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Radar Fundamentals

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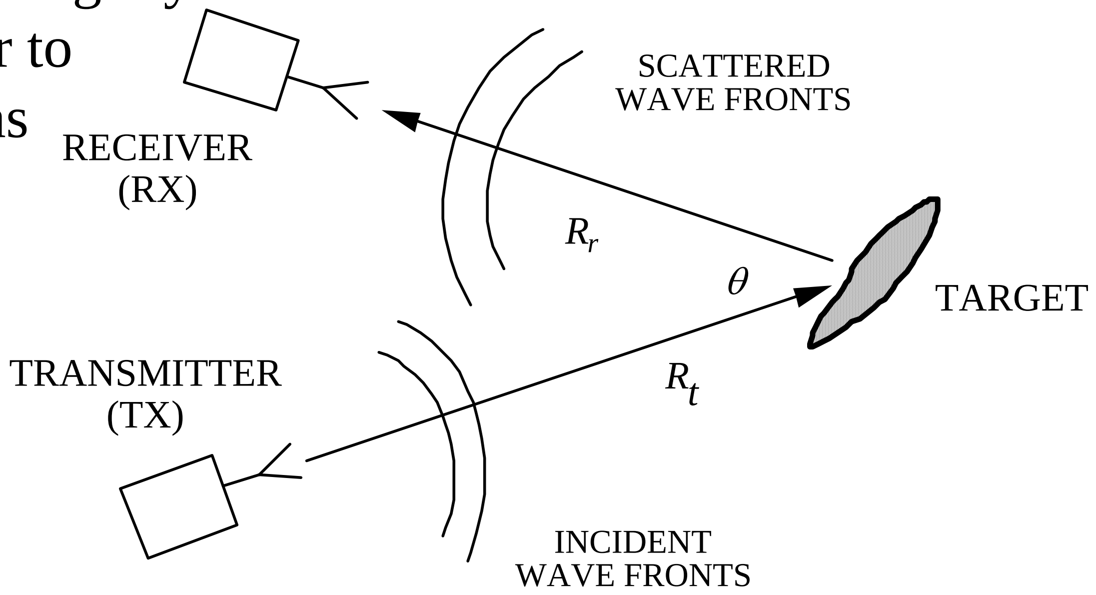
Overview

- Introduction
- Radar functions
- Antennas basics
- Radar range equation
- System parameters
- Electromagnetic waves
- Scattering mechanisms
- Radar cross section and stealth
- Sample radar systems

Radio Detection and Ranging

- Bistatic: the transmit and receive antennas are at different locations as viewed from the target (e.g., ground transmitter and airborne receiver).
- Monostatic: the transmitter and receiver are colocated as viewed from the target (i.e., the same antenna is used to transmit and receive).
- Quasi-monostatic: the transmit and receive antennas are slightly separated but still appear to be at the same location as viewed from the target (e.g., separate transmit and receive antennas on the same aircraft).



Radar Functions

- Normal radar functions:
    1. range (from pulse delay)
    2. velocity (from Doppler frequency shift)
    3. angular direction (from antenna pointing)
- Signature analysis and inverse scattering:
    4. target size (from magnitude of return)
    5. target shape and components (return as a function of direction)
    6. moving parts (modulation of the return)
    7. material composition
- The complexity (cost & size) of the radar increases with the extent of the functions that the radar performs.

Electromagnetic Spectrum

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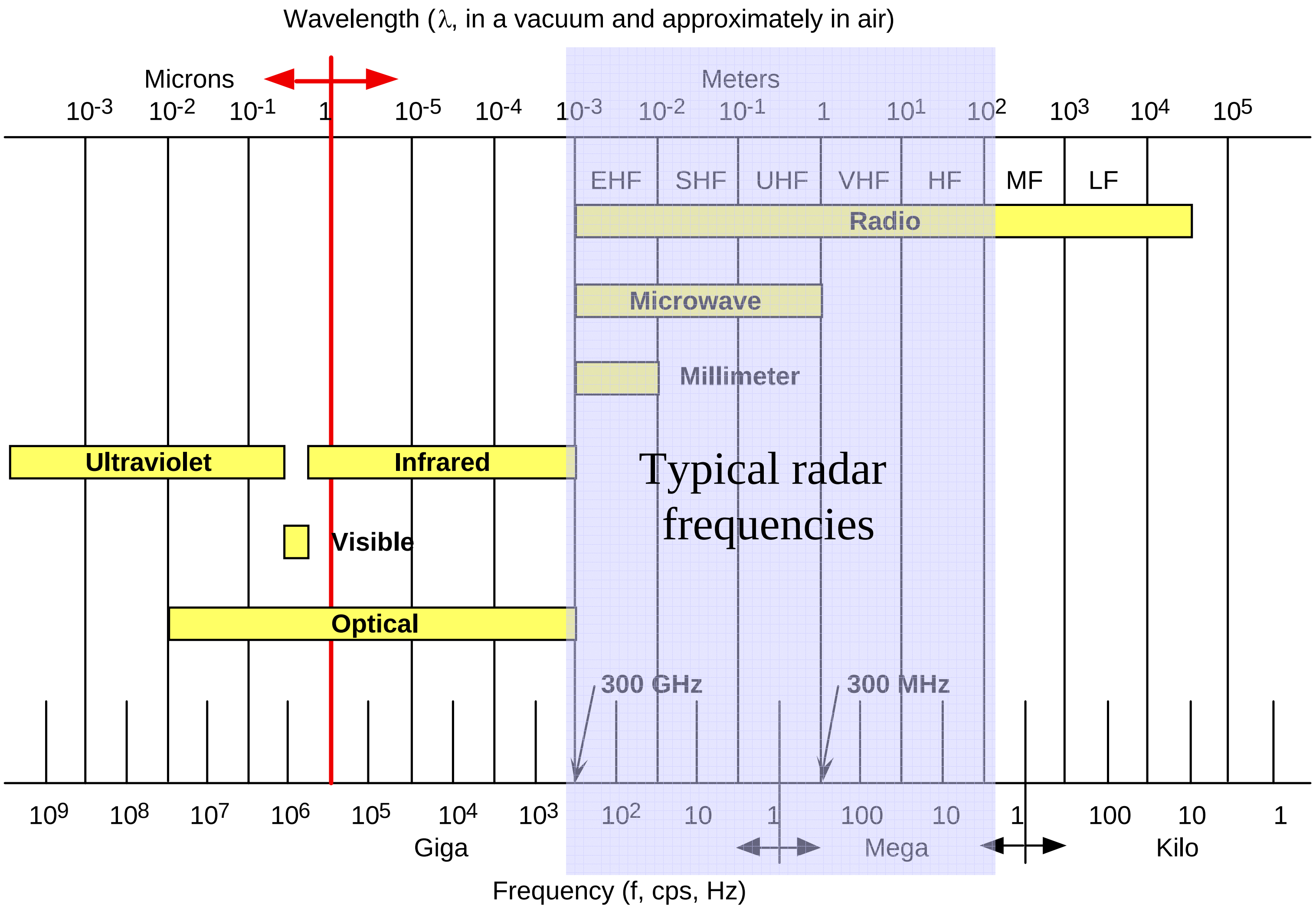
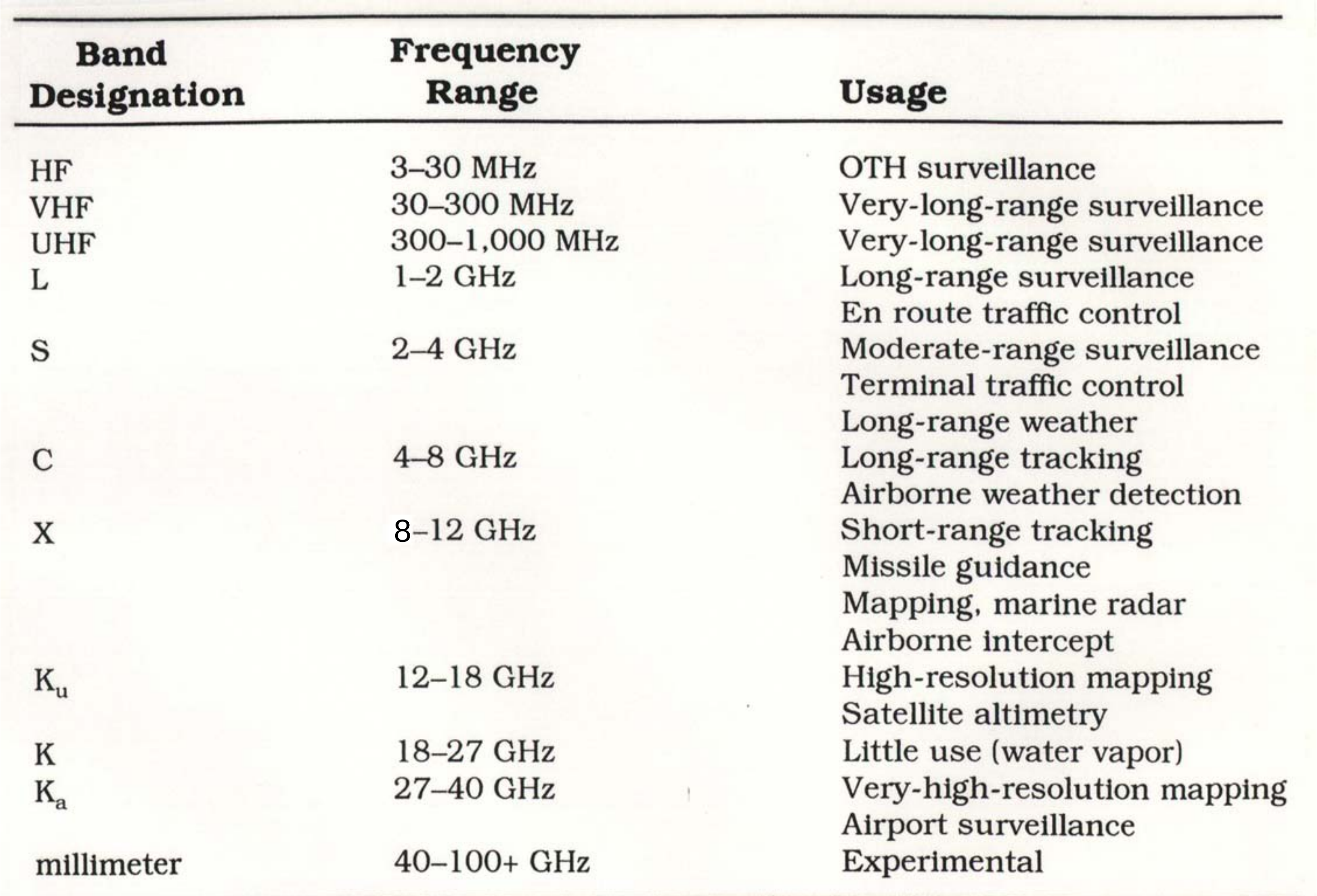


Radar Bands and Usage



Band Designation	Frequency Range	Usage
HF	3–30 MHz	OTH surveillance
VHF	30–300 MHz	Very-long-range surveillance
UHF	300–1,000 MHz	Very-long-range surveillance
L	1–2 GHz	Long-range surveillance En route traffic control
S	2–4 GHz	Moderate-range surveillance Terminal traffic control Long-range weather
C	4–8 GHz	Long-range tracking Airborne weather detection
X	8–12 GHz	Short-range tracking Missile guidance Mapping, marine radar Airborne intercept
K_u	12–18 GHz	High-resolution mapping Satellite altimetry
K	18–27 GHz	Little use (water vapor)
K_a	27–40 GHz	Very-high-resolution mapping Airport surveillance
millimeter	40–100+ GHz	Experimental

(Similar to Table 1.1 and Section 1.5 in Skolnik)

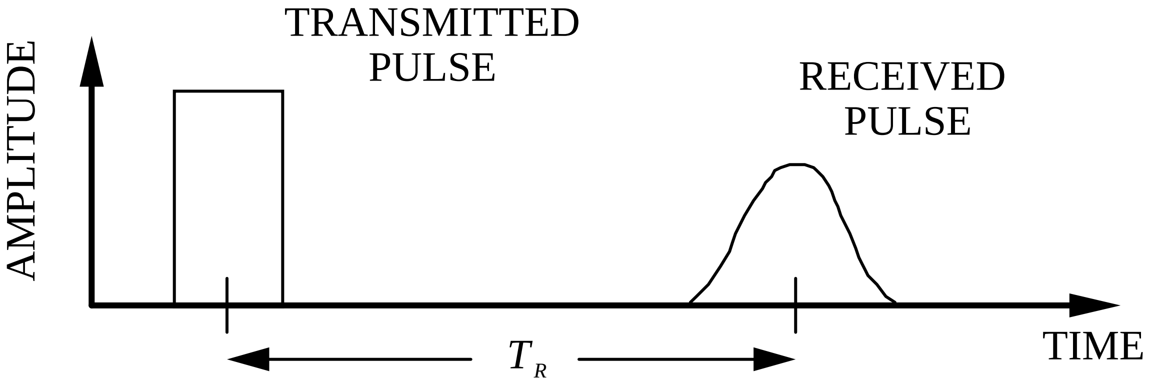
Time Delay Ranging

- Target range is the fundamental quantity measured by most radars. It is obtained by recording the round trip travel time of a pulse, T_R , and computing range from:

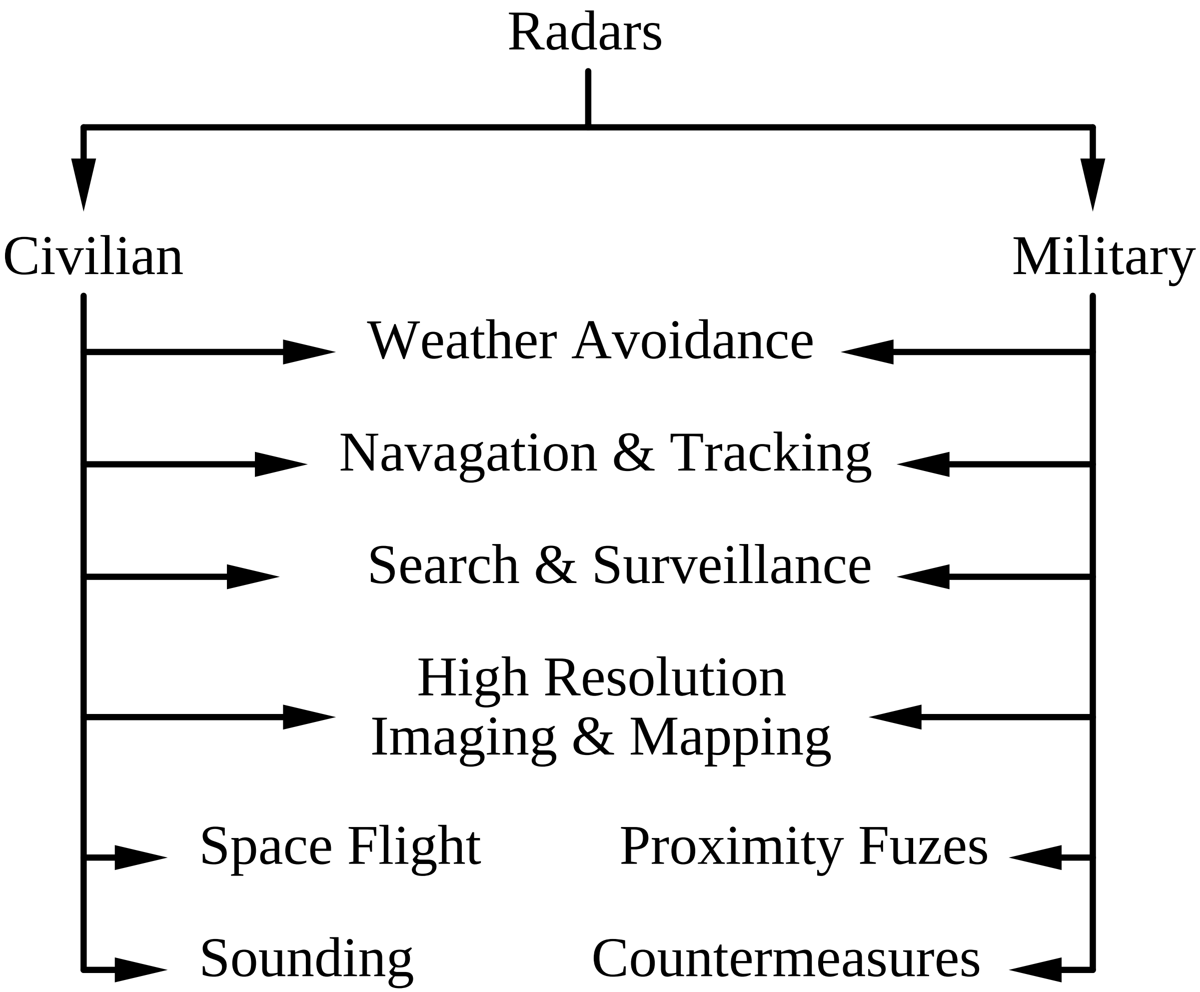
$$\text{Bistatic: } R_t + R_r = cT_R$$

$$\text{Monostatic: } R = \frac{cT_R}{2} \quad (R_t = R_r = R)$$

where $c = 3 \text{x} 10^8$ m/s is the velocity of light in free space.



Classification by Function



Radars

Civilian

Military

Weather Avoidance

Navagation & Tracking

Search & Surveillance

High Resolution
Imaging & Mapping

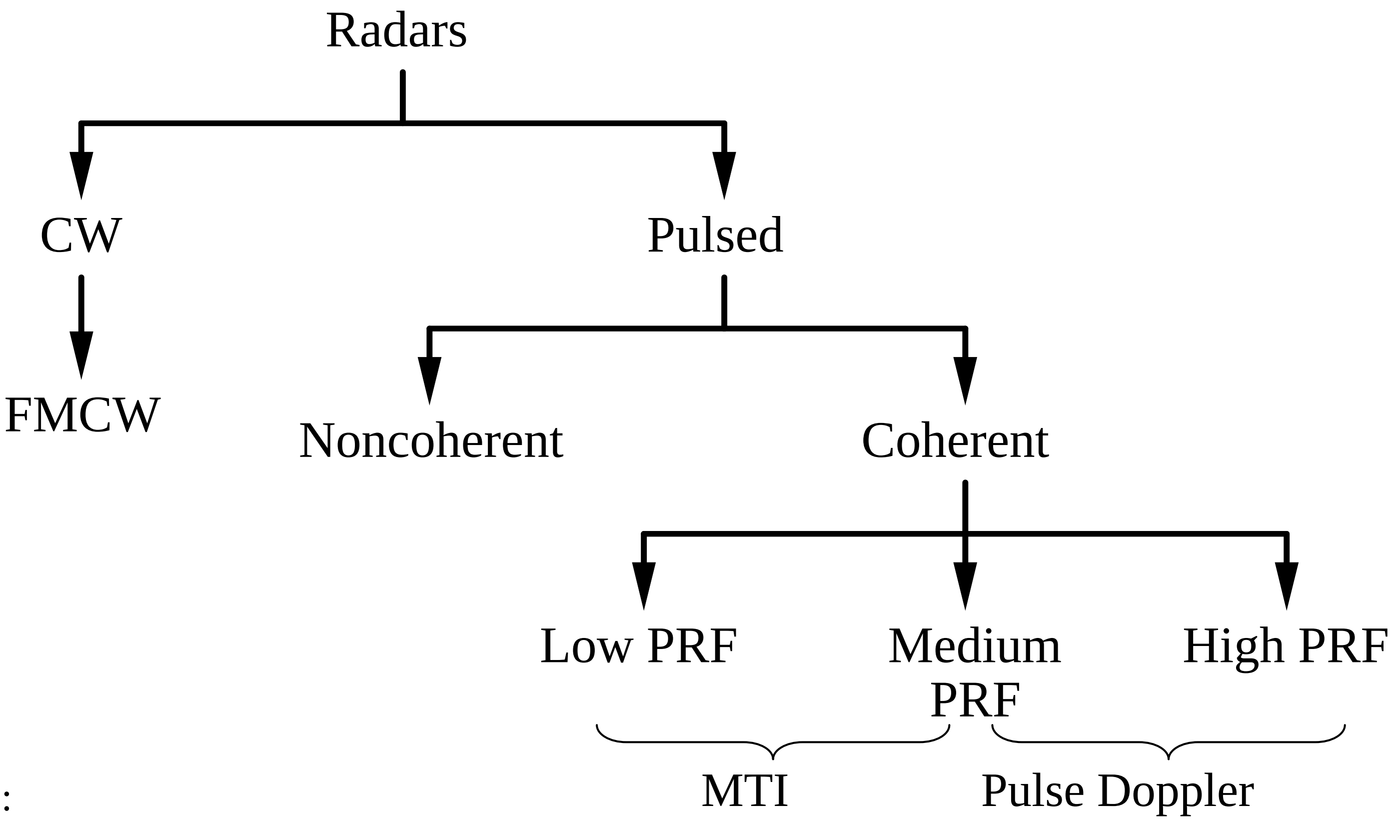
Space Flight

Proximity Fuzes

Sounding

Countermeasures

Classification by Waveform


Radars

CW

FMCW

Pulsed

Noncoherent

Coherent

Low PRF

Medium PRF

High PRF

MTI

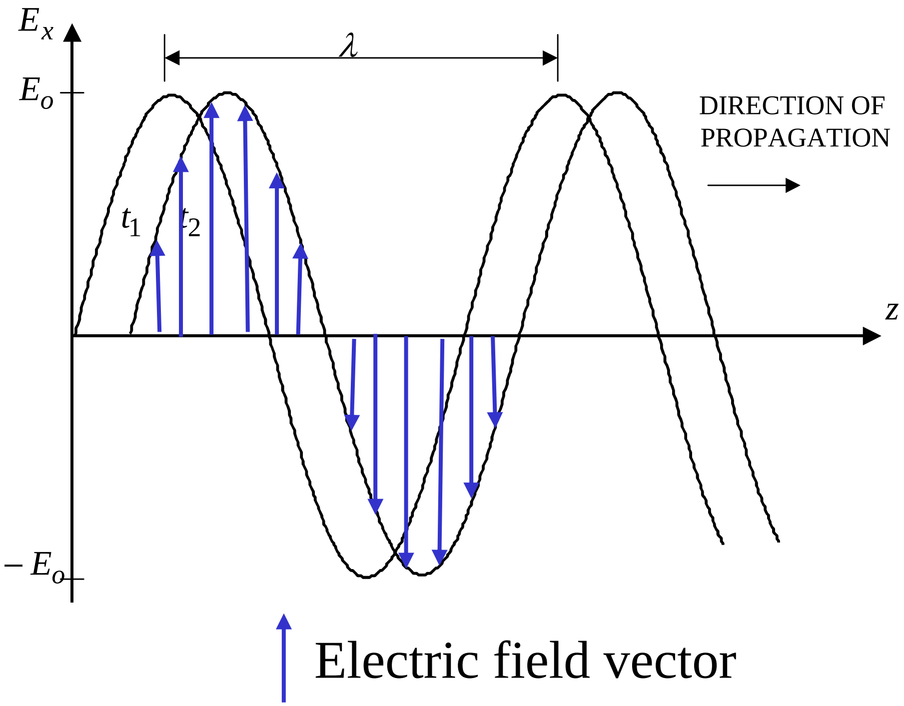
Pulse Doppler

Note:

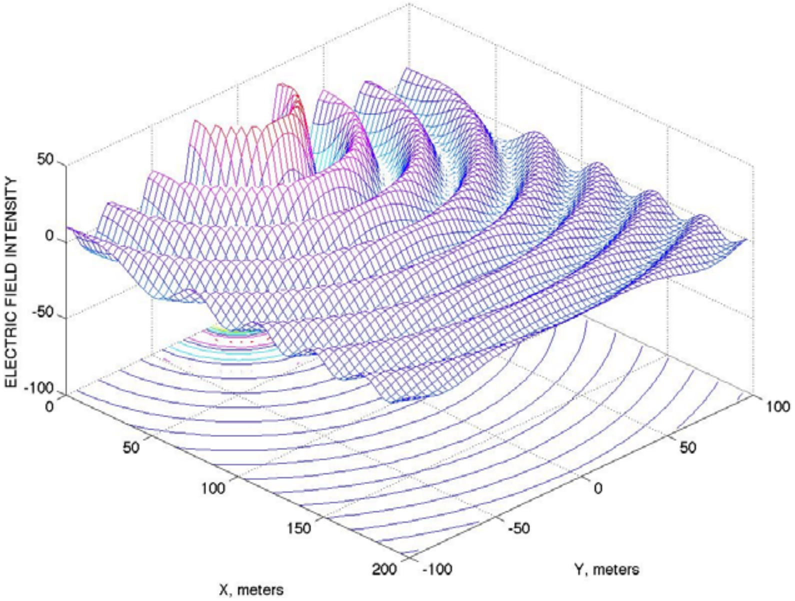
CW = continuous wave
FMCW = frequency modulated continuous wave
PRF = pulse repetition frequency
MTI = moving target indicator

Plane Waves

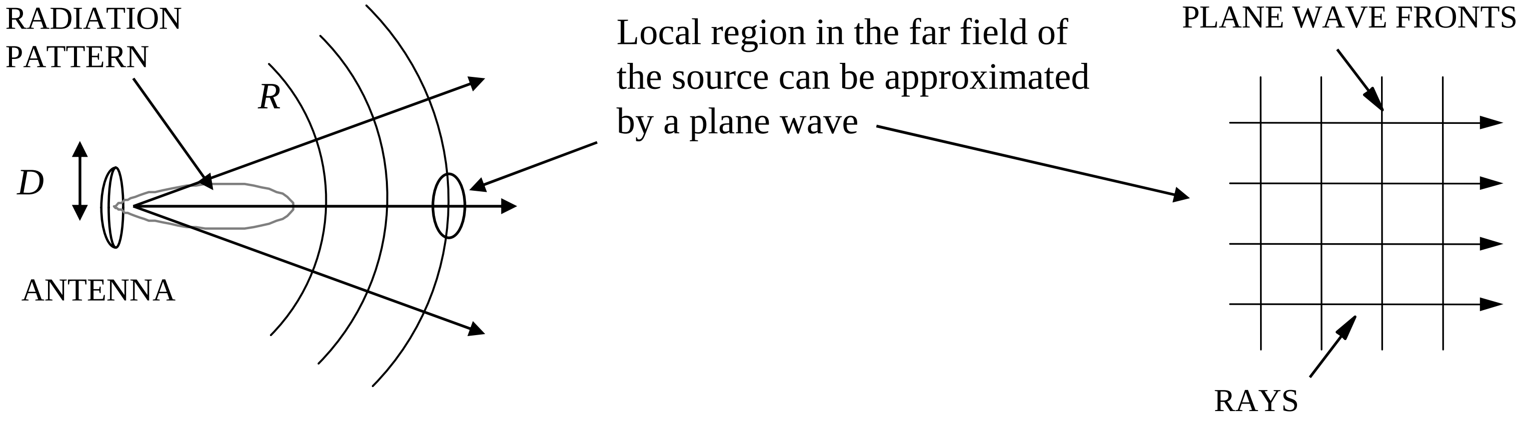
- Wave propagates in the z direction
- Wavelength, λ
- Radian frequency $\omega = 2\pi f$ (rad/sec)
- Frequency, f (Hz)
- Phase velocity in free space is c (m/s)
- x-polarized (direction of the electric field vector)
- E_o, maximum amplitude of the wave



Wavefronts and Rays



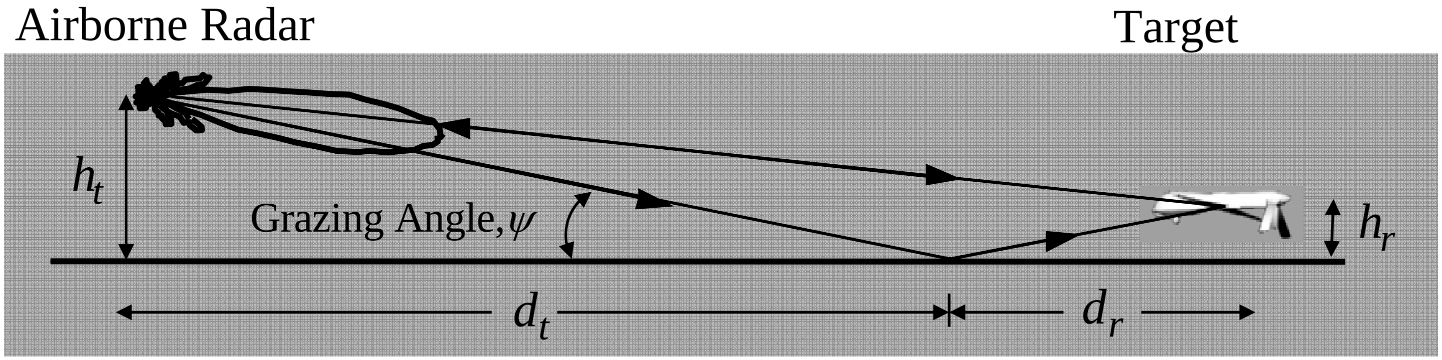
- In the antenna far-field the waves are spherical $(R > 2D^2/\lambda)$
- Wavefronts at large distances are locally plane
- Wave propagation can be accurately modeled with a locally plane wave approximation



Local region in the far field of the source can be approximated by a plane wave

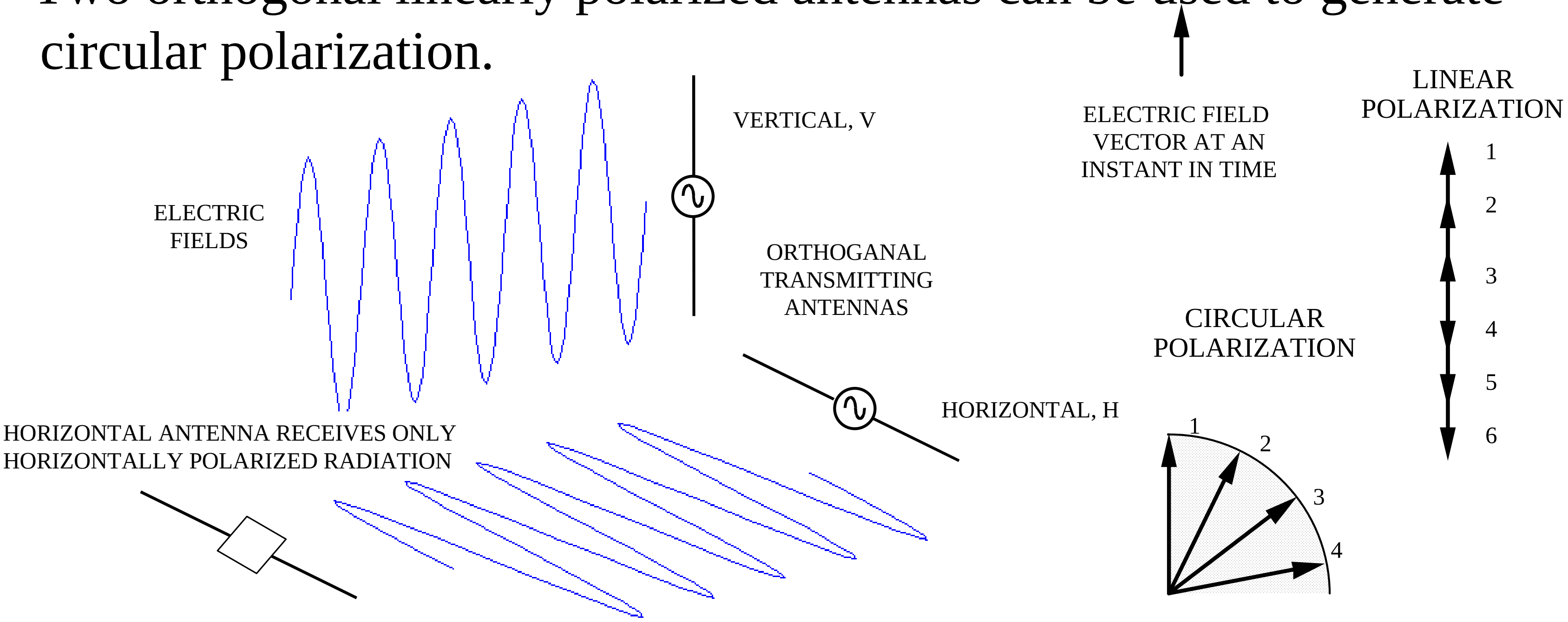
Superposition of Waves

- If multiple signal sources of the same frequency are present, or multiple paths exist between a radar and target, then the total signal at a location is the sum (superposition principle).
- The result is <u>interference</u>: constructive interference occurs if the waves add; destructive interference occurs if the waves cancel.
- Example: <u>ground bounce</u> multi-path can be misinterpreted as multiple targets.



Wave Polarization

- Polarization refers to the shape of the curve traced by the tip of the electric field vector as a function of time at a point in space.
- Microwave systems are generally designed for linear or circular polarization.
- Two orthogonal linearly polarized antennas can be used to generate circular polarization.



Antenna Parameters

- Gain is the radiation intensity relative to a lossless isotropic reference.
- Fundamental equation for gain:

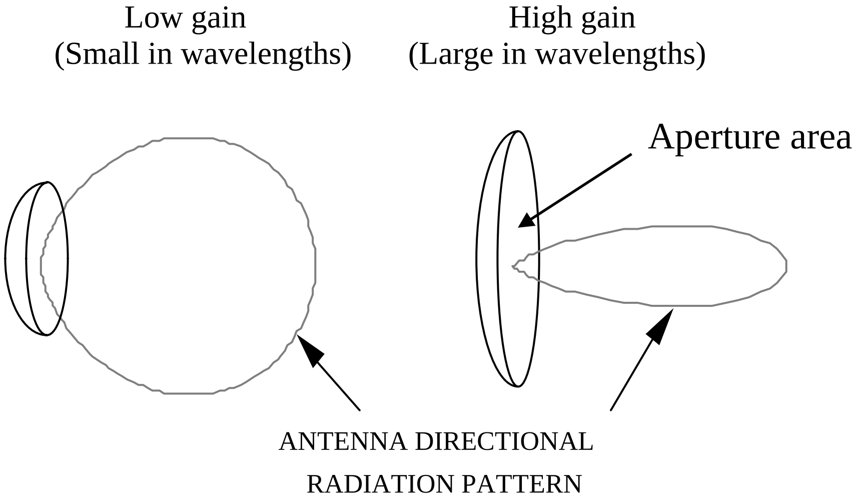
$$G = 4\pi A_e / \lambda^2$$

$$A_e = A\varepsilon, \text{ effective area}$$

$$A = \text{aperture area}$$

$$\varepsilon = \text{efficiency } (0 \le \varepsilon \le 1)$$

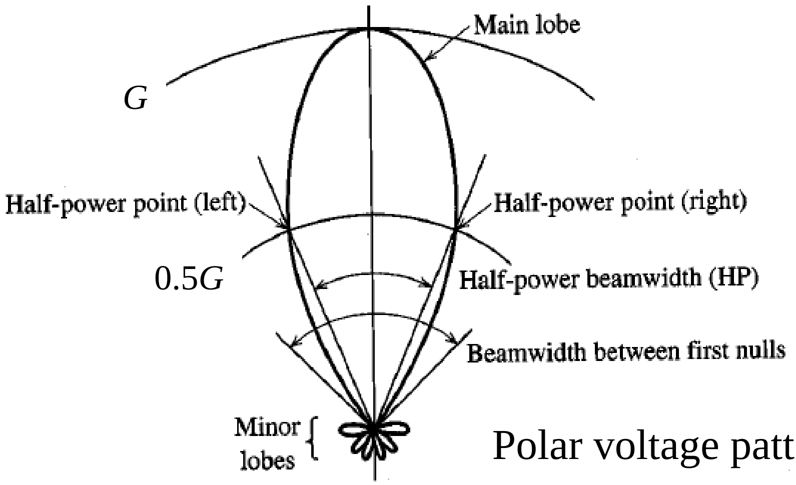
$$\lambda = c / f, \text{ wavelength}$$



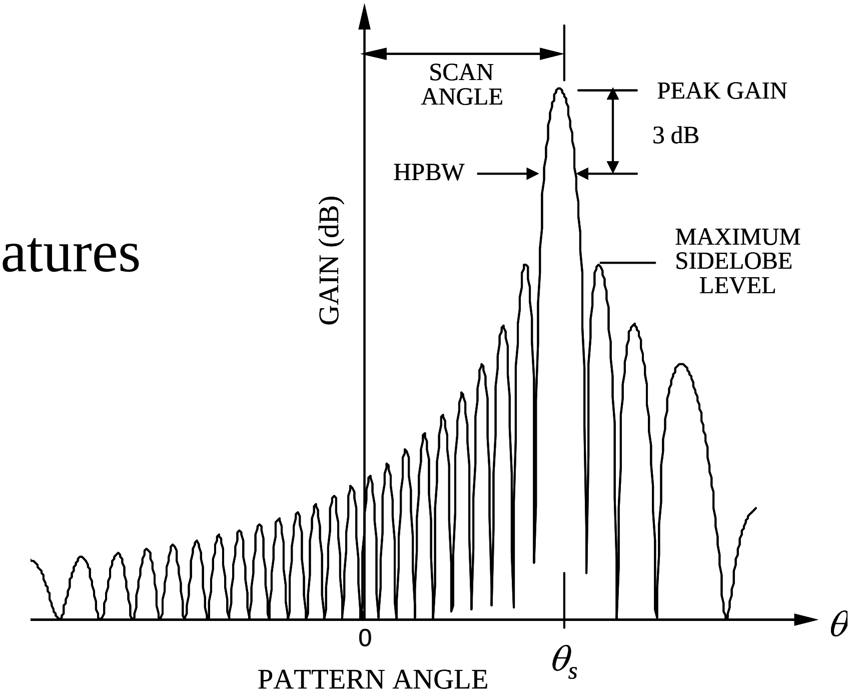
- In general, an increase in gain is accompanied by a decrease in beamwidth, and is achieved by increasing the antenna size relative to the wavelength.
- With regard to radar, high gain and narrow beams are desirable for long detection and tracking ranges and accurate direction measurement.

Antenna Parameters

- Half power beamwidth, HPBW (θ_B)
- Polarization
- Sidelobe level
- Antenna noise temperature (T_A)
- Operating bandwidth
- Radar cross section and other signatures



Polar voltage pattern plot



Rectangular dB pattern plot

Radar Antenna Tradeoffs

- Airborne applications:
  - > Size, weight, power consumption
  - > Power handling
  - > Location on platform and required field of view
  - > Many systems operating over a wide frequency spectrum
  - > Isolation and interference
  - > Reliability and maintainability
  - > Radomes (antenna enclosures or covers)
- Accommodate as many systems as possible to avoid operational restrictions (multi-mission, multi-band, etc.)
- Signatures must be controlled: radar cross section (RCS), infrared (IR), acoustic, and visible (camouflage)
- New antenna architectures and technologies
  - > Conformal, integrated
  - > Digital “smart” antennas with multiple beams
  - > Broadband

Radar Range Equation

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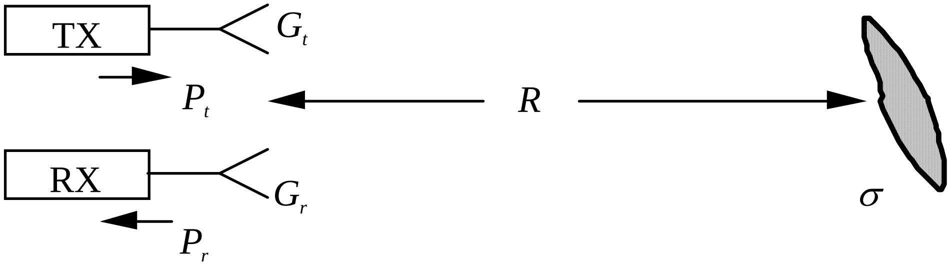
- Quasi-monostatic



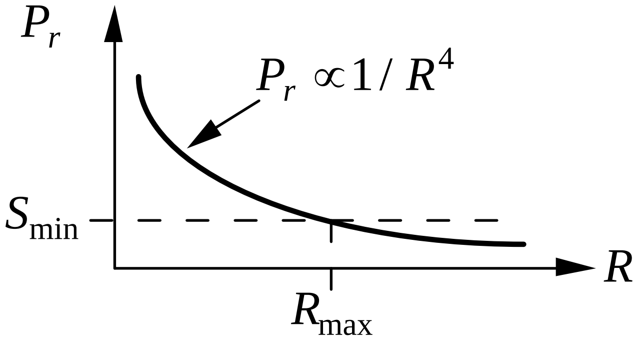
$P_t =$ transmit power (W)
$P_r =$ received power (W)
$G_t =$ transmit antenna gain
$G_r =$ receive antenna gain
$\sigma =$ radar cross section (RCS, m^2)
$A_{er} =$ effective aperture area of receive antenna

$$P_r = \frac{P_t G_t \sigma A_{er}}{(4\pi R^2)^2} = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4}$$

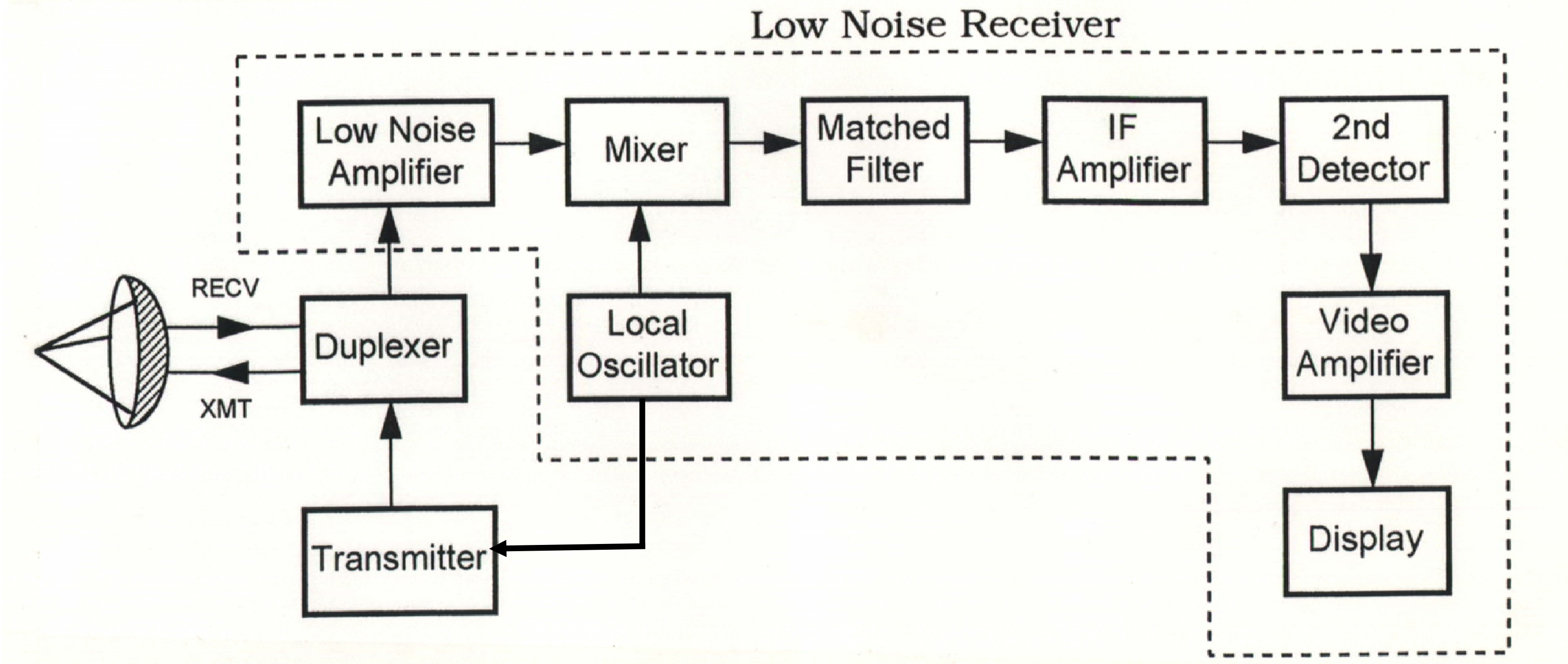
Minimum Detection Range

- The minimum received power that the radar receiver can "sense" is referred to a the minimum detectable signal (MDS) and is denoted $S_{\min}$.
- Given the MDS, the maximum detection range can be obtained:

$$P_r = S_{\min} = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4} \Rightarrow R_{\max} = \left(\frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 S_{\min}} \right)^{1/4}$$



Radar Block Diagram



- This receiver is a <u>superheterodyne</u> receiver because of the intermediate frequency (IF) amplifier. (Similar to Figure 1.4 in Skolnik.)
- <u>Coherent</u> radar uses the same local oscillator reference for transmit and receive.

Coordinate Systems

- Radar coordinate systems

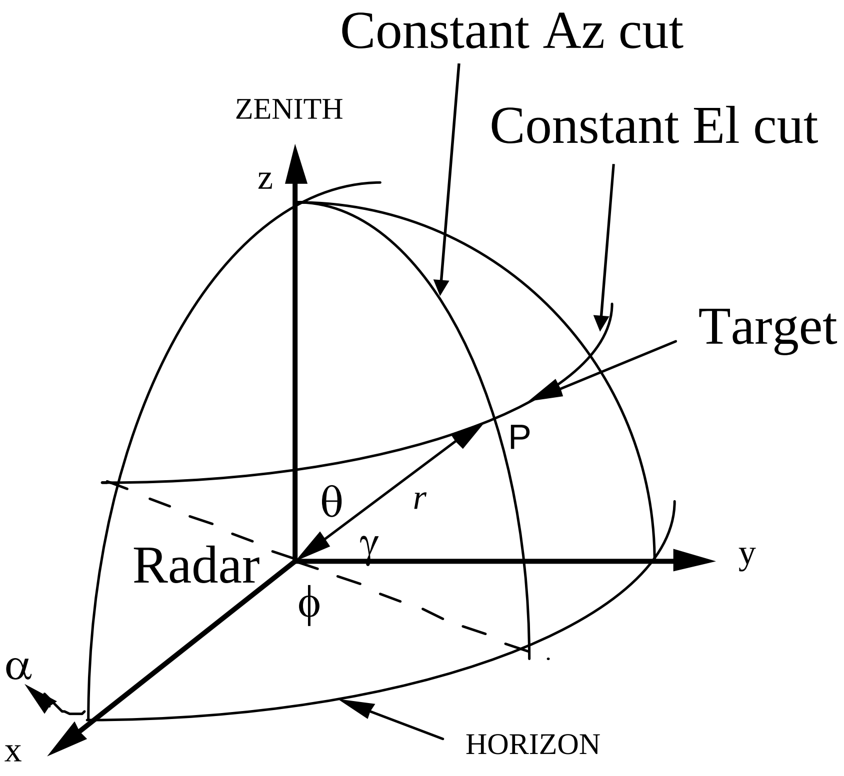
  spherical polar: (r,θ,ϕ)

  azimuth/elevation: (Az,El)

  or (α,γ)
- The radar is located at the origin of the coordinate system; the Earth's surface lies in the *x*-*y* plane.
- Azimuth (α) is generally measured clockwise from a reference (like a compass) but the spherical system azimuth angle (ϕ) is measured counterclockwise from the *x* axis. Therefore

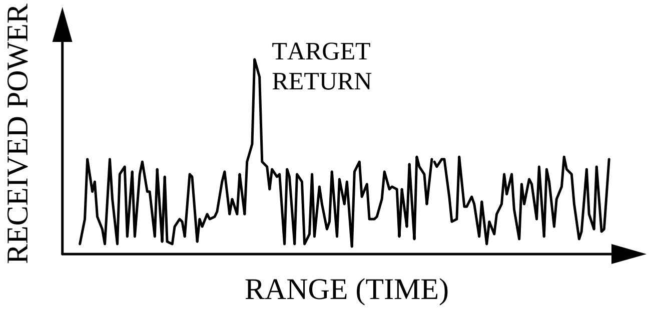
$$\gamma = 90 - \theta$$

$$\alpha = 360 - \phi$$

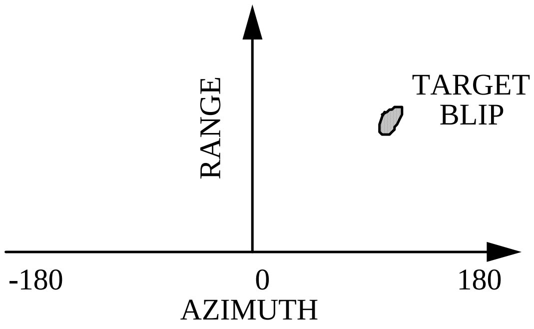


Radar Display Types

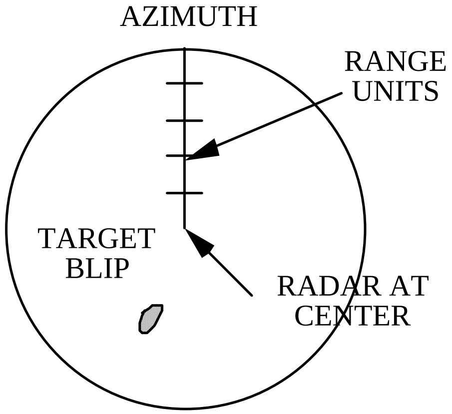
"A" DISPLAY



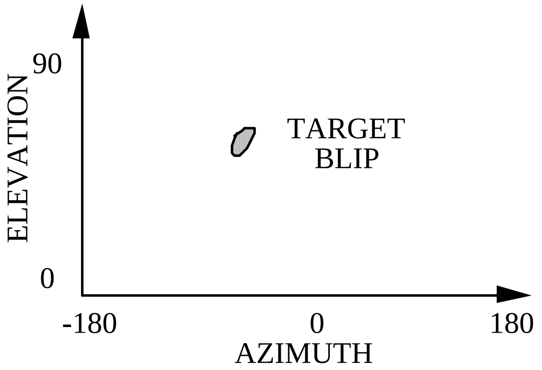
"B" DISPLAY



PLAN POSITION INDICATOR (PPI)



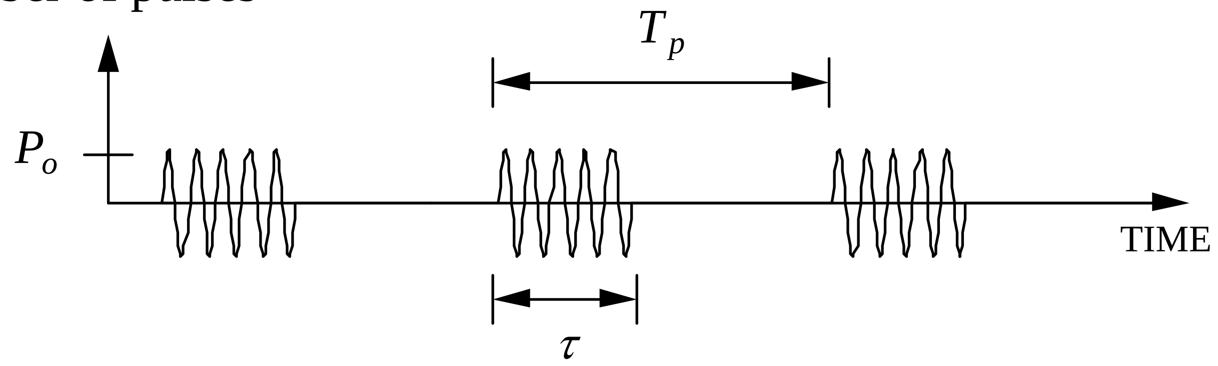
"C" DISPLAY



Pulsed Waveform

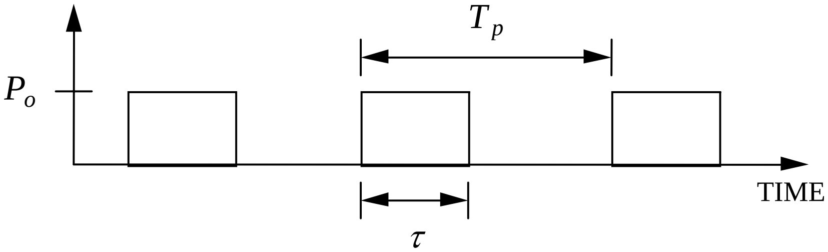
- In practice multiple pulses are transmitted to:
  1. cover search patterns
  2. track moving targets
  3. integrate (sum) several target returns to improve detection
- The pulse train is a common waveform

P_o = peak instantaneous power (W)
τ = pulse width (sec)
$f_p = 1/T_p$, pulse repetition frequency (PRF, Hz)
T_p = interpulse period (sec)
N = number of pulses

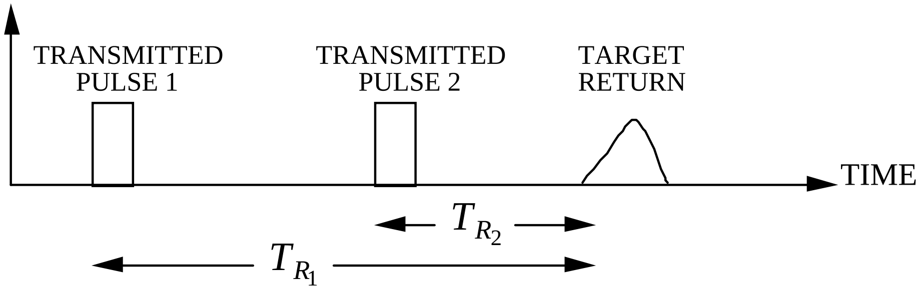


Range Ambiguities

- For convenience we omit the sinusoidal carrier when drawing the pulse train



- When multiple pulses are transmitted there is the possibility of a range ambiguity.

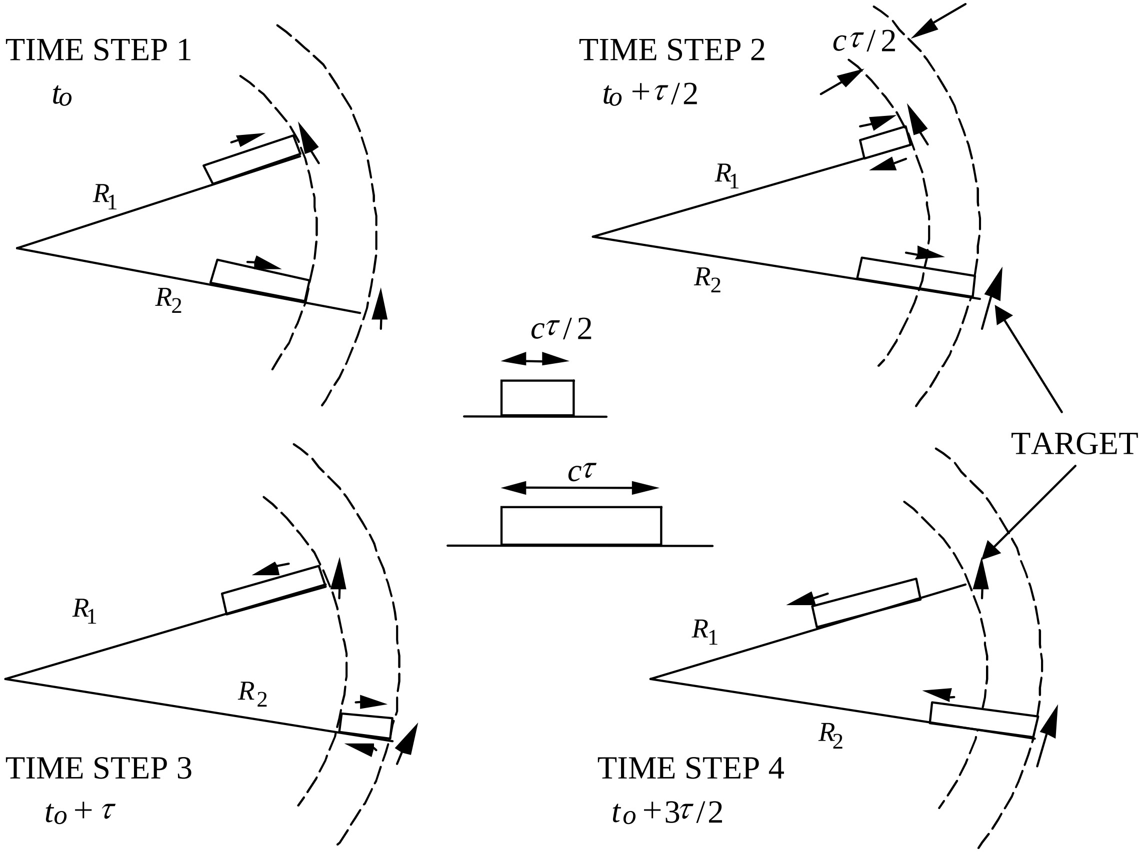


- To determine the range unambiguously requires that $T_p \geq \frac{2R}{c}$. The unambiguous range is

$$R_u = \frac{cT_p}{2} = \frac{c}{2f_p}$$

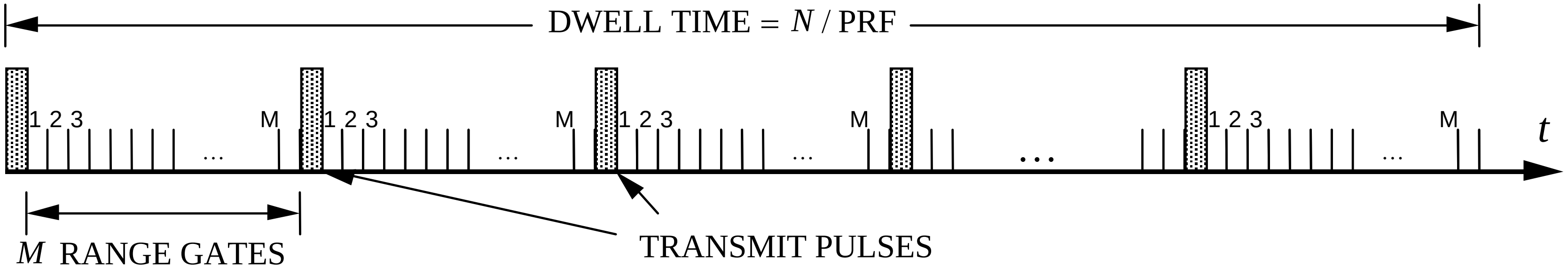
Range Resolution

- Two targets are resolved if their returns do not overlap. The range resolution corresponding to a pulse width τ is $\Delta R = R_2 - R_1 = c\tau/2$.

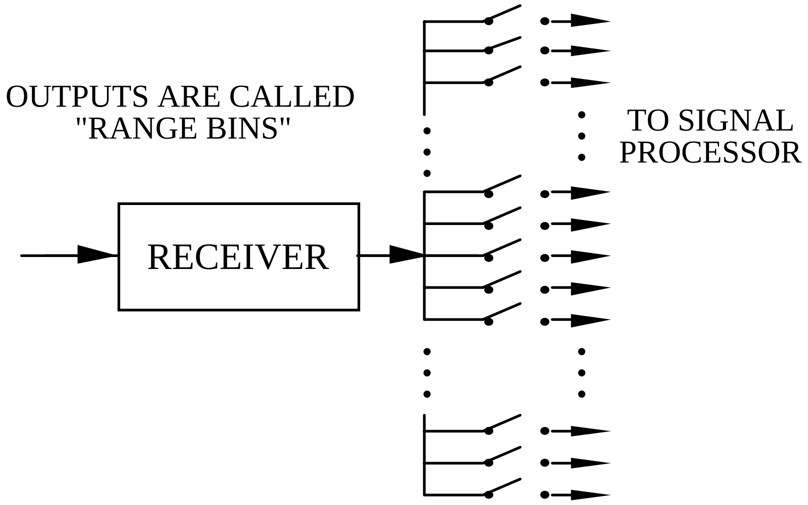


Range Gates

- Typical pulse train and range gates

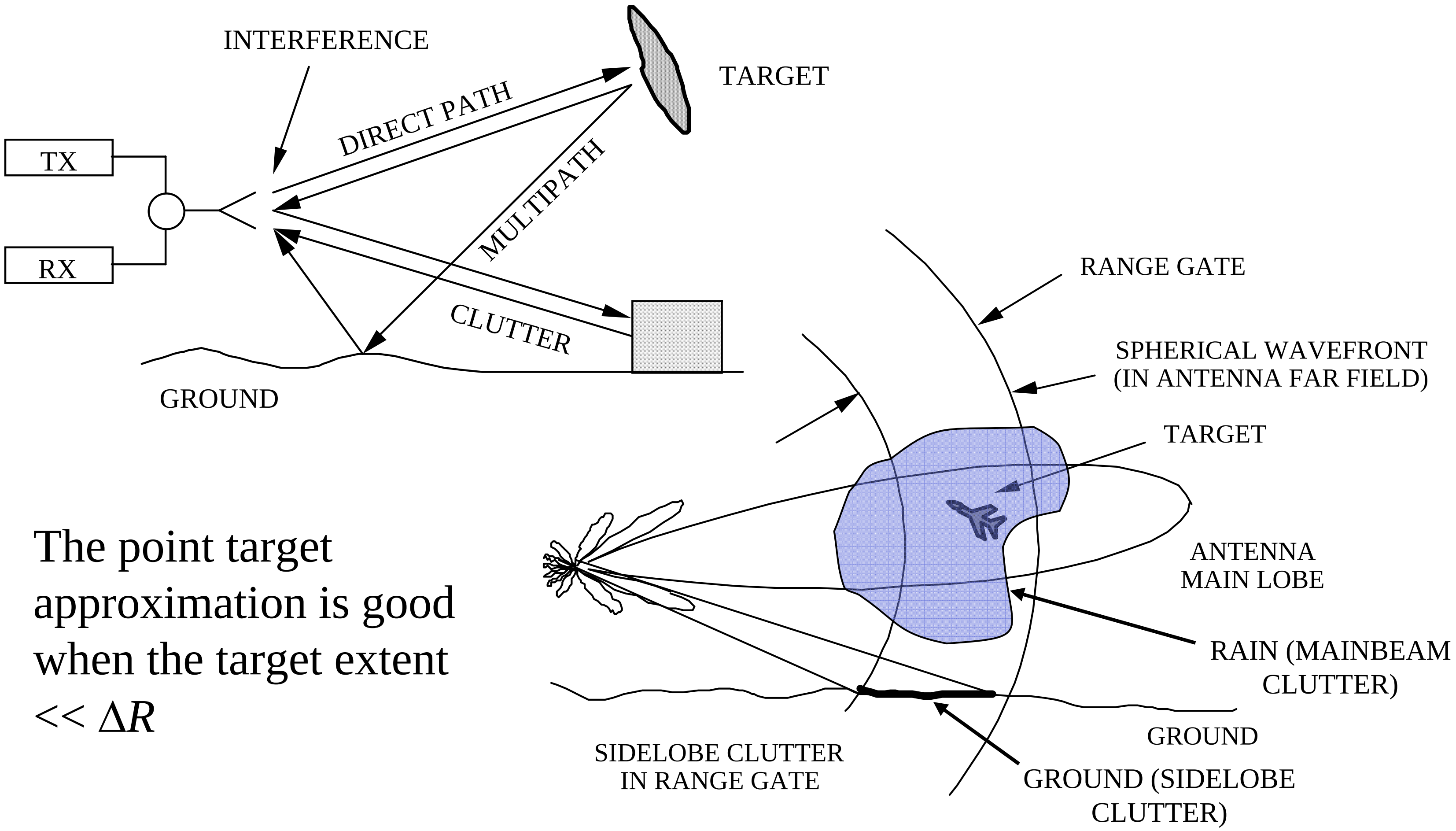


- Analog implementation of range gates



- Gates are opened and closed sequentially
- The time each gate is closed corresponds to a range increment
- Gates must cover the entire interpulse period or the ranges of interest
- For tracking a target a single gate can remain closed until the target leaves the bin

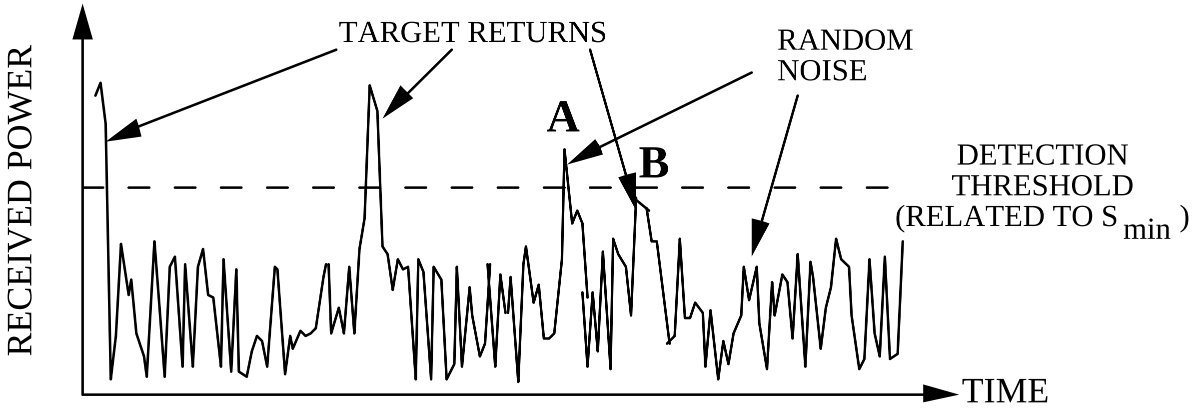
Clutter and Interference



The point target approximation is good when the target extent $<< \Delta R$

Thermal Noise

- In practice the received signal is "corrupted" (distorted from the ideal shape and amplitude) by thermal noise, interference and clutter.
- Typical return trace appears as follows:



- <u>Threshold detection</u> is commonly used. If the return is greater than the detection threshold a target is declared. **A** is a <u>false alarm</u>: the noise is greater than the threshold level but there is no target. **B** is a <u>miss</u>: a target is present but the return is not detected.

Thermal Noise Power

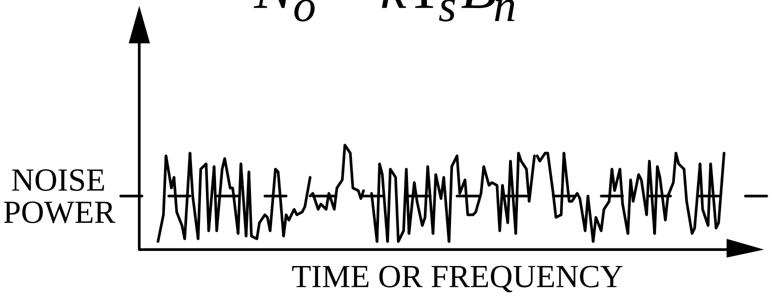
- Consider a receiver at the standard temperature, T_o degrees Kelvin (K). Over a range of frequencies of bandwidth B_n (Hz) the available noise power is

$$N_o = k T_o B_n$$

where $k_B = 1.38 \times 10^{-23}$ (Joules/K) is Boltzman's constant.

- Other radar components will also contribute noise (antenna, mixer, cables, etc.). We define a system noise temperature T_s, in which case the available noise power is

$$N_o = k T_s B_n$$



Signal-to-Noise Ratio (SNR)

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- Considering the presence of noise, the important parameter for detection is the signal-to-noise ratio (SNR)

$$\mathrm{SNR} = \frac{P_r}{N_o} = \frac{P_t G_t G_r \sigma \lambda^2 G_p L}{(4\pi)^3 R^4 k_B \mathrm{T}_s B_n}$$

- Factors have been added for processing gain G_p and loss L
- Most radars are designed so that $B_n \approx 1/\tau$
- At this point we will consider only two noise sources:

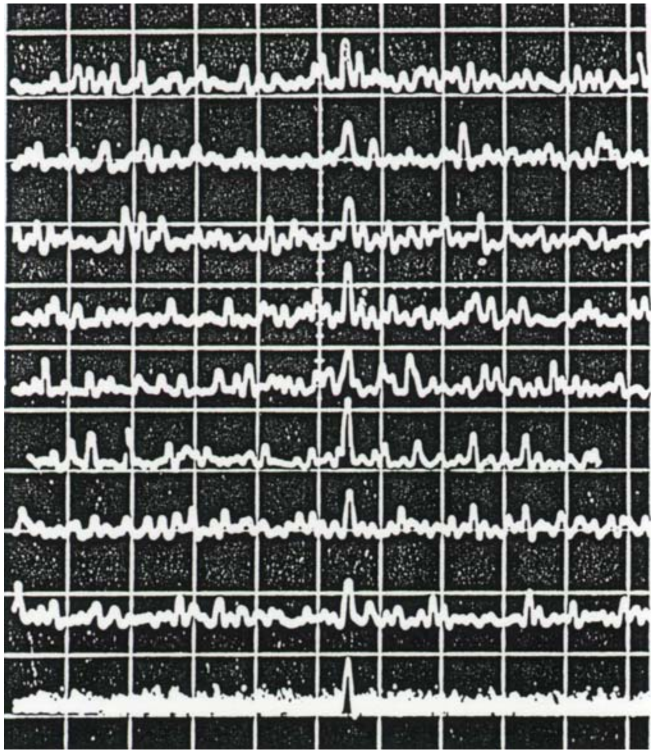
  1. background noise collected by the antenna ($\mathrm{T_A}$)

  2. total effect of all other system components (T_o, system effective noise temperature)

$$\mathrm{T}_s = \mathrm{T_A} + \mathrm{T}_e$$

Integration of Pulses

- Noncoherent integration (postdetection integration): performed after the envelope detector. The magnitudes of the returns from all pulses are added. SNR increases approximately as $\sqrt{N}$.
- Coherent integration (predetection integration): performed before the envelope detector (phase information must be available). Coherent pulses must be transmitted. The SNR increases as N.
- The last trace shows a noncoherent integrated signal.
- Integration improvement an example of processing gain.



From Byron Edde, *Radar: Principles, Technology, Applications*, Prentice-Hall

Dwell Time

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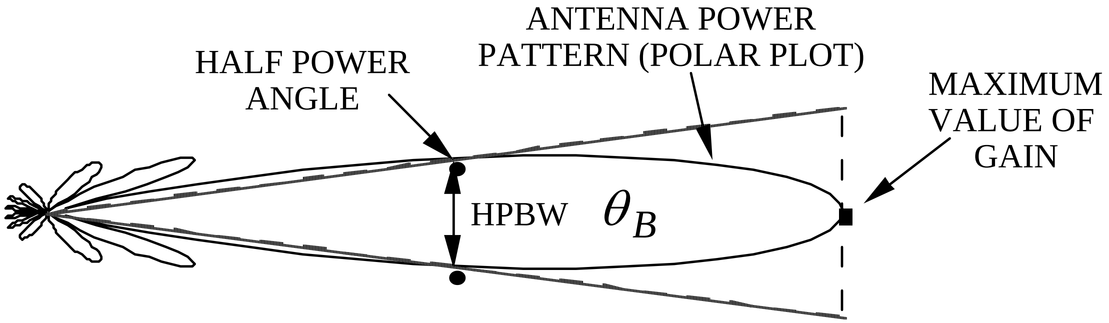
- Simple antenna model: constant gain inside the half power beamwidth (HPBW), zero outside. If the aperture has a diameter *D* with uniform illumination $\theta_B \approx \lambda / D$.
- The time that the target is in the beam (dwell time, look time, or time on target) is t_{ot}

$$t_{\text{ot}} = \theta_B / \dot{\theta}_s$$

- The beam scan rate is ω_s in revolutions per minute or $\frac{d\theta_s}{dt} = \dot{\theta}_s$ in degrees per second.
- The number of pulses that will hit the target in this time is

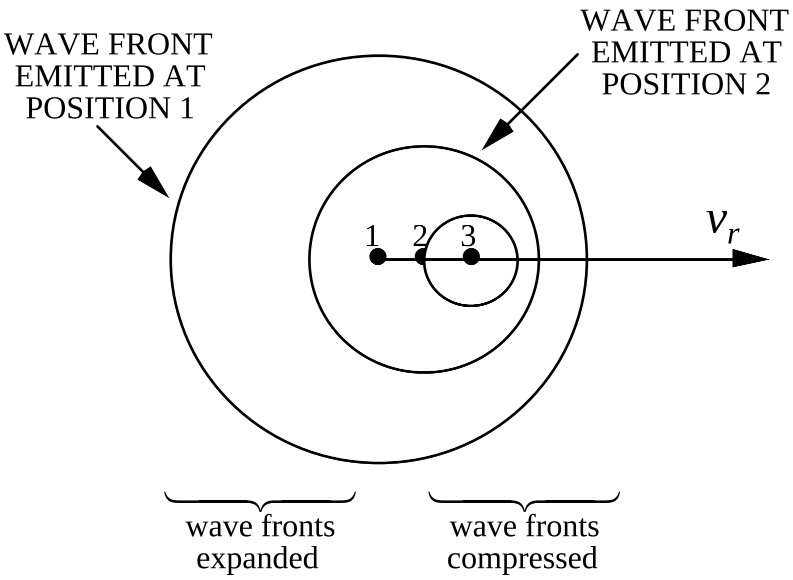
$$n_B = t_{\text{ot}} f_p$$

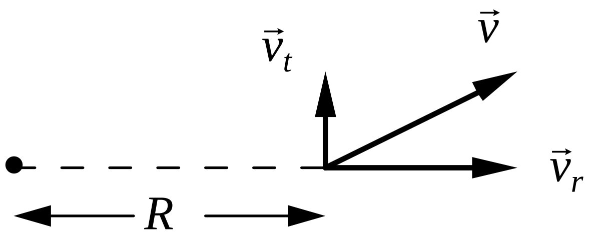


Doppler Shift

- Targets in motion relative to the radar cause the return signal frequency to be shifted.
- A Doppler shift only occurs when the relative velocity vector has a radial component. In general there will be both radial and tangential components to the velocity

$$f_d = -2v_r / \lambda$$



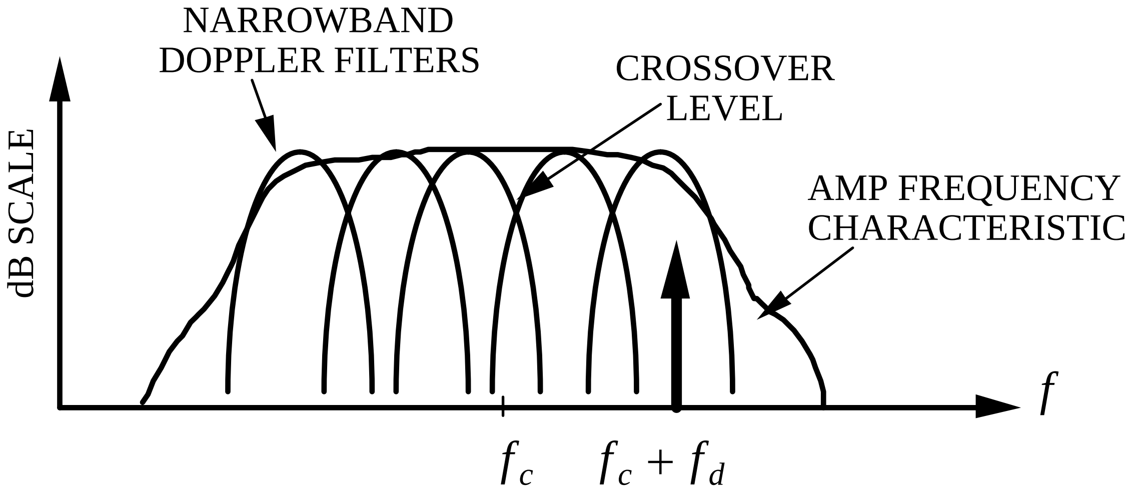


$$R \text{ decreasing } \Rightarrow \frac{dR}{dt} < 0 \Rightarrow f_d > 0 \text{ (closing target)}$$

$$R \text{ increasing } \Rightarrow \frac{dR}{dt} > 0 \Rightarrow f_d < 0 \text{ (receeding target)}$$

Doppler Filter Banks

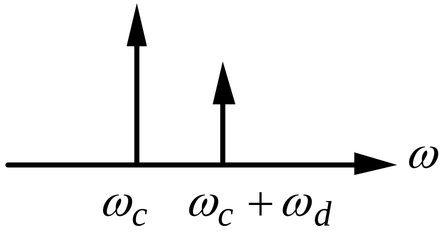
- The radar’s operating band is divided into narrow sub-bands. Ideally there should be no overlap in sub-band frequency characteristics.
- The noise bandwidth of the Doppler filters is small compared to that of the radar’s total bandwidth, which improves the SNR.
- Velocity estimates can be made by monitoring the power out of each filter.
- If a signal is present in a filter, the target's velocity range is known.



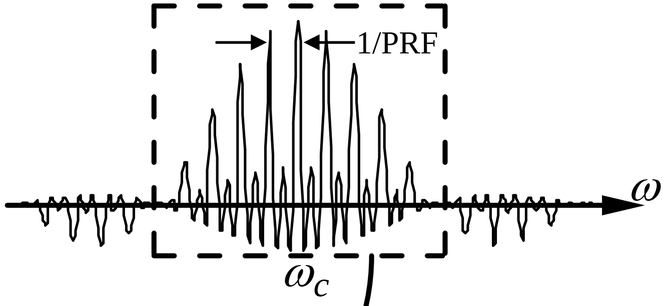
Velocity Ambiguities

- The spectrum is the Fourier transform of the pulse train waveform.

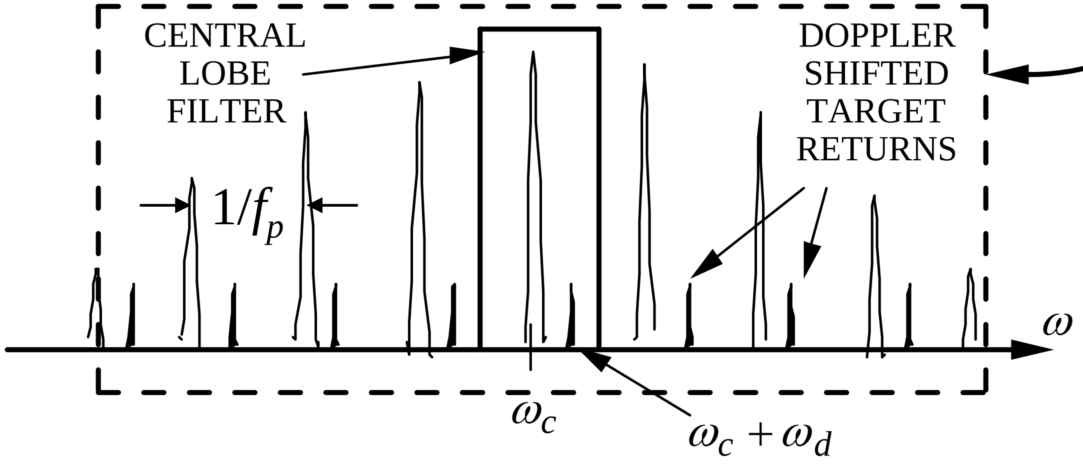
Spectrum of doppler shifted CW signal



Coherent pulse train spectrum (fixed target -- no doppler)



Expanded central lobe region with target doppler shift

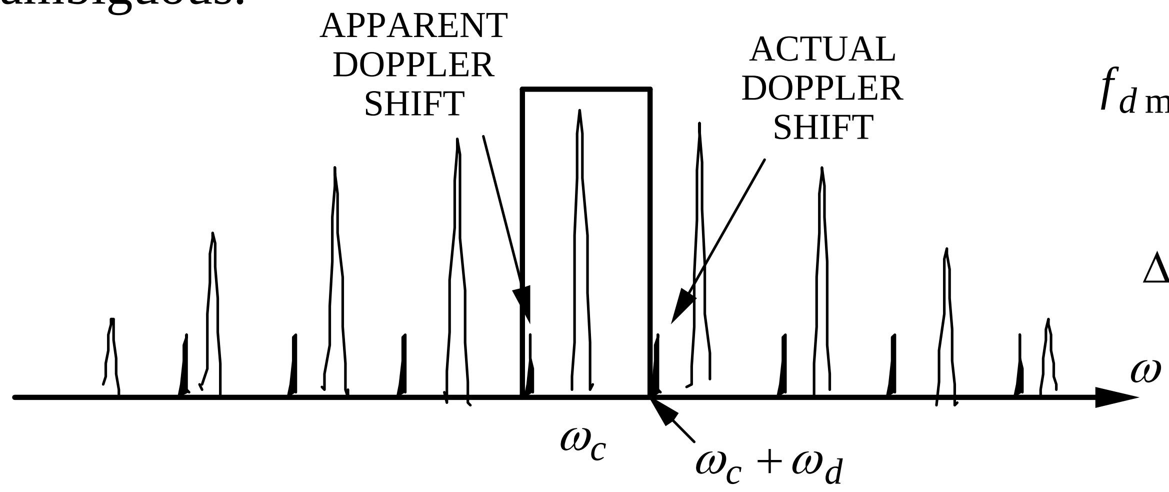


$$f_d\big|_{\text{observed}} = \frac{2v_r}{\lambda} \bmod(\text{PRF})$$

$$f_d = n\,\text{PRF} + f_d\big|_{\text{apparent}}$$

Low, High, Medium PRF

- If f_d is increased the true target Doppler shifted return moves out of the passband and a lower sideband lobe enters. Thus the Doppler measurement is ambiguous.



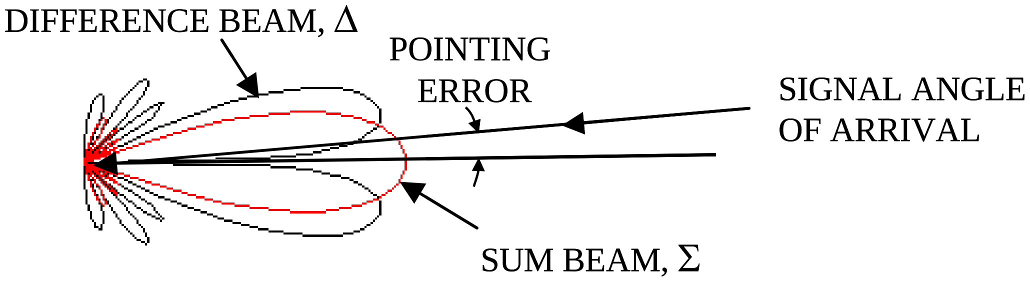
$$\begin{aligned} f_{d\max} &= \pm f_p / 2 \\ v_u &= \lambda f_{d\max} / 2 \\ &= \pm\lambda f_p / 4 \\ \Delta v_u &= \lambda f_p / 2 \end{aligned}$$

- PRF determines Doppler and range ambiguities:

PRF	RANGE	DOPPLER
High	Ambiguous	Unambiguous
Medium	Ambiguous	Ambiguous
Low	Unambiguous	Ambiguous

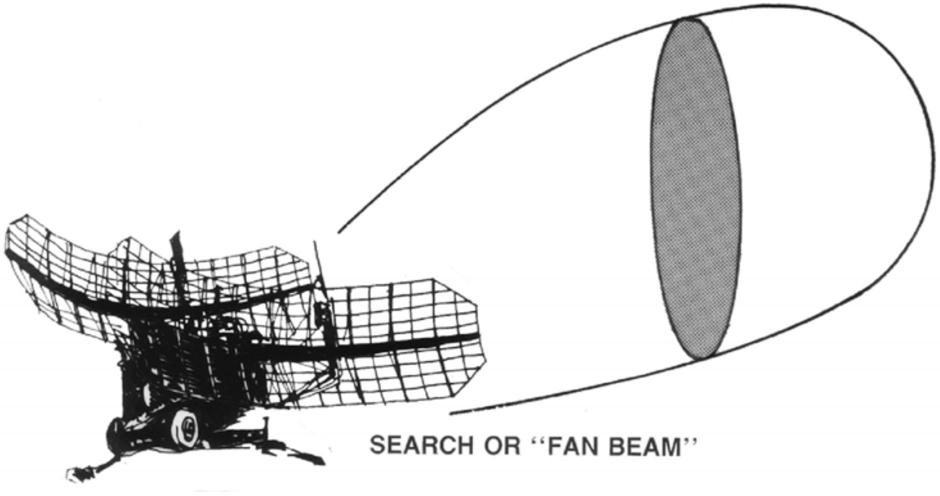
Track Versus Search

- Search radars
  - > Long, medium, short ranges (20 km to 2000 km)
  - > High power density on the target: high peak power, long pulses, long pulse trains, high antenna gain
  - > Low PRFs, large range bins
  - > Search options: rapid search rate with narrow beams or slower search rate with wide beams
- Tracking radar
  - > Accurate angle and range measurement required
  - > Minimize time on target for rapid processing
  - > Special tracking techniques: monopulse, conical scan, beam switching

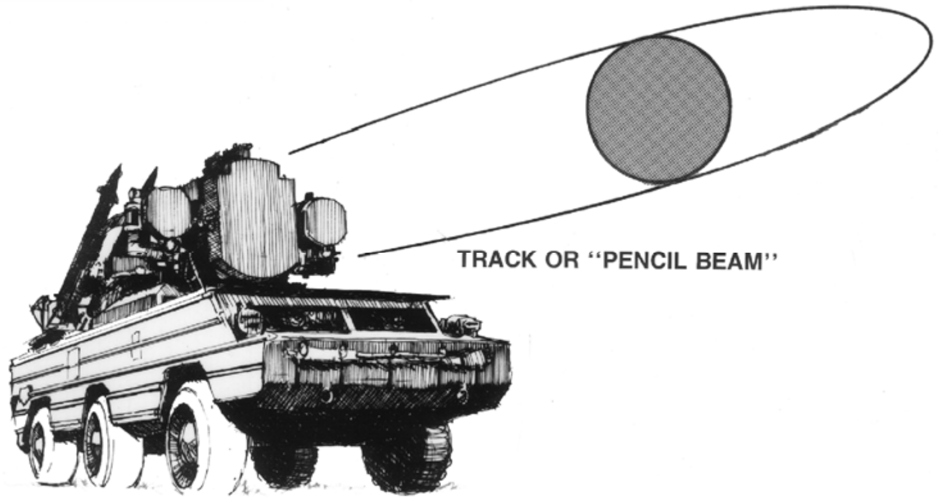


Monopulse
Technique

Antenna Patterns



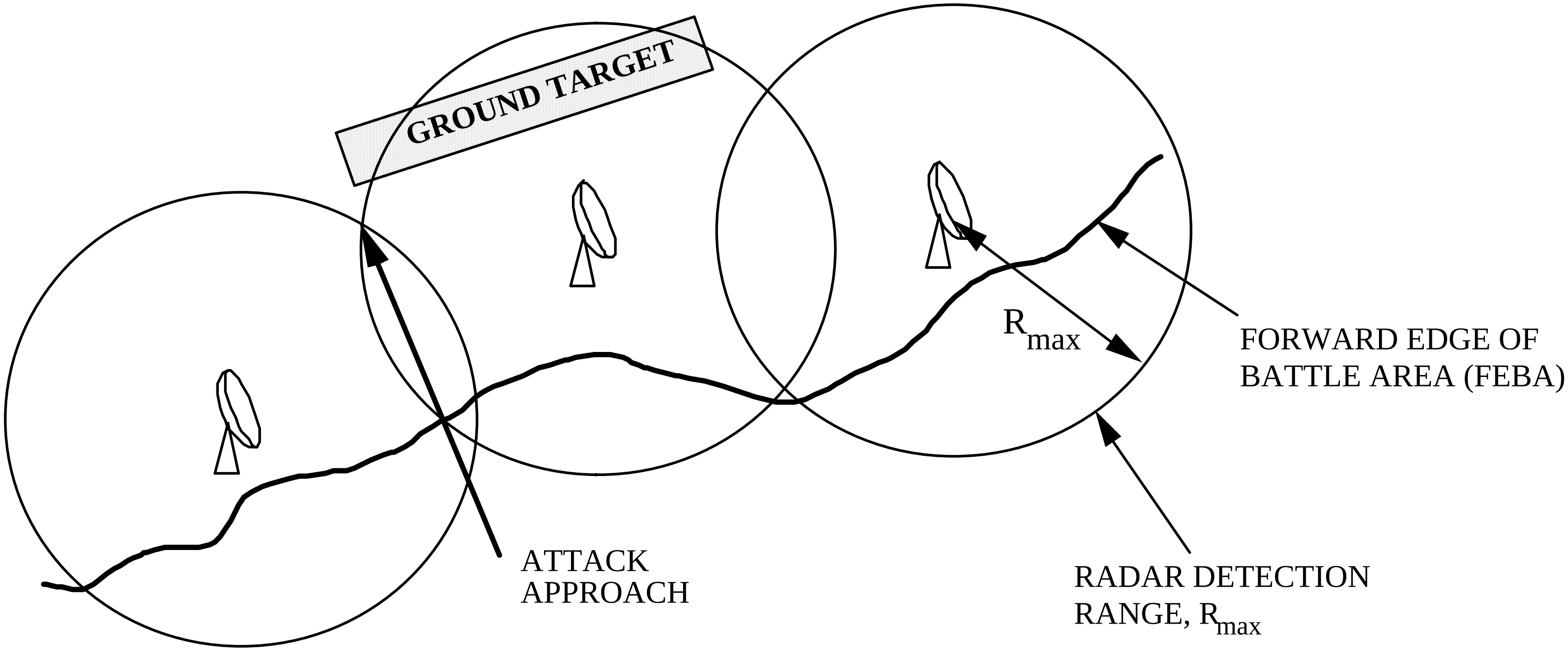
- Fan beam for 2-d search



- Pencil beam for tracking for 3-d search

Attack Approach

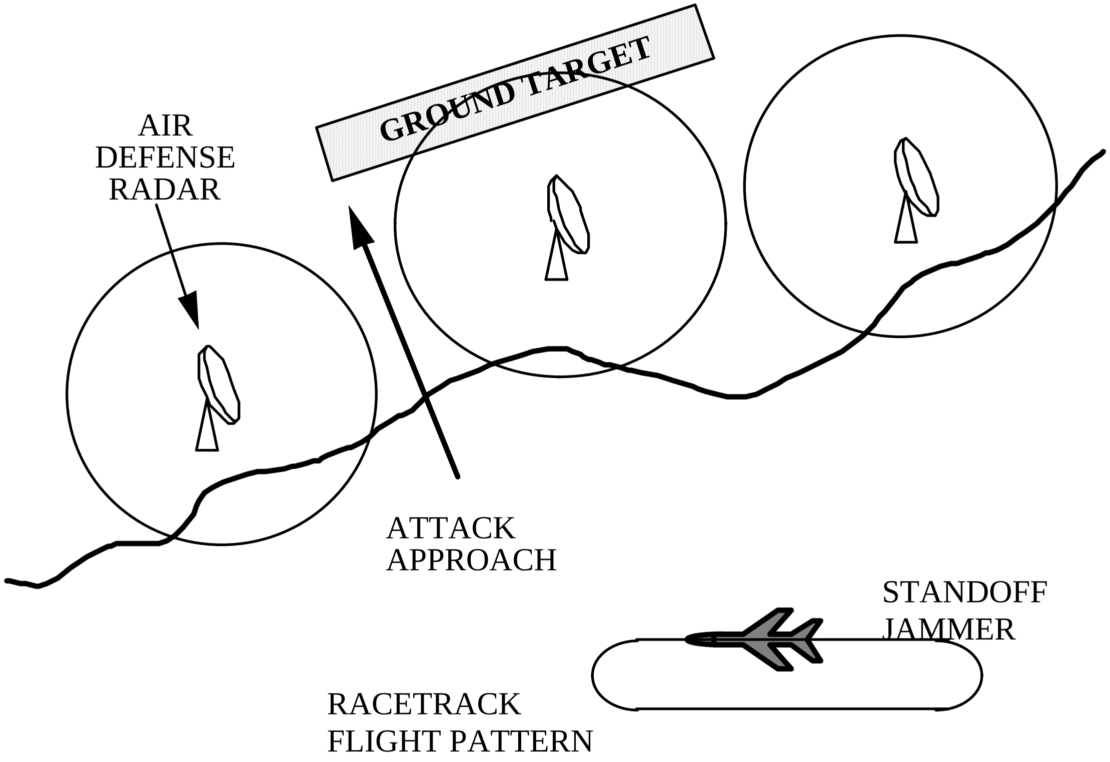
- A network of radars are arranged to provide continuous coverage of a ground target.
- Conventional aircraft cannot penetrate the radar network without being detected.



Radar Jamming

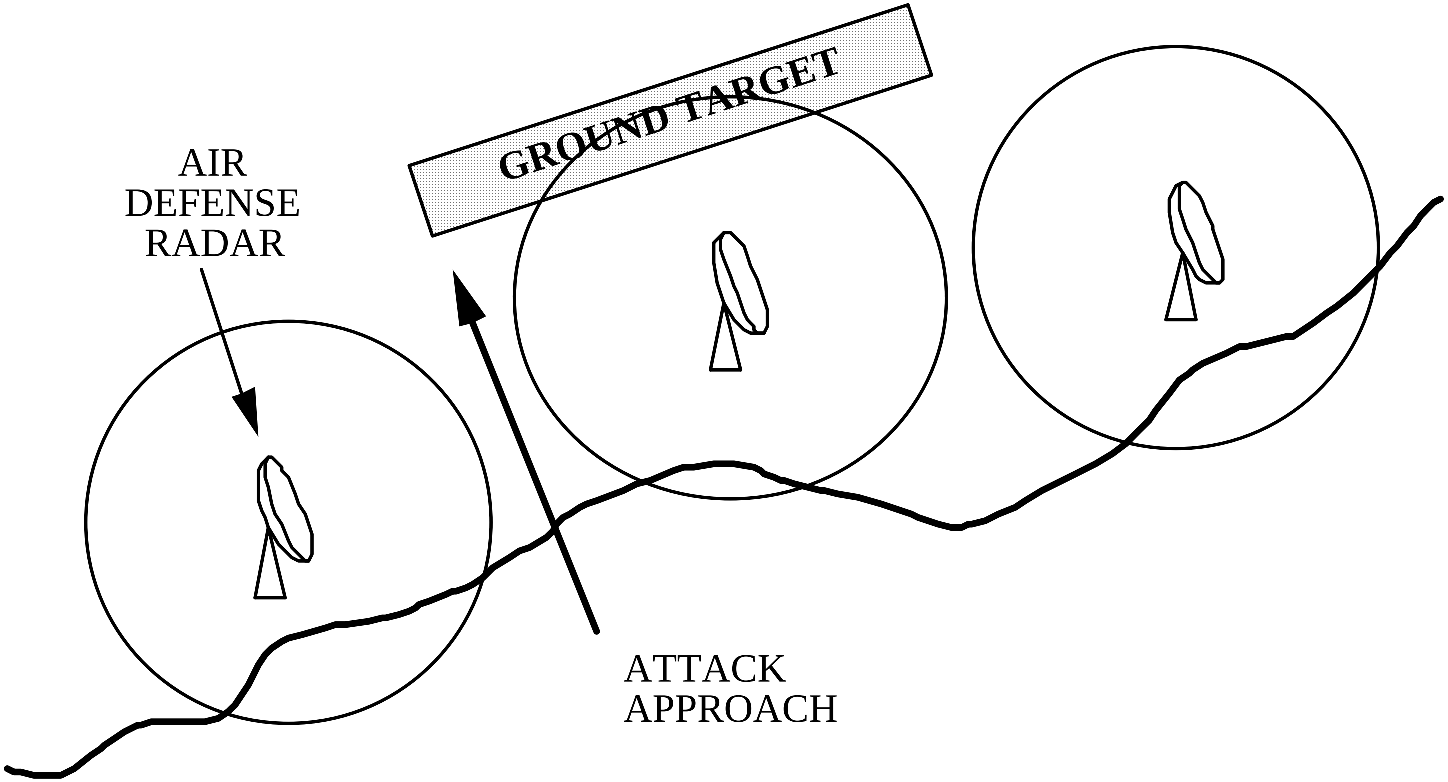
NAVAL
POSTGRADUATE
SCHOOL

- The barrage jammer floods the radar with noise and therefore decreases the SNR.
- The radar knows it is being jammed.



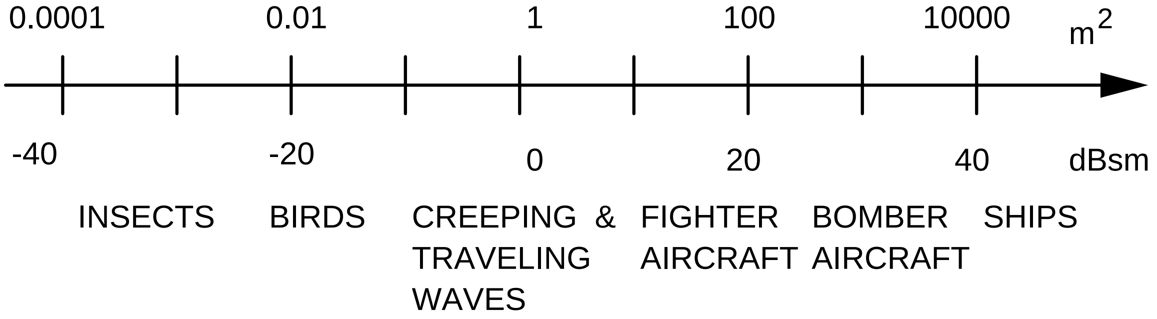
Low Observability

- Detection range depends on RCS, $R_{\max} \propto \sqrt[4]{\sigma}$, and therefore RCS reduction can be used to open holes in a radar network.
- There are cost and performance limitations to RCS reduction.



Radar Cross Section (RCS)

- Typical values:



- Fundamental equation for the RCS of a “electrically large” perfectly reflecting surface of area *A* when viewed directly by the radar

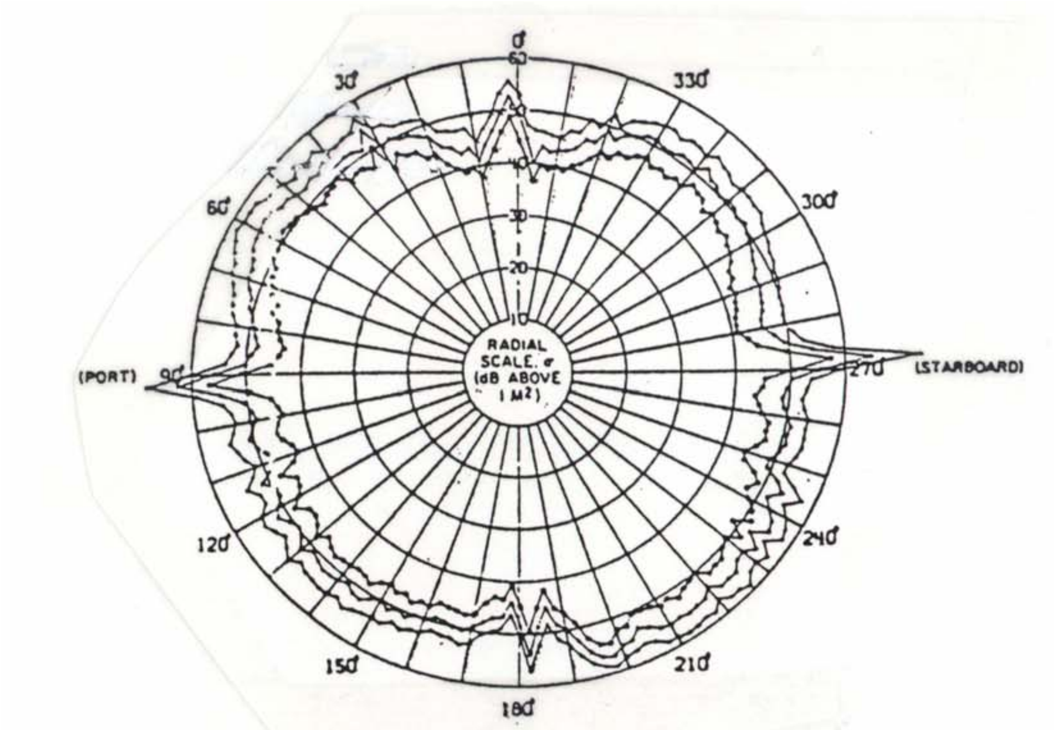
$$\sigma \approx \frac{4\pi A^2}{\lambda^2}$$

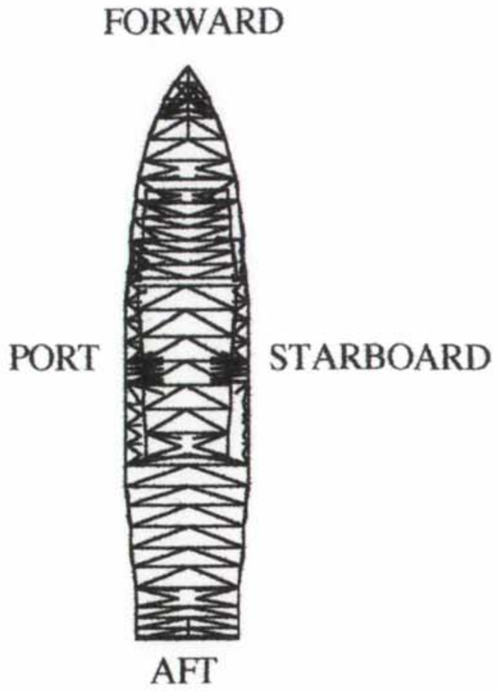
- Expressed in decibels relative to a square meter (dBsm):

$$\sigma_{\mathrm{dBsm}} = 10\log_{10}(\sigma)$$

RCS Target Types

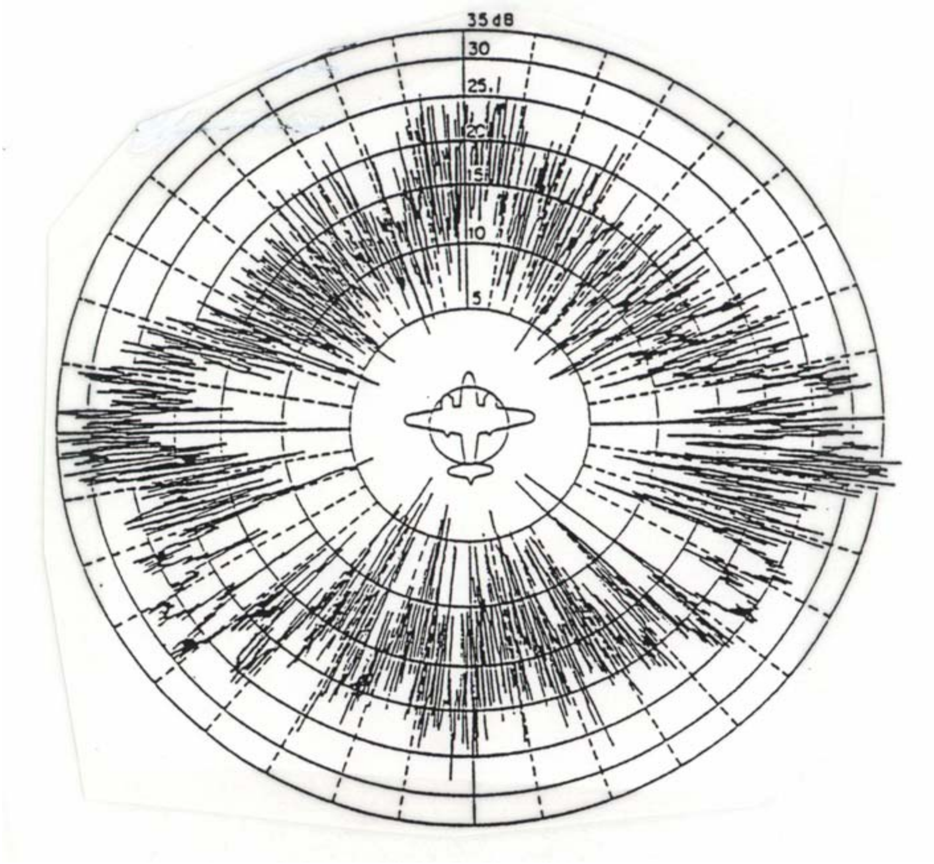
- A few dominant scatterers (e.g., hull) and many smaller independent scatterers
- S-Band (2800 MHz), horizontal polarization, maximum RCS = 70 dBsm





RCS Target Types

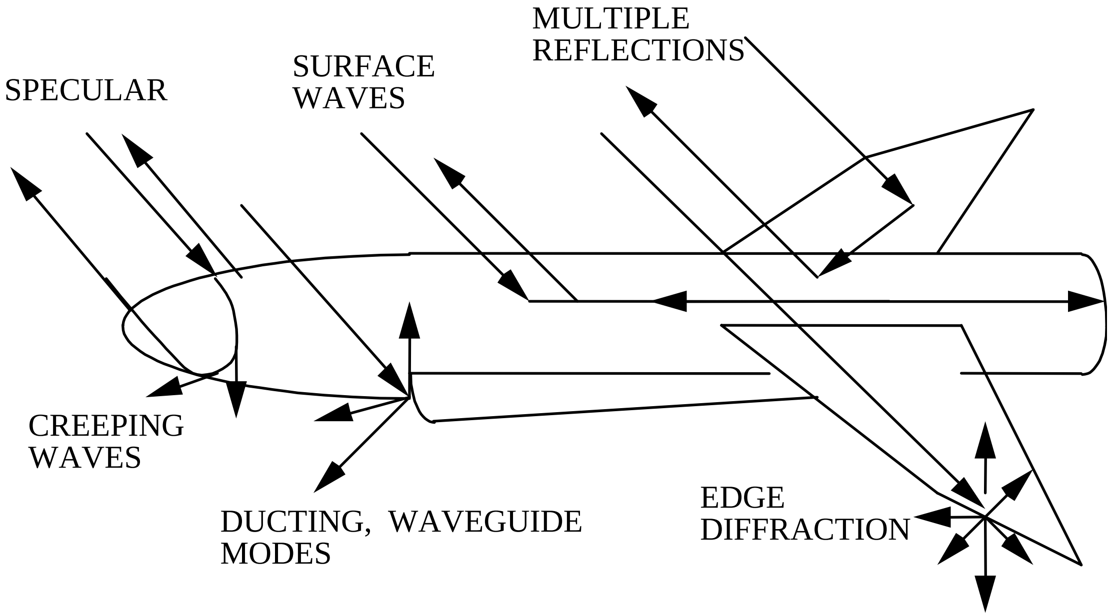
- Many independent random scatterers, none of which dominate (e.g., large aircraft)

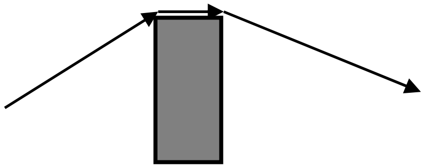


From Skolnik
- S-Band (3000 MHz)
- Horizontal Polarization
- Maximum RCS = 40 dBsm

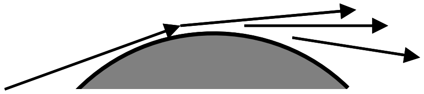
Scattering Mechanisms

- Scattering mechanisms are used to describe wave behavior. Especially important at radar frequencies:
  specular = "mirror like" reflections that satisfy Snell's law
  surface waves = the body surface acts like a transmission line
  diffraction = scattered waves that originate at abrupt discontinuities





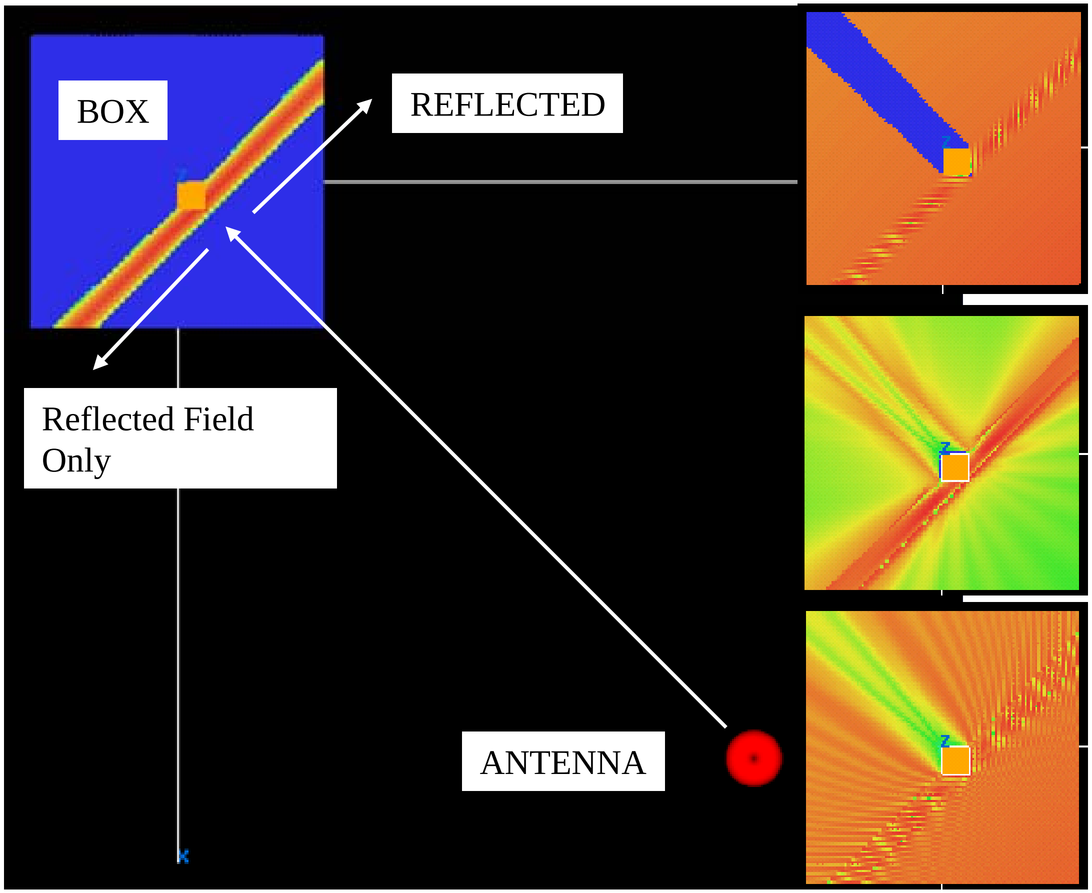
Double diffraction from sharp corners



Diffraction from rounded object

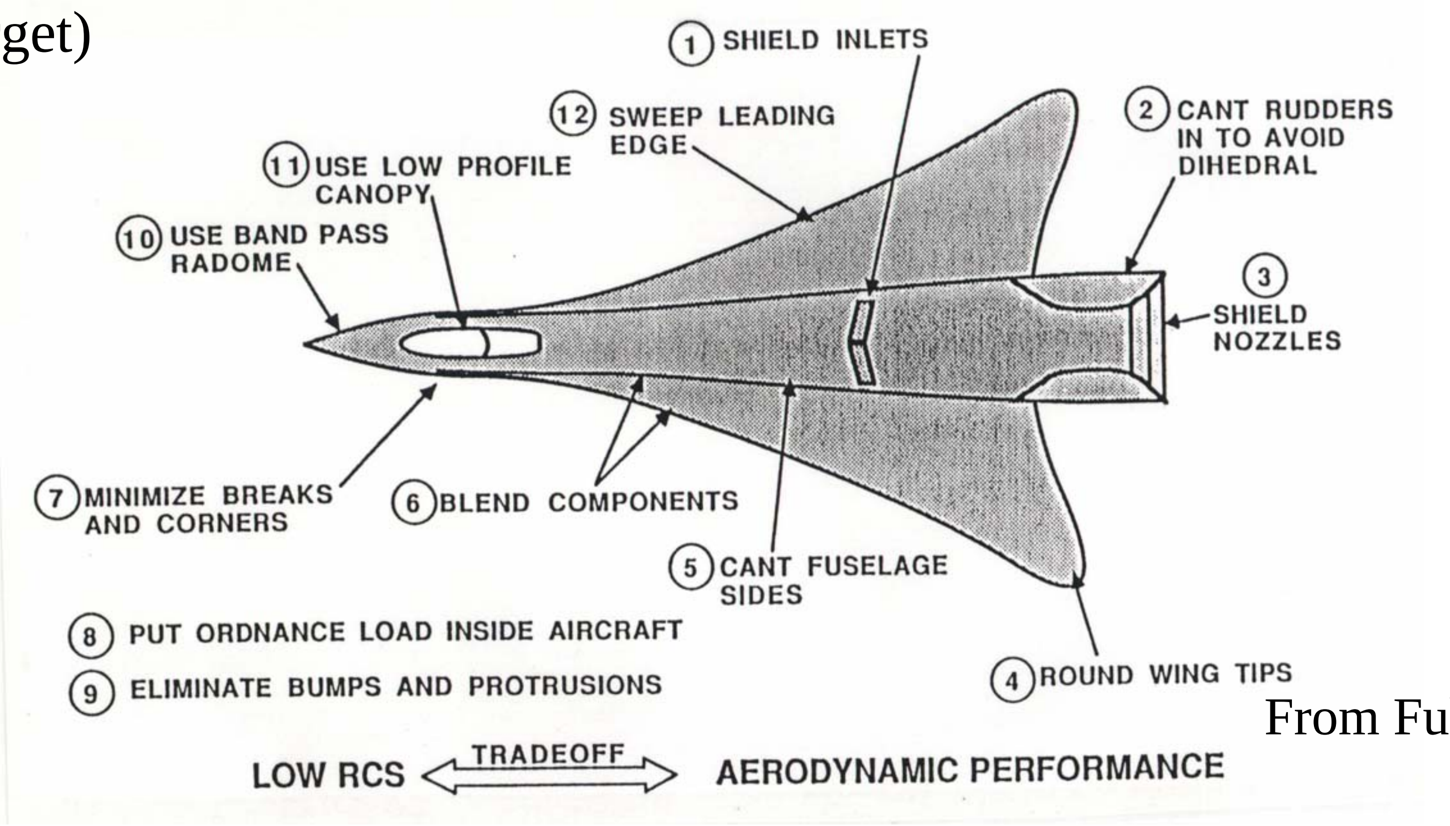
Example: Dipole and Box

- *f* =1 GHz, –100 dBm (blue) to –35 dBm (red), 0 dBm Tx power, 1 m metal cube



RCS Reduction Methods

- Shaping (tilt surfaces, align edges, no corner reflectors)
- Materials (apply radar absorbing layers)
- Cancellation (introduce secondary scatterers to cancel the “bare” target)



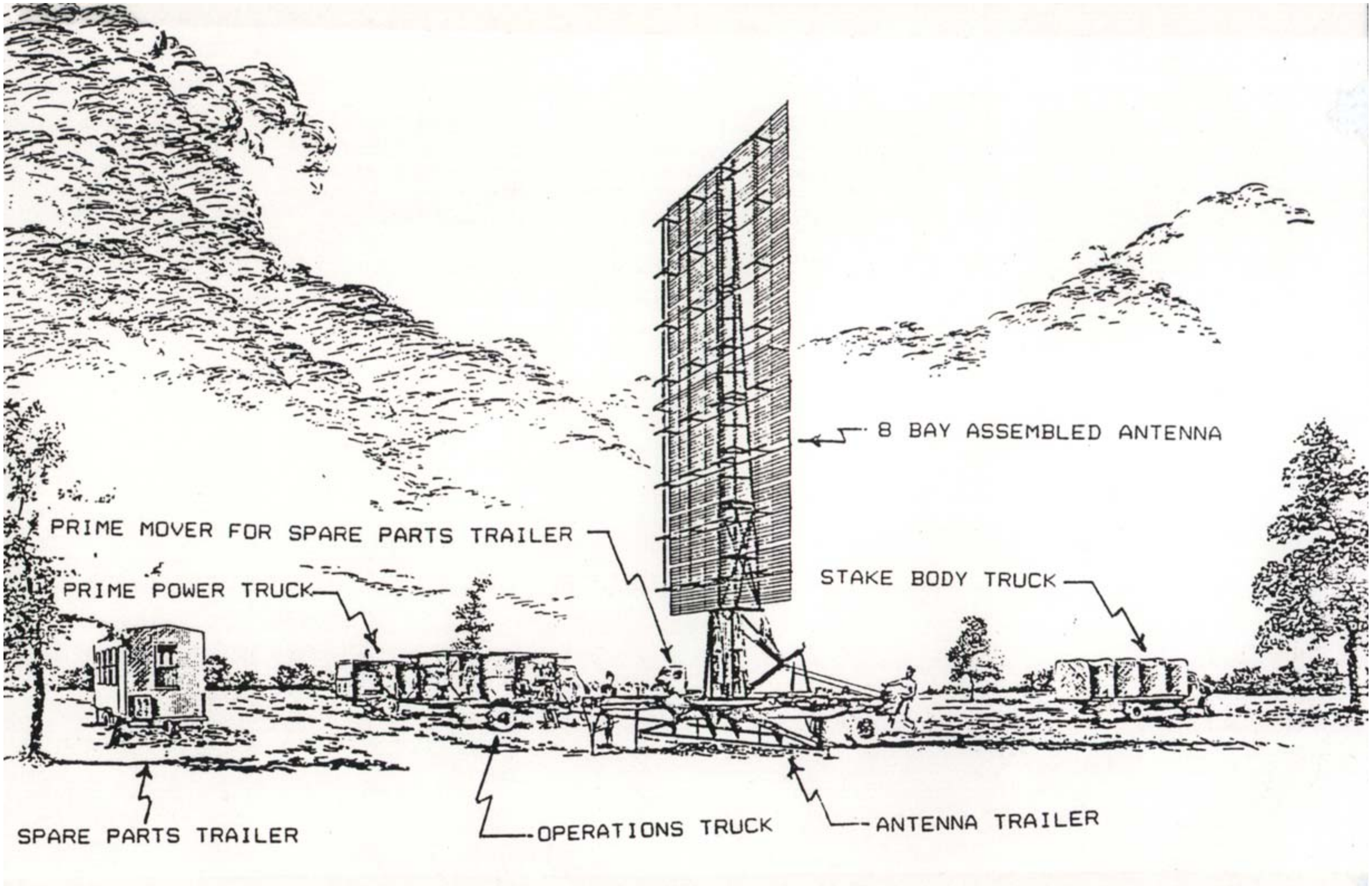
From Fuhs

AN/TPQ-37 Firefinder

- Locates mortars, artillery, rocket launchers and missiles
- Locates 10 weapons simultaneously
- Locates targets on first round
- Adjusts friendly fire
- Interfaces with tactical fire
- Predicts impact of hostile projectiles
- Maximum range: 50 km
- Effective range:

  Artillery: 30 km, Rockets: 50 km
- Azimuth sector: 90°
- Frequency: S-band, 15 frequencies
- Transmitted power: 120 kW
- Permanent storage for 99 targets; field exercise mode; digital data interface

SCR-270 Air Search Radar



SCR-270-D-RADAR

- Detected Japanese aircraft approaching Pearl Harbor
- Performance characteristics:

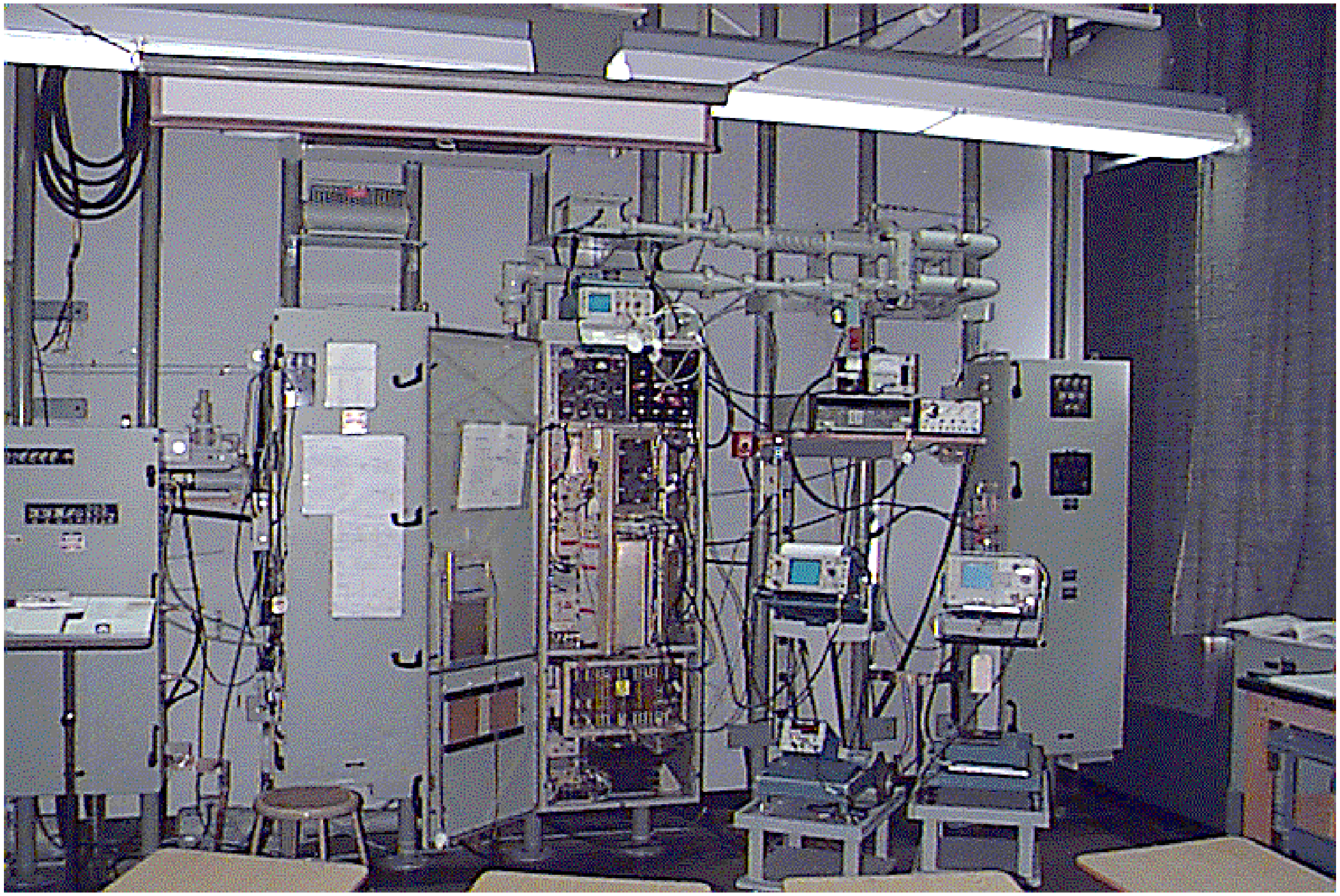
SCR-270-D Radio Set Performance Characteristics (Source: *SCR-270-D Radio Set Technical Manual, 1942*)

Maximum Detection Range	250 miles
Maximum Detection altitude	50,000 ft
Range Accuracy	4 miles*
Azimuth Accuracy	2 degrees
Operating Frequency	104-112 MHz
Antenna	Directive array **
Peak Power Output	100 kw
Pulse Width	15-40 microsecond
Pulse Repetition Rate	621 cps
Antenna Rotation	up to 1 rpm, max
Transmitter Tubes	2 tridoes***
Receiver	superheterodyne
Transmit/Receive/Device	spark gap

* Range accuracy without calibration of range dial.
** Consisting of dipoles, 8 high and 4 wide.
*** Consisting of a push-pull, self excited oscillator, using a tuned cathode circuit.

AN/SPS-40 Surface Search

- UHF long range two-dimensional surface search radar



AN/SPS-40 Surface Search

- UHF long range two-dimensional surface search radar. Operates in short and long range modes
- Range
  - Maximum: 200 nm
  - Minimum: 2 nm
- Target RCS: 1 sq. m.
- Transmitter Frequency:
  - 402.5 to 447.5 MHz
- Pulse width: 60 s
- Peak power: 200 to 255 kW
- Staggered PRF: 257 Hz (ave)
- Non-staggered PRF: 300 Hz
- Antenna
  - Parabolic reflector
  - Gain: 21 dB
  - Horizontal SLL: 27 dB
  - Vertical SLL: 19 dB
  - HPBW: 11 by 19 degrees
- Receiver
  - 10 channels spaced 5 MHz
  - Noise figure: 4.2
  - IF frequency: 30 MHz
  - PCR: 60:1
  - Correlation gain: 18 dB
  - MDS: –115 dBm
  - MTI improvement factor: 54 dB