Introduction to Radar Systems

Dr. Robert M. O'Donnell

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Introduction to Radar Systems

Introduction

Acknowledgement

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  - And many others

Background on the Course

- One of Many Radar Courses Presented at the Laboratory
- Relatively Short
  - 10 lectures
  - 40 to 60 minutes each
- Introductory in Scope
  - Basic Radar Concepts
  - Minimal Mathematical Formalism
- Prerequisite – A College Degree
  - Preferred in Engineering or Science, but not Required
- More Advanced Issues Dealt with in Other Laboratory Radar Courses

Outline

- **Why radar?**
- **The basics**
- **Course agenda**

What Means are Available for Lifting the Fog of War ?

D-Day + 1

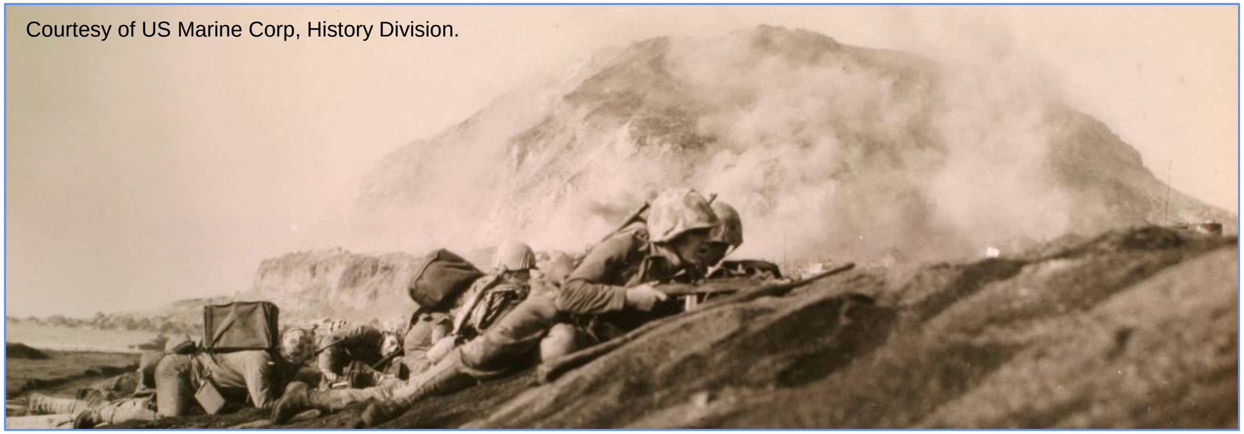
The Invasion of Normandy

D-Day

Courtesy of National Archives.

What Means are Available for Lifting the Fog of War ?

Iwo Jima 1945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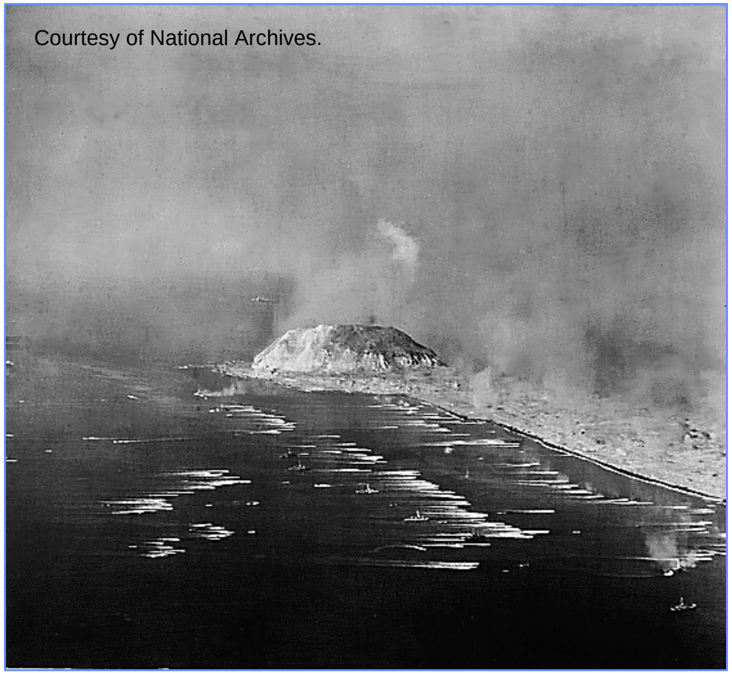
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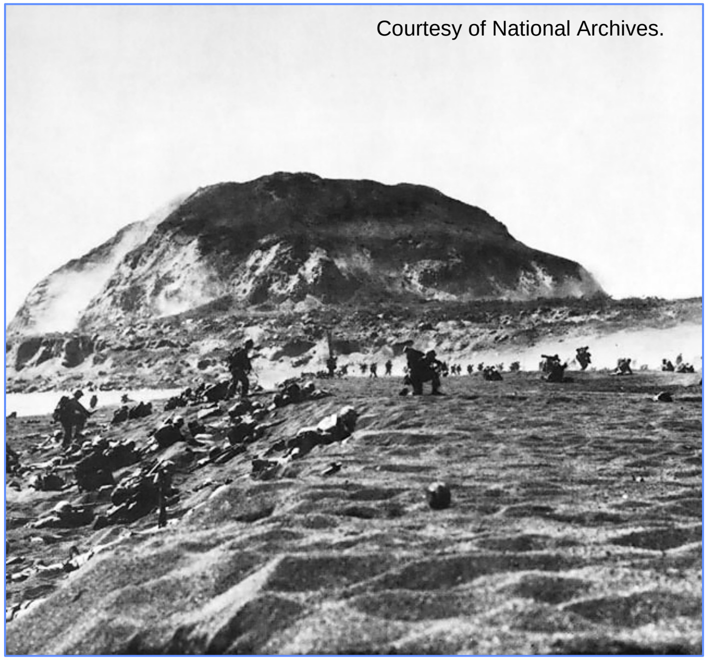

Courtesy of National Archives.

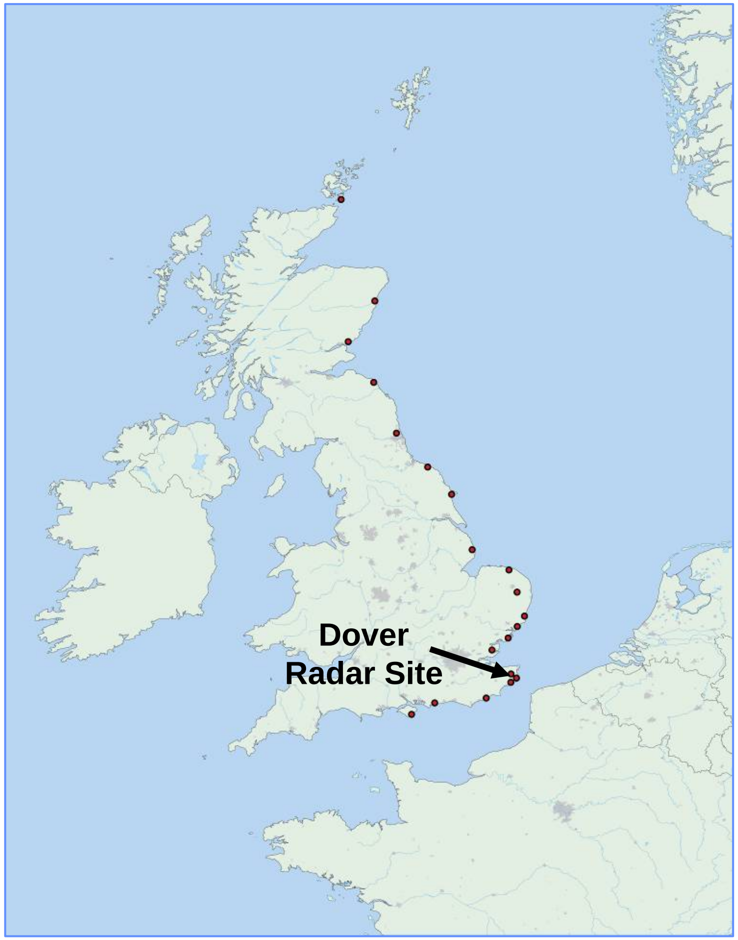
Military Means of Sensing

	Optical/IR	Radar	Acoustic	Other
Applications	• Ground surveillance/ reconnaissance/ID • Laser targeting • Night vision • Space surveillance • Missile seekers	• Surveillance • Tracking • Fire control • Target ID/ discrimination • Ground surveillance/ reconnaissance • Ground mapping • Moving target detection • Air traffic control • Missile seekers	• Sonar • Blast detection • Troop movement detection	• Chem/Bio • Radiological
Attributes		• Long range • All-weather • Day/night • 3-space target location • Reasonably robust against countermeasures		

Early Days of Radar

Chain Home Radar, Deployment Began 1936

Chain Home Radar Coverage circa 1940 (21 Early Warning Radar Sites)



Sept 2006 Photograph of Three Chain Home Transmit Towers, near Dover

Courtesy of Robert Cromwell.
Used with permission.

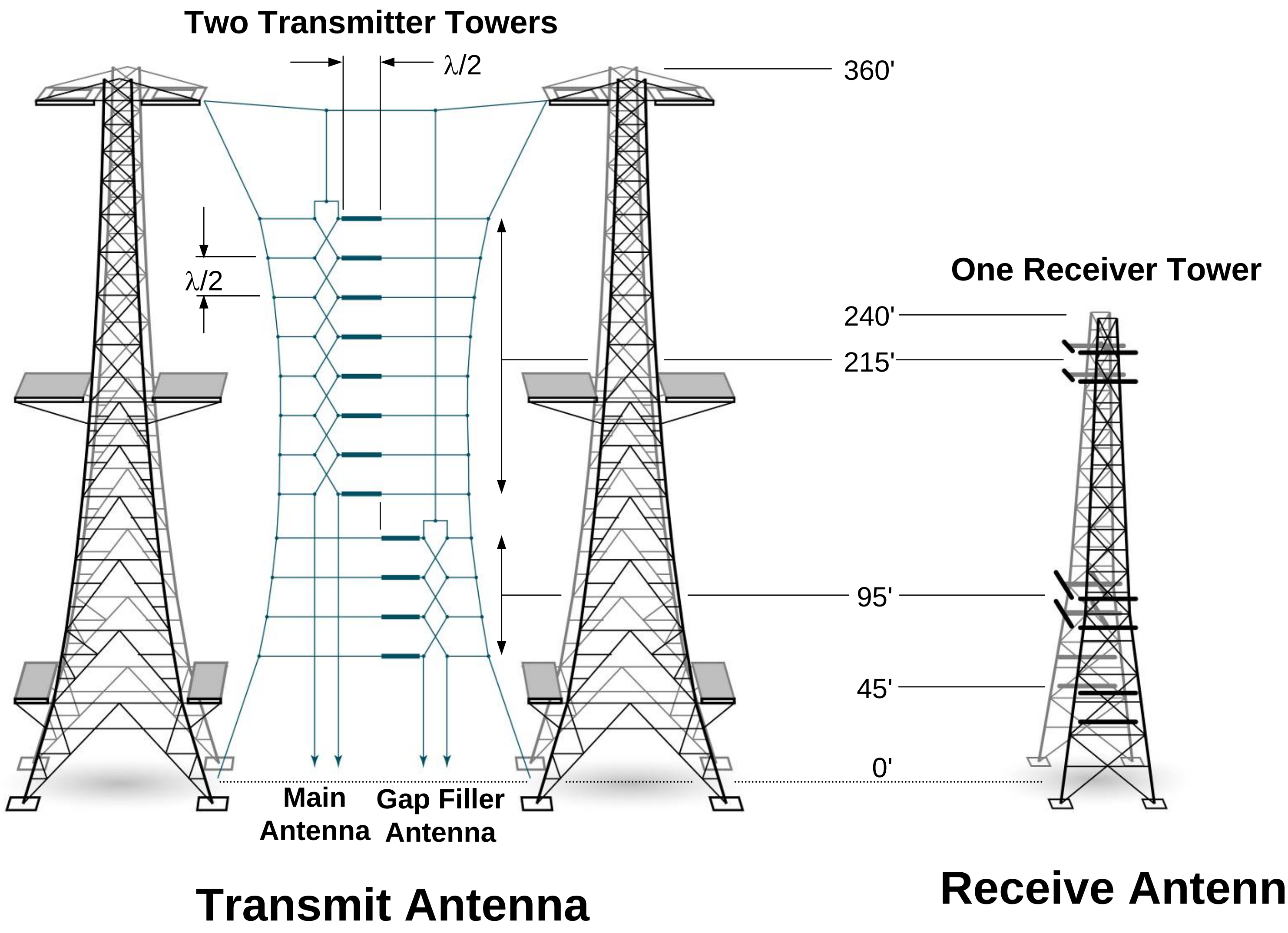
Chain Home Radar System

Typical Chain Home Radar Site

Radar Parameters

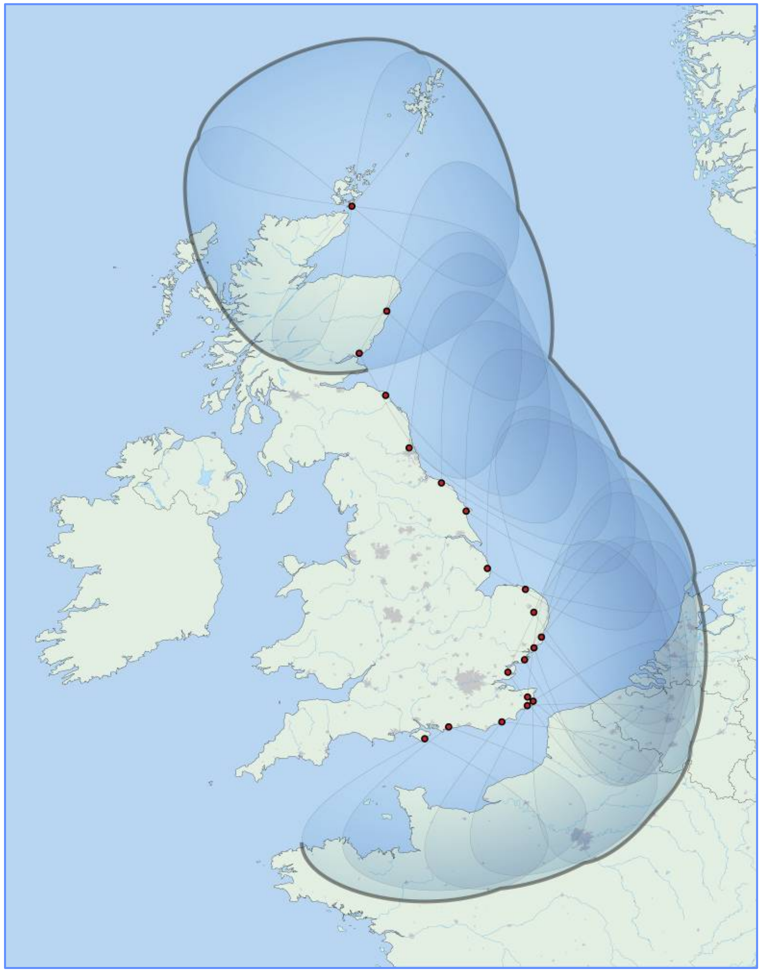
- Frequency
  - 20-30 MHz
- Wavelength
  - 10-15 m
- Antenna
  - Dipole Array on Transmit
  - Crossed Dipoles on Receive
- Azimuth Beamwidth
  - About 100^{o}
- Peak Power
  - 350 kW
- Detection Range
  - ~160 nmi on German Bomber

Chain Home Transmit & Receive Antennas



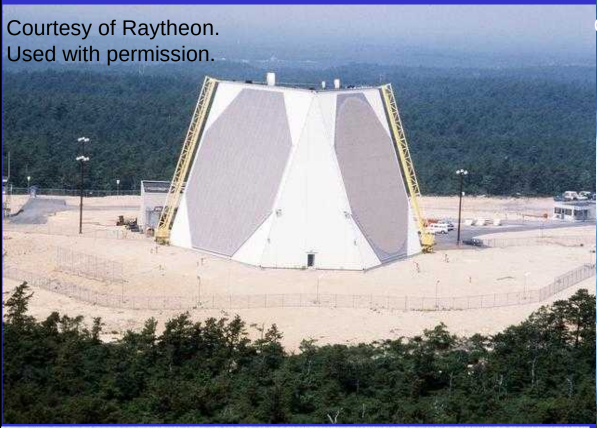
Radar and "The Battle of Britain"

Chain Home Radar Coverage circa 1940 (21 Early Warning Radar Sites)



- **The Chain Home Radar**
  - **British "Force Multiplier" during the Battle of Britain"**
- **Timely warning of direction and size of German aircraft attacks allowed British to**
  - **Focus their limited numbers of interceptor aircraft**
  - **Achieve numerical parity with the attacking German aircraft**
- **Effect on the War**
  - **Germany was unable to achieve Air Superiority**
  - **Invasion of Great Britain was postponed indefinitely**

Surveillance and Fire Control Radars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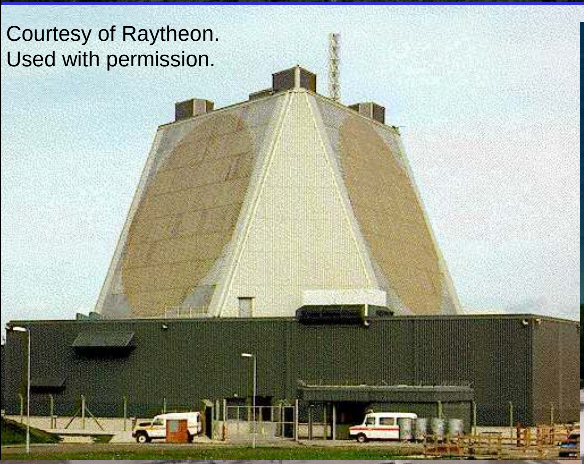
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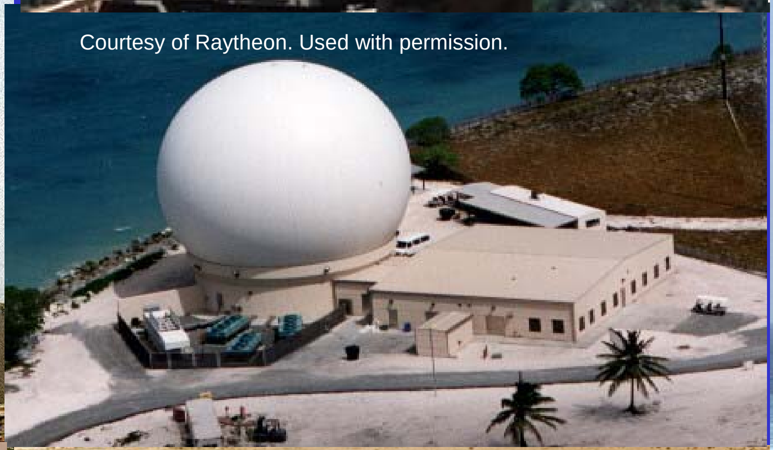
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Courtesy of US Navy.


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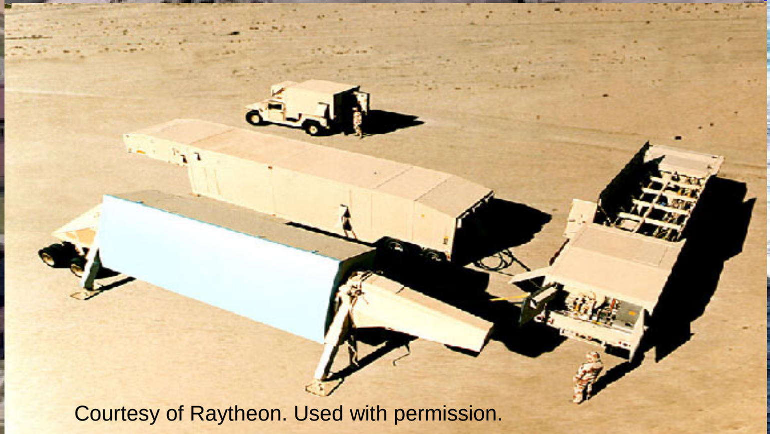
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Airborne and Air Traffic Control Radars

Courtesy Lincoln Laboratory.

Courtesy of US Air Force.

Courtesy of US Navy.

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Courtesy of US Air Force.

Courtesy of US Air Force.

Courtesy of US Air Force.

Instrumentation Radars



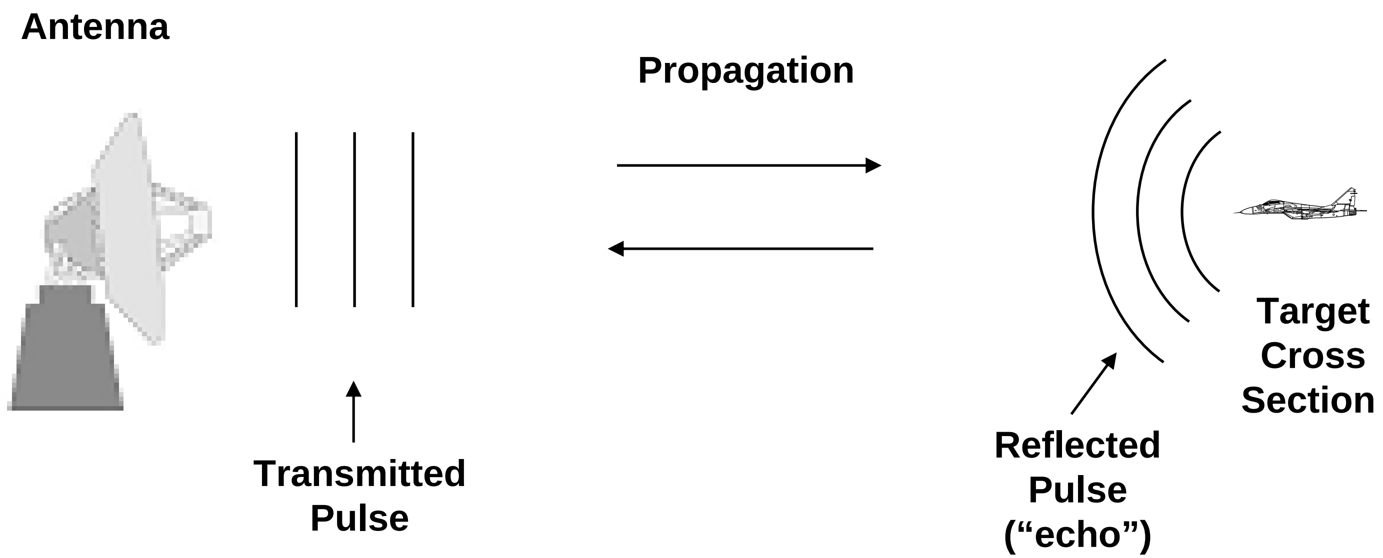



Outline

- **Why radar?**
- **The basics**
- **Course agenda**

RADAR

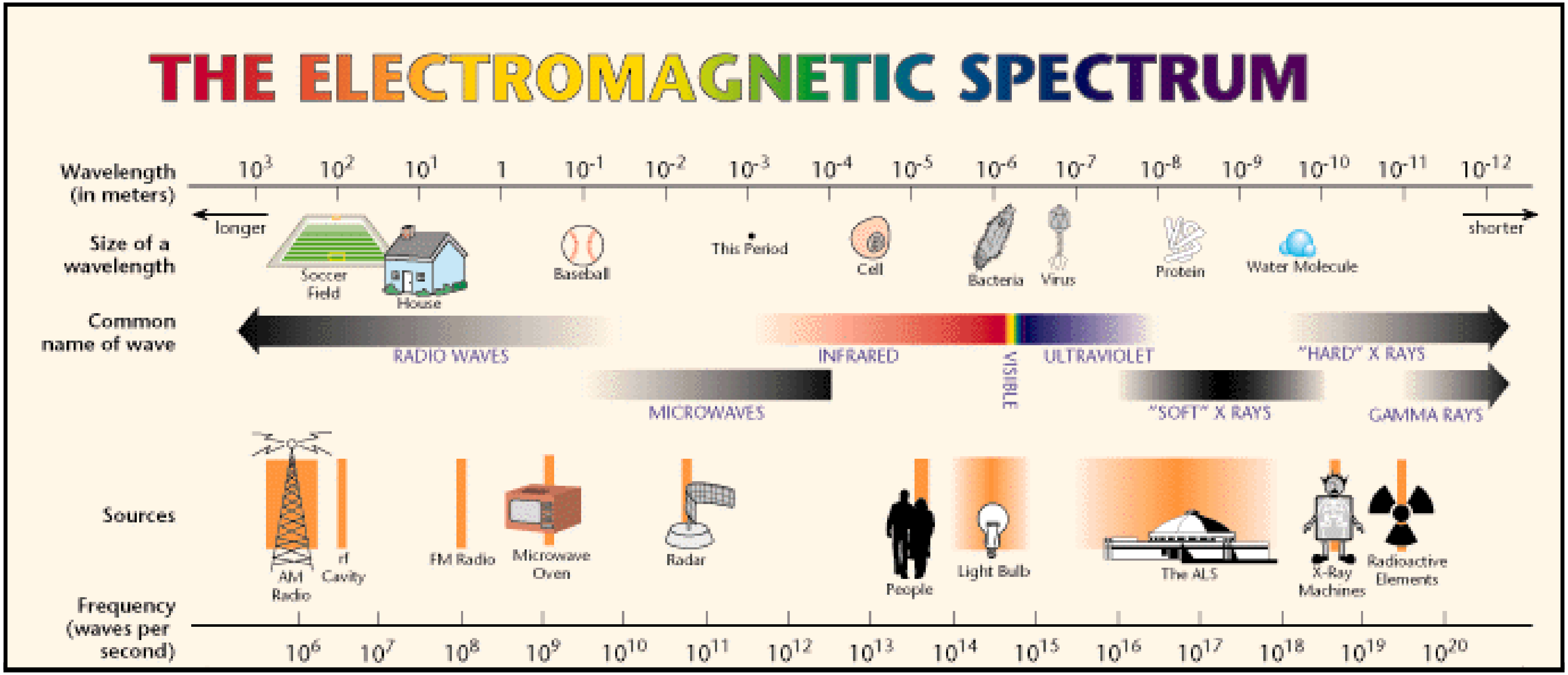
RAdio Detection And Ranging



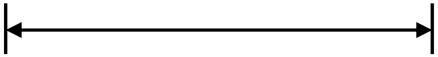
Radar observables:

- Target range
- Target angles (azimuth & elevation)
- Target size (radar cross section)
- Target speed (Doppler)
- Target features (imaging)

Electromagnetic Waves



Courtesy Berkeley National Laboratory



Radar Frequencies

Properties of Waves
Relationship Between Frequency and Wavelength

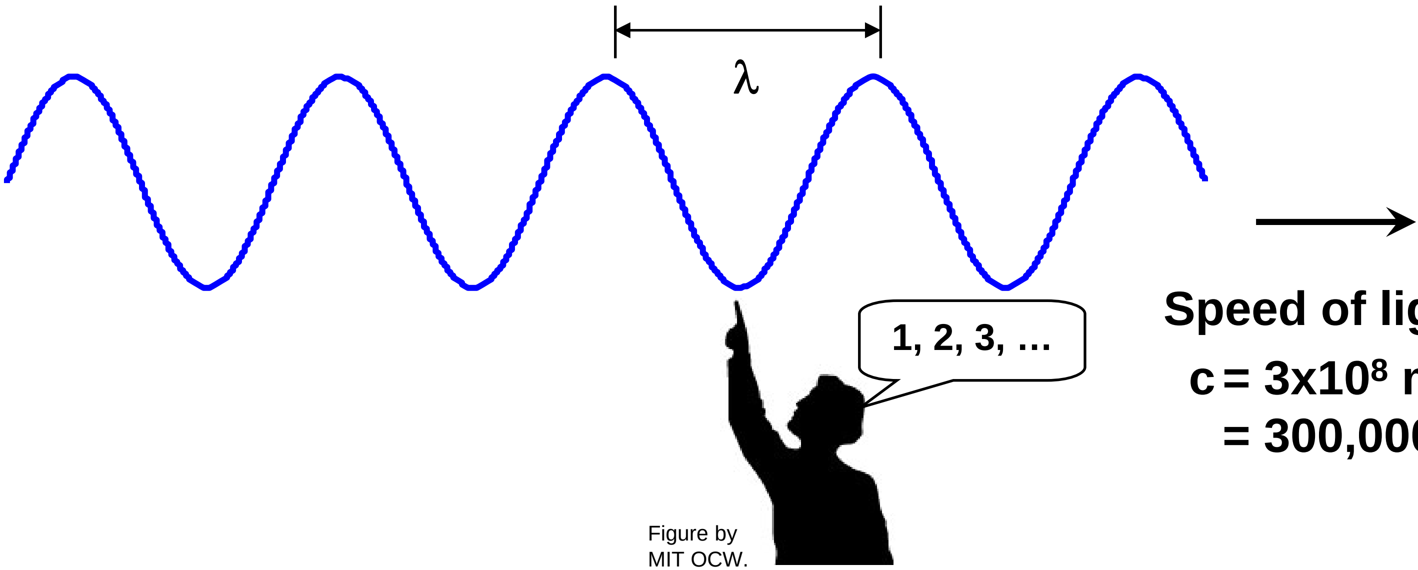


Figure by MIT OCW.

Speed of light, c

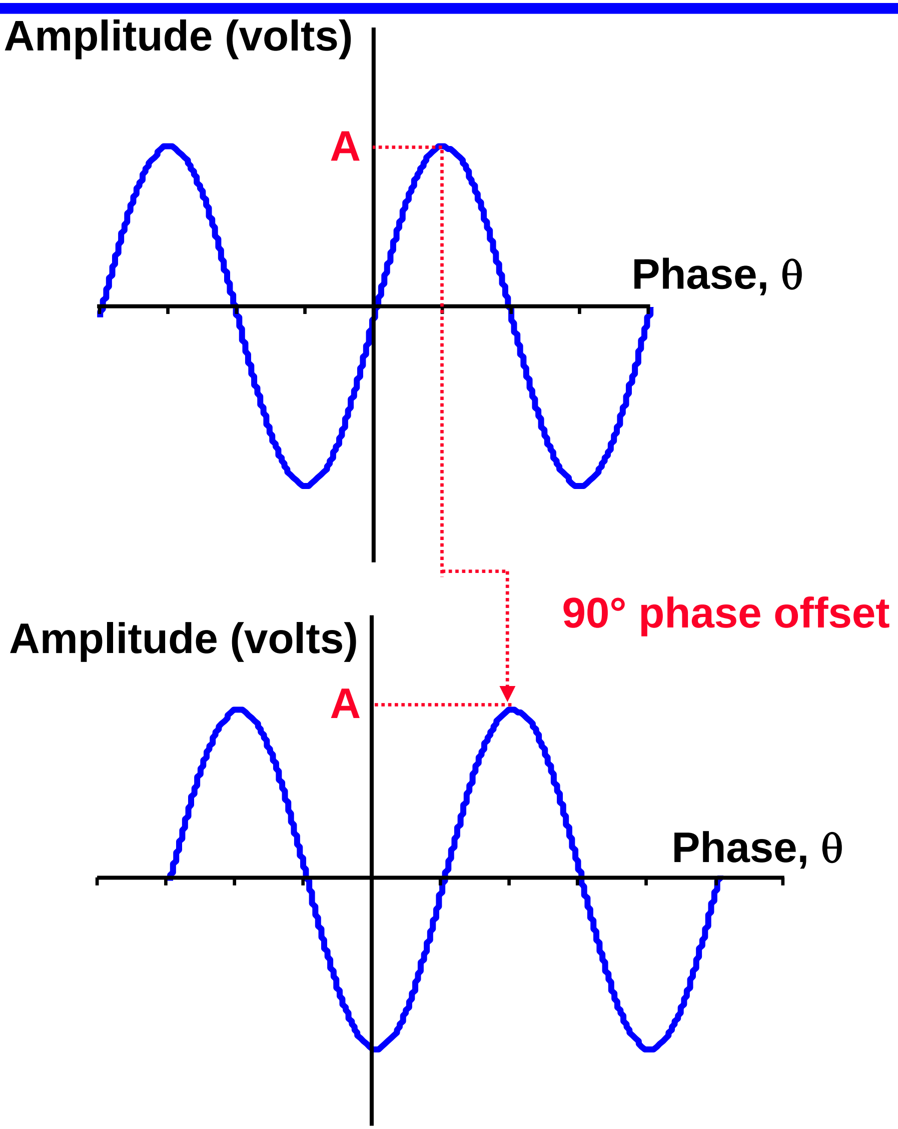
$c = 3 \times 10^8$ m/sec
= 300,000,000 m/sec

$$\text{Frequency (1/s)} = \frac{\text{Speed of light (m/s)}}{\text{Wavelength } \lambda \text{ (m)}}$$

Examples:

Frequency	Wavelength
100 MHz	3 m
1 GHz	30 cm
3 GHz	10 cm
10 GHz	3 cm

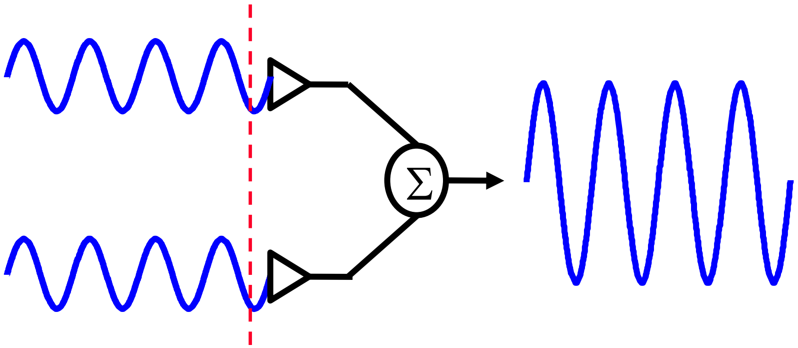
Properties of Waves
Phase and Amplitude



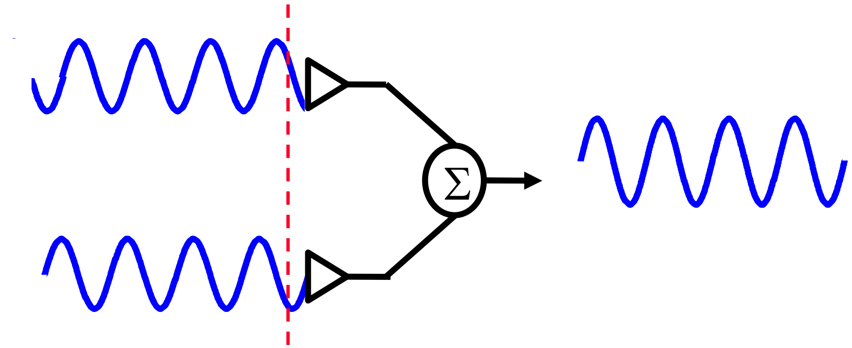
$\mathbf{A\ sin}(\theta)$

$\mathbf{A\ sin}(\theta - 90^o)$

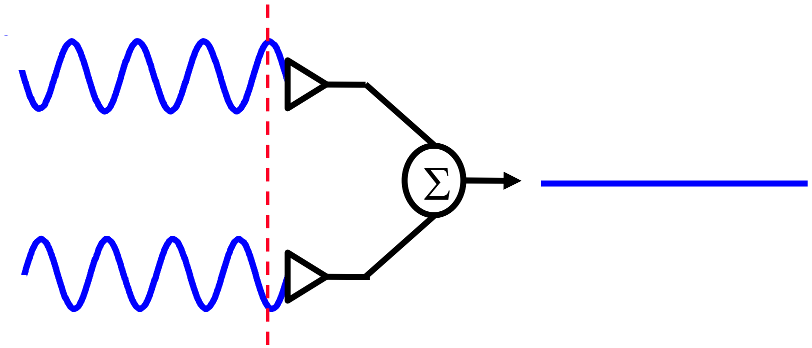
Properties of Waves
Constructive vs. Destructive Addition



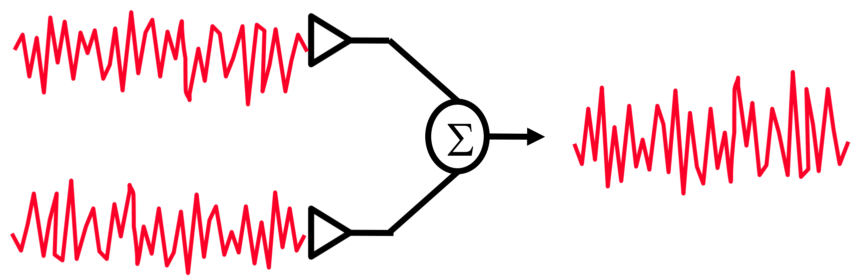
Constructive
(in phase)



Partially Constructive
(somewhat out of phase)



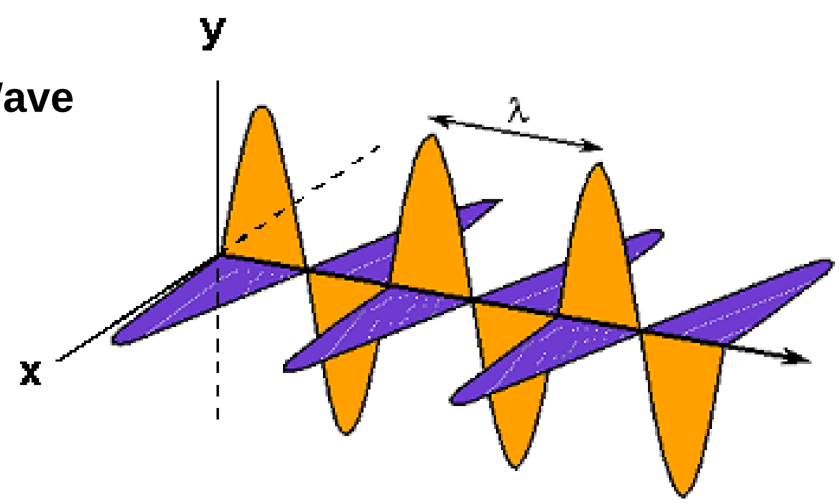
Destructive
(180° out of phase)

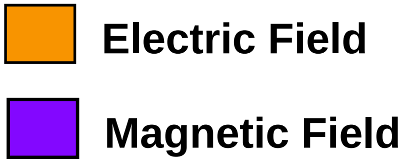


Non-coherent signals
(noise)

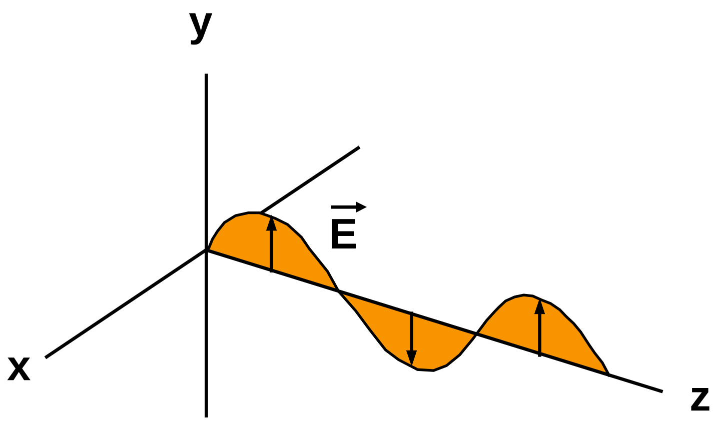
Polarization

Electromagnetic Wave

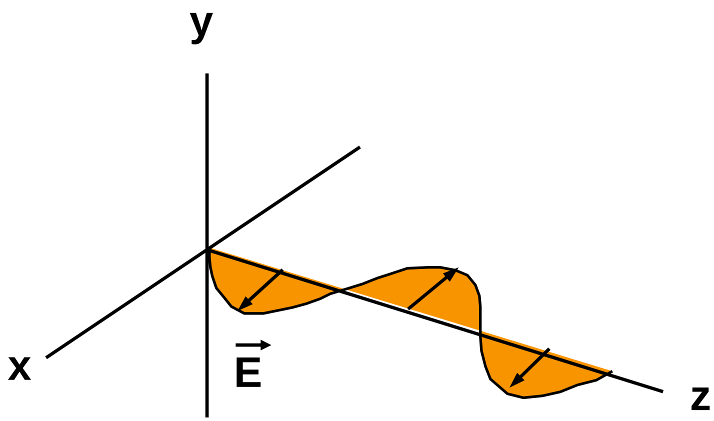




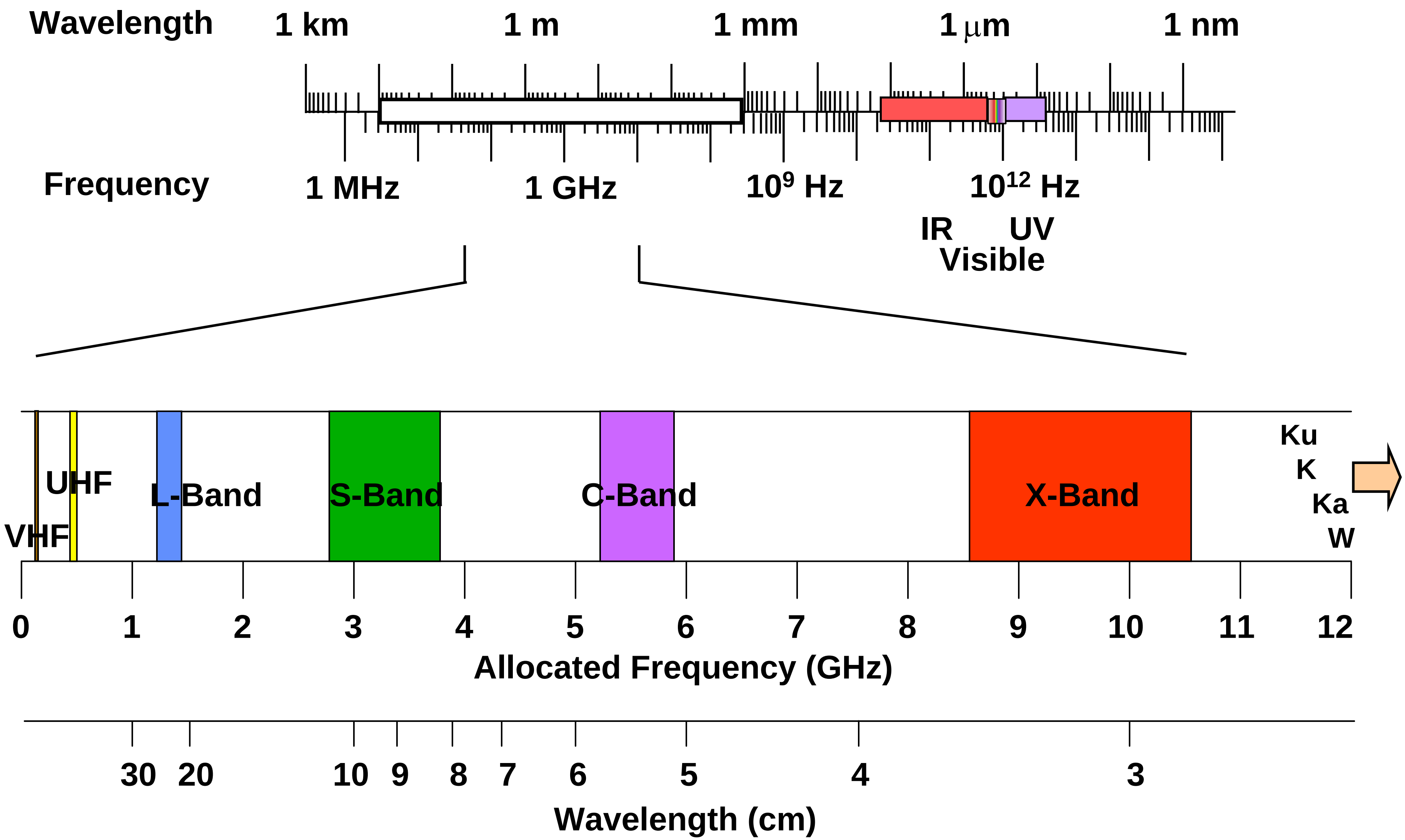
Vertical Polarization



Horizontal Polarization



Radar Frequency Bands



IEEE Standard Radar Bands
(Typical Use)

HF	3 – 30 MHz
VHF	30 MHz–300 MHz
UHF	300 MHz–1 GHz
L-Band	1 GHz–2 GHz
S-Band	2 GHz–4 GHz
C-Band	4 GHz–8 GHz
X-Band	8 GHz–12 GHz
Ku-Band	12 GHz–18 GHz
K-Band	18 GHz–27 GHz
Ka-Band	27 GHz–40 GHz
W-Band	40 GHz – 100+ GHz

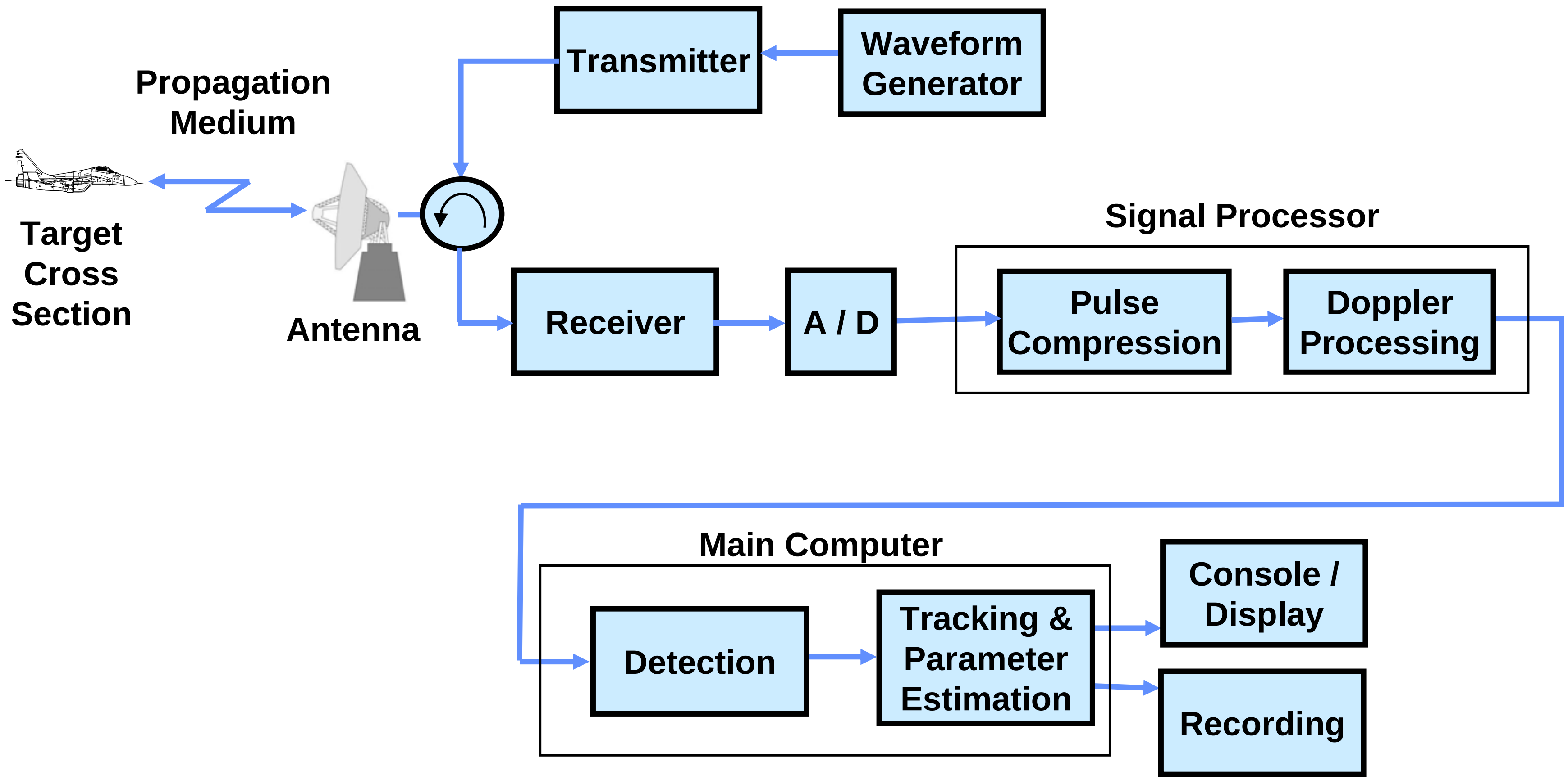
Search Radars

Search & Track Radars

Fire Control & Imaging Radars

Missile Seekers

Radar Block Diagram



Radar Range Equation

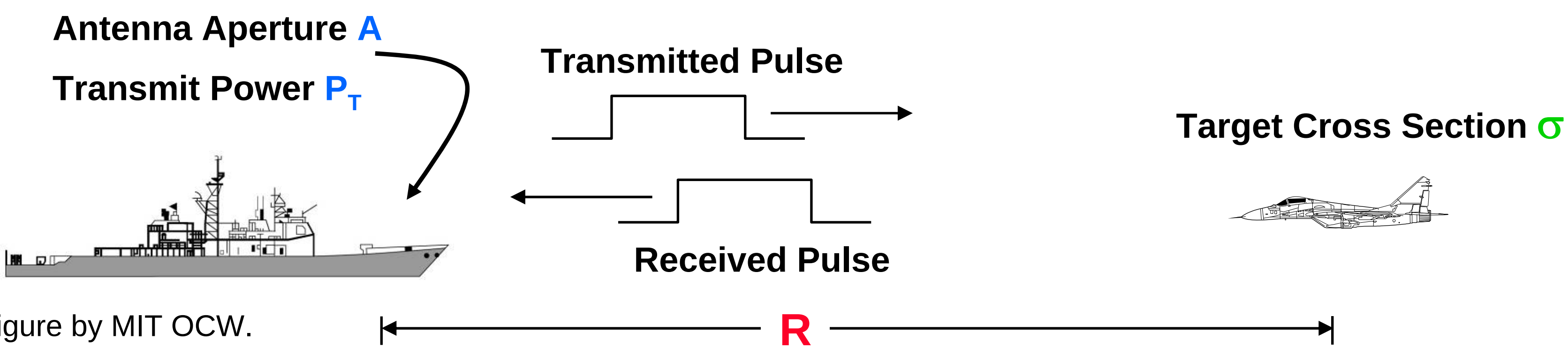
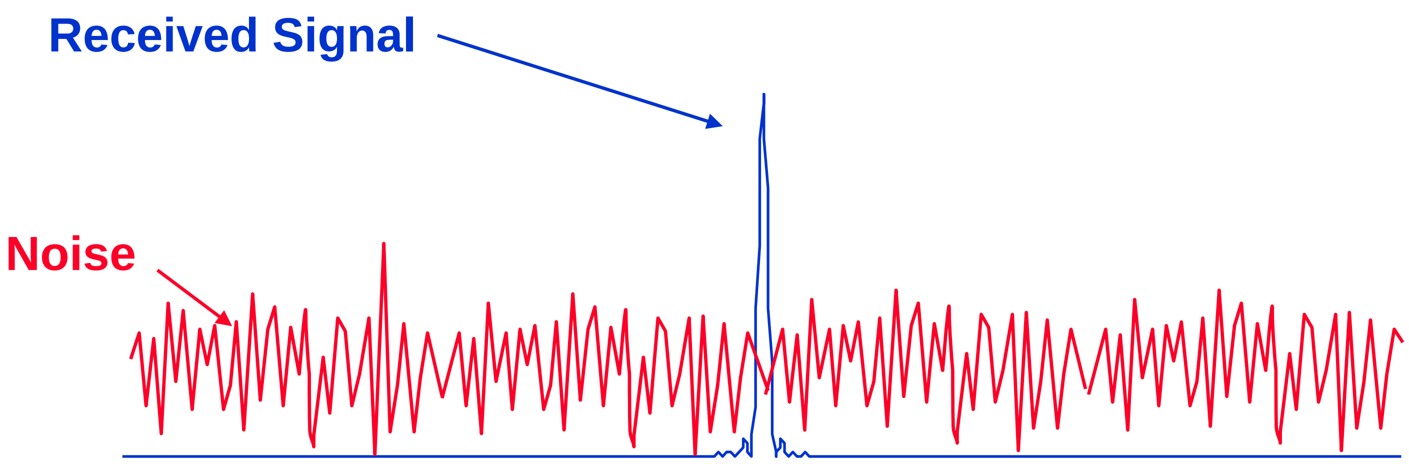


Figure by MIT OCW.

	Transmit Power	Transmit Gain	Spread Factor	Losses	Target RCS	Spread Factor	Receive Aperture	Dwell Time

$$\text{Received Signal Energy} = \left[\, P_T \,\right] \left[\frac{4\pi A}{\lambda^2}\right] \left[\frac{1}{4\pi R^2}\right] \left[\frac{1}{L}\right] \left[\, \sigma \,\right] \left[\frac{1}{4\pi R^2}\right] \left[\, A \,\right] \left[\, \tau \,\right]$$

Signal-to-Noise Ratio



$$\text{SNR} = \frac{\text{Received Signal Energy}}{\text{Noise Energy}}$$

What the #@!*% is a dB?

The relative value of two things, measured on a logarithmic scale, is often expressed in deciBel's (dB)

Example:

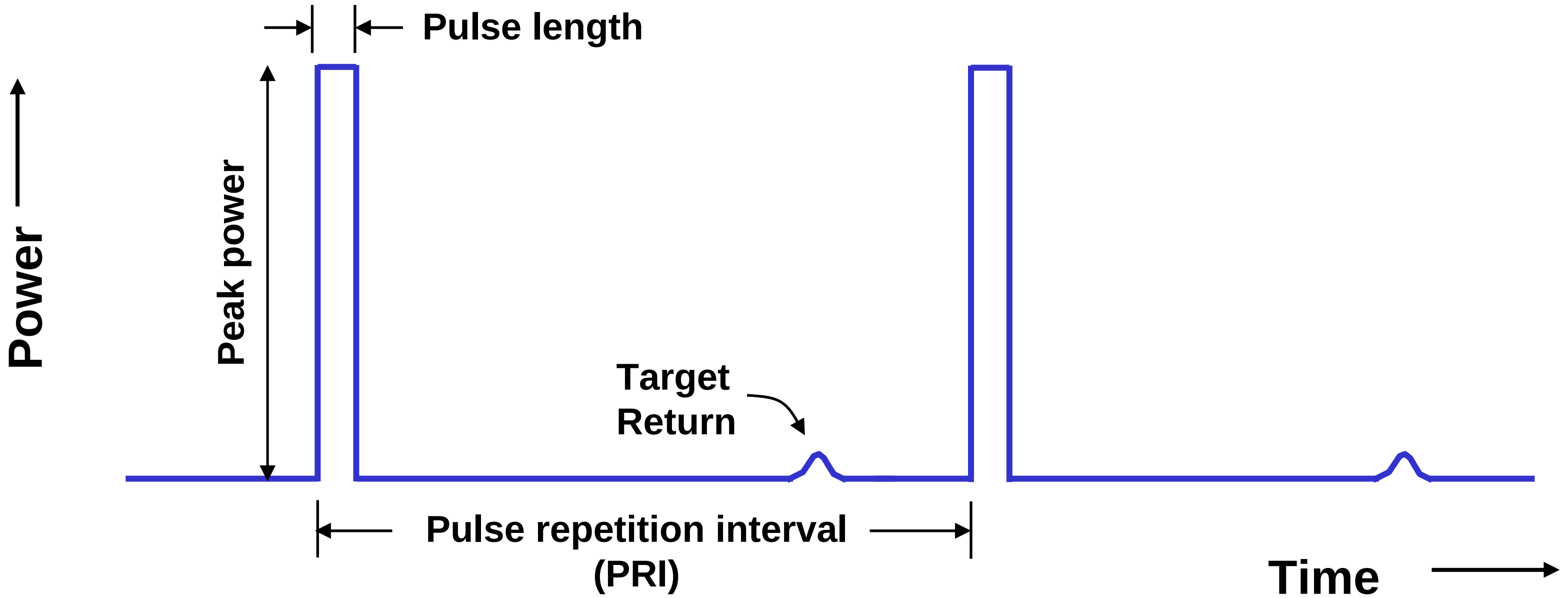
$$\text{Signal-to-noise ratio (dB)} = 10 \log_{10} \left[\frac{\text{Signal Power}}{\text{Noise Power}} \right]$$

Factor of:	Scientific Notation	dB
10	10^1	10
100	10^2	20
1000	10^3	30
⋮		
1,000,000	10^6	60

0 dB = factor of 1
-10 dB = factor of 1/10
-20 dB = factor of 1/100

3 dB = factor of 2
-3 dB = factor of 1/2

Pulsed Radar
Terminology and Concepts



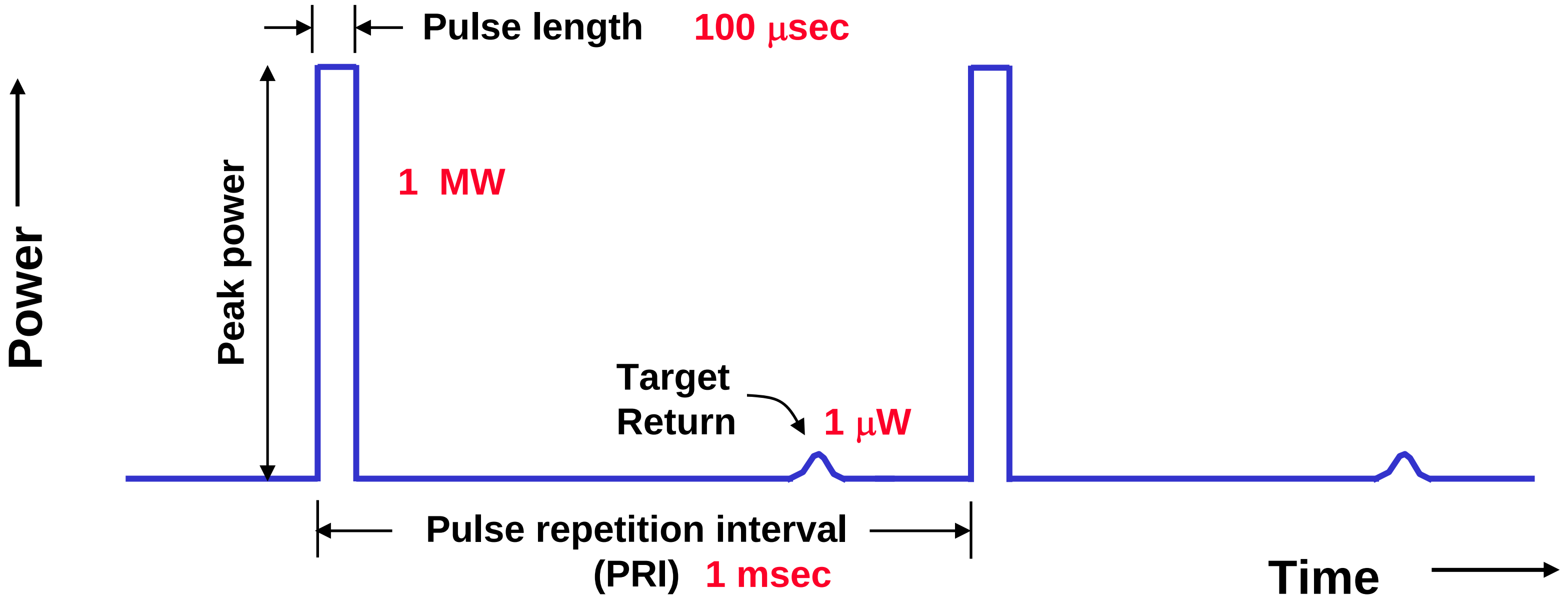
Duty cycle = $\frac{\text{Pulse length}}{\text{Pulse repetition interval}}$

Average power = Peak power * Duty cycle

Pulse repetition frequency (PRF) = 1/(PRI)

Continuous wave (CW) radar: Duty cycle = 100% (always on)

Pulsed Radar
Terminology and Concepts



Duty cycle = $\frac{\text{Pulse length}}{\text{Pulse repetition interval}}$ 10%

Average power = Peak power * Duty cycle 100 kW

Pulse repetition frequency (PRF) = 1/(PRI) 1 kHz

Continuous wave (CW) radar: Duty cycle = 100% (always on)

Brief Mathematical Digression

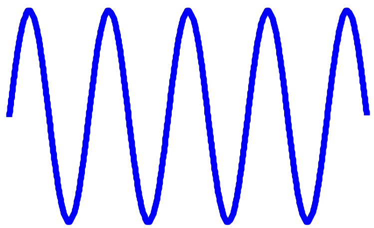
Scientific Notation and Greek Prefixes

Scientific Notation	Standard Notation	Greek Prefix	Radar Examples
10^9	1,000,000,000	Giga	GHz
10^6	1,000,000	Mega	MHz, MW
10^3	1,000	kilo	km
10^1	10	-	-
10^0	1	-	-
10^{-3}	0.001	milli	msec
10^{-6}	0.000,001	micro	μsec

MHz = Megahertz
MW = Megawatt

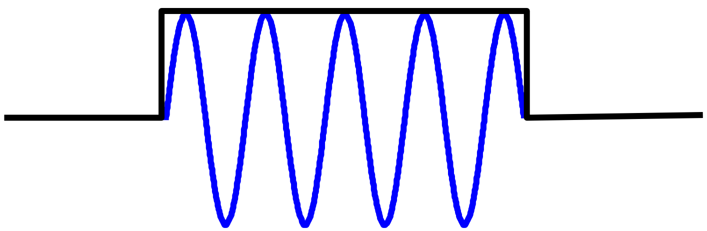
Radar Waveforms

What do radars transmit?



Waves?

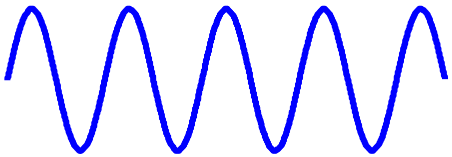
or Pulses?

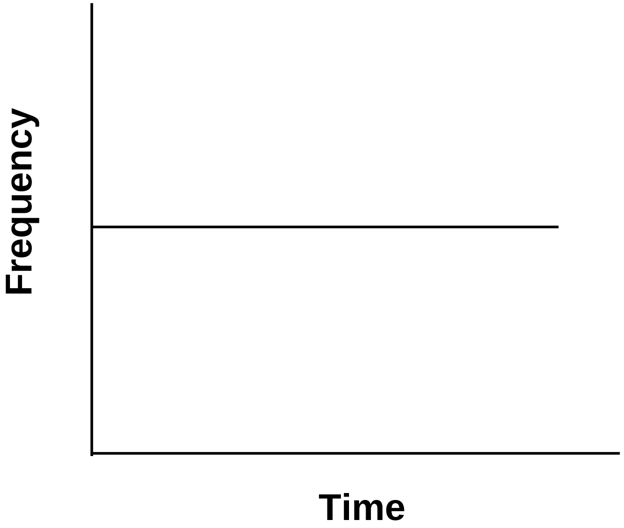


Waves, modulated by "on-off" action of pulse envelope

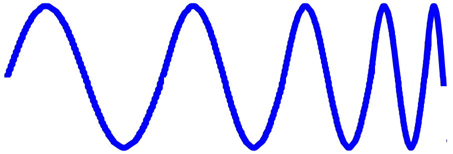
Radar Waveforms (cont'd.)

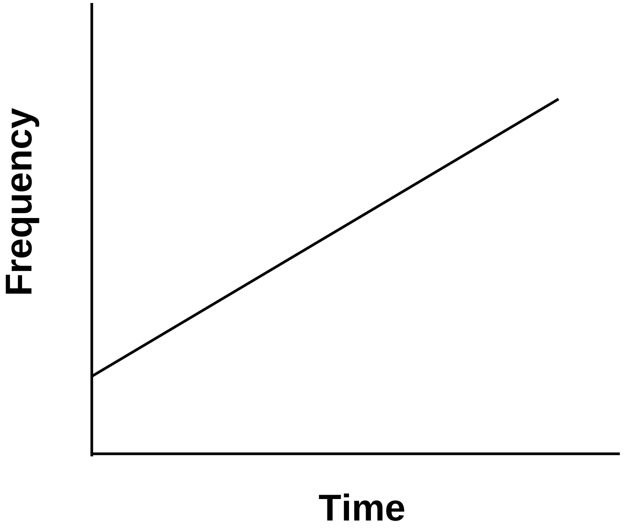
Pulse at single frequency





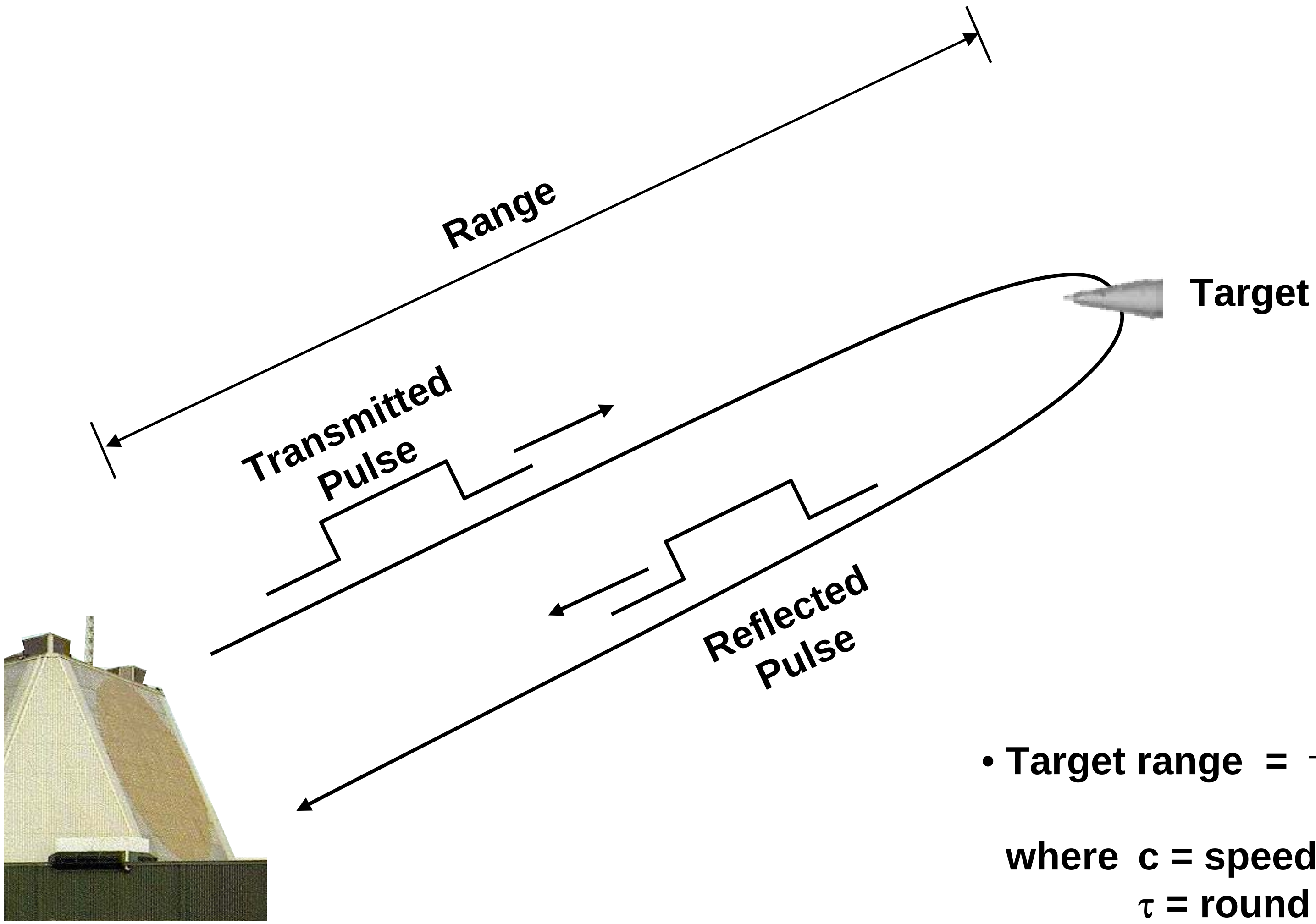
Pulse with changing frequency





Linear Frequency-Modulated (LFM) Waveform

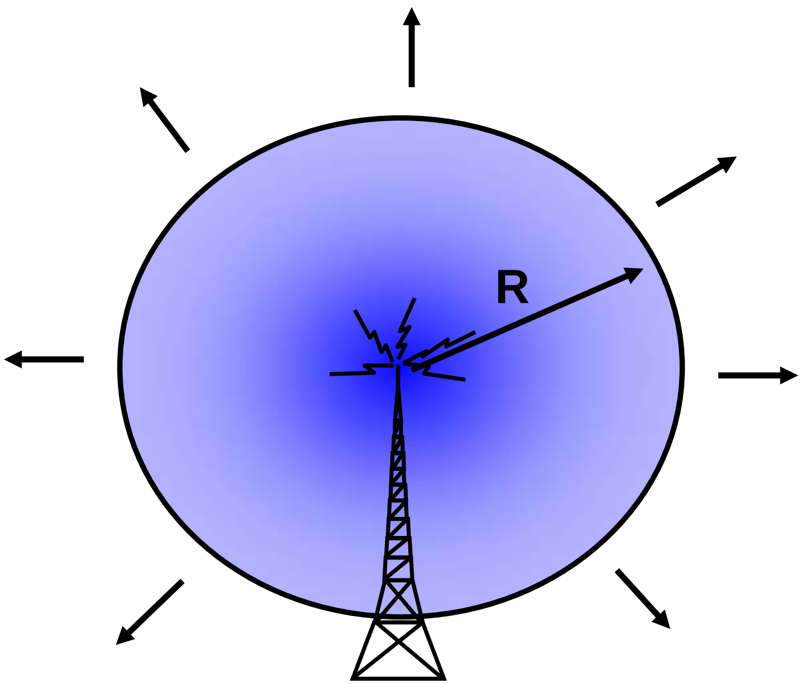
Radar Range Measurement

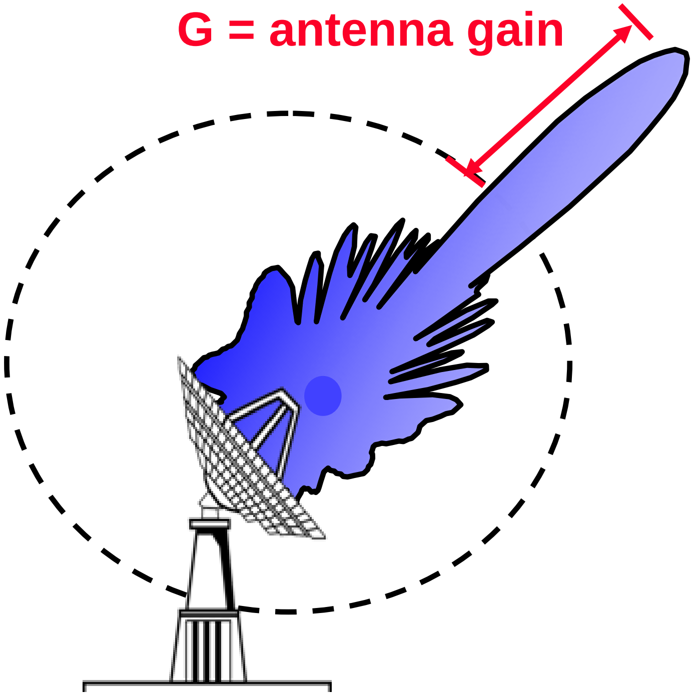


- Target range $= \dfrac{c\tau}{2}$

  where c = speed of light
  τ = round trip time

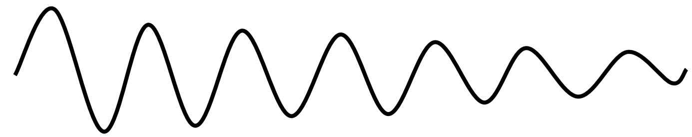
Antenna Gain



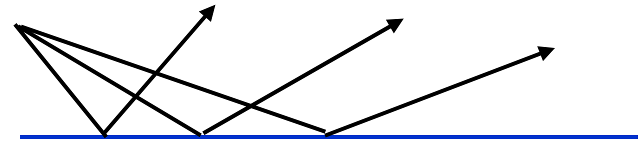


Propagation Effects on Radar Performance

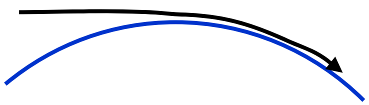
- **Atmospheric attenuation**



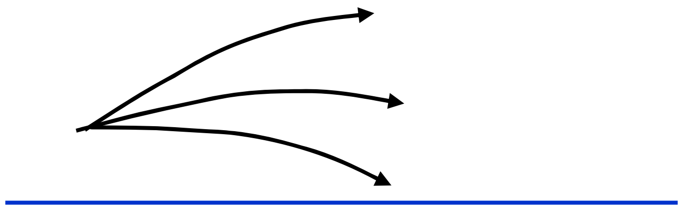
- **Reflection off of earth's surface**



- **Over-the-horizon diffraction**

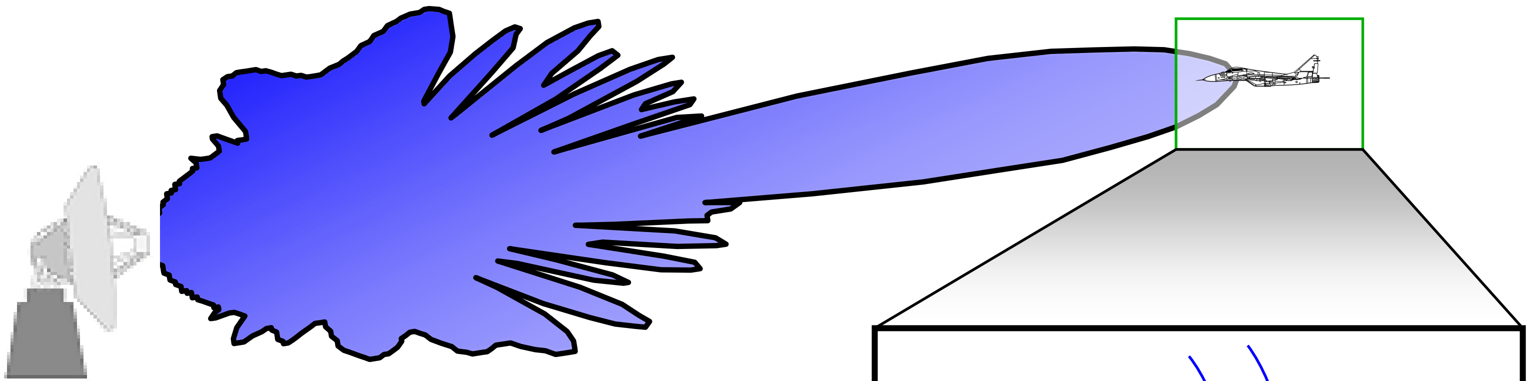


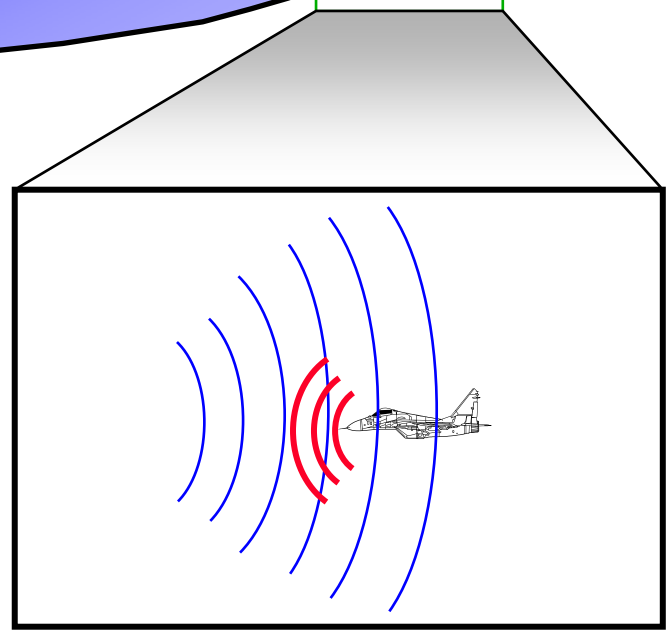
- **Atmospheric refraction**



Radar beams can be attenuated, reflected and bent by the environment

Radar Cross Section (RCS)





RCS

Incident Power Density (Watts/m^2) x σ (m^2) = **Reflected Power** (Watts)

Radar Cross Section (RCS, or s) is the *effective* cross-sectional area of the target as seen by the radar

measured in m^2, or dBm^2

Signal Processing
Pulse Compression

Problem: Pulse can be very long; does not allow accurate range measurement

$$\underbrace{1\ \text{msec}}\ \times\ \frac{c}{2} = 150\ \text{km}$$

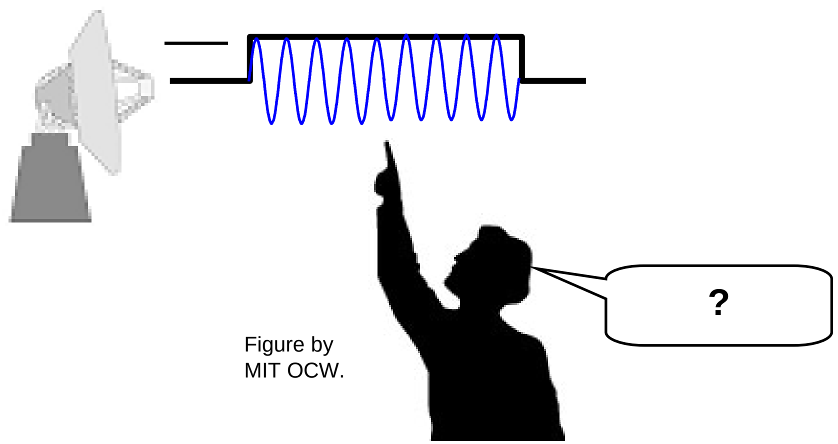
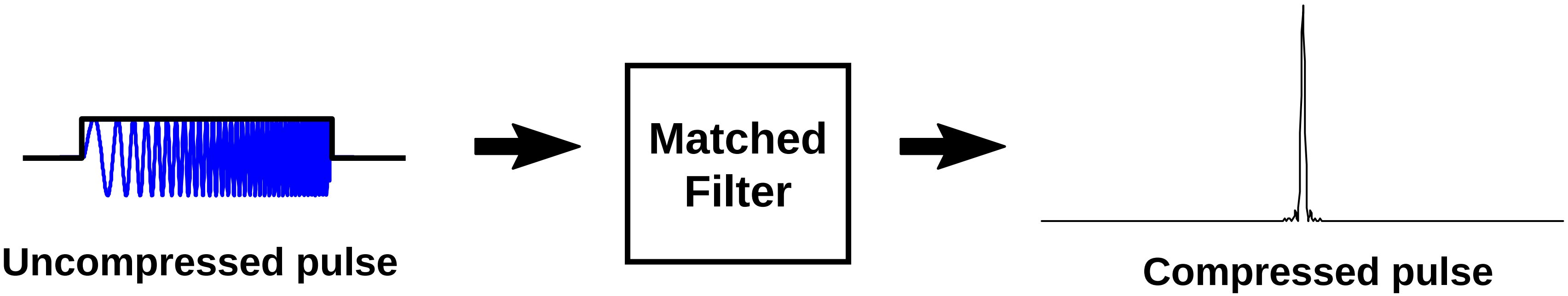
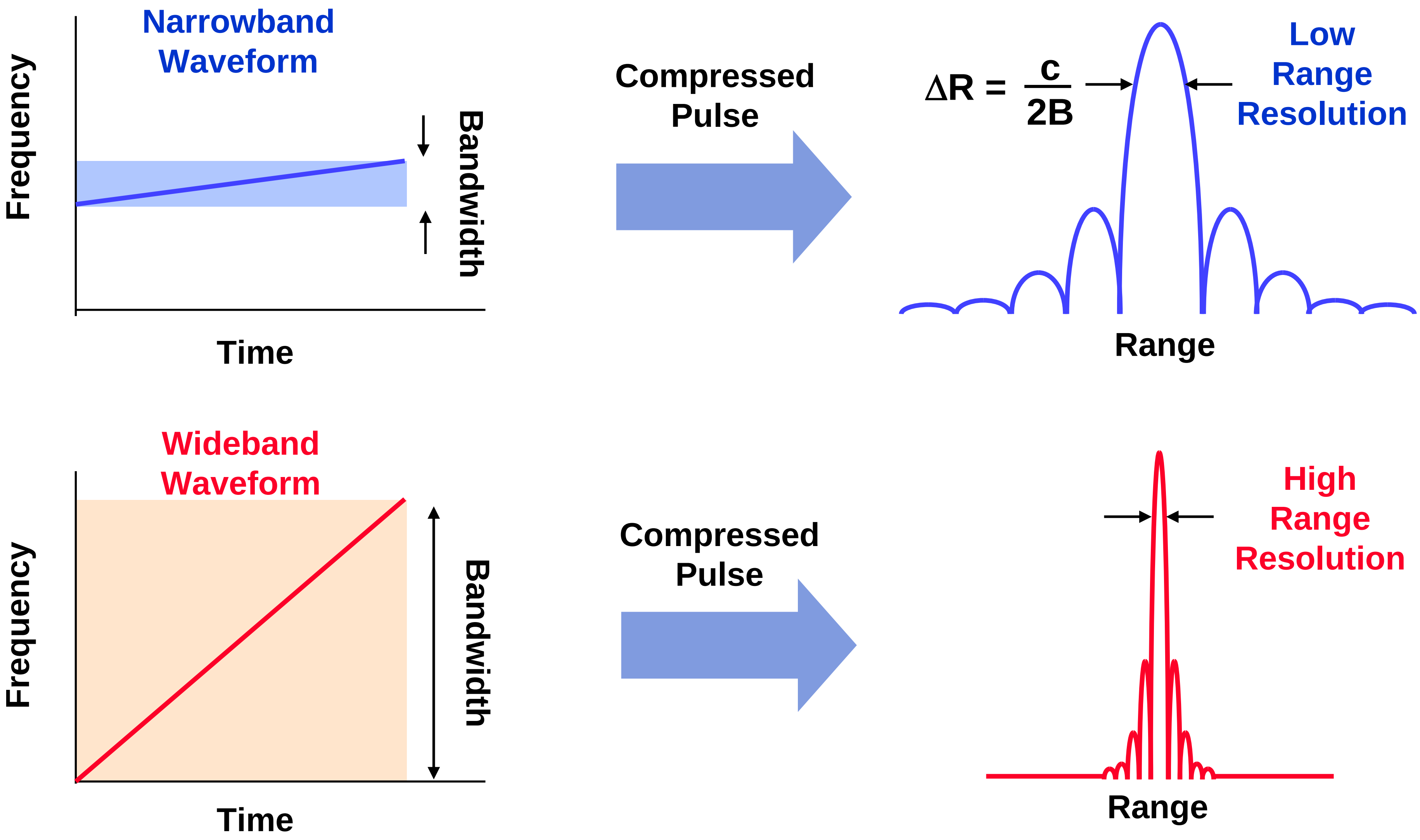


Figure by MIT OCW.

Solution: Use pulse with changing frequency and signal process using "matched filter"

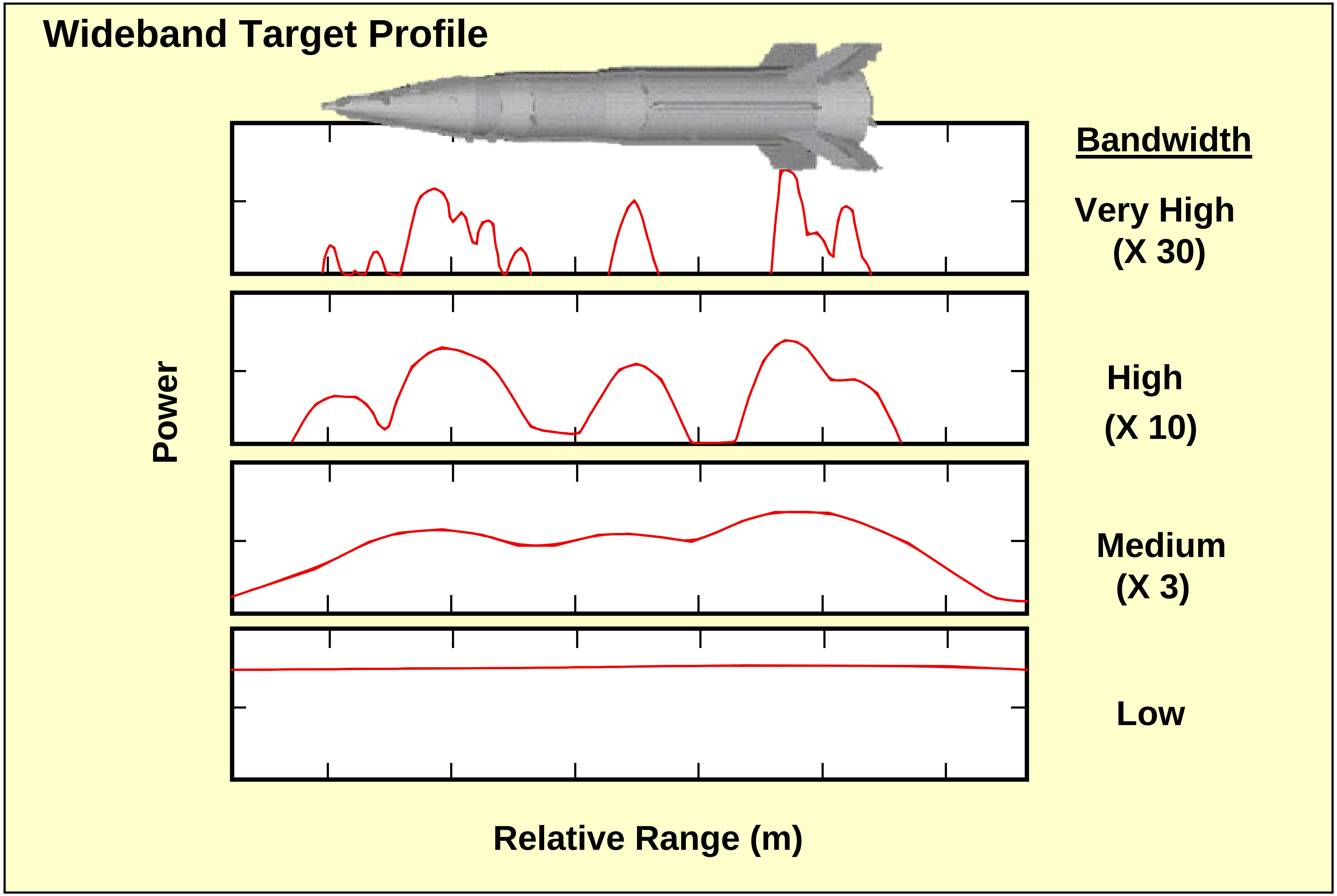


Bandwidth

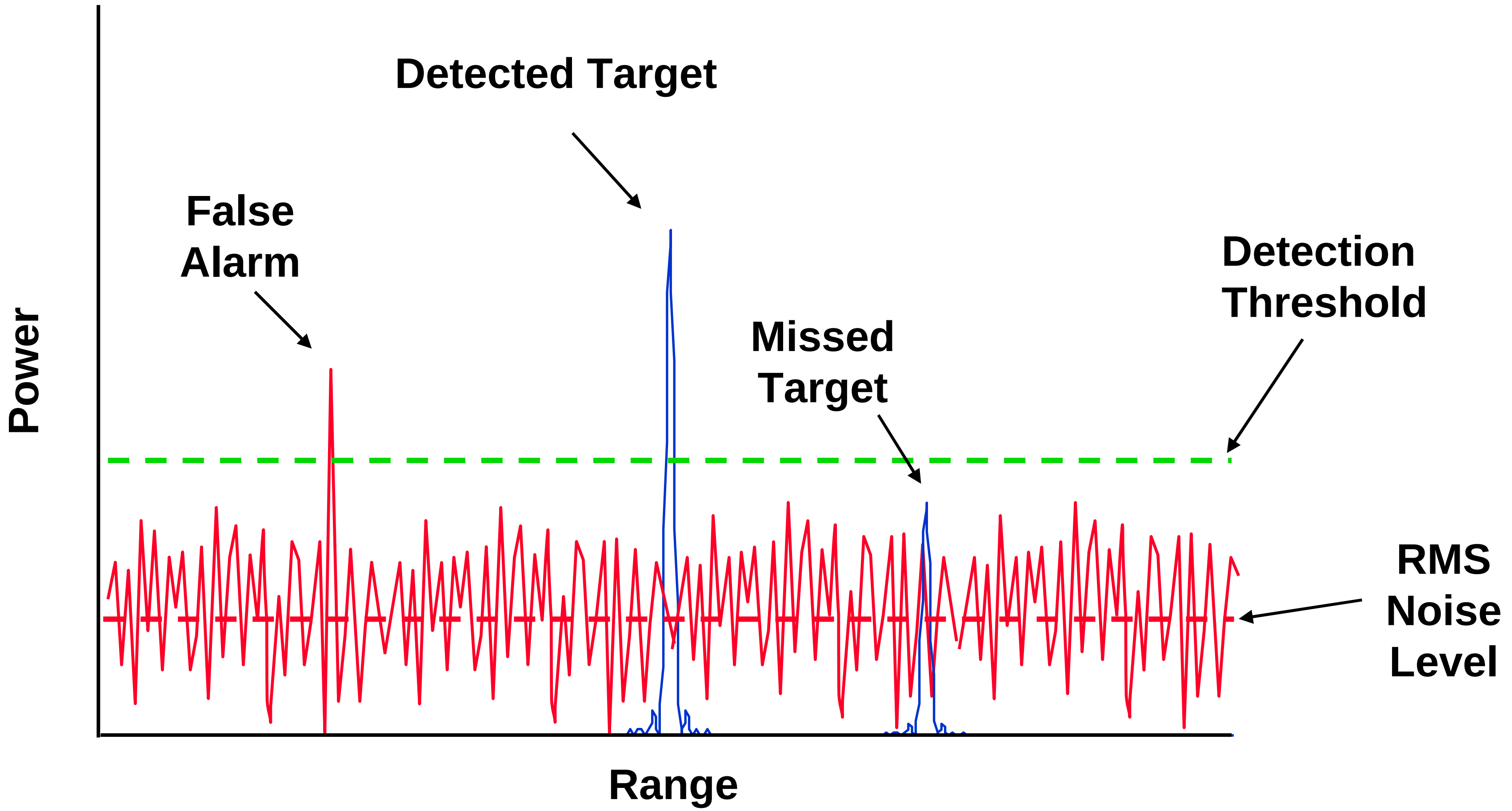


Narrowband Waveform
Frequency
Time
Bandwidth
Compressed Pulse
$\Delta R = \frac{c}{2B}$
Low Range Resolution
Range
Wideband Waveform
Frequency
Time
Bandwidth
Compressed Pulse
High Range Resolution
Range

Why Bandwidth is Important

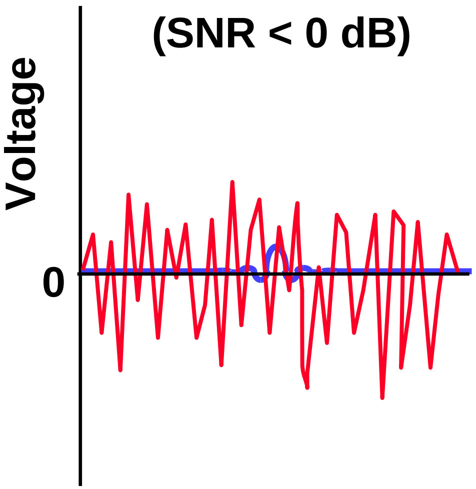


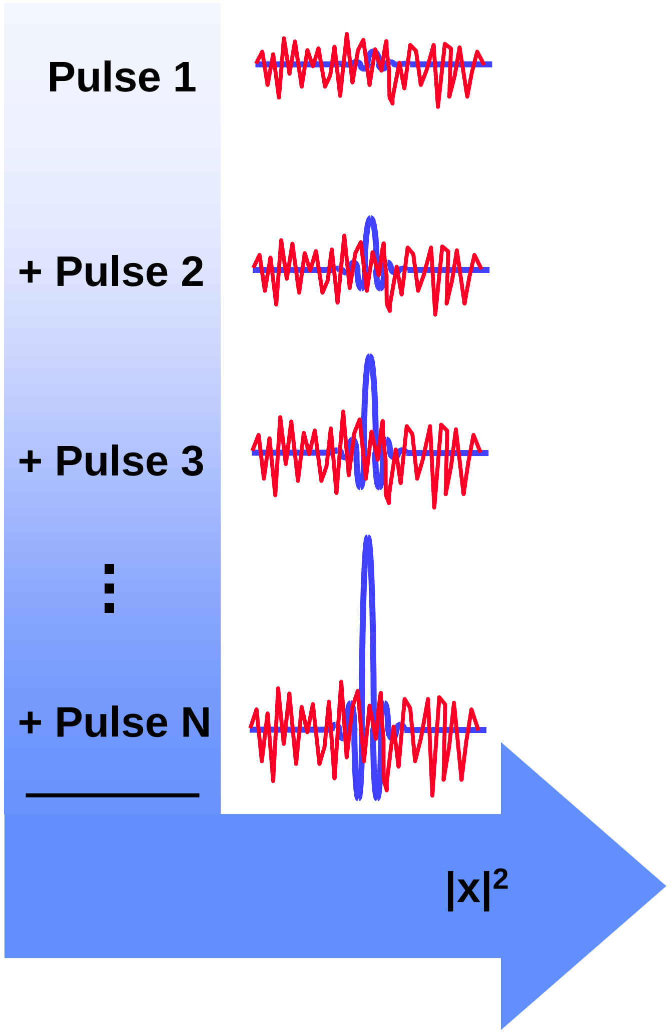
Detection of Signals in Noise



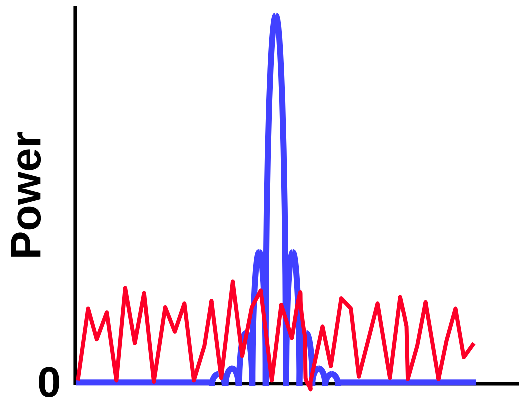
Coherent Integration

Signal buried in Noise (SNR < 0 dB)





Signal integrated out of Noise (SNR increases by N)



- **Signals are same each time; add "coherently" (N^2)**
- **Noise is different each time; doesn't add coherently (N)**

Doppler Effect

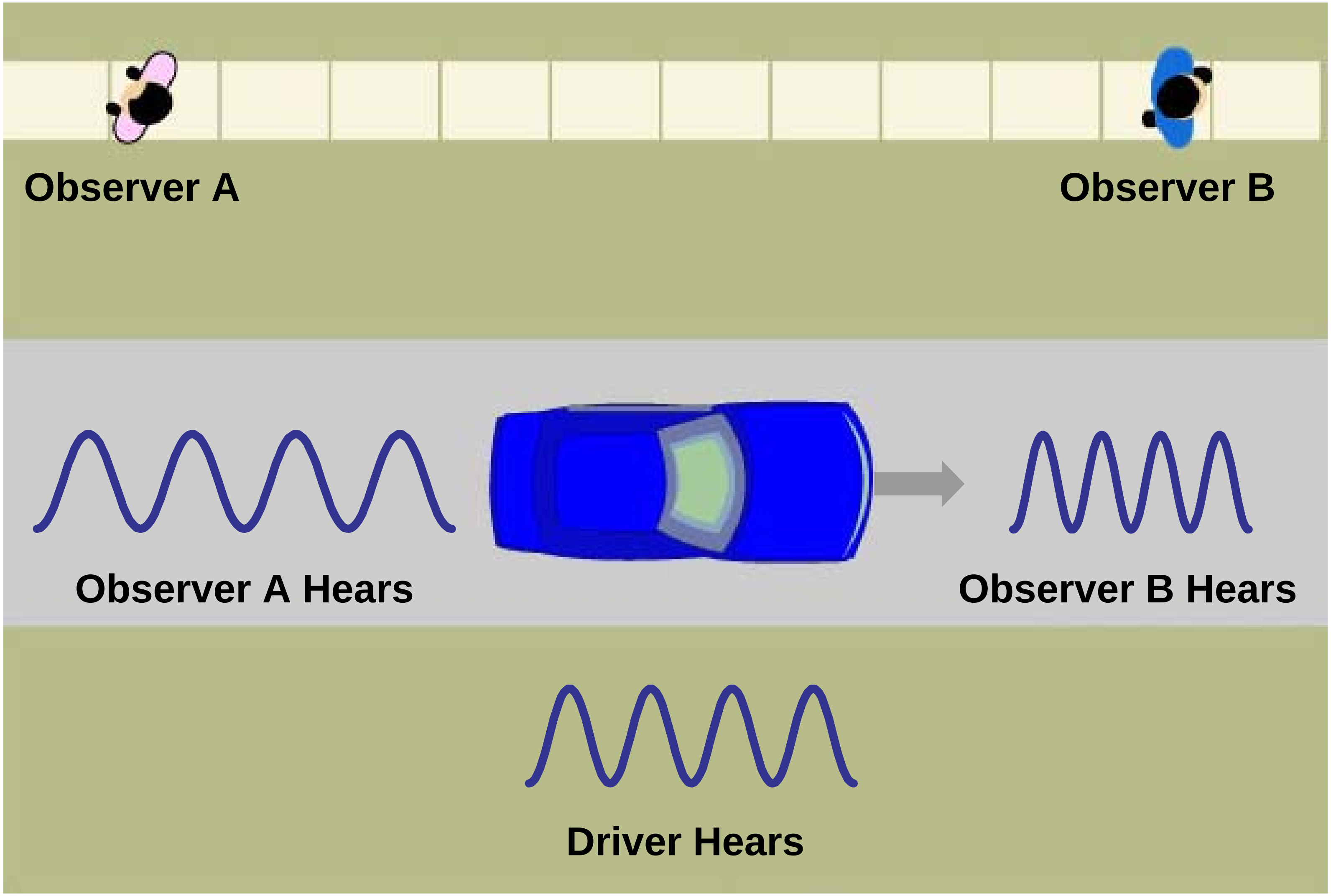
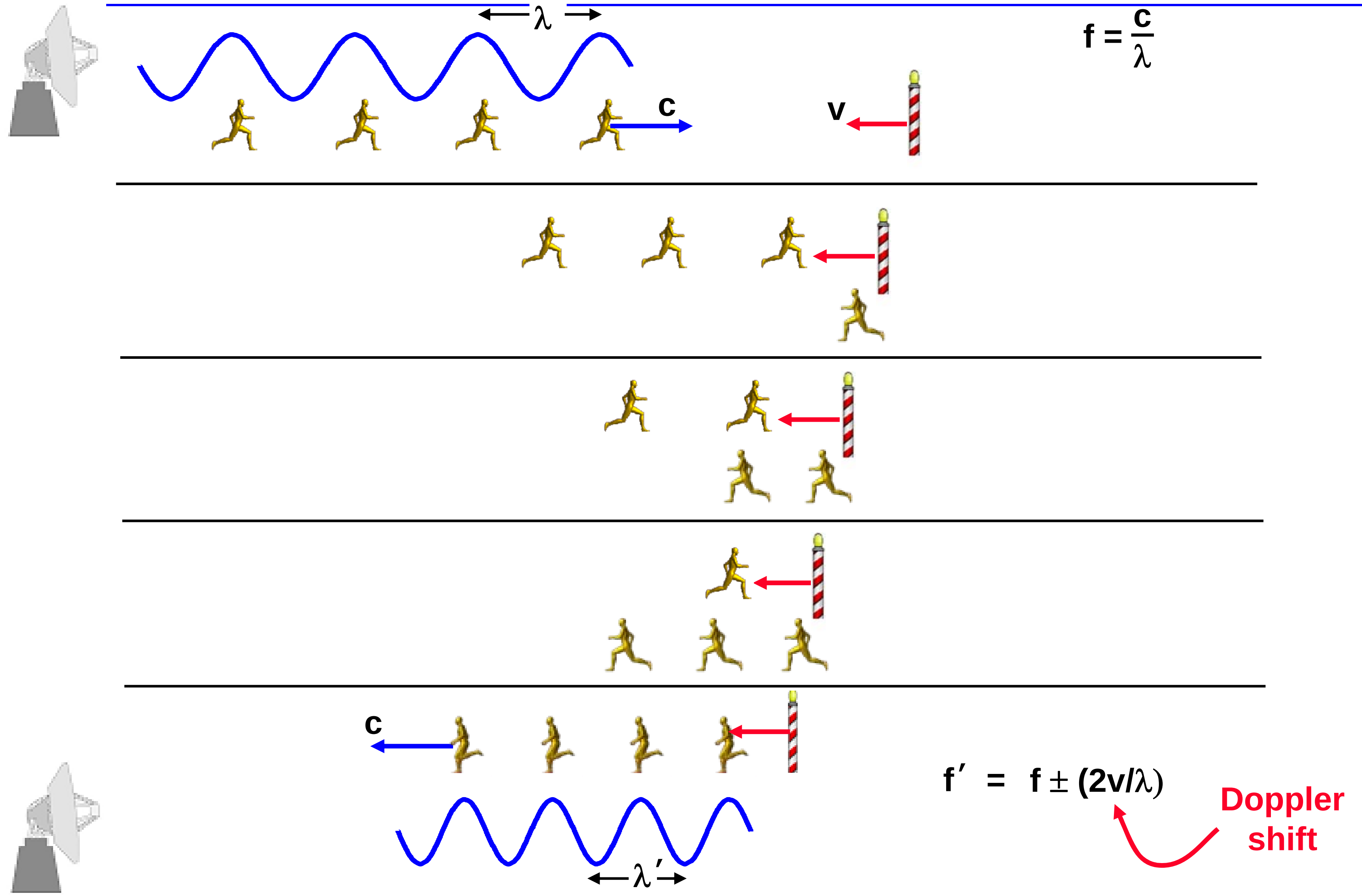


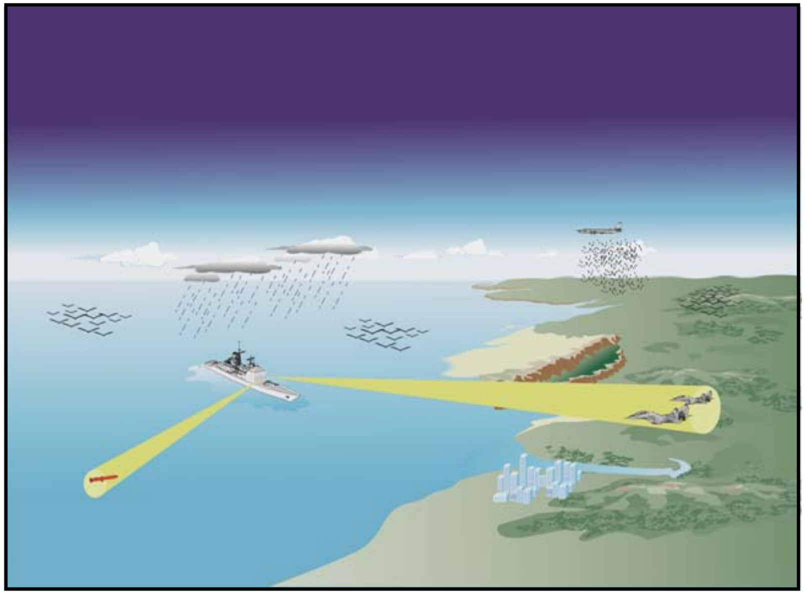
Figure by MIT OCW.

Doppler Shift Concept



Why Doppler is Important

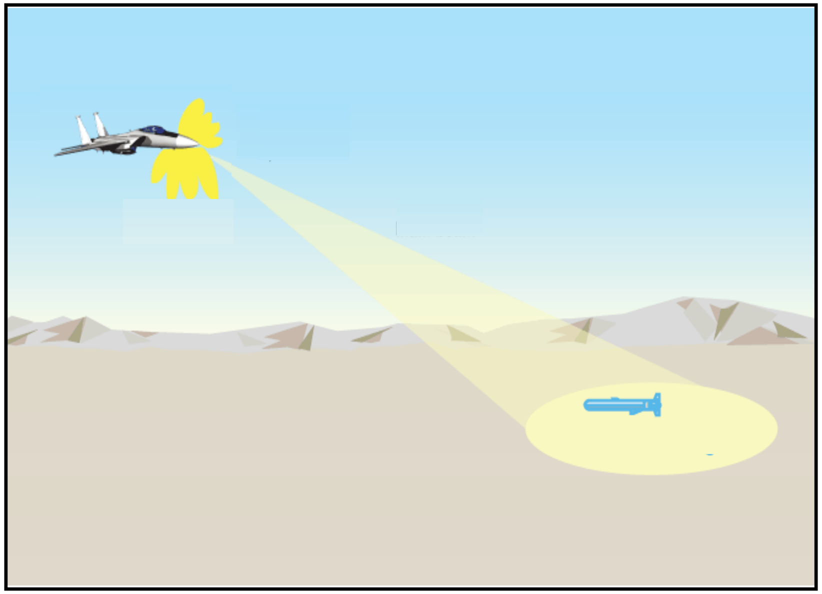
Surface Radar



Clutter returns are much larger than target returns…

…however, targets move, clutter doesn't.

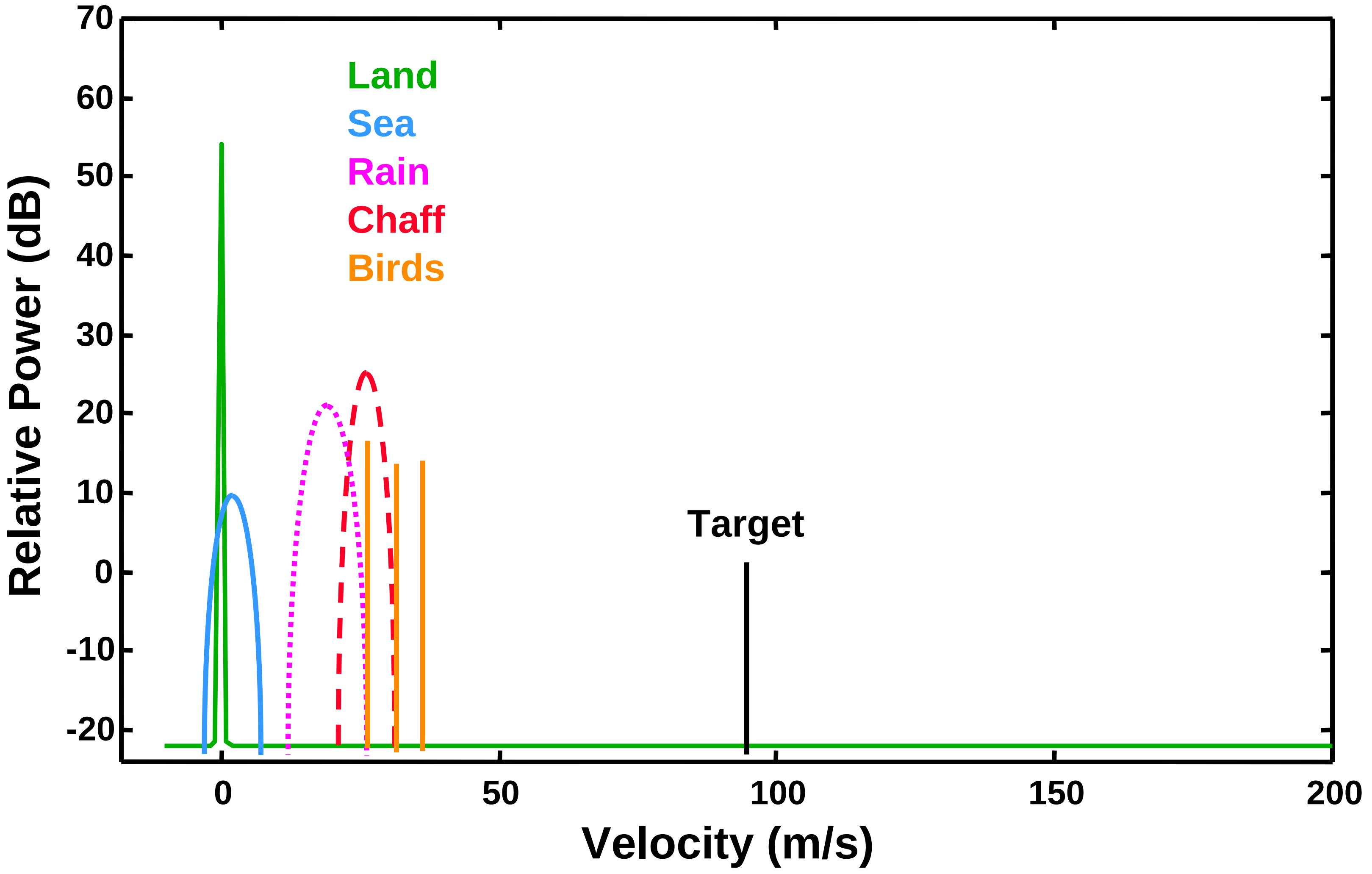
Airborne Radar



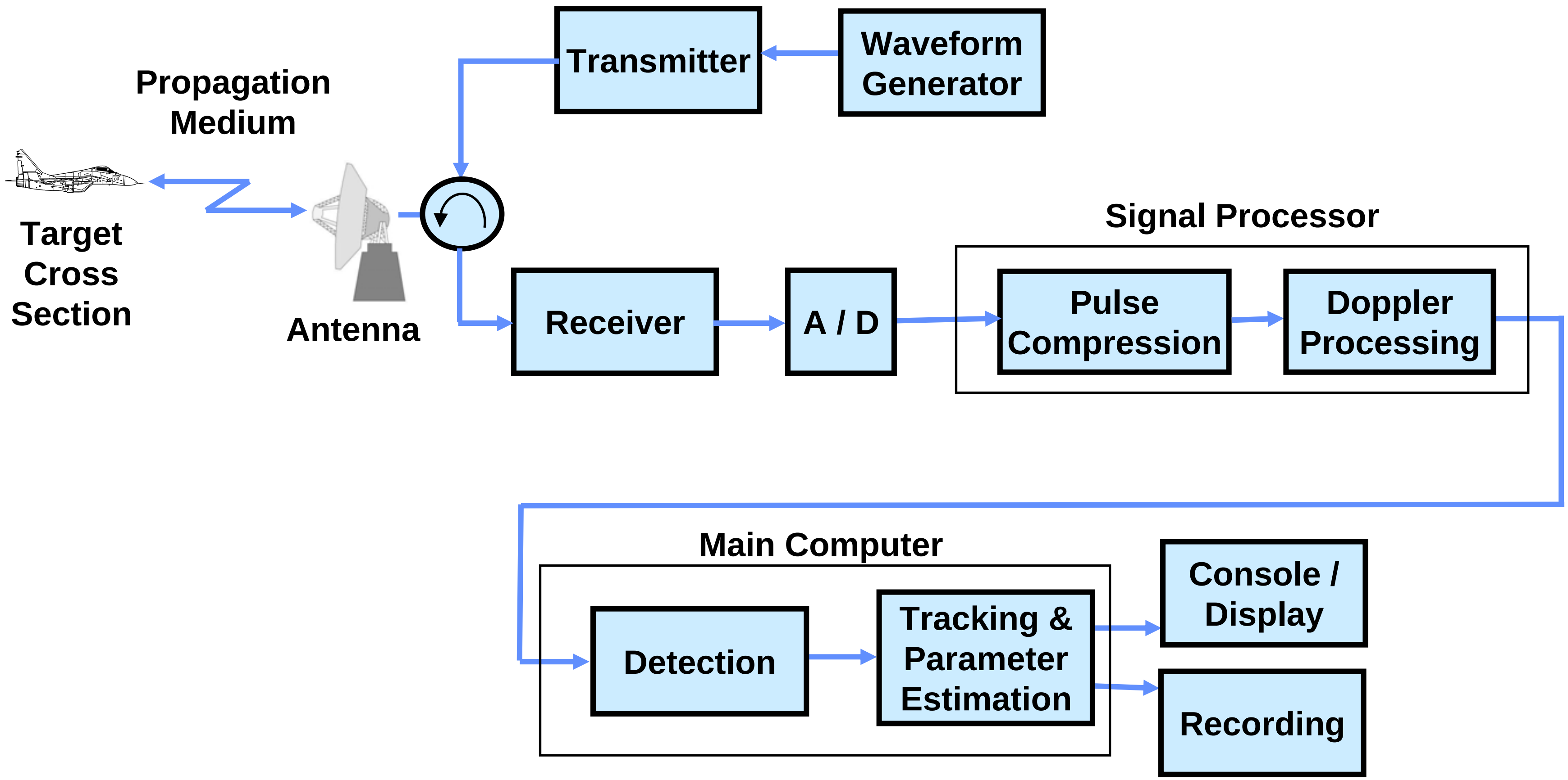
Note: if you're moving too, you need to take that into account.

Doppler lets you separate things that are moving from things that aren't

Clutter Doppler Spectra



Radar Block Diagram



Outline

- Why radar?
- The basics
- Course agenda

Agenda

- Introduction
- Radar Equation
- Propagation Effects
- Target Radar Cross Section
- Detection of Signals in Noise & Pulse Compression
- Radar Antennas
- Radar Clutter and Chaff
- Signal Processing-MTI and Pulse Doppler
- Tracking and Parameter Estimation
- Transmitters and Receivers

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- Nathanson, F. E., Radar Design Principles, New York, McGraw-Hill, 2nd Edition, 1991
- Toomay, J. C., Radar Principles for the Non-Specialist, New York, Van Nostrand Reinhold, 1989
- Buderi R., The Invention That Changed the World, New York, Simon and Schuster, 1996