SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of:

Solar-Terrestrial Centre of Excellence

Koninklijke Luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

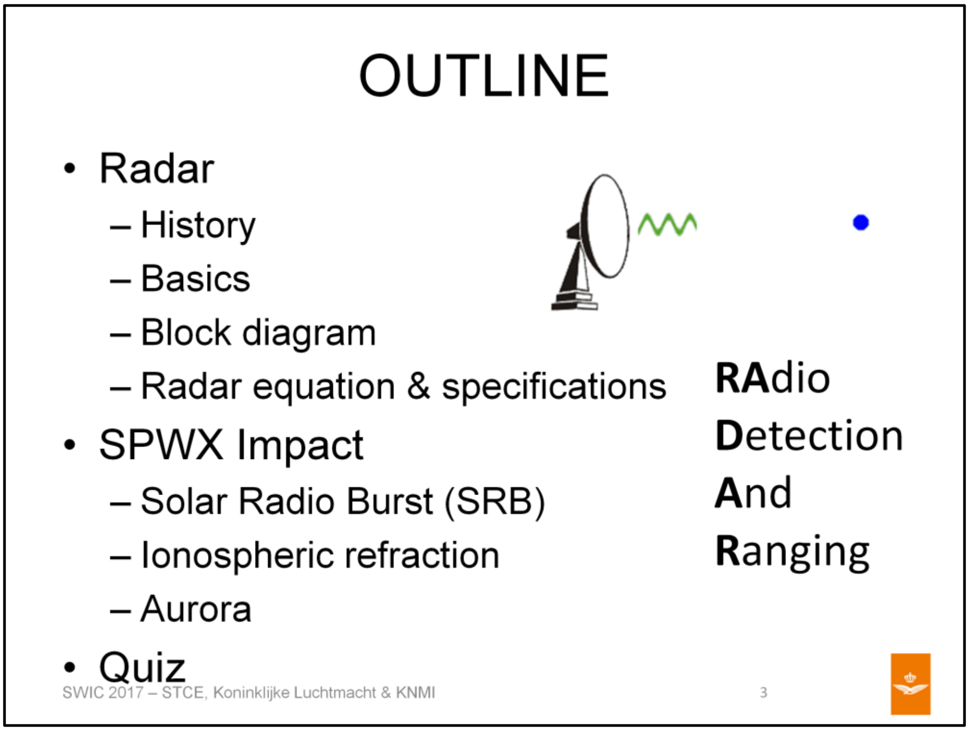
May 2017

CREDITS & THANKS TO

- Merrill I. Skolnik
- Charles Tempelman
- Christian Wolff
- US Air Force – 557th Weather Wing
  - Dr. Mills & Don Harper
- Delores J. Knipp

Sources used for this module:

- Introduction to Radar Systems by Merrill Skolnik
- Delores J. Knipp: Understanding SPWX and the Physics behind it
- Harper & Mills: AFWA SPWX course + website manual
- Modules by Charles Tempelman
- http://www.radartutorial.eu/index.html
- https://nl.wikipedia.org/wiki/Radar
- https://www.youtube.com/watch?v=oLEgqhLgGnc
- https://www.youtube.com/watch?v=CDfLR8cXj_4
- https://www.youtube.com/watch?v=bU_ABeCdWYs



On the 4th of November 2015 a Solar Radio Burst caused severe malfunction of ATC radars in Sweden. At the same day several solar flares and a geomagnetic storm were observed. Several experts discussed a supposed impact by these flares and storm, while ignoring the SRB at first. A few weeks later, during the European Space Weather Week (ESWW), prof. Opgenoorth gave an interesting presentation about the incident, focussing on the SRB as well as discussing the flares and geomagnetic storm. The SRB was an obvious cause for those who know a bit about the operation of radars. This is our motivation to elaborate on this topic.

OUTLINE

- Radar
  - History
  - Basics
  - Block diagram
  - Radar equation & specifications
- SPWX Impact
  - Solar Radio Burst (SRB)
  - Ionospheric refraction
  - Aurora
- Quiz

HISTORY OF RADAR

- WWII
  - UK: Chain Home & magnetron
  - Germany: Freya, Wurzburg & Seetakt
  - Netherlands: Type 289, 10 May 1940 (!)
  - USA: CXAM, SCR-268 & SCR-270, Pearl Harbor (!)
  - Japan, France, USSR & Italy

- Merrill Skolnik: Introduction to Radar Systems

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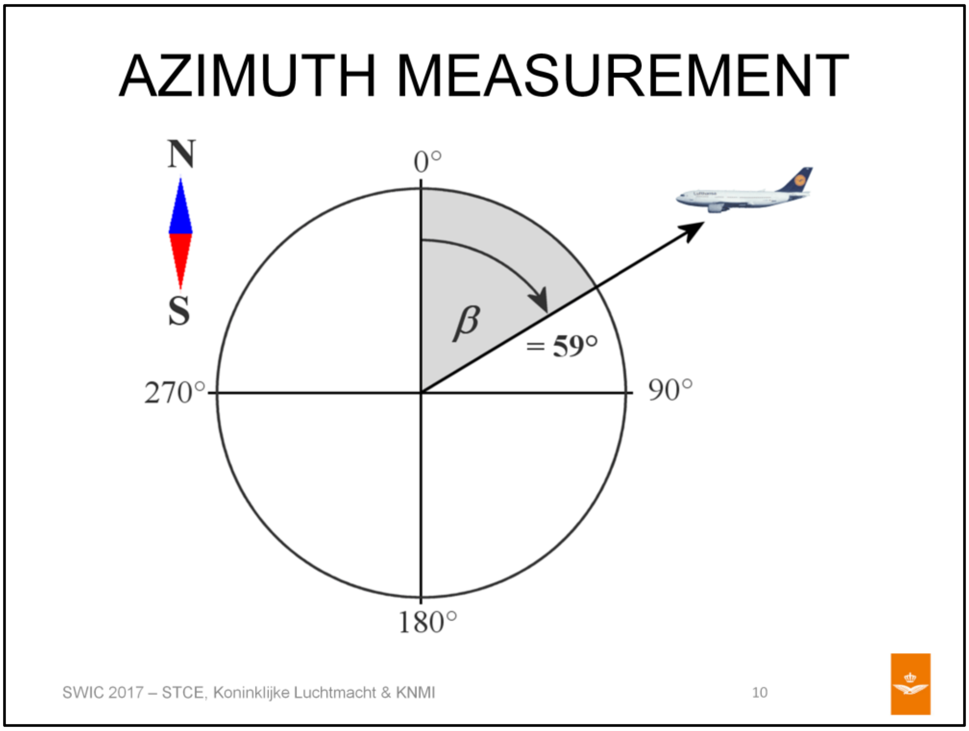
RANGE MEASUREMENT

$$R = c_0 \cdot \frac{t}{2}$$

R = range; c_0 = speed of light in vacuum; t = time between sent signal & received echo.

Pulse width ~ microsecond.
Pulse repetition time (PRT) ~ milliseconds.

- http://www.radartutorial.eu/01.basics/Distance-determination.en.html



Rotation time ~ s.
Azimuth ~ °.

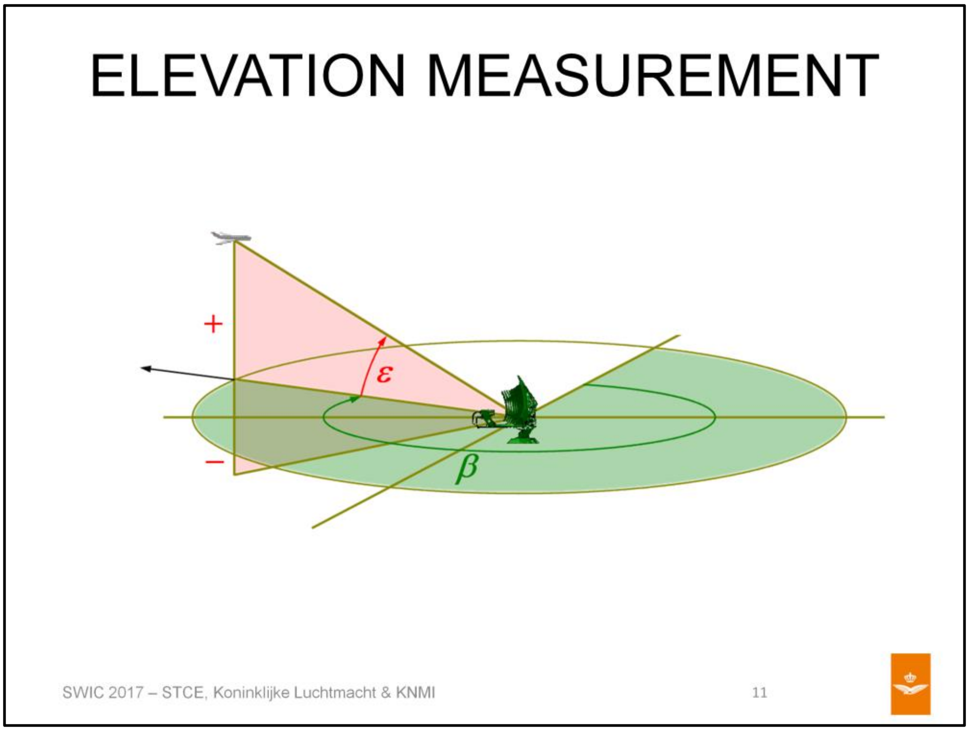
Hits per scan: Td/PRT.

Dwell time: Td = beam width / (360 * RPM/60).

RPM: rotations per minute.

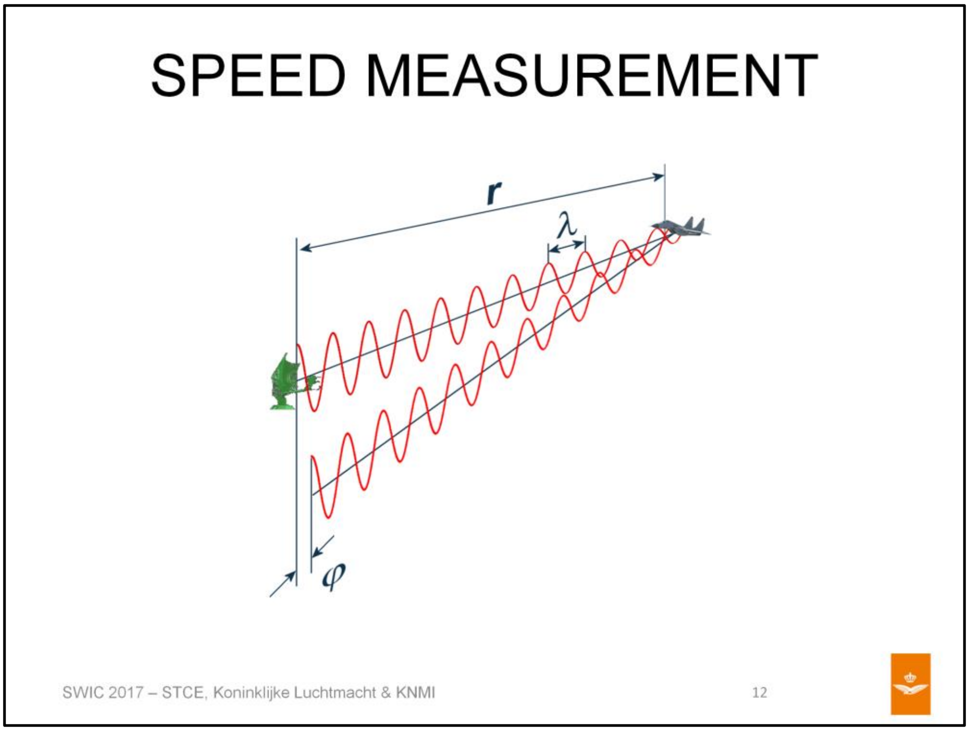
Q: how many hits does the radar receive from the aircraft if the PRT = 1ms, the horizontal beam width = 1° and the RPM = 15? A: 1/90 / 0,001 = 11.

- http://www.radartutorial.eu/01.basics/Direction-determination.en.html



Same story as azimuth. If heigth is not important the beam width in the vertical could be as large as tens of degrees (15 – 30°).

- http://www.radartutorial.eu/01.basics/Measurement%20of%20the%20elevation%20angle.en.html



Moving targets change the frequency of the emitted pulse (~GHz) by a Doppler shift (~Hz). This change is too small to be easily detected. That's why the phase shift (ϕ) is used to calculate the speed of the moving target.

- http://www.radartutorial.eu/11.coherent/co06.en.html
- http://www.radartutorial.eu/11.coherent/co07.en.html

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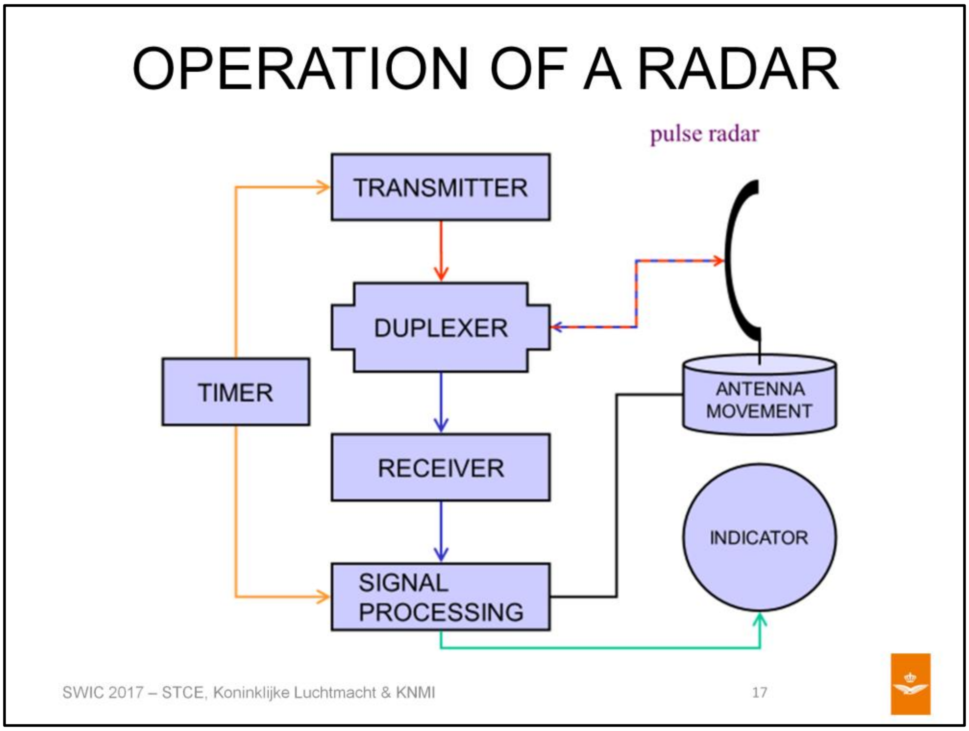
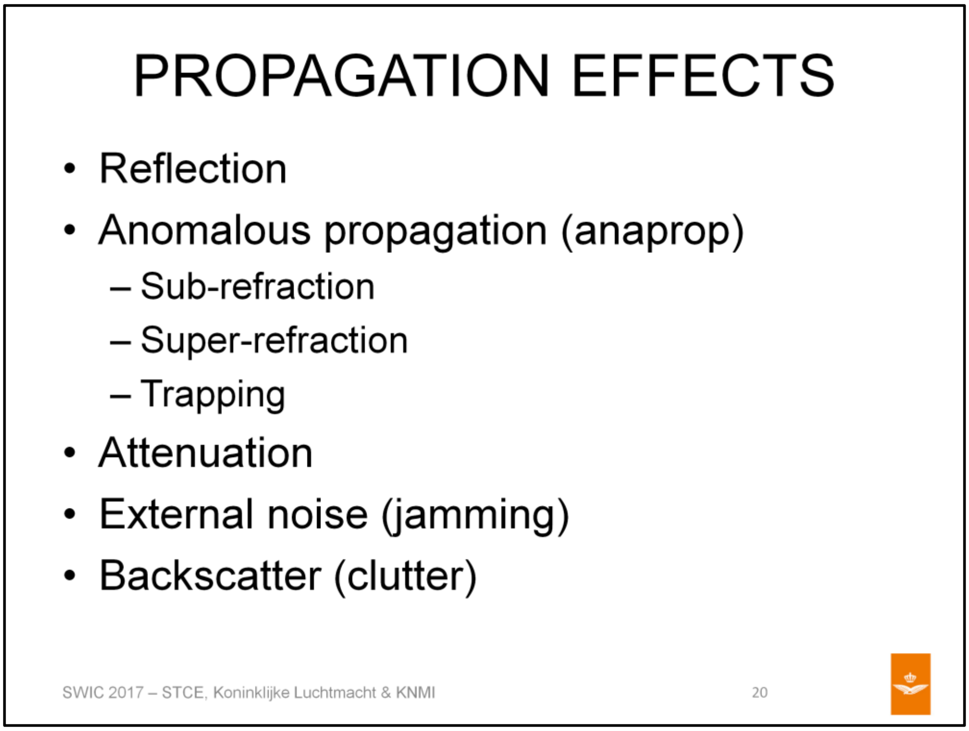


- Charles Tempelman
- Christian Wolff (radartutorial.eu)



As pulses leave the radar antenna and travel through space, they are subject to all kinds of propagation effects. Remember there are many phenomena that affect the propagation of radar waves. SPWX is a minor contributor, artificial and earth-based sources are major contributors.

- Reflection = forward scattering (don't forget to mention the reflection of the target itself!)
- Anaprop (major atmospheric issue)
    - Sub
    - Super (also in the ionosphere!)
    - Ducting
- Attenuation (minor issue)
- External noise
    - Intentional (jamming)
    - Natural (SRB)
- Backscatter/clutter (also in the ionosphere: Radar Auroral Clutter (RAC))

- Merrill Skolnik (Ch. 8)
- http://www.radartutorial.eu/11.coherent/co04.en.html
- http://www.radartutorial.eu/16.eccm/ja09.en.html

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RADAR EQUATION

$$R_{max} = \left[\frac{P_t \cdot G^2 \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot S_{min} \cdot L}\right]^{1/4}$$

$$L = L_{int} \cdot L_{refl} \cdot L_{atm}$$

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Bridge between ‘Block diagram’ & ‘Specifications’. The radar equation elegantly shows the most important aspects of radar technology.

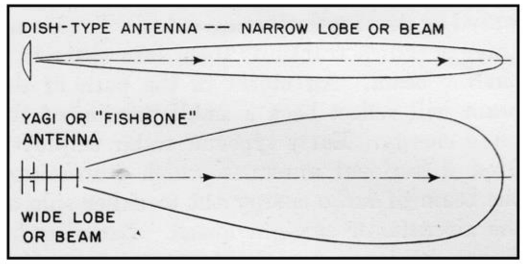
R_{max} = maximum detectable range
P_t = transmitted power
G = antenna gain [Remember: antenna gain is directly related to its directivity.]
λ = wavelength
σ = radar cross section
S_{min} = minimum detectable signal
L = losses

L_{int} = internal losses
L_{refl} = reflection losses
L_{atml} = atmospheric losses

[G^2 * λ^2 = Gt * Ar = Gt * Gr * λ^2 = G * G * λ^2 (want Gr = Gt)]

KEY SPECIFICATIONS OF RADAR

- Power (P_t)
- Gain (G)
  - Effective area (A_e)
  - Wavelength (λ)
- Cross section (σ)
- S_{min}
- Losses (L)
  - Internal (L_{int})
  - Reflection (L_{refl})
  - Atmospheric (L_{atm})



@ Power: mW (speed control) – 10W (civilian marine) – 100W (ATC) – kW (military). These are average powers.

@ Gain: G = 4*pi*A_e/λ^2. Big antennas at short wavelengths have high gains (G~50dBi). High gain antennas are highly directional and have small beam widths. A_e = effective aperture: a measure of how effective an antenna is at receiving the power of radio waves.

@ σ: stealth objects deflect and absorb radar energy thereby generating a small σ and hence a low reflectivity.

@ S_{min}: 1. rewrite the radar equation and remember 1SFU ≡ 10^{-22}W/m^2/Hz; 2. S_{min} ~1pW (military) ≡ 10log($10^{-12}/10^3$) = -150dB; 3. Mention digital processing; 4. mention substrobe recording (digitial radar correct for the sun automatically).

@ L: Internal = losses in the transmission lines, antennas and signal processes; Reflection = fluctuation loss, the loss due to changes in perceived radar cross section (RCS); Atmospheric = losses due to anaprop, relection & absorption.

RADAR EQUATION INVERTED

$$S_{min} = \frac{P_t \cdot G^2 \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot {R_{max}}^4 \cdot L}$$

Calculate S_{min} and compare to a strong SRB.

Assume: G=1; λ=1; σ=1; L=1; R_{max}=500km.

EAR VS RADAR

EAR	RADAR
CALL LOUDER	USE MORE POWER
USE A HORN	DIRECT BEAM
HANDS BEHIND EARS	BIGGER ANTENNA
SENSITIVE EARS	PROPER FILTERS
TALK SLOWLY	BIGGER PULSE WIDTH
REPEAT WORDS	PULSE INTEGRATION
TILES VS CURTAINS	BIGGER CROSS SECTION

The first Dutch radars were called ‘hoortoestellen’, as they heard (hoor) the noise of the aircraft (toestellen). Though radar doesn’t work with sound waves, there are many similarities between sound waves and electromagnetic waves. See the table. All parameters play a role in the maximum detecting range of a radar.

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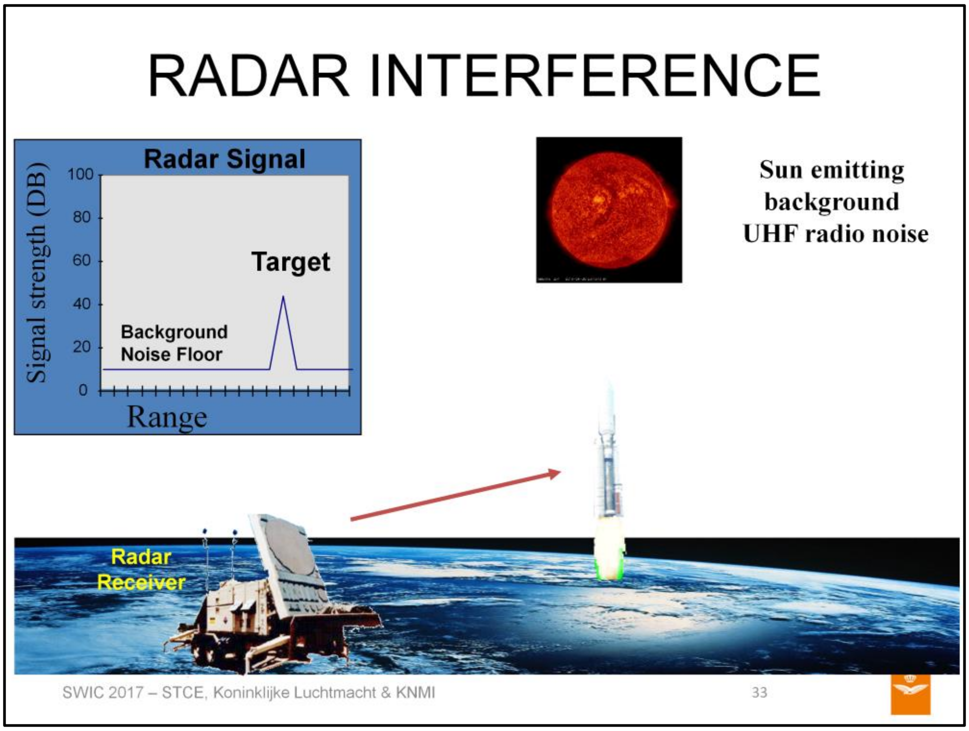
SPWX IMPACT: SRB

- Radar interference:
  - Lasts from a few minutes to hours
  - Generally the larger the flare, the greater intensity of the radio burst
  - Only affects the **sun-lit side of the earth**
  - Radio bursts directly interfere with the radar signals, causing false returns or false targeting

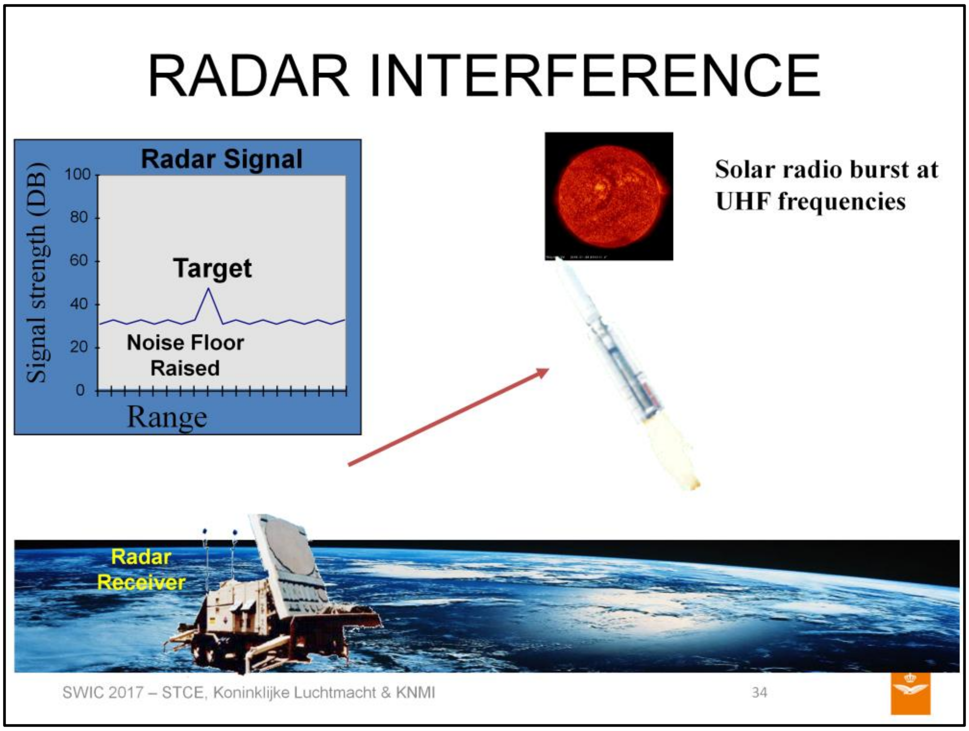
SRB are associated with flares & CMEs. If they are strong enough, they are able to jam/interfere with a radar. Especially the far looking radars, as these are more sensitive. After all, the detecting threshold of the receiver ~ 1/R^4.

Don't forget there are many other (artificial) sources that might cause inteference, e.g. jamming.

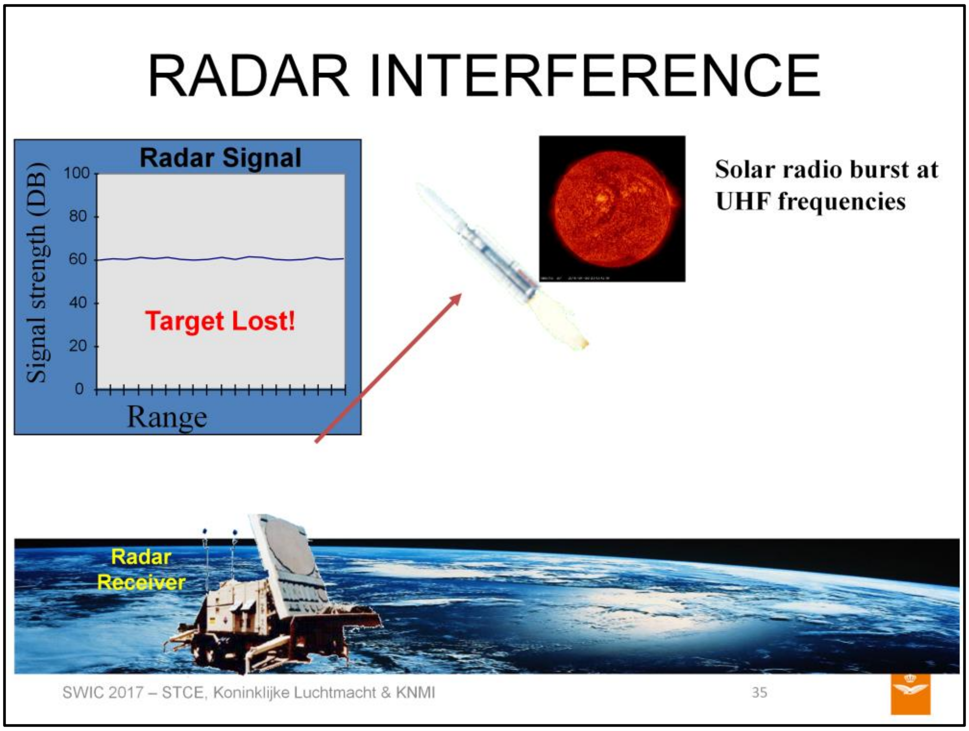
Receive systems are designed to include protective circuitry between the antenna and receiver to filter out off-frequency signals. This prevents or limits interference, desensitization, or burnout. Electromagnetic interference can be reduced or eliminated by using various suppression techniques. The amount of EMI that is produced by a radio transmitter can be controlled by limiting bandwidth, and using electronic filtering networks and metallic shielding. Depending upon the system, these protective devices may include filters, multicouplers, preselectors, and so forth. These devices can minimize interference caused by inadequate frequency separation or poor physical isolation between transmit and receive antennas.



Radio bursts can cause the amount of radio wave energy emitted by the sun to increase dramatically over certain Very High Frequencies (VHF) and Super High Frequencies (SHF). This can produce direct radio frequency interference on missile detection or space tracking. In this example a radar receiver is tracking a missile with normal background conditions.



A small radio burst affects transmission of radar frequency causing some noise but no severe effects.



Severe radio bursts can cause the radar receiver to loose track of the missile.

THREE CASES

– 1942
– 1967
– 2015

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@ 1942: discovery of SRB
@ 1967: on the brink of a nuclear war
@ 2015: ATC lost control

- http://www.spaceacademy.net.au/library/notes/firstsolburst.htm
- https://news.agu.org/press-release/1967-solar-storm-nearly-took-us-to-brink-of-war/
- https://www.lfv.se/en/news/news-2016/full-capacity-after-90-minutes-radar-loss

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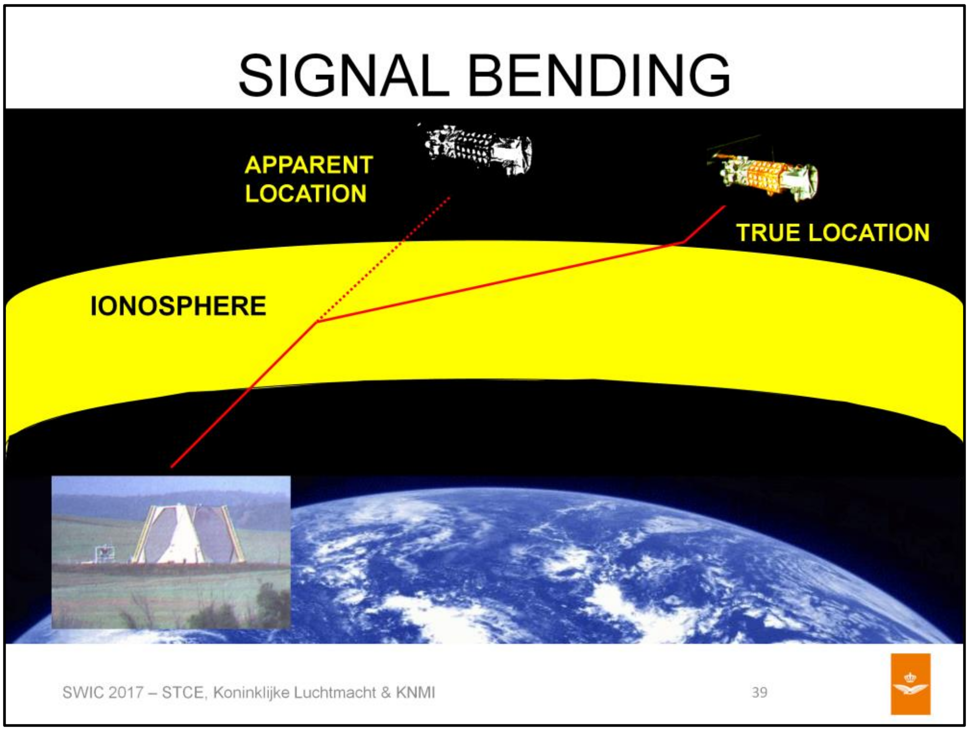
SPWX IMPACT: IONOSPHERIC REFRACTION

- Signal bending:
  - Caused by TEC gradients
  - Associated with geomagnetic storms
  - Mainly affects the night side of the earth

TEC gradients in the ionosphere cause refraction of radar beams looking to or from space. Think of Space Object Tracking (SOT), Ballistic Missile Defense (BMD) and satellite based radars for remote sensing or surveillance.

If radar is disturbed by the ionosphere, we can use it to assess the ionosphere too. EISCAT: radar observations of the ionosphere.

- https://en.wikipedia.org/wiki/EISCAT



The presence of free electrons in the ionosphere causes UHF and SHF radio waves from missile detection and space track radars to be bent (or refracted), as well as slowed (or retarded) somewhat from the speed of light. These effects will produce unacceptable errors in target bearing and range. The bearing (or direction) error is caused by signal bending, while the range (or distance) error is caused by both a longer path length for the refracted signal and a slower signal speed. (NOTE: For range errors, the effect of longer path length dominates for UHF signals, while slower signal speed dominates for SHF signals.)

Radar operators routinely try to compensate for these errors by applying correction factors derived from the predicted ionospheric Total Electron Content (TEC) along the radar beam's path. These TEC values are based on time of day, season, and the overall level of solar activity. Unfortunately, individual solar and geophysical events will cause unanticipated, short-term variations from the predicted TEC values and correction factors. These variations (which may be either higher or lower than anticipated values) will lead to inaccurate position determinations or difficulty in acquiring targets. Real-time warnings when significant TEC variations are occurring help operators minimize the impacts of their radar's degraded accuracy.

These bearing and range errors caused by refraction and signal retardation **also affect space-based surveillance systems**. For example, a space sensor trying to lock on to a ground radio emitter may experience a geolocation error.

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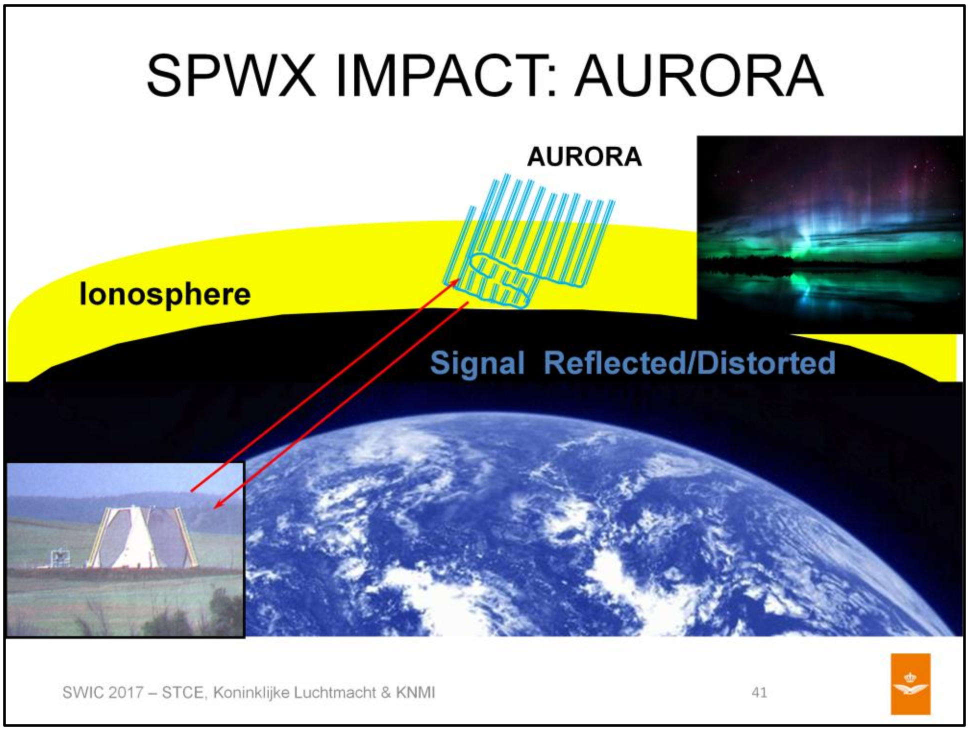
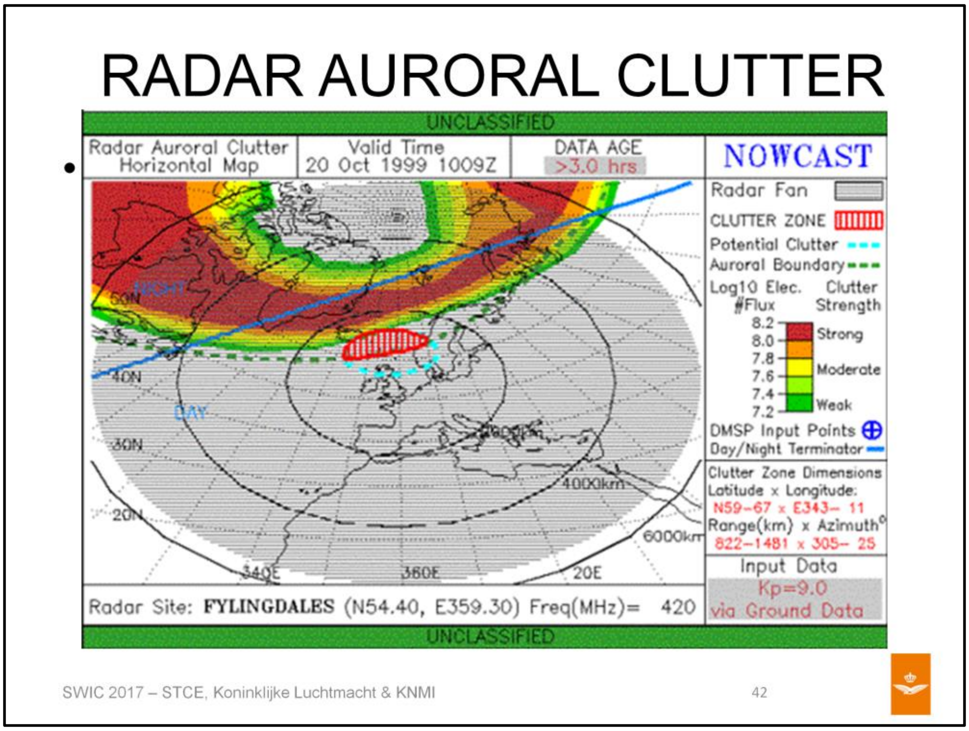


Pulsed radar echoes backscatter from irregular plasma structures. This can cause abnormal radar signal back-scatter on poleward looking radars.
This happens at the aurora and is called Radar Auroral Clutter (RAC). Systems experience clutter, noise and interference in radar returns when the signal is incident on or passes through the aurora. RAC can produce false targets & tracks. The effect is most noticable when radar beam and geomagnetic field lines are perpendicular.



Eliminating the clutter is not feasible: operators identify and map the RAC as part of their SSA.

Remember: RAC is also an issue for space based radars looking to earth.

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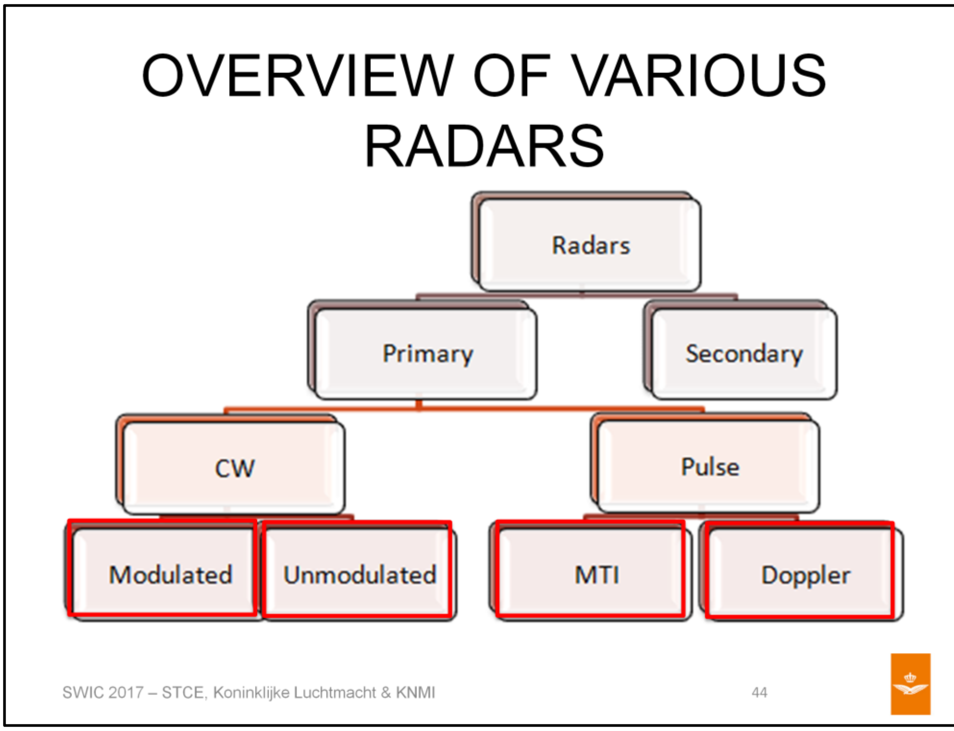

Primary: send & receive echo. Secondary: send & receive autonomous broadcast.

Modulated CW (Continuous Wave) is for range measuring (like heigth). Unmodulated CW only for velocity measuring by Doppler.

Pulse radar is typically for range measuring: military, ATC, meteorology, remote sensing.

MTI (Moving Target Indicator) was invented to get rid of ground clutter. It operates analog, old fashioned and after demodulation. Used until the 70’s. Uses (reverse) phase shift of the Doppler shifted reflection. **Low PRF**.

Doppler: same as MTI, though modern and before demodulation. Also uses the phase shift of the Doppler shifted reflection. **High PRF**.

Difference MTI/Doppler: different techniques to distinguish moving targets from non-moving clutter and different PRF.

Left: former LVNL surveillance radar @ Herwijnen. Will be replaced by the SMART-L (ELR?).

Right: former LVNL secondary surveillance radar. Recently replaced by a weather radar from the KNMI.

AIR TRAFFIC CONTROL

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MASS: Military Approach Surveillance System (MASS). 5 sensors over air bases NL. Primary (Raytheon ASR-10SS Mk II) & secondary (Cossor Condor Mk 2S Mode-S).

Primary: dual beam (high & low). S-band (2,7GHz).

Secondary: mono pulse. Large vertical aperture (small cone of silence). Interrogation @ 1030MHz / response @ 1090MHz.

WEATHER

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Pulse Doppler radar. ~ S-band. 100’s km. Uses solar radiation for alignment (!).

- https://nl.wikipedia.org/wiki/Weerradar
- https://en.wikipedia.org/wiki/Weather_radar

WEATHER

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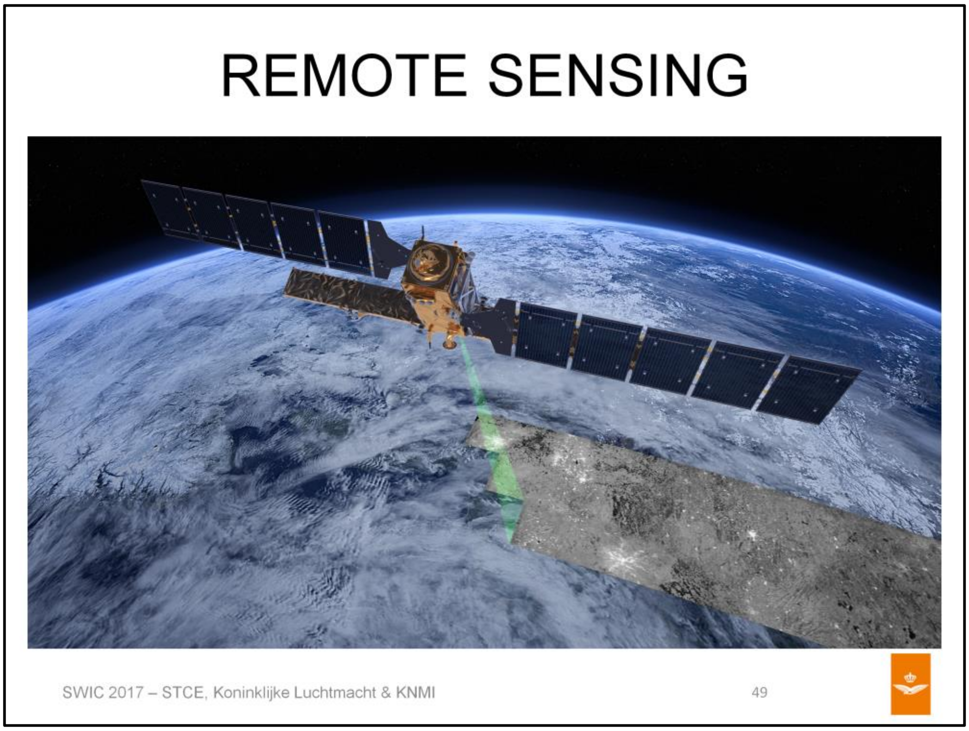
Cougar helicopter weather radar.

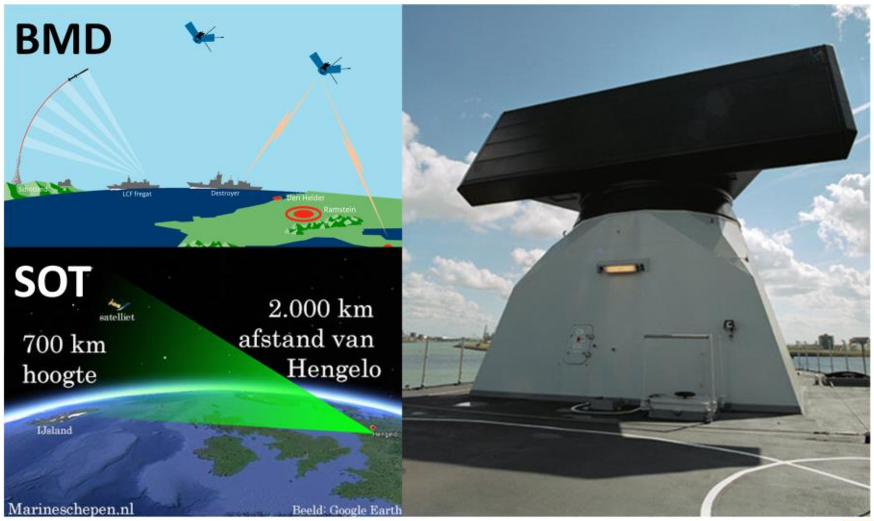
Honeywell Bendix/King RDR1400C.



Sentinel-1: C-band.

- https://en.wikipedia.org/wiki/European_Remote-Sensing_Satellite
- https://en.wikipedia.org/wiki/SAR-Lupe
- http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-1/Instrument

MILITARY



SMART-L ELR: BMD/EWC & SOT
L-band

- https://en.wikipedia.org/wiki/SMART-L
- http://marineschepen.nl/nieuws/Radar-Thales-ziet-satelliet-120916.html

CRC PSR + IFF (secondary)
S-band (2,7 – 2,9 GHz)
3D: multi beam radar (multiple feed horns)

AOCS Nieuw Milligen + RPN (“Bandbox”)
Control and Reporting Center (CRC)
Medium Power Radar (MPR)
Thomson CSF ARES 3D

MILITARY

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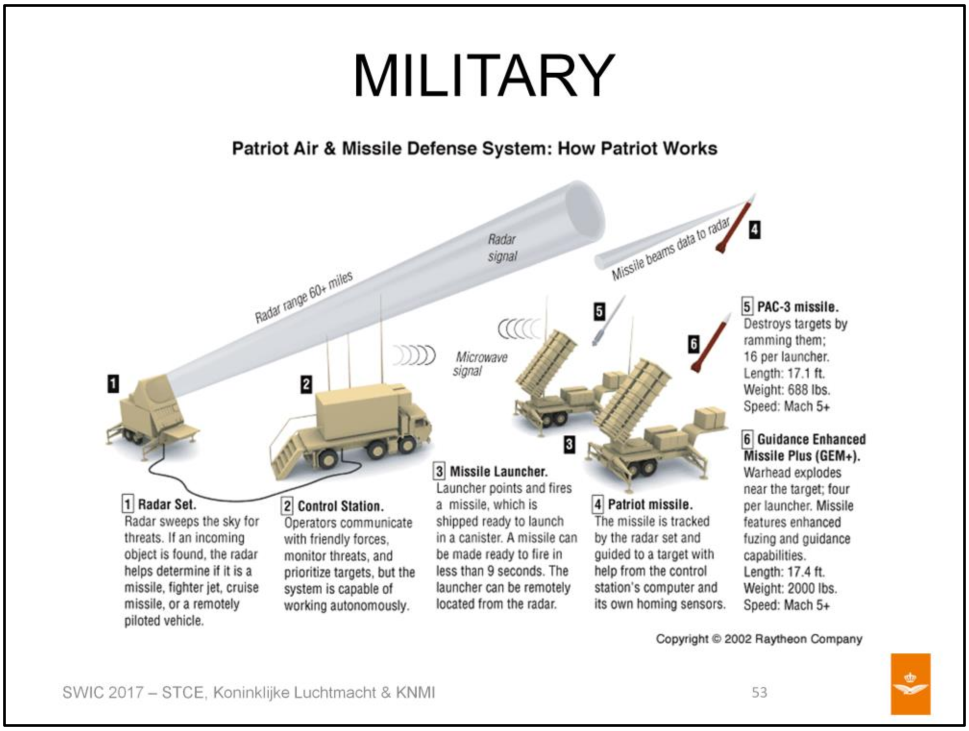
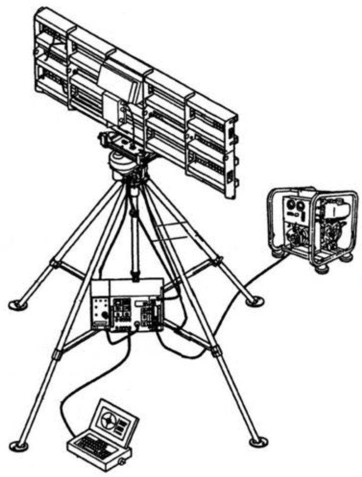
Electronical vertical scan, mechanical azimuth → 3D. ~S-band.
Airborne Warning and Control Station (AWACS)
AN/APY-2



Patriot Radar = **P**hased **A**rray **TR**acking to **I**ntercept **O**f **T**arget
~C-band (~5GHz)
Radar Set (RS) en Launcher Station (LS)
Raytheon AN/MPQ53 + TPX-46(V)1
Raytheon AN/TSM-165

MILITARY



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Stingerteam radar TDAR (WALS)
Lear Astronics AN/UPS-3 + SB-16H4

MILITARY

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F16 radar
FCR = Fire Control RADAR Surveillance mode, Tracking Mode
F16 radar
Northrop Grumman APG-66V2

MILITARY

RANGE &TRACK RATE

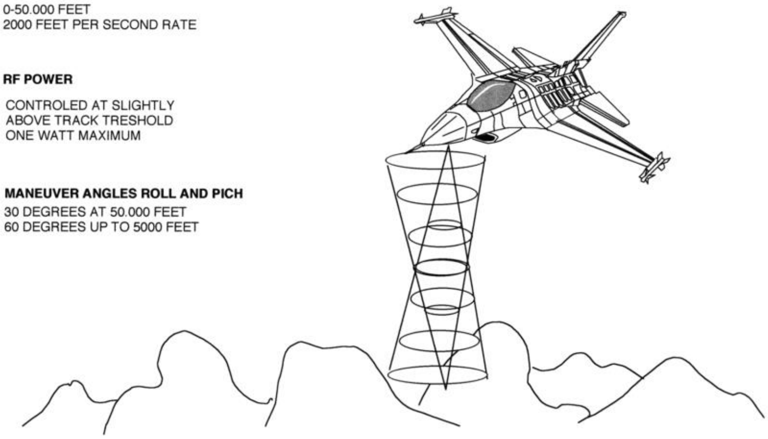
0-50.000 FEET
2000 FEET PER SECOND RATE

RF POWER

CONTROLED AT SLIGHTLY
ABOVE TRACK TRESHOLD
ONE WATT MAXIMUM

MANEUVER ANGLES ROLL AND PICH

30 DEGREES AT 50.000 FEET
60 DEGREES UP TO 5000 FEET



COMBINED ALTITUDE RADAR ALTIMETER

SUMMARY

- SPWX impact on radar is caused by:
  - Solar Radio Bursts (SRB)
  - Ionospheric gradients & aurora
- And dependant on the radar's:
  - Elevation, azimuth & beam width
  - Frequency & sensitivity
  - Circuitry & software