RADAR

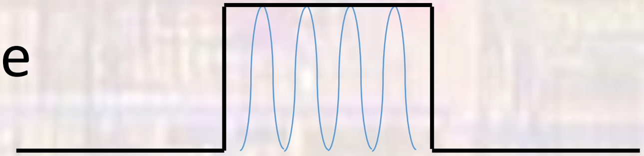
Last updated 4/21/20

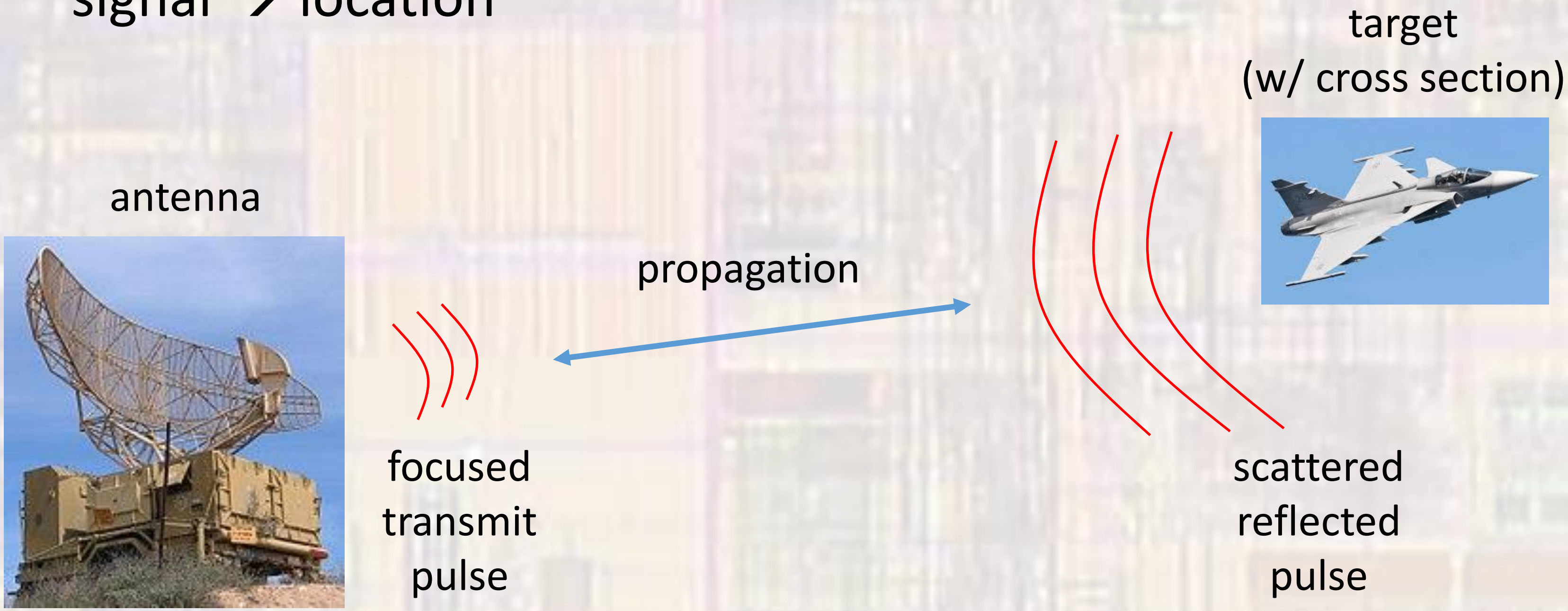
RADAR

- RADAR
  - RAdio Detection And Ranging
  - Early development in 1936
  - Significant advancements during WWII
    - Detect incoming bombers
    - Prevented Germany from achieving air superiority
- Key advantages
  - Long range
  - All weather
  - 3D target position detection
  - Can be mobile
  - Many variations achievable

RADAR

- Basic idea
  - Transmit a focused pulsed radio wave
  - Detect the returning radio wave
  - Direction of transmit and time of arrival of the returned signal → location





antenna

focused
transmit
pulse

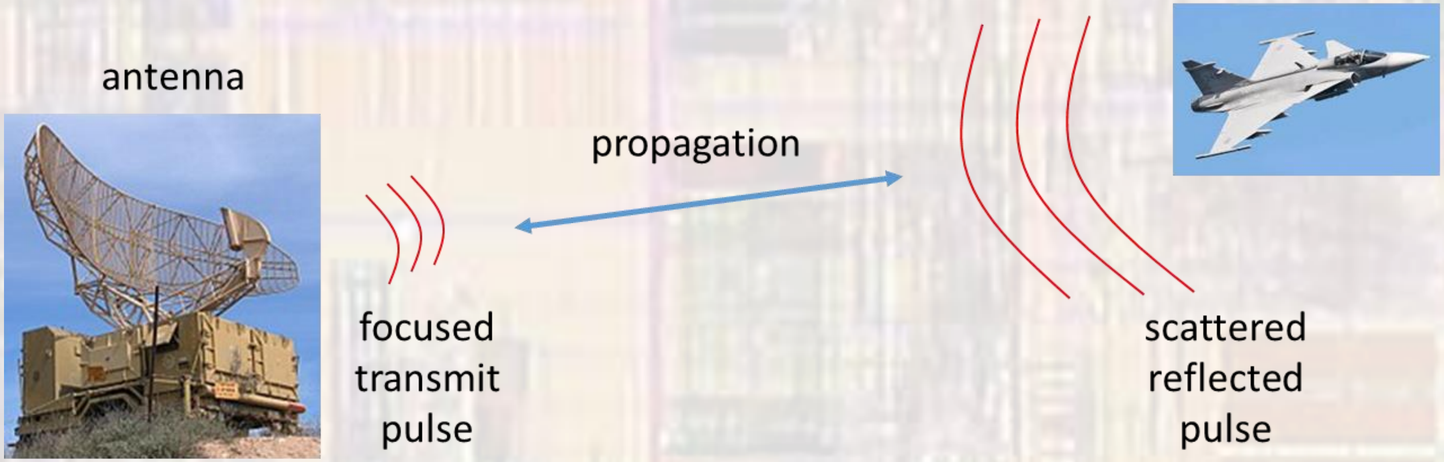
propagation

target
(w/ cross section)

scattered
reflected
pulse

RADAR

- Basic idea
  - Detect range
  - Detect azimuth (angle wrt north)
  - Detect elevation
  - Detect size (cross section)
  - Detect speed (using doppler)



target
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antenna

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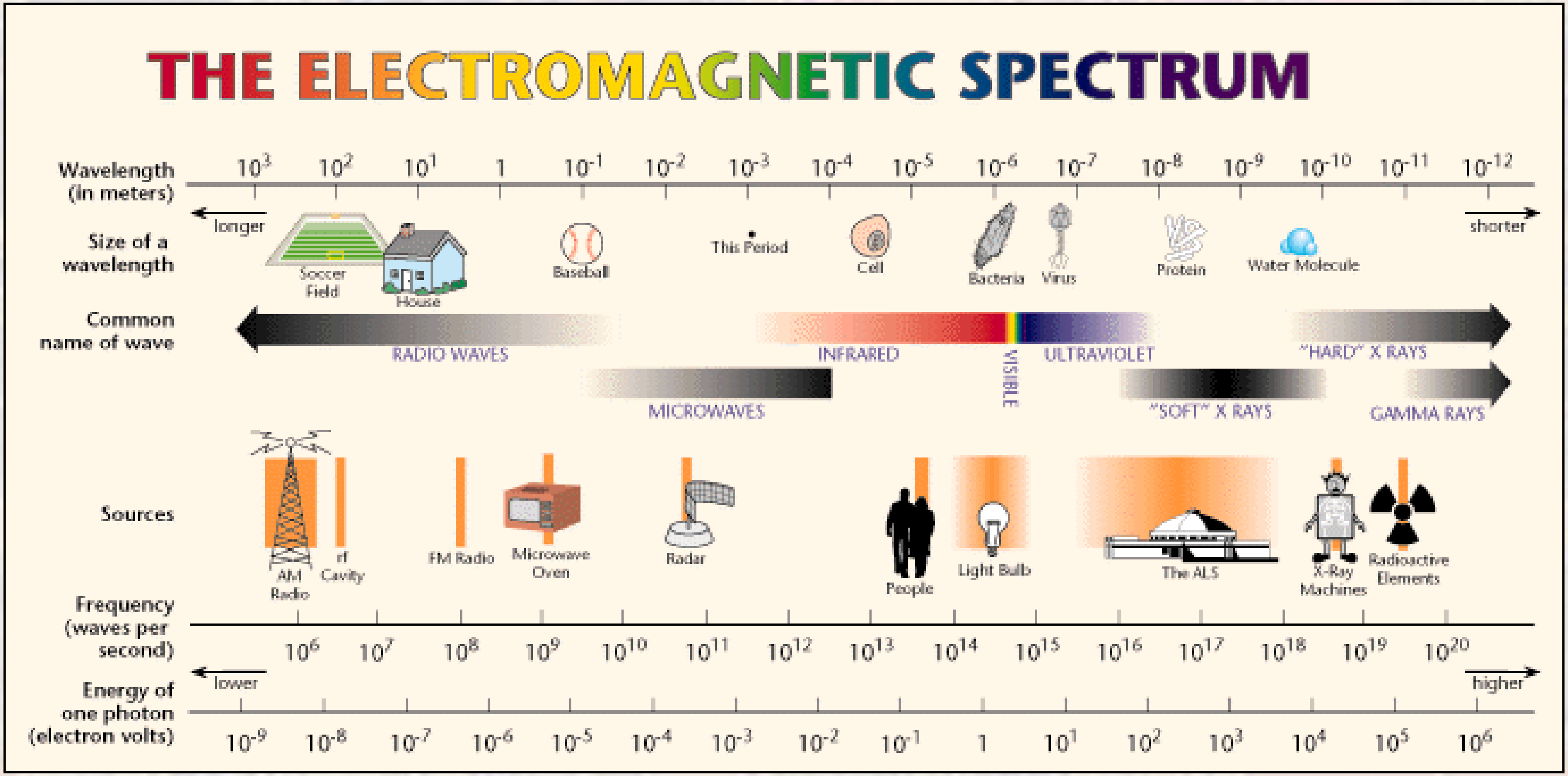
RADAR

- RADAR frequencies

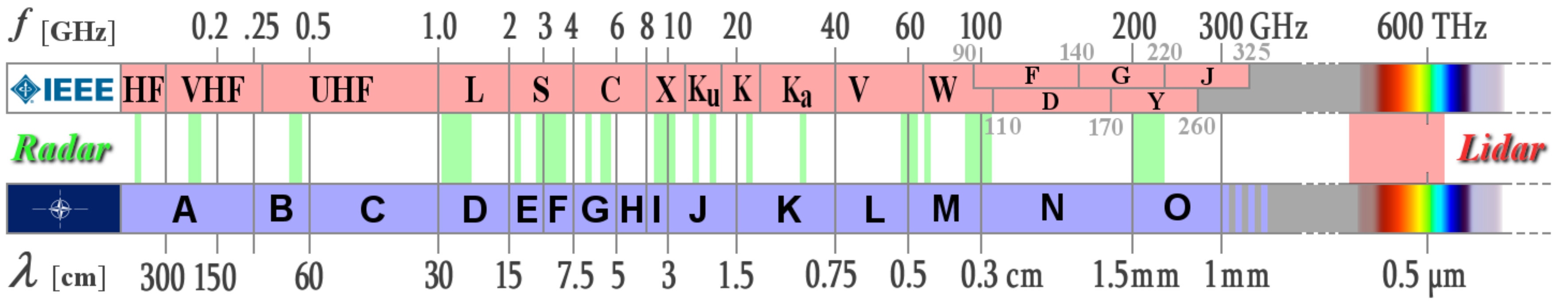


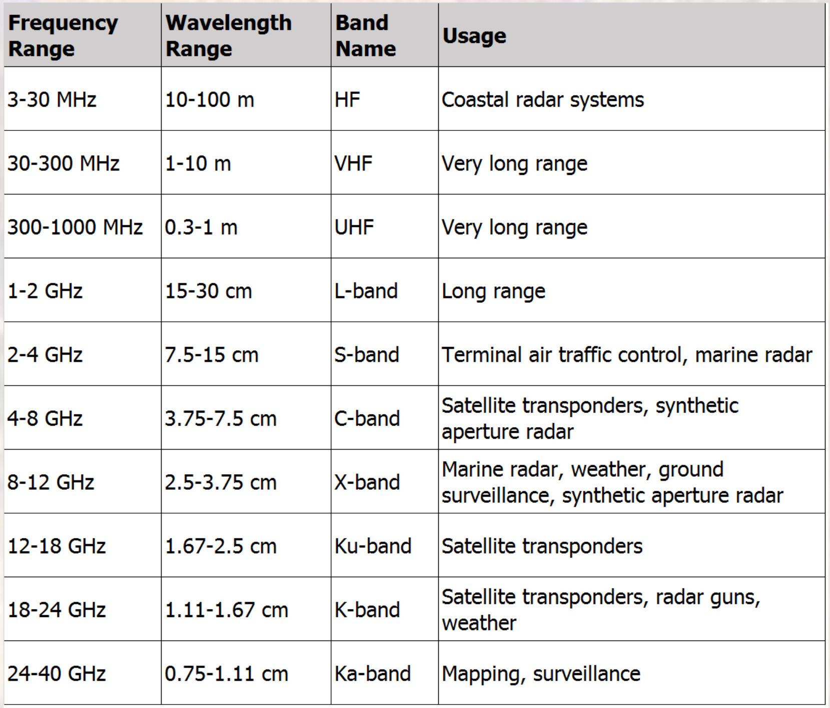
src: lbl.gov

RADAR

RADAR

- RADAR frequency bands





Frequency Range	Wavelength Range	Band Name	Usage
3-30 MHz	10-100 m	HF	Coastal radar systems
30-300 MHz	1-10 m	VHF	Very long range
300-1000 MHz	0.3-1 m	UHF	Very long range
1-2 GHz	15-30 cm	L-band	Long range
2-4 GHz	7.5-15 cm	S-band	Terminal air traffic control, marine radar
4-8 GHz	3.75-7.5 cm	C-band	Satellite transponders, synthetic aperture radar
8-12 GHz	2.5-3.75 cm	X-band	Marine radar, weather, ground surveillance, synthetic aperture radar
12-18 GHz	1.67-2.5 cm	Ku-band	Satellite transponders
18-24 GHz	1.11-1.67 cm	K-band	Satellite transponders, radar guns, weather
24-40 GHz	0.75-1.11 cm	Ka-band	Mapping, surveillance

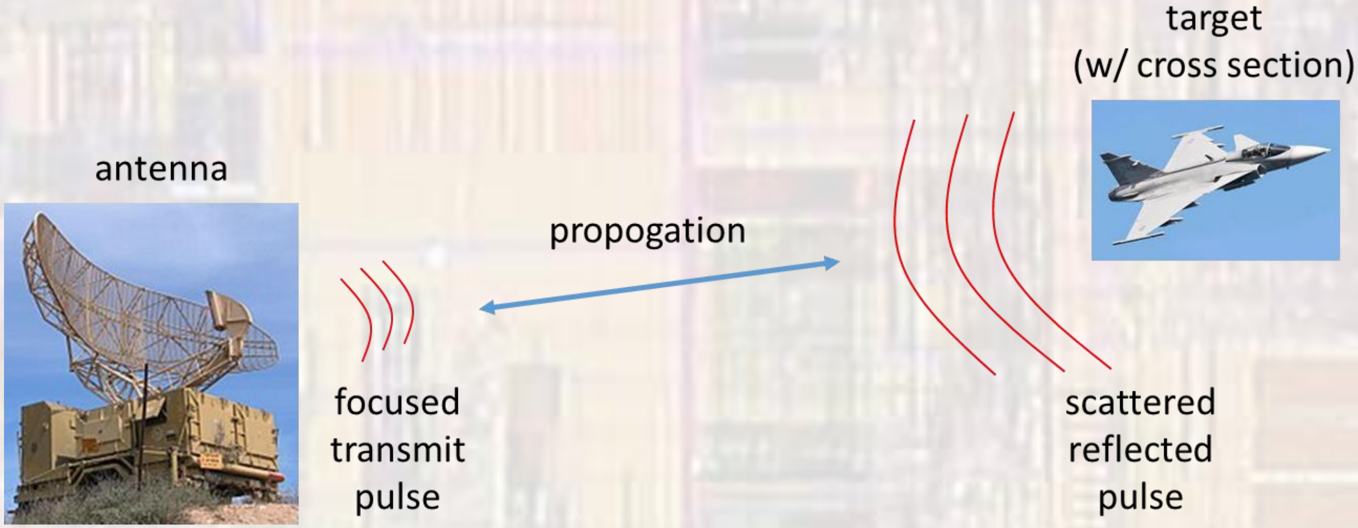
RADAR

- RADAR equation
  - Trivial version

range = Ct/2

C = Speed of light = 3×10^8m/s

t = time between transmit and return



target
(w/ cross section)

antenna

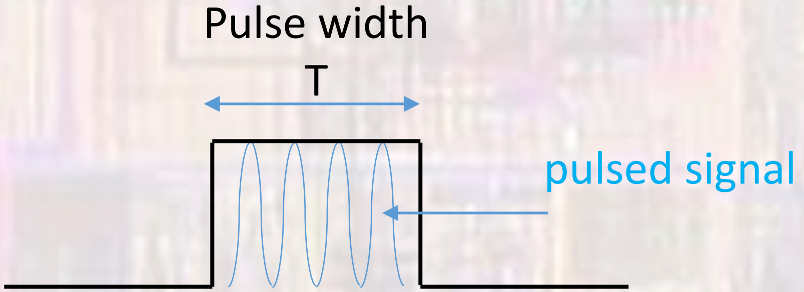
propogation

focused
transmit
pulse

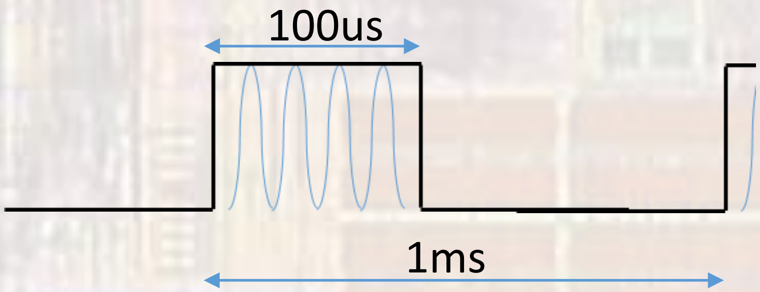
scattered
reflected
pulse

RADAR

- RADAR equation
  - Transmitter power
  - P_T = Peak transmit power
  - P_{AVE} = Average value
    - Transmitting pulses
    - Duty cycle = pulse width / pulse repetition interval
    - $P_{AVE} = P_T * \text{Duty Cycle}$

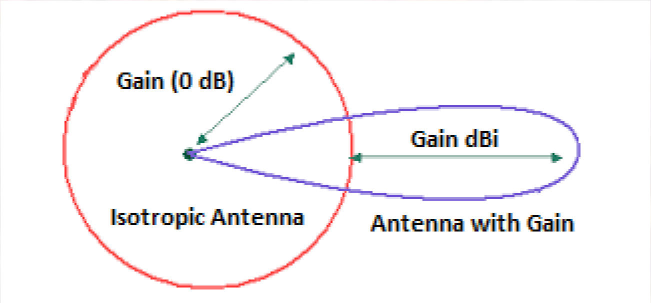


- Ex.
  - 100us pulse with a 1MW peak power
  - 1ms pulse repetition interval (1Kz pulse frequency)
  - →10% duty cycle
  - → 100KW average transmit power



RADAR

- RADAR equation
  - Transmit Gain
    - Use directional antennas for transmit

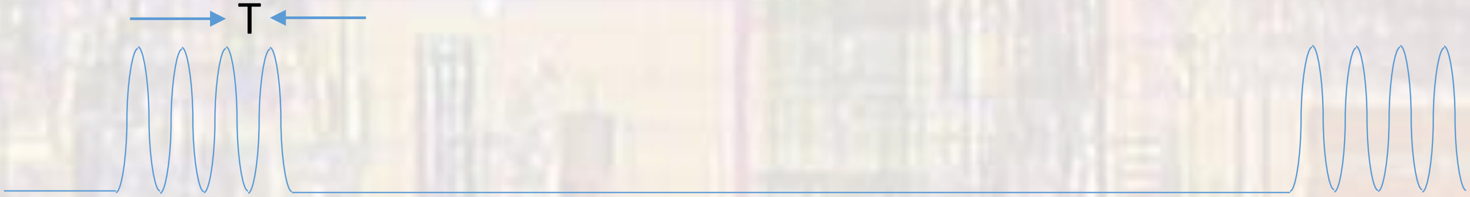


src: everything RF

$$G = \frac{4\pi A}{\lambda^2}$$

- A = Antenna aperture (effective aperture)
- λ = pulse signal wavelength

  = CT = C/f

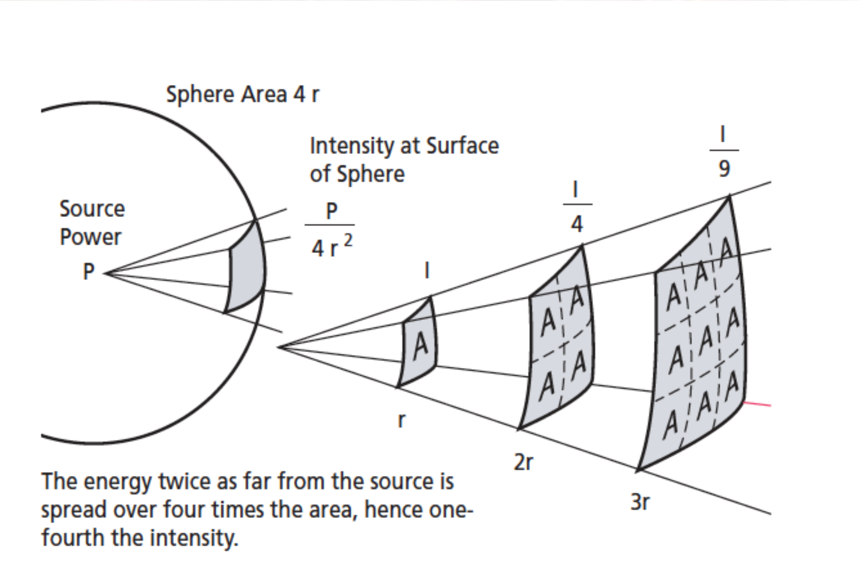


RADAR

- RADAR equation
  - Transmit signal spread factor

$$S_{Tx} = \frac{1}{4\pi R^2}$$

- R = range



The energy twice as far from the source is spread over four times the area, hence one-fourth the intensity.

src: NASA/JPL

RADAR

- RADAR equation
  - Transmit losses
    - Signal generation losses
    - Antenna losses
    - Environmental losses (atmospheric)
    - Generally lumped together into a single factor

$$L$$

RADAR

- RADAR equation
  - Signal power density at the target

$$P_{D_{target}} = [P_T]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L}\right]$$

RADAR

- RADAR equation
  - Radar cross section – RCS
    - σ
    - Apparent size of target
    - No necessarily the actual size , but a measure of how much of the incident radiation it reflects
    - m^2

    - Front of a truck vs the front to a sports car
    - smooth surface vs a concave space

RADAR

- RADAR equation
  - Reflected power
    - Incident wave power density x radar cross section
    - $P_{Reflected} = [P_T]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L}\right]\sigma$

RADAR

- RADAR equation
  - Receive signal spread factor

$$S_{Rx} = \frac{1}{4\pi R^2}$$

  - R = range

RADAR

- RADAR equation
  - Receive Aperture
    - Measure of how effective an antenna is at receiving the power of specific electromagnetic radiation

$$A$$

RADAR

- RADAR equation
  - Dwell Time
    - The time that an antenna beam spends on a target
    - Dependent on the beam size and speed of rotation of the antenna

$$\tau$$

RADAR

- RADAR equation

$$Receive\ Signal\ Energy =$$

$$[P_T]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L}\right][\sigma]\left[\frac{1}{4\pi R^2}\right][A][\tau\ ]$$

$$W \qquad \frac{1}{m^2} \qquad m^2 \quad \frac{1}{m^2} \quad m^2\ \ s = Ws$$

RADAR

- RADAR equation
  - Noise
    - Atmospheric interference
    - Solar noise
    - Ground noise
    - Other EM noise
    - System noise
    - Assume – Noise can be characterized as a noise temperature = T_S

$$\text{Noise power(N)} = kB_N T_S$$

- k – Boltzmann's constant = 1.38 x 10^{-23} joules / K
- B_N – receiver noise bandwidth

RADAR

- RADAR equation
  - Signal to Noise Ratio - Tracking version
    - Know where the target is → dwell time not part of the analysis
    - S/N = Received signal power / Noise power

$$\frac{[P_T]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L}\right][\sigma]\left[\frac{1}{4\pi R^2}\right][A]}{kB_NT_S}$$

- Note : $G_T = \left[\frac{4\pi A}{\lambda^2}\right]$
- Let : $G_R = \left[\frac{4\pi A}{\lambda^2}\right]$

$[A] \rightarrow \left[\frac{G_R\lambda^2}{4\pi}\right]$

- Assume $G_T = G_R = G$

$$S/_N = \frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_S B_N L}$$

RADAR

- RADAR equation
  - Signal to Noise Ratio - Searching version
    - Need to scan for the target
      - Average power = P_{AV}
      - Solid Angle = Ω
      - Scan time for Ω = t_S

$$S/_{N} = \frac{P_{av} A t_s \sigma}{4\pi \Omega R^4 k T_S L}$$

RADAR

- RADAR equation
  - Signal to Noise Ratio - Searching version

$$S/N = \frac{P_{av} A t_s \sigma}{4\pi \Omega R^4 k T_S L}$$

solving for P_{av}

$$P_{av} = \frac{4\pi \Omega R^4 k T_S L \left(S/N\right)}{A t_s \sigma}$$

- Linear function of everything except R
- Strong function of R

RADAR

- RADAR equation
  - P_{av} - Searching version

$$P_{av} = \frac{4\pi\Omega R^4 k T_S L \left({}^{S}/{}_{N}\right)}{A t_s \sigma}$$

- Assuming a given RADAR system performance and hardware:
  - doubling the search range requires a 16x increase in the average power
  - capturing a ½ size target with the same s/n requires a 2x increase in average power

RADAR

- RADAR equation – ex. – Airport Tracking RADAR
  - RADAR parameters

RADAR SYSTEM PARAMETERS		
Peak Power	1.4 MW	61.46 dB
Antenna Aperture	5 m x 3 m	
Pulsed Signal Frequency	2.8 GHz	
Pulse Signal Wavelength	103 mm	-9.9 dB
Pulse Width	600 ns	
Pulse Repetition Rate	1200 Hz	
Pulse Duty Cycle	0.00072%	
Receiver Noise Bandwidth	1.5 MHz	61.7 dB
Effective Noise Temperature	900 K	29.5 dB
Typical system Losses	6.3	8 dB
Antenna Rotation Rate	12 rpm	
Azimuth Beamwidth	1.3 °	
Calculated Parameters		
Antenna Gain 4 π A / λ2	17,767	42 dB
with beam forming losses	1,700	32.3 dB
Pulses per Beamwidth	22.5	
Constants		
4pi	12.566	11 dB
k	1.38E-23	-228.6 dB

RADAR

- RADAR equation – ex. – Airport Tracking RADAR
  - RADAR parameters

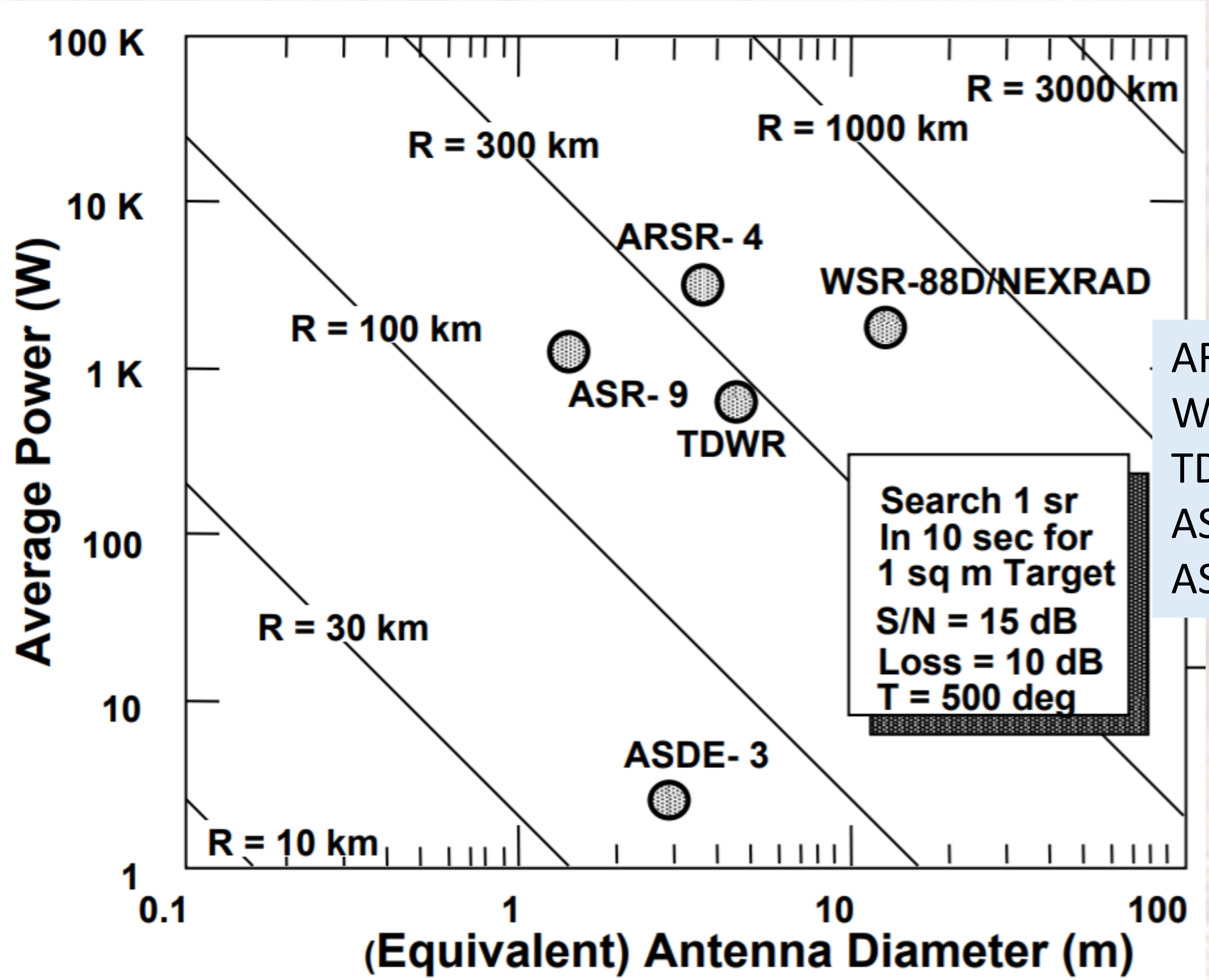
$$S/_N = \frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_S B_N L}$$

$$S/_N\ per\ pulse = 1.84 \text{ x } 10^{20} \frac{\sigma}{R^4} = 202.6dB \frac{\sigma}{R^4}$$

- given a 1m^2 target at 70miles
  - S/N per pulse = 1.14 = 0.569dB
  - S/N per dwell = 25.7 = 14.09dB

RADAR

- RADAR performance

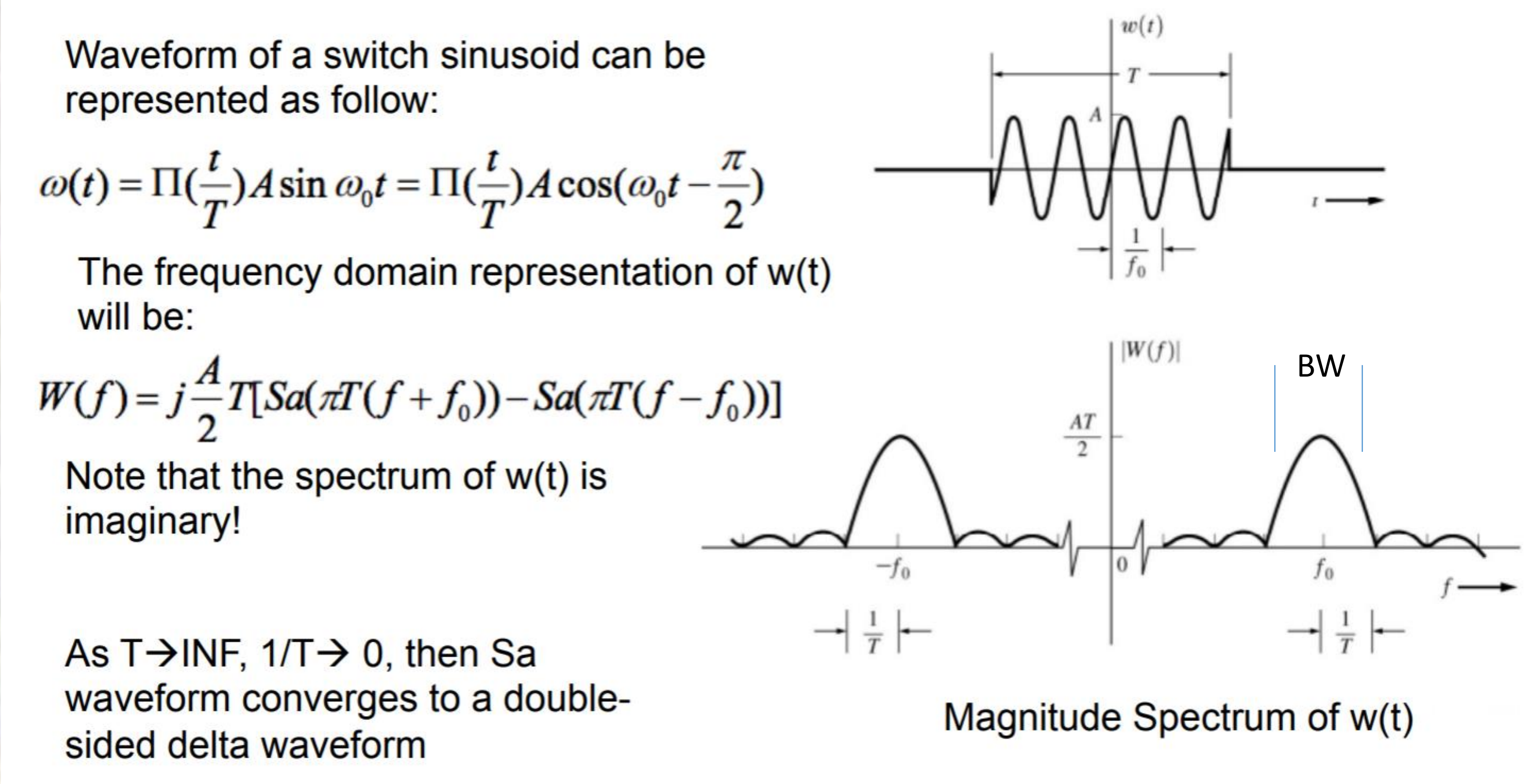


src: MIT Lincoln Laboratory

ARSR: Air Route Surveillance
WSR-88D: Weather
TDWR: Doppler Weather
ASR-9: Airport Surveillance
ASDE-3: Airport Surface

RADAR

- RADAR performance



Waveform of a switch sinusoid can be represented as follow:

$$\omega(t) = \Pi(\frac{t}{T})A\sin\omega_0 t = \Pi(\frac{t}{T})A\cos(\omega_0 t - \frac{\pi}{2})$$

The frequency domain representation of w(t) will be:

$$W(f) = j\frac{A}{2}T[Sa(\pi T(f+f_0)) - Sa(\pi T(f-f_0))]$$

Note that the spectrum of w(t) is imaginary!

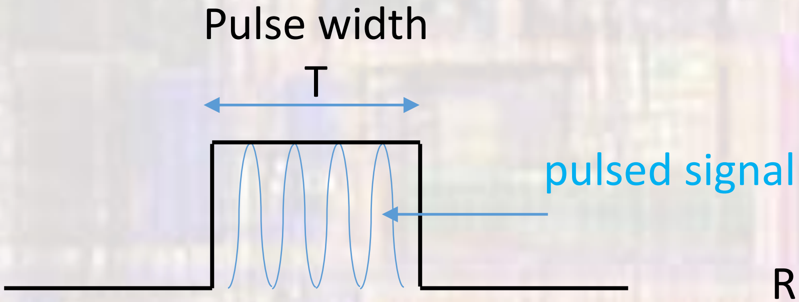
As T→INF, 1/T→ 0, then Sa waveform converges to a double-sided delta waveform

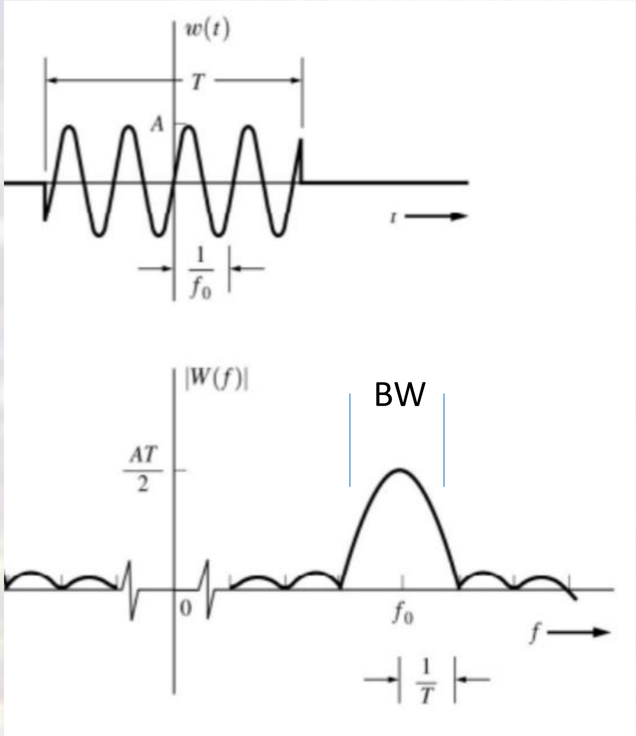
Magnitude Spectrum of w(t)

src: Middle Tennessee State University
un-attributed

RADAR

- RADAR performance





Range Resolution Δr

– Proportional to pulse width (T)

$$\Delta r = (CT)/2$$

– Inversely proportional to bandwidth (B = 1/T)

$$\Delta r = C/(2B)$$

1 MHz Bandwidth => Δr = 150 m of range error

RADAR

- RADAR performance

$$\Delta r = (CT)/2 = C/(2B)$$

$$S/_N = \frac{P_{av} A t_s \sigma}{4\pi\Omega R^4 k T_S L}$$

- P_{av} ~ pulse width T
- Δr ~ pulse width T, ~ 1/B

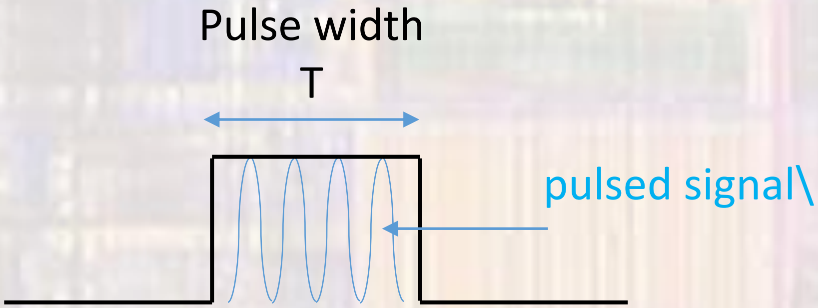
- Difficult to get good S/N and good range error at the same time

RADAR

- RADAR performance
  - 2 approaches to get: high average power (wide T) and low range error (high B)
    - Frequency modulated carrier
    - Phase modulated carrier

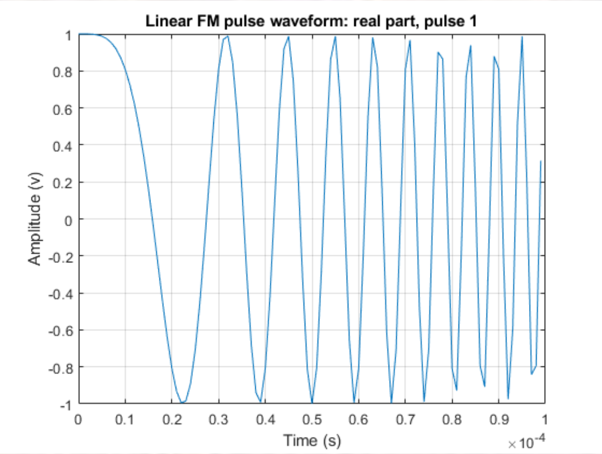
RADAR

- RADAR performance
  - Frequency modulated pulse – Linear



B = 1/T

T x B = 1

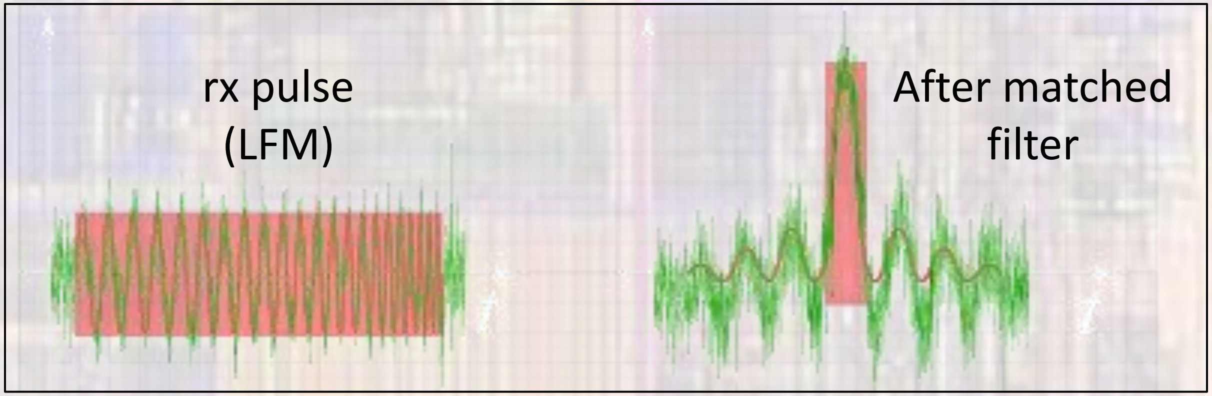


B = ΔF = F2 – F1

T x B = T C

RADAR

- RADAR performance
  - Frequency modulated pulse – Linear



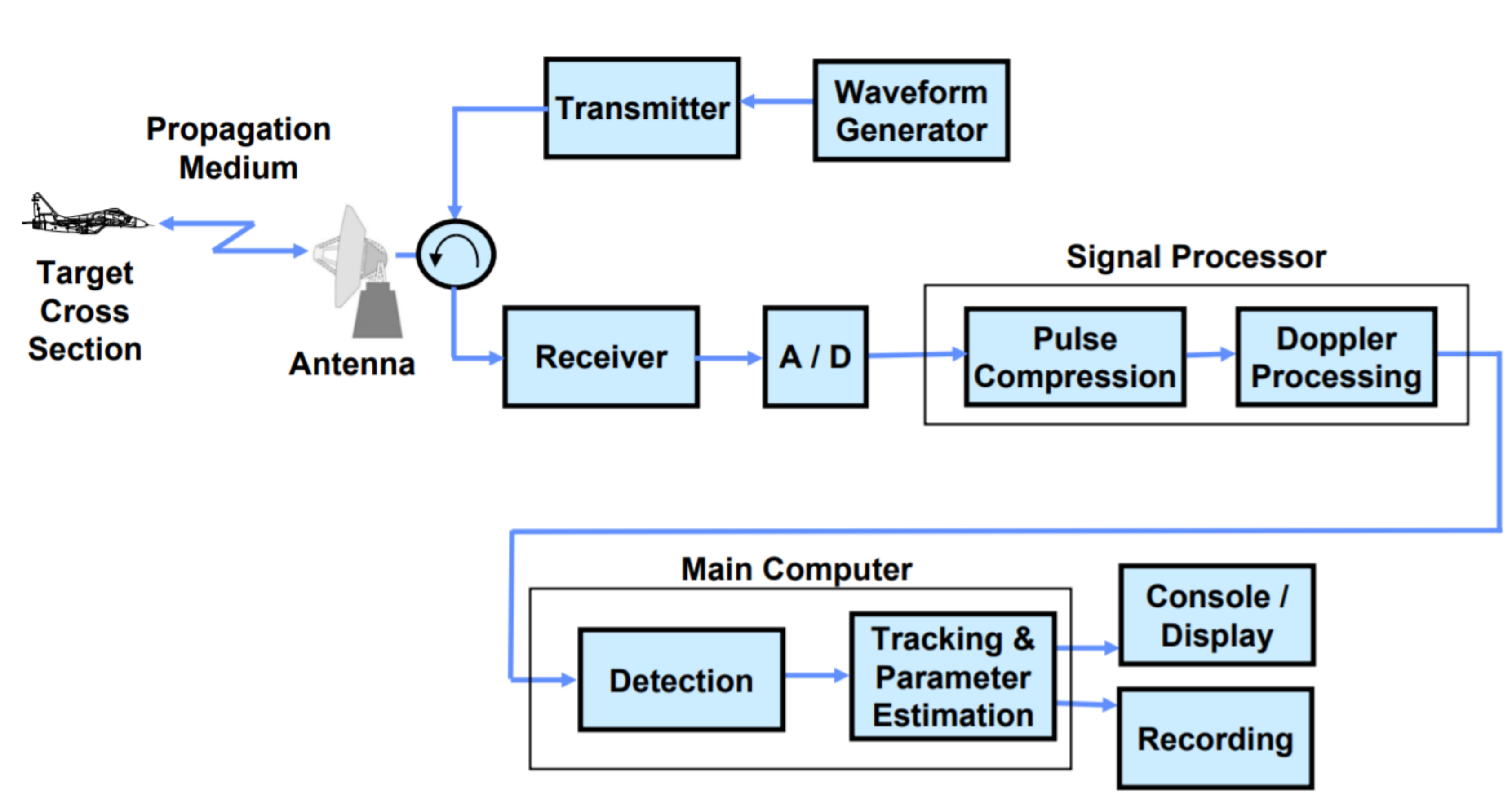
src: radartutorial.eu

  - Fix T → P_{av} → good S/N
  - Linear frequency Modulation → ↑B → ↓ Δr

  - Requires a matched filter in receiver

RADAR

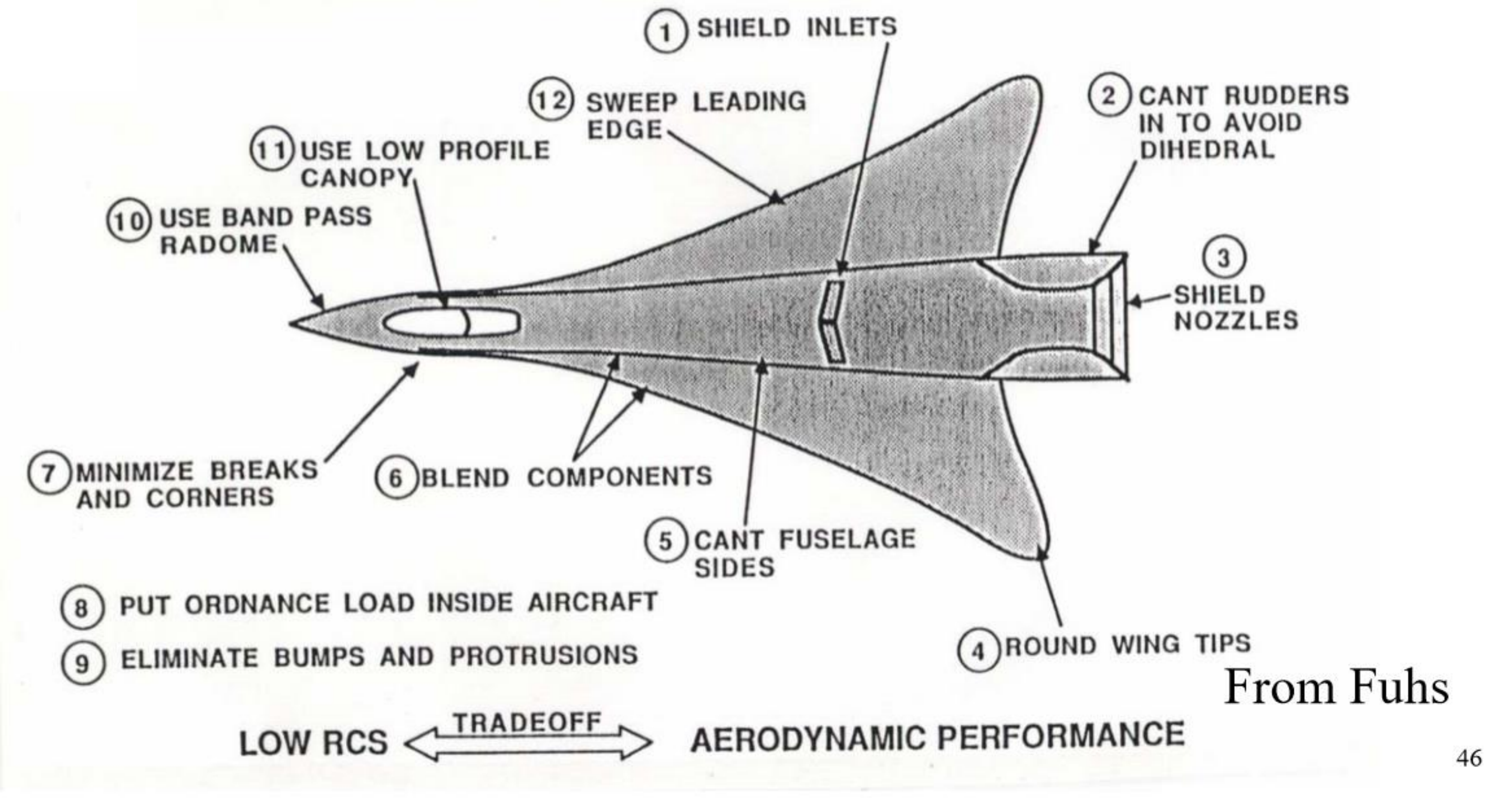
- RADAR System



src: MIT Lincoln Laboratory

RADAR

- RADAR Mitigation



From Fuhs