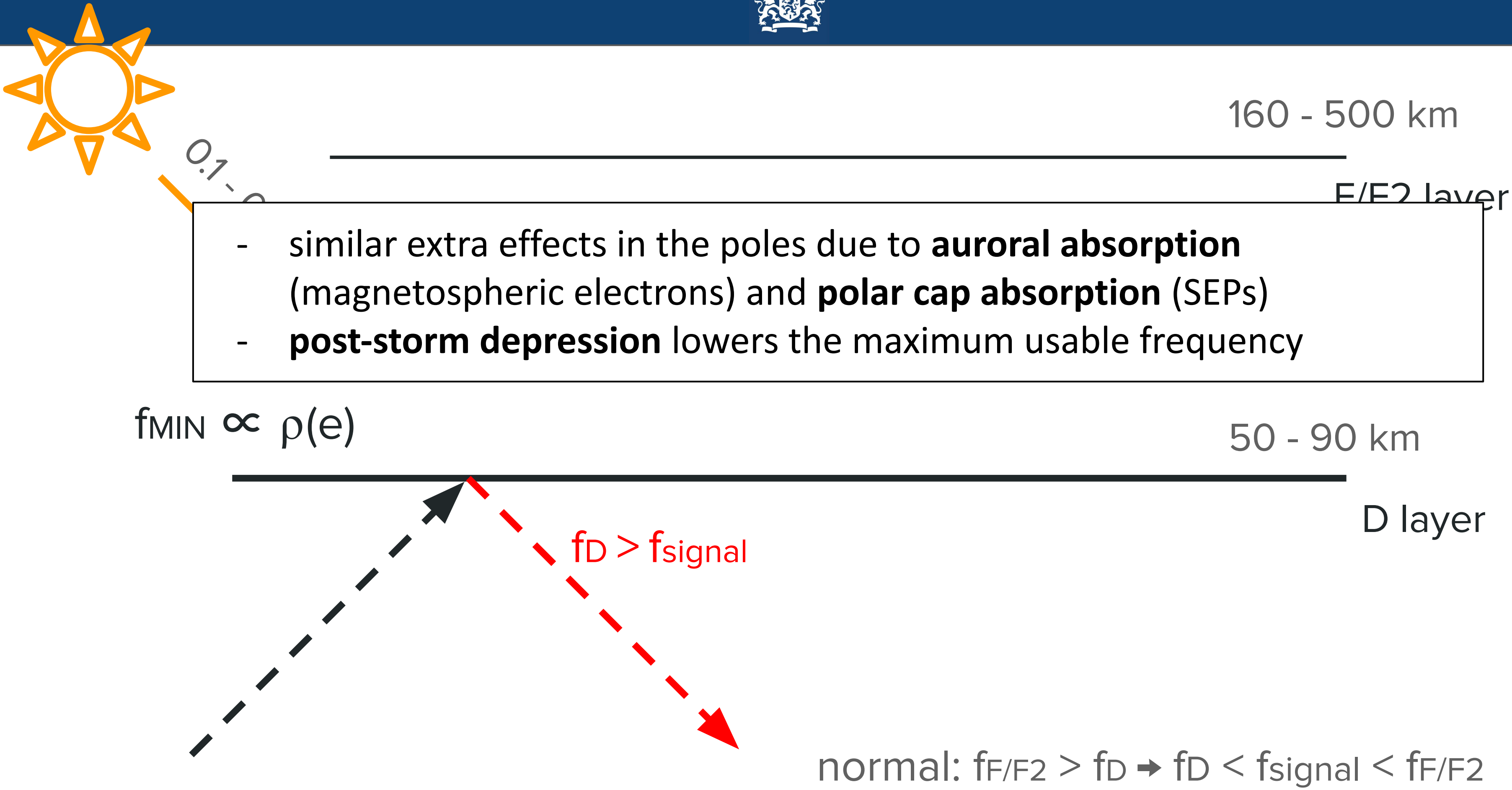

- similar extra effects in the poles due to **auroral absorption** (magnetospheric electrons) and **polar cap absorption** (SEPs)
- **post-storm depression** lowers the maximum usable frequency

SWx vulnerability examples:

- **HF radio (radar): frequency limits → fade-outs**
- UHF & VHF radio (radar)
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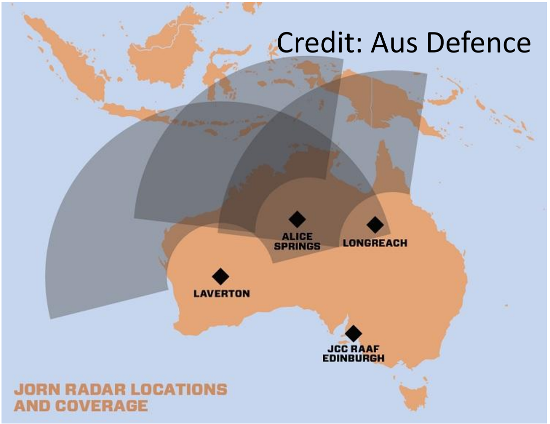
Credit: Harris



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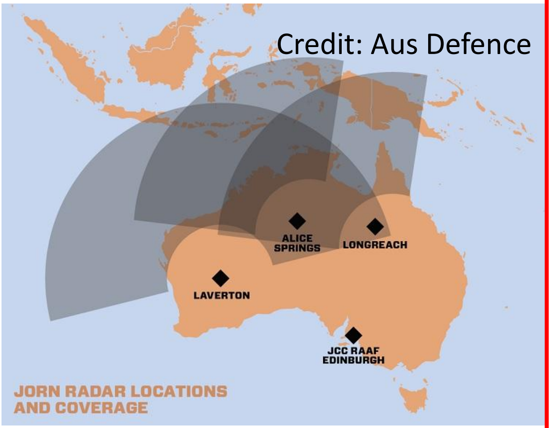
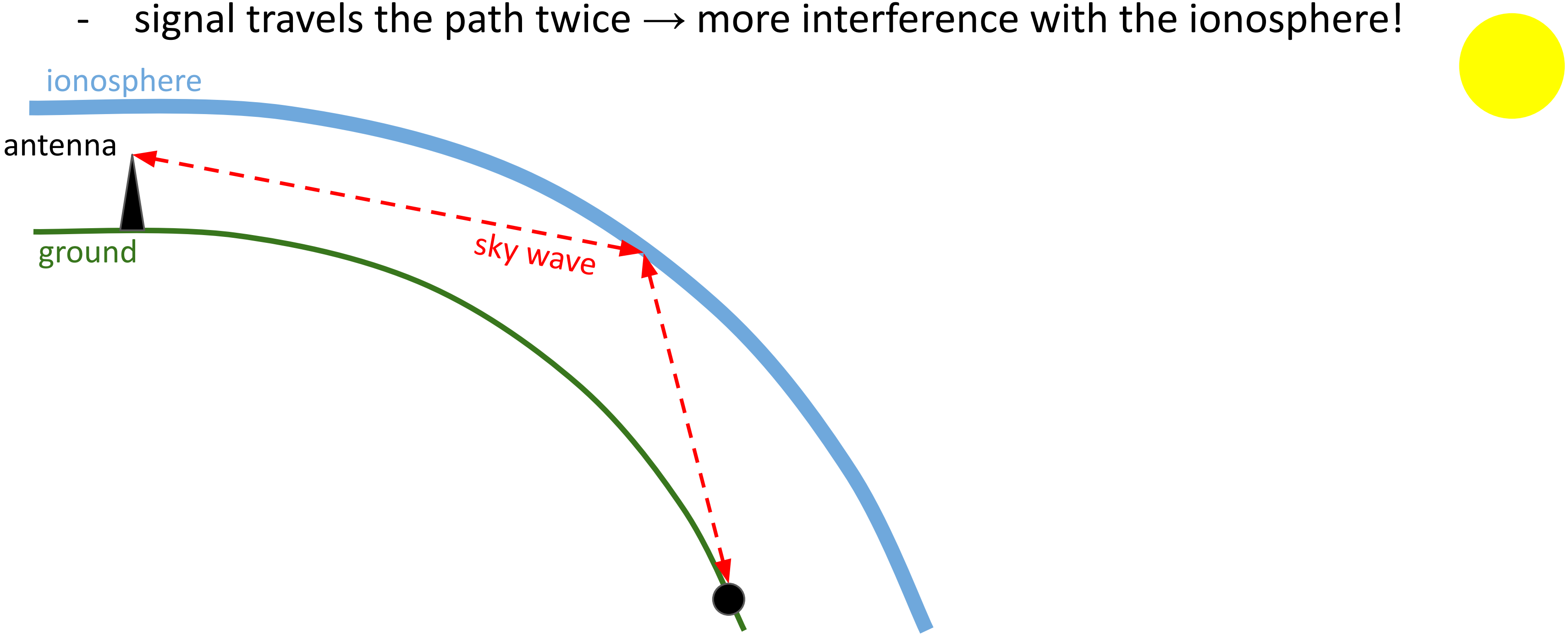


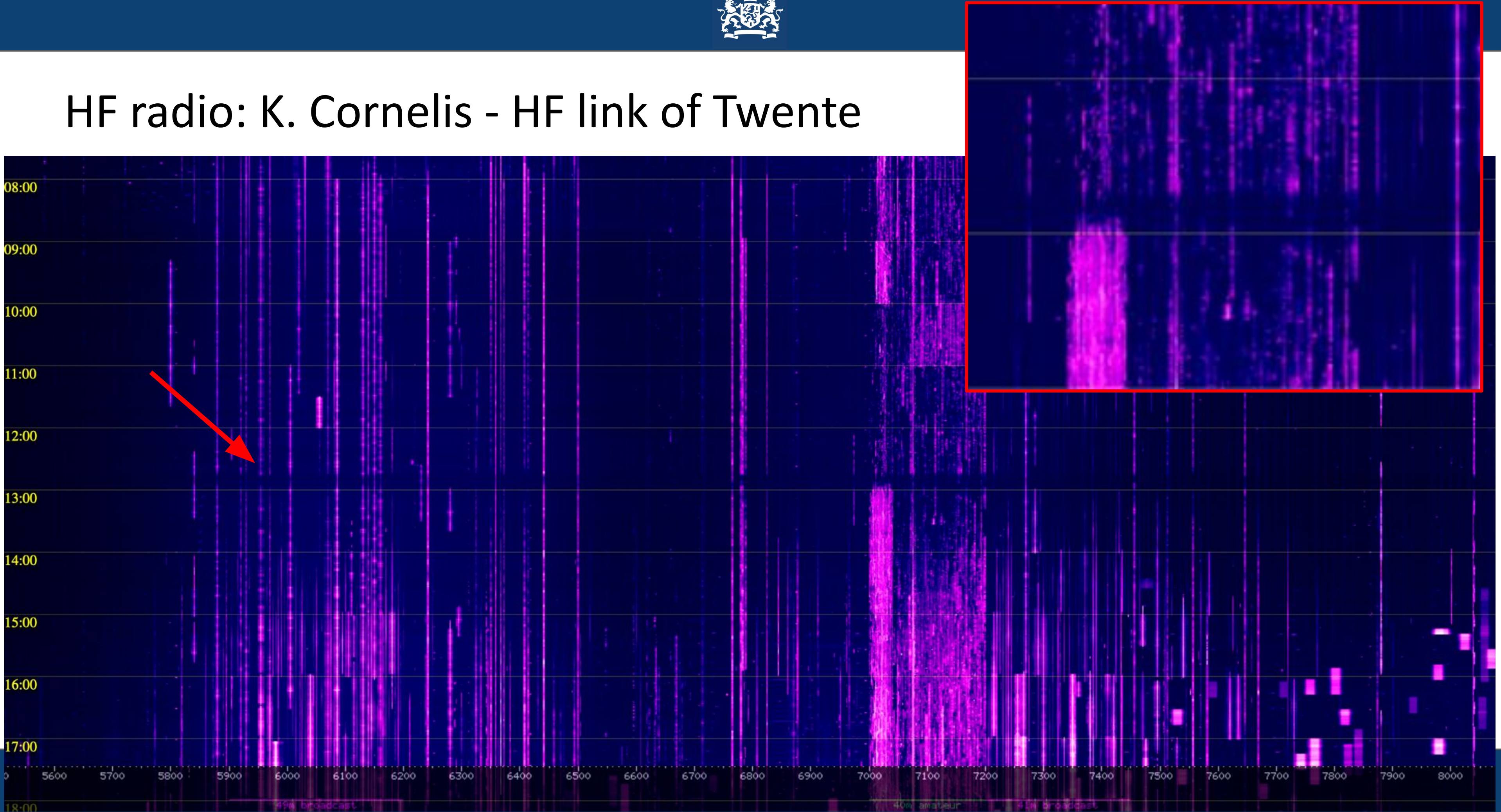
Credit: Aus Defence

HF radio/ radar differences

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



HF radio: K. Cornelis - HF link of Twente



HF radio: How much of a problem is this really?

Event		Moderate events in solar maximum [h]			Moderate events in solar minimum [h]		
Frequency range		0 - 10 MHz	10 - 20 MHz	20 - 30 MHz	0 - 10 MHz	10 - 20 MHz	20 - 30 MHz
SWF	1-5 dB loss	> 300	50 - 300	5 - 50	> 200	30 - 200	3 - 30
AA	1-5 dB loss	> 30		10 - 30	> 20		5 - 20
PCA	1-5 dB loss	≫ 100	> 100	50 - 100	≫ 50	> 50	10 - 50
PSD	30-50% ΔMUF	N/A	100 - 200		N/A	10 - 100	

solar max, moderate: weeks/ year at low frequencies, days/year at high frequencies

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

solar max, severe: days/ year at low frequencies, hours/year at high frequencies

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HF radio: where does it matter?

- HF the only high-data-rate link without the need of human infrastructure
  - in polar regions: SATCOM may be easily disturbed due to scintillation & unavailability
  - the same for SATCOM-denied environments

  → interest in HF growing

- HF radars used for beyond-line-of-sight (BLOS) detection (e.g., Australian Jindalee)

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HF radio: mitigation strategies

- short term:
  - change frequencies in use if possible
    - to higher during absorption events (PCA, AA, SWF)
    - to lower during post-storm depression
  - fast-track/ delay operations if HF necessary
  - monitor the status of the ionosphere and forecasts

- long term:
  - improve operator awareness
  - implement more diversity into operations & systems

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VHF & UHF radio

SWx vulnerability examples:

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- **UHF & VHF radio (radar)**
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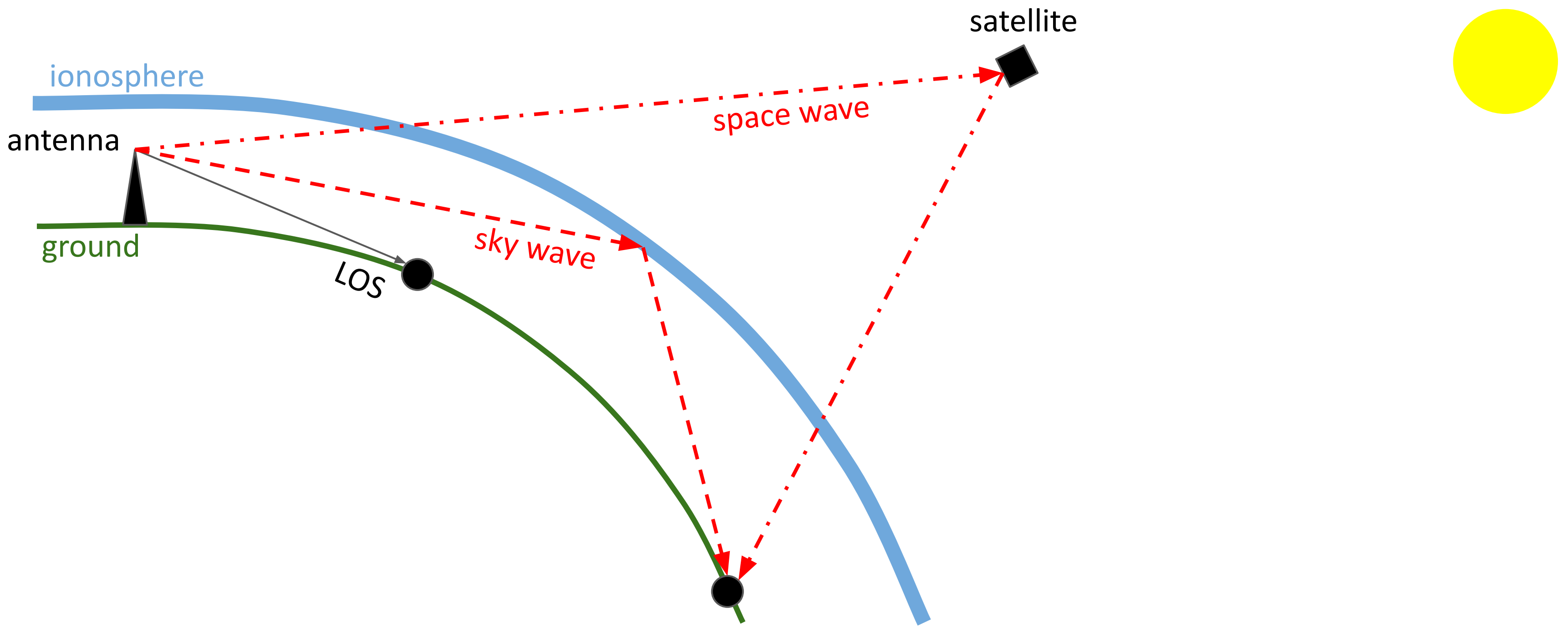

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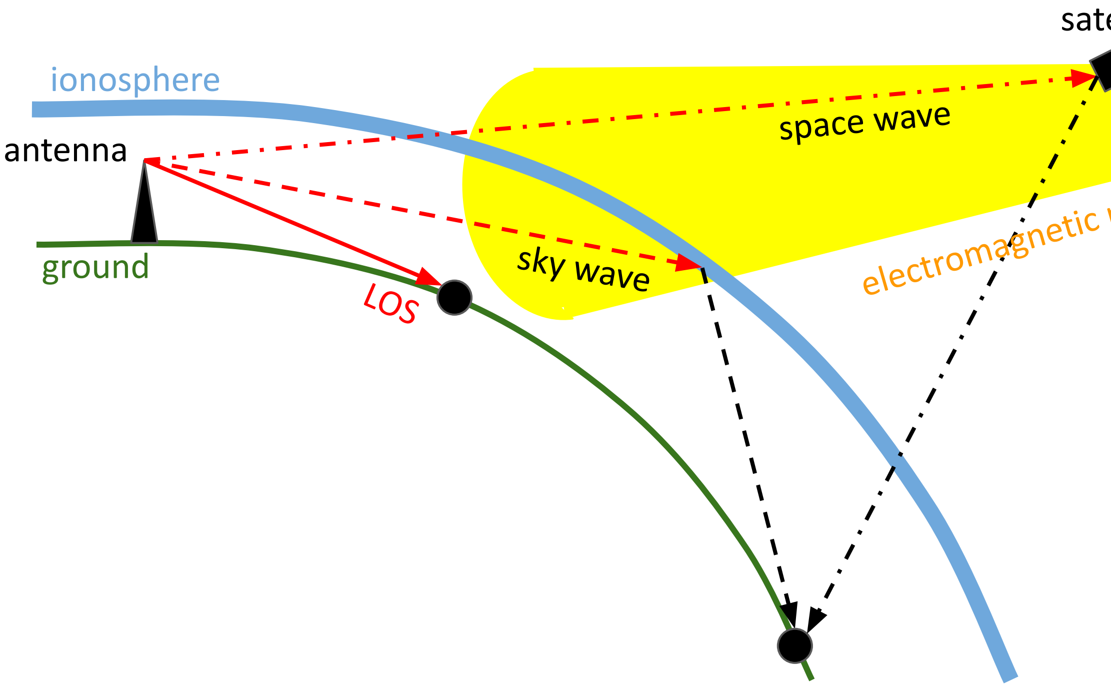

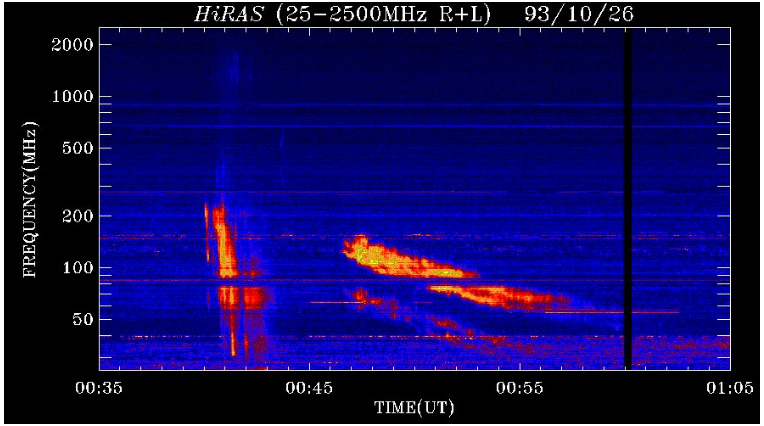

SWx vulnerability examples:

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- **UHF & VHF radio (radar): noise → blackouts**
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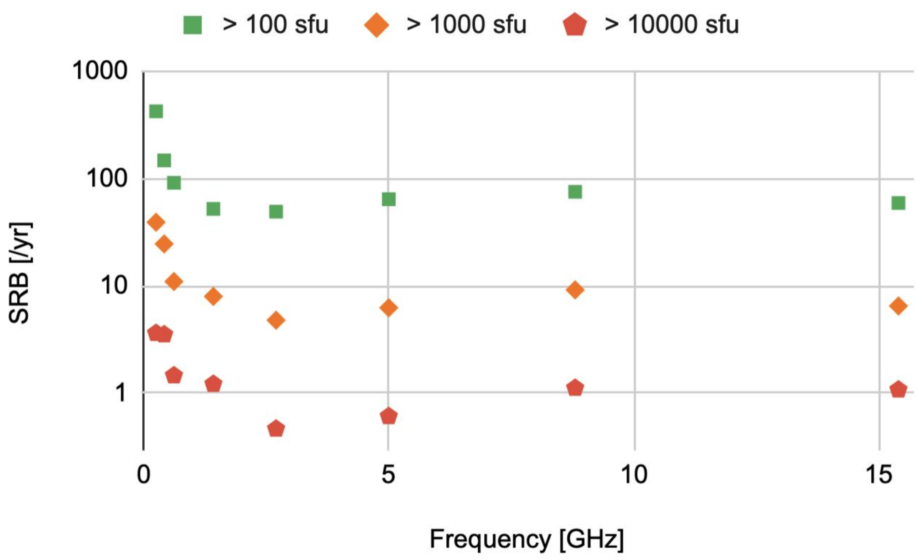
Credit: Naval Technology

Credit: T. Baba

VHF & UHF radio: statistics

- antenna must have the Sun in FOV
- SRB must happen at the right frequency
- antenna must be sensitive enough:
    - 100 sfu:
        - noise very sensitive systems
    - 1000 sfu:
        - noise for many systems
        - blackout for sensitive systems
    - 10000 sfu:
        - blackout for many systems



Frequency [GHz]	$t_{>100\ sfu}$ [h/yr]	$t_{>1000\ sfu}$ [h/yr]	$t_{>10000\ sfu}$ [h/yr]
0.245	50 - 100	0 - 10	0 - 1
0.41	10 - 50	0 - 10	0 - 1
0.61	10 - 20	0 - 3	0 - 1
1.415	0 - 20	0 - 3	0 - 1
2.695	0 - 20	0 - 3	0 - 1
4.995	0 - 20	0 - 3	0 - 1
8.8	0 - 20	0 - 3	0 - 1
15.4	0 - 20	0 - 3	0 - 1

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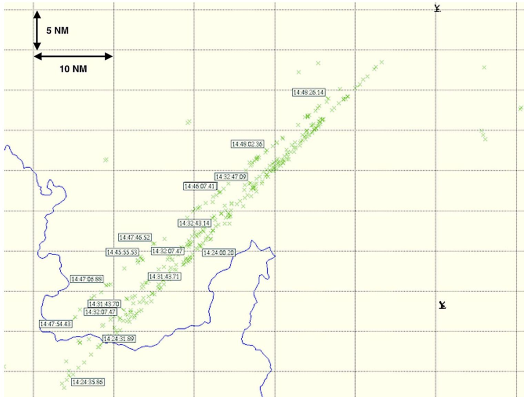
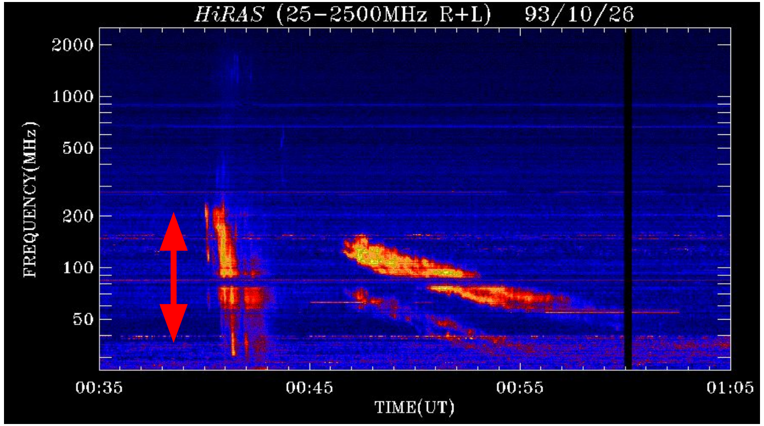
VHF & UHF radio: where does this matter?

- all radio and radar systems that are:
  - pointed towards the sky
  - operate with narrow frequency band/ single frequency
  - operate at low frequencies
  - sensitive to weak signals

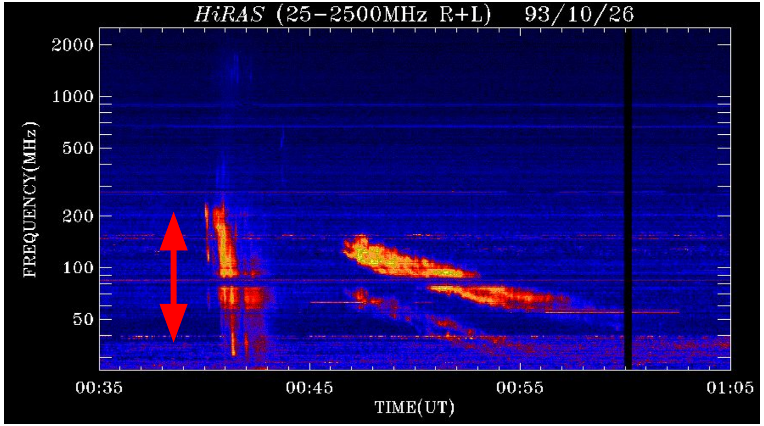
- for instance:
  - far looking radars (sensitivity)
  - ATC (single band, frequency)
  - emergency radio (low frequency)





VHF & UHF radio: mitigation strategies

- short term:
  - change frequencies in use
    - lower chance of interference at higher
  - change the pointing of the system
  - increase transmitting power
  - monitor solar radio bursts



- long term:
  - improve operator awareness
  - implement more diversity into operations & systems

SWx vulnerability examples:

- HF radio (radar): frequency limits ⟶ fade-outs
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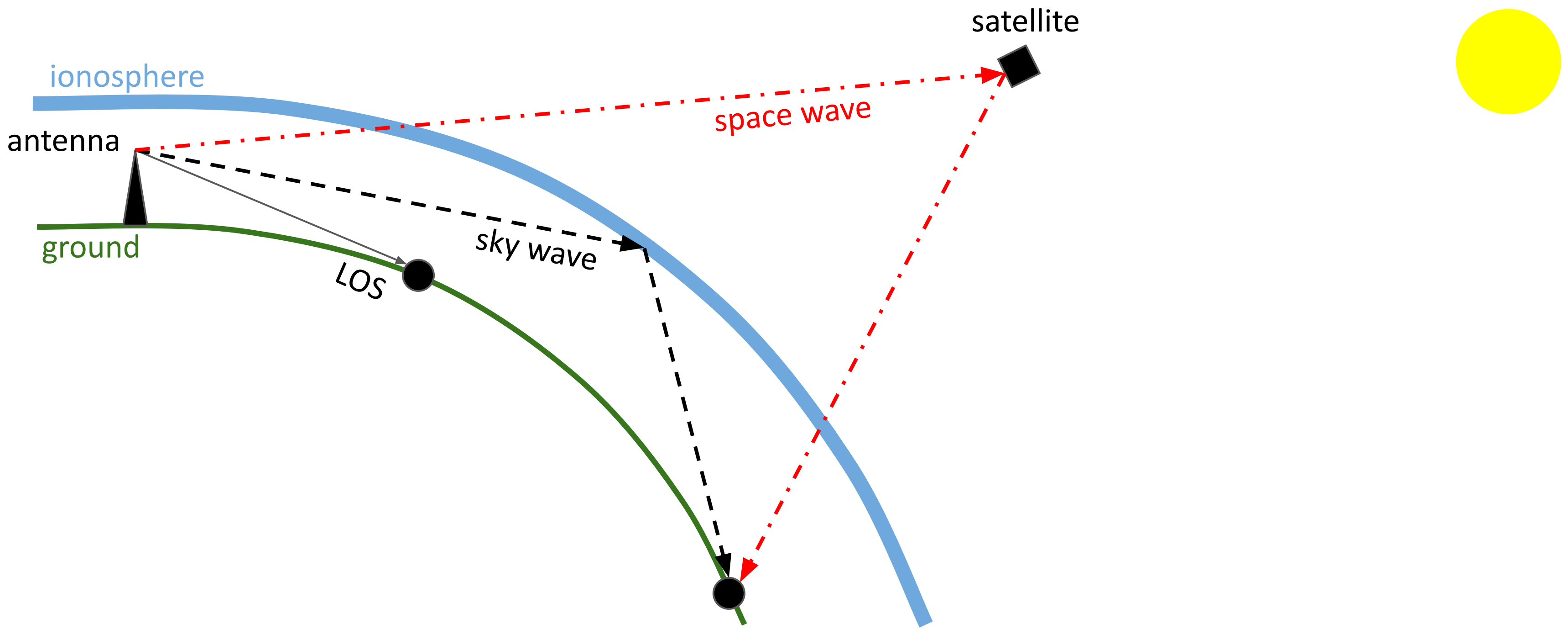
How do we communicate? Why is the ionosphere important?



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SWx vulnerability examples:

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- UHF & VHF radio (radar): noise → blackouts
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- **SATCOM, GNSS: inaccuracy → unavailability**
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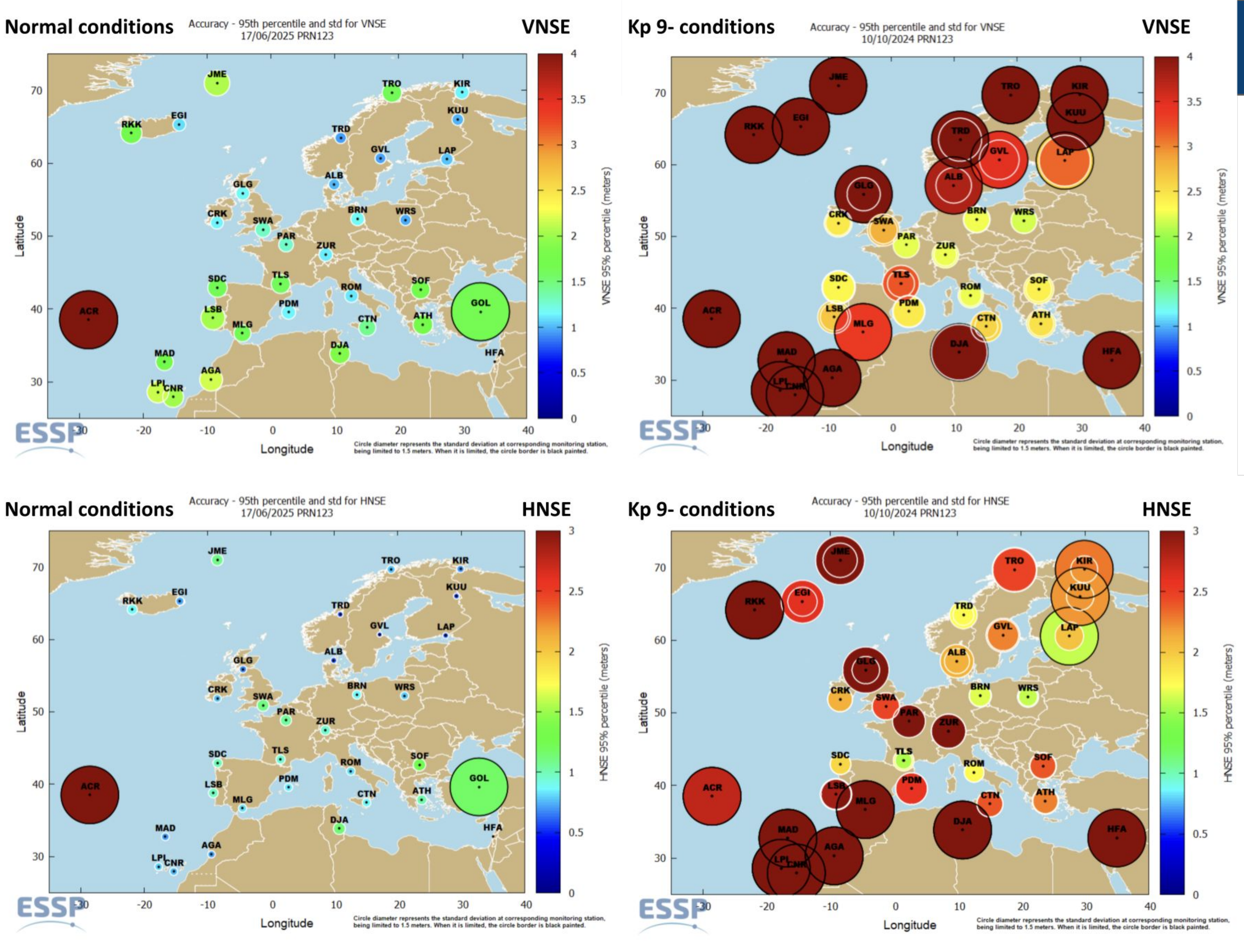
GNSS: error

- especially equatorial and polar regions affected

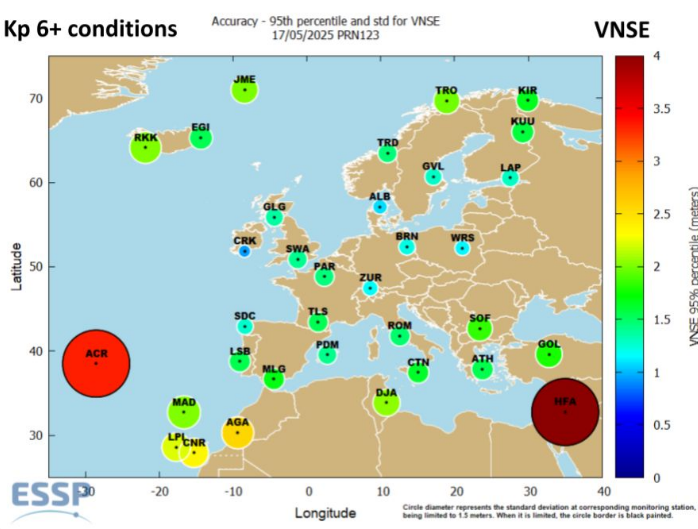
- in strong events, mid-latitude effects also observable

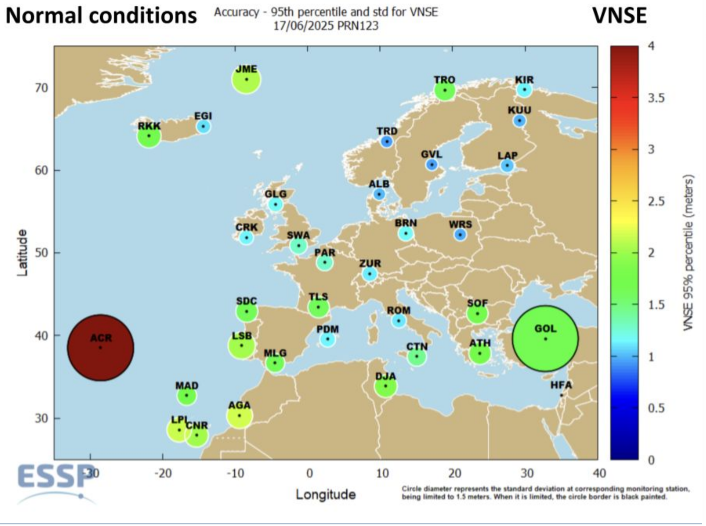


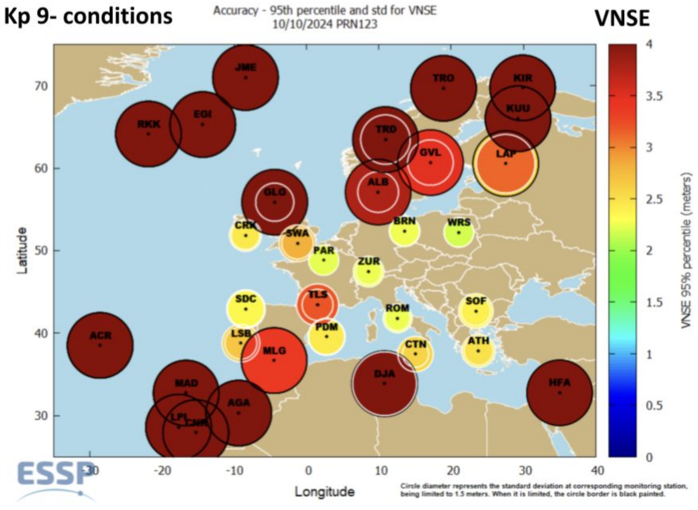
GNSS: mid-latitude effects

- especially after strong geomagnetic storms
- extra 0.5 m inaccuracy already at some Kp 6-7 events
    - weeks to > month/ year in a maximum, days/ year in minimum

- > 3m inaccuracy for Kp 8+ events
    - days/ year in max.







GNSS: polar effects

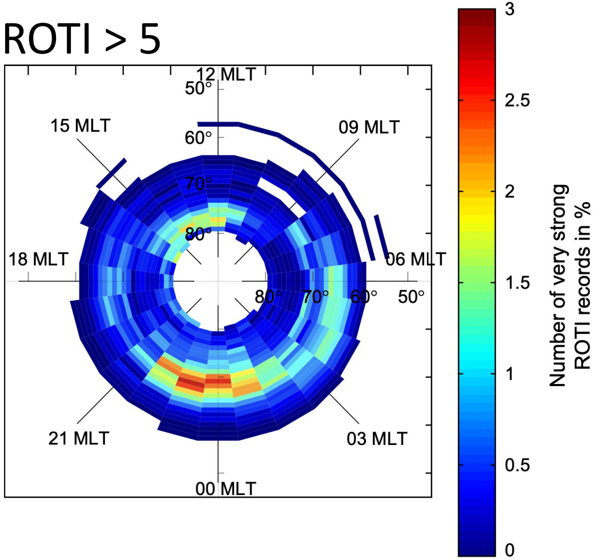
- doubling/ tripling of GNSS error: weeks to months/ year in max., days to weeks in min.
- error tenfold and more: days/ year in max., hours/ year in min.

[Jacobsen & Dähnn 2014]

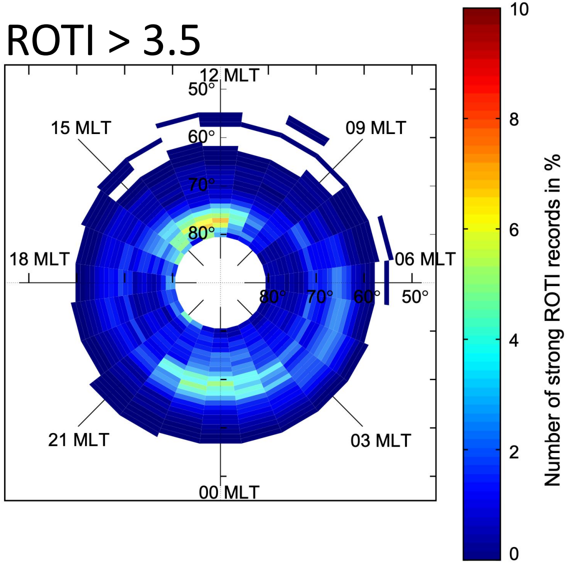
- either during post-noon (mostly moderate) or midnight (more severe)

- mostly < hour

ROTI > 5



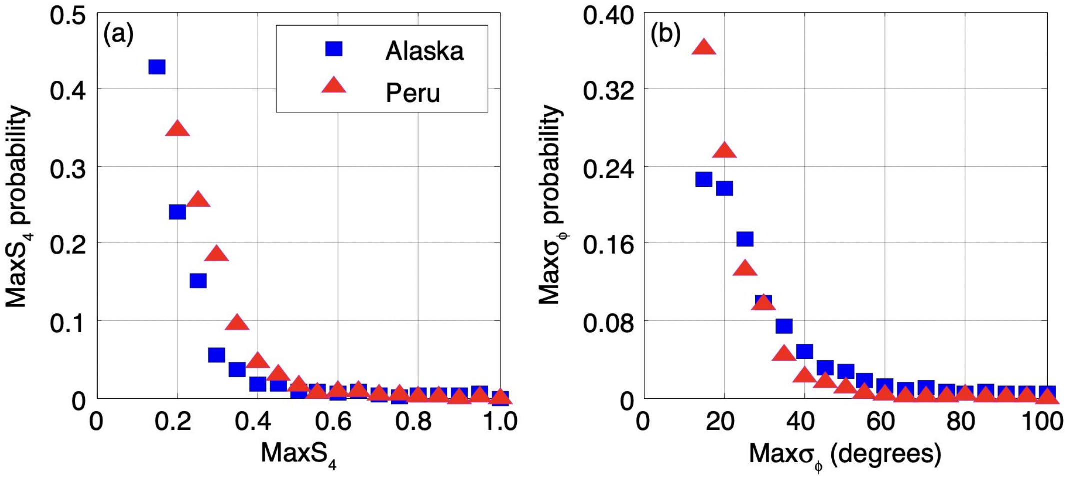
ROTI > 3.5

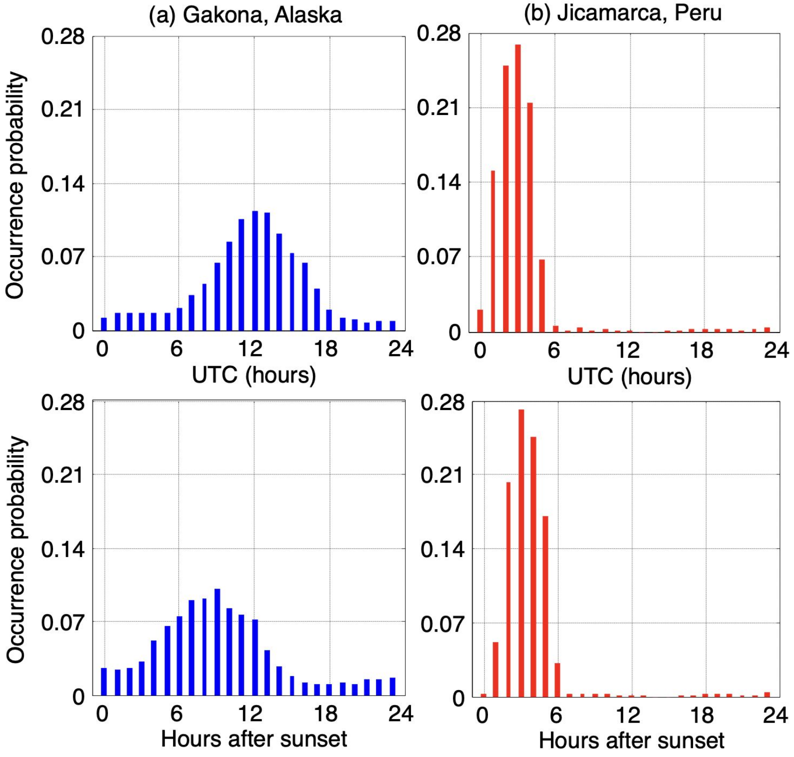


GNSS: equatorial effects

[Jiao+ 2014]

- similar statistics, different mechanisms
- also usually less than an hour
- almost always within first six hours after sunset





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GNSS: where does this matter?

- systems that are:
  - require precise positioning
  - require precise time-signal

- for instance:
  - guided systems (INS decreases accuracy significantly)
  - precision navigation systems (JPALS)
  - advanced communication links (time-signal for encryption)

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GNSS: mitigation strategies

- short term:
    - monitor the state of the ionosphere and forecasting:
        - state: scintillation indices/ ROTI
        - forecasting: Kp index

- long term:
    - improve operator awareness
    - implement more diversity into operations & systems (Galileo, internal time-keeping)

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Other effects

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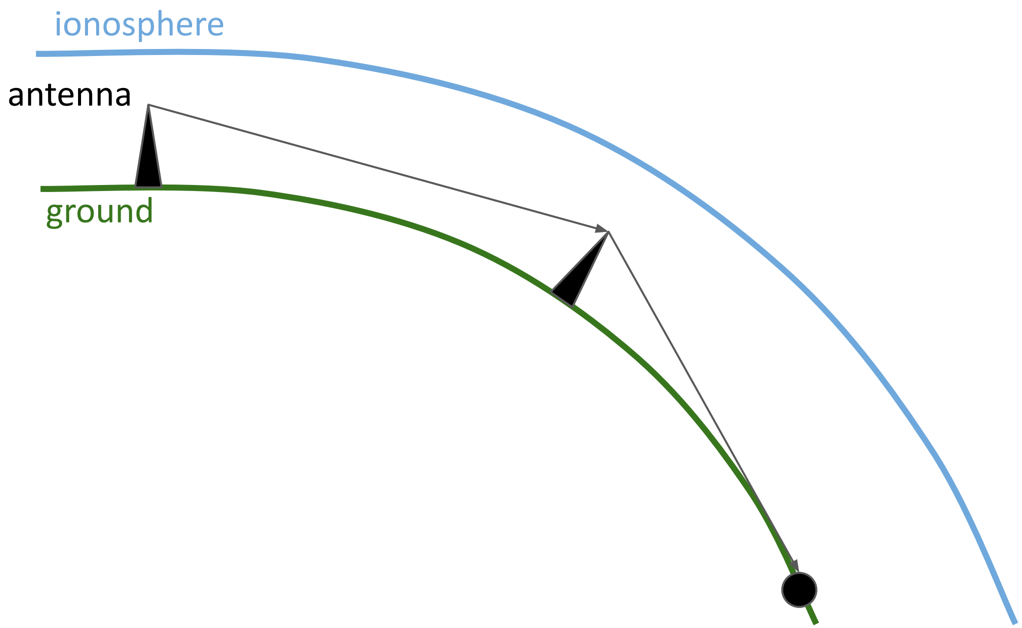
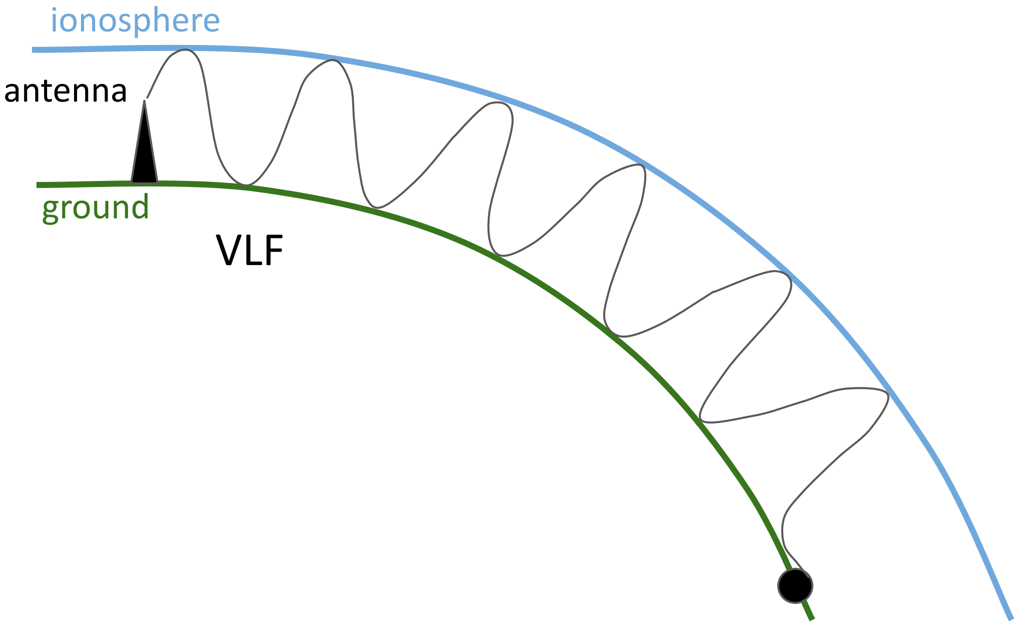


How do we communicate? Why is the ionosphere important?



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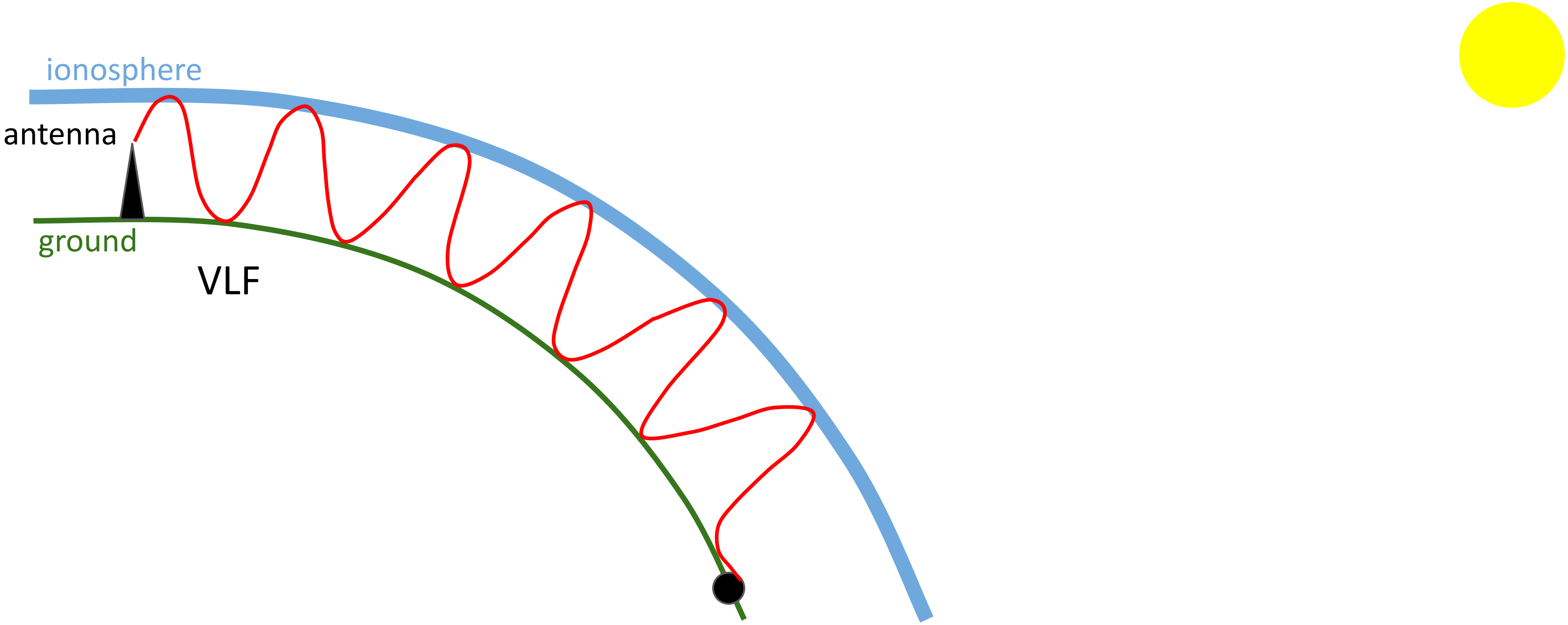
How do we communicate? Why is the ionosphere important?



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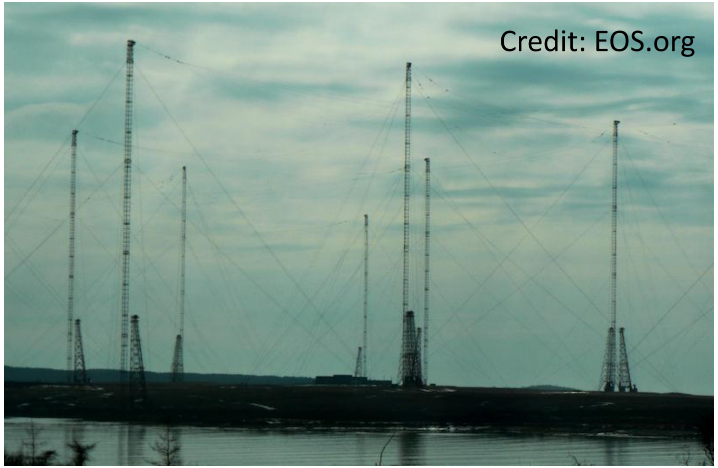
SWx vulnerability examples:

- HF radio (radar): frequency limits → fade-outs
- UHF & VHF radio (radar): noise → blackouts
- **VLF radio: noise → fade-outs**
- SATCOM, GNSS
- MAD/ magnetic navigation
- power systems
- SATOPS:
  - atmosphere
  - particle environment
  - COM loss


Credit: EOS.org

Credit: Getty

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
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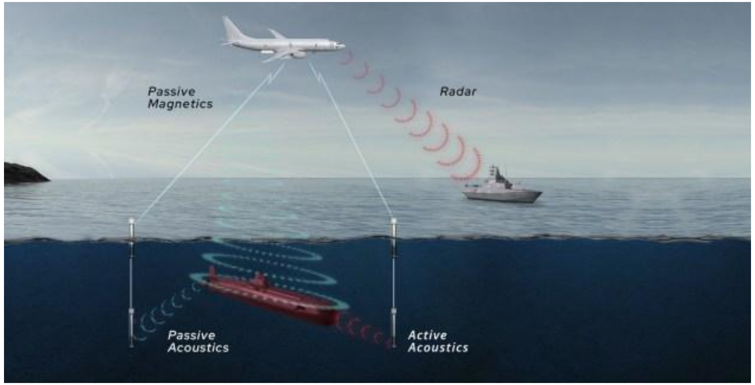
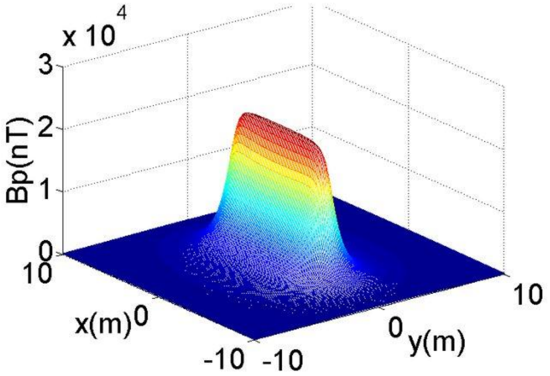


Credit: Australiandefence.com

Credit: Guo et al. 2012



SWx vulnerability examples:

- HF radio (radar): frequency limits ⟶ fade-outs
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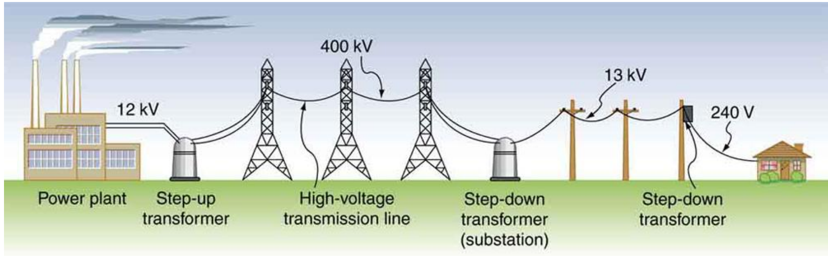
- SATCOM, GNSS: scintillation, delay ⟶ loss of lock
- MAD: accuracy issues ⟶ low range of detection
- **power systems: limited loads ⟶ failures**
- SATOPS:
    - atmosphere
    - particle environment
    - COM loss



Credit: Lumen

SWx vulnerability examples:

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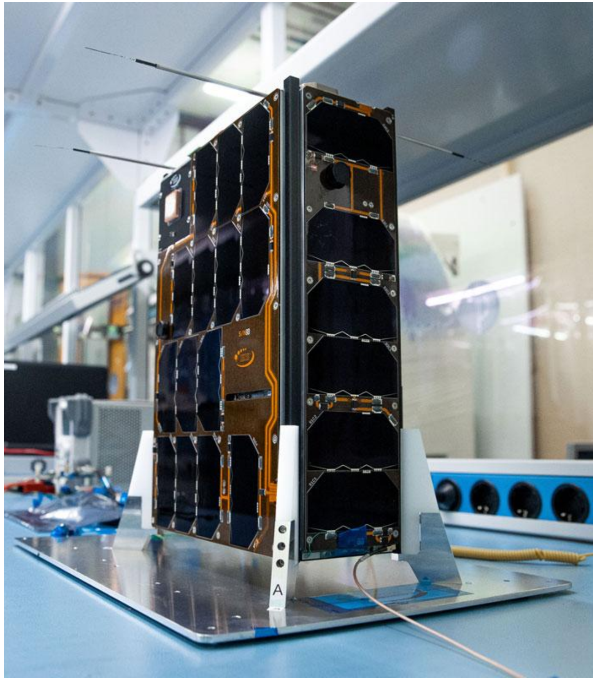
- VLF radio: noise → fade-outs
- SATCOM, GNSS: scintillation, delay → loss of lock
- MAD: accuracy issues → low range of detection
- power systems: limited loads → failures
- **SATOPS:**
  - **atmosphere: increased fuel usage → reentry**
  - **particle environment: excessive charging → failure**
  -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

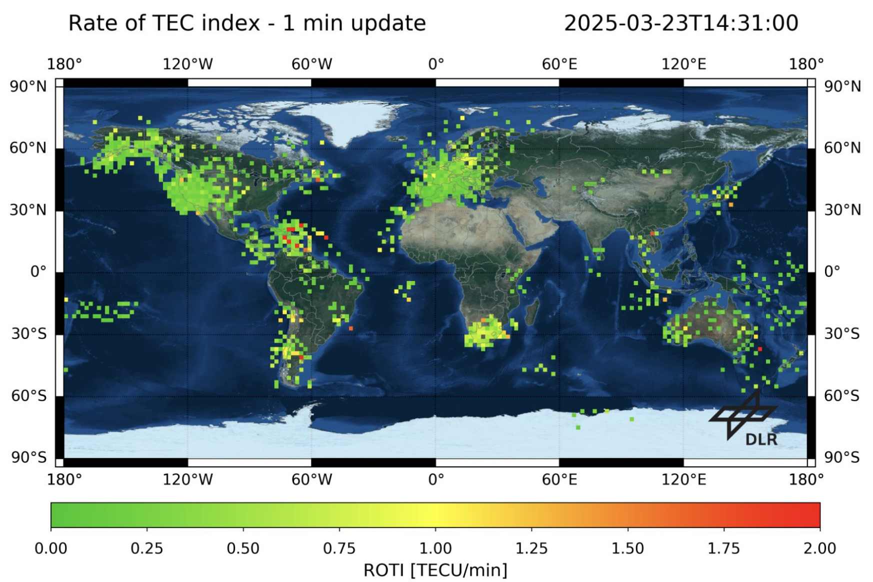
Examples of SWx vulnerabilities

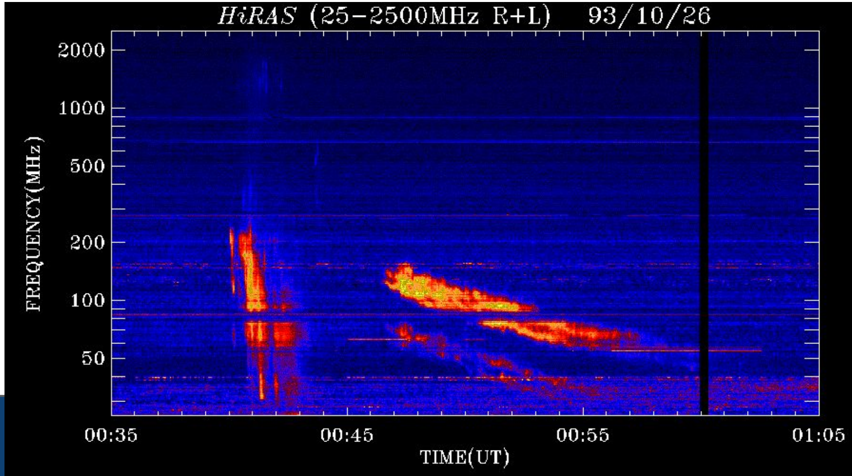
- HF-radio system for long-distance comms:

  … 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

- we rely on the US too much:
  - 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?) …

Credits: NOAA

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

Thank you for your attention

m.brchnelova@mindef.nl