Space weather risks: the military user's perspective

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Content

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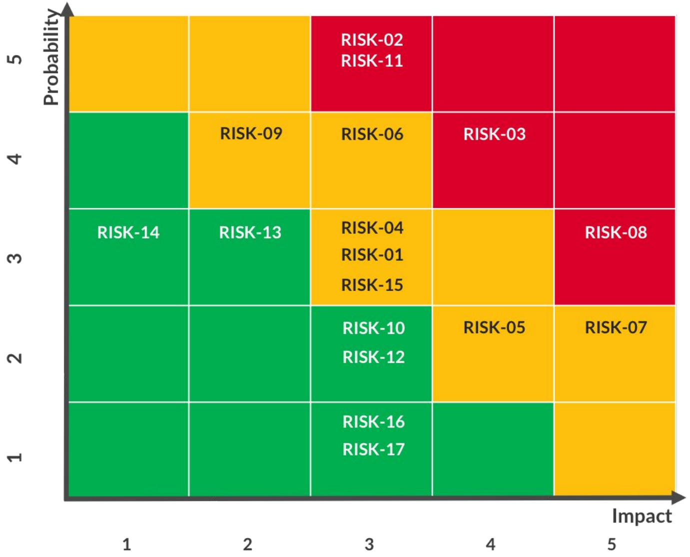
Space weather (SW) effects risks

- chance/ likelihood: a probability of an event in a given timespan

risk = chance x cost

- cost may be political, military, societal, financial, economic etc.
- when evaluating SW risks, looking at the probability alone is often not enough
- **the resulting risks are organisation- and platform-dependent, depending on the procedures in place, the protocols and the diversity/ redundancy in available systems**

→ DISCLAIMER: here I only provide my personal view on the risks



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Band designation

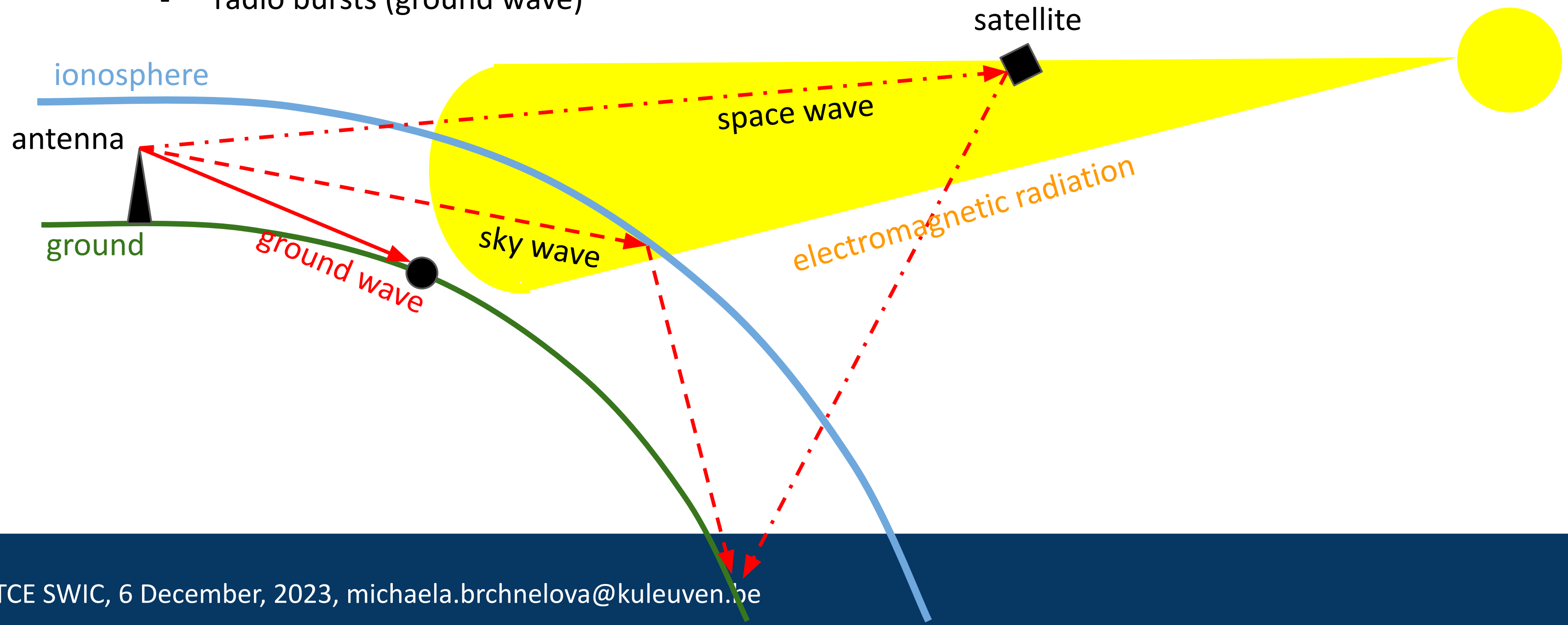
- three different commonly-used band designations - IEEE, ITU and NATO/ EU
- here: depending on the system's provider preference, frequencies/ frequency ranges always stated

Frequency	IEEE Band	European Union, NATO, US ECM	ITU Band	ITU Abbreviation
0.3 Hz				
3 Hz		A	1	ELF
30 Hz			2	SLF
300 Hz			3	ULF
3 kHz			4	VLF
30 kHz			5	LF
300 kHz			6	MF
3 MHz	HF		7	HF
30 MHz	VHF		8	VHF
250 MHz		B		
300 MHz	UHF		9	UHF
500 MHz		C		
1 GHz	L	D		
2 GHz	S	E		
3 GHz		F	10	SHF
4 GHz	C	G		
6 GHz		H		
8 GHz	X	I		
10 GHz		J		
12 GHz	Ku			
18 GHz	K			
20 GHz		K		
27 GHz	Ka			
30 GHz			11	EHF
40 GHz	V	L		
60 GHz		M		
75 GHz	W			
100 GHz				
110 GHz	mm			
300 GHz			12	THF
3 THz				

Military radio systems

Space weather impacts on radio waves

- two main types of interference:
  - transionospheric effects (sky wave, space wace)
  - radio bursts (ground wave)



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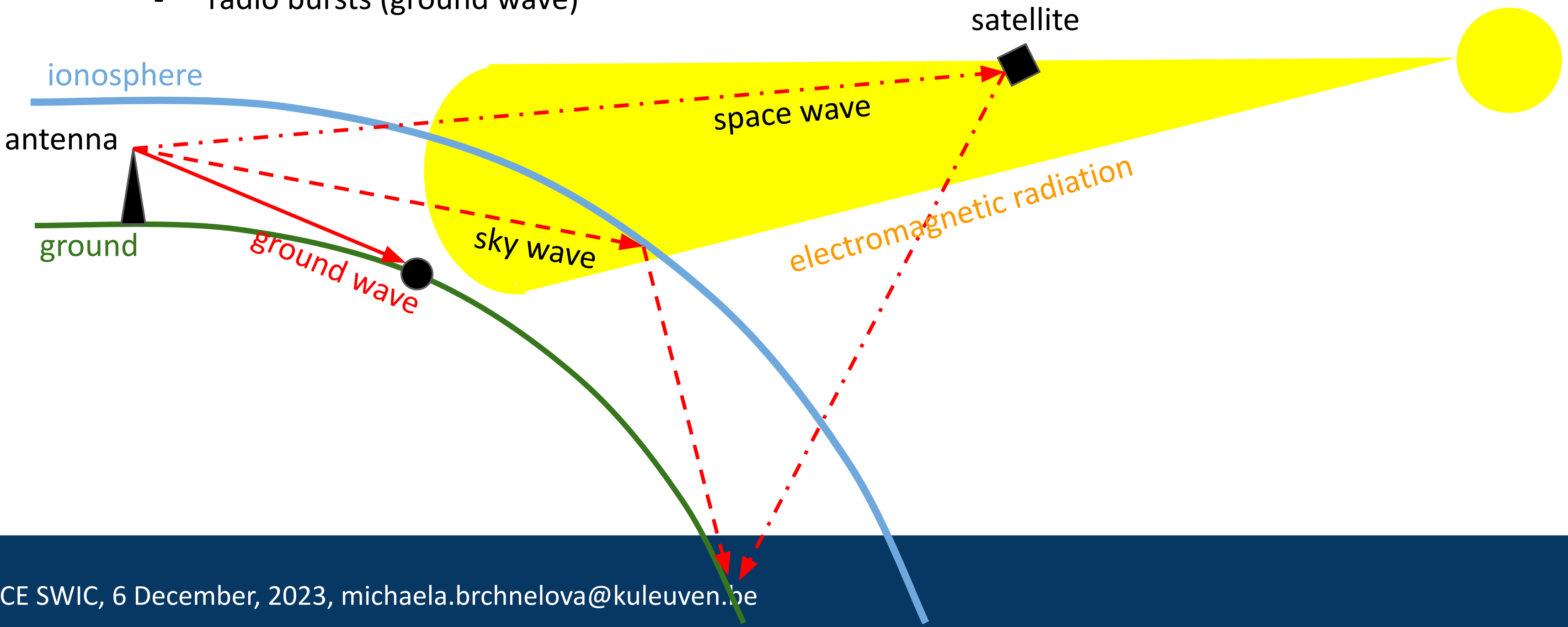
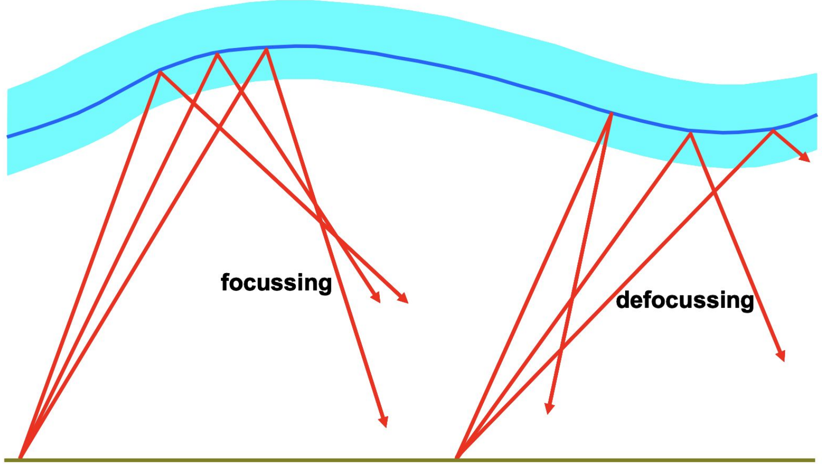


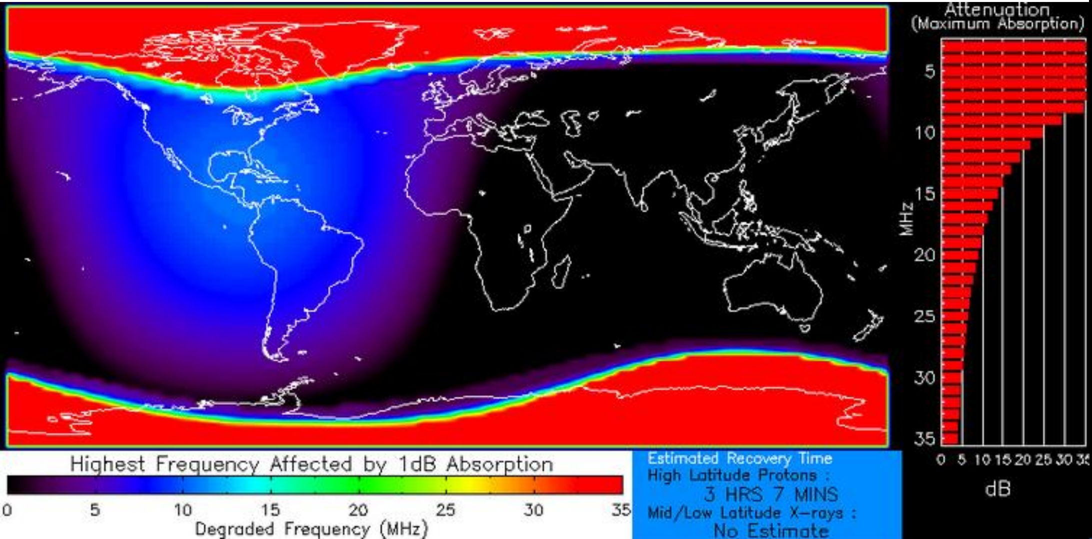
Transionospheric effects

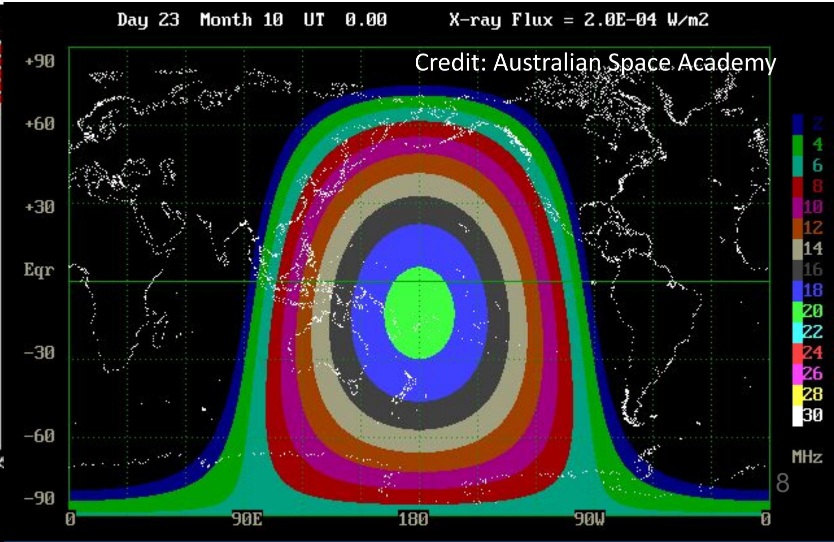
- due to phenomena such as:
    - travelling ionospheric disturbances
    - short wave fade-outs
    - plasma bubble
    - polar cap absorption, etc.

Credit: MET Office



Spaceweather.com, SWPC





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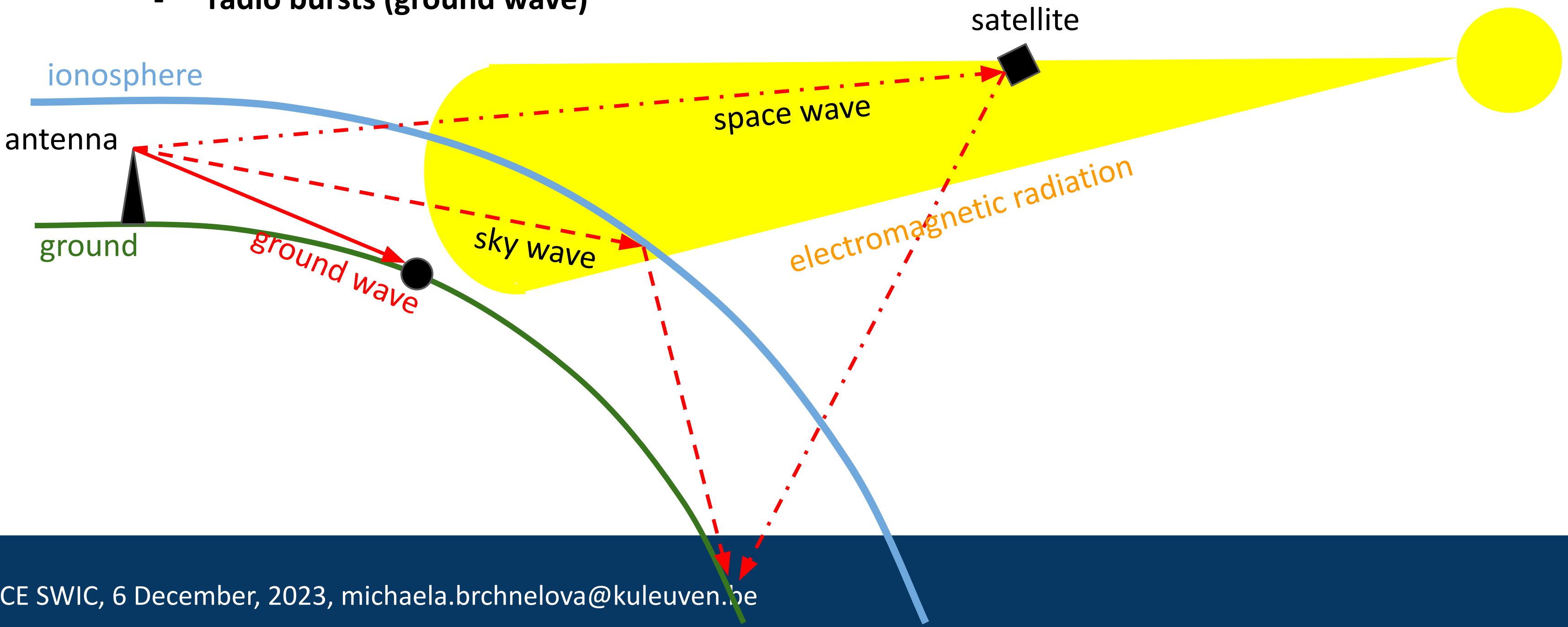
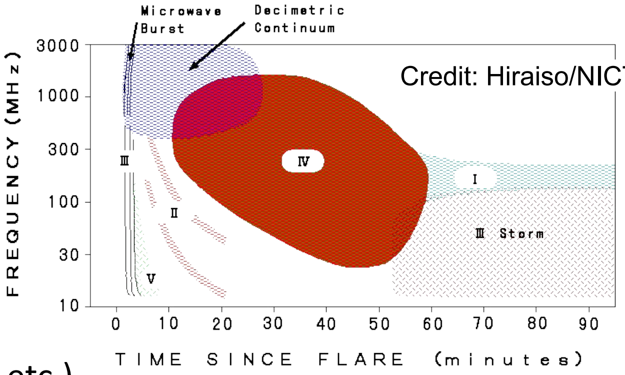


Solar radio bursts

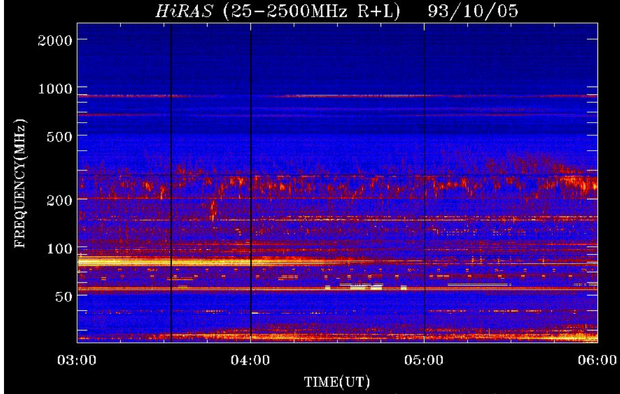
- a variety of types, depending on the origin (CME, active regions, solar flares, combined, etc.)

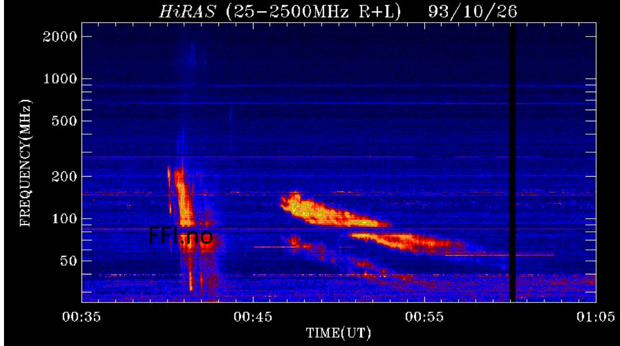


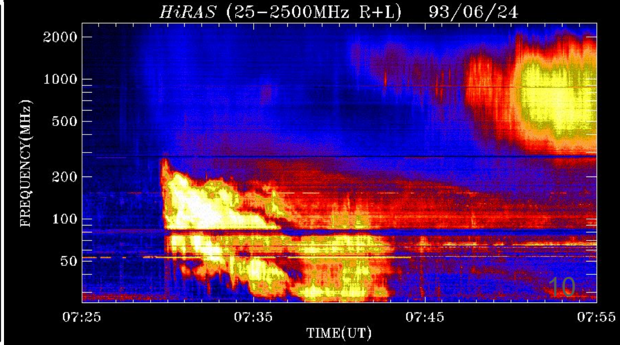
Credit: Hiraiso/NICT

- have different radar signatures, some (especially IV) can **blind** radars completely for a significant period of time → shows as **static in radio**

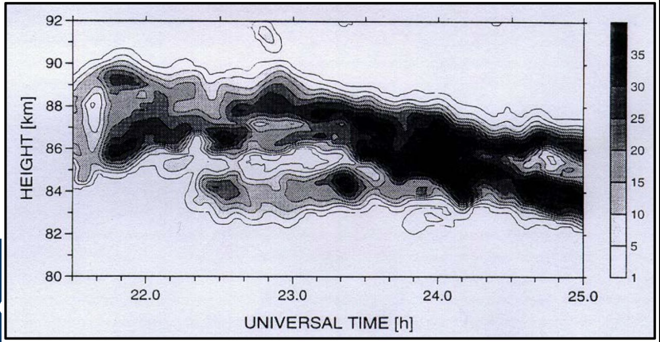
- radar blinding at lower frequencies not just due to solar bursts:
    - polar mesospheric summer (and winter!) clouds = PMSE, visible in polar regions on 30 MHz to 300 MHz





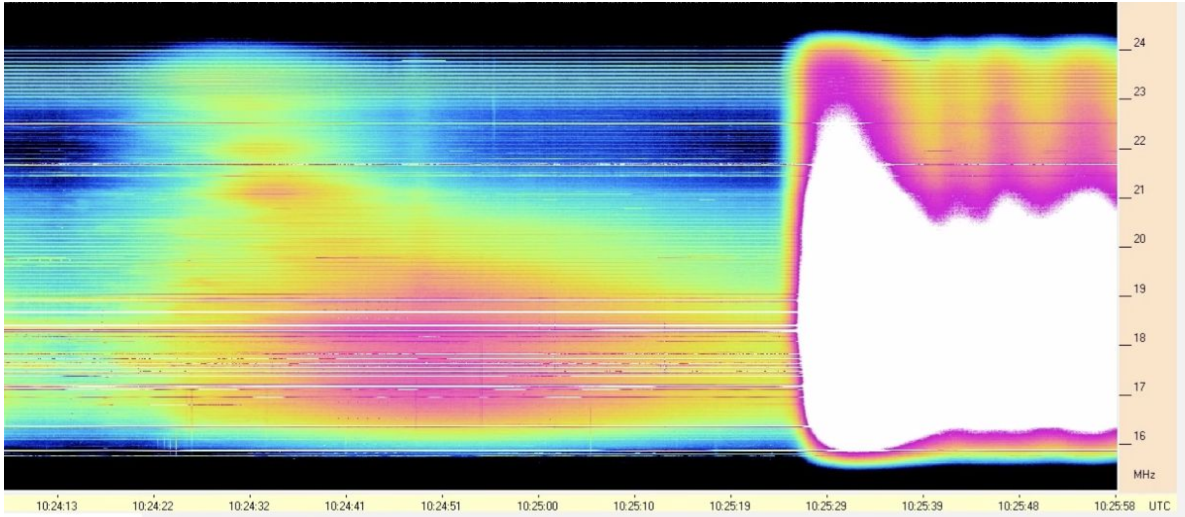


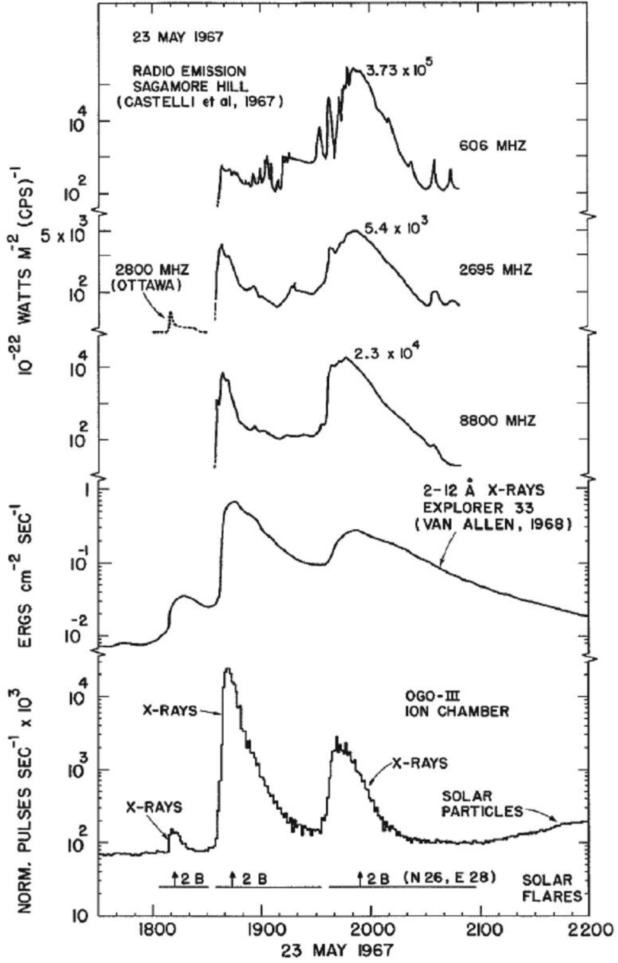
Credit: FFI



Radio/ radar effects

- radar blinding: e.g. 1967 (Alaska), 2015 (Sweden)
- radio noise

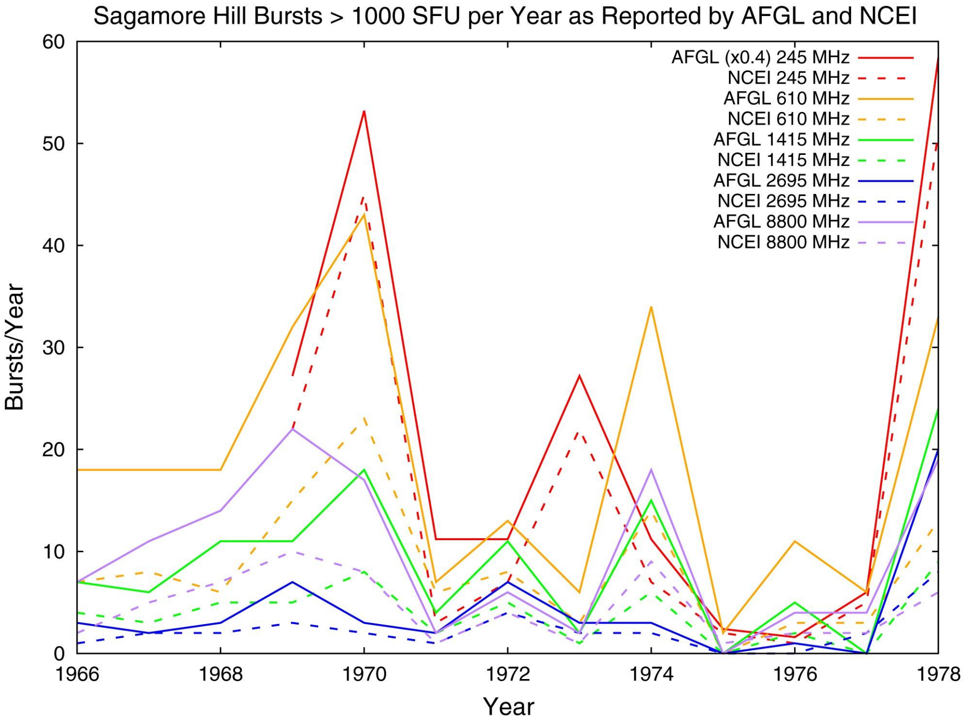




Solar radio bursts: expected frequencies?

- strong radio bursts 1966 - 2017 from a variety of stations, based on frequency

Frequency (MHz)	Number of bursts observed	Burst rate (bursts/year)
245	15,251	421
410	5,056	147
610	3,449	91
1,415	1,942	52
2,695	1,864	49
4,995	2,395	64
8,800	2,807	75
15,400	2,216	59



Credit: Giersch et al. 2017

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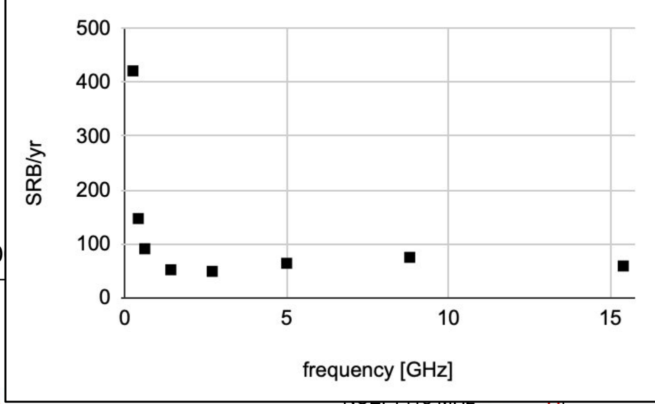

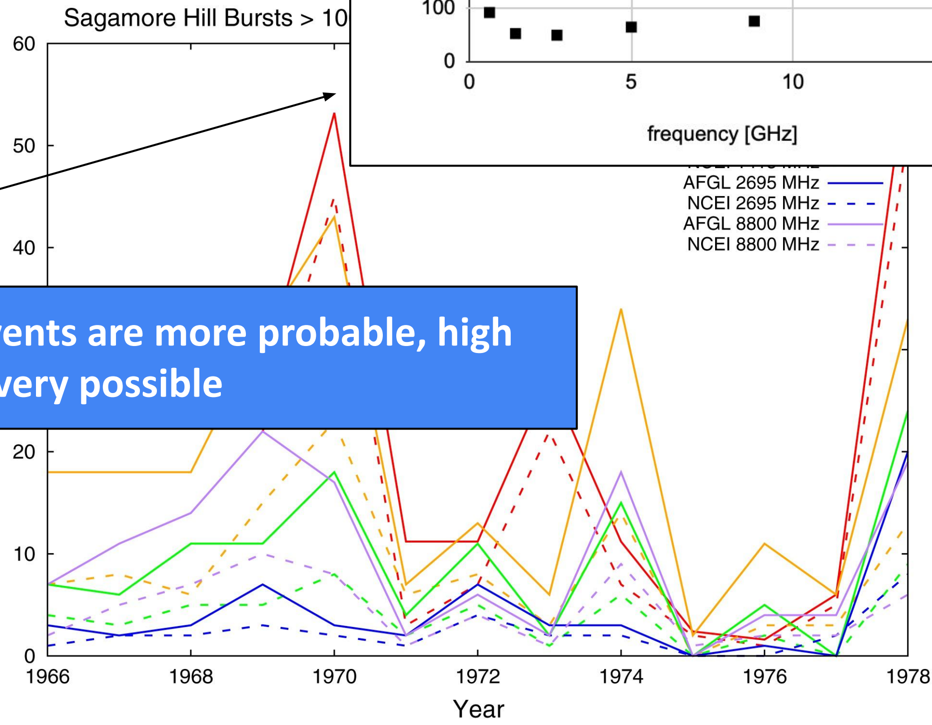

→ while lower frequency events are more probable, high frequency (SHF) events still very possible

Credit: Giersch et al. 2017

Space weather impacts on radio waves

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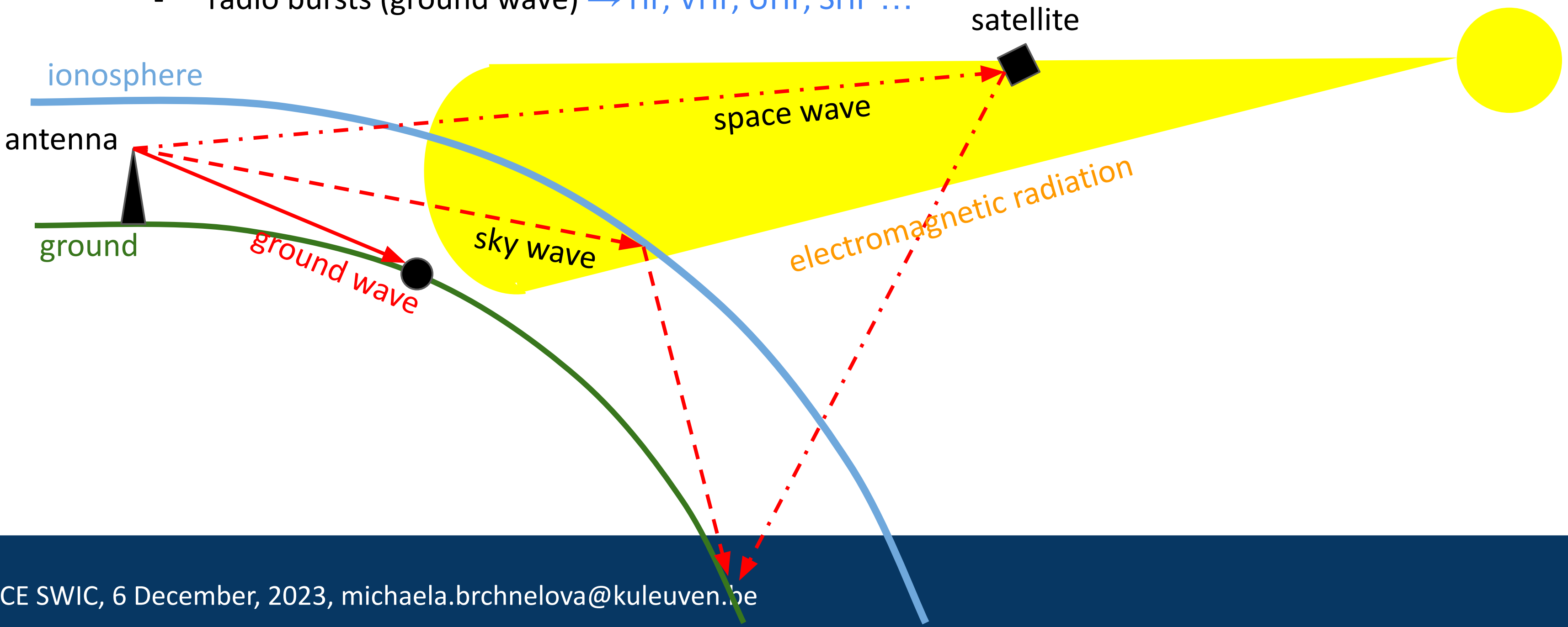
  - radio bursts (ground wave) ⟶ HF, VHF, UHF, SHF …



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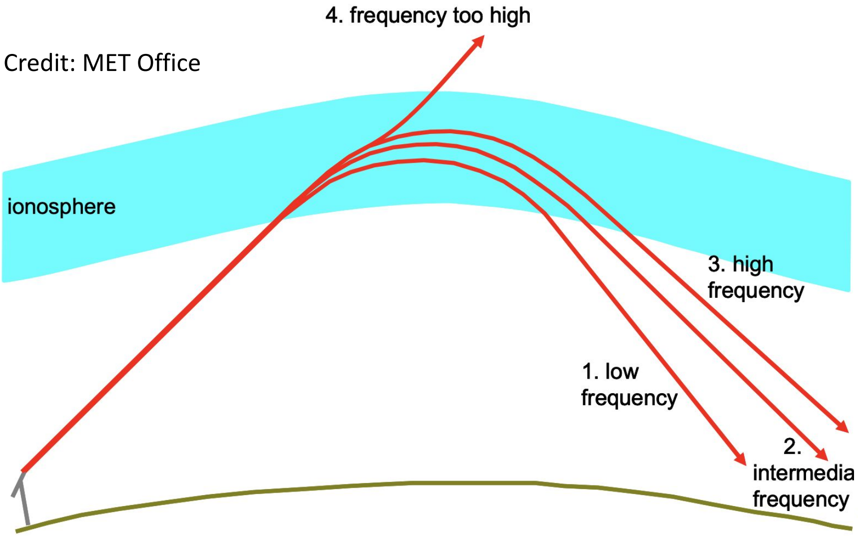
High frequency effects

- HF (3 MHz to 30 MHz) mostly used for ionospheric refraction to increase the range → beyond line-of-sight (BLOS) / over-the-horizon (OTH) communication

  → signal quality and reception directly dependent on ionospheric conditions

Credit: MET Office



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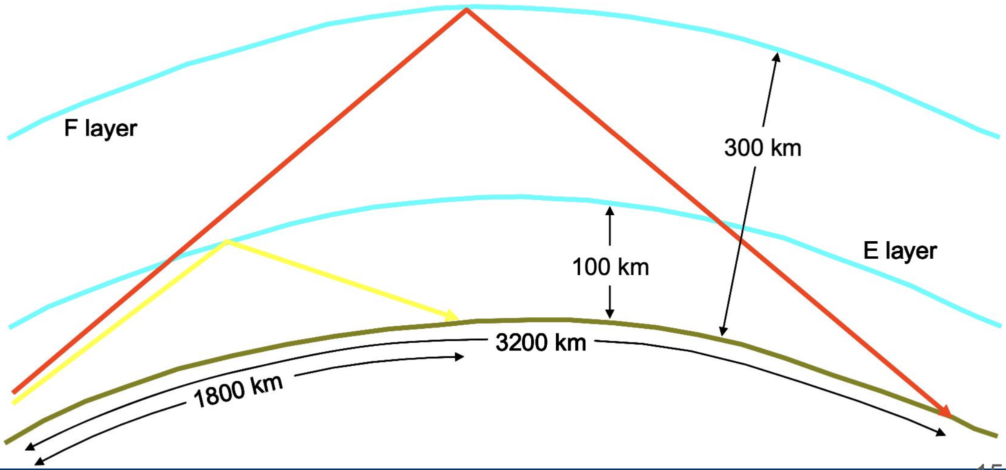

Example HF radio systems

- AN/VRC-104 vehicle mounted radio:
  - on some of the new generation combat vehicles

- AN/ARC-190 airborne radio:
  - found on a large variety of current aircraft, e.g., B-52, C-5, C-9, E-3, E-8

- AN/PRC-150 Falcon II manpack radio:
  - currently used by US Marine Corps, US SOCOM and USAF

Credit: Harris

Credit: USAF

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→ performance of all of these if used for BLOS comm. directly affected by the ionospheric conditions

→ inability to communicate

→ a very high SW risk as in-theater communication is essential for most operations

Credit: H

Credit: USAF

Credit: US Marine Corps

Integrated meteorological system (IMETS)

- Northrop Grumman developed for the US Army: a weather data communication system that receives, processes, and disseminates weather observations

- IMETS employed to inform units if weather conditions might affect operations

- one of the means in which IMETS receives data is through HF OTH (BLOS) radio signals

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→ the ability to propagate signals BLOS directly dependent on the ionospheric conditions

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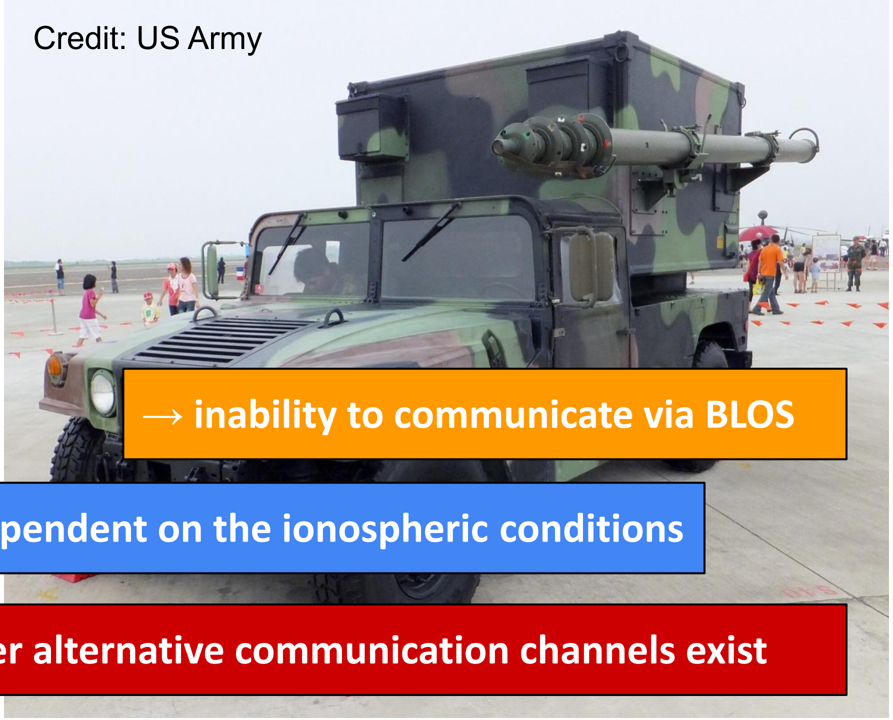
Credit: US Army

→ inability to communicate via BLOS

→ the ability to propagate signals BLOS directly dependent on the ionospheric conditions

→ a medium to high SW risk depending on whether alternative communication channels exist

Very-high and ultra-high frequency effects

- VHF: 30 MHz to 300 MHz, UHF: 300 MHz to 3 GHz
- **Line-of-sight (LOS) communication use:**
  - generally for an in-theatre communication
  - for surface-to-surface defense like land and navy, often dual band because UHF can penetrate walls (better in urban areas)
  - SW effects only from solar radio bursts: broadband radio noise increasing the static

- **SATCOM communication use (usually from UHF up)**
  - while travelling through the ionosphere, weakening of the signal and shifting of its phase, e.g. when there are large electron density gradients → scintillation
  - scintillation dependent on geographical location, time of the day and of the year
  - signal significantly degraded for minutes up to hours after a SW event

SINCGARS (single channel ground and airborne radio system) VHF

- several models, short and long range, mostly LOS
- concept designed to maximise interoperability among various ground/ air/ naval configurations
- VHF range, typically between 30 MHz to 87.975 MHz
- half-duplex, so-called "combat-net radio", CNR, for command and control of combat and combat support
- widely used in the US
- incorporates anti-jamming features, e.g. frequency hopping

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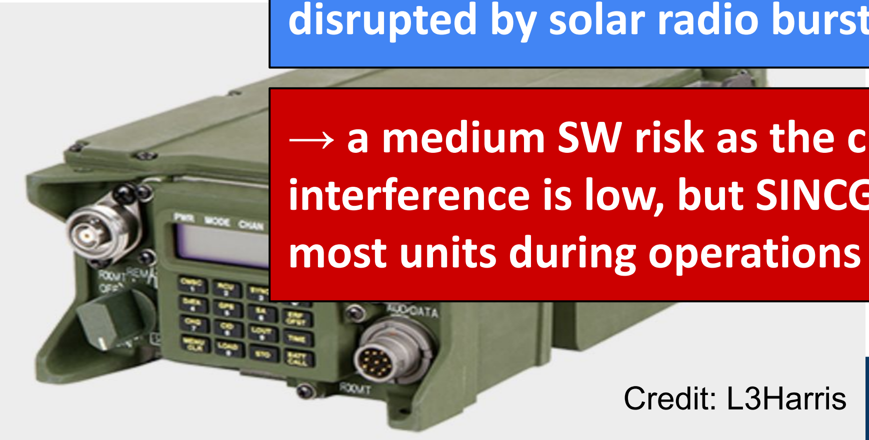
→ inability to communicate

→ a medium SW risk as the chance of radio interference is low, but SINCGARS is essential for most units during operations for communications



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Other typical VHF to UHF radio products

- **P25 (project 25):** a suite of standards for interoperable two-way products
  - both full/ half duplex, mostly by Motorola
  - usually found in 138-174 MHz, 380-512 MHz, 769-824 MHz, and 851-869 MHz (VHF to UHF), SATCOM capable

- **Tadiran PNR-500: personal**
  - popular for smaller groups, e.g. platoon level
  - full duplex, 410-450 MHz (UHF)

- **AN/PRC-162: mounted**
  - 30-88, 225-450, 1250-1450, 1755-1850 MHz (VHF to UHF), two way (full/ half duplex), SATCOM capable, with GPS embedded

Credit: Forester

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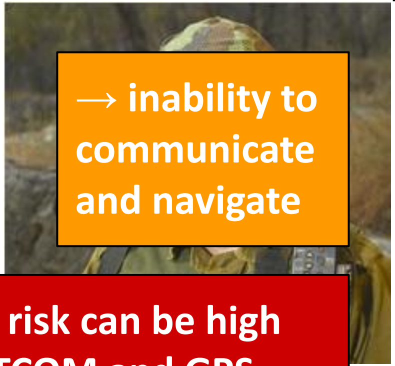

→ inability to communicate and navigate

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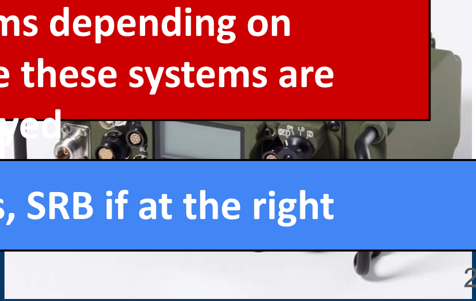

→ the SW risk can be high for the SATCOM and GPS systems depending on where these systems are deployed

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Super-high frequency effects

- high-volume communications for inter-theater communication through satellite systems
- less affected by ionospheric effects
- mostly affected by solar radio bursts

- for example, used by the Defence Satellite Communications System (DSCS):
    - for a global communication coverage
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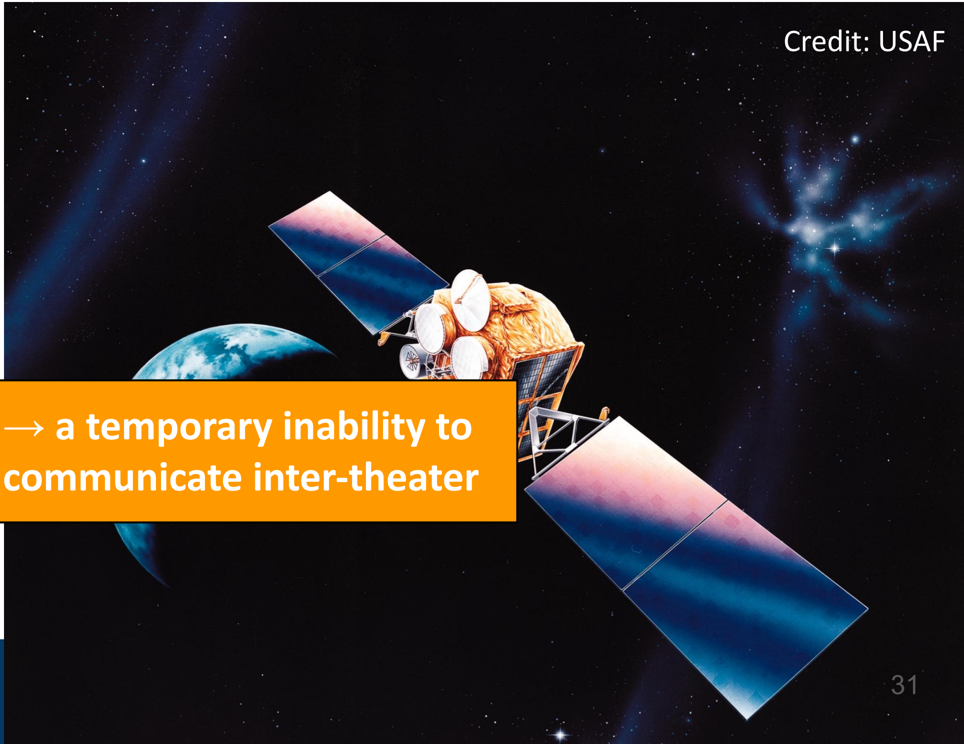
→ a medium to low SW risk due to the low chance of interference and to the nature of the communications

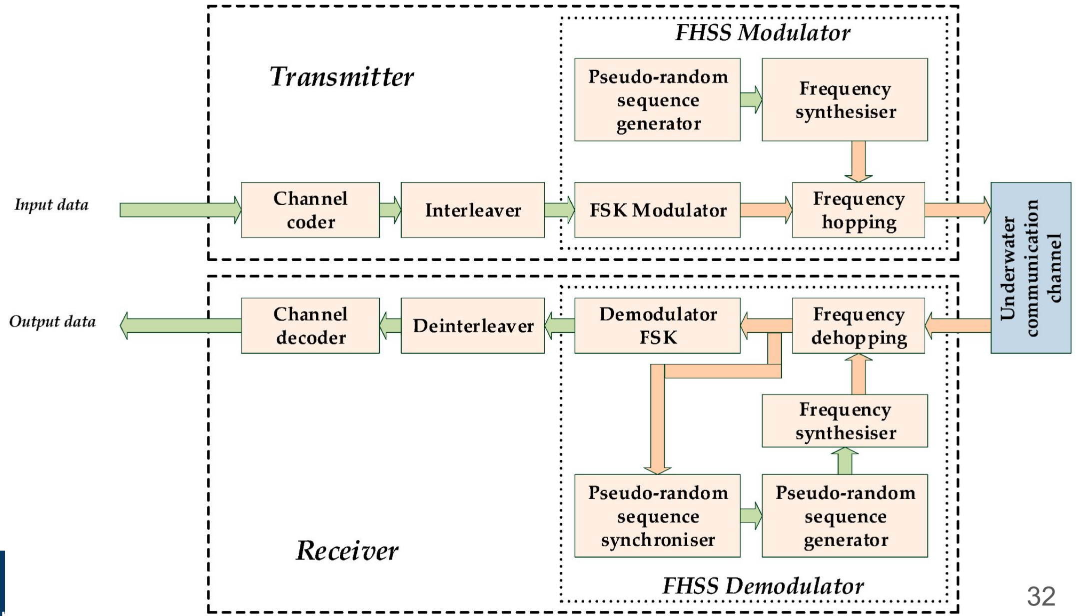


→ a temporary inability to communicate inter-theater

Military radio systems: protocol vulnerabilities

- used frequency band not the only problem
- inclusion of protocols and features such as frequency hopping:
  - signal loss does not have to occur for long periods of time to impact operations
  - techniques such as frequency hopping require protocols to operate properly
    - loss of communications continuity through the inability to synchronise the Rx and Tx
    - partial loss of information might make the message impossible to decrypt

Credit: Schmidt 2020



Military radio: conclusions

- medium to high risk systems:
  - BLOS HF systems
  - GPS systems
  - SATCOM systems
  - systems with advanced anti-jamming protocols in place

- mitigation strategies:
  - presence of multiple systems/ operations at multiple frequencies (system/ frequency diversity)
    - not relying especially solely on BLOS and VHF/ UHF SATCOM
  - constant SW monitoring

Military radar systems

Space weather impacts on radio waves

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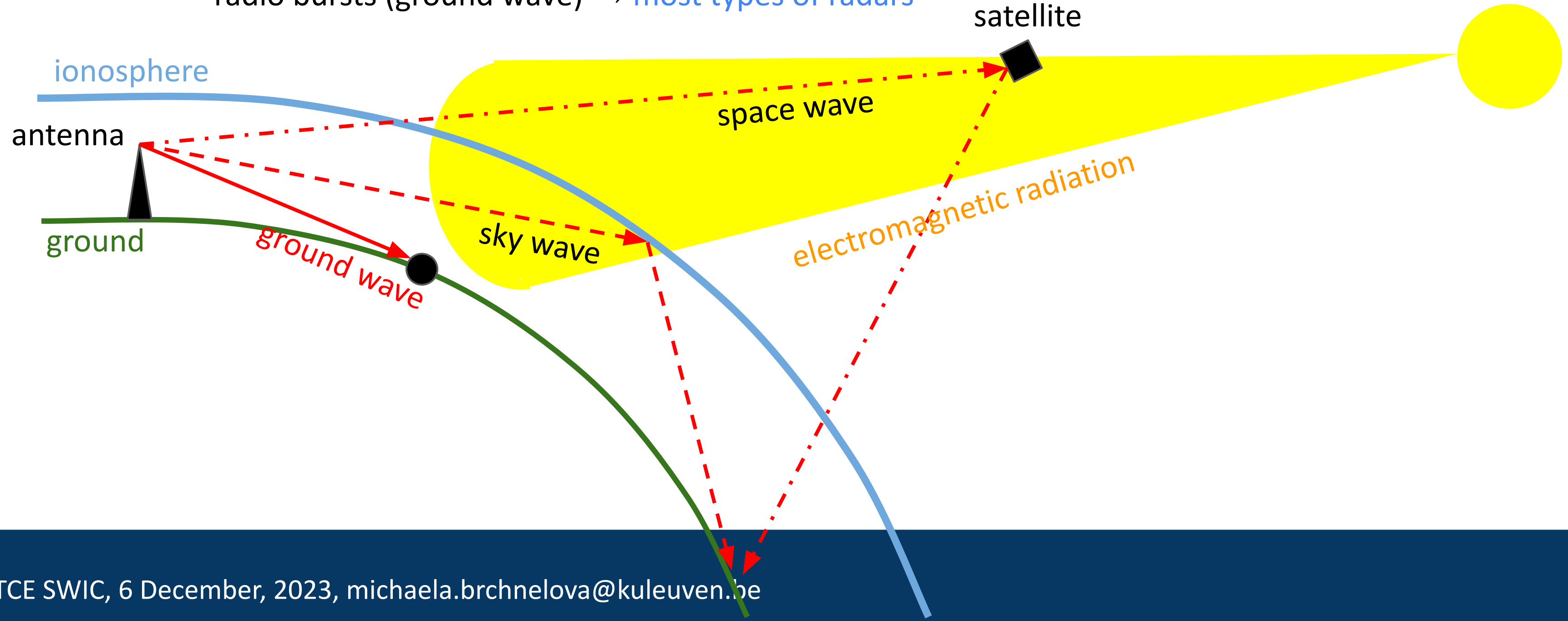
  - radio bursts (ground wave) ⟶ most types of radars



Type of military radar systems

- search and detection radars
- targeting/ fire-control radars
- navigation radars
- mapping radars
- instrumentation radars

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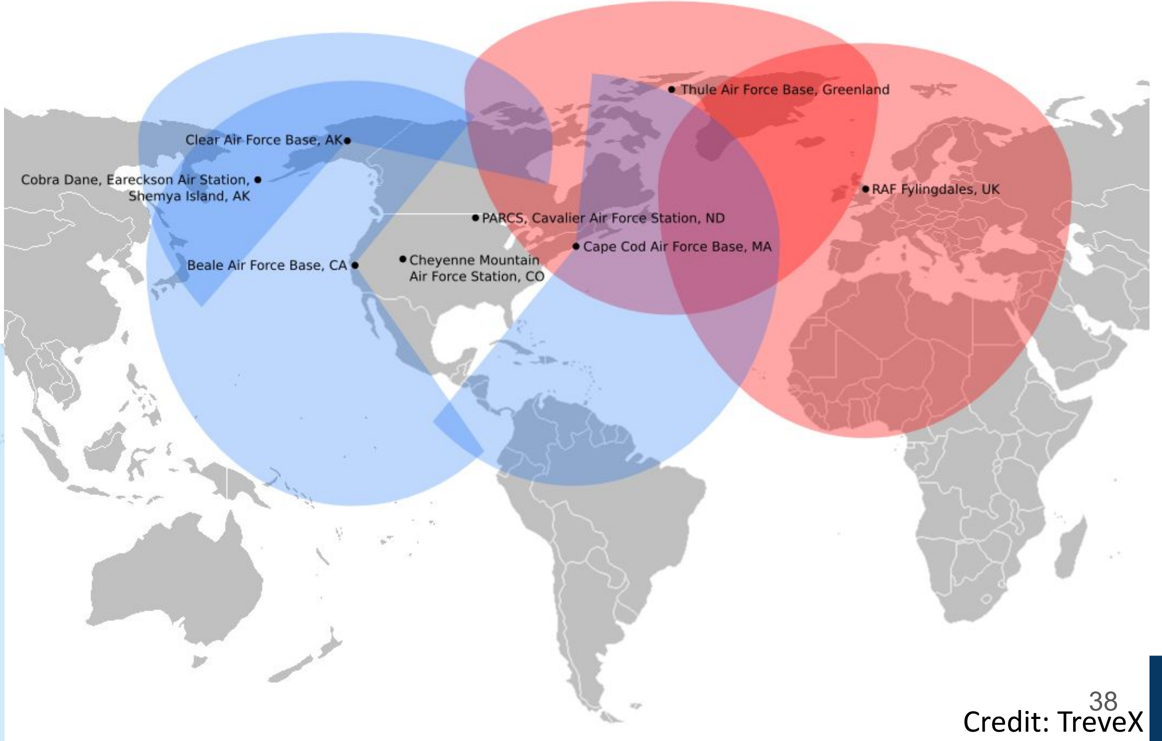
Search and detection radars

- **early warning radars**: for long range (early) target detection
  - US coverage: BMEWS (SSPARS) in UHF (420-450 MHz) range
  - Russian coverage: Voronezh EWS radars operating in VHF (red) and UHF (blue)



Credit: TreveX

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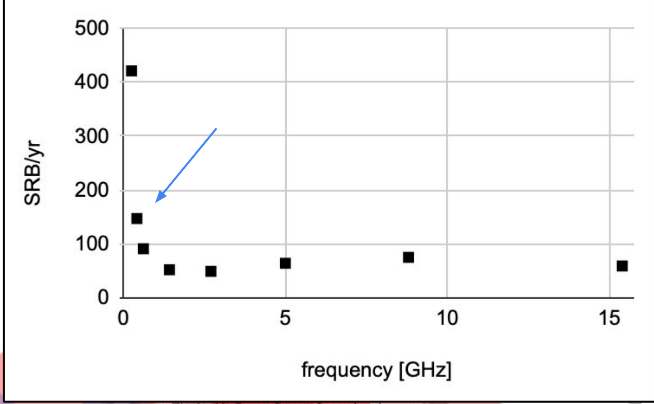
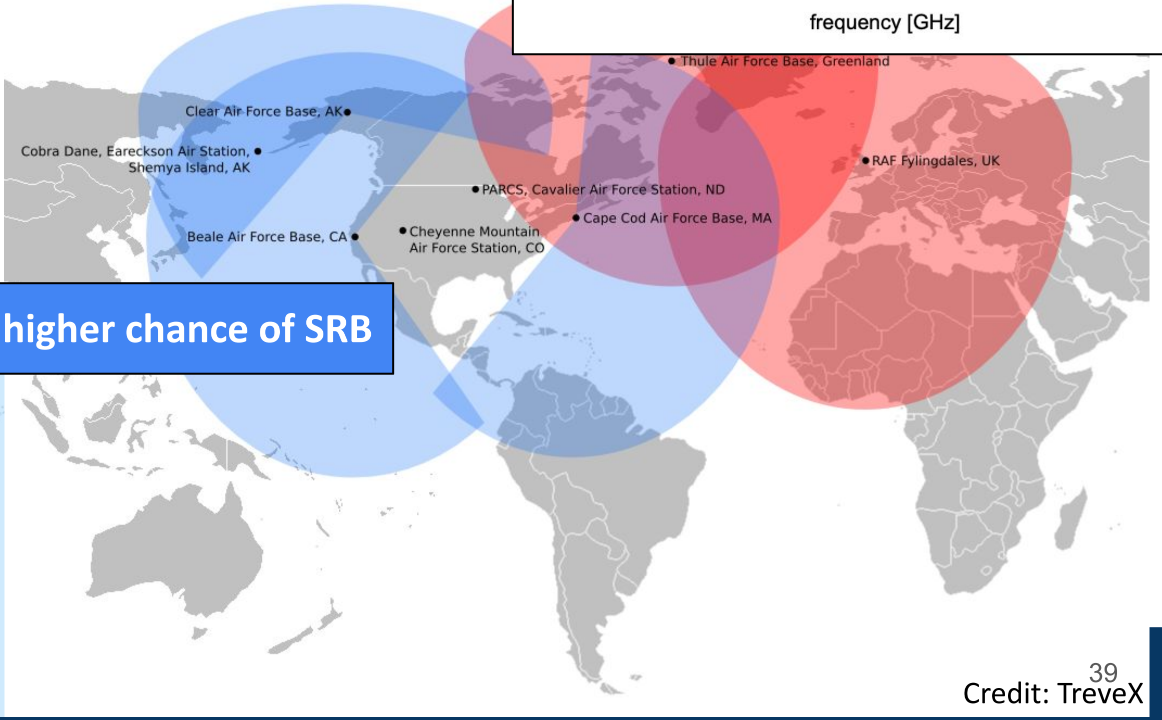
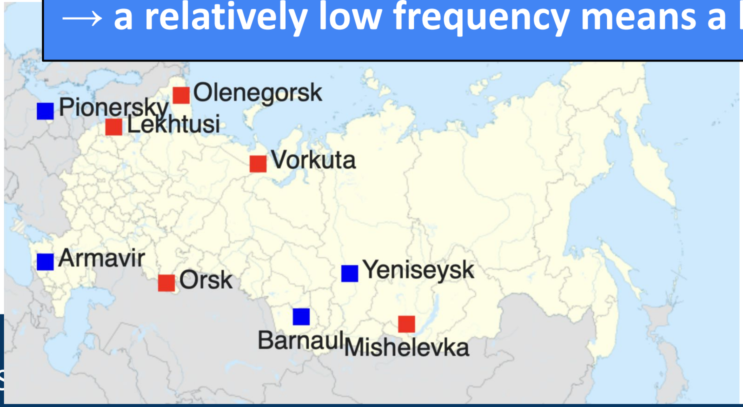




→ a relatively low frequency means a higher chance of SRB



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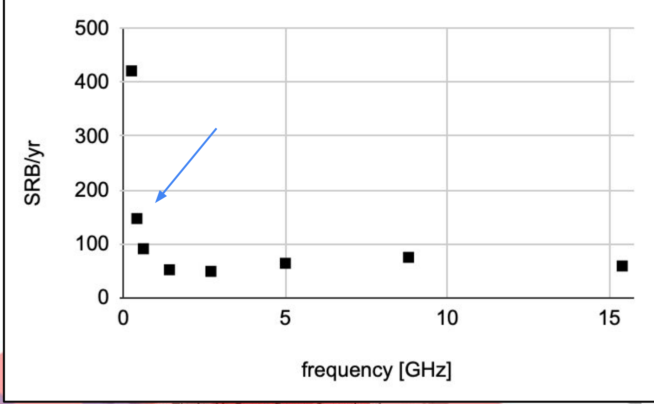

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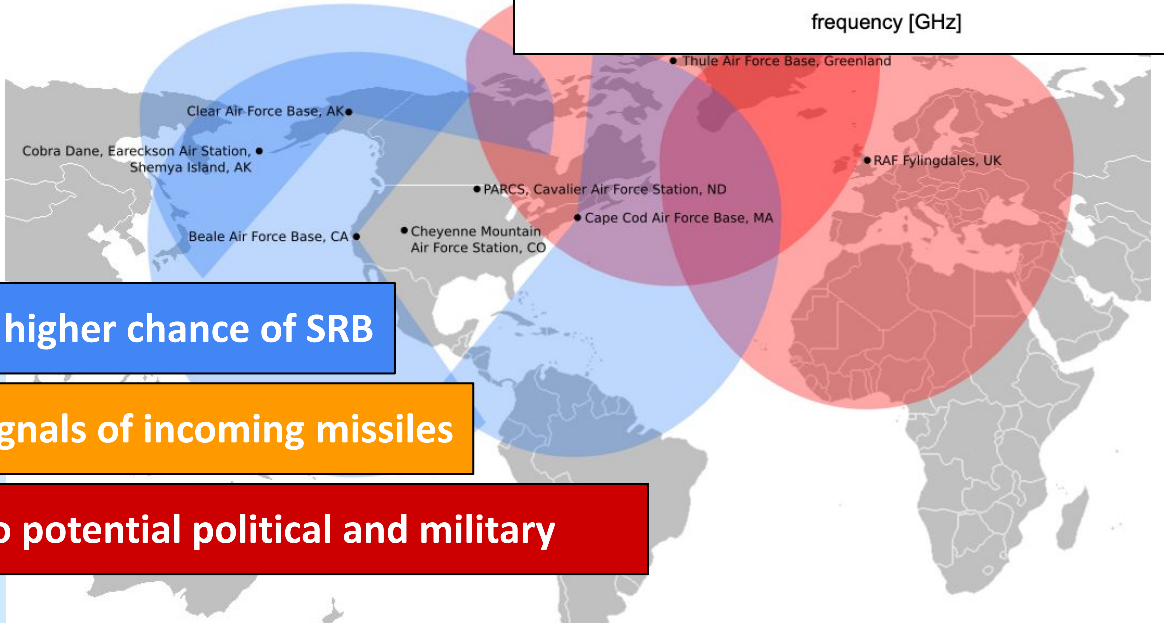

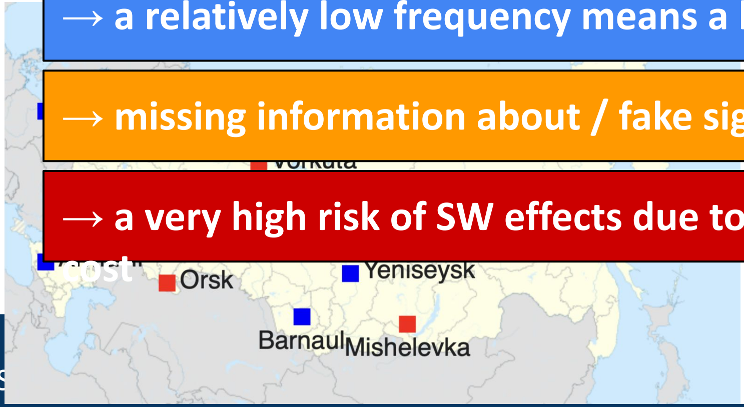

→ a relatively low frequency means a higher chance of SRB

→ missing information about / fake signals of incoming missiles

→ a very high risk of SW effects due to potential political and military cost

Credit: TreveX

Search and detection radars

- early warning radars: VHF to UHF
- **ground control intercept radars**: originally one or more radars are used to guide an interceptor aircraft towards the target, today **Airborne Early Warning and Control** (AEW&C/ AWACS)
  - Boeing 737 AEW&C: Northrop Grumman Electronic Systems Multi-role Electronically Scanned Array (MESA) radar in L band (1 GHz -2 GHz)
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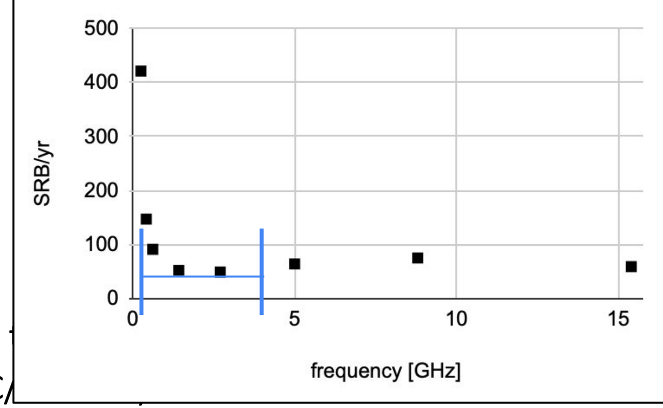
Credit: Republic of Korea Armed Forces


Credit: Saab

Credit: US Navy

Search and detection radars



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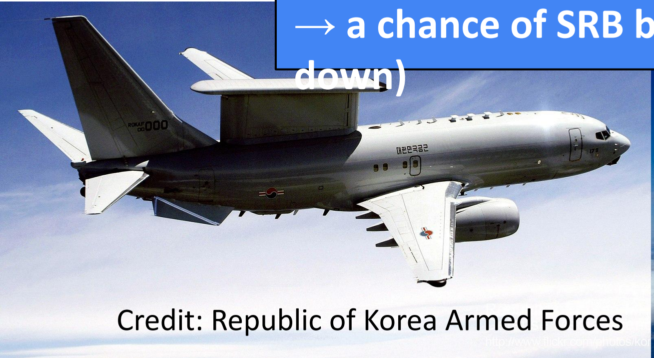
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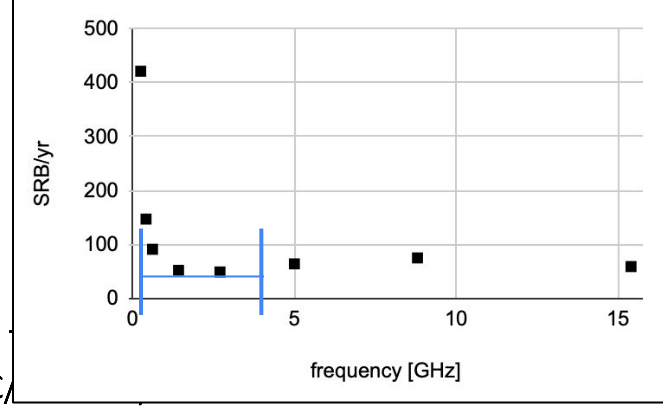

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→ missing information about / fake signals of incoming missiles

→ a relatively high risk of SW effects due to potential political and military cost

Credit: Republic of Korea Armed Forces

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Search and detection radars

- early warning radars: VHF to UHF
- ground control intercept radars & AWACS: UHF to L/ S-band
- **airborne ground surveillance:** unlike AWACS, for surveillance of ground targets (not airborne)
    - E-8 Joint Surveillance Target Attack Radar System (Joint STARS): APY-7 in Ku band (12 GHz - 18 GHz)
    - Boeing P-8 Poseidon: APY-10 in X band (8 GHz - 12 GHz)
    - Northrop Grumman RQ-4 Global Hawk: a synthetic aperture radar in X band (8 GHz - 12 GHz)

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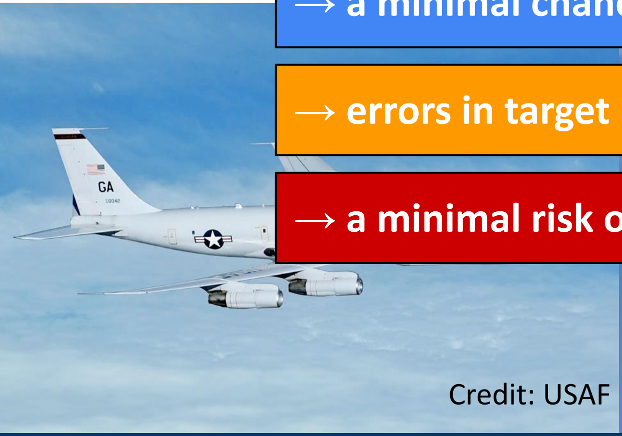

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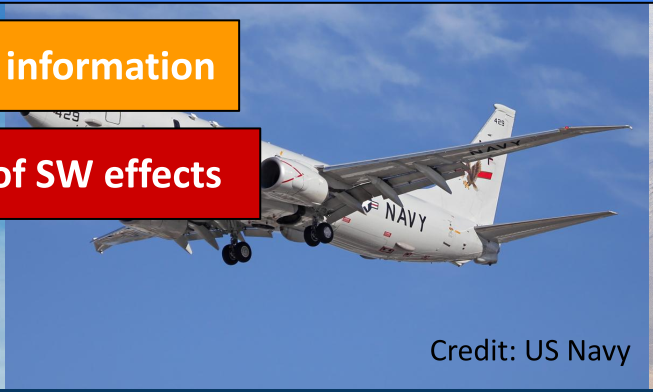

Credit: US Navy

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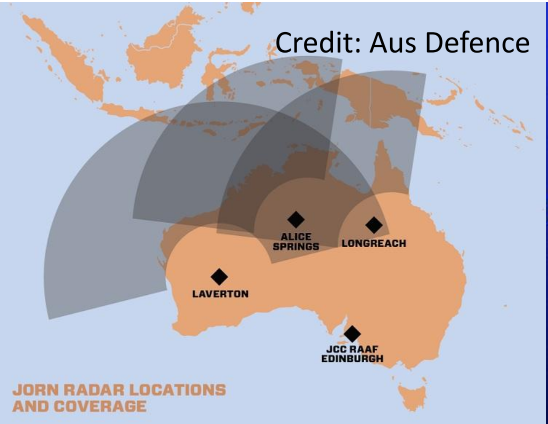
Search and detection radars

- early warning radars: VHF to UHF
- ground control intercept radars & AWACS: UHF to L/ S-band
- airborne ground surveillance: X band to Ku band
- **over-the-horizon:** 1000 to 3000 km range vision through ionospheric refraction
    - Australian Jindalee Operational Radar Network: 10.153 MHz, 22.95 MHz, 8.992 MHz (HF)
    - AN/TPS-71 ROTHR (Relocatable Over-the-Horizon Radar) of the US Navy: 5 to 28 MHz (HF)
    - Russian Kontayner OTH radar: HF



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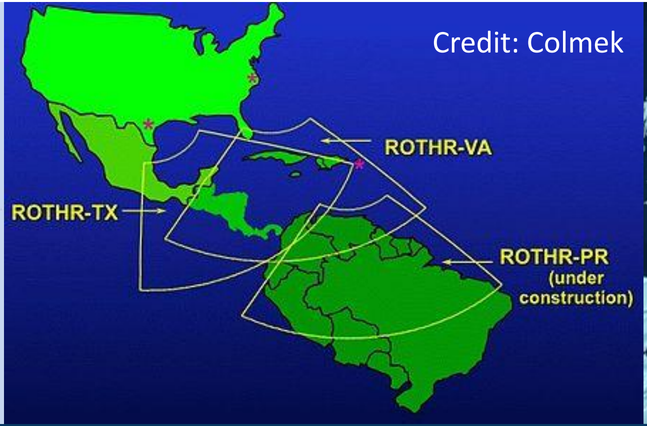

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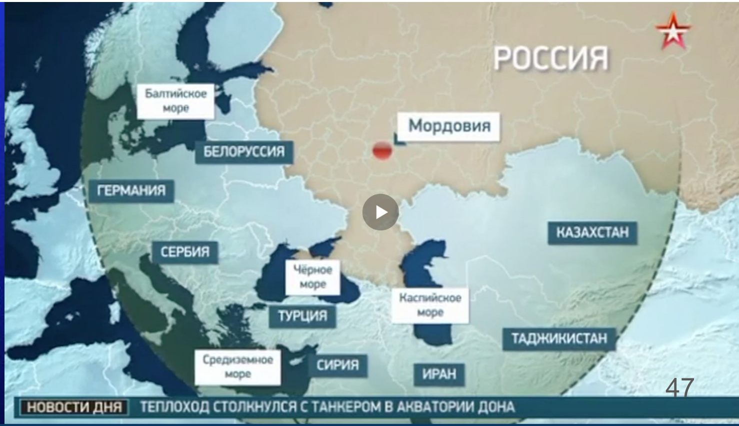

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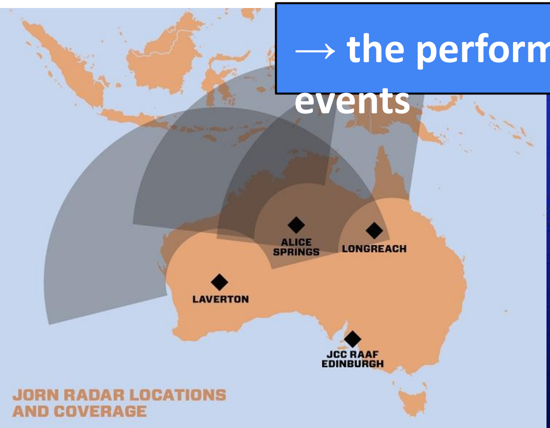

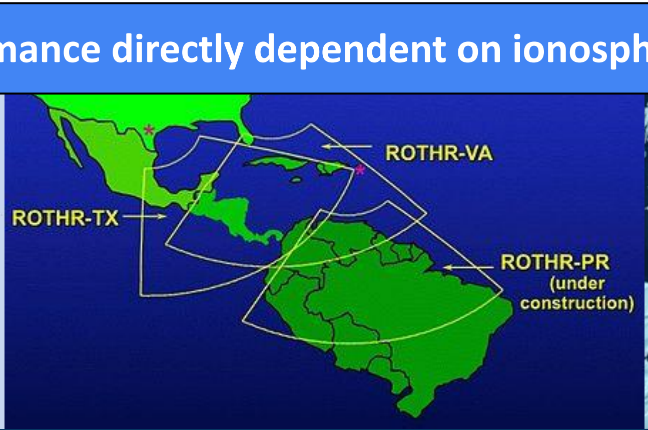

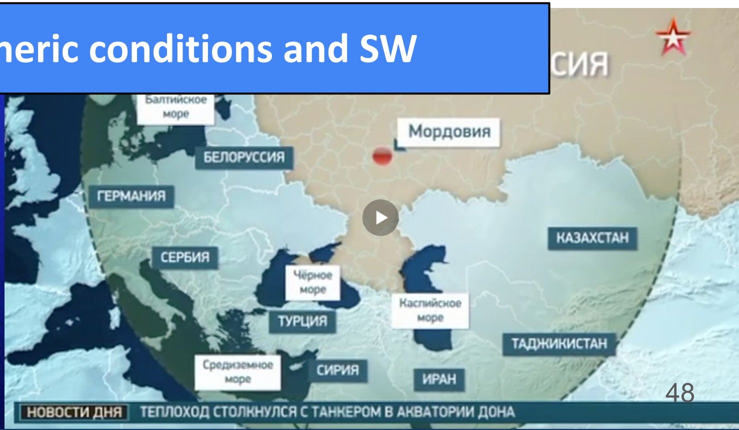

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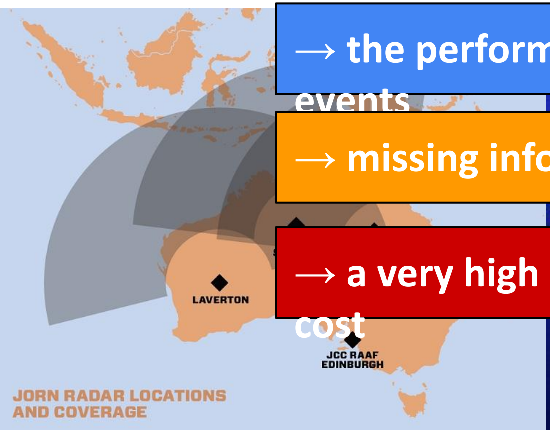

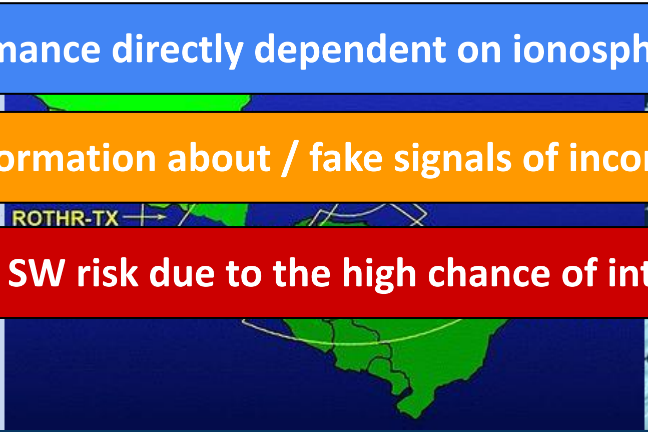

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  - Soviet Tor Surface-to-Air missile system: target acquisition radar in F band (3 GHz - 4 GHz), target engagement in G (4 GHz - 6 GHz)/ H (6 GHz - 8 GHz) and later K band (20 GHz - 27 GHz)
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Credit: V. Kuzmin


Credit: US Def


Credit: Military.com


Credit: Russian Def

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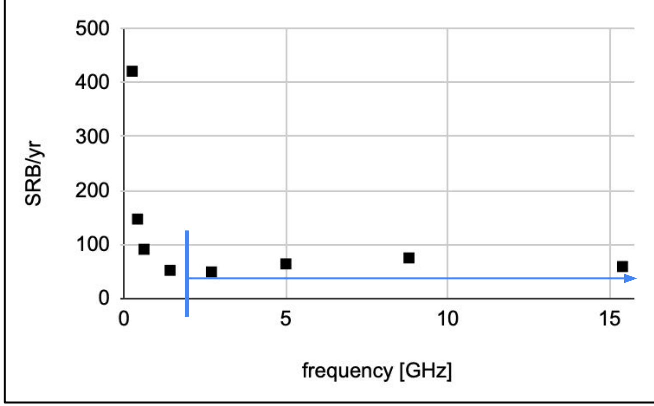

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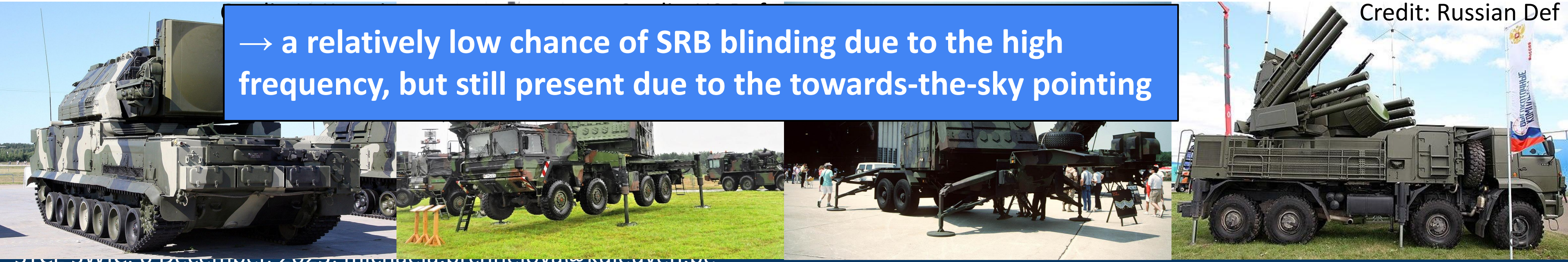

→ a relatively low chance of SRB blinding due to the high frequency, but still present due to the towards-the-sky pointing

Credit: Russian Def

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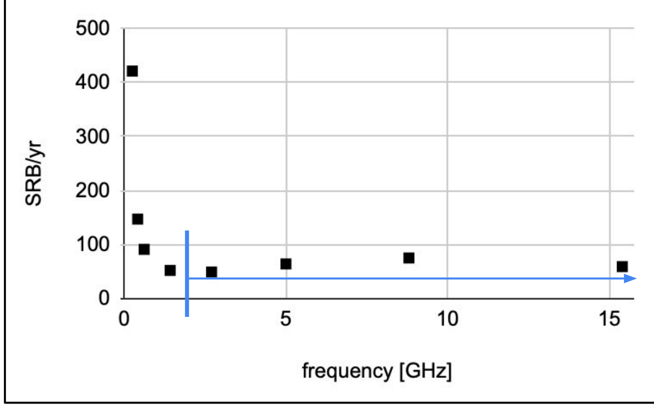

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→ missing of the target

→ a medium to low SW risk due to the low chance of interference and consequences

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- **surface search radars:** > 10 km for e.g.
    - Indian Integrated Coastal Surveillance System: primarily in X band (8 GHz - 12 GHz)
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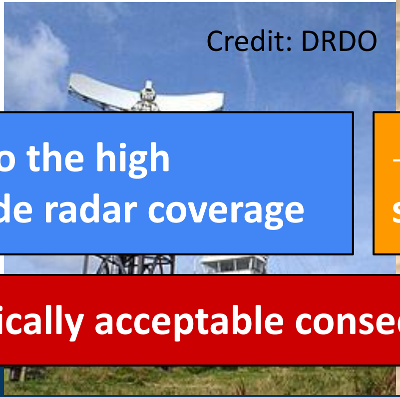

→ a relatively low chance of SRB blinding due to the high frequency, but still present as a result of the wide radar coverage

→ missing on/ fake signals of surface objects

→ a low SW risk due to the low chance and typically acceptable consequences

Type of military radar systems

- search and detection radars
- **targeting/ fire-control radars**
- navigation radars
- mapping radars
- instrumentation radars

Targeting/ Fire-control radars

- to provide data, such as azimuth, elevation and range of the target to the fire-control system
- some examples:
  - Raytheon AN/SPG-62 for terminal target illumination for destroyers: X band (8 GHz - 12 GHz)
  - Lockheed Martin/ Northrop Grumman AN/APG-78 Longbow or Apache: Ka band (27 GHz - 40 GHz)
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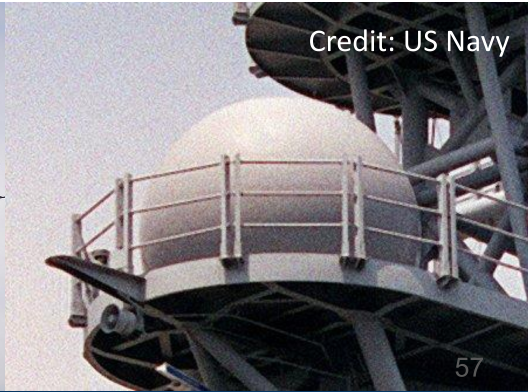
Credit: T. Baba



Credit: Lockheed Martin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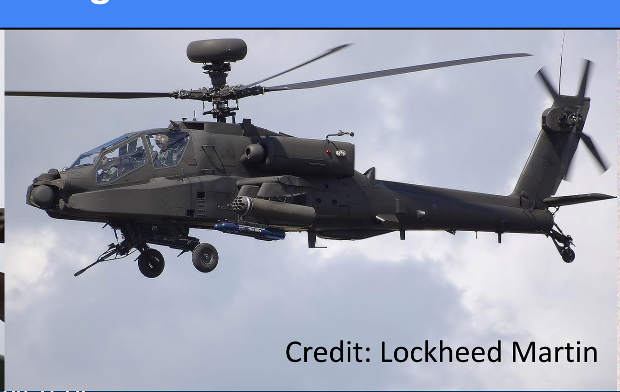

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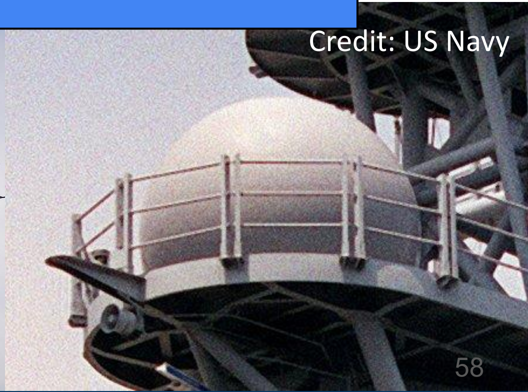

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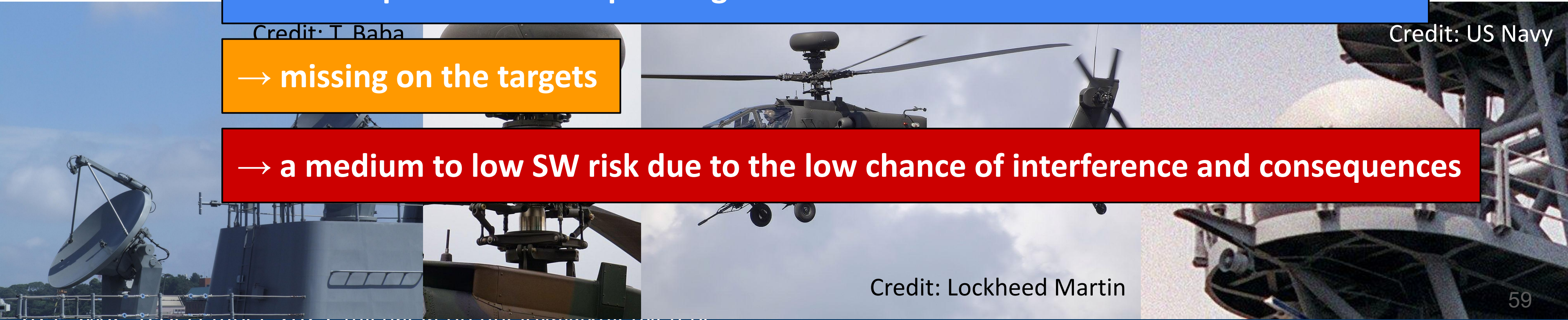

Credit: T. Baba

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→ missing on the targets

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Navigation radars

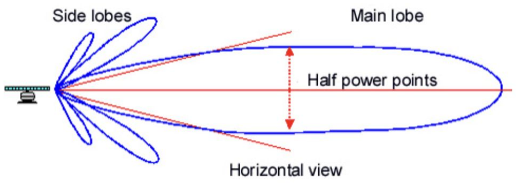
- **marine/ naval radars:** short range for surface navigation and surveillance
  - AN/SPS-73(V)12 navigation radar of the US Navy: 2D, short range, X band (8 GHz to 12 GHz)
  - AN/SPS-49 surveillance radar of the US Navy: 2D, long range, in UHF/ L band (851–942 MHz)
  - MR-800 Voskhod surveillance radar: in NATO C/D/E/F bands (0.5 GHz to 4 GHz)

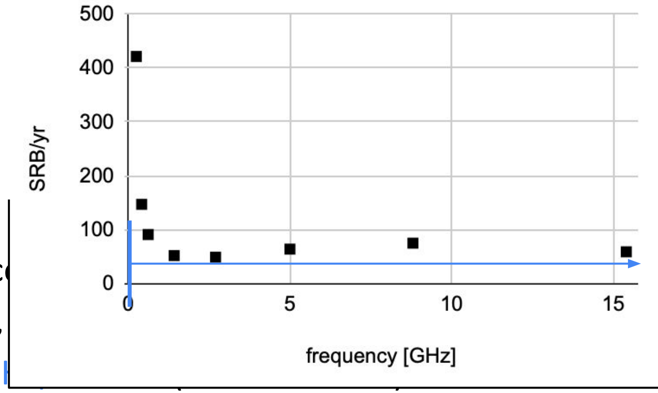

Credit: US Navy


Credit: US Navy


Credit: Unknown

Navigation radars





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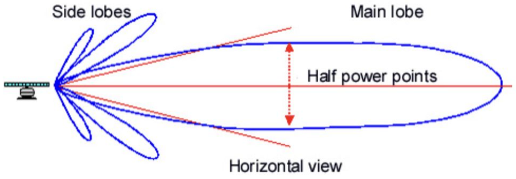

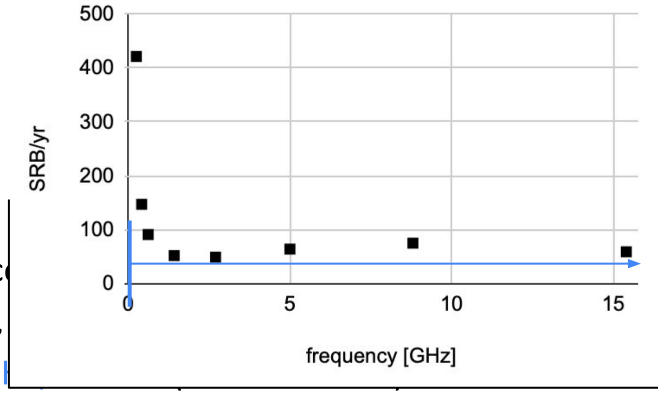

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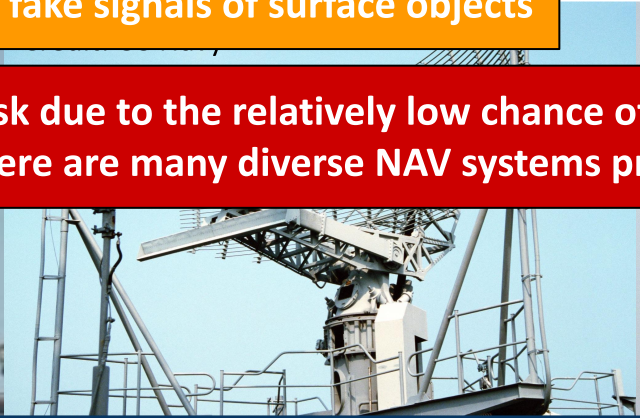
→ **missing on/ fake signals of surface objects**

→ **a low SW risk due to the relatively low chance of interference and the fact that usually there are many diverse NAV systems present onboard**


Credit: US Navy




Credit: Unknown

Navigation radars

- marine/ naval radars: for navigation and surveillance, generally between UHF and X-band
- **Air Traffic Control radars:** primary (reflection) and secondary (interrogation)
    - ASR-9 Airport Surveillance Radar (primary): S band (2.5 GHz - 2.9 GHz)
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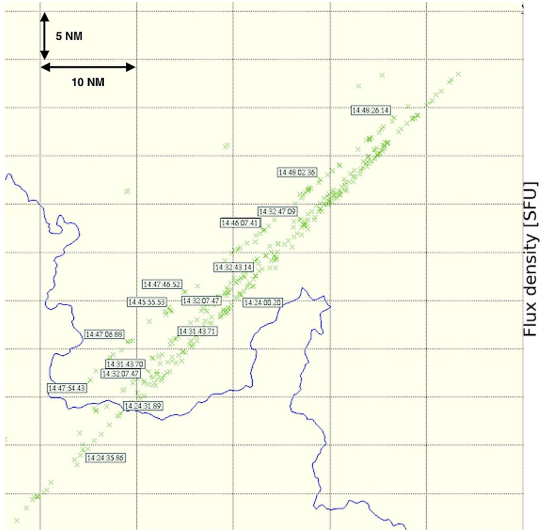
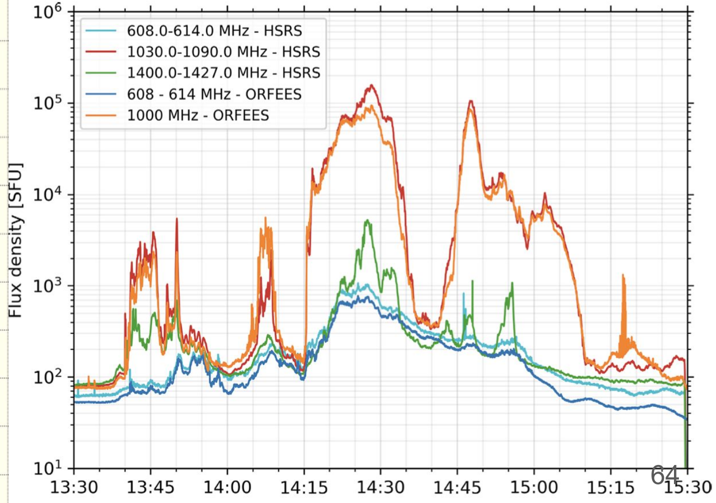
Credit: Unknown



Credit: Marqué et al. 2018



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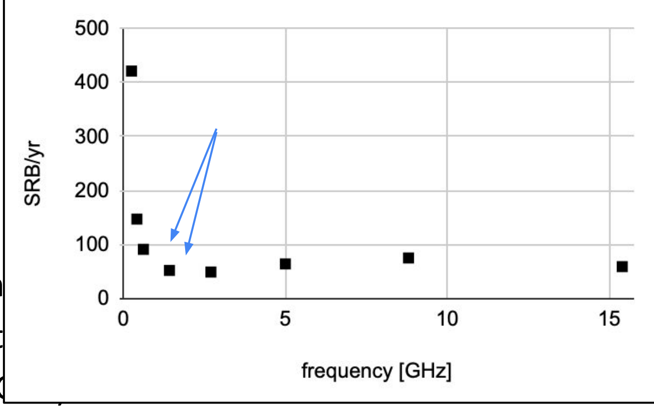
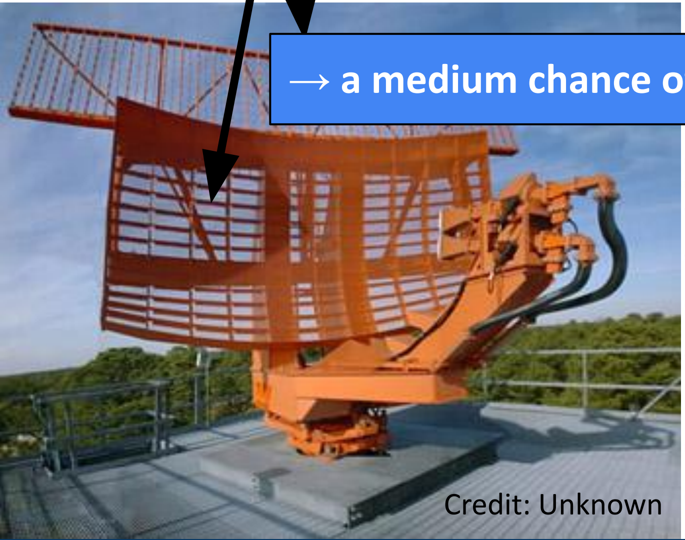


→ a medium chance of SRB blinding



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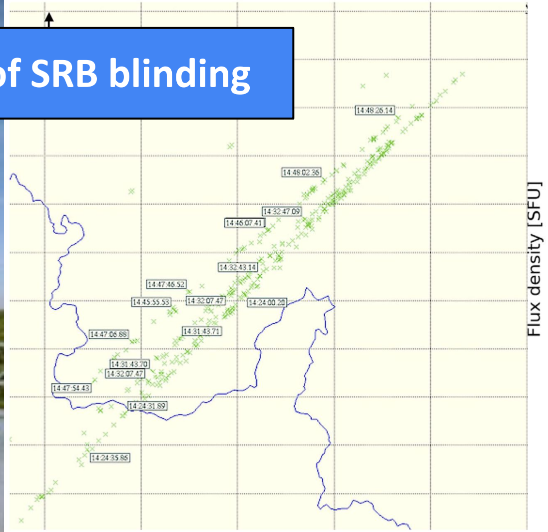

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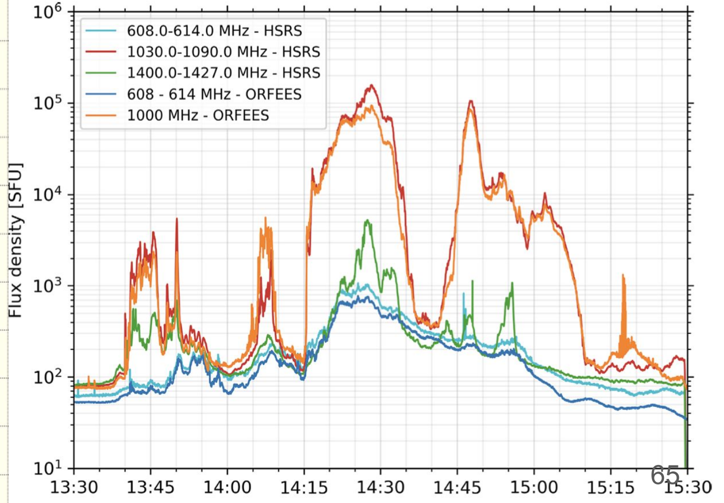

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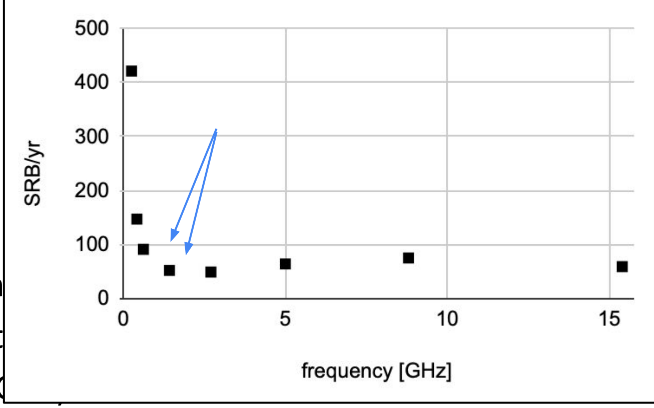

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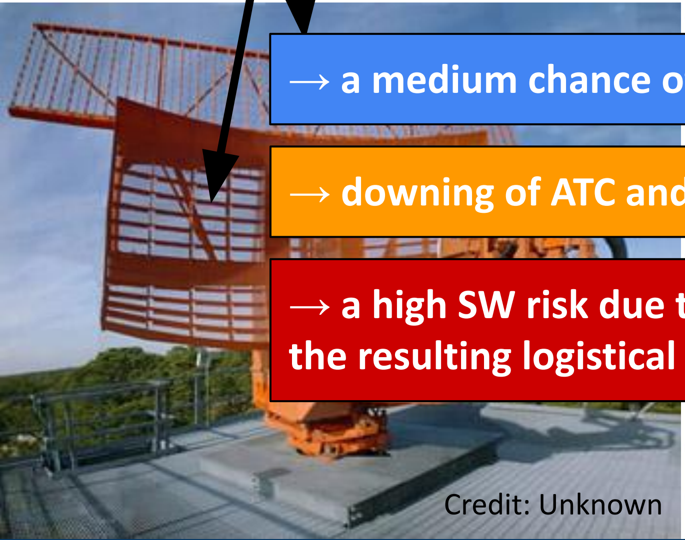

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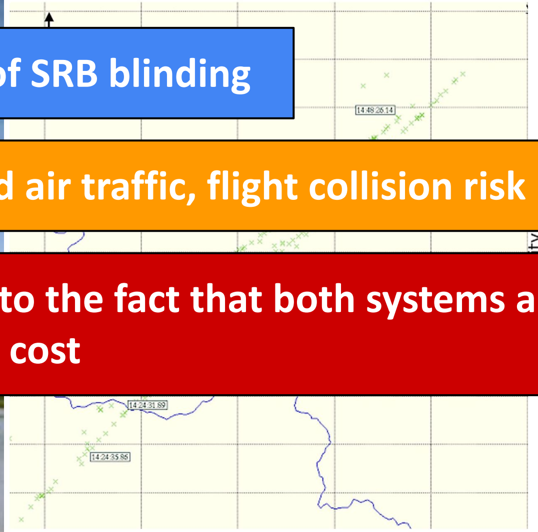
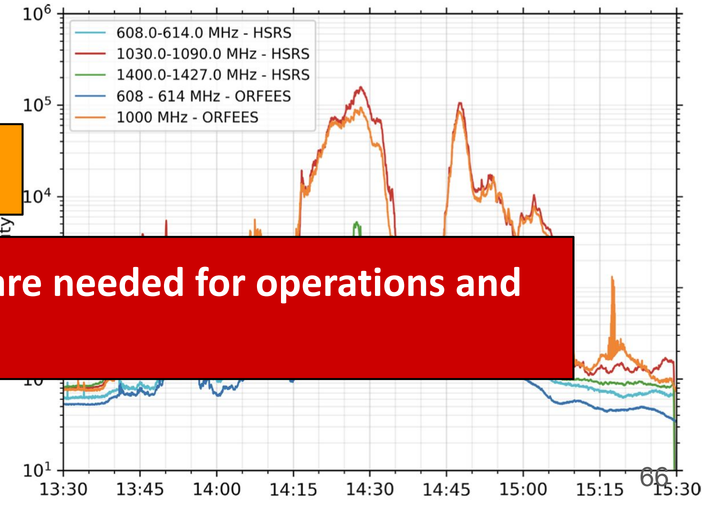




→ a medium chance of SRB blinding

→ downing of ATC and air traffic, flight collision risk

→ a high SW risk due to the fact that both systems are needed for operations and the resulting logistical cost

Navigation radars

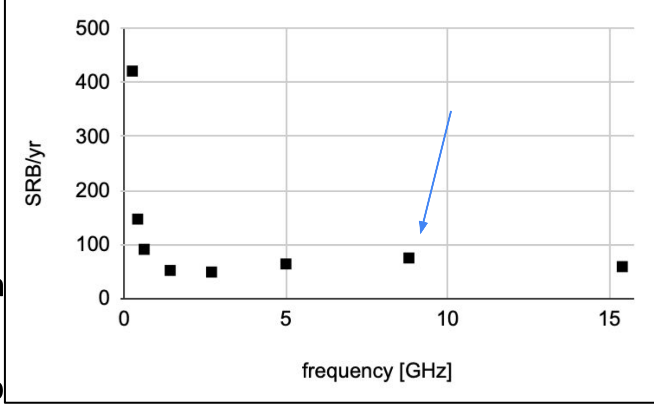
- marine/ naval radars: for navigation and surveillance, generally between UHF and X-band
- Air Traffic Control radars: primary and secondary in S and L bands
- **precision approach radars:** lateral and vertical guidance during final approach
    - PAR-2090C precision approach radar: in X band (9 GHz to 9.18 GHz)
    - GCA-2000 ground control approach radar: in X band (8 GHz to 12 GHz)
    - PAR-80 precision approach radar: in I band (8 GHz to 10 GHz)


Credit: Selex System Integration


Credit: l3Harris


Credit: Averse

Navigation radars



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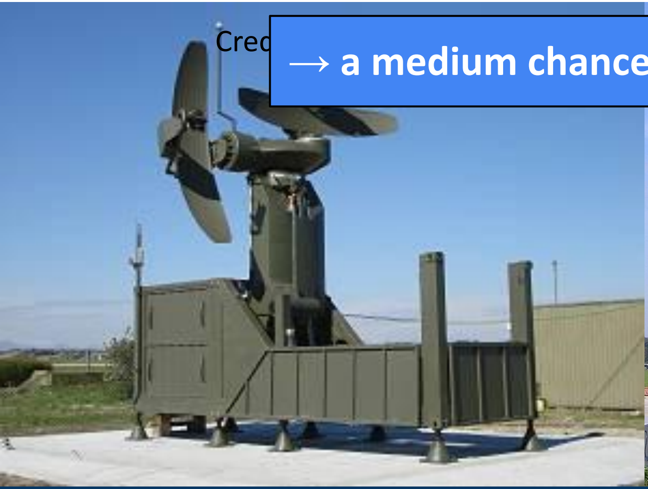

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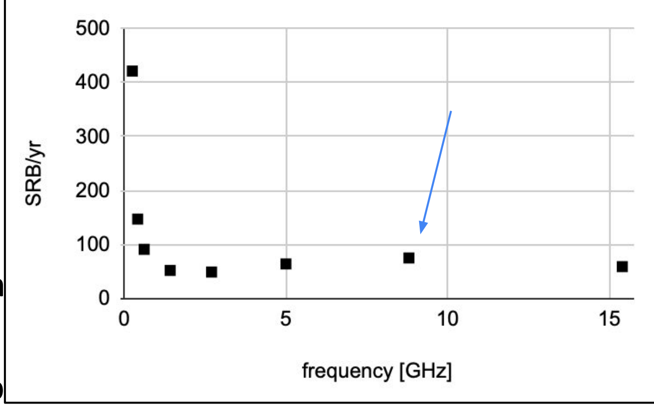

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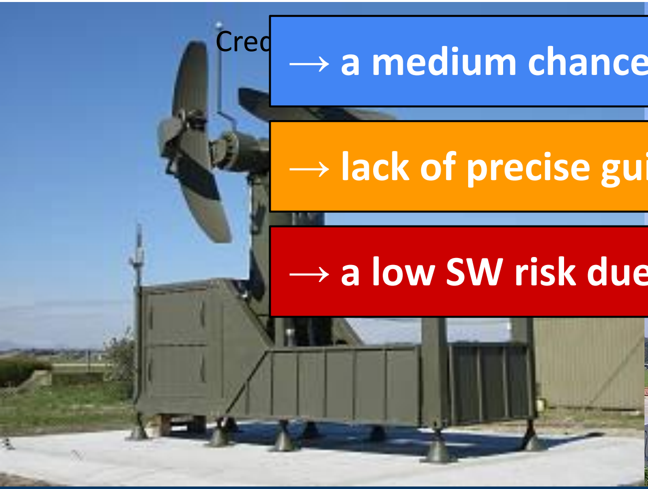

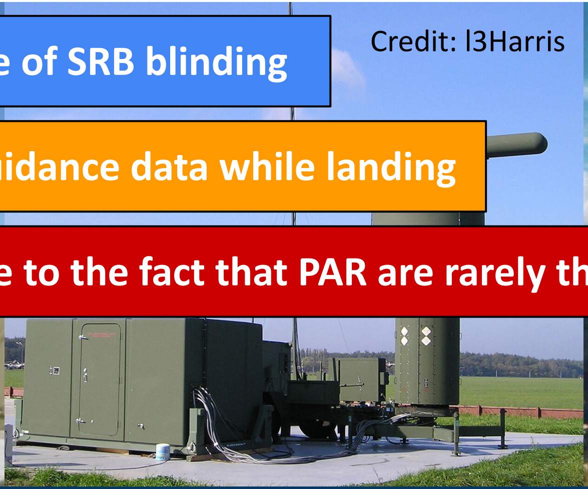

→ a medium chance of SRB blinding

→ lack of precise guidance data while landing

→ a low SW risk due to the fact that PAR are rarely the only landing system

Type of military radar systems

- search and detection radars
- targeting/ fire-control radars
- navigation radars
- **mapping radars**
- instrumentation radars

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Mapping radars

- typically synthetic aperture radars, SAR, for 2D and 3D reconstruction and ISTAR
- generally mounted on a moving vehicle - aircraft/ spacecraft
  - Ku band (12 GHz to 18 GHz): very high resolution SAR
  - X band (8 GHz - 12 GHz): high resolution SAR
  - C band (4 GHz - 8 GHz): SAR workhorse
  - L to S band (1 GHz - 4 GHz): medium/ low resolution SAR

- aircraft-mounted SAR, e.g., MALE or HALE UAV:
  - MQ-9 Reaper Lynx SAR: Ku band (15.2 GHz - 18.2 GHz)

- spacecraft-mounted SAR:
  - ESA's ICEYE SAR constellation: X band (8 GHz - 12 GHz)


Credit: GA-ASI

Credit: ESA

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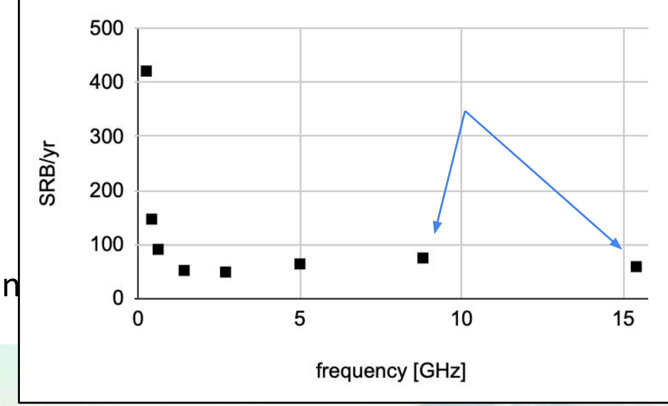
Mapping radars



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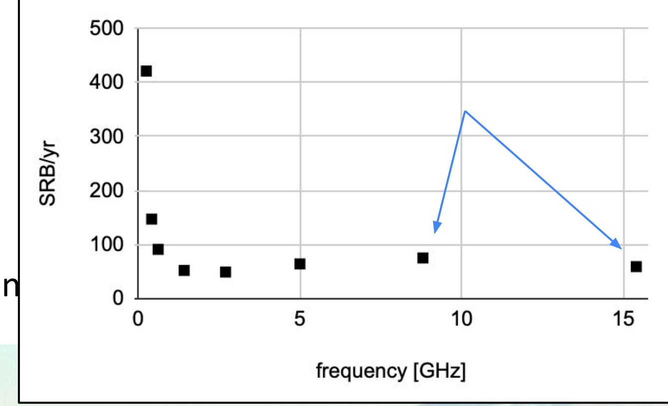

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→ a low SW risk thanks to the low chance and the relatively low cost of the consequences

Credit: ESA

→ lack of target reconstruction and ISTAR

Type of military radar systems

- search and detection radars
- targeting/ fire-control radars
- navigation radars
- mapping radars
- **instrumentation radars**

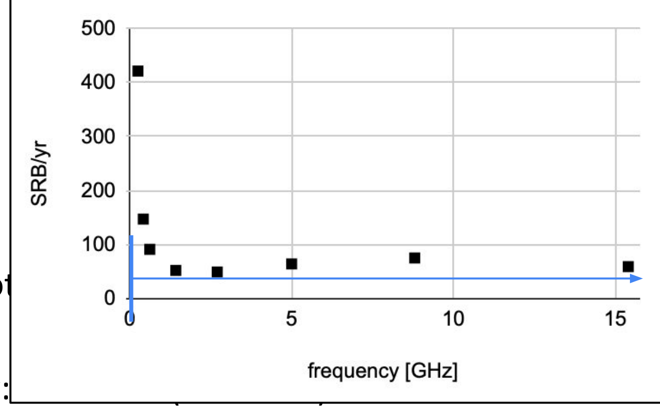
Instrumentation radars

- for experimental and test applications, e.g. on bases and test ranges, both decommissioned/ COTS/ MOTS
- examples:
  - AN/FPS-16 high accuracy radar used by NASA, USAF and US Army: in C band (5.48 GHz)
  - Weibel MFTR/ MSTS series for (military) research purposes: in X band (8 GHz - 12 GHz)


Credit: USAF


Credit: Weibel

Instrumentation radars



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→ an existing chance of SRB blinding, depending on the system's use and pointing

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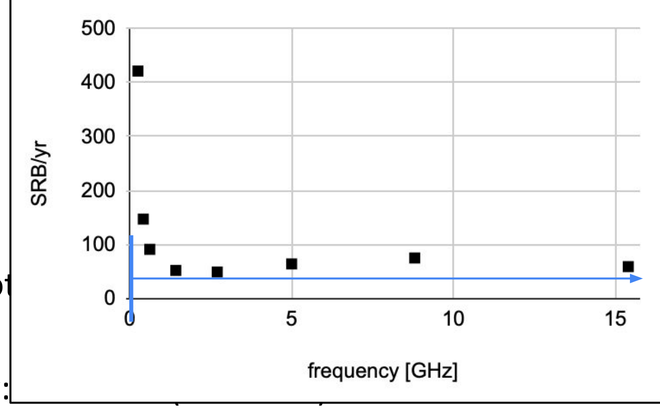

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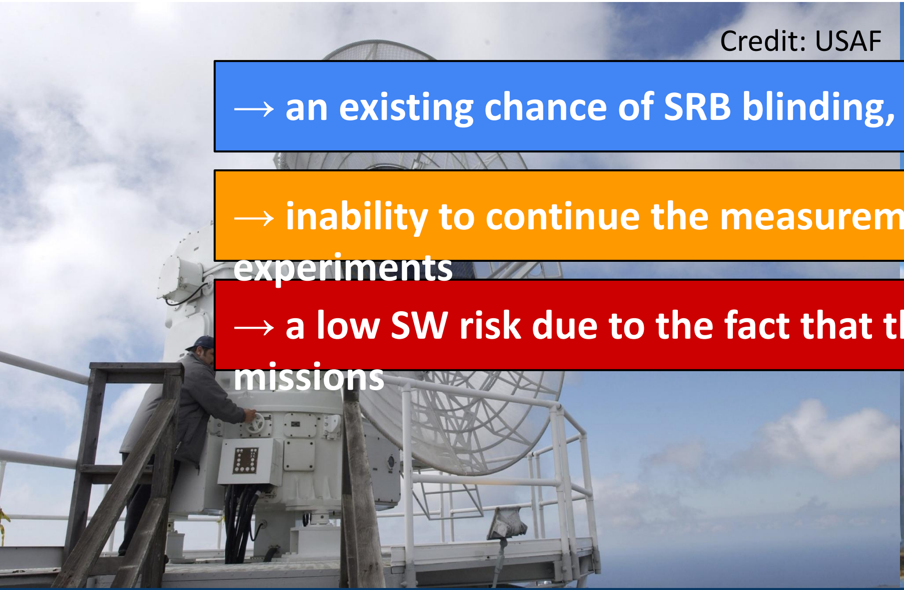
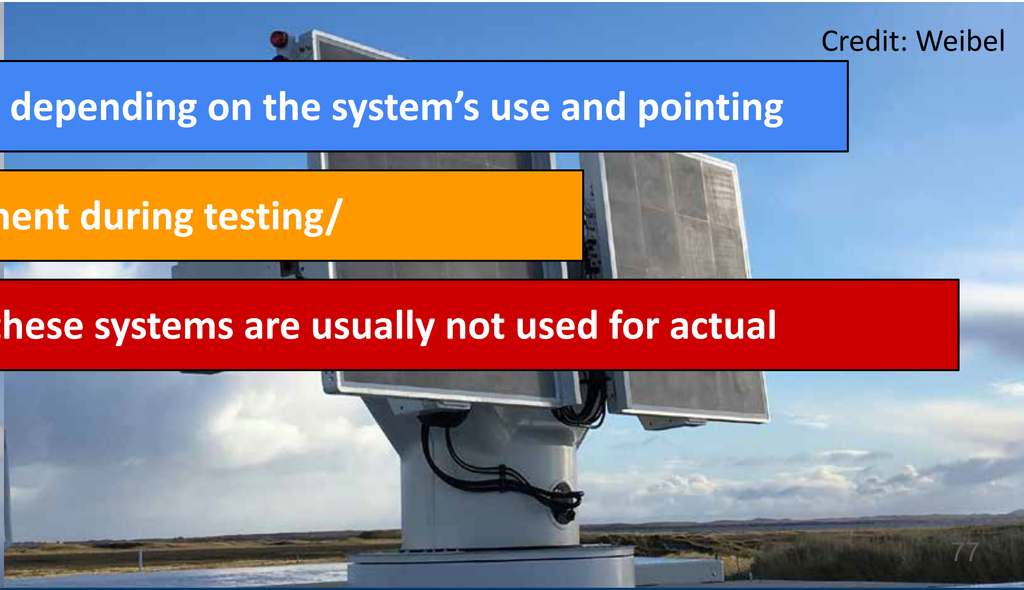

Credit: USAF


Credit: Weibel

→ an existing chance of SRB blinding, depending on the system's use and pointing

→ inability to continue the measurement during testing/ experiments

→ a low SW risk due to the fact that these systems are usually not used for actual missions

Military radar conclusions

- high risk systems:
  - Early Warning systems
  - Airborne Early Warning and Control systems
  - Air Traffic Control radars
  - OTH radars

- mitigation strategies:
  - presence of multiple systems/ operations at multiple frequencies (system/ frequency diversity)
  - SW advisory while interpreting measurements
  - constant SW monitoring

Examples of vulnerabilities

Examples of vulnerabilities

Land component

Tanks/ Armored fighting vehicles

- Leopard 1:
  - navigation & SSA mostly from periscopes and visual/ IR cameras
  - equipped with SAM 80/90 radio (low VHF)
  - Belgian ones with a fire control system

- Mowag Piranha III:
  - prototype has Thales VHF 50W radio
  - most versions contain HF, VHF, UHF and SATCOM capability

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→ **especially HF & SATCOM vulnerable to ionospheric conditions**


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→ especially HF & SATCOM vulnerable to ionospheric conditions

→ inability to communicate mostly via HF and SATCOM

→ a low SW risk due to sufficiently diverse communication systems

Anti-tank missiles

- Spike SR/MR/LR
  - communication generally through fibre optics
  - targeting mostly reliant on infrared homing
  - Spike LR II also relies on a helicopter RF link
  - coordination through GPS

- Akeron MP (from 2025 onwards)
  - dual band seeker in IR and low-light video
  - at the firing post - TV camera, fibre optics and GPS receiver to exchange target coordinates


Credit: Defense Brief


Credit: MBDA inc.

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→ performance depends on GPS accuracy

→ a misdirection/ a loss of the missile while in flight

→ a medium to low SW risk, depending on the protocol in case of a loss of the GPS signal

Examples of vulnerabilities

Naval component

Leopold I frigate (similar to Louise-Marie)

- multiple radars onboard:
  - 3D combined watch radar, a SMART-S 3D: in F band (3 GHz - 4 GHz)
  - Signaal LW-08 combined watch radar: in D band (1 GHz - 2 GHz)
  - Kelvin Hughes navigation radar: in I band (8 GHz - 10 GHz)
  - SCOUT LPI surveillance radar: in J band (10 GHz to 20 GHz)
  - two Signaal STIR 18 fire control systems with missile control: in I/J/K band (8 GHz - 40 GHz)

Credit: Belgian Naval Component

Credit: BNC

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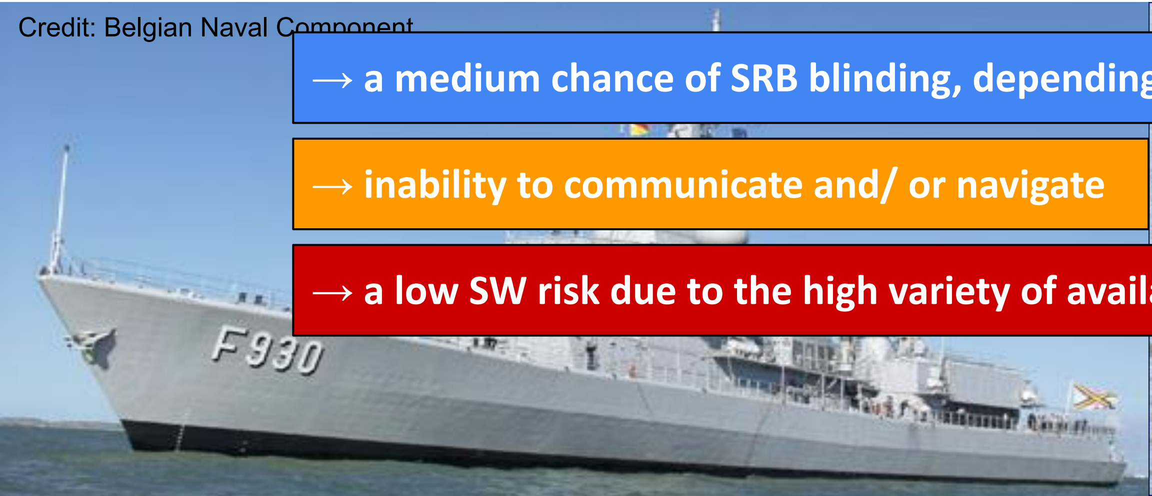

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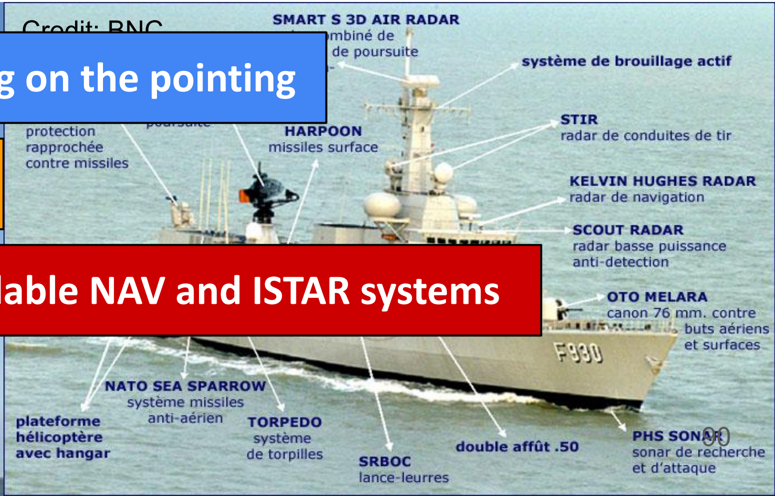

→ a medium chance of SRB blinding, depending on the pointing

→ inability to communicate and/ or navigate

→ a low SW risk due to the high variety of available NAV and ISTAR systems

Examples of vulnerabilities

Air component

F-16 radar and navigation systems

- BAE Systems Terprom digital terrain navigation system:
    - a radar altimeter C-band in 4.2 GHz to 4.4 GHz (UHF)
- Gould AN/APN-232 radar altimeter: C-band ar 4.3 GHz (UHF)
- Rockwell Collins AN/ARN-118 tactical air navigation system
    - receivers in 1025 MHz to 1150 MHz, L Band
    - transmitters in 962 MHz to 1213 MHz, L Band
- Rockwell Collins AN/ARN-108 instrument landing system: radio signals on 108.10 MHz to 111.95 MHz (VHF) frequency for horizontal guidance, 329.15 to 335 MHz (UHF) for vertical guidance
- AN/APG-68 fire control radar in X-band (UHF) or AN/APG-80 upgraded version operating in X-band (UHF)

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- AN/APG-68 fire control radar in X-band (UHF) or

→ inability to communicate and/ or navigate

→ a medium to low chance of SRB blinding

→ a low SW risk due to the diversity in NAV systems

F-16 communication systems

- Raytheon UHF AN/ARC-164 receiver / transmitter:
  225 MHz to 399.975 MHz (VHF to UHF)

- Rockwell Collins VHF AM/FM AN/ARC-186 transceiver:
  - FM: on 30 MHz to 87.975 MHz
  - AM: on 108 MHz to 115.975 MHz (Receive only) and from 116 MHz to 151.975 MHz

- AN/APX-101 identification friend or foe (IFF) transponder:
  - interrogate: 1030 MHz (UHF)
  - replay: 1090 MHz (UHF)

- many have now integrated a SATCOM capability

Credit: USAF

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→ inability to communicate mostly through SATCOM

→ a low SW risk due to the high diversity in the systems involved

→ a present chance of SRB blinding, SATCOM dependent on ionospheric conditions

Puma AE UAS

- Belgian army → Puma LE
- GPS link for navigation

- communications:
    - 8 channels
    - uplink (e.g., sending commands for navigation and flight equipment control): UHF (371.75 MHz to 395.05 MHz)
    - downlink (e.g., downloading telemetry data): UHF (1717.5 MHz - 1840.0 MHz)

Credit: AeroVironment

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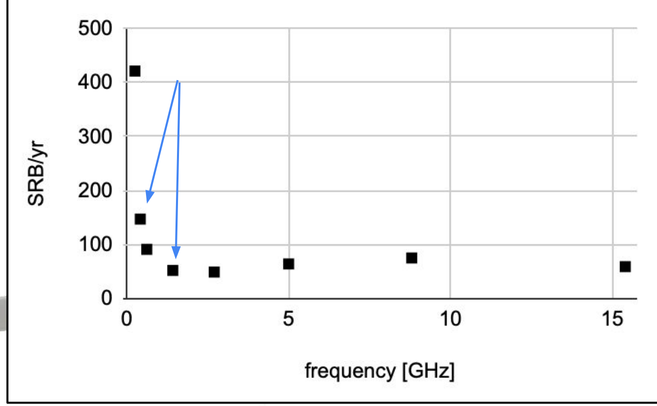

Credit: AeroVironment

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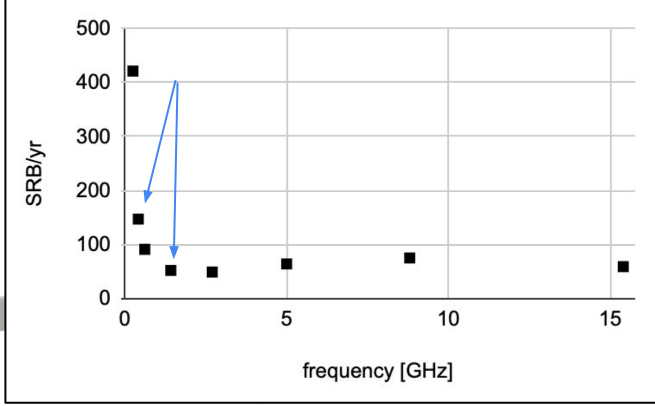

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→ a medium chance of SRB blinding

→ UAS loss/ misdirection to civil space and/ or capture by adversaries

→ a medium to low SW risk, depending on the protocol in case of loss of contact

8. Recommendations

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 power 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 double-frequency & EGNOS or similar

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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

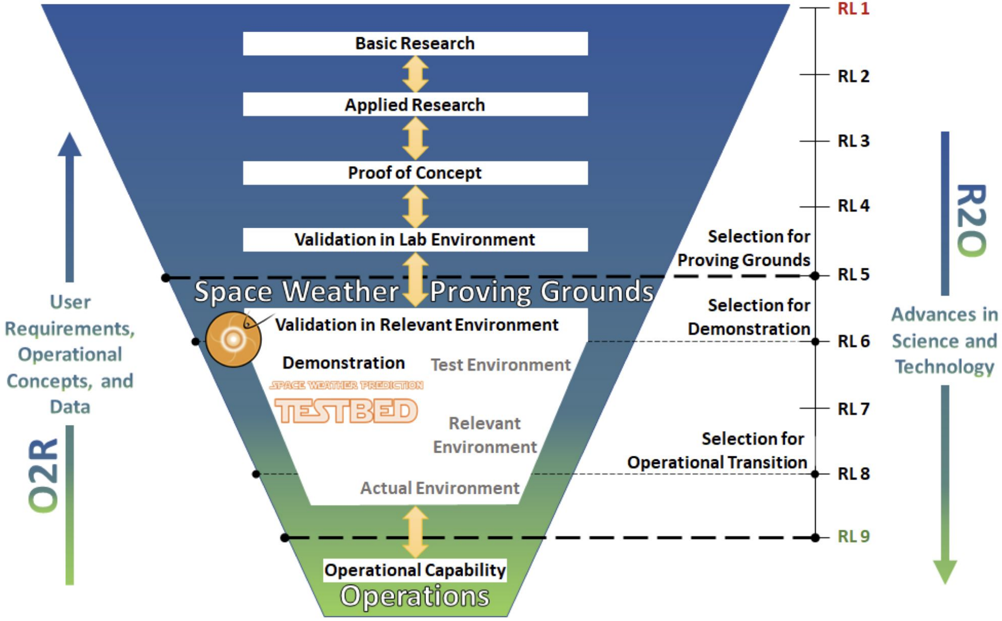

Figure 1: Research to Operations to Research Process (NOAA Example)

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Thank you for your attention!

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(m.brchnelova@gmail.com after summer 2024)