Introduction to Radar Systems

Dr. Robert M. O'Donnell

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Introduction to Radar Systems

Introduction

Acknowledgement

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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 ?

The Invasion of Normandy

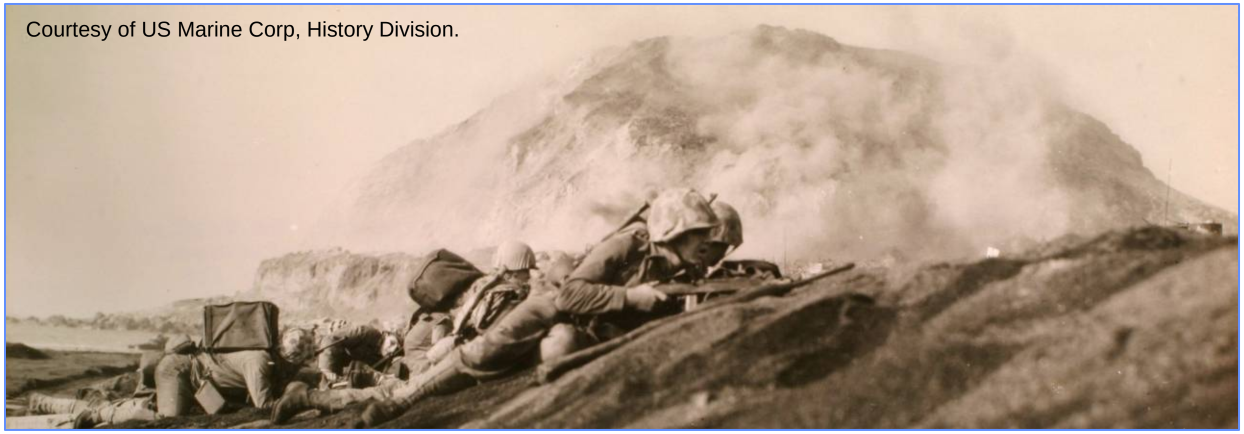
D-Day

D-Day + 1

Courtesy of National Archives.

What Means are Available for Lifting the Fog of War ?

Iwo Jima 1945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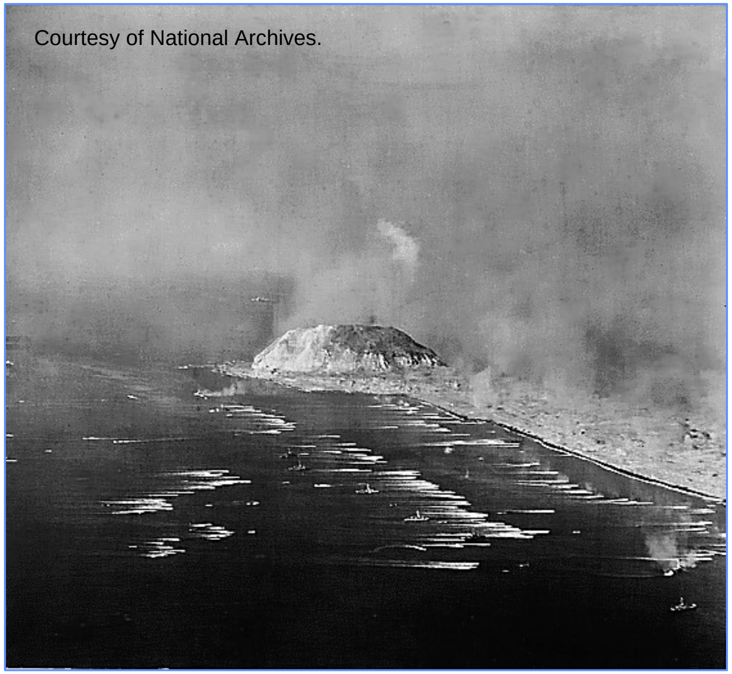
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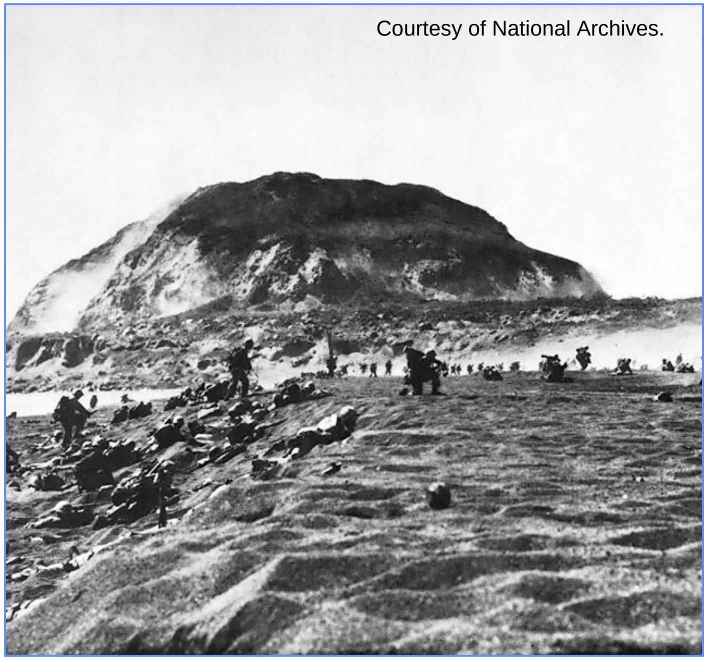

Courtesy of National Archives.

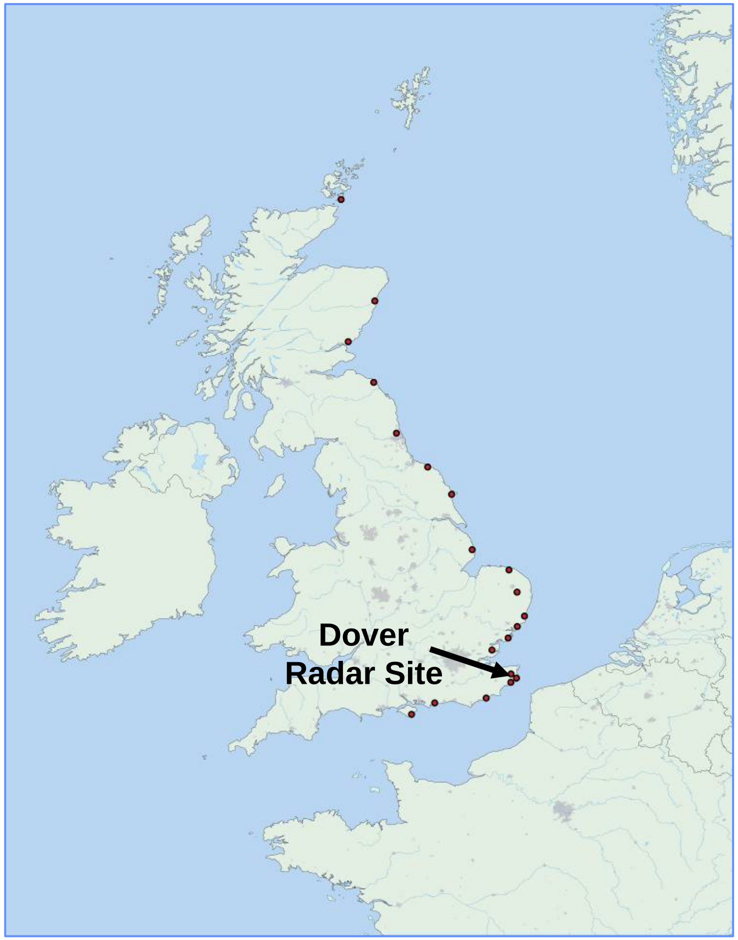
Military Means of Sensing

	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.

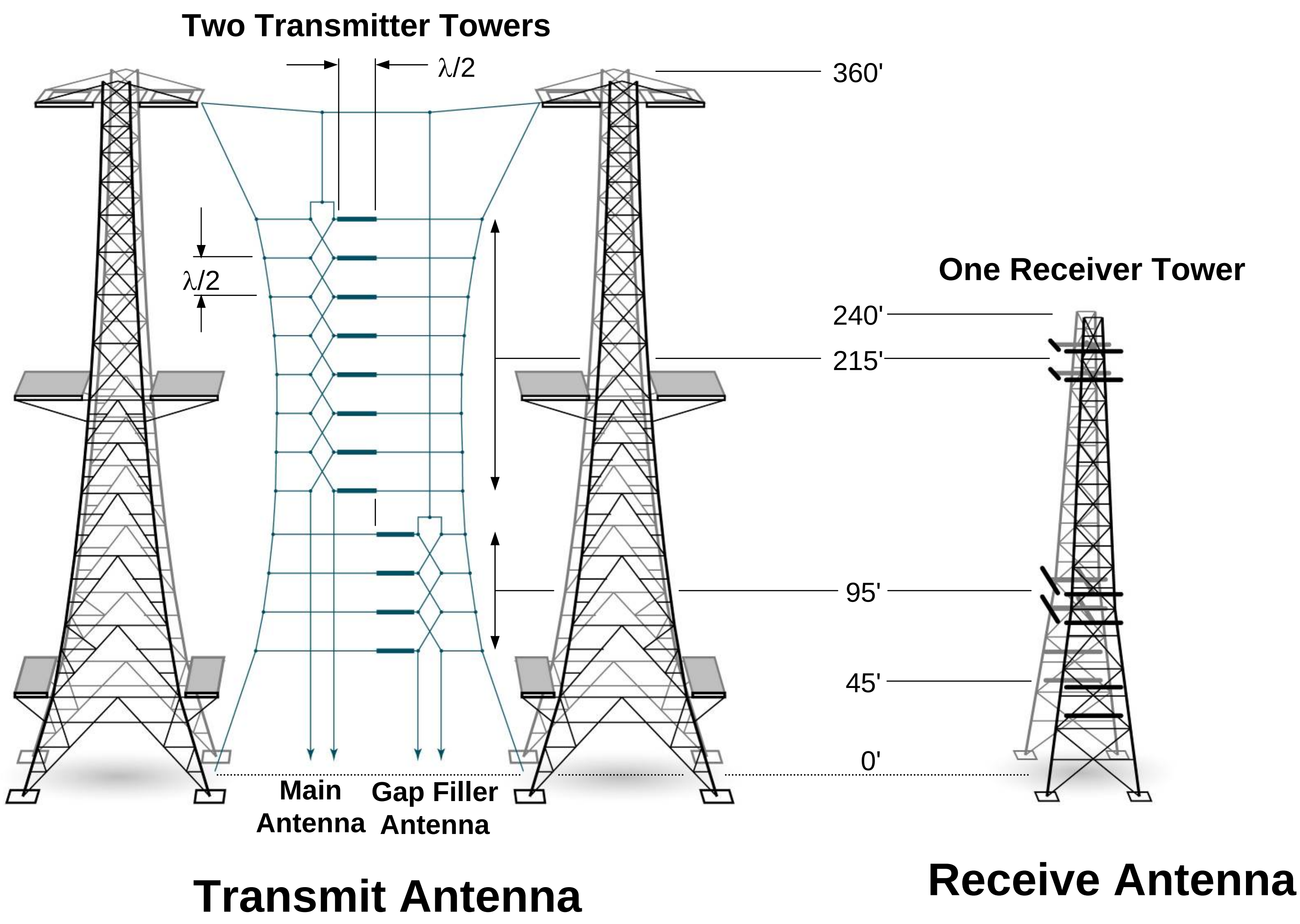
Chain Home Radar System

Typical Chain Home Radar Site

Radar Parameters

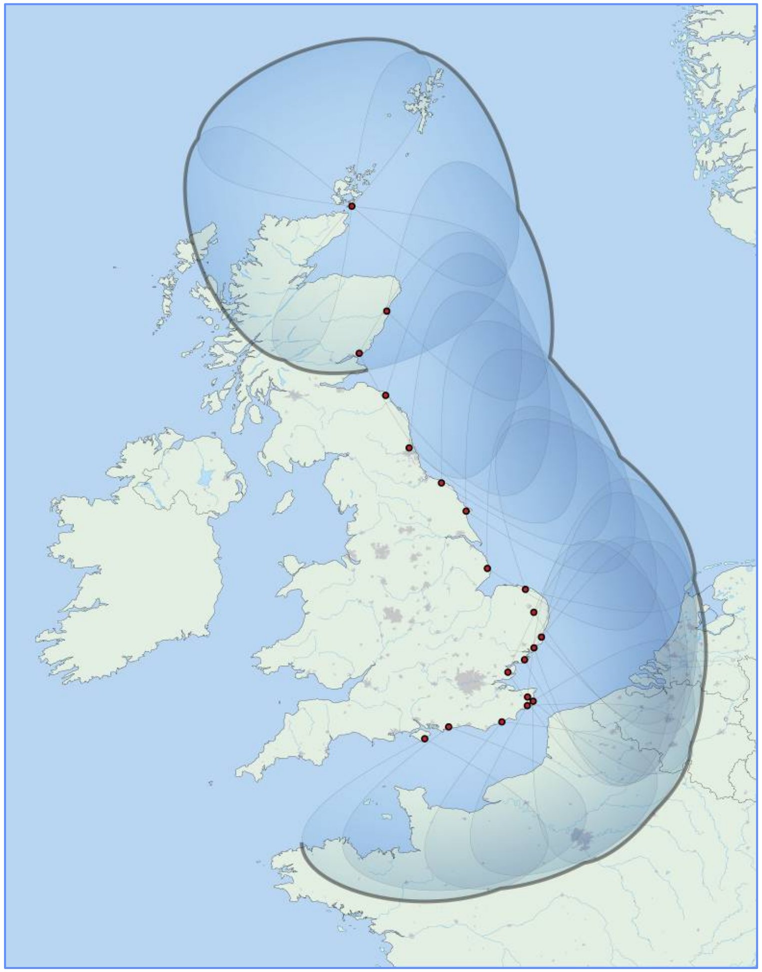
- Frequency
  - 20-30 MHz
- Wavelength
  - 10-15 m
- Antenna
  - Dipole Array on Transmit
  - Crossed Dipoles on Receive
- Azimuth Beamwidth
  - About 100^{o}
- Peak Power
  - 350 kW
- Detection Range
  - ~160 nmi on German Bomber

Chain Home Transmit & Receive Antennas



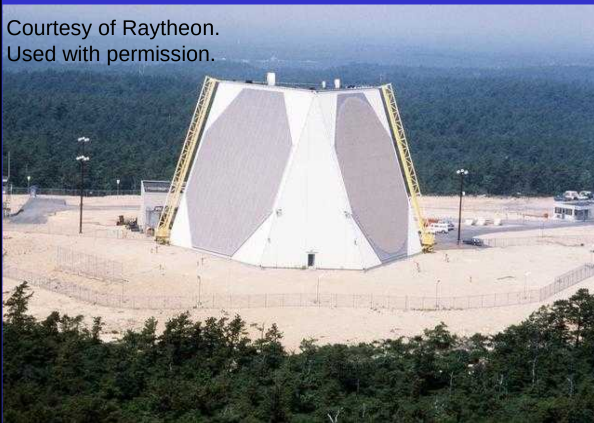
Radar and "The Battle of Britain"

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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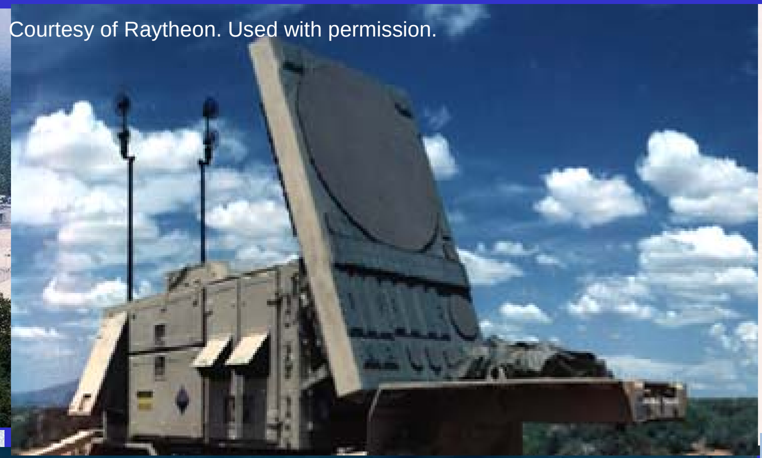
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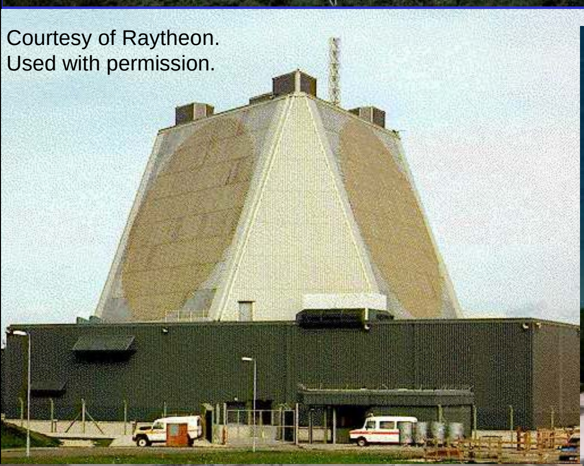
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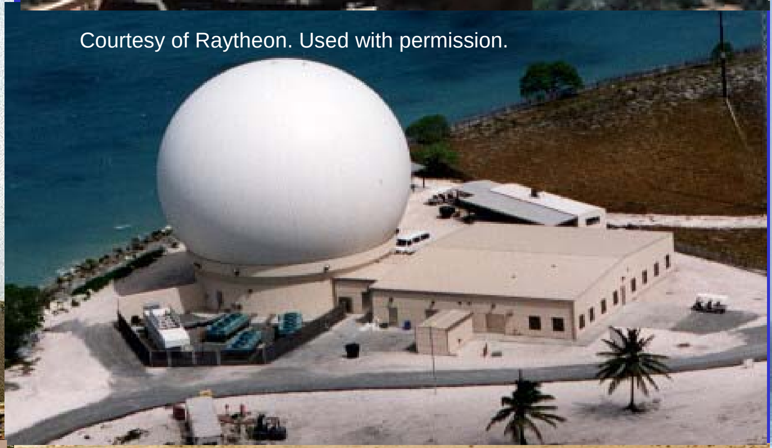
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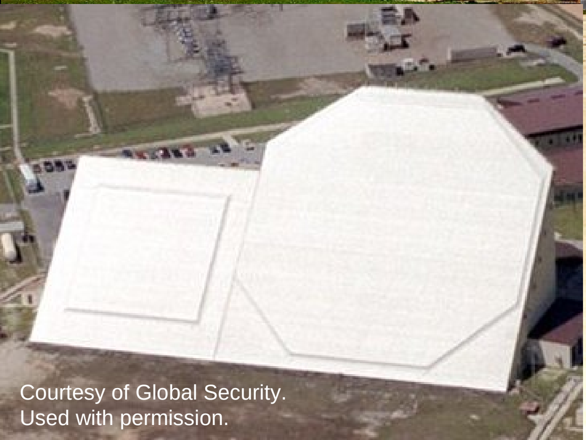
Courtesy of US Navy.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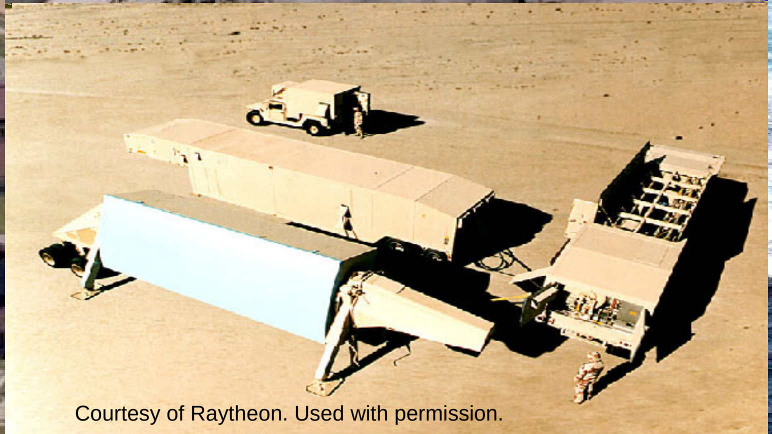
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Airborne and Air Traffic Control Radars


Courtesy Lincoln Laboratory.

Courtesy of US Air Force.

Courtesy of US Navy.


Courtesy of Northrop Grumman.
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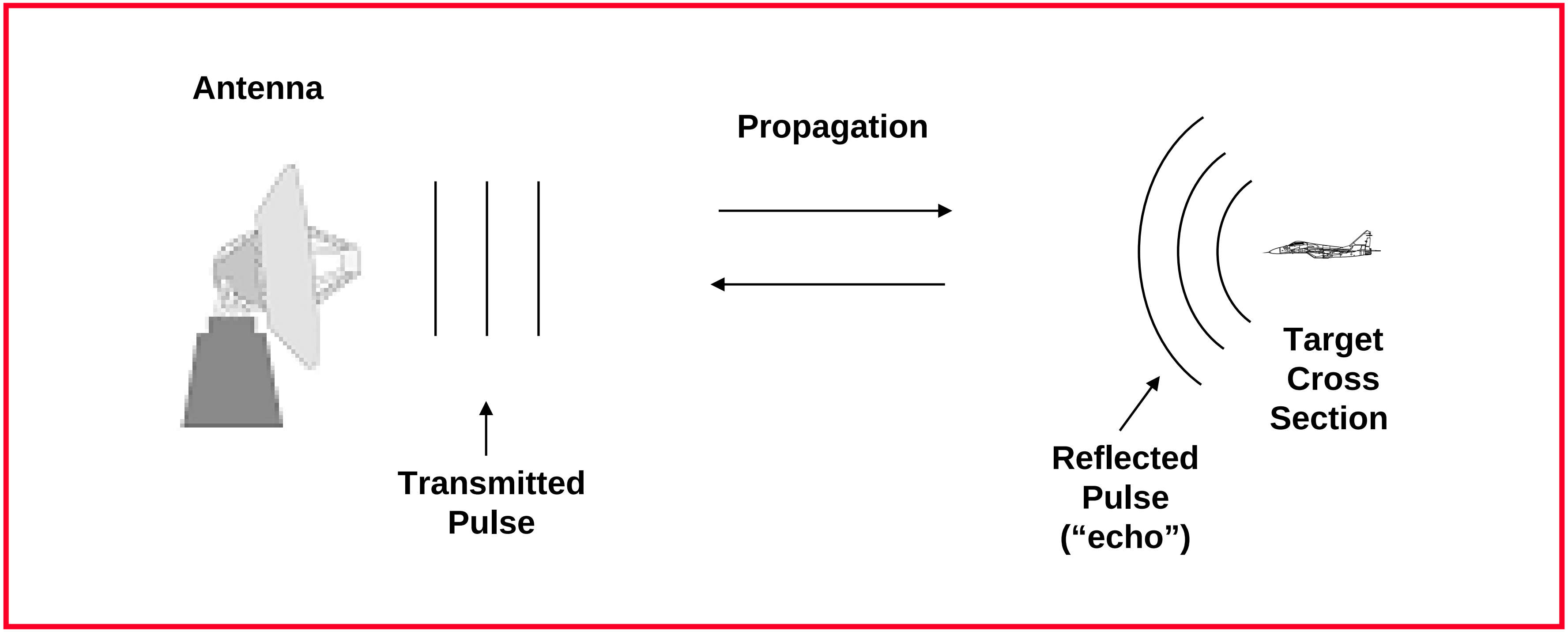
Instrumentation Radars

Outline

- Why radar?
- The basics
- Course agenda

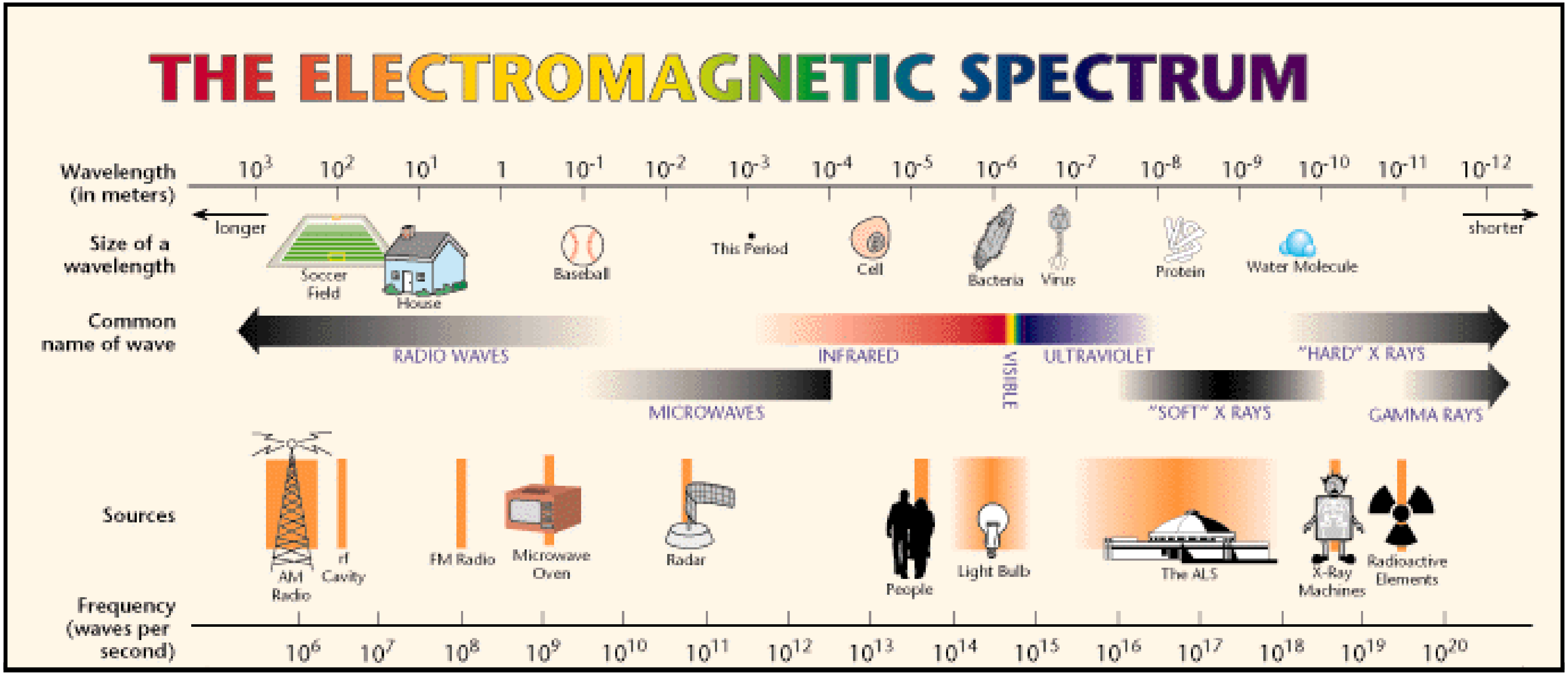
RADAR

RAdio Detection And Ranging

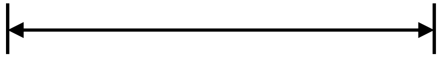


Radar observables:
- Target range
- Target angles (azimuth & elevation)
- Target size (radar cross section)
- Target speed (Doppler)
- Target features (imaging)

Electromagnetic Waves



Courtesy Berkeley National Laboratory



Radar Frequencies

Properties of Waves
Relationship Between Frequency and Wavelength

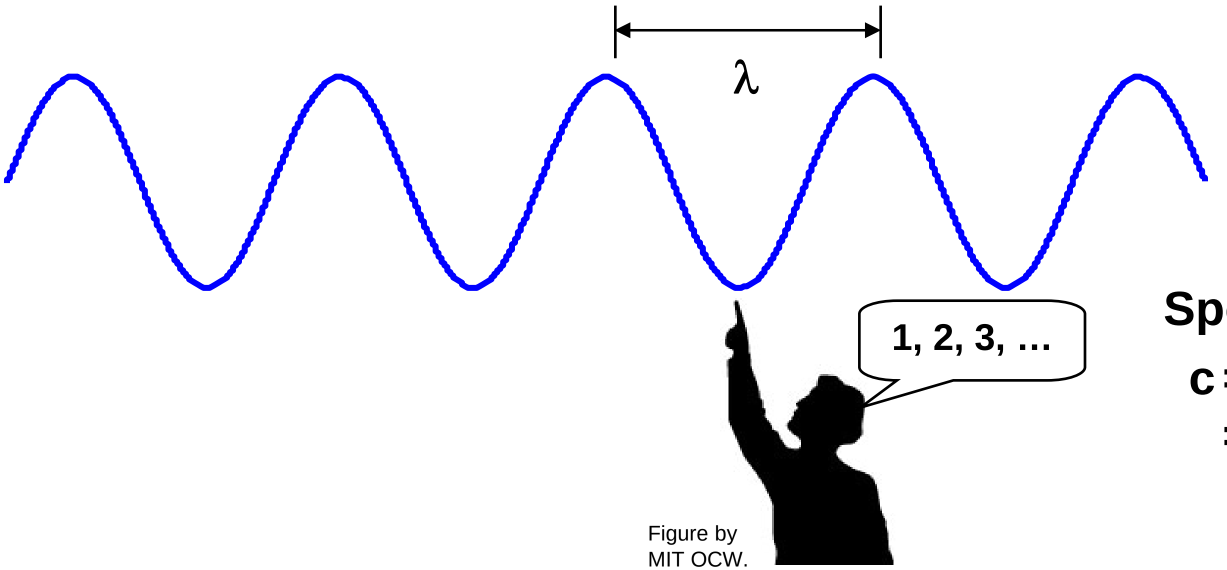


Figure by MIT OCW.

Speed of light, c

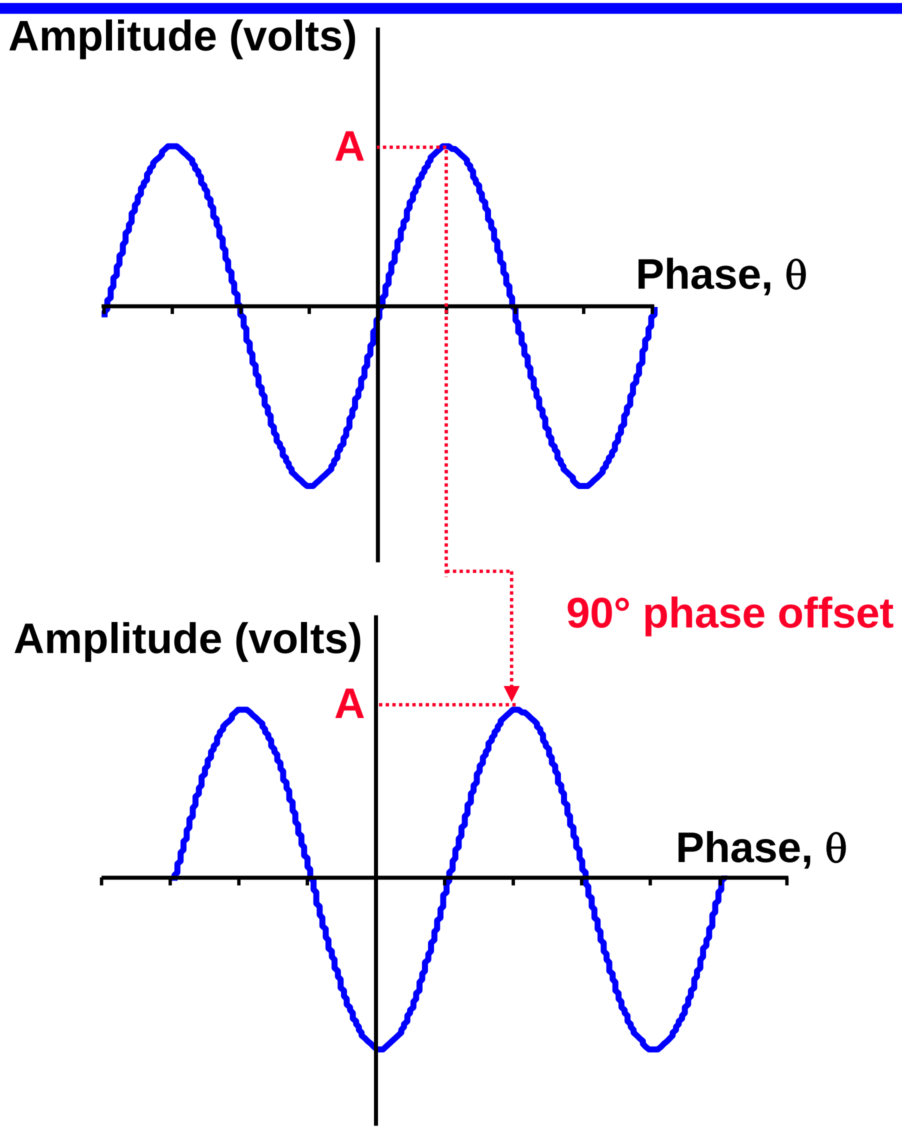
$c = 3 \times 10^8$ m/sec
$= 300{,}000{,}000$ m/sec

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

Examples:

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

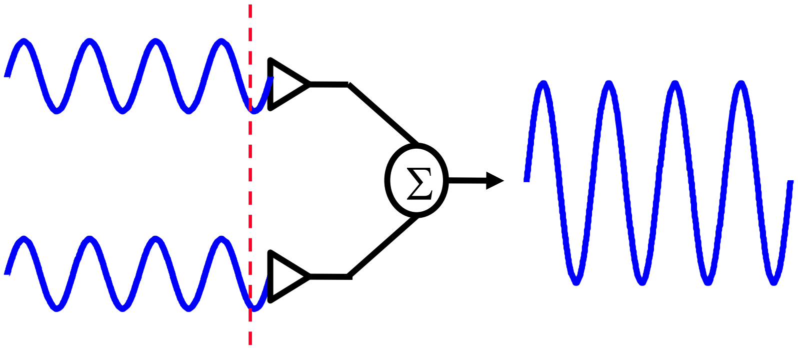
Properties of Waves
Phase and Amplitude



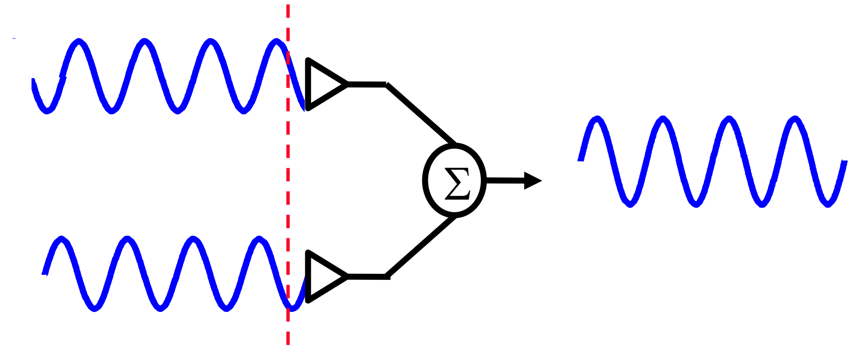
$$A \sin(\theta)$$

$$A \sin(\theta - 90^o)$$

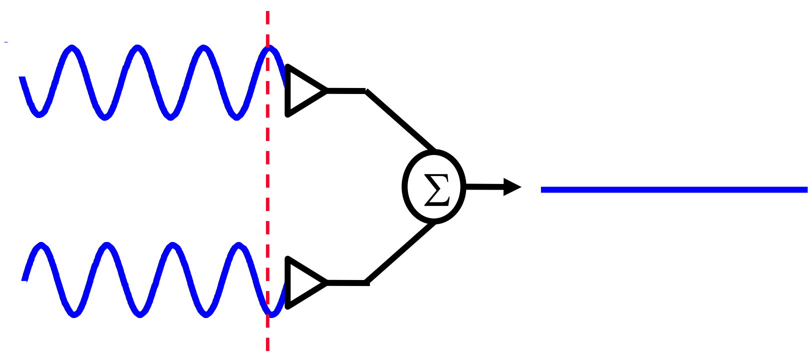
Properties of Waves
Constructive vs. Destructive Addition



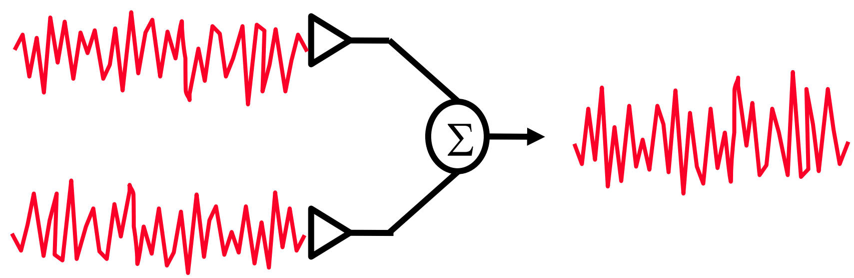
Constructive
(in phase)



Partially Constructive
(somewhat out of phase)

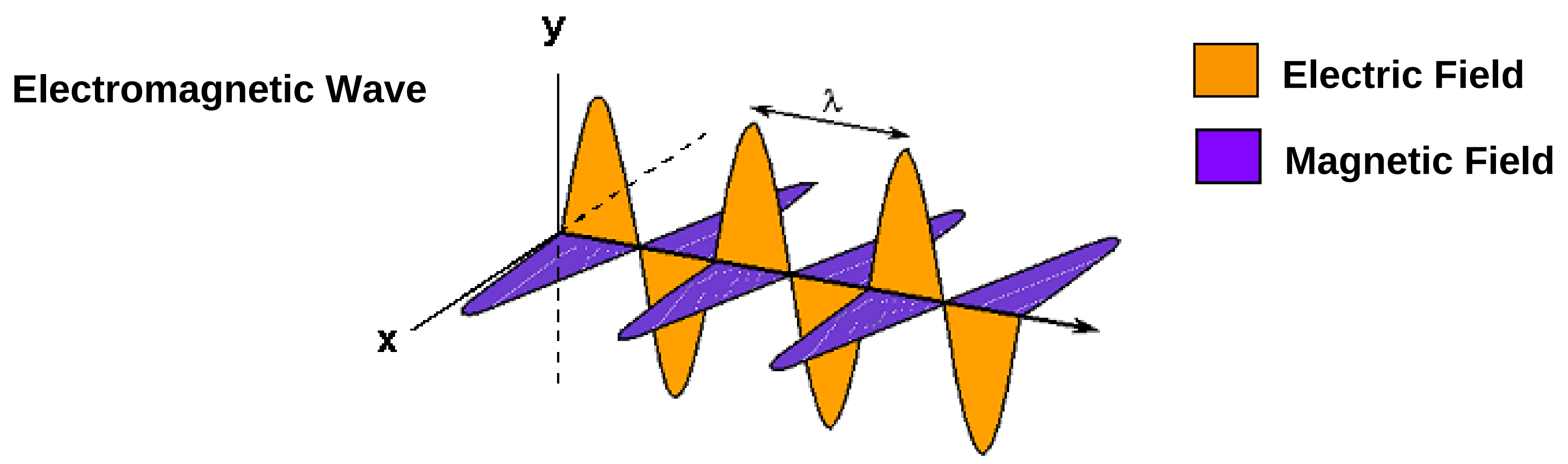


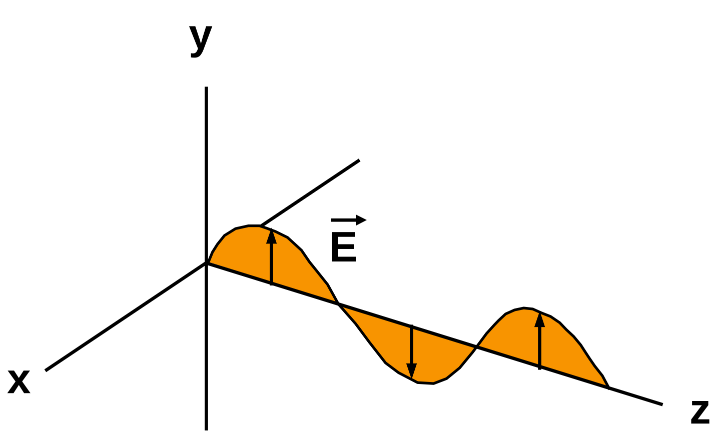
Destructive
(180° out of phase)

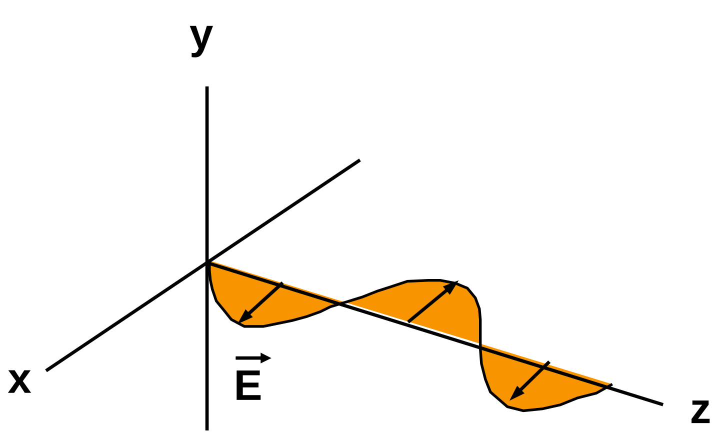


Non-coherent signals
(noise)

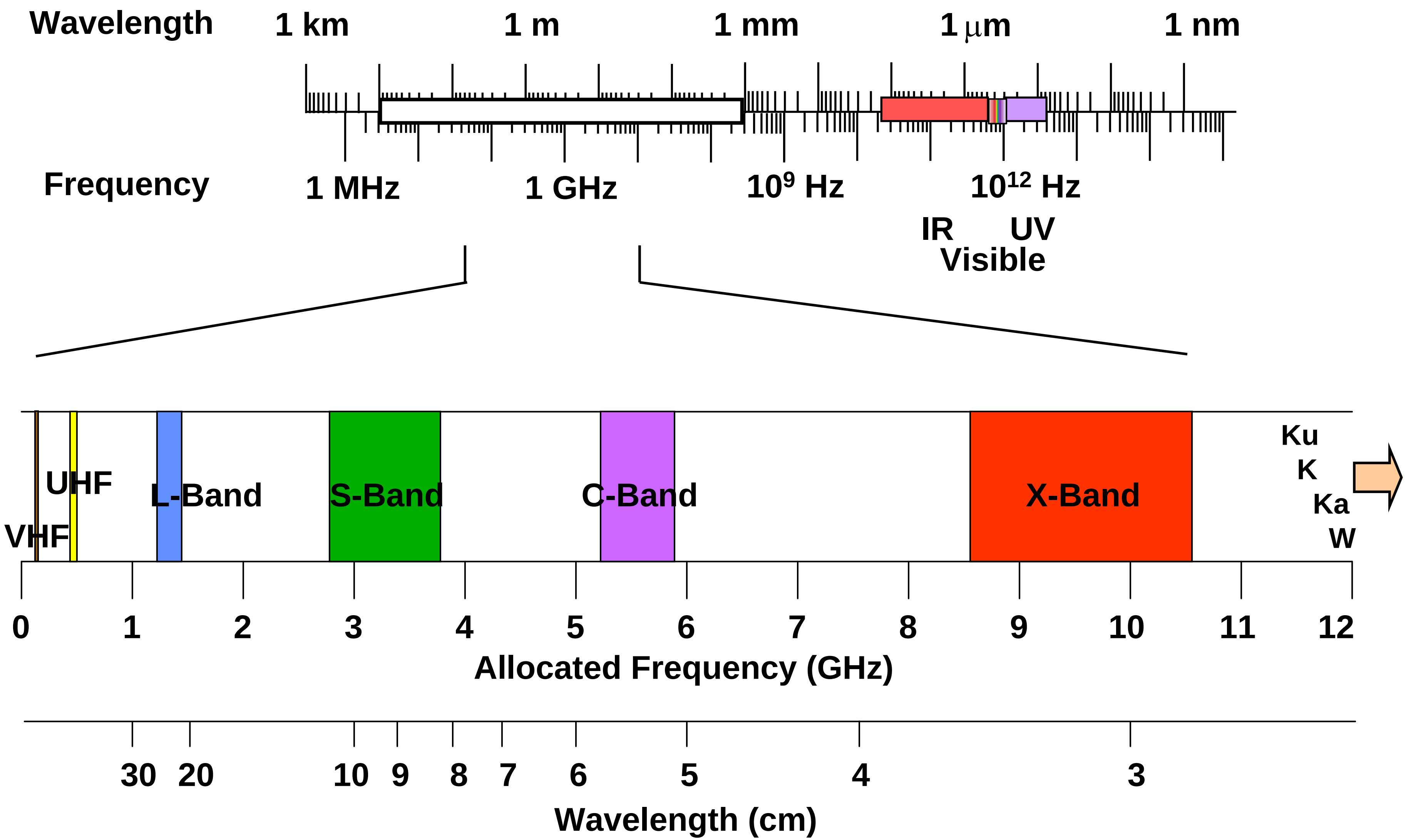
Polarization







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

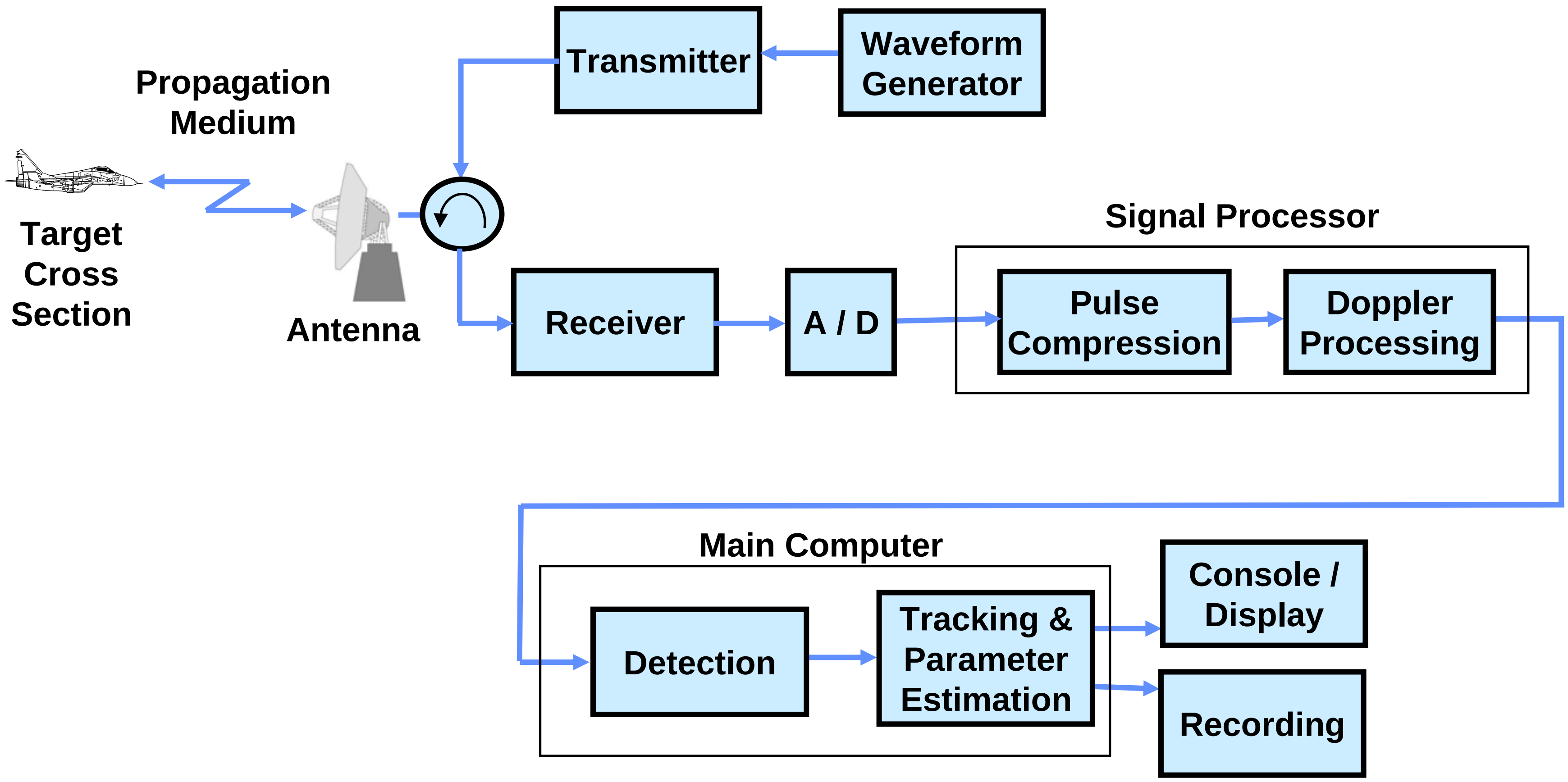
Search Radars

Search & Track Radars

Fire Control & Imaging Radars

Missile Seekers

Radar Block Diagram



Radar Range Equation

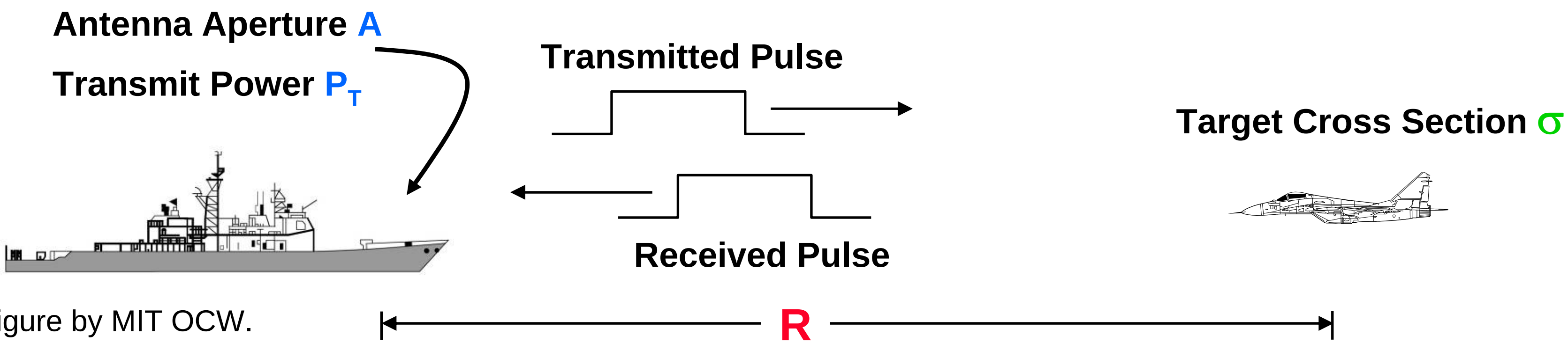
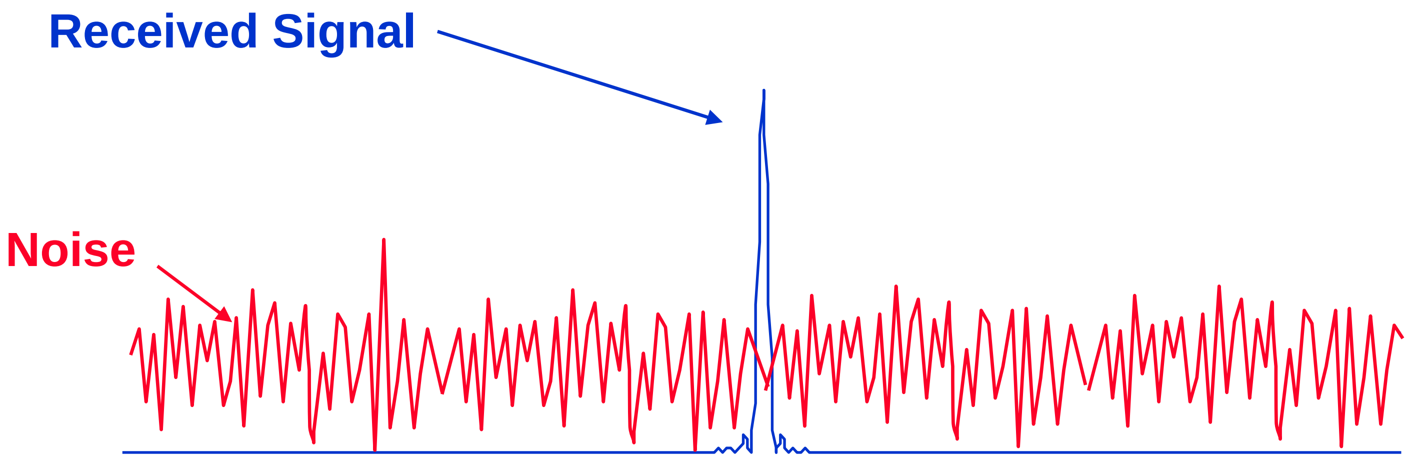


Figure by MIT OCW.

$$\begin{array}{cccccccccc} & & \text{Transmit Power} & \text{Transmit Gain} & \text{Spread Factor} & \text{Losses} & \text{Target RCS} & \text{Spread Factor} & \text{Receive Aperture} & \text{Dwell Time} \\ \text{Received Signal Energy} & = & \left[P_T \right] & \left[\dfrac{4\pi A}{\lambda^2} \right] & \left[\dfrac{1}{4\pi R^2} \right] & \left[\dfrac{1}{L} \right] & \left[\sigma \right] & \left[\dfrac{1}{4\pi R^2} \right] & \left[A \right] & \left[\tau \right] \end{array}$$

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)

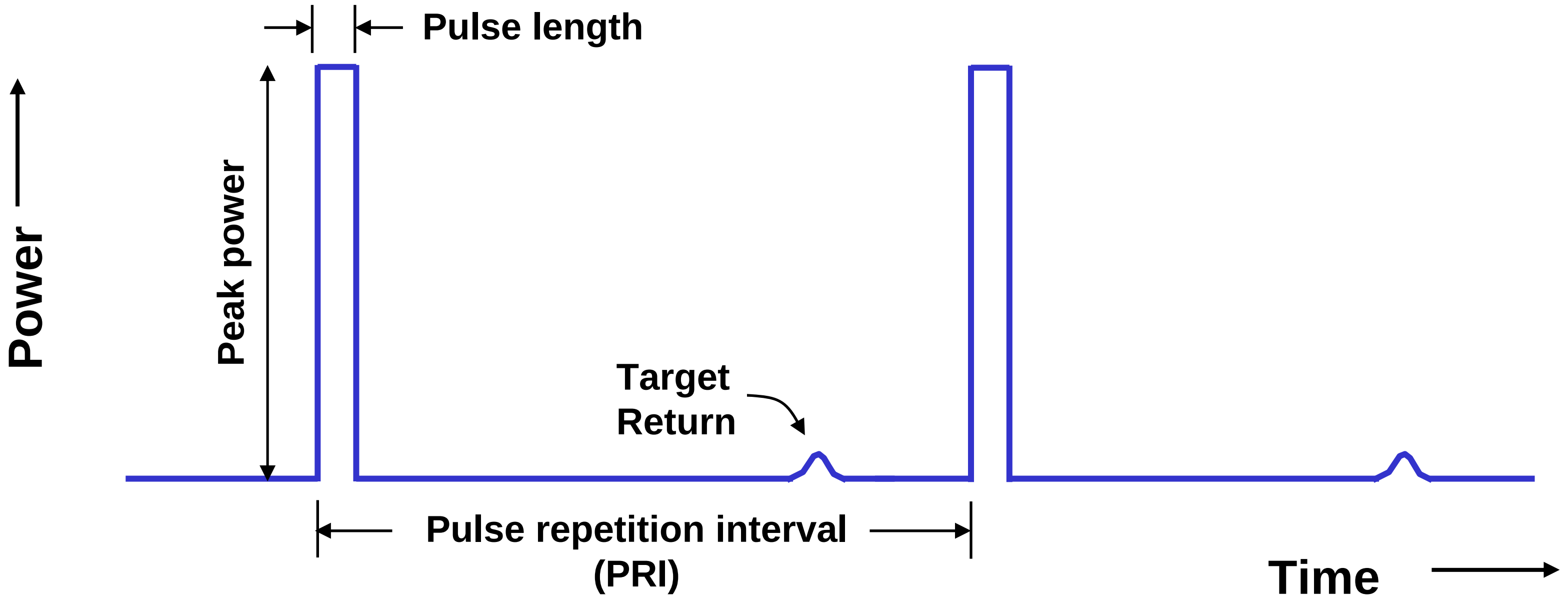
Example:

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

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



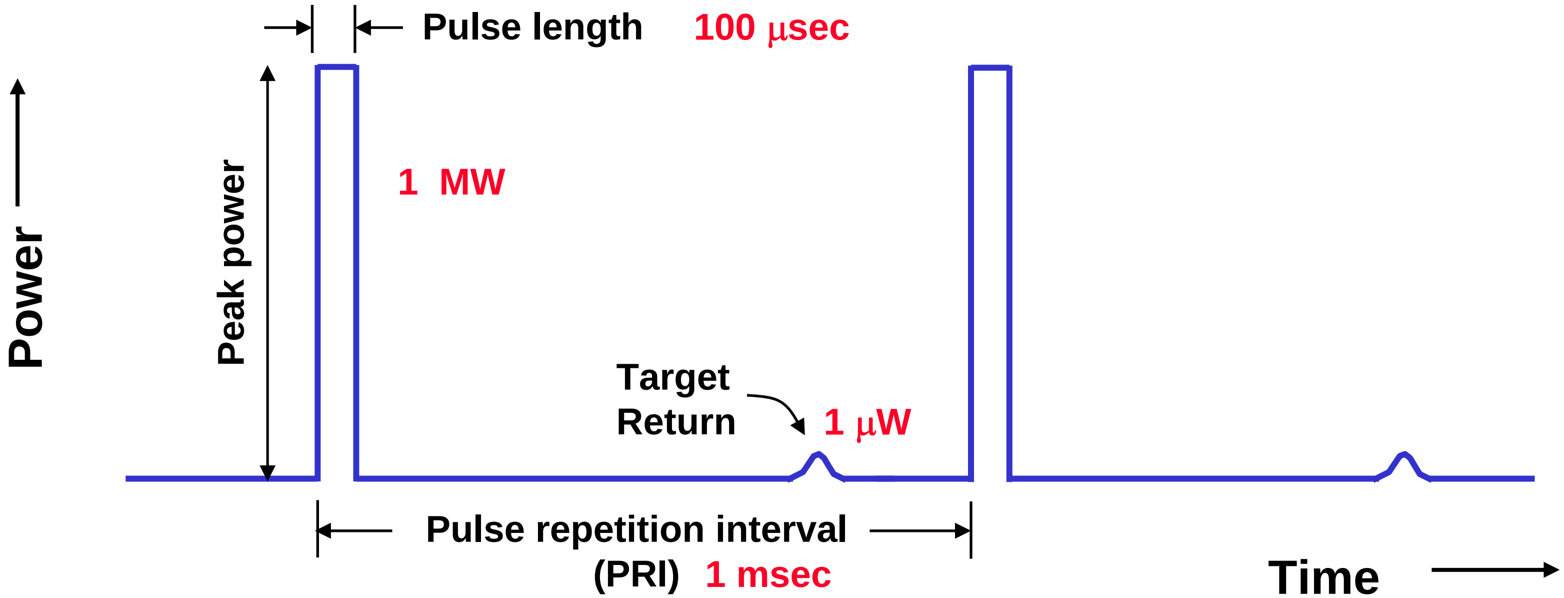
$$\text{Duty cycle} = \frac{\text{Pulse length}}{\text{Pulse repetition interval}}$$

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)

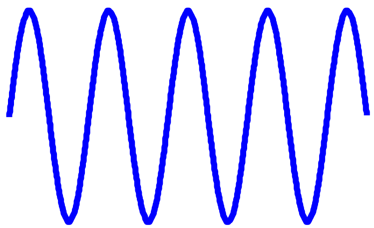
Brief Mathematical Digression
Scientific Notation and Greek Prefixes

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

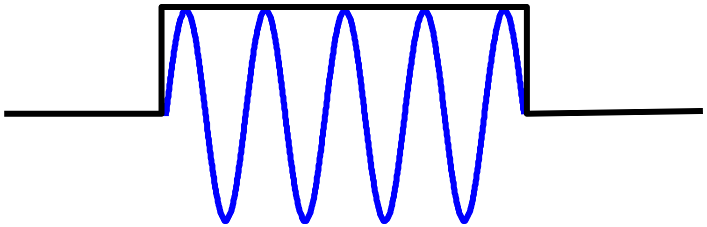
Radar Waveforms

What do radars transmit?



Waves?

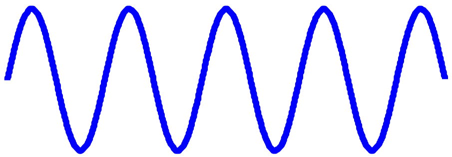
or Pulses?

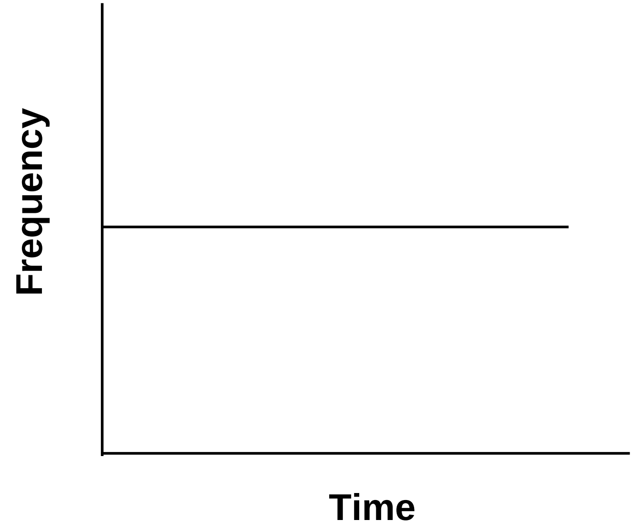


Waves, modulated by “on-off” action of pulse envelope

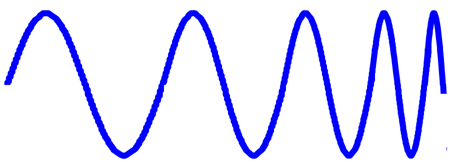
Radar Waveforms (cont'd.)

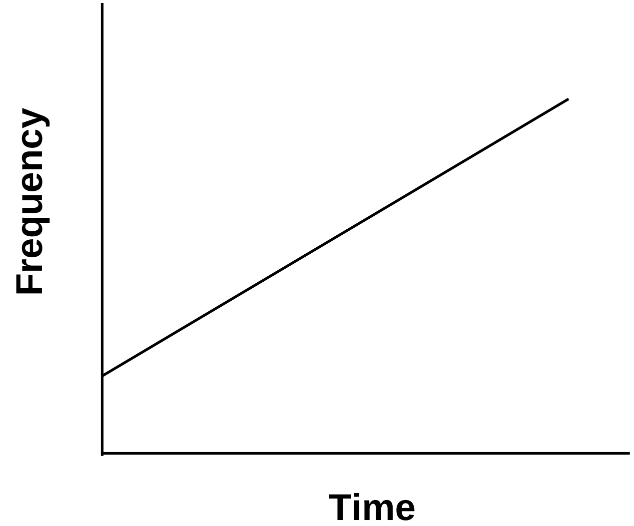
Pulse at single frequency





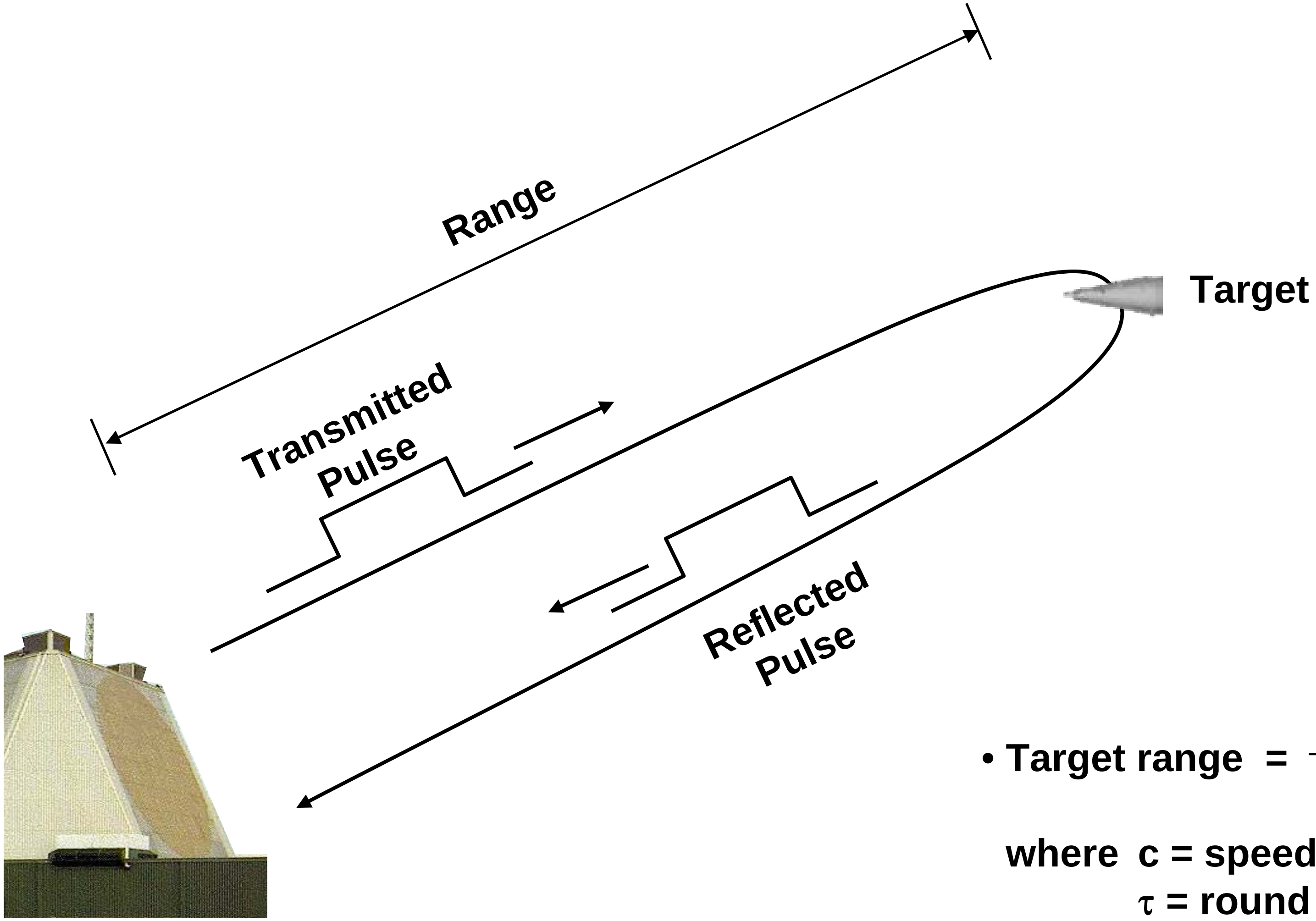
Pulse with changing frequency





Linear Frequency-Modulated (LFM) Waveform

Radar Range Measurement

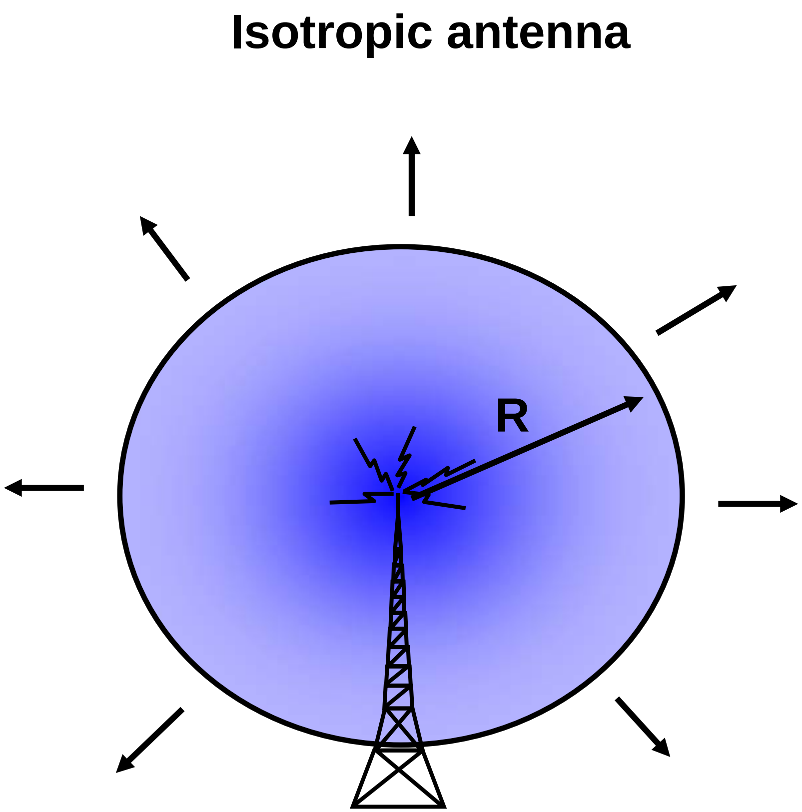


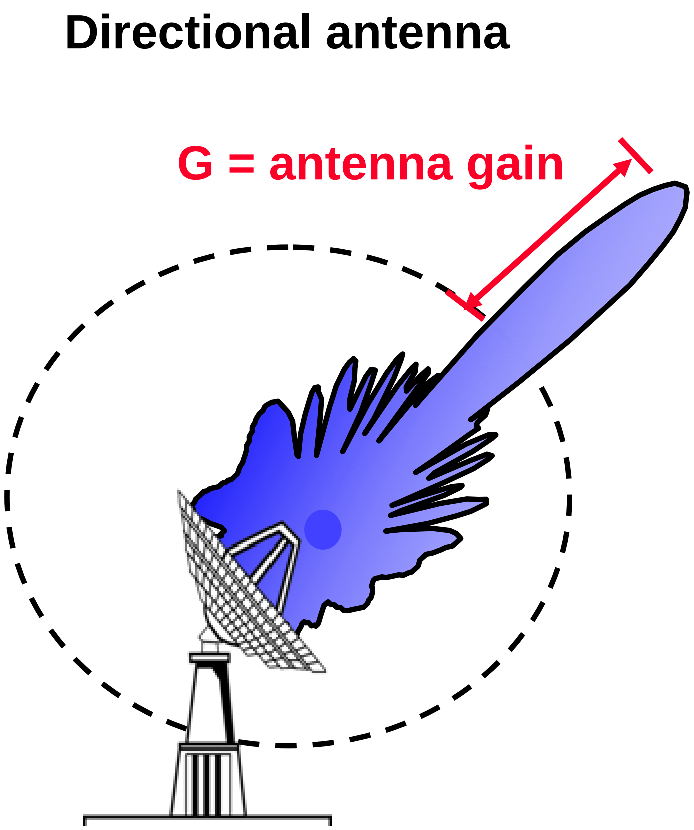
- Target range $= \frac{c\tau}{2}$

  where c = speed of light
  τ = round trip time

Courtesy of Raytheon. Used with permission.

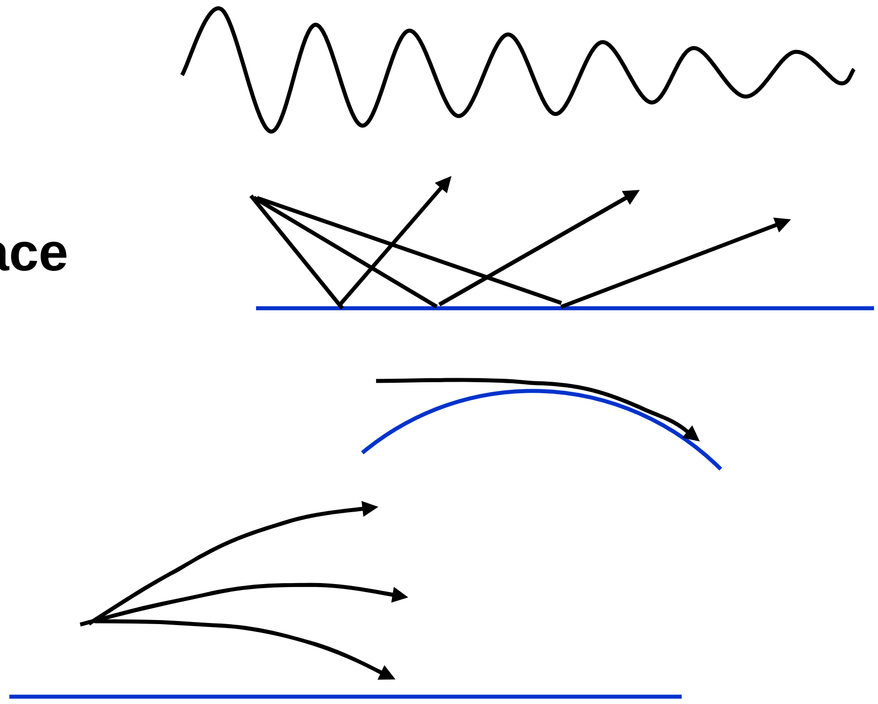
Antenna Gain





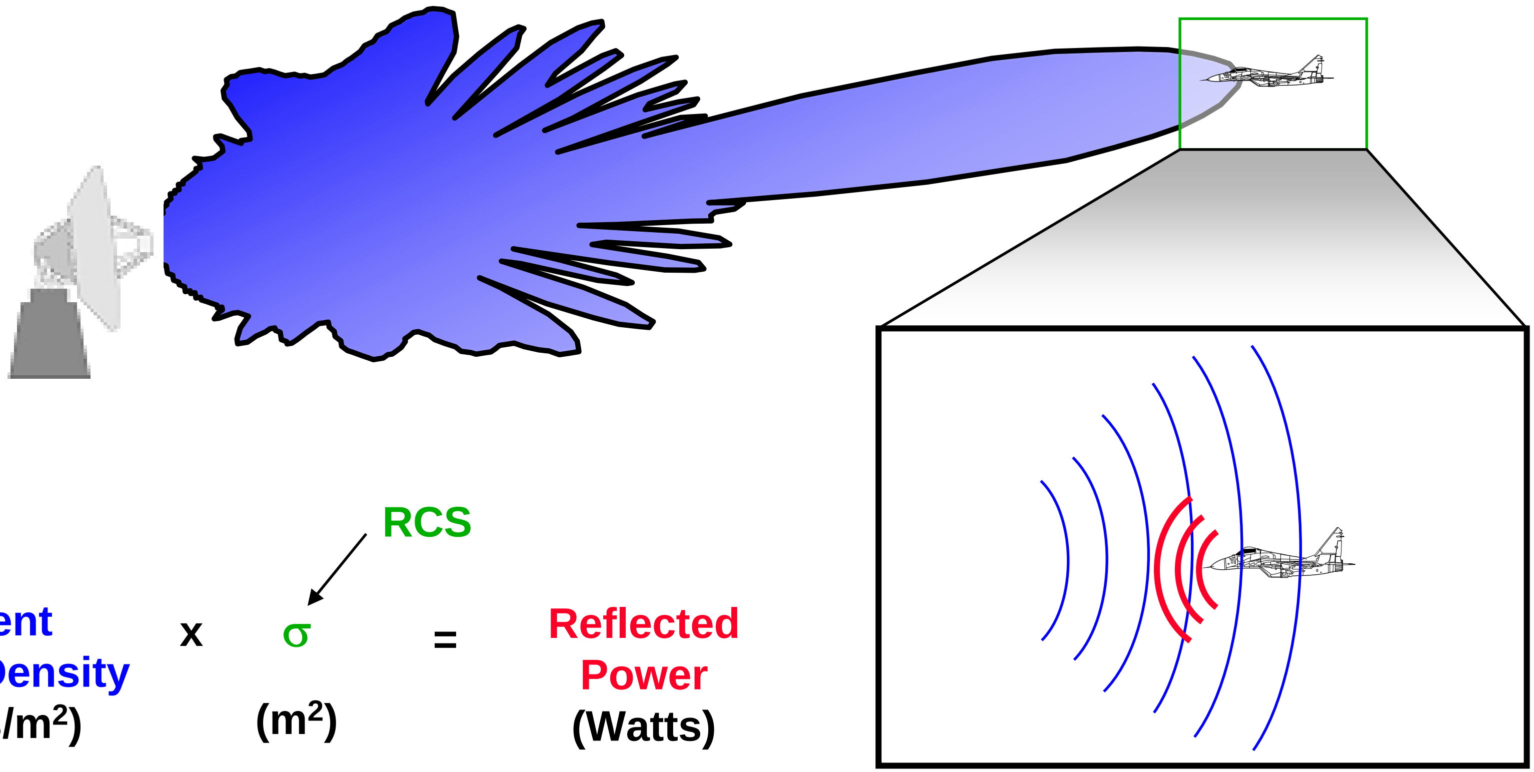
Propagation Effects on Radar Performance

- 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

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

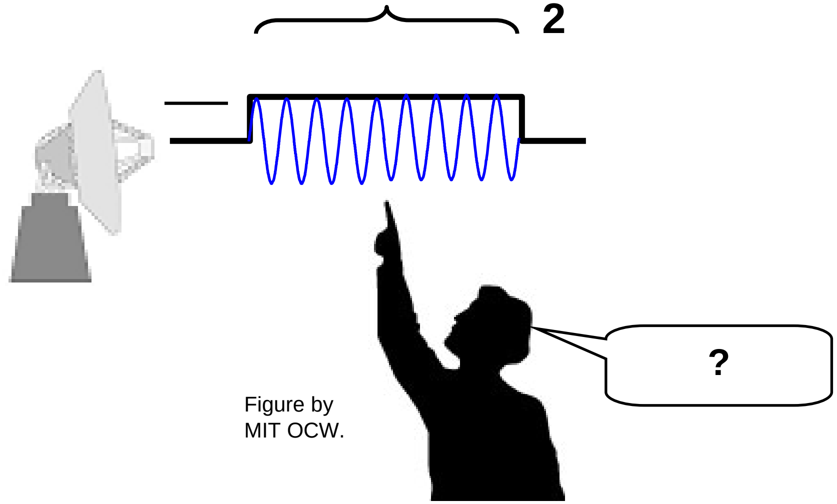
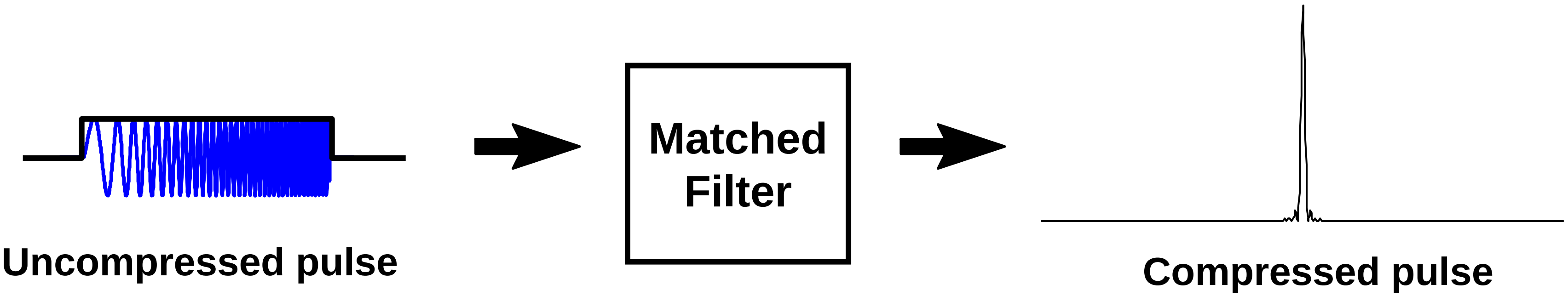
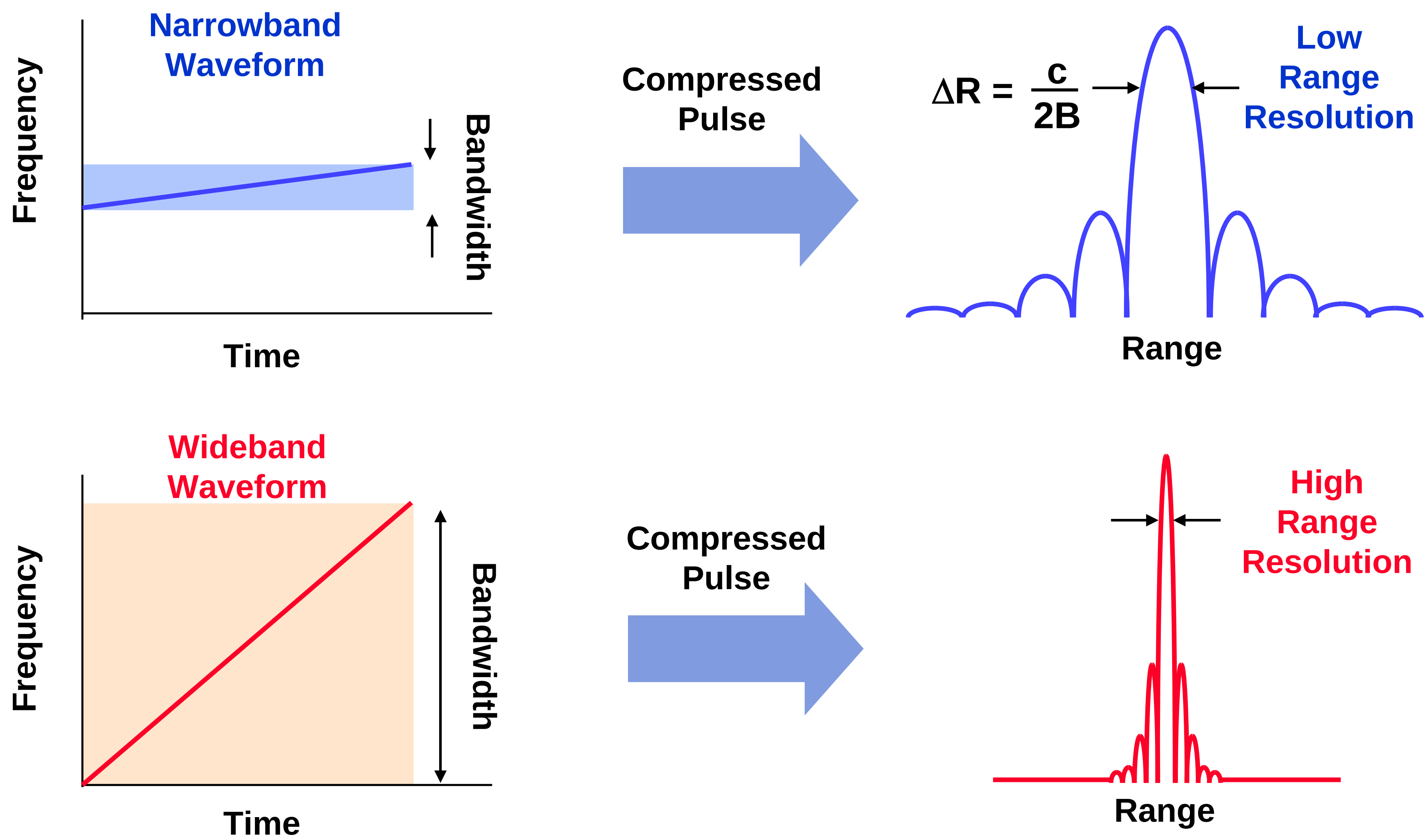


Figure by
MIT OCW.

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

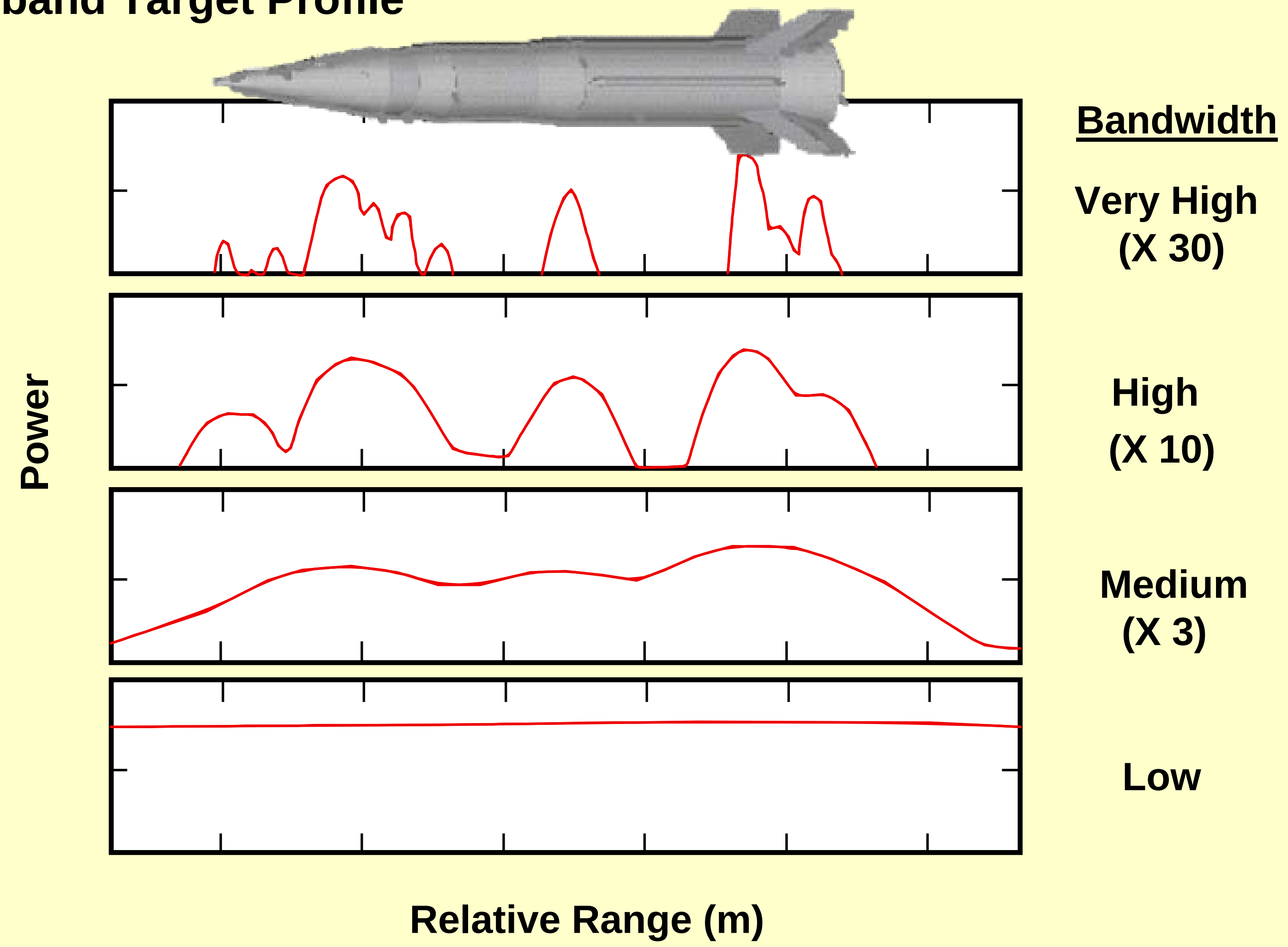


Bandwidth

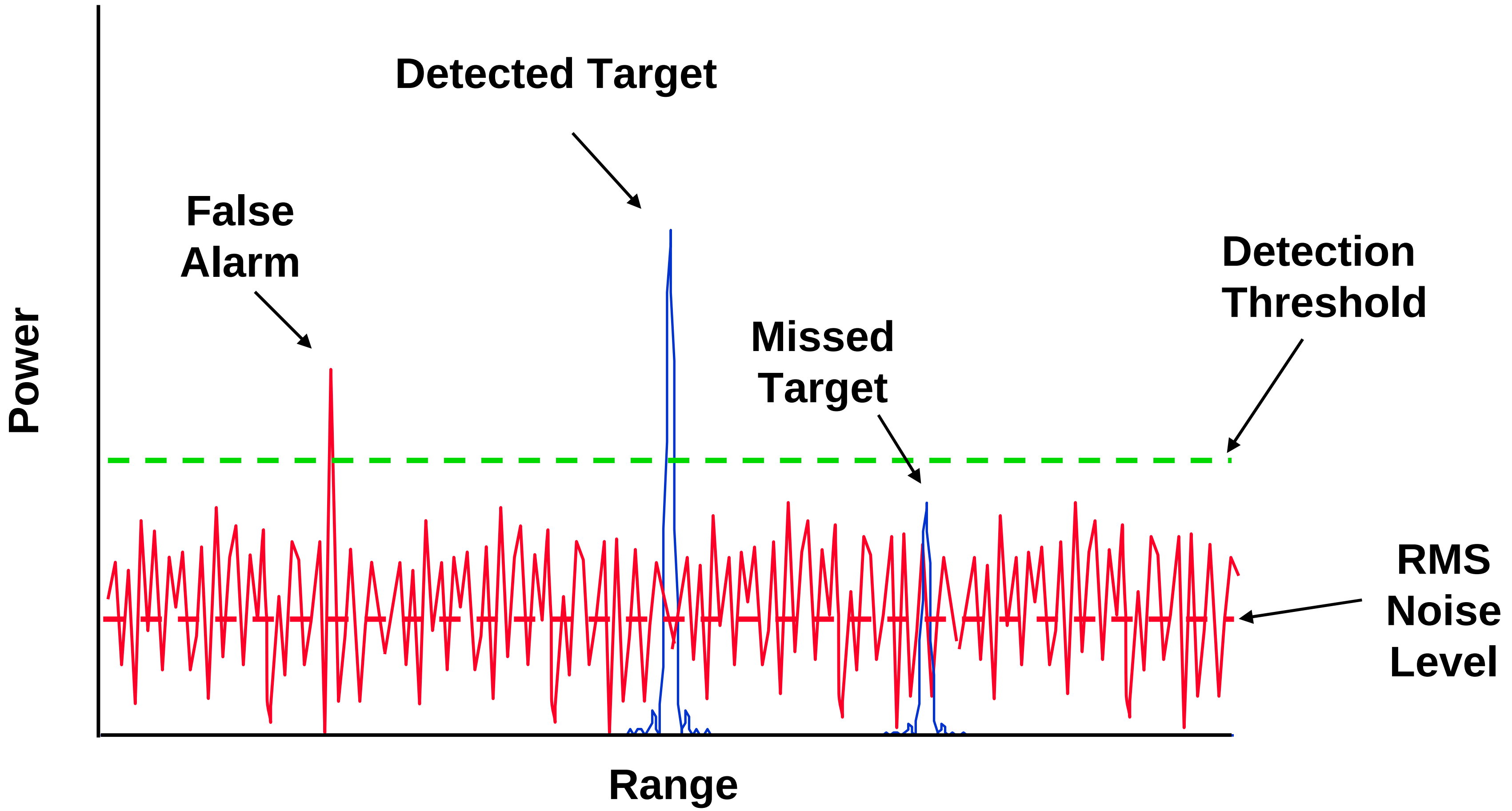

Narrowband Waveform
Frequency
Time
Bandwidth
Compressed Pulse
$\Delta R = \frac{c}{2B}$
Low Range Resolution
Range
Wideband Waveform
Frequency
Time
Bandwidth
Compressed Pulse
High Range Resolution
Range

Why Bandwidth is Important

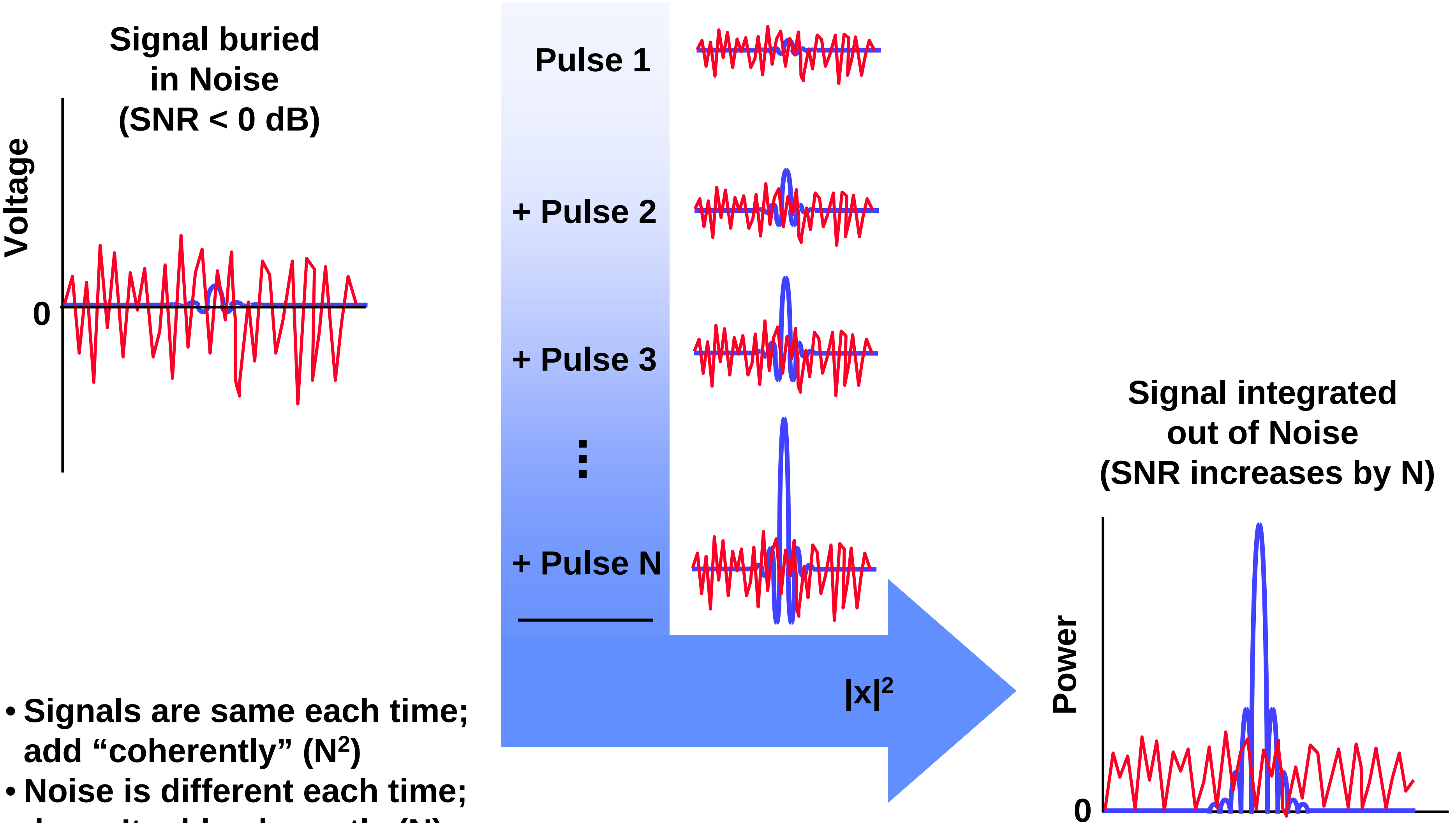
Wideband Target Profile



Detection of Signals in Noise



Coherent Integration



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

Doppler Effect

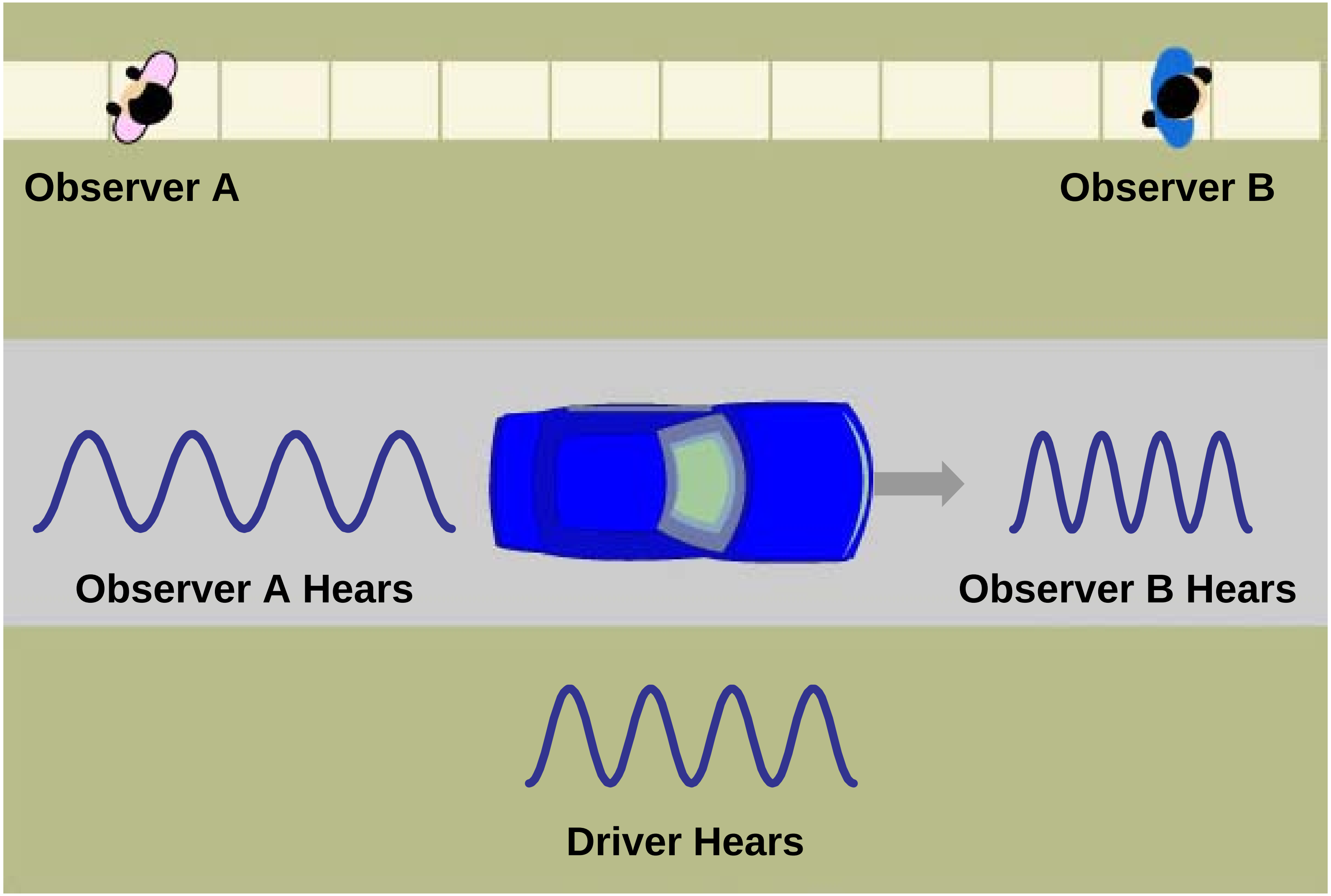
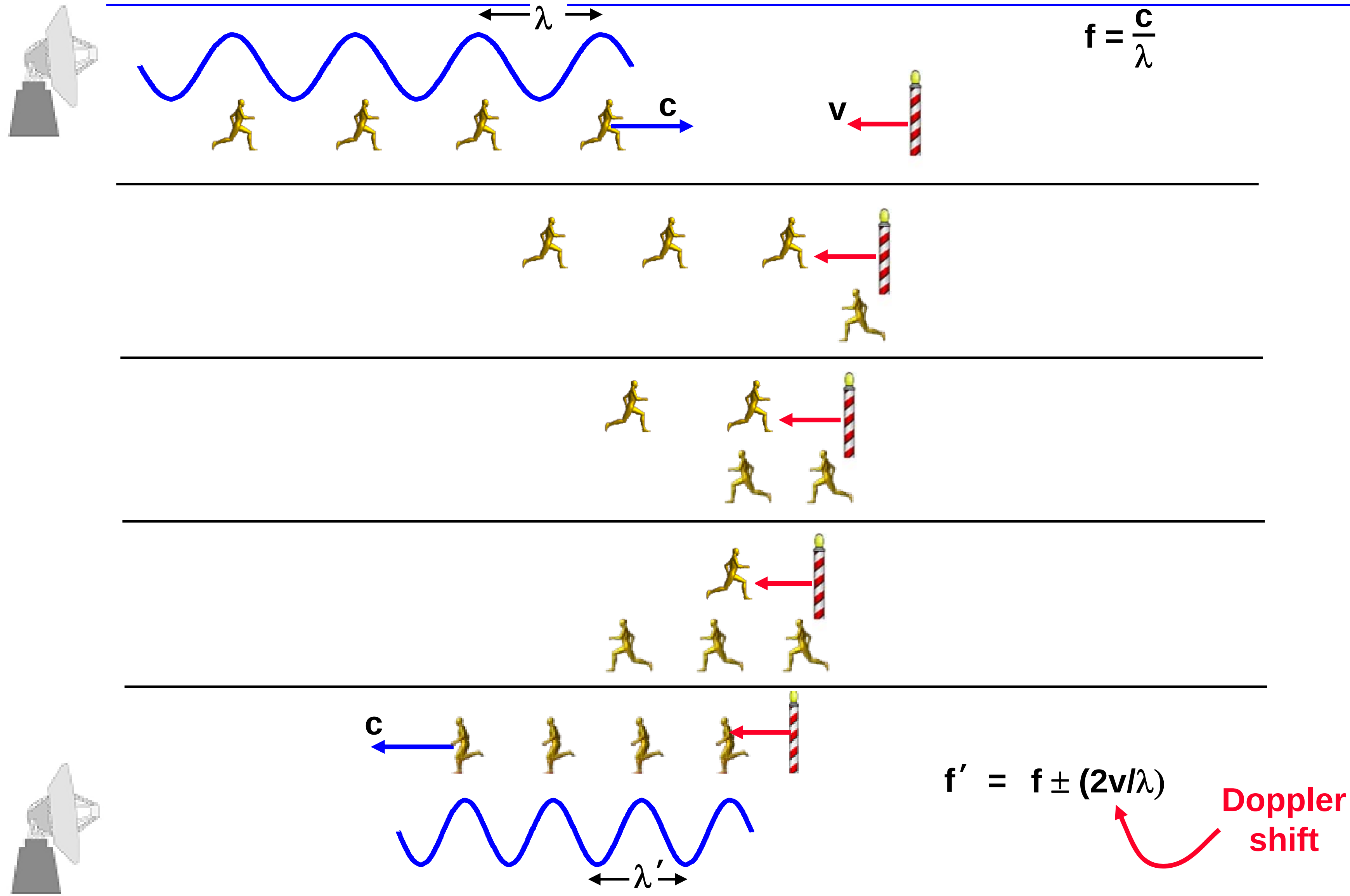


Figure by MIT OCW.

Doppler Shift Concept

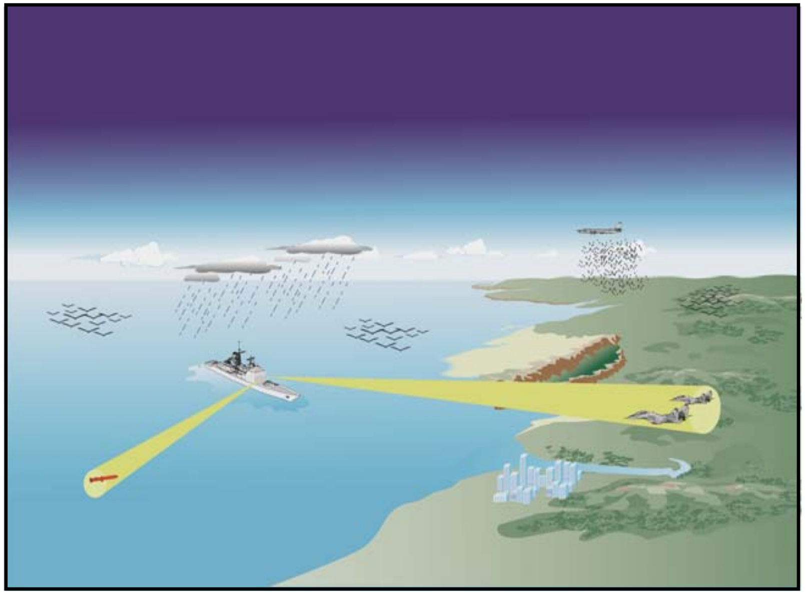


$f = \frac{c}{\lambda}$

$f' = f \pm (2v/\lambda)$

Why Doppler is Important

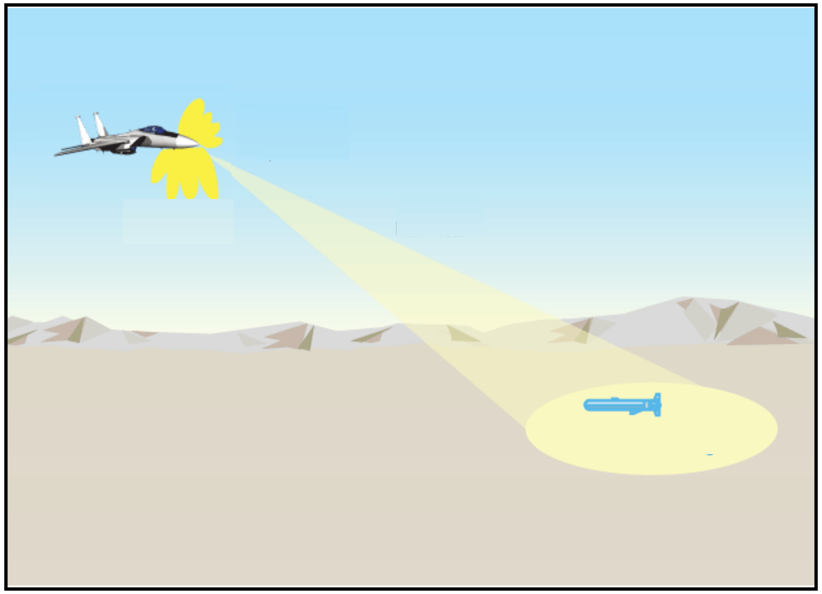
Surface Radar



Clutter returns are much larger than target returns…

…however, targets move, clutter doesn't.

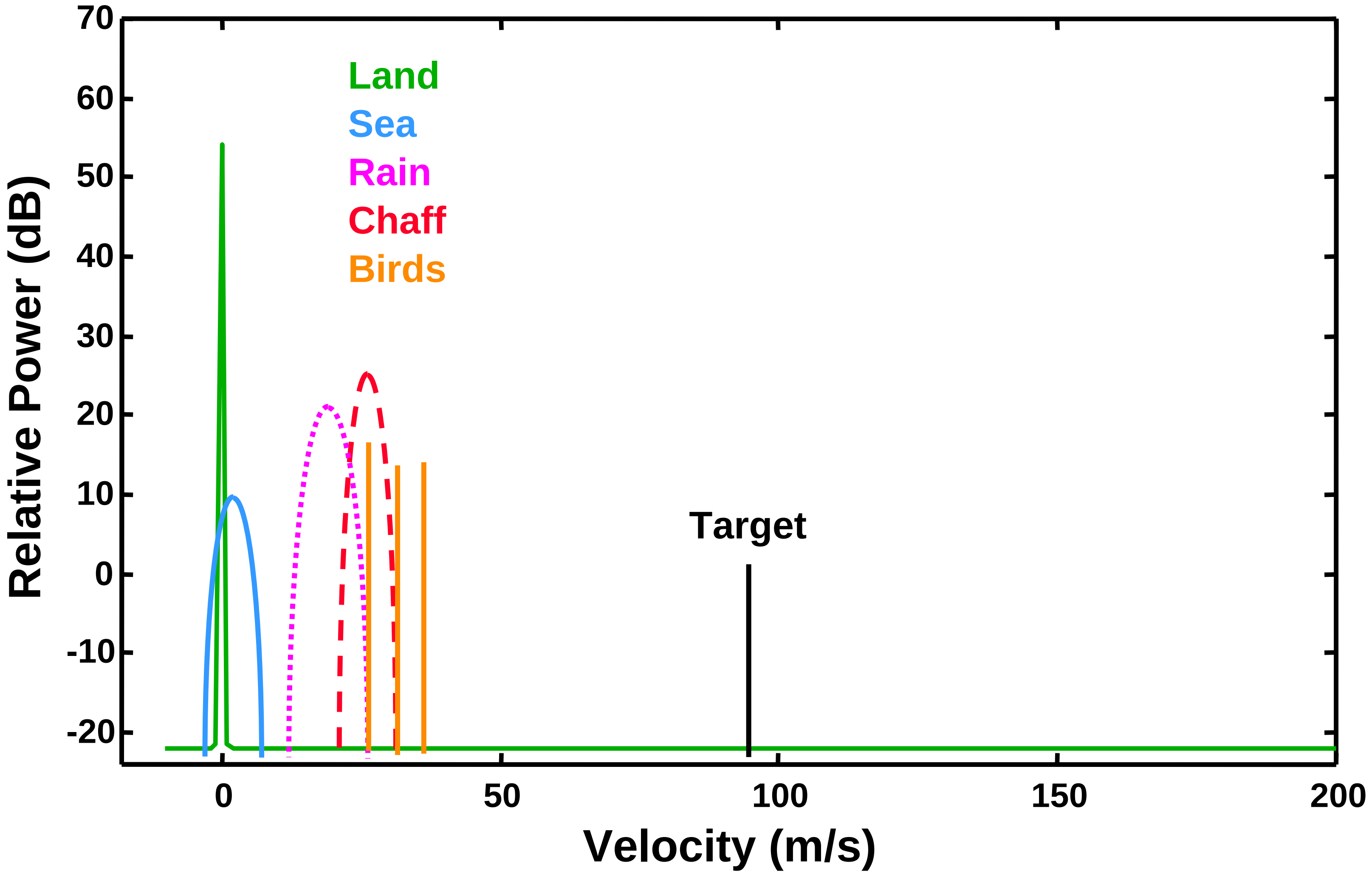
Airborne Radar



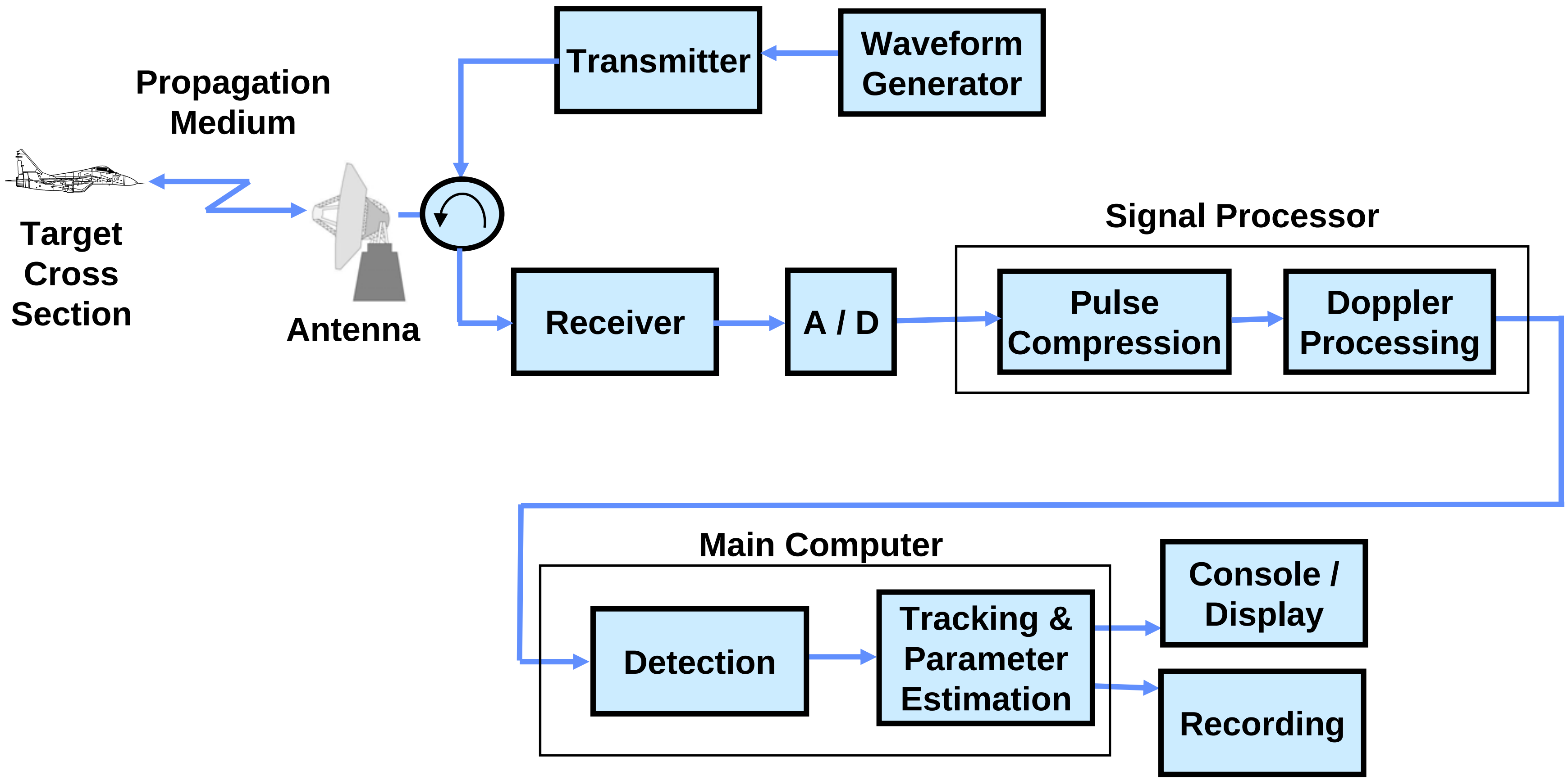
Note: if you're moving too, you need to take that into account.

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

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- 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

Introduction to Radar Systems

The Radar Equation

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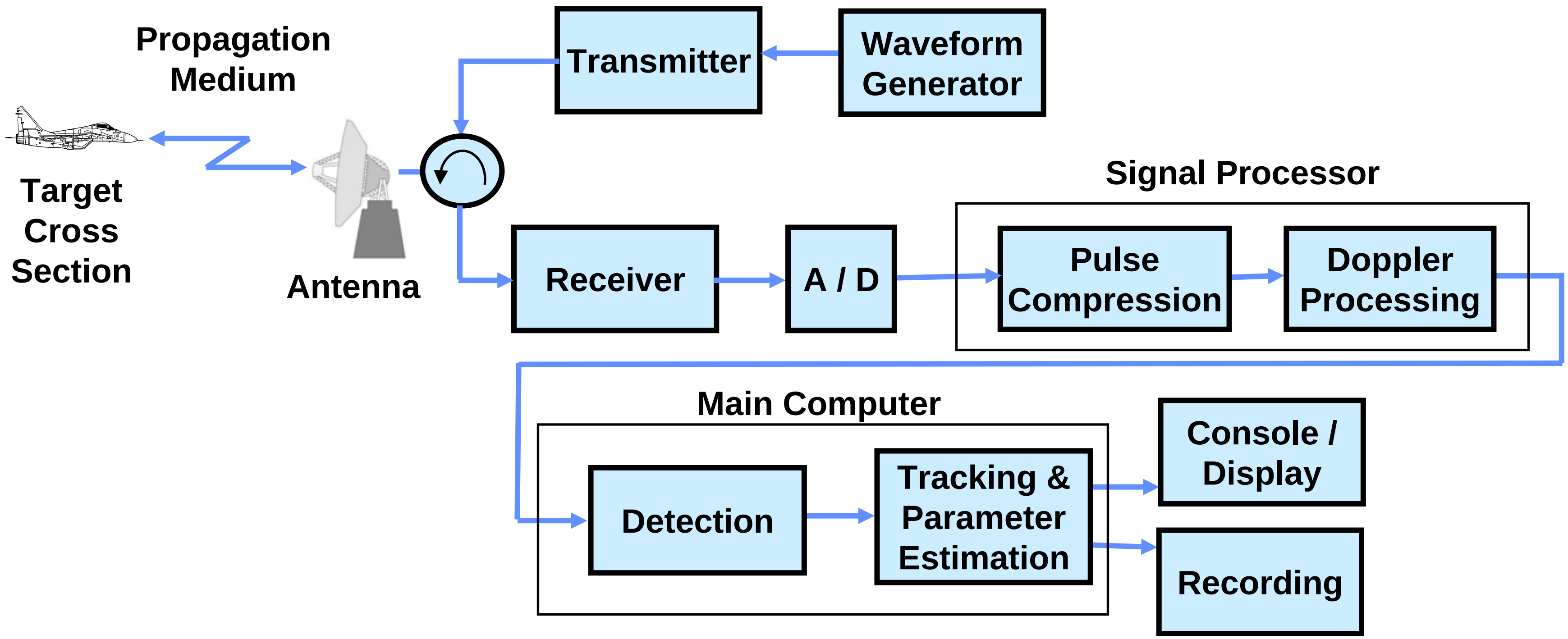
Introduction – The Radar Range Equation



The Radar Range Equation Connects:

1. **Target Properties - e.g. Target Reflectivity (radar cross section)**
2. **Radar Characteristics - e.g. Transmitter Power, Antenna Aperture**
3. **Distance between Target and Radar - e.g. Range**
4. **Properties of the Medium - e.g. Atmospheric Attenuation.**

Outline

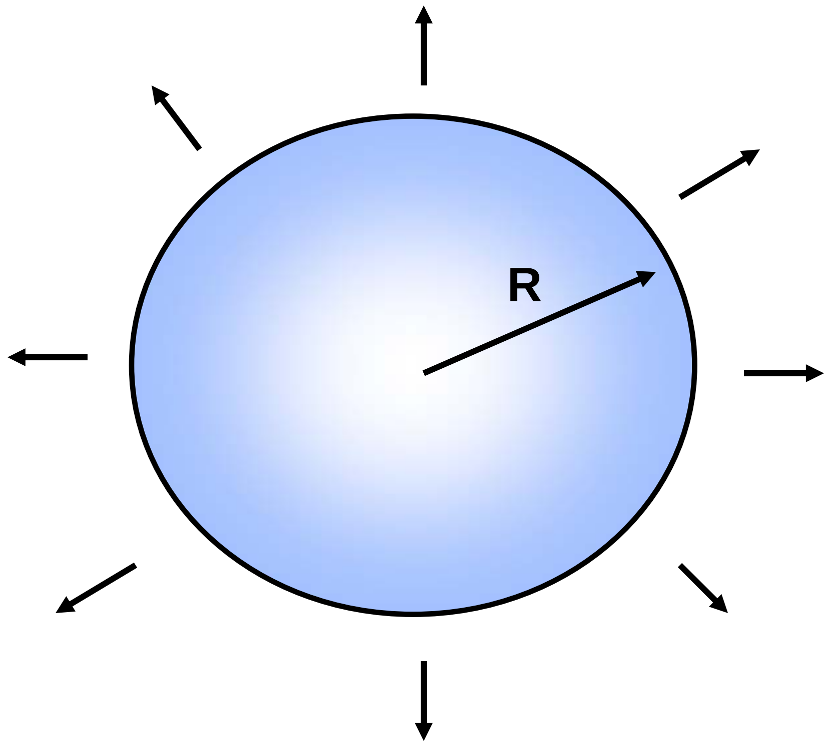
- Introduction
- Introduction to Radar Equation
- Surveillance Form of Radar Equation
- Radar Losses
- Example
- Summary

Radar Range Equation

Power density from uniformly radiating antenna transmitting spherical wave

$$\frac{P_t}{4 \pi R^2}$$

P_t = peak transmitter power
R = distance from radar



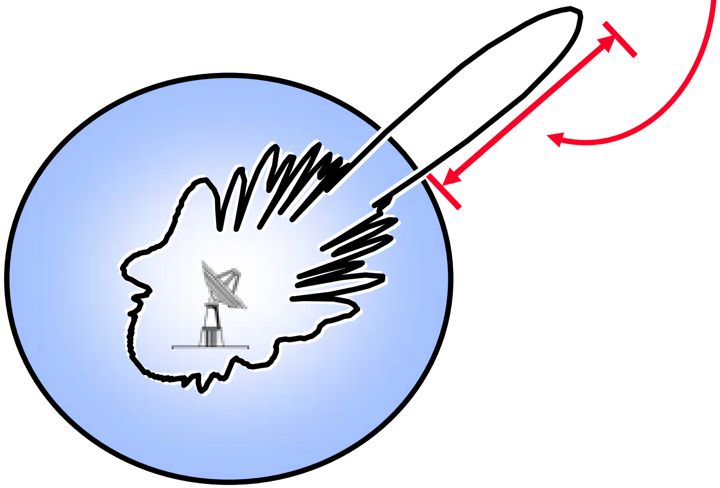
Radar Range Equation (continued)

Power density from isotropic antenna $\dfrac{P_t}{4 \pi R^2}$

Power density from directive antenna $\dfrac{P_t G_t}{4 \pi R^2}$

P_t = peak transmitter power
R = distance from radar

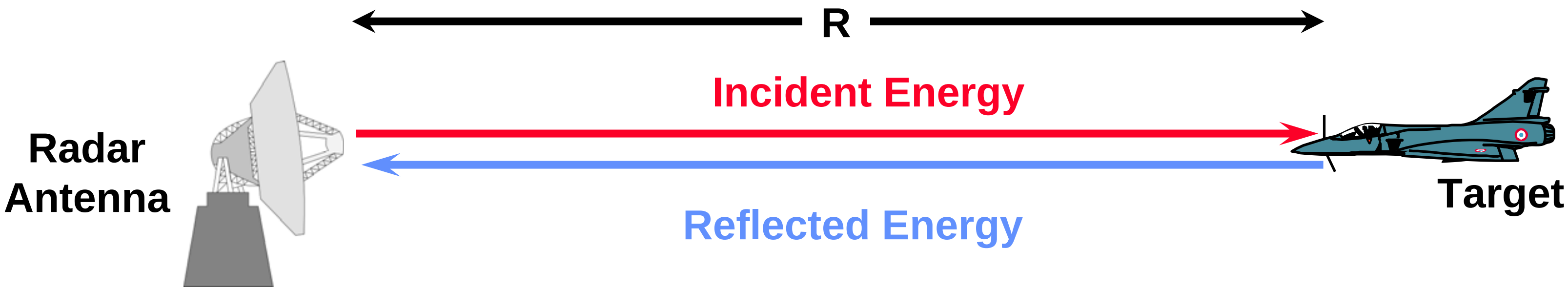
G_t = transmit gain



Gain is the radiation intensity of the antenna in a given direction over that of an isotropic (uniformly radiating) source

Gain = $4 \pi A / \lambda^2$

Definition of Radar Cross Section (RCS or σ)



Radar Cross Section (RCS or σ) is a measure of the energy that a radar target intercepts and scatters back toward the radar

Power of reflected signal at target

$$\frac{P_t G_t \sigma}{4 \pi R^2}$$

Power density of reflected signal at the radar

$$\frac{P_t G_t}{4 \pi R^2} \frac{\sigma}{4 \pi R^2}$$

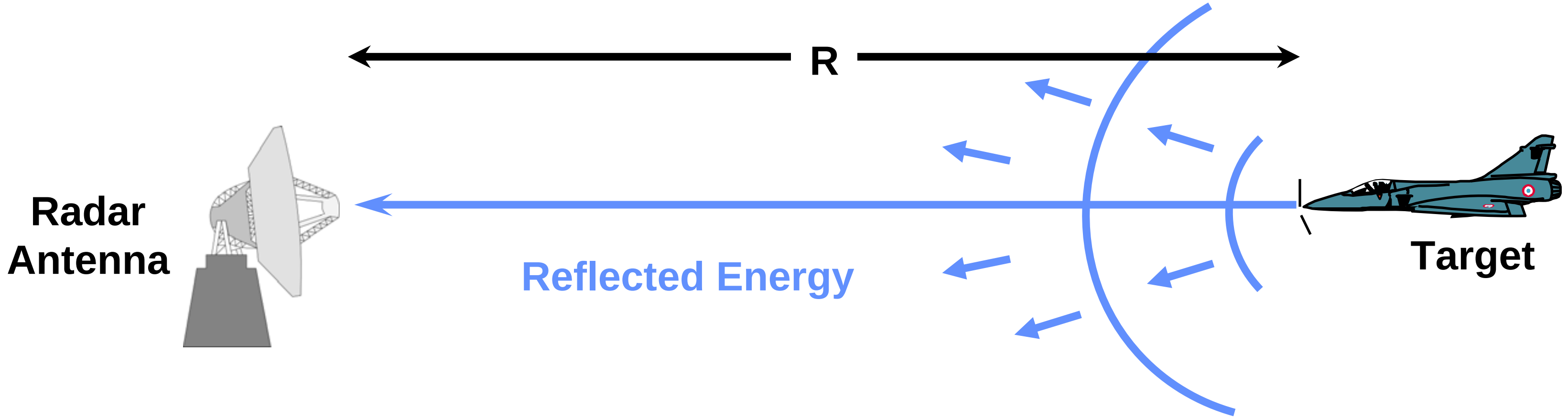
σ = radar cross section units (meters)^2

Power density of reflected signal falls off as ($1/R^2$)

Radar Range Equation (continued)

Power density of reflected signal at radar

$$\frac{P_t G_t}{4 \pi R^2} \; \frac{\sigma}{4 \pi R^2}$$



The received power = the power density at the radar times the area of the receiving antenna

Power of reflected signal from target and received by radar

$$P_r = \frac{P_t G_t}{4 \pi R^2} \; \frac{\sigma A_e}{4 \pi R^2}$$

P_r = power received

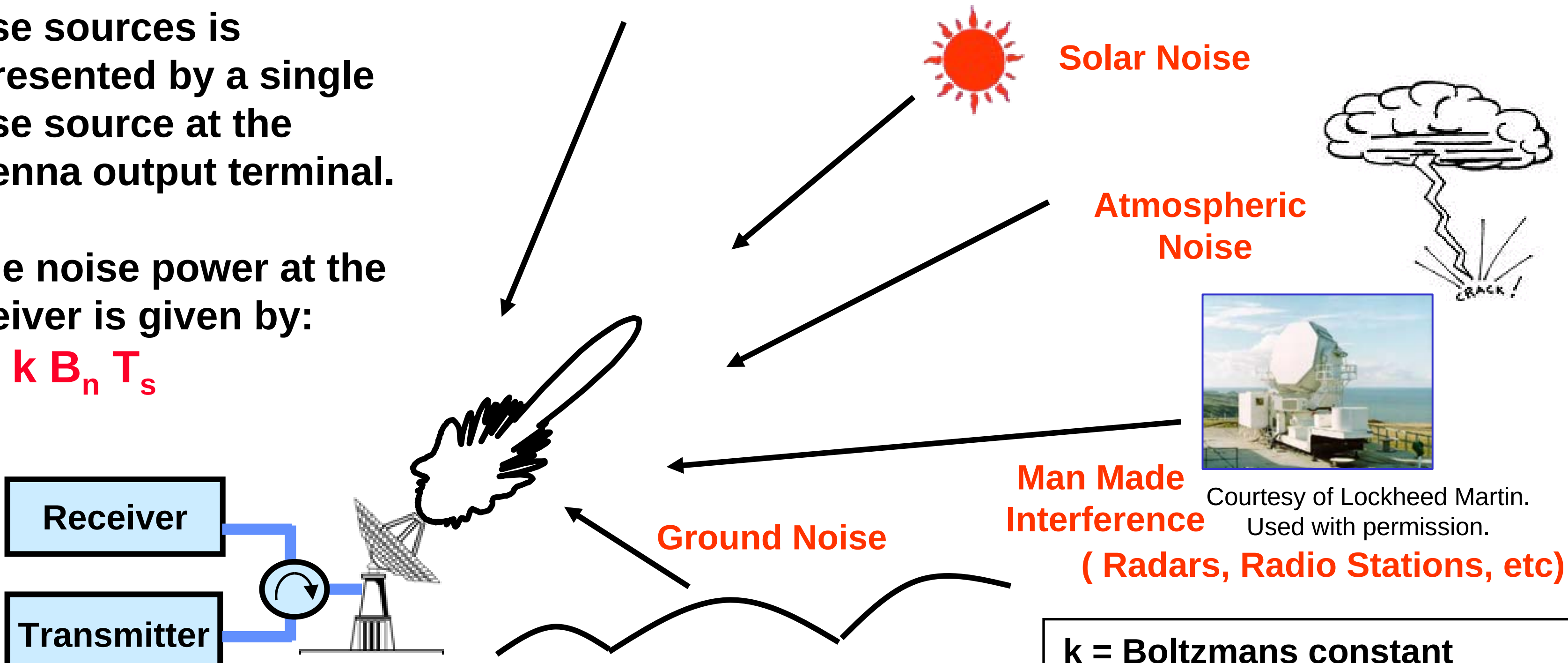
A_e = effective area of receiving antenna

Sources of Noise Received by Radar

- The total effect of these noise sources is represented by a single noise source at the antenna output terminal.

- The noise power at the receiver is given by:

$N = k\,B_n\,T_s$



(Receiver, waveguide, and duplexer noise)

Noise from Many Sources Competes with the Target Echo

k = Boltzmans constant
= 1.38 x 10^{-23} joules / deg ^{o}K
T_s = System Noise Temperature
B_n = Noise bandwidth of receiver

Radar Range Equation (continued)

Signal Power reflected from target and received by radar

$$P_r = \frac{P_t G_t}{4 \pi R^2} \frac{\sigma A_e}{4 \pi R^2}$$

Average Noise Power

$$N = k T_s B_n$$

Signal to Noise Ratio

$$S / N = P_r / N$$

Assumptions :
$G_t = G_r$
L = Total System Losses
$T_o = 290^o$ K

$$\boxed{S / N = \frac{P_t G^2 \lambda^2 \sigma}{(4 \pi)^3 R^4 k T_s B_n L}}$$

Signal to Noise Ratio (S/N or SNR) is the standard measure of a radar's ability to detect a given target at a given range from the radar

" S/N = 13 dB on a 1 m^2 target at a range of 1000 km"

radar cross section of target

System Noise Temperature

- The System Noise Temperature, T_S , is divided into 3 components :

$$T_s = T_a + T_r + L_r\,T_e$$

- T_a is the contribution from the antenna
  - Apparent temperature of sky (from graph)
  - Loss within antenna
- T_r is the contribution from the RF components between the antenna and the receiver
  - Temperature of RF components
- L_r is the loss of input RF components
- T_e is the temperature of the receiver
  - Noise factor of receiver

Outline

- Introduction
- Introduction to Radar Equation
- Surveillance Form of Radar Equation
- Radar Losses
- Example
- Summary

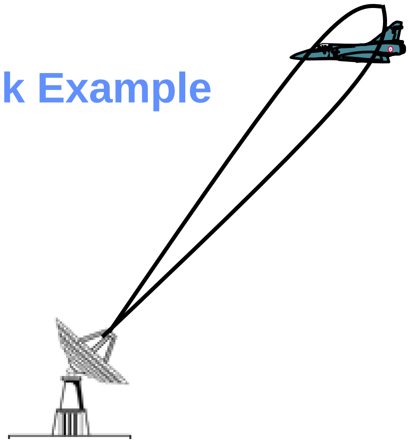
Track Radar Range Equation

Track Radar Equation

$$S / N = \frac{P_t \, G^2 \, \lambda^2 \, \sigma}{(4 \pi)^3 \, R^4 \, k \, T_s \, B_n \, L}$$

- **When the location of a target is known and the antenna is pointed toward the target.**

Track Example



Track & Search Radar Range Equations

Track Radar Equation

$$S / N = \frac{P_t \, G^2 \lambda^2 \sigma}{(4 \pi)^3 R^4 k \, T_s \, B_n \, L}$$

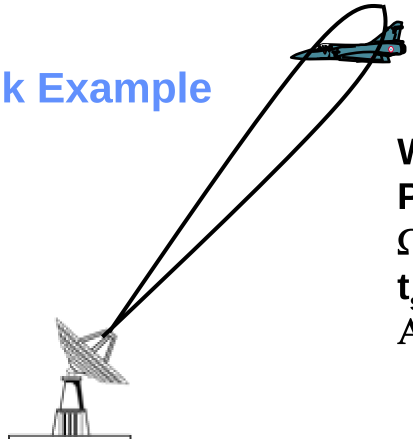
- When the location of a target is known and the antenna is pointed toward the target.

Search Radar Equation

$$\boxed{S / N = \frac{P_{av} \, A_e \, t_s \, \sigma}{4 \pi \Omega \; R^4 k \, T_s \; L}}$$

- When the target's location is unknown, and the radar has to search a large angular region to find it.

Track Example



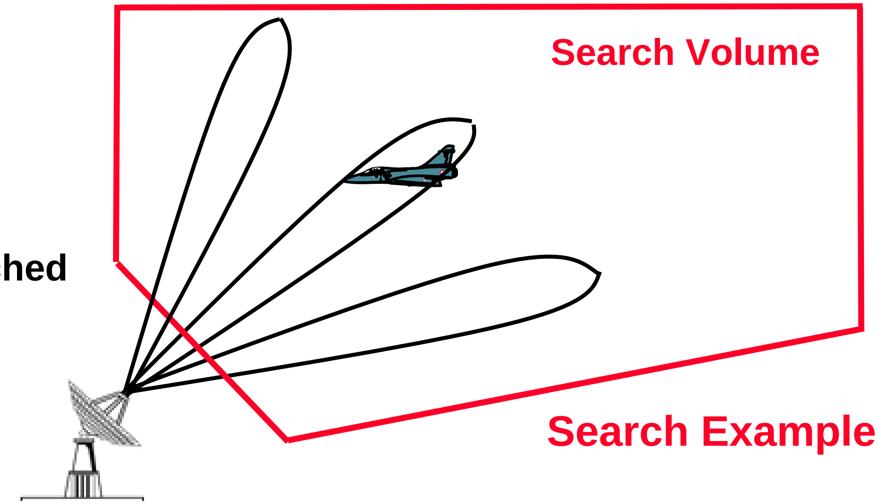
Where:

P_{av} = average power

Ω = solid angle searched

t_s = scan time for Ω

A_e = antenna area



Search Radar Range Equation

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

Re-write as:

f (design parameters) = g (performance parameters)

$$\frac{P_{av}\, A_e}{k T_s\, L} = \frac{4\, \pi\, \Omega\, R^4\, (S/N)}{\sigma\, t_s}$$

Angular coverage

Range coverage

Measurement quality

Time required

Target size

Scaling of Radar Equation

$$\frac{S}{N} = \frac{P_{av}\, A_e\, t_s\, \sigma}{4\pi\, R^4\, \Omega\;\; k\, T_s\, L} \quad \Longrightarrow \quad P_{av} = \frac{4\pi\, R^4\, \Omega\, k\, T_s\, L\, (S/N)}{A_e\, t_s\, \sigma}$$

- **Power required is:**
  - **Independent of wavelength**
  - **A very strong function of R**
  - **A linear function of everything else**

Example Radar Can Perform Search at 1000 km Range
How Might It Be Modified to Work at 2000 km ?

Solutions Increasing R by 3 dB (x 2) Can Be Achieved by:

1. Increasing P_{av} by 12 dB (x 16)

or 2. Increasing Diameter by 6 dB (A by 12 dB)

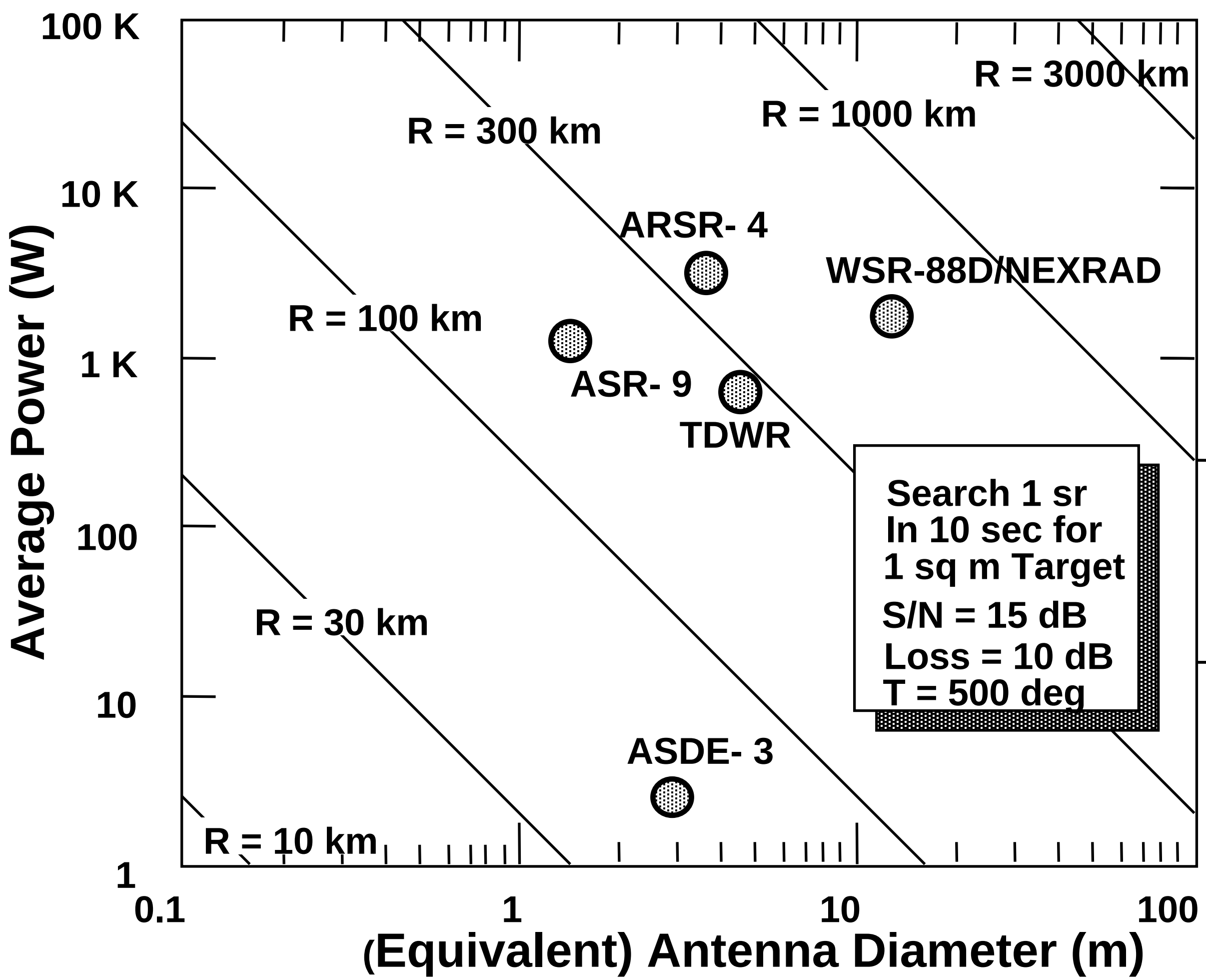
or 3. Increasing t_s by 12 dB

or 4. Decreasing Ω by 12 dB

or 5. Increasing σ by 12 dB

or 6. An Appropriate Combination of the Above

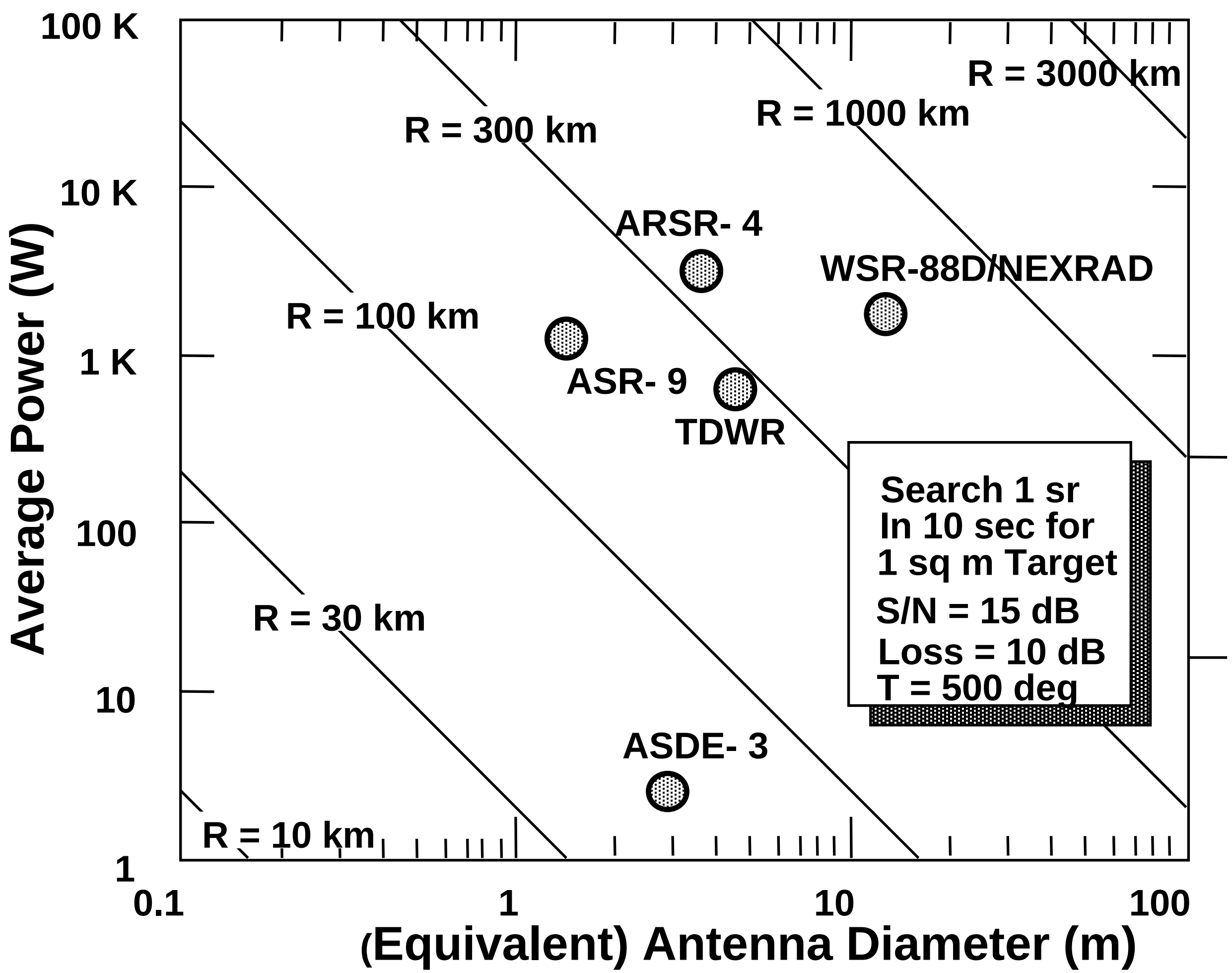
Search Radar Performance



ASR- 9
Airport Surveillance Radar

Courtesy of Northrop Grumman.
Used with permission.

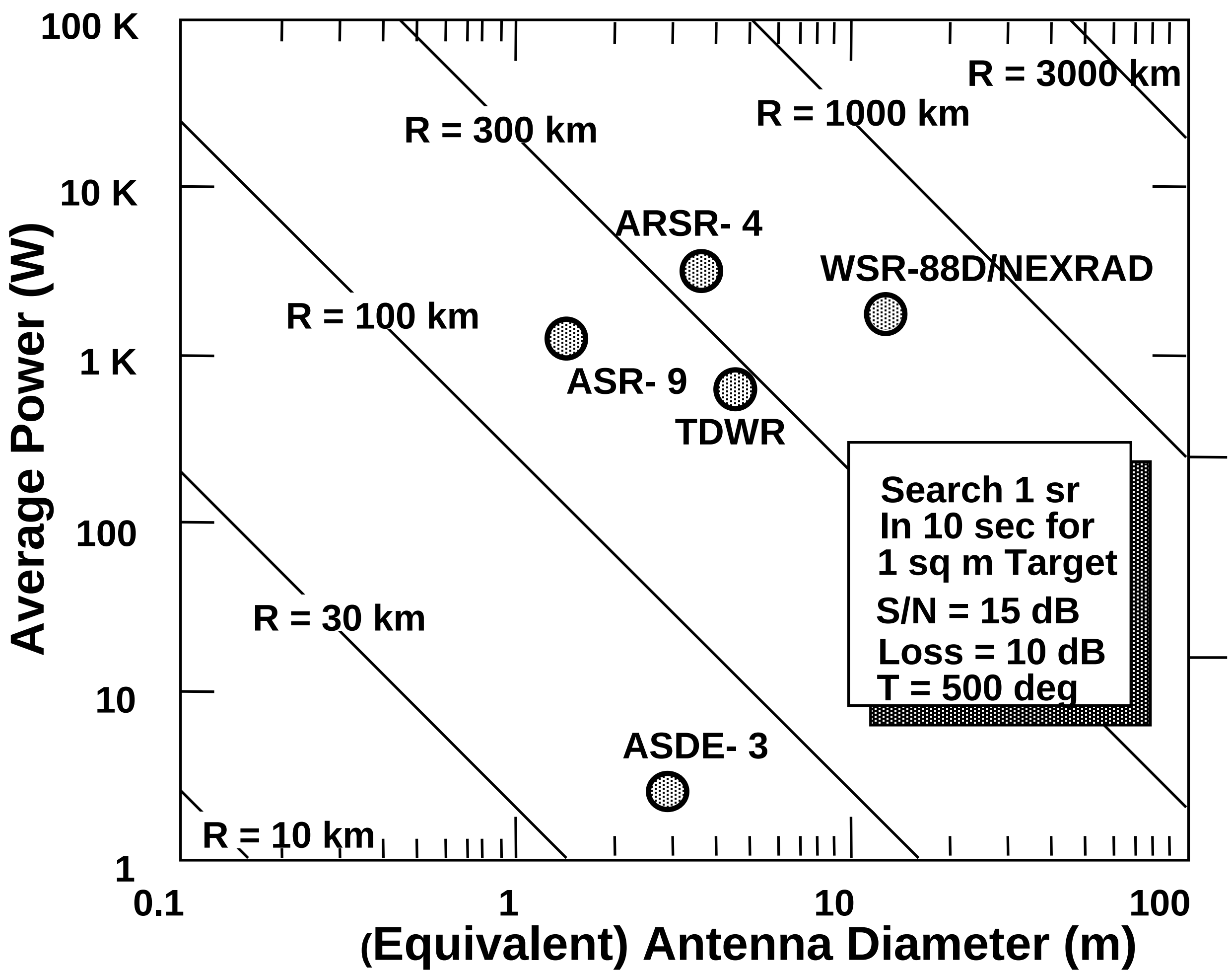
Search Radar Performance



ASDE- 3
Airport Surface Detection Equipment

Courtesy Lincoln Laboratory

Search Radar Performance

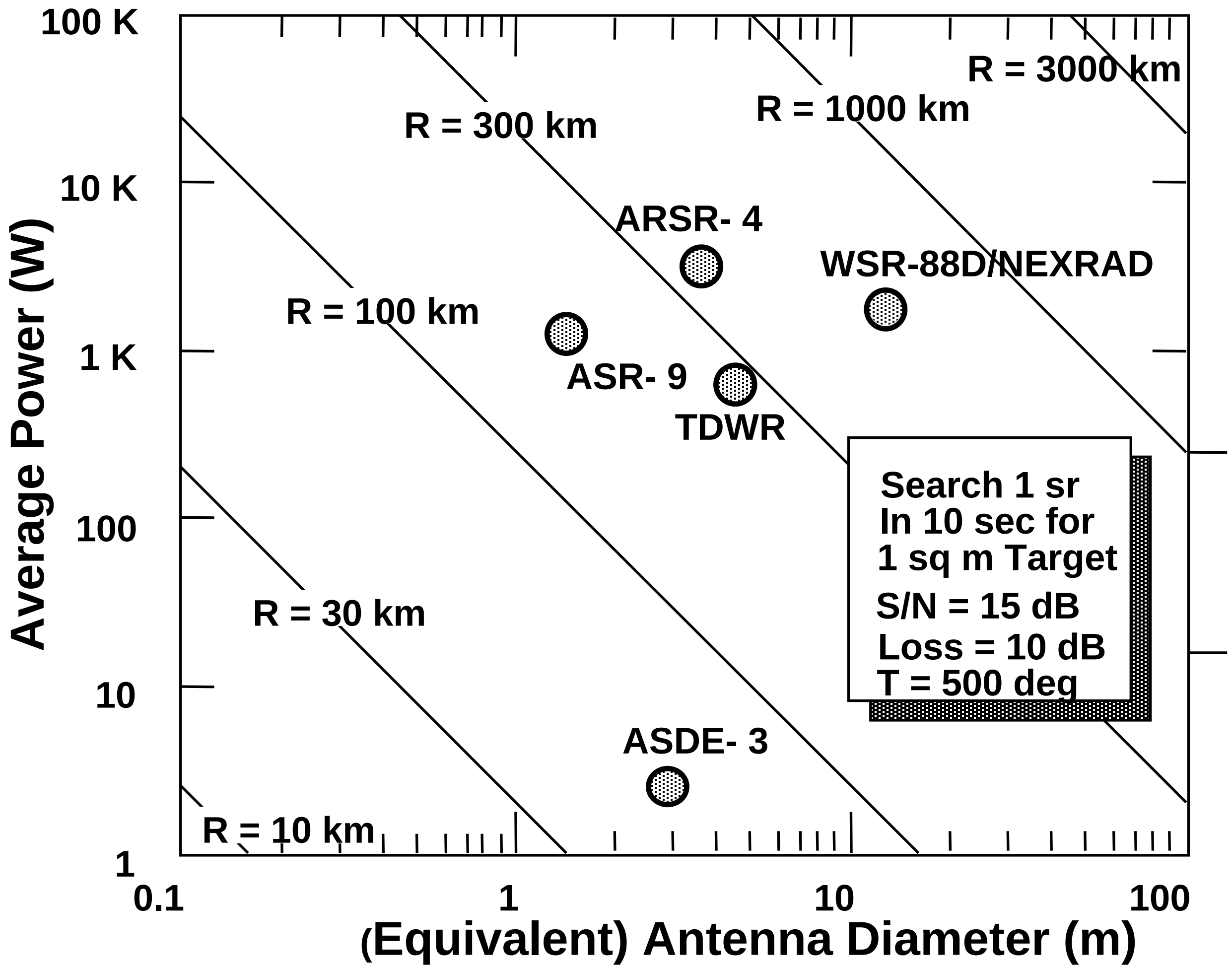


ARSR- 4
Air Route Surveillance Radar

ARSR- 4 Antenna
(without Radome)

Courtesy of Northrop Grumman.
Used with permission.

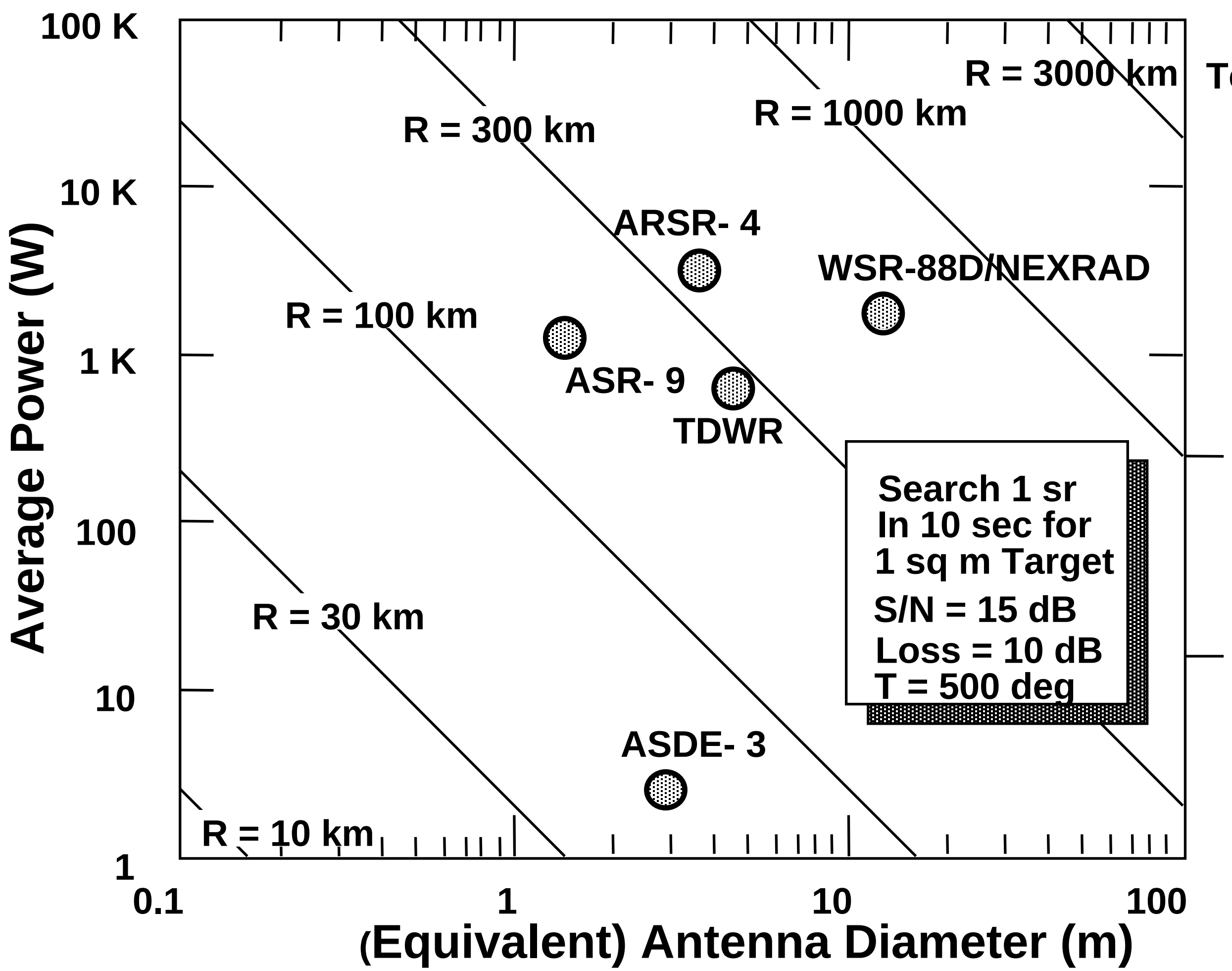
Search Radar Performance



WSR-88D / NEXRAD

Courtesy of NOAA.

Search Radar Performance



TDWR
Terminal Doppler Weather Radar

Courtesy of Raytheon.
Used with permission

Outline

- Introduction
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Loss Terms for Radar Equation

Transmit Losses

- Radome
- Waveguide Feed
- Waveguide
- Circulator
- Low Pass Filters
- Rotary Joints
- Antenna Efficiency
- Beam Shape
- Scanning
- Quantization
- Atmospheric
- Field Degradation

Receive Losses

- Radome
- Waveguide Feed
- Waveguide
- Combiner
- Rotary Joints
- Receiver Protector
- Transmit / Receive Switch
- Antenna Efficiency
- Beam Shape
- Scanning
- Quantization
- Weighting
- Non-Ideal Filter
- Doppler Straddling
- Range Straddling
- CFAR
- Atmospheric
- Field Degradation

Examples of Losses in Radar Equation

- **Beam Shape Loss**
  - Radar return from target with scanning radar is modulated by shape of antenna beam as it scans across target. Can be 2 to 4 dB
- **Scanning Antenna Loss**
  - For phased array antenna, gain of beam off boresight less than that on boresight
- **Plumbing Losses**
  - Transmit waveguide losses
  - Rotary joints, circulator, duplexer
- **Signal Processing Loss**
  - A /D Quantization Losses
  - Adaptive thresholding (CFAR) Loss
  - Range straddling Loss
  - Range and Doppler Weighting

Examples of Losses in Radar Equation

- Atmospheric Attenuation Loss
  - Radar beam attenuates as it travels through atmosphere (2 way loss)
- Integration Loss
  - Non coherent integration of pulses not as efficient as coherent integration
- Margin (Field Degradation) Loss
  - Characteristics of radar deteriorates over time.(3 dB not unreasonable
    - Water in transmission lines
    - Deterioration in receiver noise figure
    - Weak or poorly tuned transmitter tubes

Outline

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Example - Airport Surveillance Radar

- **Problem : Show that a radar with the parameters listed below, will get a reasonable S / N on an small aircraft at 60 nmi.**

<u>Radar Parameters</u>

Range	60 nmi
Aircraft cross section	1 m^2
Peak Power	1.4 Megawatts
Duty Cycle	0.000525
Pulsewidth	.6 microseconds
Bandwidth	1.67 MHz
Frequency	2800 MHz
Antenna Rotation Rare	12.8 RPM
Pulse Repetition Rate	1200 Hz
Antenna Size	4.9 m wide by 2.7 m high
Azimuth Beamwidth	1.35 º
System Noise Temp.	950 º K

$\lambda =$ c / f = .103 m

G = 4 π A / λ^2 = 15670 m^2
= 42 dB, (actually 33 dB with beam shaping losses)

Number of pulses per beamwidth = 21

Assume Losses = 8dB

Example - Airport Surveillance Radar

$$S / N = \frac{P_t \, G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k \, T_s \, B_n \, L}$$

P_t = 1.4 Megawatts	R = 111, 000 m
G = 33 dB = 2000	T_s = 950 ^{o} K
$\lambda = .1$ m	B_n = 1.67 MHz
$\sigma = 1$ m^2	L = 8dB = 6.3
k = 1.38 x 10 $^{-23}$ w / Hz ^{o} K	$(4\pi)^3 = 1984$

$$\frac{(1.4 \times 10^6 \text{ w})(2000)(2000)(.1\text{m})(.1\text{m})(1\text{m}^2)}{(1984)\,(1.11 \text{ X } 10^5 \text{ m})^4 (1.38 \times 10^{-23} \text{ w / Hz } ^o\text{K})\,(950\ ^o\text{K})\,(6.3)\,(1.67 \times 10^6 \text{ Hz})}$$

$$\frac{5.6 \times 10^{+6+3+3-1-1}}{415 \times 10^{+3+20-23+2+6}} = \frac{5.6 \times 10^{+10}}{4.15 \times 10^{+2+3+20-23+2+6}} = \frac{5.6 \times 10^{+10}}{4.15 \times 10^{+10}} = 1.35 = 1.3 \text{ dB}$$

S / N = 1.3 dB per pulse (21 pulses integrated) => S / N per dwell = 14.5 dB
+ 13.2 dB

Example - Airport Surveillance Radar

dB Method

		(+)	(-)
Peak Power	1.4 MW	61.5	
(Gain) ^{2}	33 db	66	
(Wavelength) ^{2}	.1 m		20
Cross section	1 m^2	0	
$(4\pi)^3$	1984		33
(Range)^4	111 km		201.8
k	1.38 x 10^{-23} w / Hz ^{o} K	228.6	
System temp	950		29.8
Losses	8 dB		8
Bandwidth	1.67 MHz		62.2
		+ 356.1	- 354.8

+ 1.3 dB

S / N = 1.3 dB per pulse (21 pulses integrated) => S / N per dwell = 14.5 dB (+ 13.2 dB)

Outline

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Cautions in Using the Radar Equation (1)

- The radar equation is simple enough that everybody can learn to use it

- The radar equation is complicated enough that anybody can mess it up if you are not careful (see next VG)

Cautions in Using the Radar Equation (2)

The Sanity Check

Take a Candidate Radar Equation

$$\frac{P\,A^2}{\lambda^2\,kT_s\,L} = \frac{4\,\pi\,R^4\,(S/N)}{\sigma\,t_t}$$

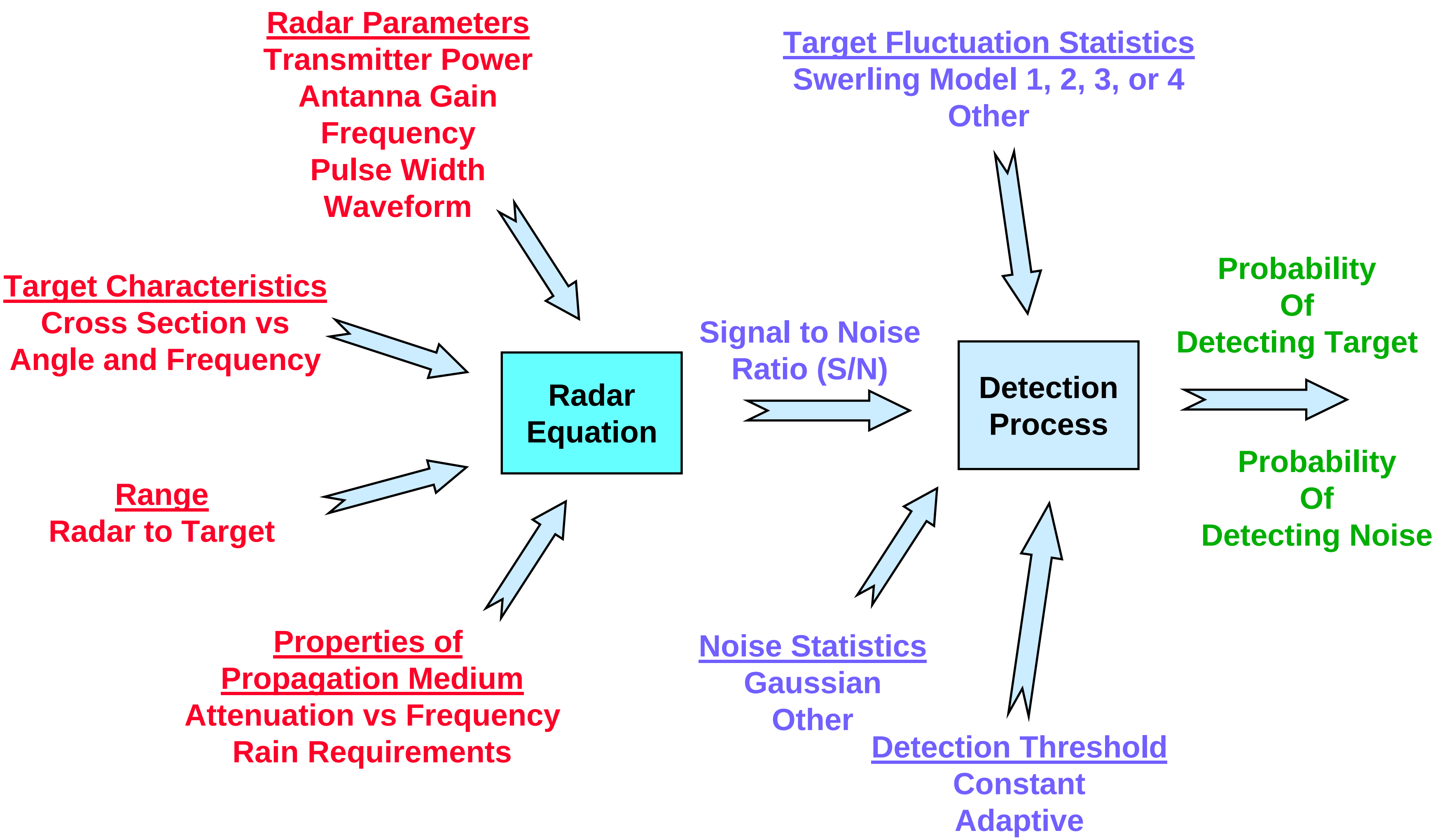
Check it Dimensionally

- **P is energy/time**
- **kT_s is energy**
- **A and σ are distance squared**
- **λ and R are distance**
- **t_t is time**
- **S/N, L and 4π are dimensionless**

Check if Dependencies Make Sense

- **Increasing Range and S/N make requirements tougher**
- **Decreasing σ and t_t makes requirements tougher**
- **Increasing P and A make radar more capable**
- **Decreasing Noise Temp and Loss make radar more capable**
- **Decreasing λ makes radar more capable**

Radar Equation and Detection Process



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ODonnell 06-13-02

Summary

- The radar equation provides a simple connection between radar performance parameters and radar design parameters
- There are different radar equations for different radar functions
- Scaling of the radar equation lets you get a feeling for how the radar design might change to accommodate changing requirements
- Combination of the radar equation with cost or other constraints permits quick identification of critical radar design issues
- Be careful if the radar equation leads to unexpected results
  - Do a sanity check
  - Look for hidden variables or constraints
  - Try to compare parameters with those of a real radar

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Barton, D. K., Modern radar System Analysis, Norwood, Mass., Artech House, 1988

Introduction to Radar Systems

Propagation Effects

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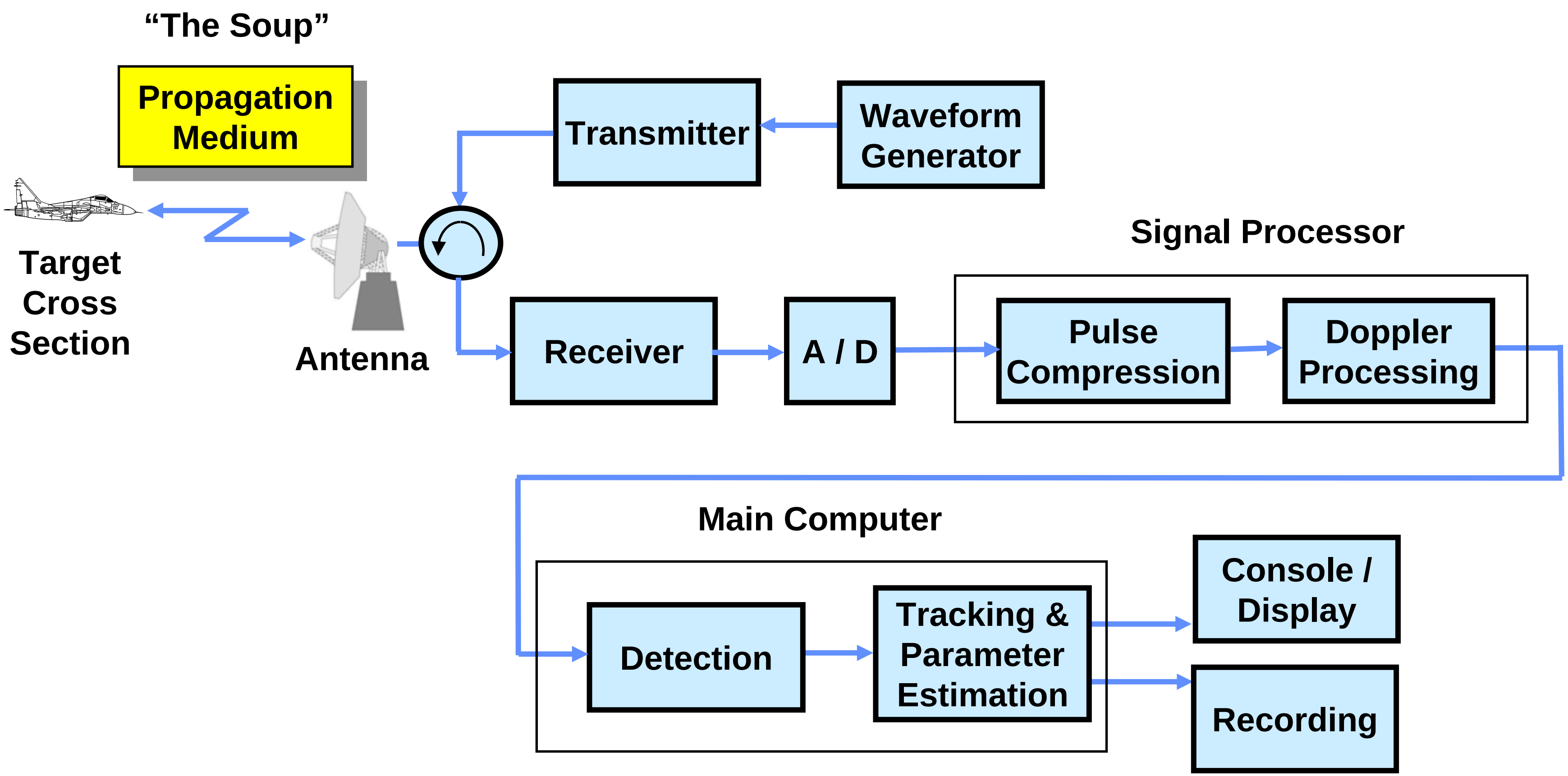
Radar Block Diagram



Radar Classes

- Ground based
- Sea based
- Airborne

Patriot

Courtesy of Raytheon. Used with permission.

AWACS

Courtesy of U.S. Air Force.

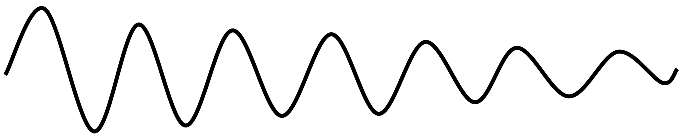
AEGIS

Courtesy of U.S. Navy.

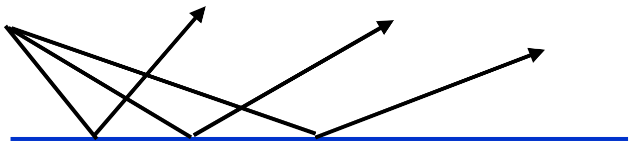
Nearly all radar systems operate through the atmosphere and near the Earth's surface

Propagation Effects on Radar Performance

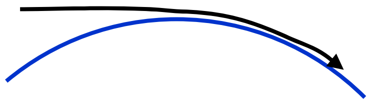
- **Atmospheric attenuation**



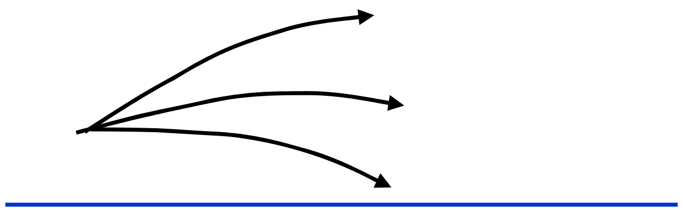
- **Reflection off of Earth's surface**



- **Over-the-horizon diffraction**



- **Atmospheric refraction**



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

What's in the Soup?

- Atmospheric parameters vary with altitude
  - Air density and humidity
  - Rain rate
  - Fog/cloud water content
  - Index of refraction

- Earth's surface
  - Surface material (water vs land)
  - Surface roughness (waves, mountains)
  - Earth's curvature

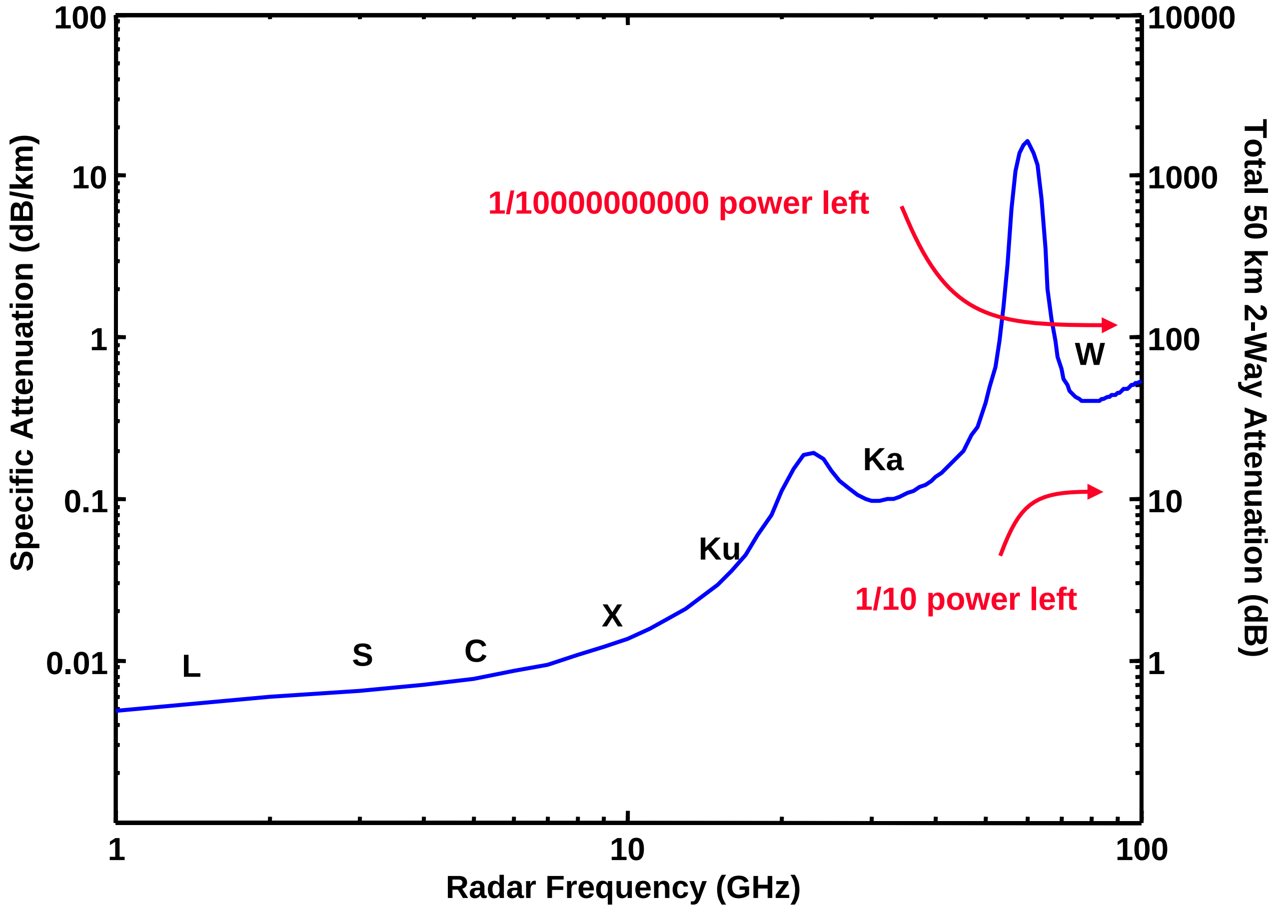
Outline

- Atmospheric attenuation
- Reflection from the Earth's surface
- Over-the-horizon diffraction
- Atmospheric refraction

Atmospheric Attenuation at Sea Level

Radar power absorbed by water vapor and oxygen

Attenuation is a loss of power characterized by L in radar range equation



High frequencies are not well suited for long-range low-altitude surveillance

Attenuation in Rain and Fog

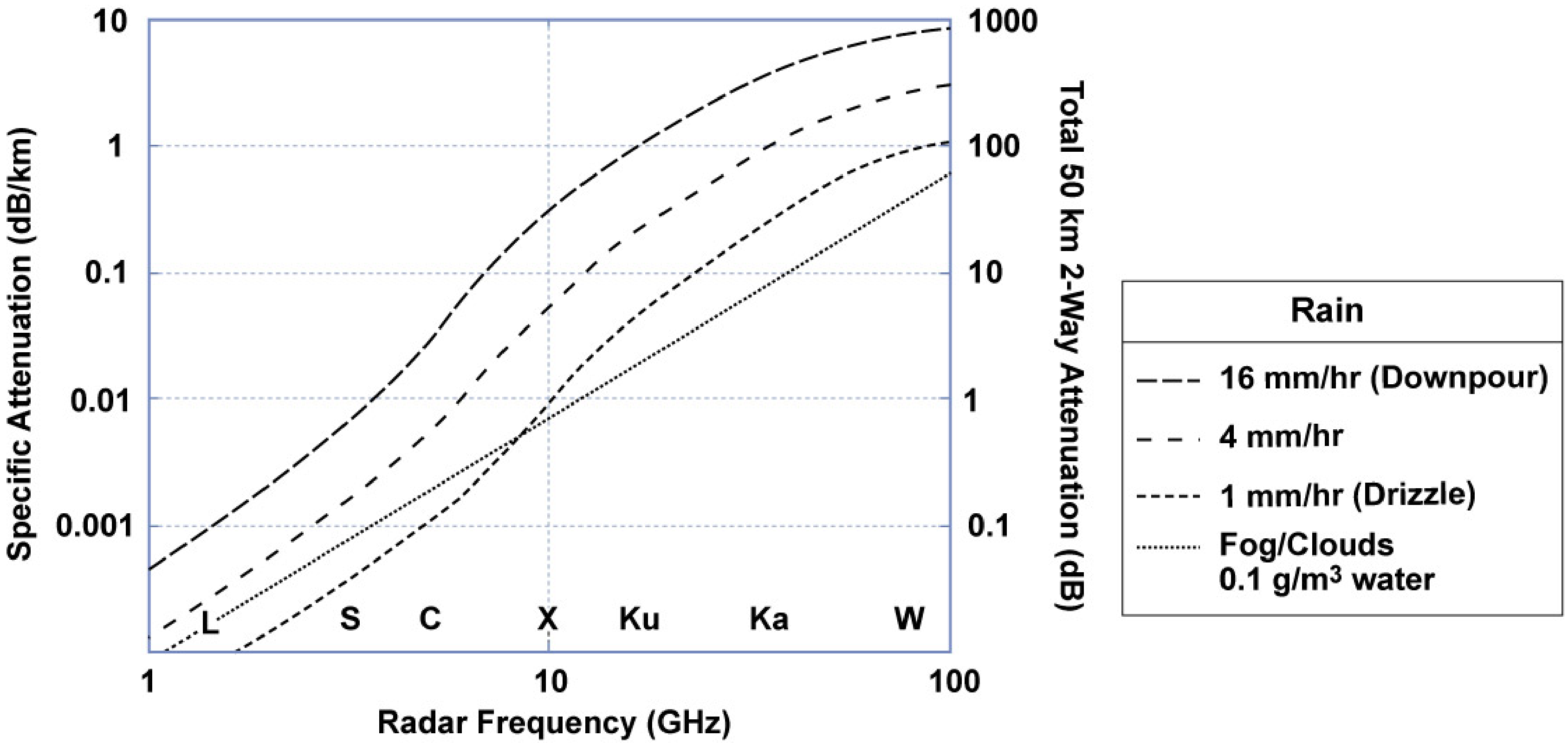


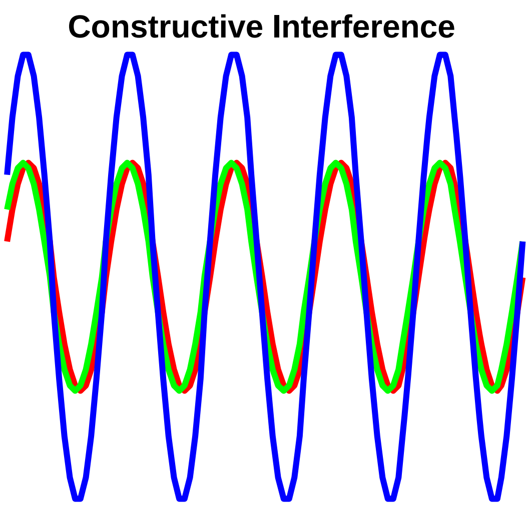
Figure by MIT OCW.

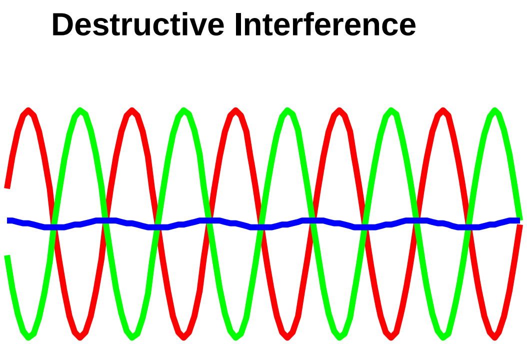
Radar performance at high frequencies is highly weather dependent

Outline

- Atmospheric attenuation
- Reflection from the Earth's surface
- Over-the-horizon diffraction
- Atmospheric refraction

Interference Basics

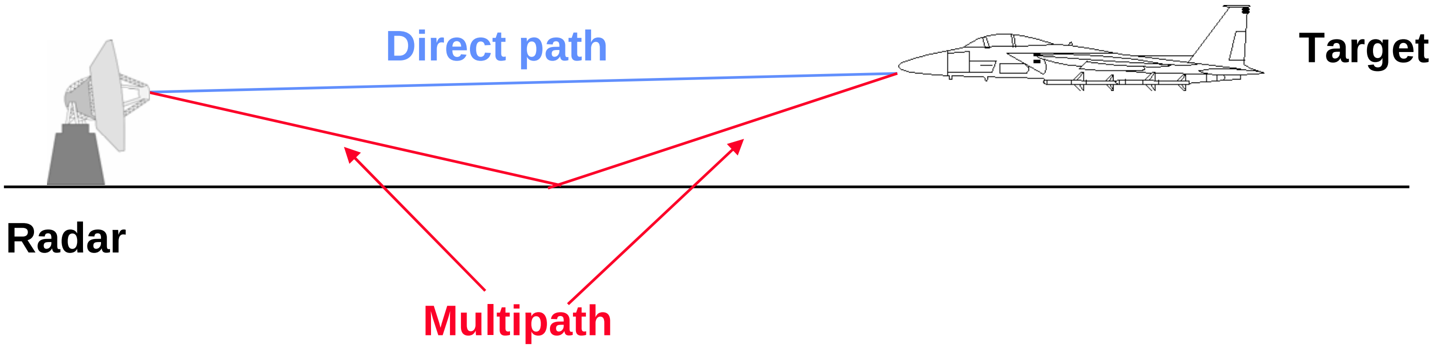




Wave 1 Wave2 Sum of Waves 1 + 2

- **Two waves can interfere constructively or destructively**
- **Resulting field strength depends only on relative amplitude and phase of the two waves**
  - **Radar voltage can range from 0-2 times single wave**
  - **Radar power is proportional to (voltage)^2 for 0-4 times the power**
  - **Interference operates both on outbound and return trips for 0-16 times the power**

Propagation over a Plane Earth

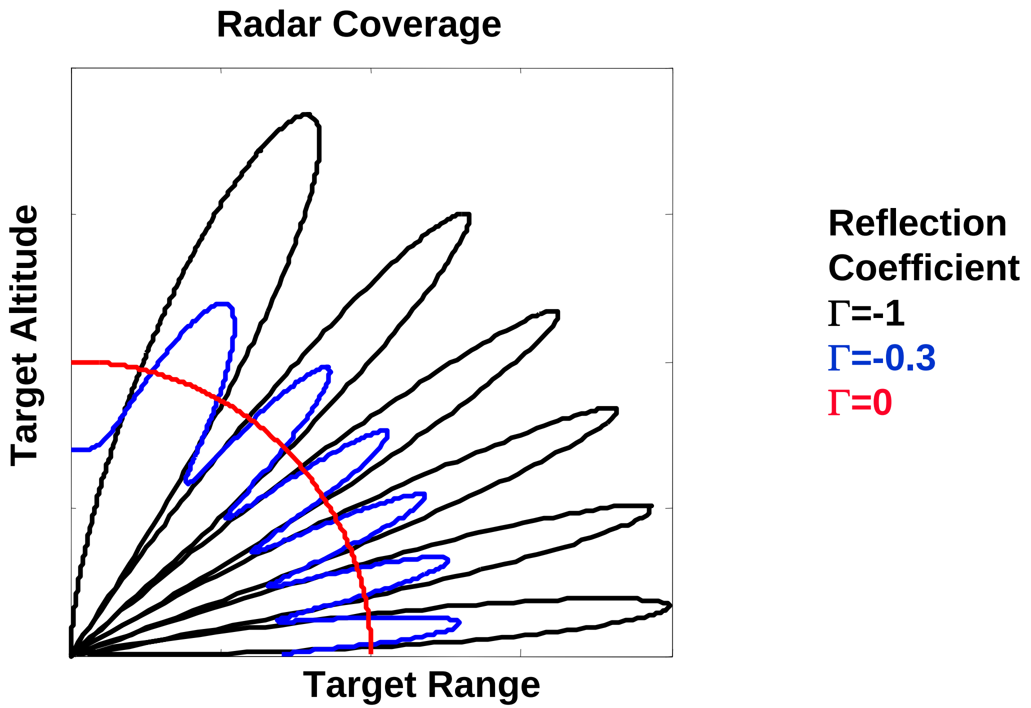


- Reflection from the Earth's surface results in interference of the direct radar signal with the signal reflected off of the surface

- Surface reflection coefficient (Γ) determines relative signal amplitudes
  - Dependent on: surface material, roughness, polarization, frequency
  - Close to 1 for smooth ocean, close to 0 for rough land

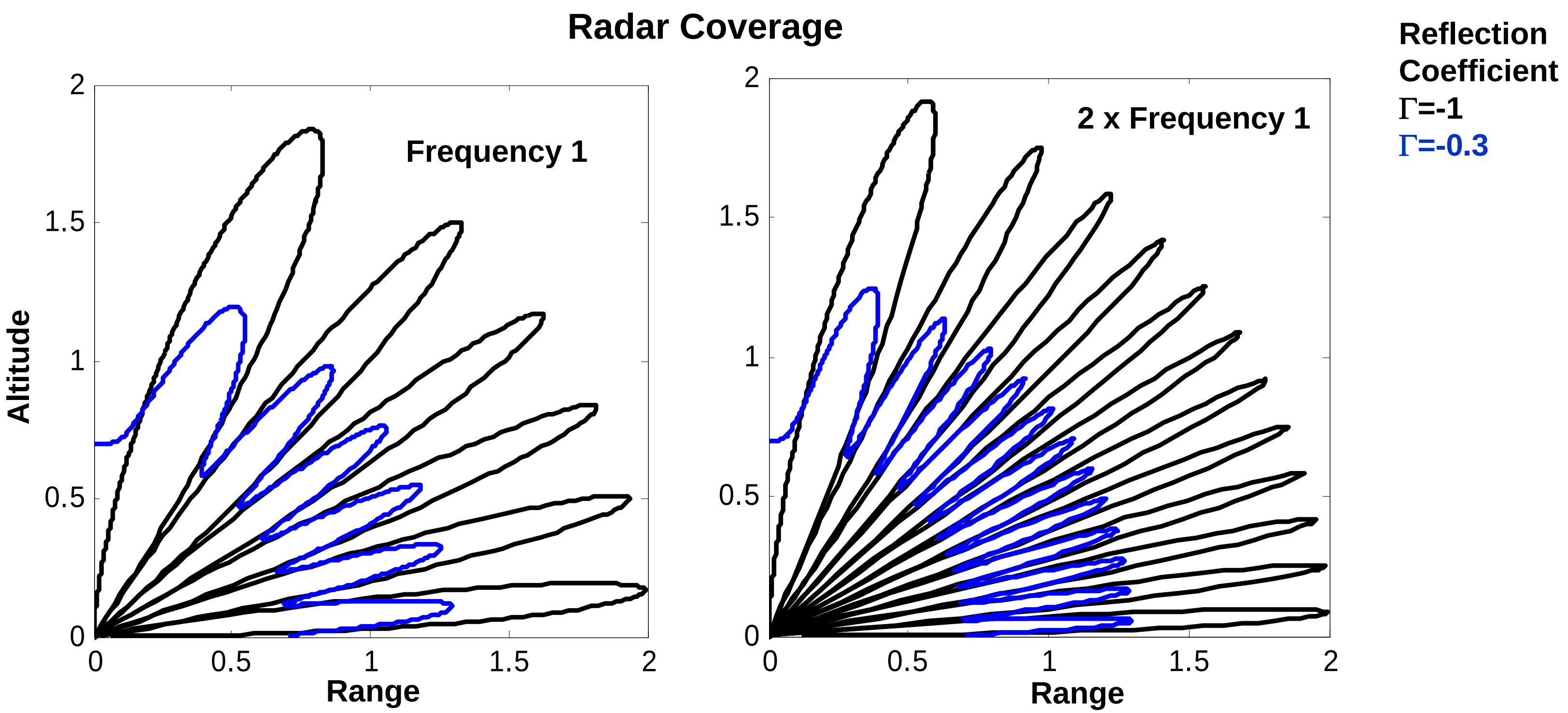
- Relative phase determined by path length difference and phase shift on reflection
  - Dependent on: height, range and frequency

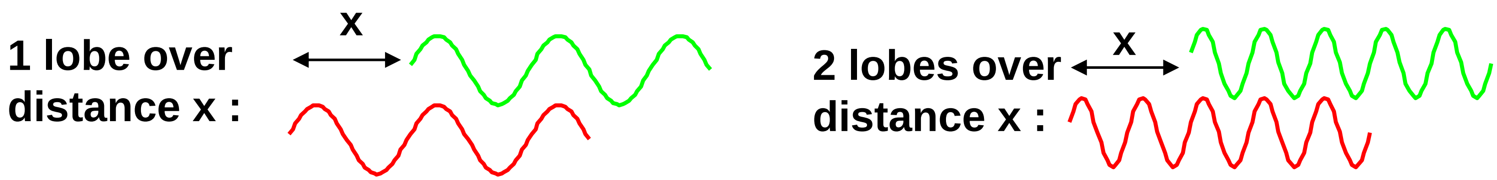
Multipath Alters Radar Detection Range



- Multipath causes elevation coverage to be broken up into a lobed structure
- A target located at the maximum of a lobe will be detected as far as twice the free-space detection range
- At other angles the detection range will be less than free space and in a null no echo signal will be received

Multipath is Frequency Dependent



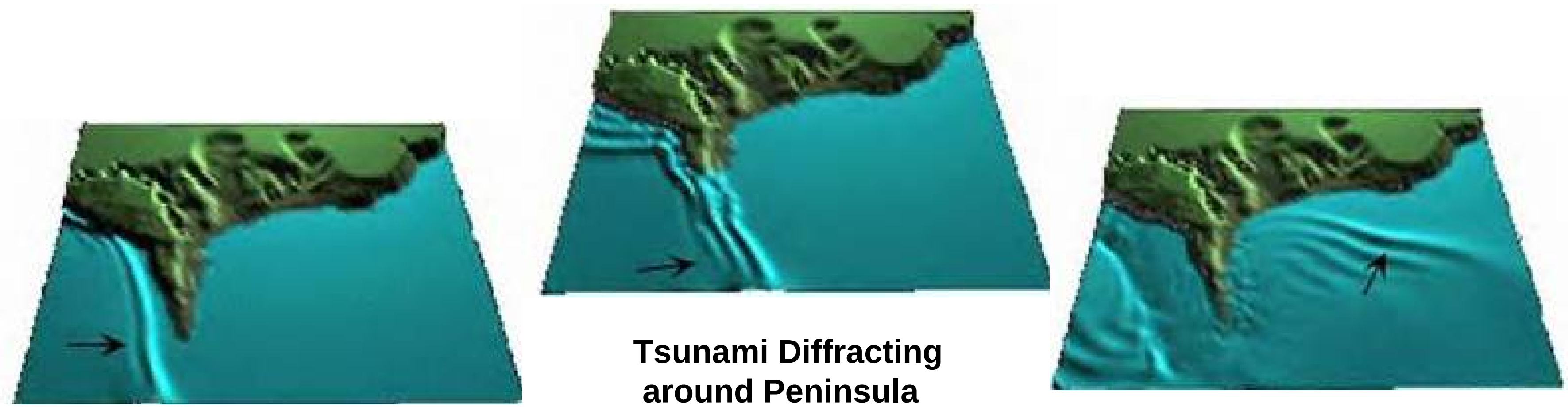


Lobing density increases with increased radar frequency

Outline

- Atmospheric attenuation
- Reflection from the Earth's surface
- Over-the-horizon diffraction
- Atmospheric refraction

Diffraction

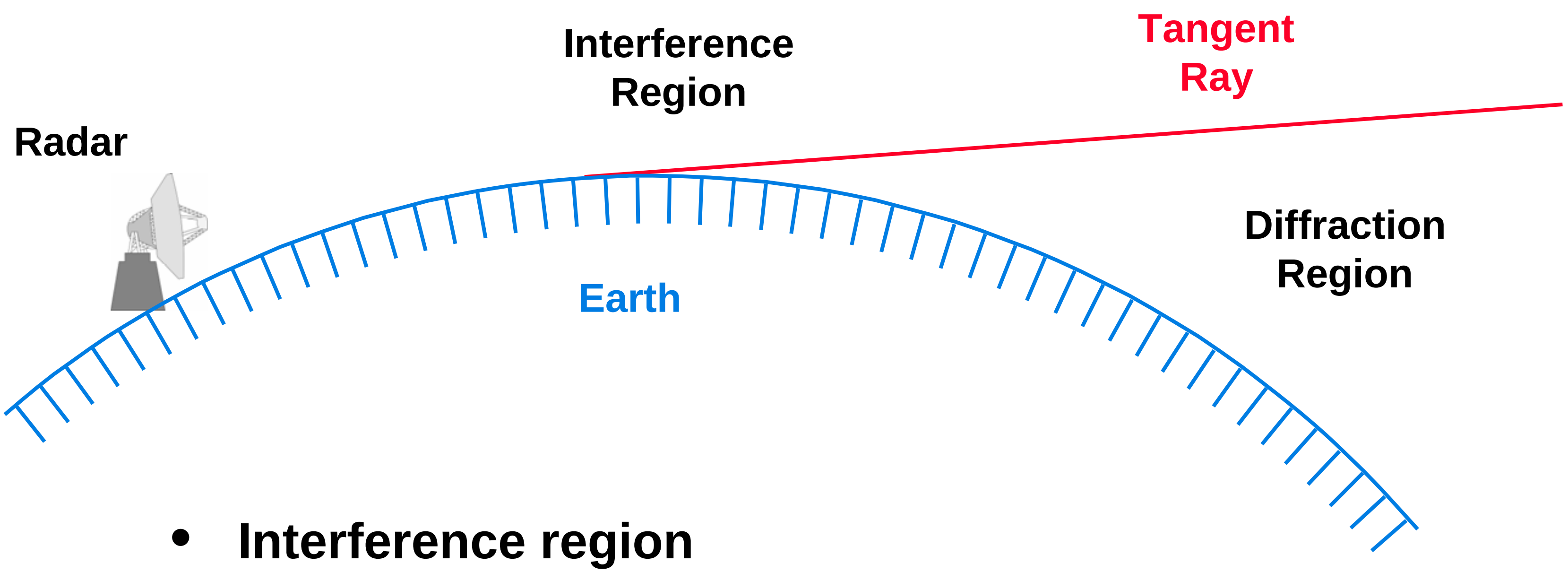


Tsunami Diffracting around Peninsula

Courtesy of NOAA / PMEL / Center for Tsunami Research.
See animation at http://nctr.pmel.noaa.gov/animations/Aonae.all.mpg

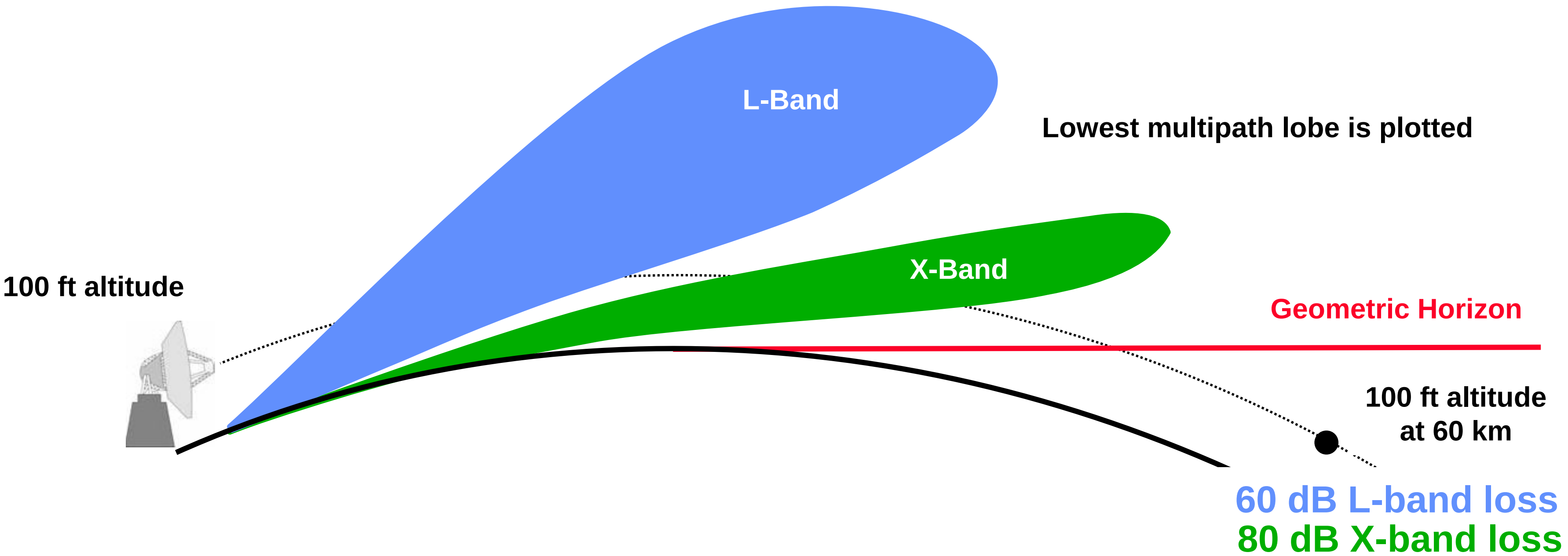
- **Radar waves are diffracted around the curved Earth just as ocean waves are bent by an obstacle**
- **Web references for excellent water wave photographic examples:**
  - **http://upload.wikimedia.org/wikipedia/commons/b/b5/Water_diffraction.jpg**
  - **http://yhspatriot.yorktown.arlington.k12.va.us/~ckaldahl/wave.gif**
- **The ability of radar to propagate beyond the horizon depends upon frequency and radar height**

Propagation Over Round Earth



- **Interference region**
  - Located within line of sight radar
- **Diffraction region**
  - Below radar line of sight
  - Signals are severely attenuated

Combined Diffraction and Multipath vs Radar Frequency



- **Low altitude multipath detection: favors higher frequencies**
- **Diffraction detection:**
  - **Favors lower frequencies**
  - **Is tough at any frequency**

Outline

- Atmospheric attenuation
- Reflection from the Earth's surface
- Over-the-horizon diffraction
- Atmospheric refraction

Refraction of Radar Beams

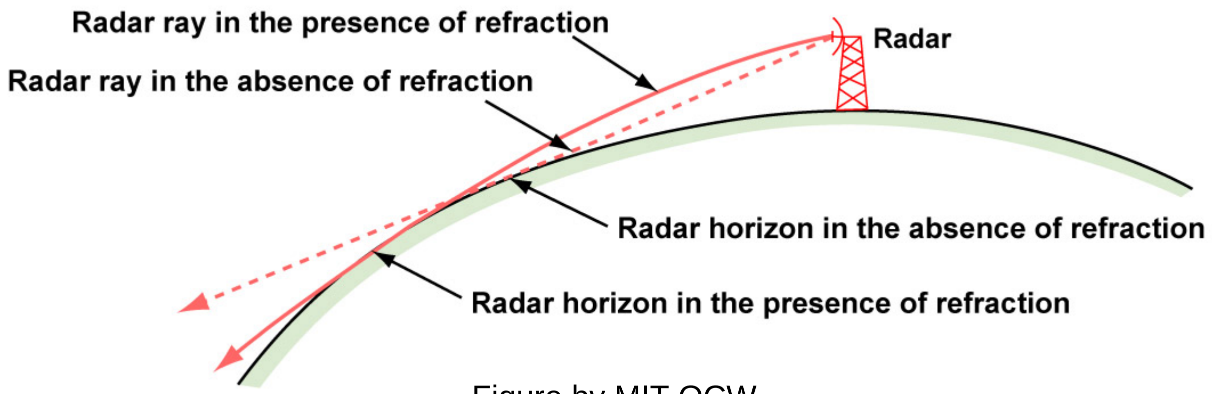


Figure by MIT OCW.

Radar rays bend downwards due to decreasing index of refraction of air with altitude

Same effect as refraction of light beam shining from water into air

Earth's Radius Modified to Account for Refraction Effects

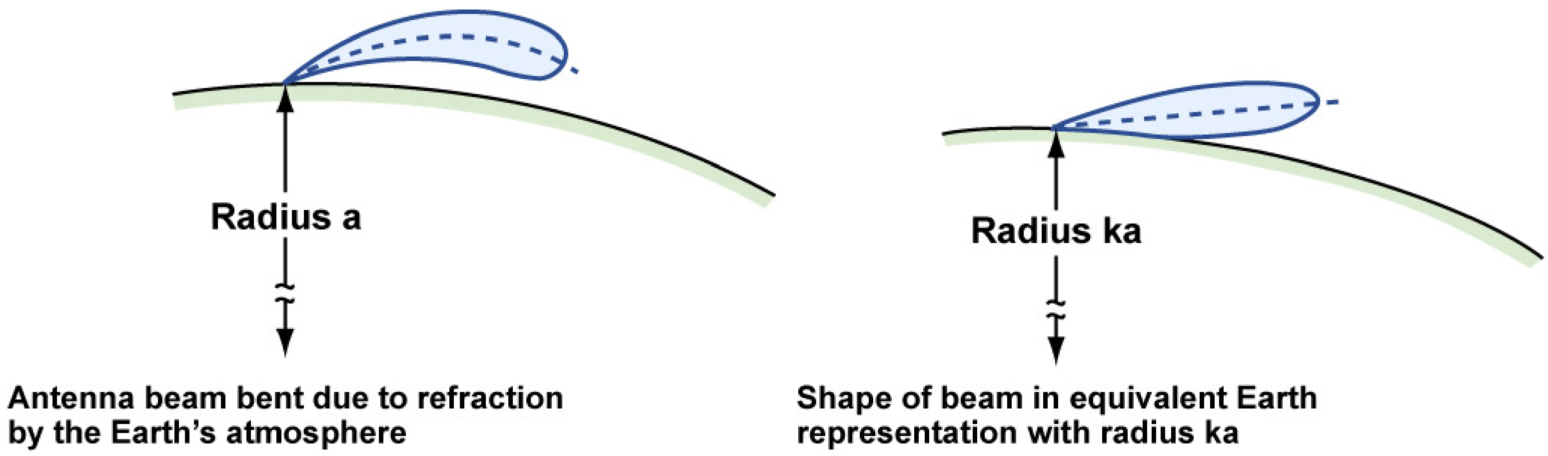


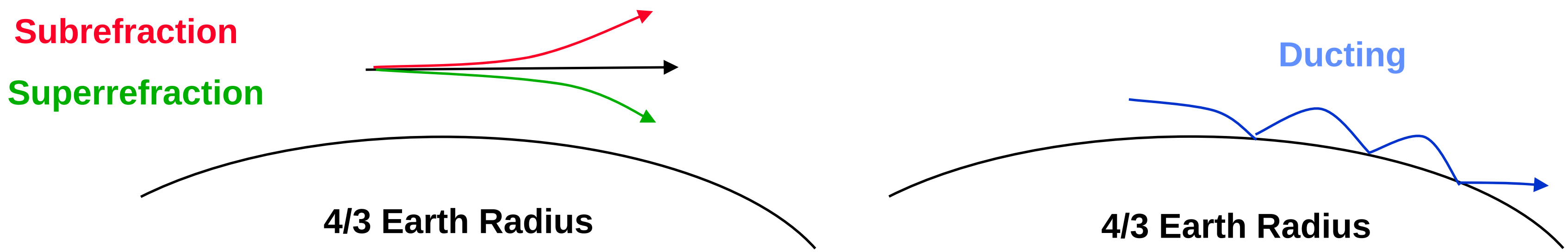
Figure by MIT OCW.

Atmospheric refraction is accounted for by replacing the actual Earth radius a, in calculations, by an equivalent earth radius ka and assuming straight line propagation

4/3 is a typical value for k

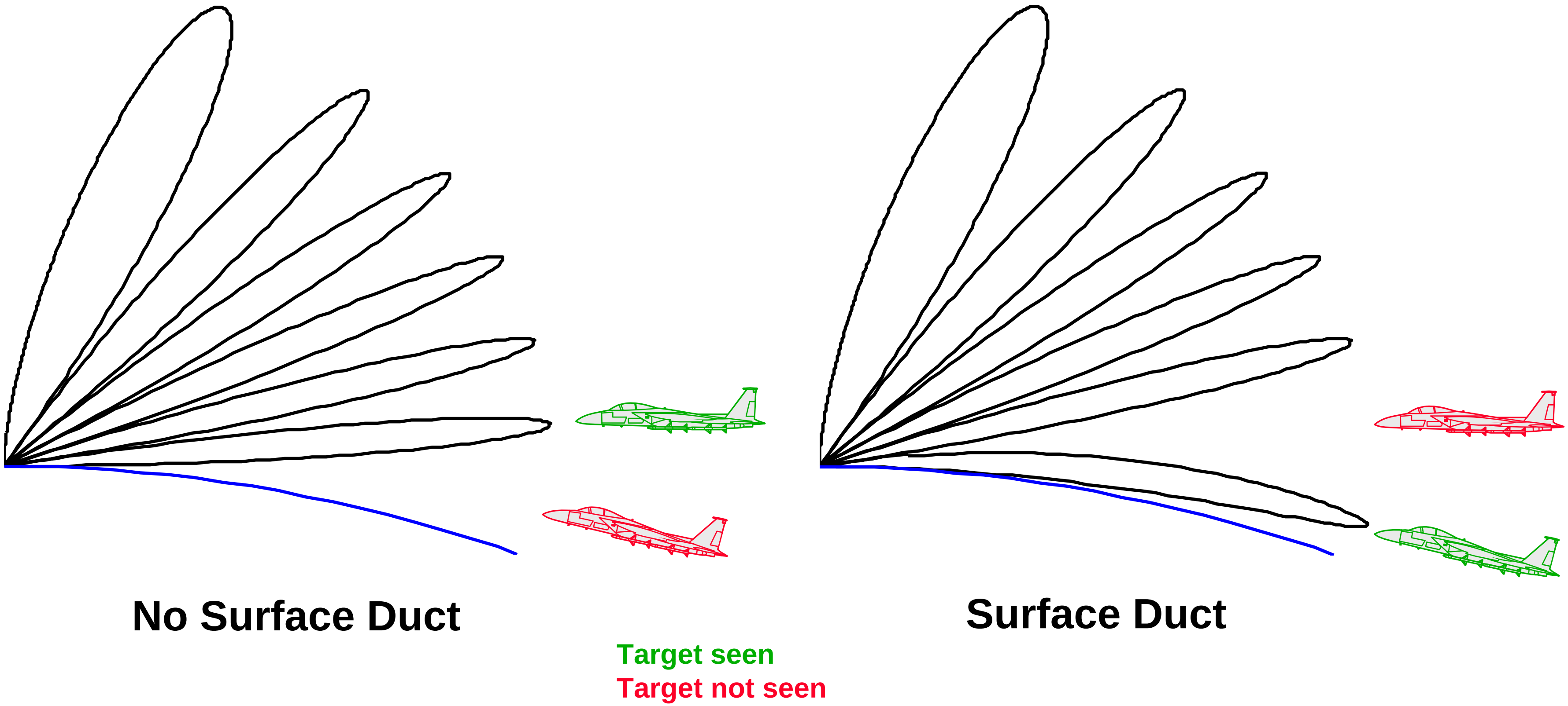
Average propagation is referred to as a "4/3 Earth"

Anomalous Propagation



- **Occurs when k not equal to 4/3**
- **Categorized as: superrefraction, subrefraction and ducting**
  - **Superrefraction extends the radar horizon**
  - **Subrefraction limits the radar horizon**
  - **Ducting traps radar energy near the Earth's surface**

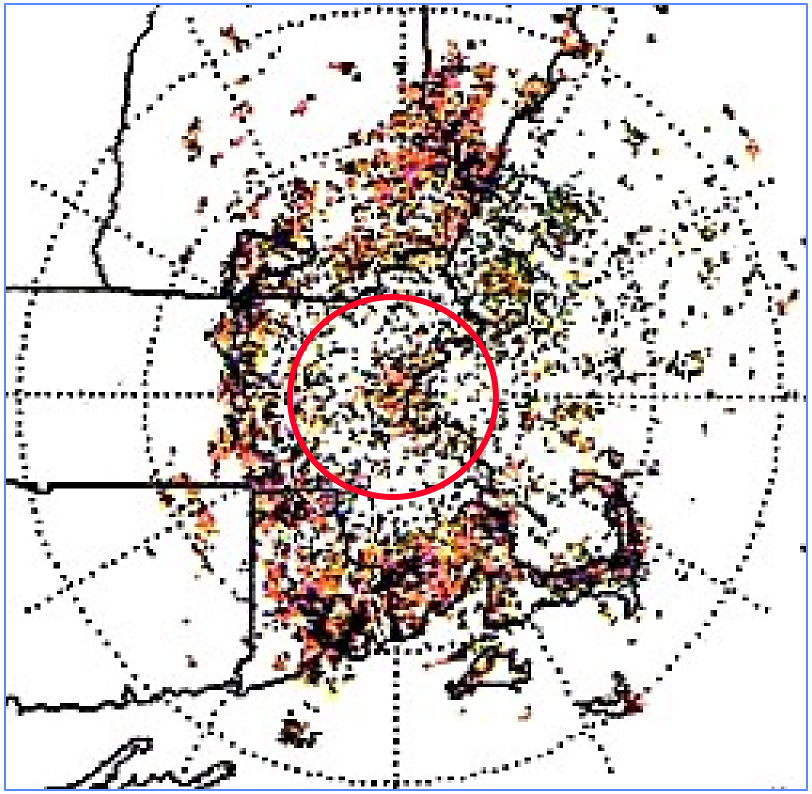
Ducting Effects on Target Detection



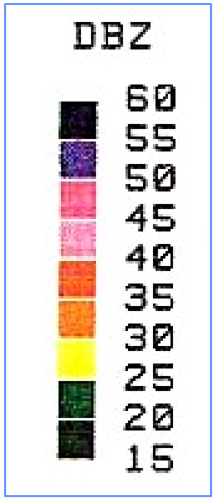
Ducting extends low-altitude detection ranges but can cause unexpected holes in radar coverage

Ducted Clutter from New England

PPI Display



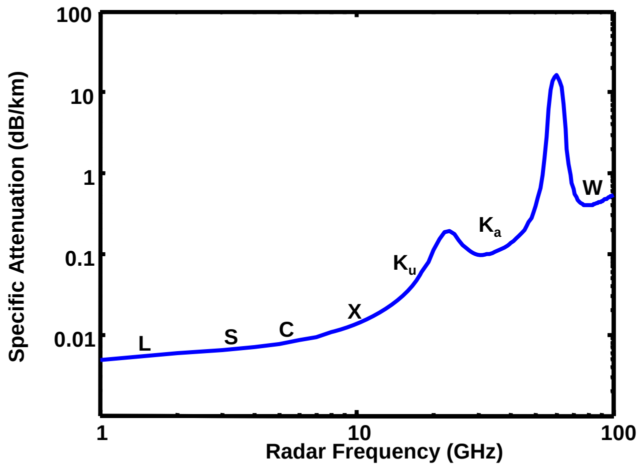
50 km range rings



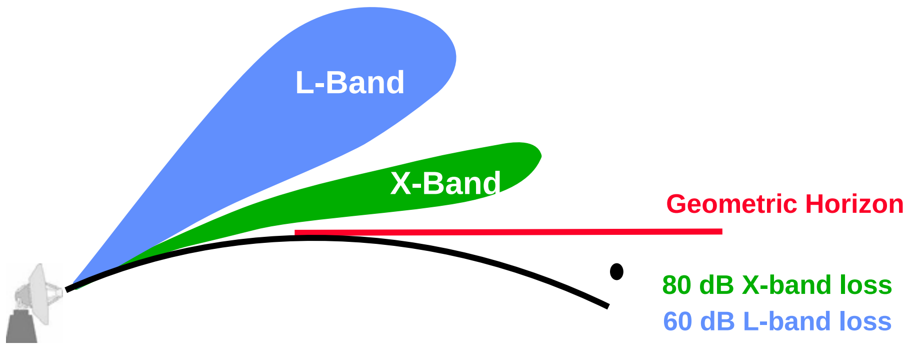
Ducting conditions can extend horizon to extreme ranges

Radar Propagation Effects Summary

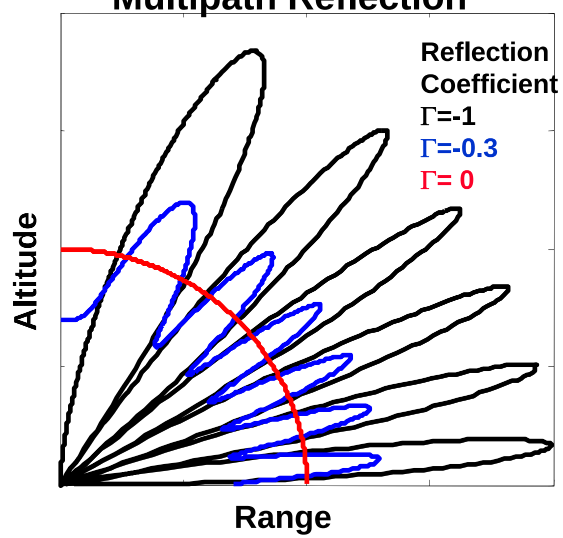
Atmospheric Attenuation



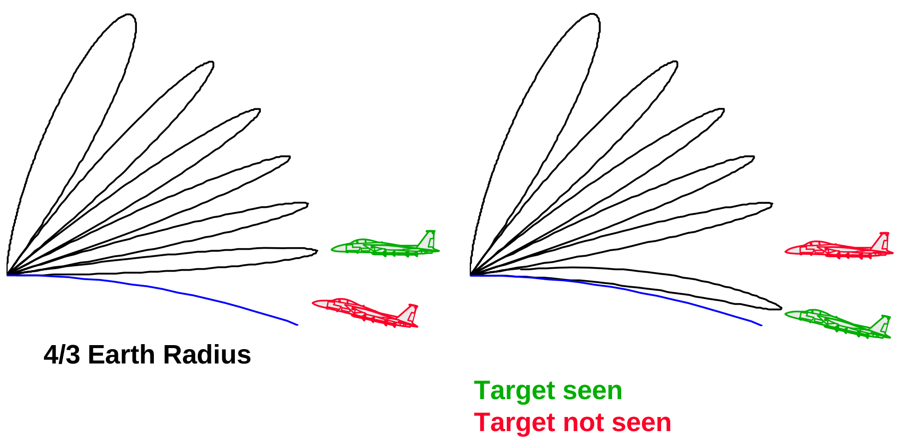
Multipath and Diffraction



Multipath Reflection



Refraction (Ducting)



References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Skolnik, M., Radar Handbook, New York, McGraw-Hill, 2rd Edition, 1990

Introduction to Radar Systems

Target Radar Cross Section

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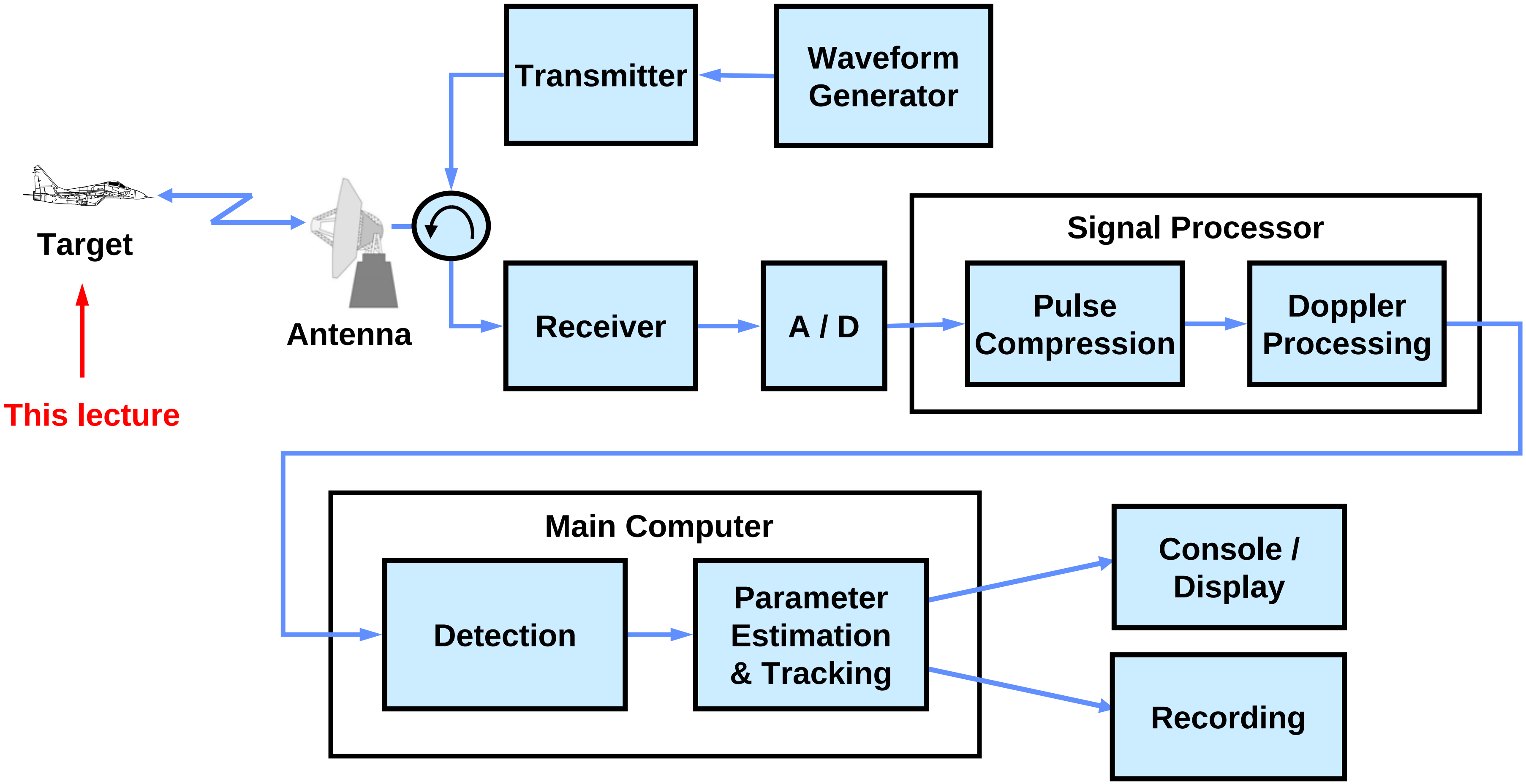
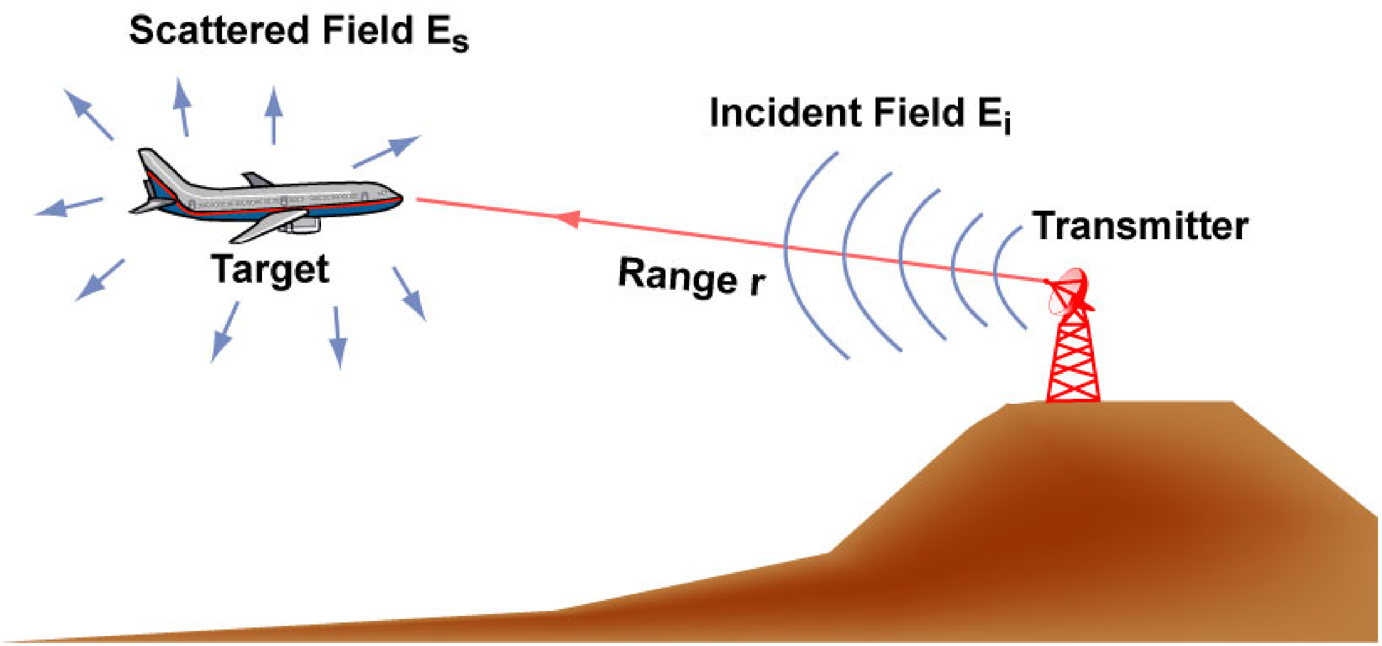
Generic Radar Block Diagram



Definition of Radar Cross Section (RCS or σ)

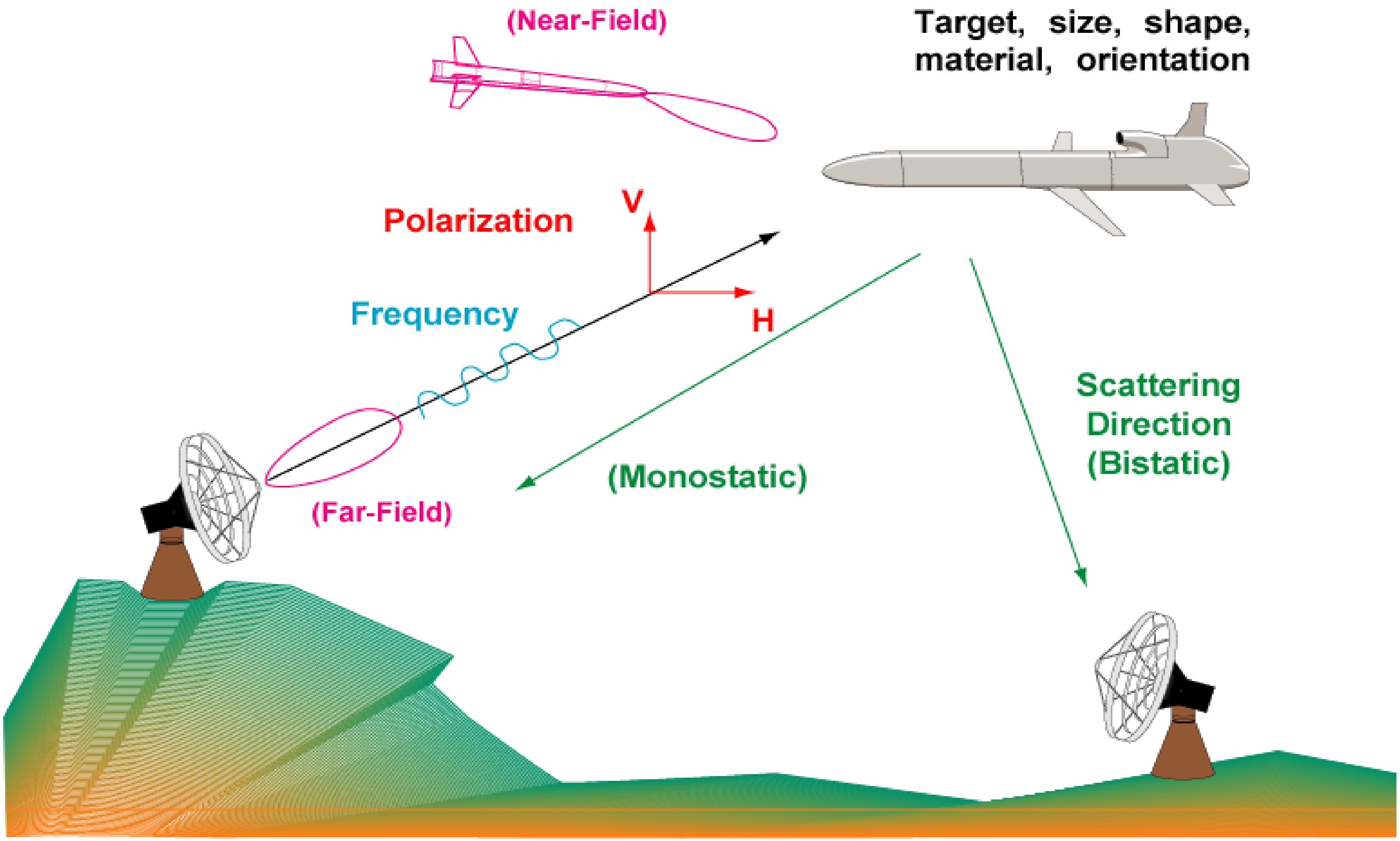


$$RCS = \lim_{r \to \infty} 4\pi r^2 \frac{|E_s|^2}{|E_i|^2} \quad \text{(Unit: Area)}$$

Figure by MIT OCW.

Radar Cross Section is the area intercepting that amount of power which, if radiated isotropically, produces the same received power in the radar.

Factors Determining RCS



Threat's View of the Radar Range Equation

What I can control

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

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

What I can not control

Outline

- What are typical levels of radar cross section?
  - On what do these depend?
- What contributes to radar cross section?
  - What are the scattering mechanisms?
  - What are typical signature contributors?
- How can target radar cross section be determined?
  - Measurement
  - Prediction

Radar Cross Section of Sphere

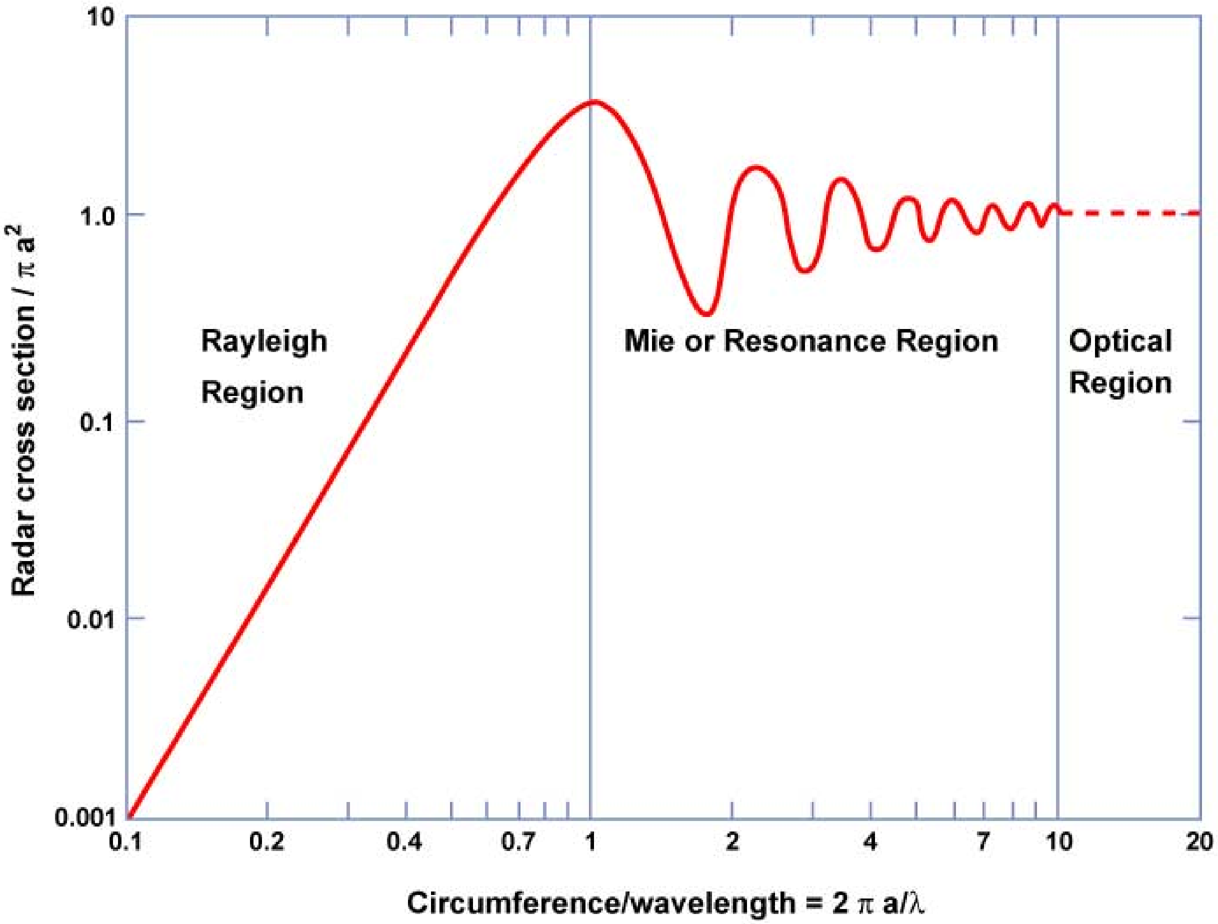


Figure by MIT OCW.

Rayleigh Region

$\lambda >> a$

$\sigma = k / \lambda^4$

Resonance or Mie Region

Oscillations

Backscattered wave interferes with creeping wave

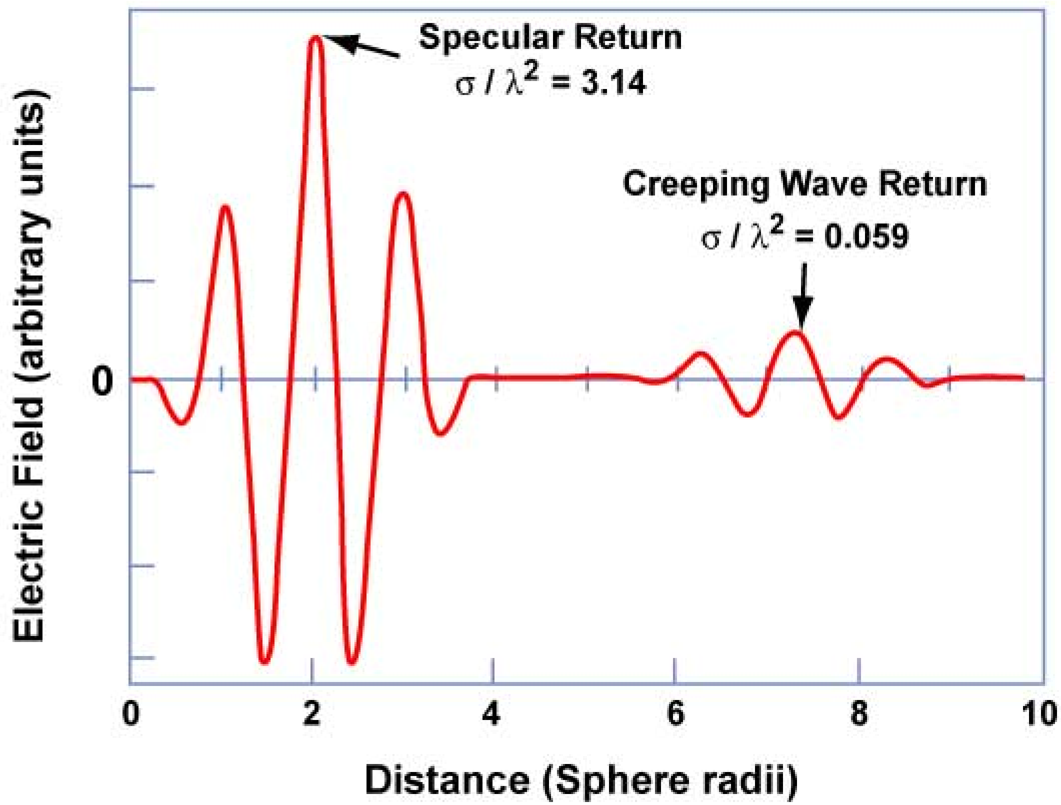
Optical Region

$\lambda << a$

$\sigma = \pi a^2$

Surface and edge scattering occur

Backscatter of Short Pulse from Sphere



Radius of Sphere is equal to the radar wavelength

Figure by MIT OCW.

Radar Cross Section of Typical RV

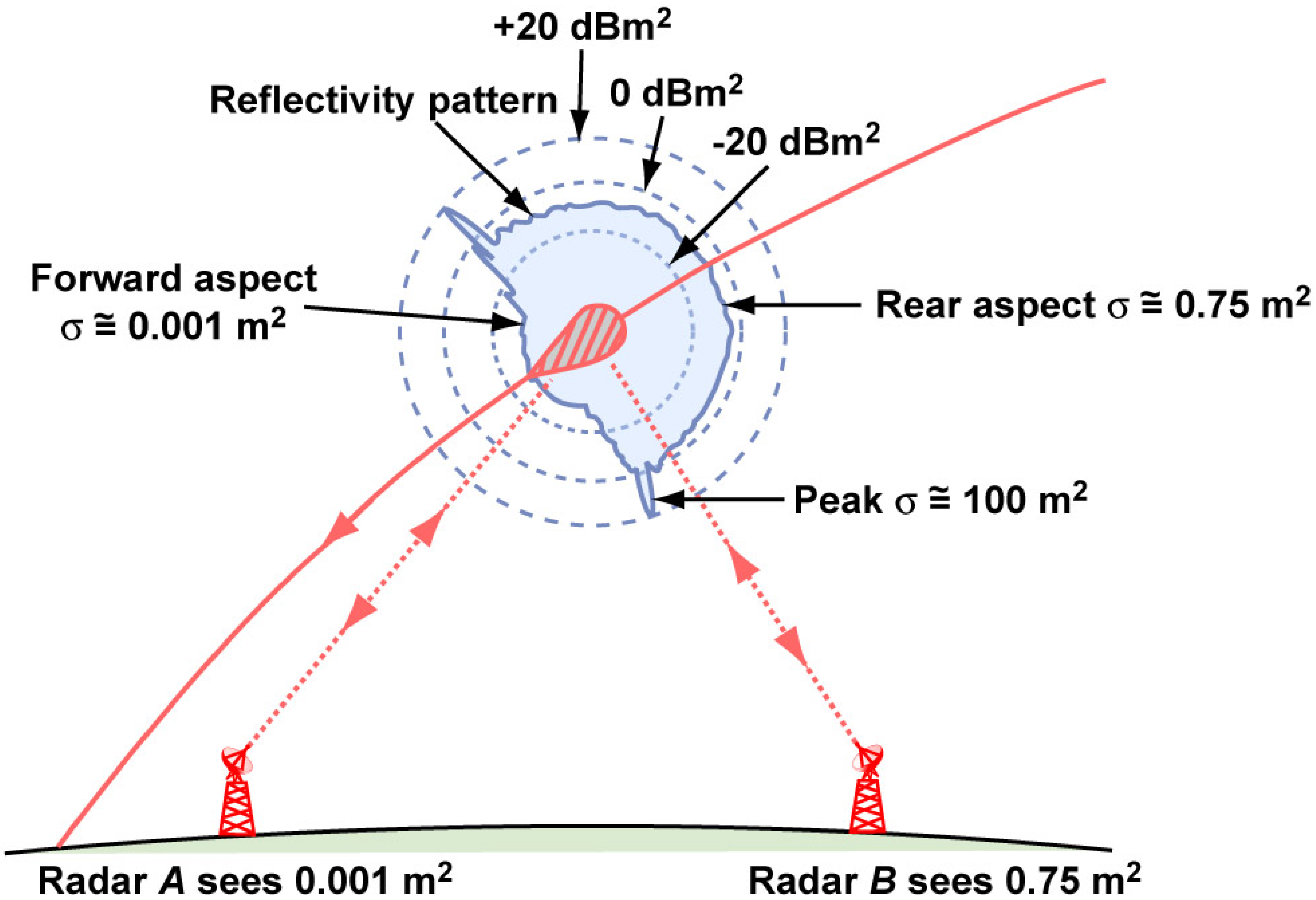


Figure by MIT OCW.

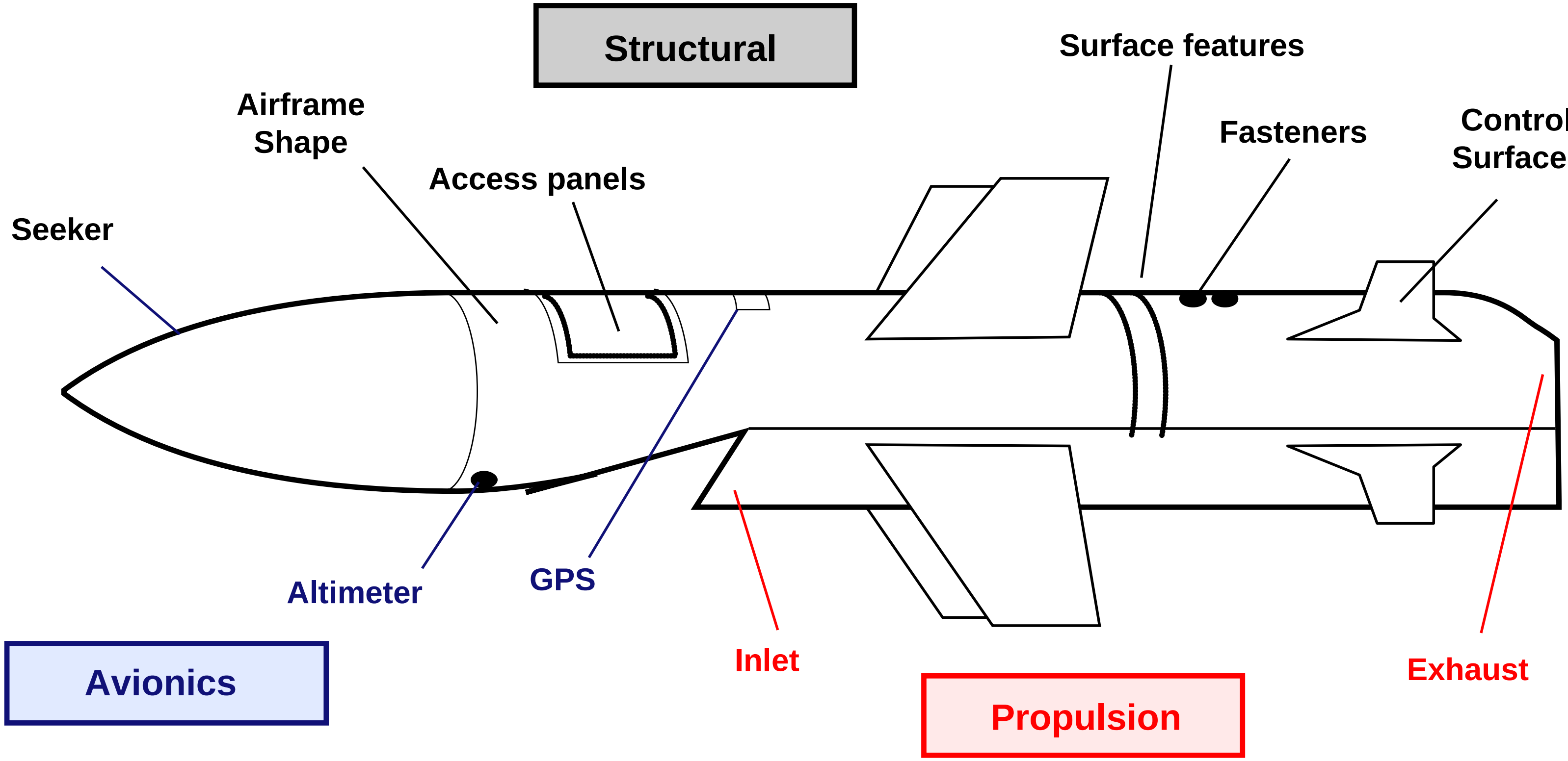
Examples of Radar Cross Sections

	Square meters
Small, single engine aircraft	1
Four passenger jet	2
Large fighter	6
Medium jet airliner	40
Jumbo jet	100
Helicopter	3
Small open boat	0.02
Small pleasure boat (20-30 ft)	2
Cabin cruiser (40-50 ft)	10
Ship(5,000 tons displacement, L Band)	10,000
Automobile / Small truck	100 - 200
Bicycle	2
Man	1
Birds	10^{-2} - 10^{-3}
Insects	10^{-4} - 10^{-5}

Outline

- **What are typical levels of radar cross section?**
  - **On what do these depend?**
- **What contributes to radar cross section?**
  - **What are the scattering mechanisms?**
  - **What are typical signature contributors?**
- **How can target radar cross section be determined?**
  - **Measurement**
  - **Prediction**

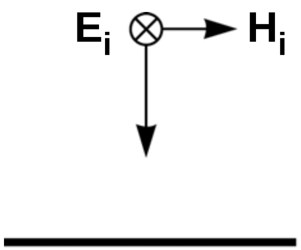
Components of Target RCS



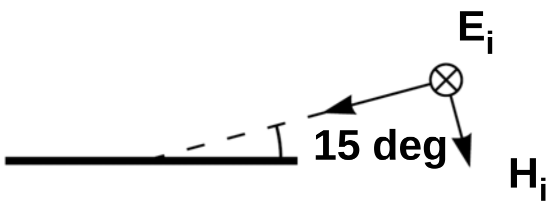
- Three types of RCS contributors:
  - Structural (body shape, control surfaces, etc.)
  - Propulsion (inlets, exhaust, etc.)
  - Avionics (seeker, GPS, altimeter, etc.)

Description of Sample Cases on Video

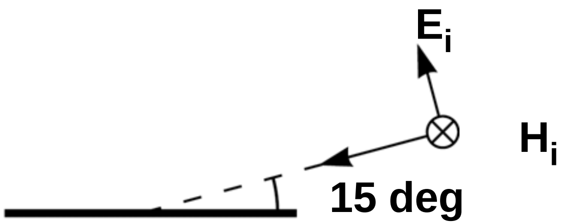
- **Case 1**



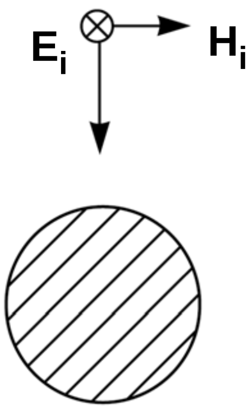
- **Case 2**



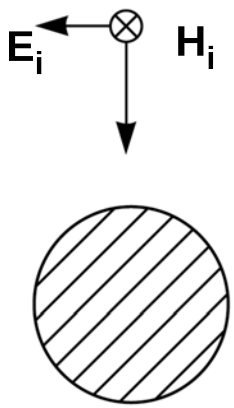
- **Case 3**



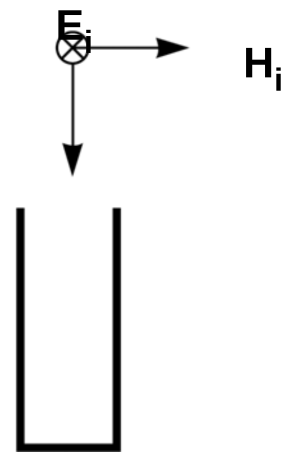
- **Case 4**



- **Case 5**

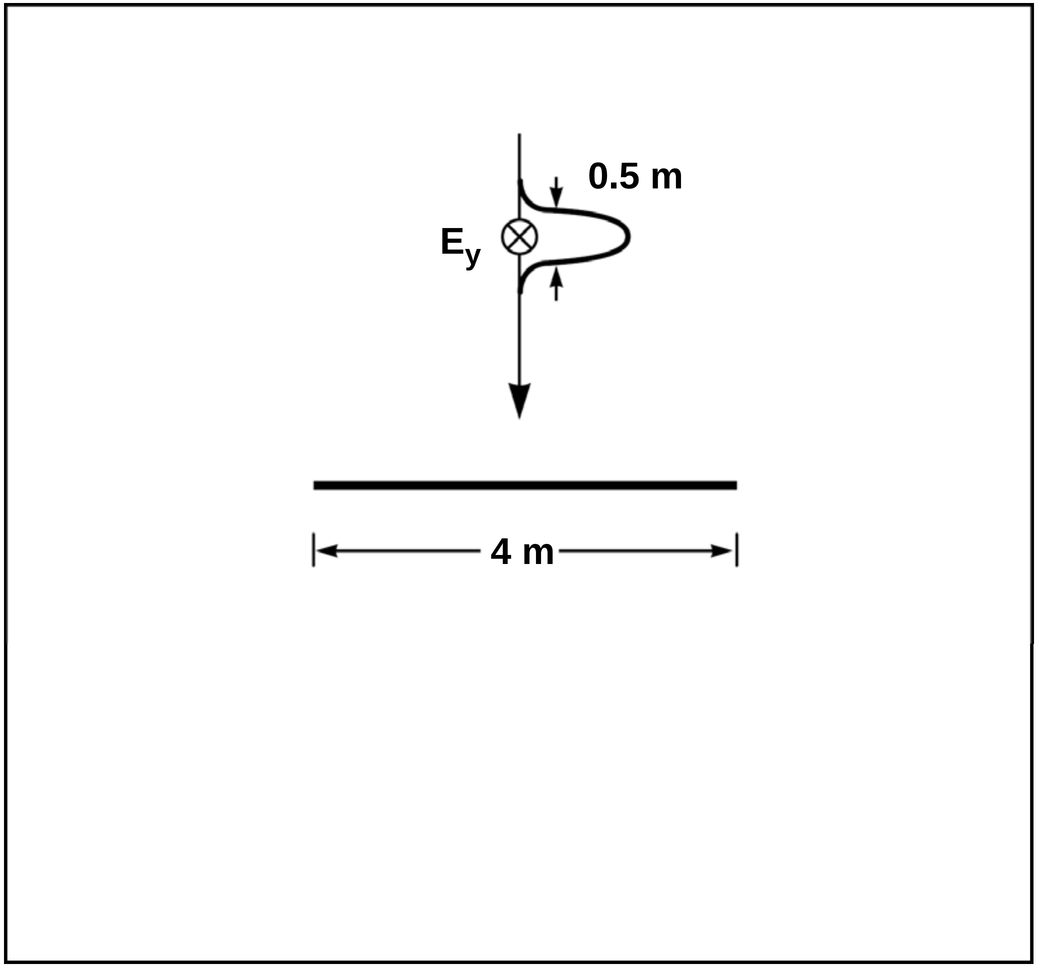


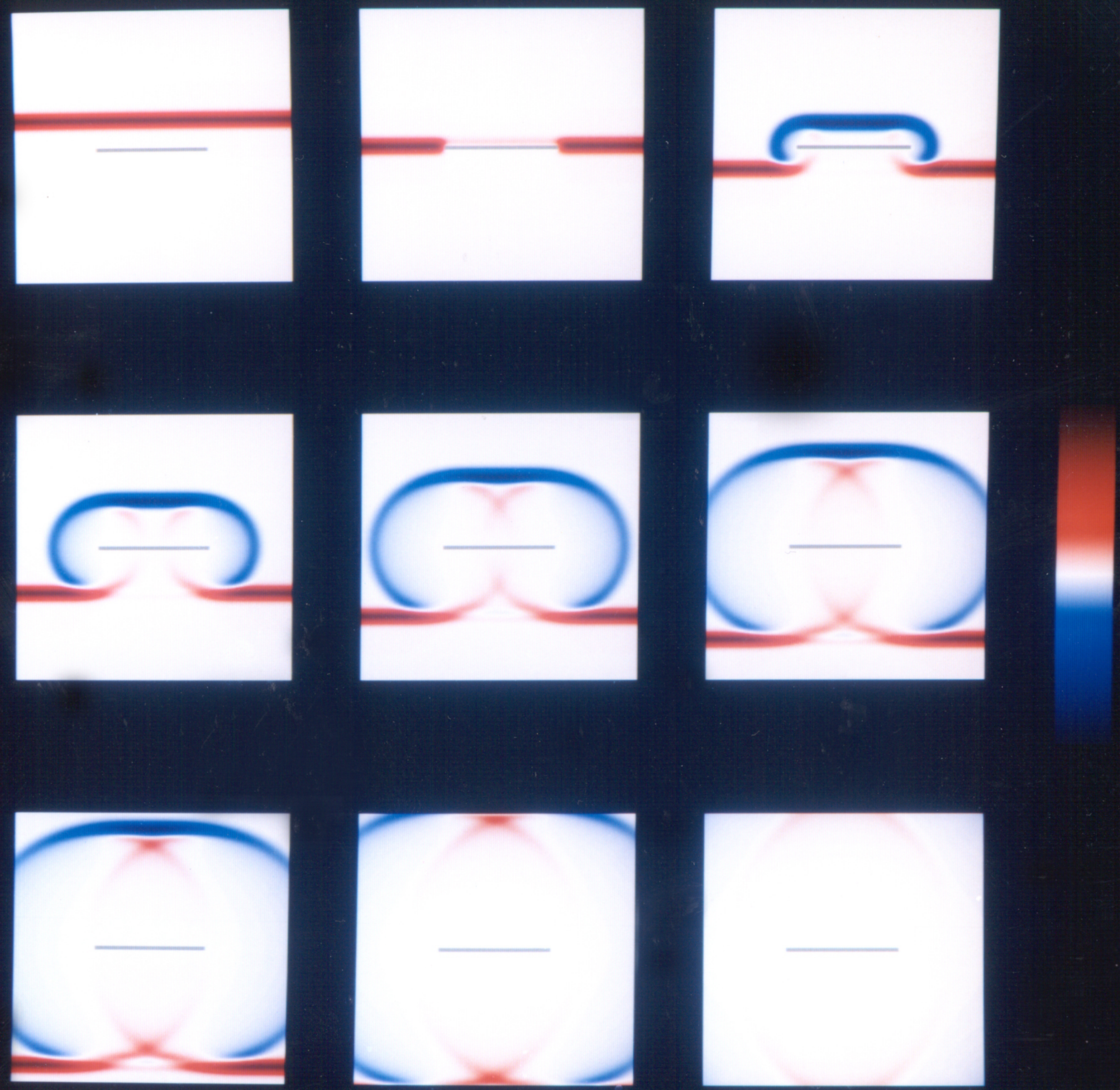
- **Case 6**



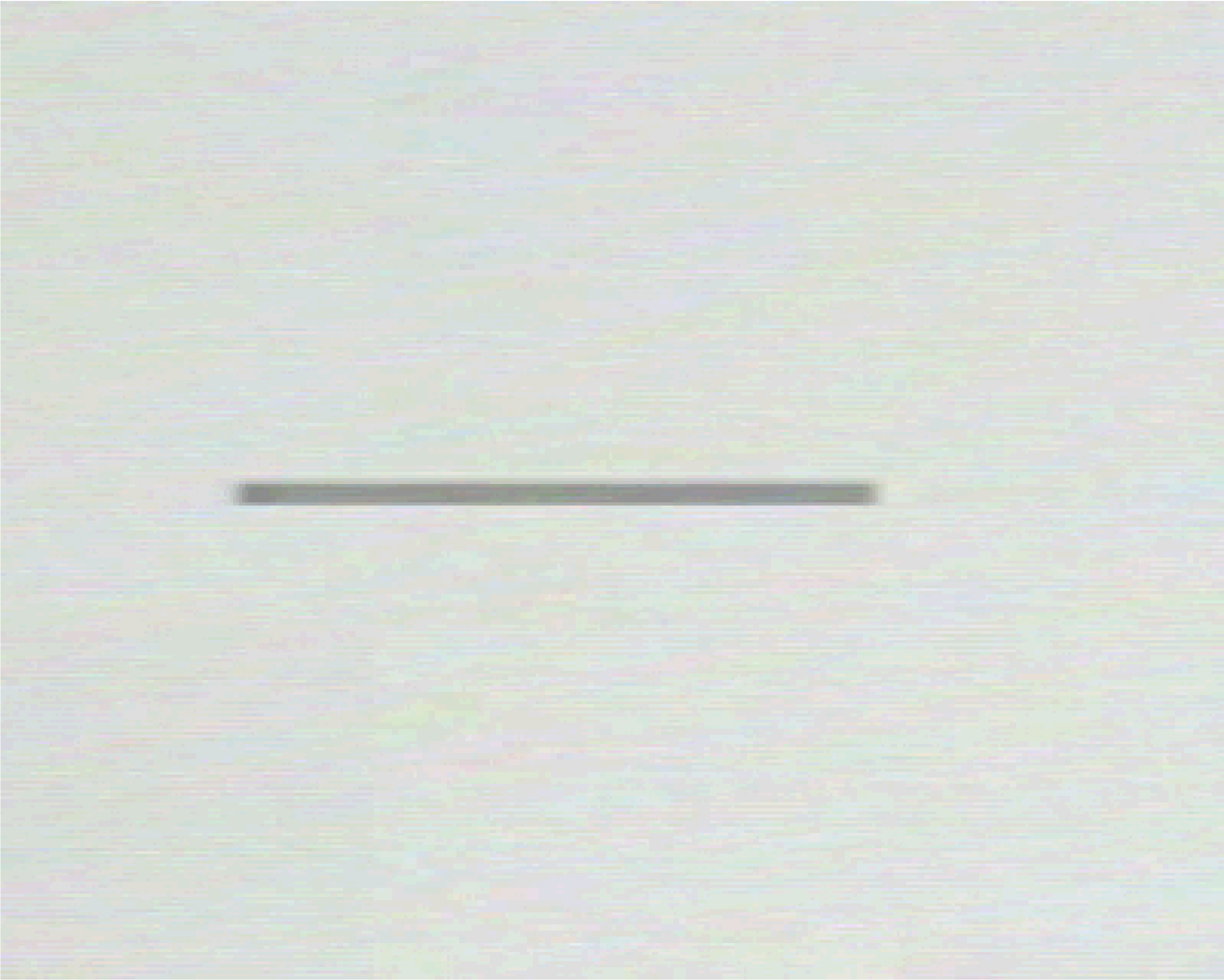
FD-TD Simulation of Scattering by Strip

- Gaussian pulse plane wave incidence
- E-field polarization (E_y plotted)
- Phenomena: specular reflection



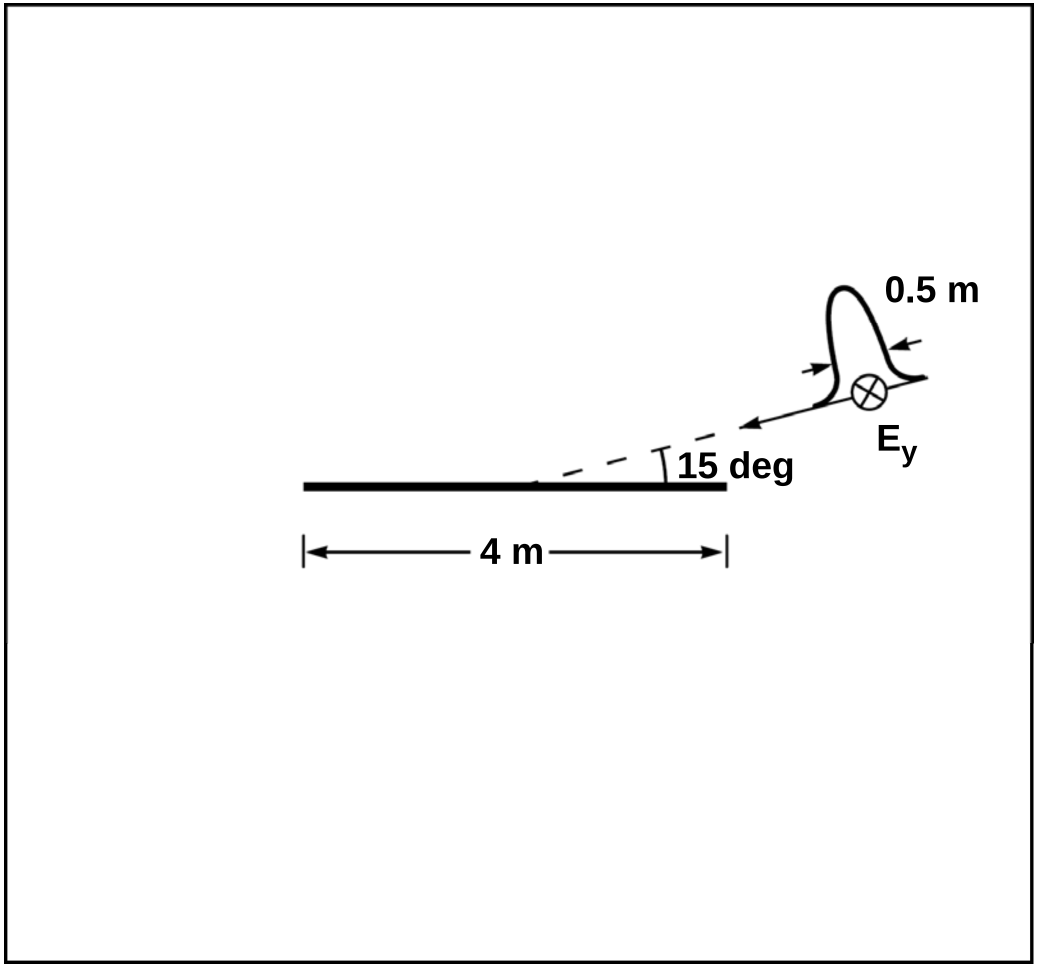


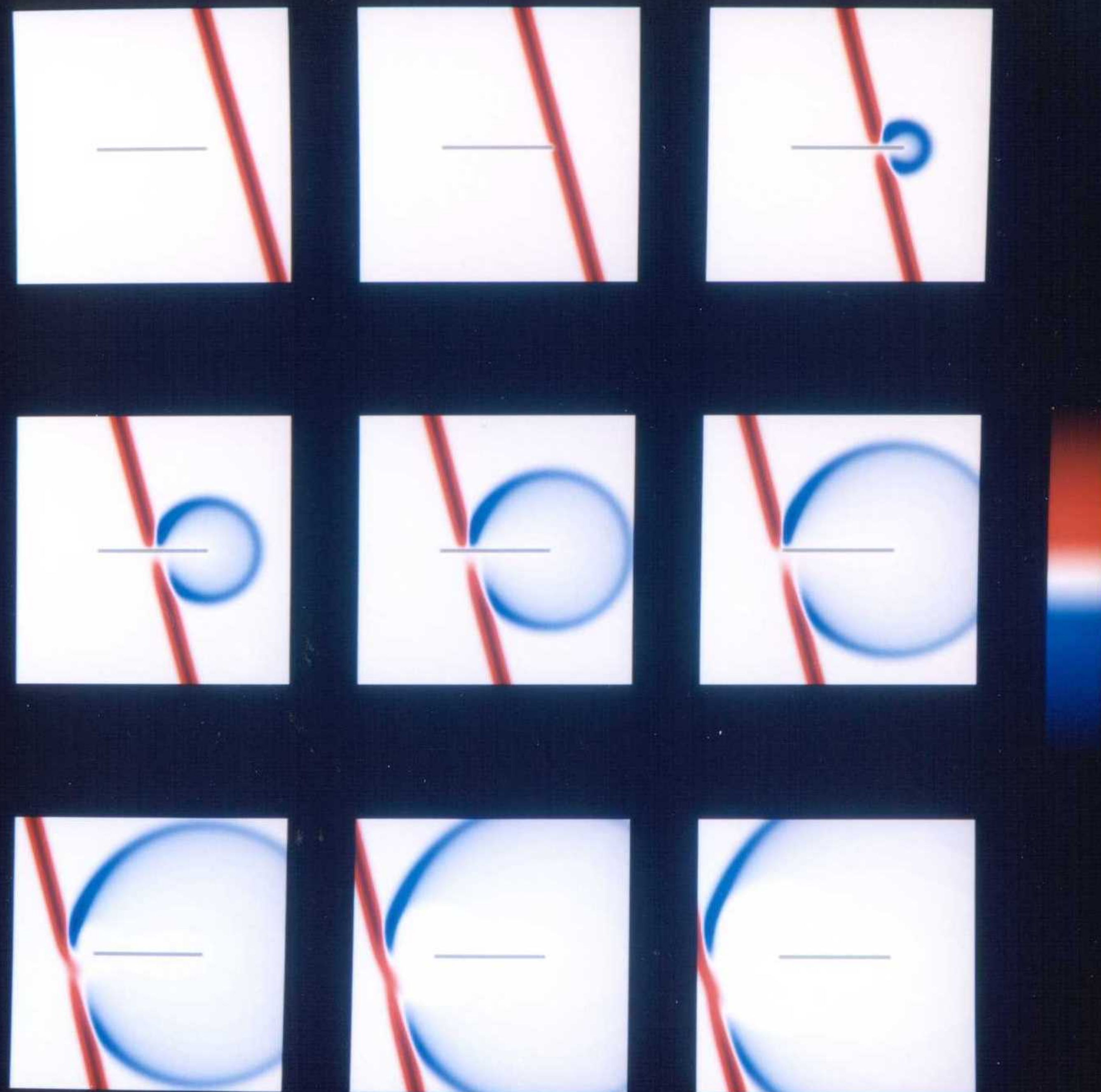
FD-TD Simulation of Scattering by Strip



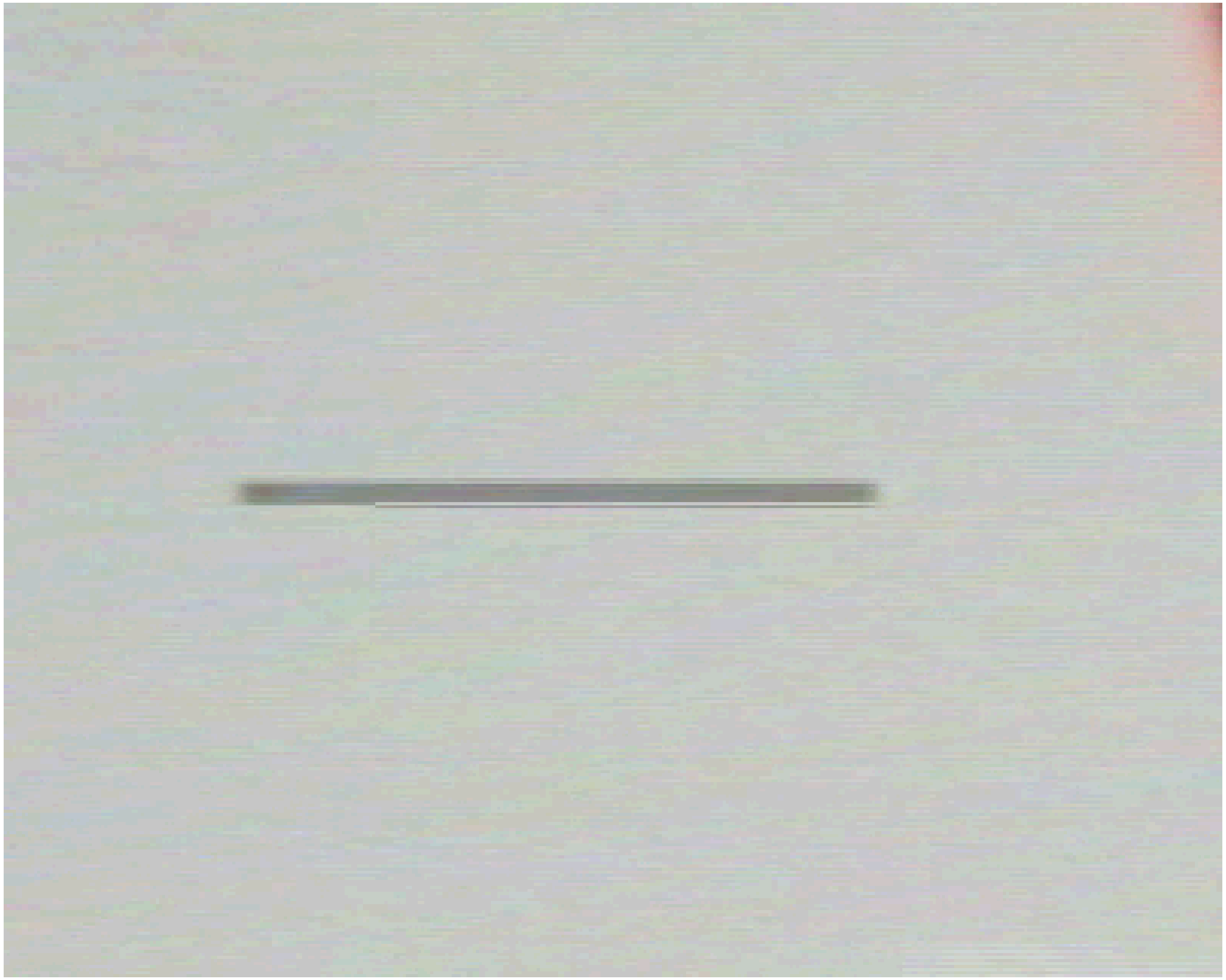
FD-TD Simulation of Scattering by Strip

- Gaussian pulse plane wave incidence
- E-field polarization (E_y plotted)
- Phenomena: leading edge diffraction



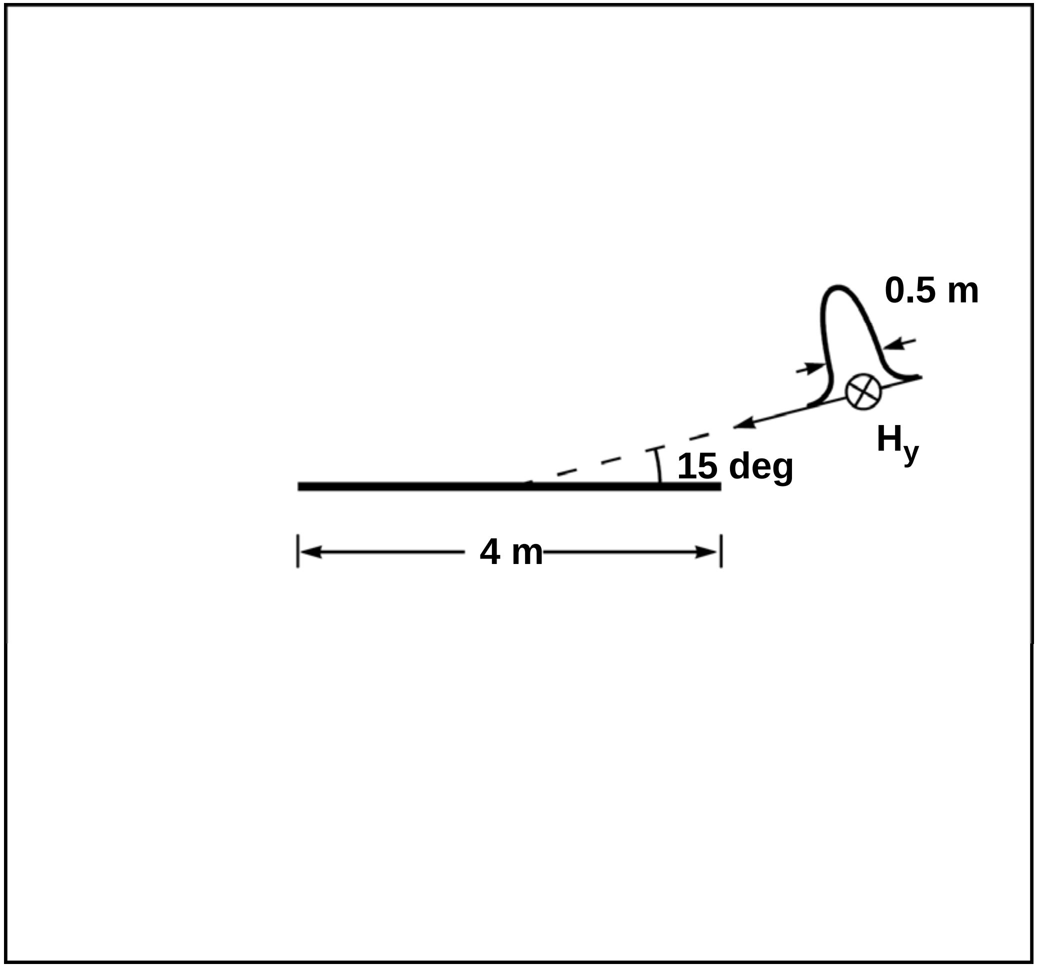


FD-TD Simulation of Scattering by Strip

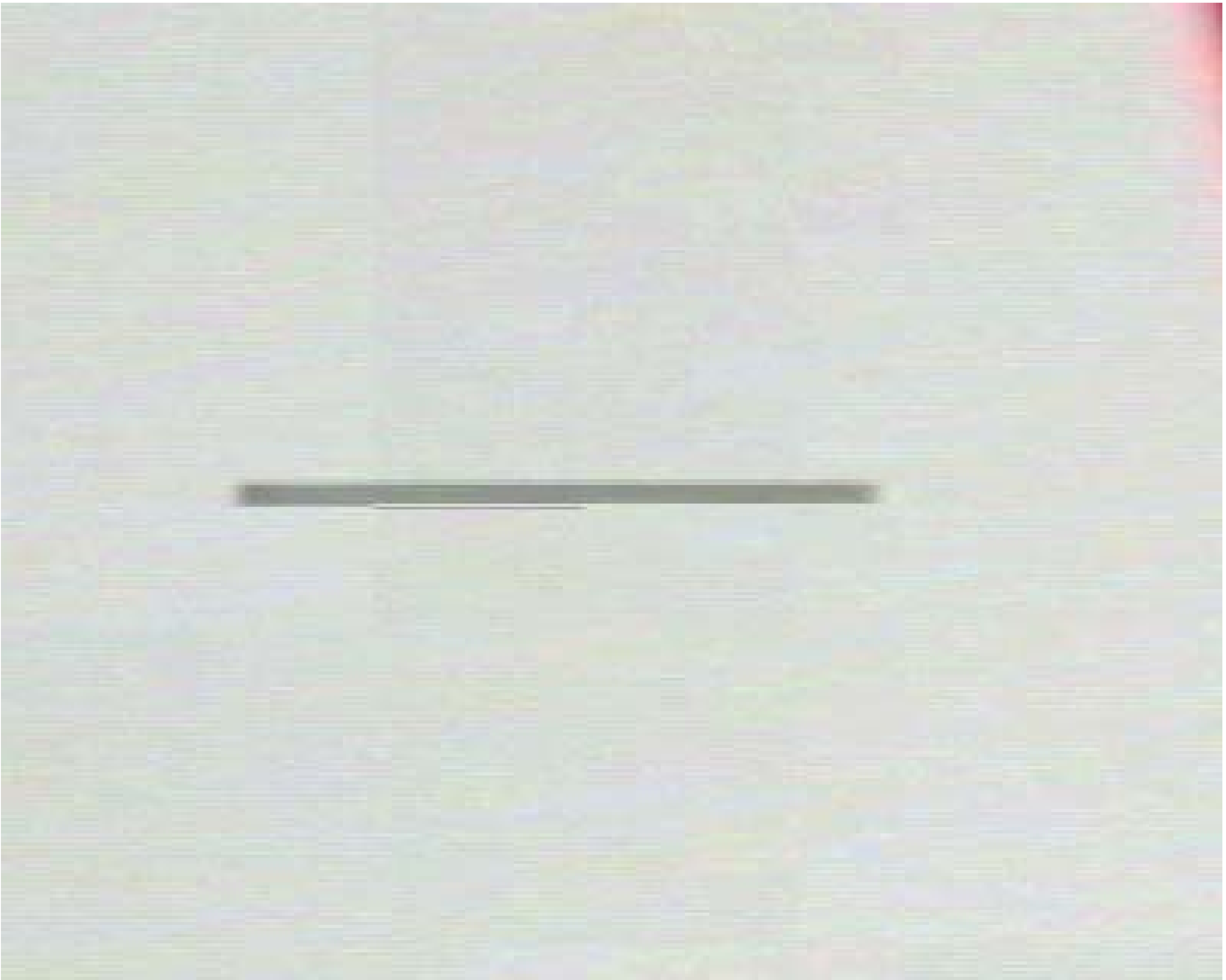


FD-TD Simulation of Scattering by Strip

- Gaussian pulse plane wave incidence
- H-field polarization (H_y plotted)
- Phenomena: trailing edge diffraction

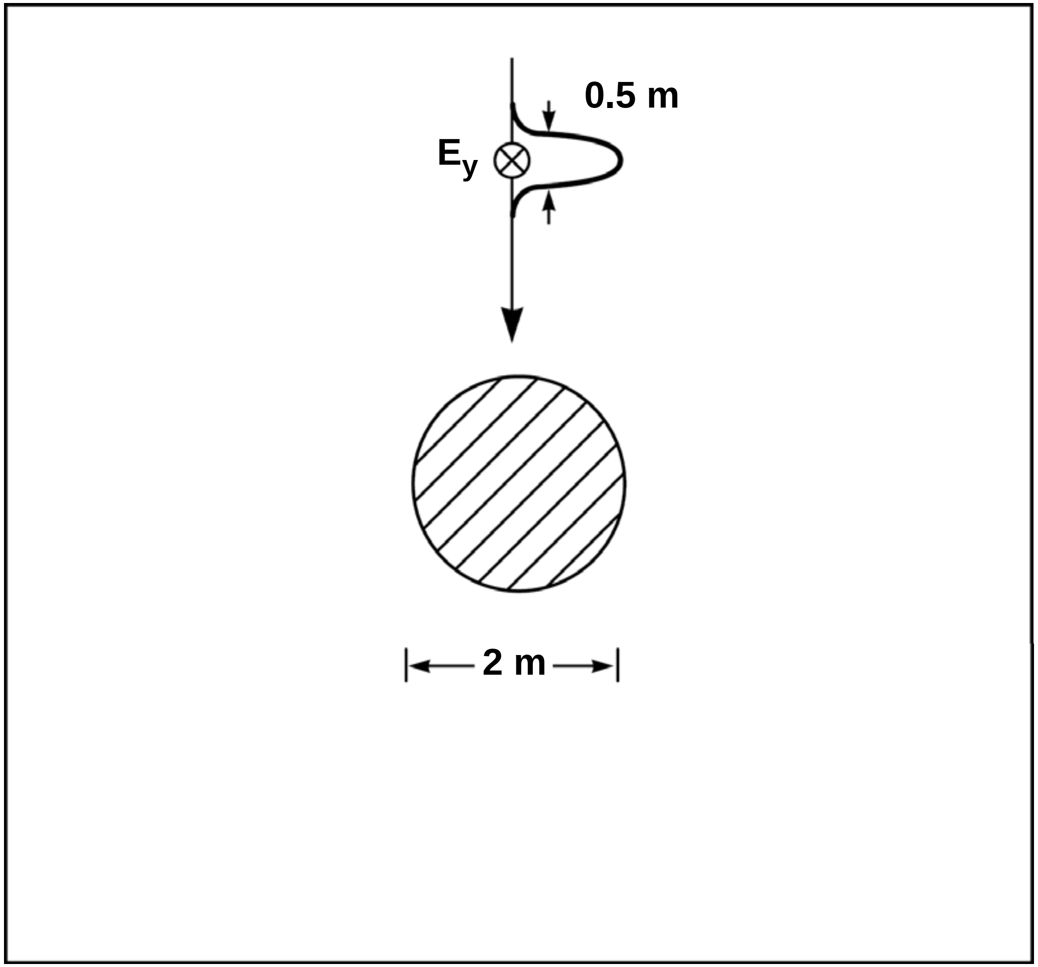


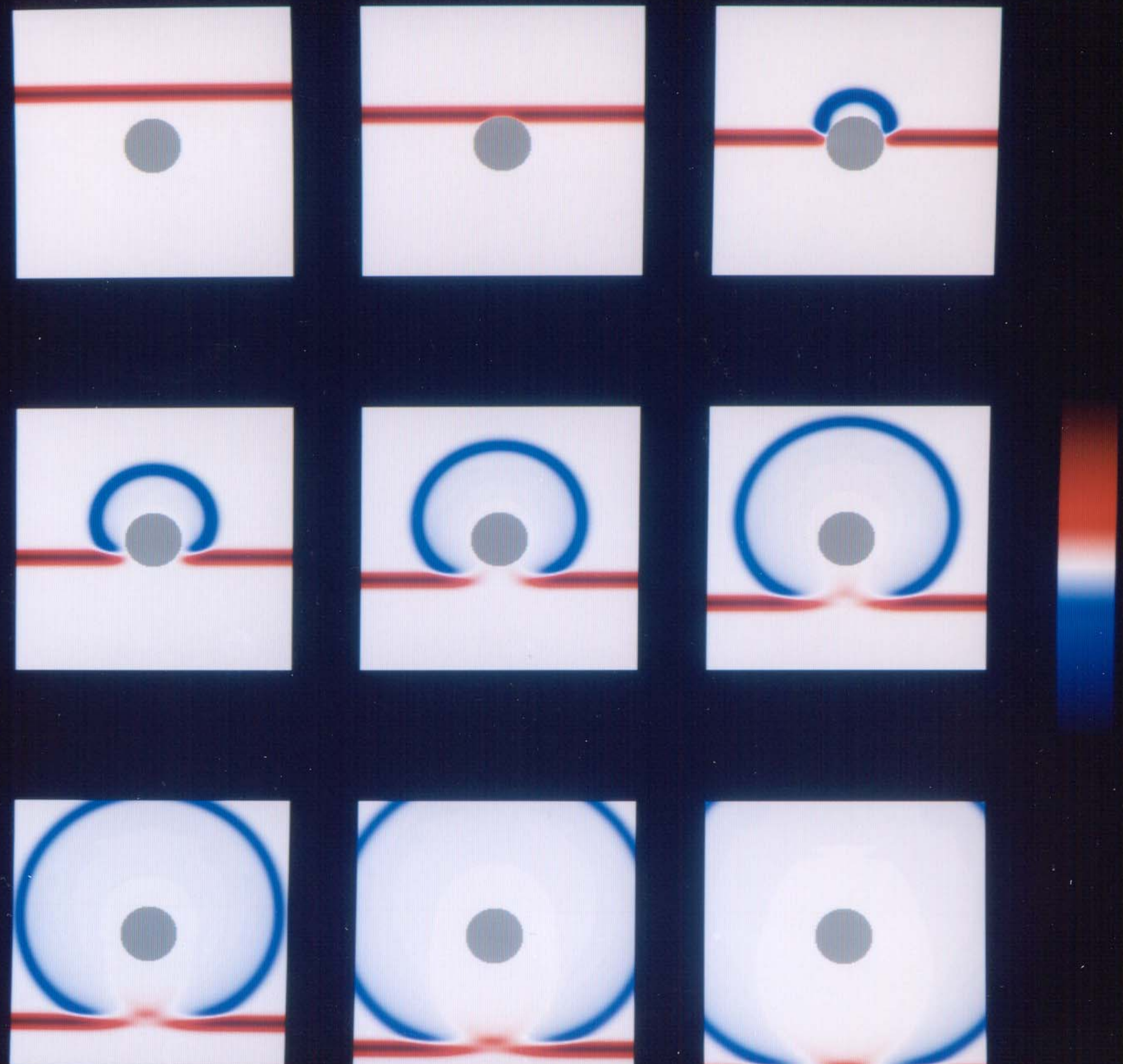
FD-TD Simulation of Scattering by Strip



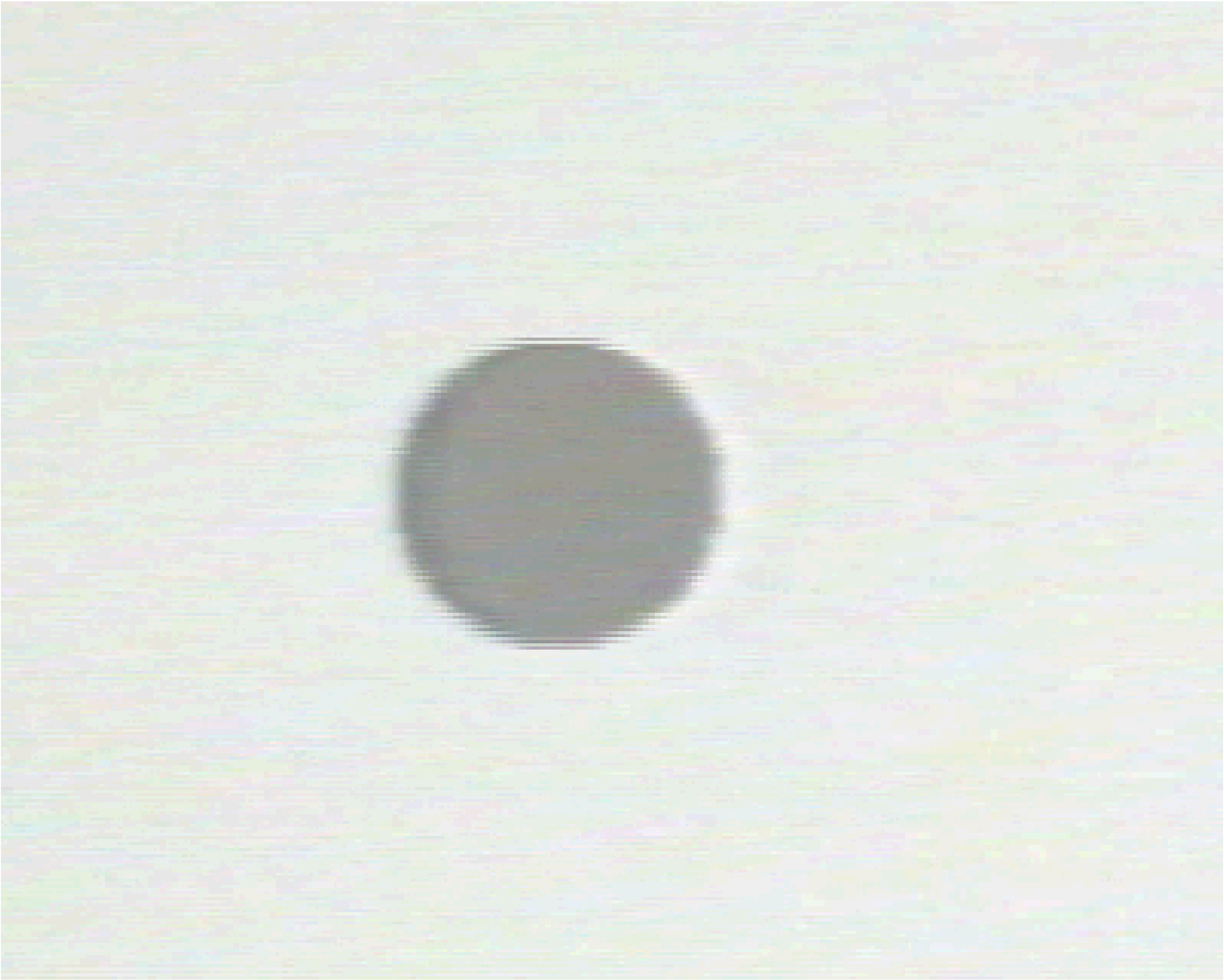
FD-TD Simulation of Scattering by Cylinder

- Gaussian pulse plane wave incidence
- E-field polarization (E_y plotted)
- Phenomena: specular reflection



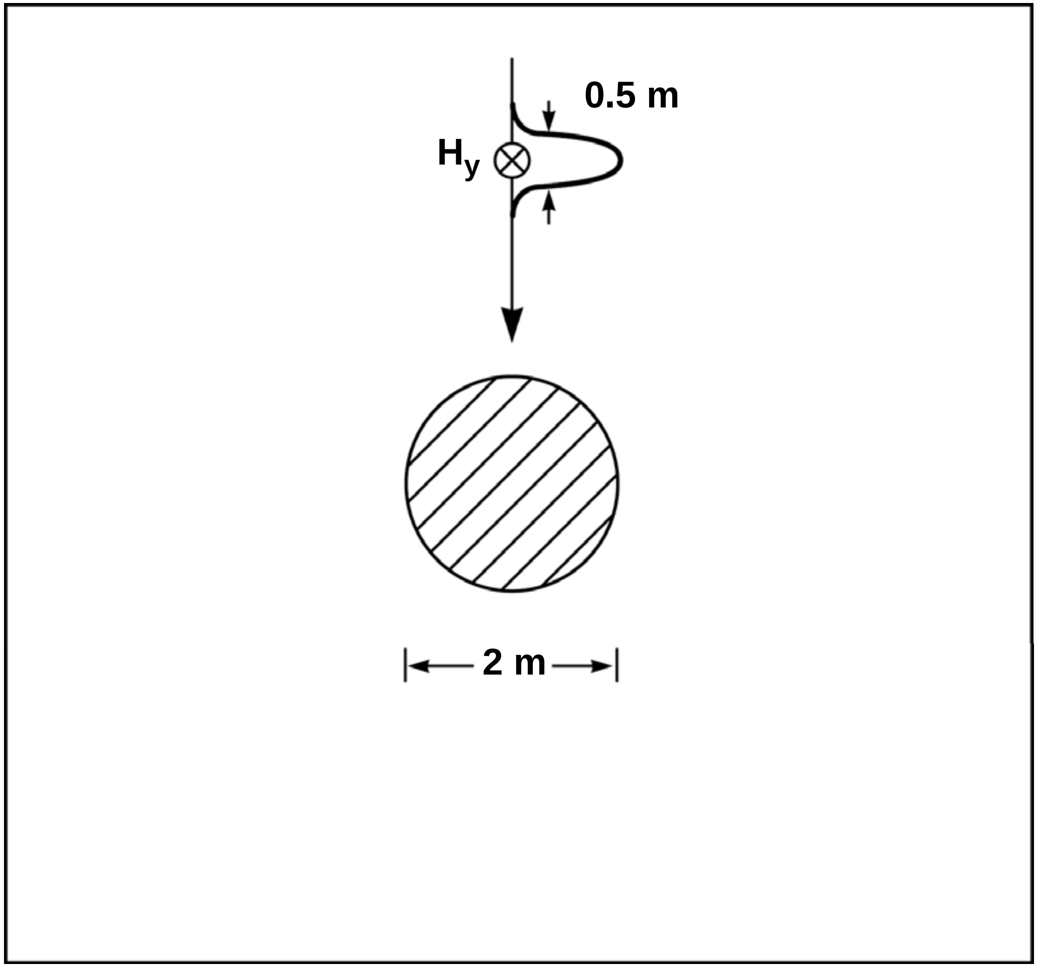


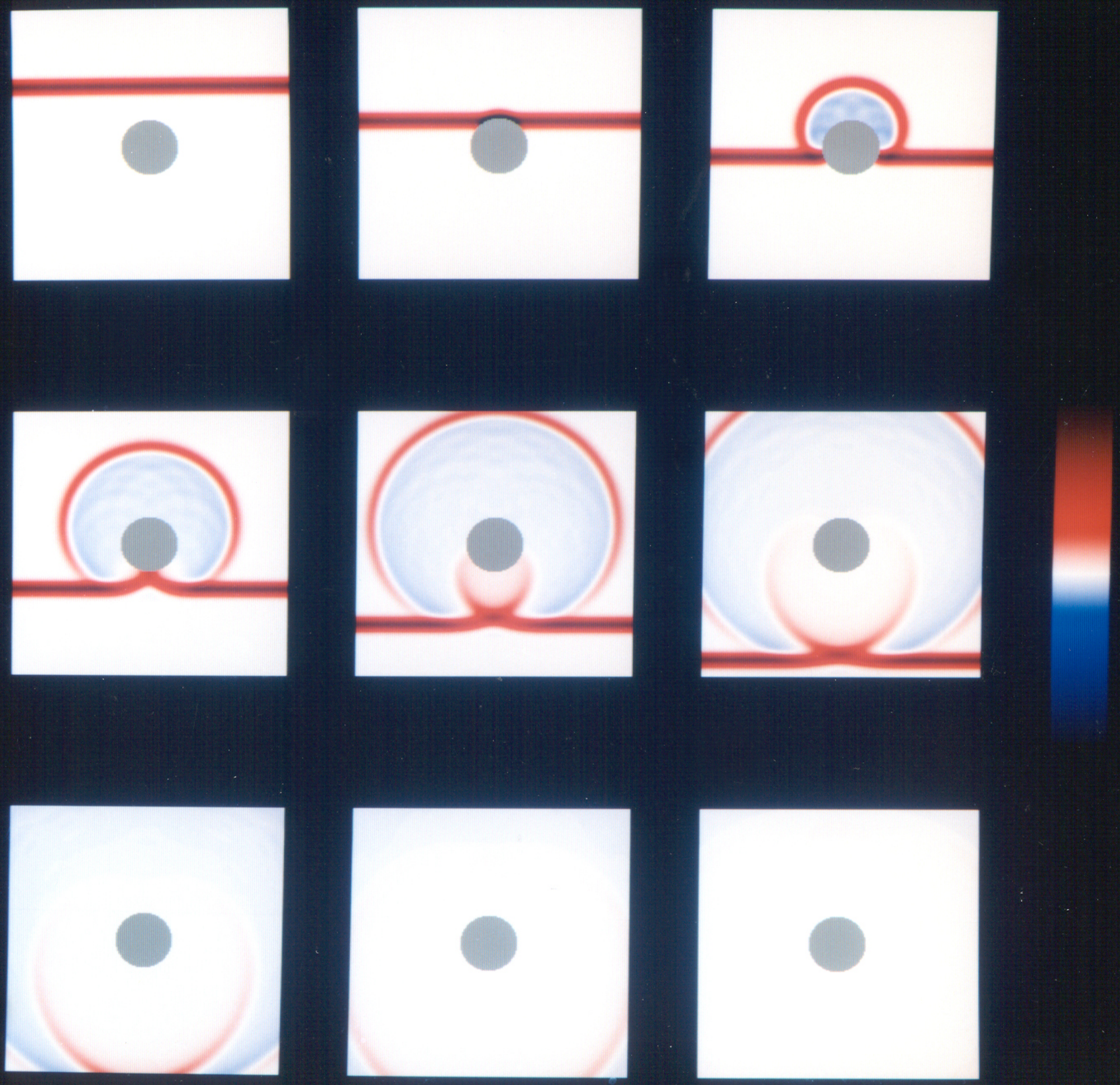
FD-TD Simulation of Scattering by Cylinder



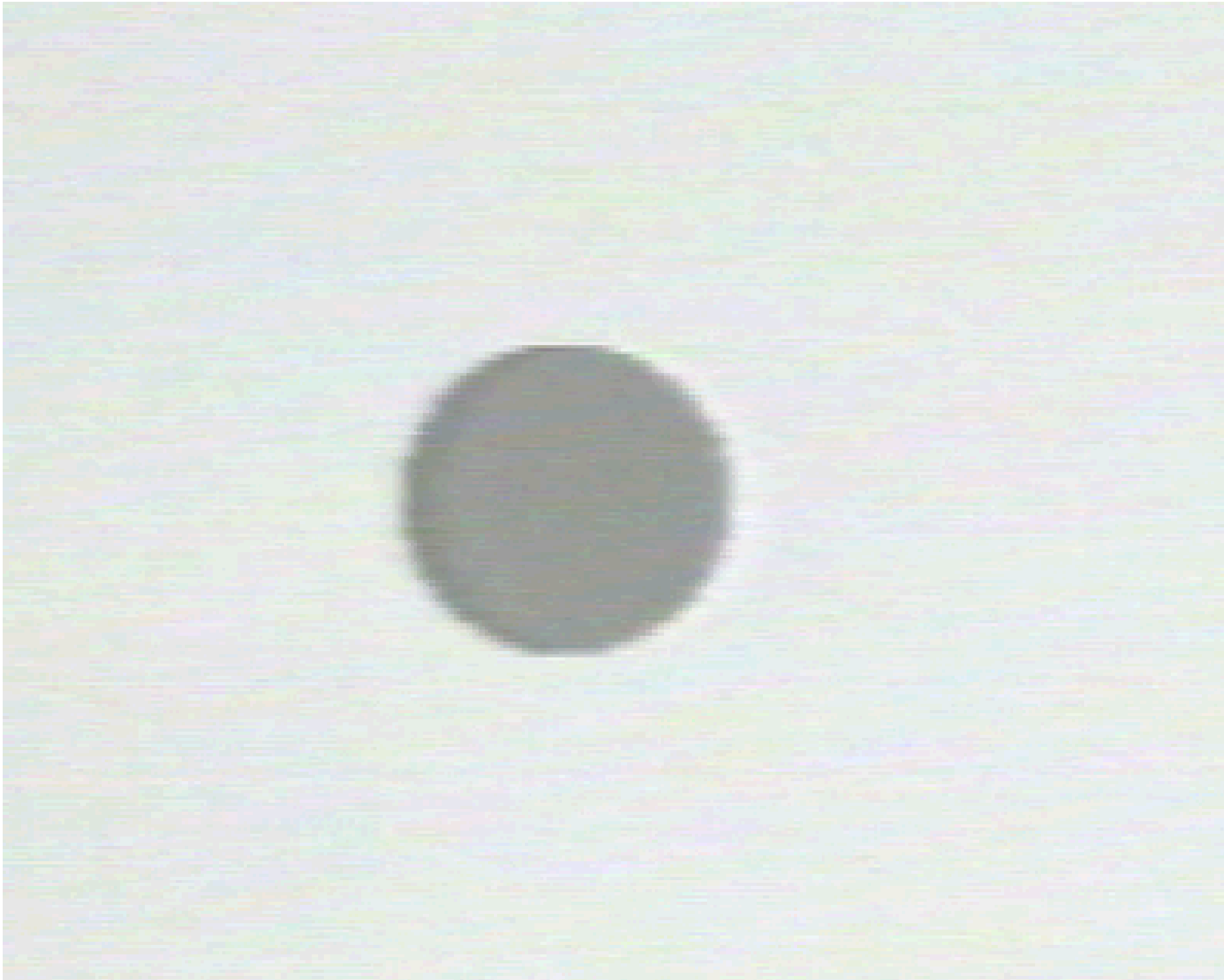
FD-TD Simulation of Scattering by Cylinder

- Gaussian pulse plane wave incidence
- H-field polarization (H_y plotted)
- Phenomena: creeping wave



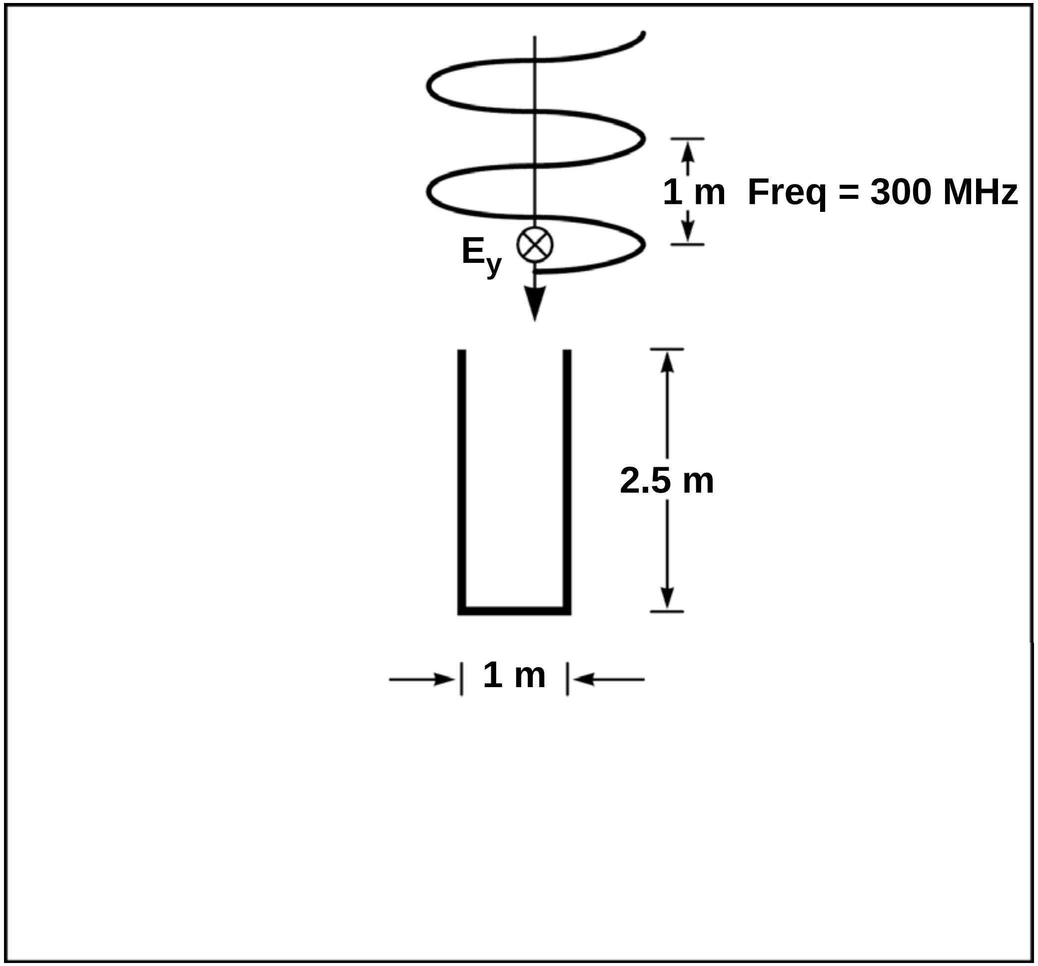


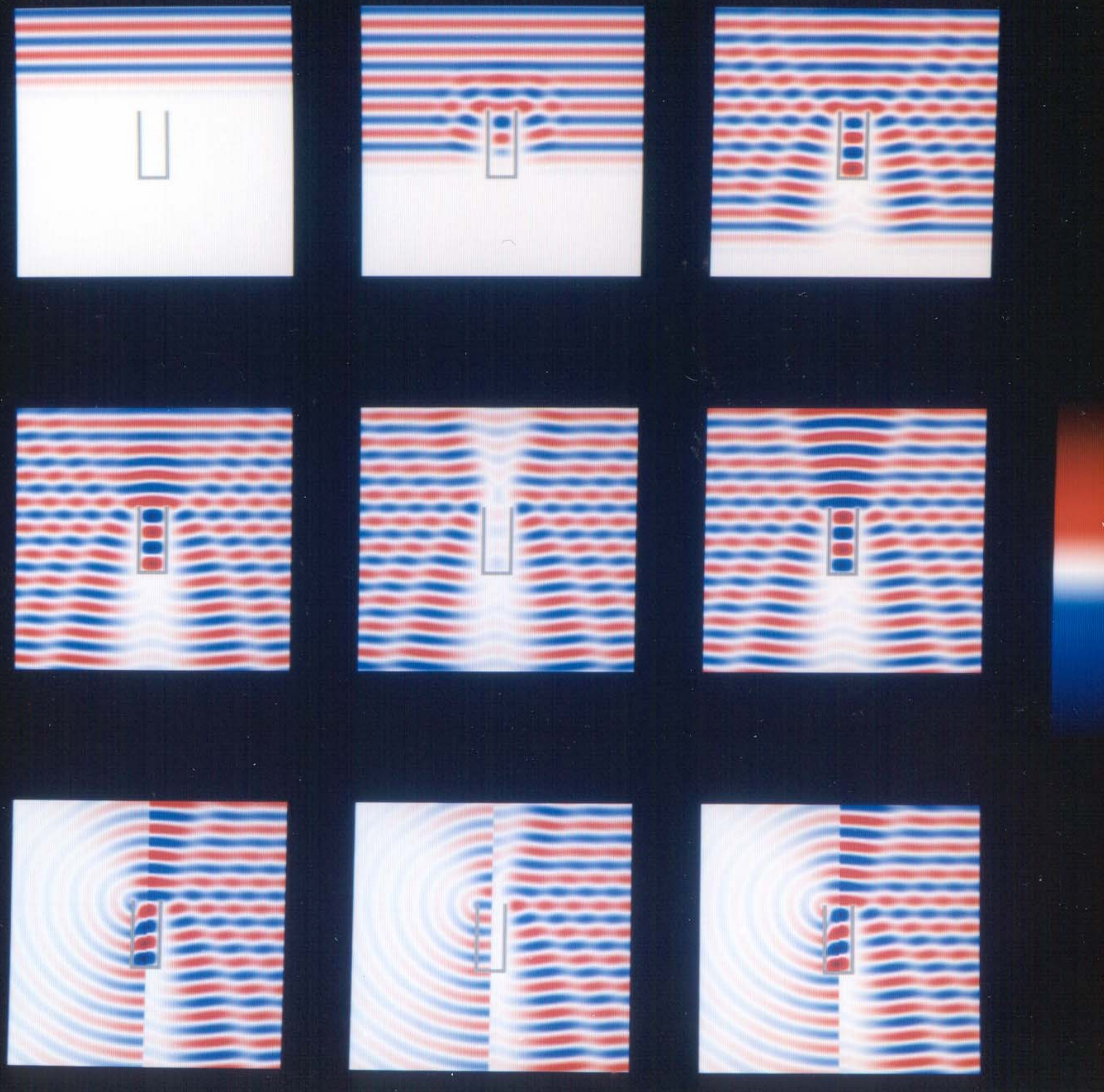
FD-TD Simulation of Scattering by Cylinder



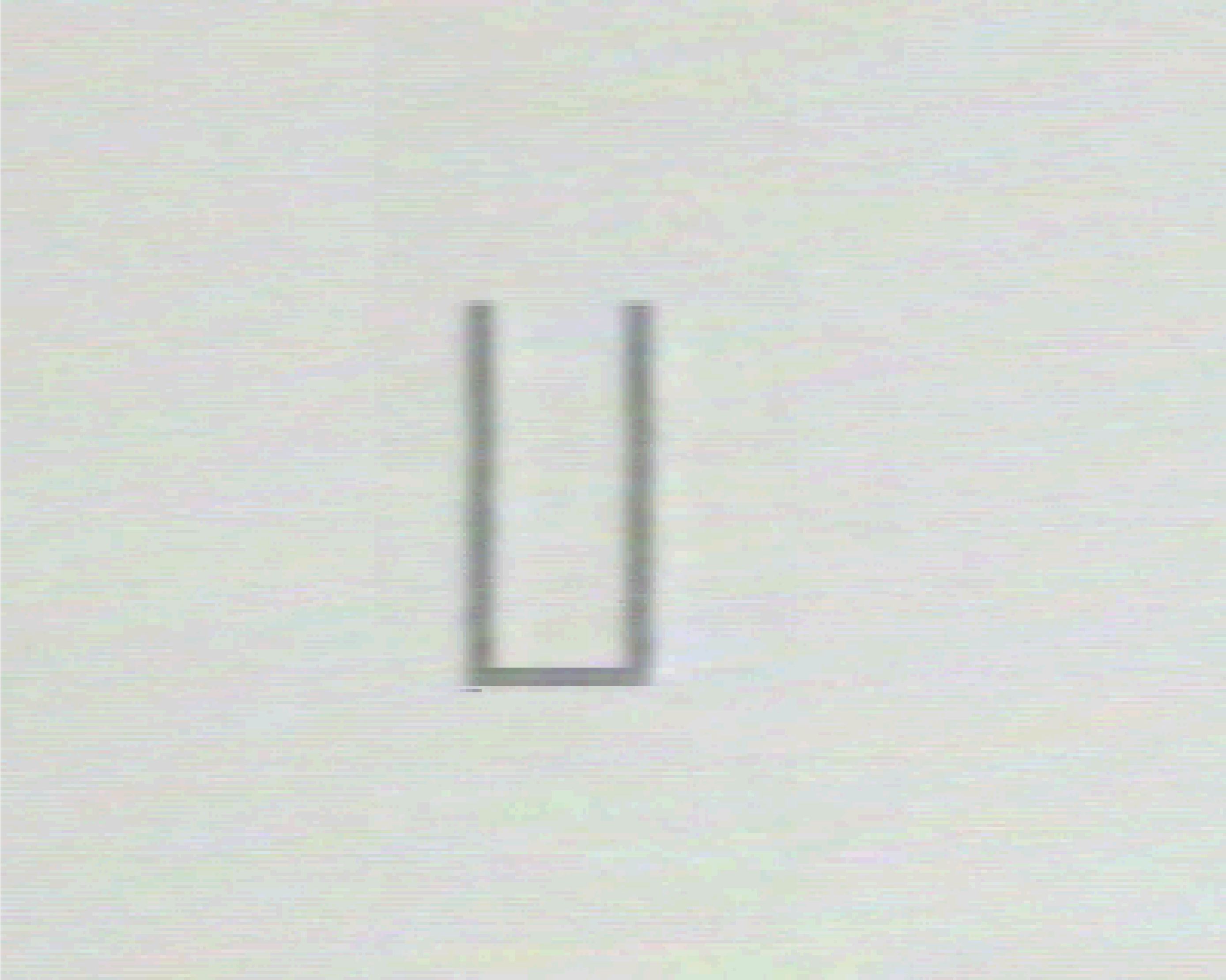
FD-TD Simulation of Scattering by Cavity

- Sinusoidal plane wave incidence
- E-field polarization (E_y plotted)
- Phenomena: standing wave





FD-TD Simulation of Scattering by Cavity



Outline

- What are typical levels of radar cross section?
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  – Prediction

Techniques for RCS Analysis

FULL SCALE MEASUREMENTS

RCS PREDICTION

SCALED MODEL MEASUREMENTS

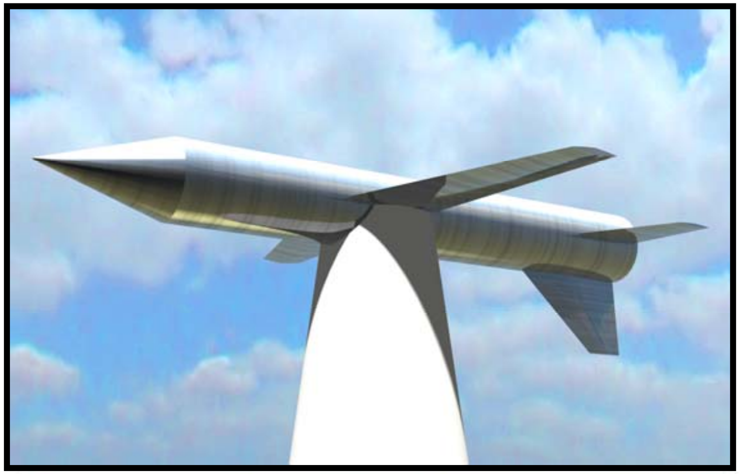
Full Scale Measurements

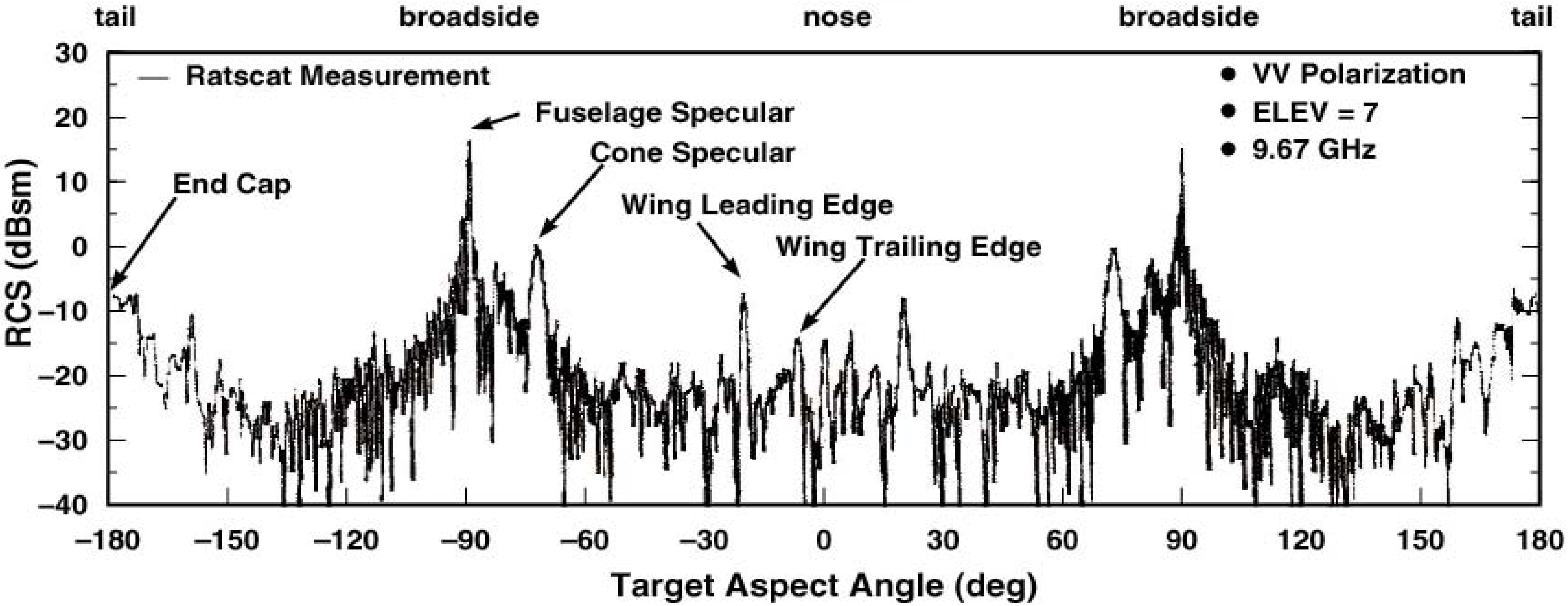
Target on support

- **Foam column mounting**
  - **Dielectric properties of styrofoam close to those of free space**
- **Metal pylon mounting**
  - **Metal pylon shaped to reduce radar reflections**
  - **Background subtraction can be used**

Derived from: http://www.af.mil/shared/media/photodb/photos/050805-F-0000S-003.jpg

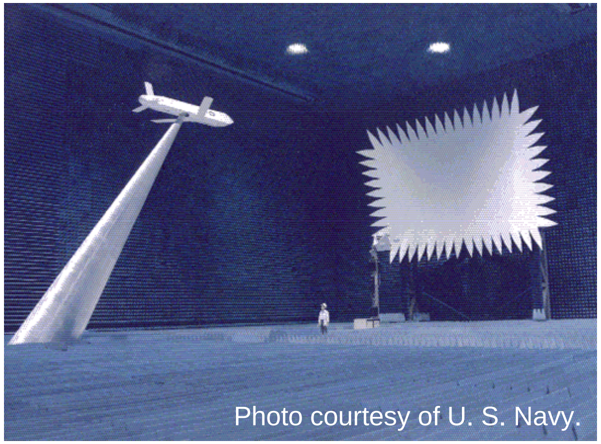
Johnson Generic Aircraft Model (JGAM)

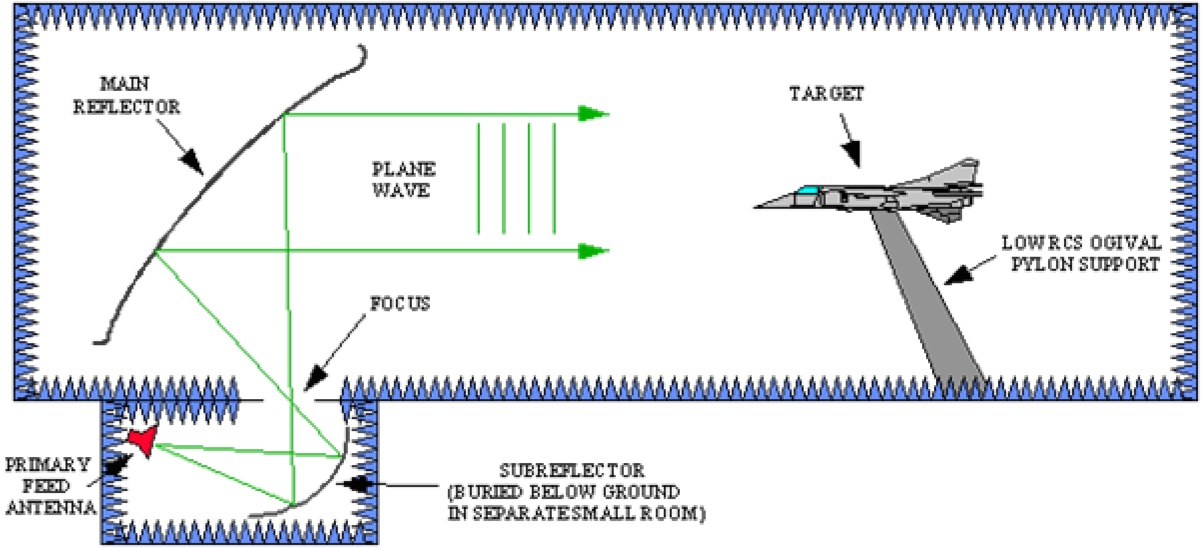




Compact Range RCS Measurement

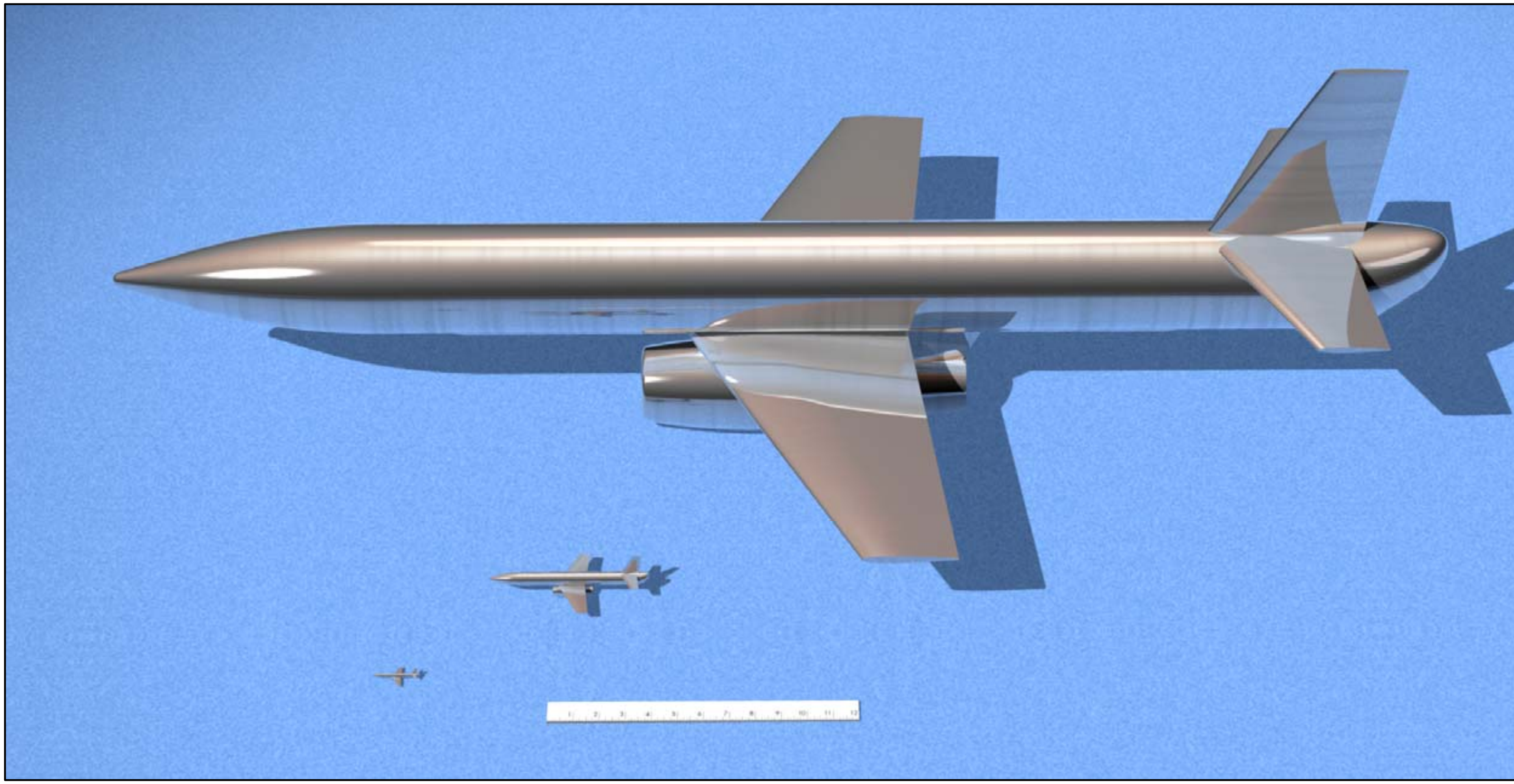
- **Radar Reflectivity Laboratory (Pt. Mugu) / AFRL Compact Range (WPAFB)**

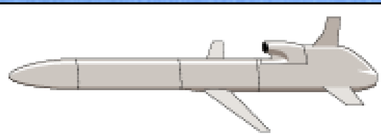


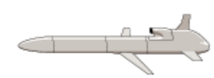


Scale Model Measurement

- **MQM-107 Drone in 0.29, 0.034, and 0.01 scaled sizes**







<u>Full Scale</u>
Measure at frequency f

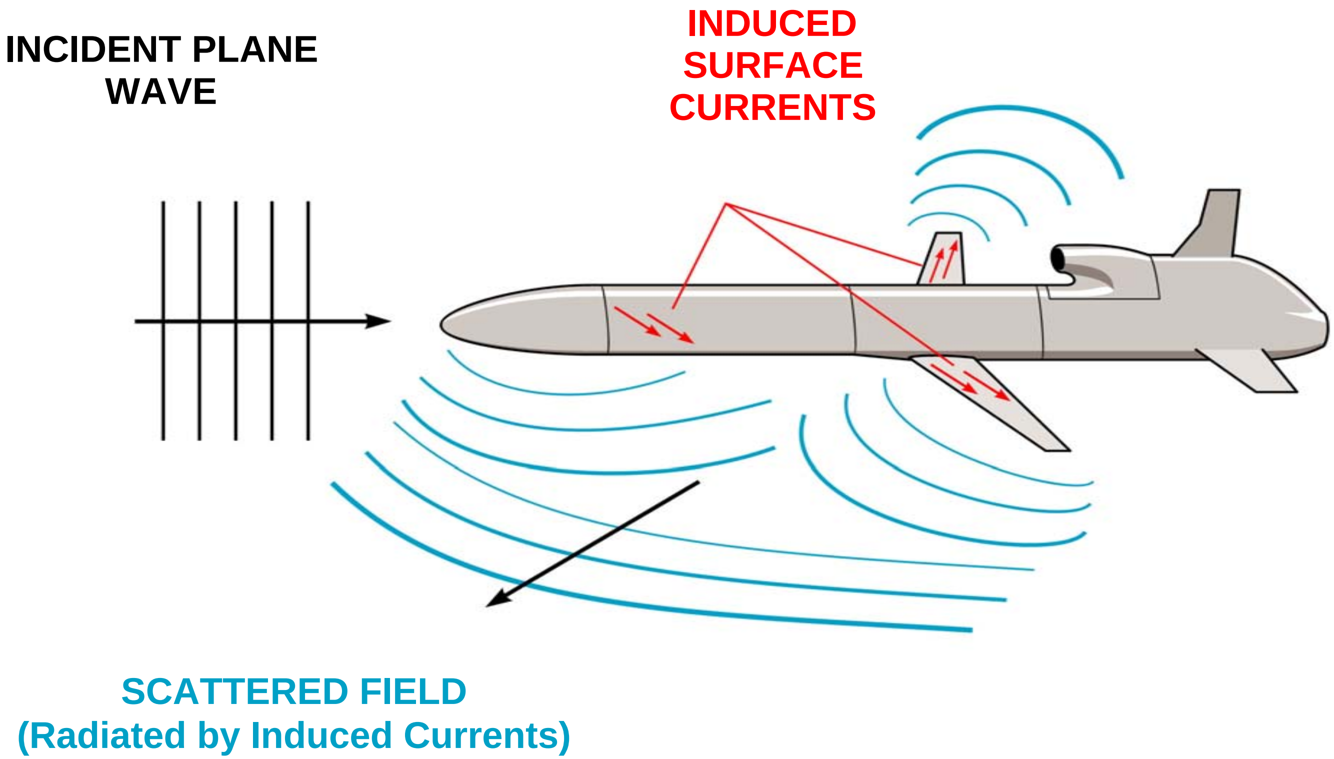
<u>Scale Factor</u>
S
(Reduced Size)

<u>Subscale</u>
Measure at frequency S x F

Scaling of Targets for RCS Measurements

QUANTITY	FULL-SCALE	SUBSCALE
LENGTH	L	$L' = L/S$
TIME	t	$t' = t/S$
FREQUENCY	f	$f' = Sf$
WAVELENGTH	λ	$\lambda' = \lambda/S$
CONDUCTIVITY	g	$g' = Sg$
PERMITTIVITY	ε	$\varepsilon' = \varepsilon$
PERMEABILITY	μ	$\mu' = \mu$
RCS	σ	$\sigma' = \sigma/S^2$

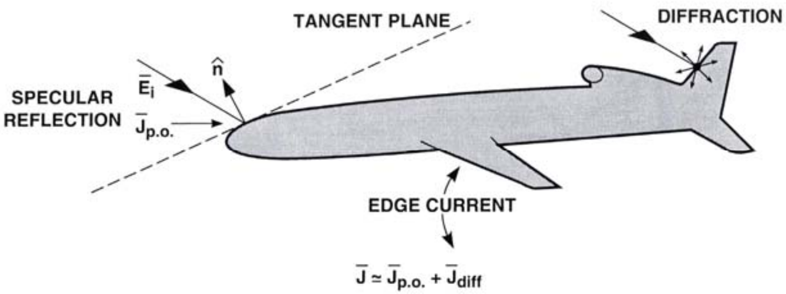
Electromagnetic Scattering



- **TWO STEP PROCESS TO DETERMINE SCATTERED FIELD**
  - **DETERMINE INDUCED SURFACE CURRENTS**
  - **CALCULATE FIELD RADIATED BY CURRENTS**

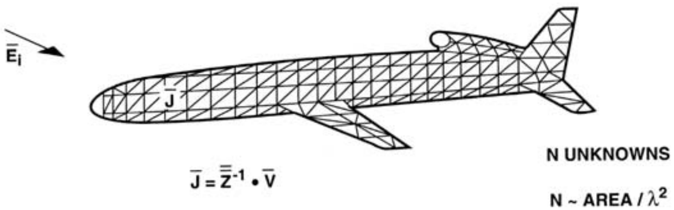
RCS Prediction Approaches

- **High frequency approximations**
  - **Physical theory of diffraction**



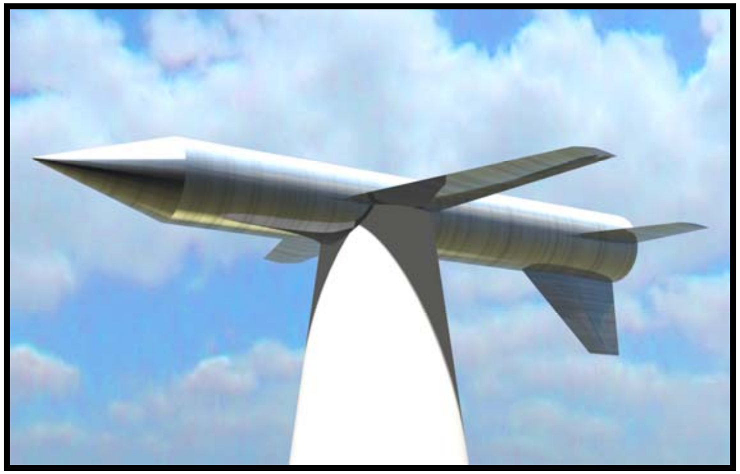
- **Advantages**
  - Reduced computational requirements
  - Arbitrary, complex geometries
- **Disadvantages**
  - Neglects some scattering
  - Applicable only to large, smooth geometries
- **Codes**
  - Xpatch

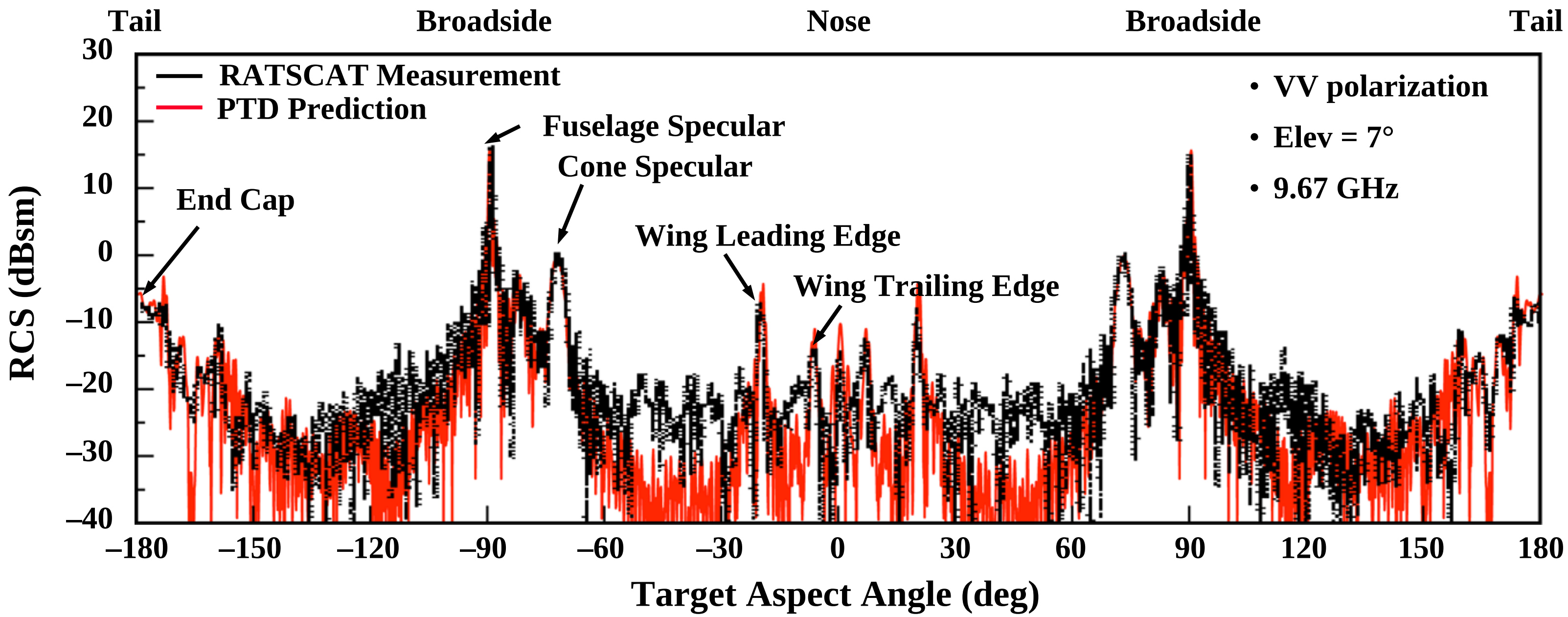
- **Exact numerical approaches**
  - **Method of Moments**



- **Advantages**
  - Exact formulation
- **Disadvantages**
  - Computationally intensive
- **Codes**
  - CARLOS
  - CICERO (Body of revolution)
  - FISC
  - FERM

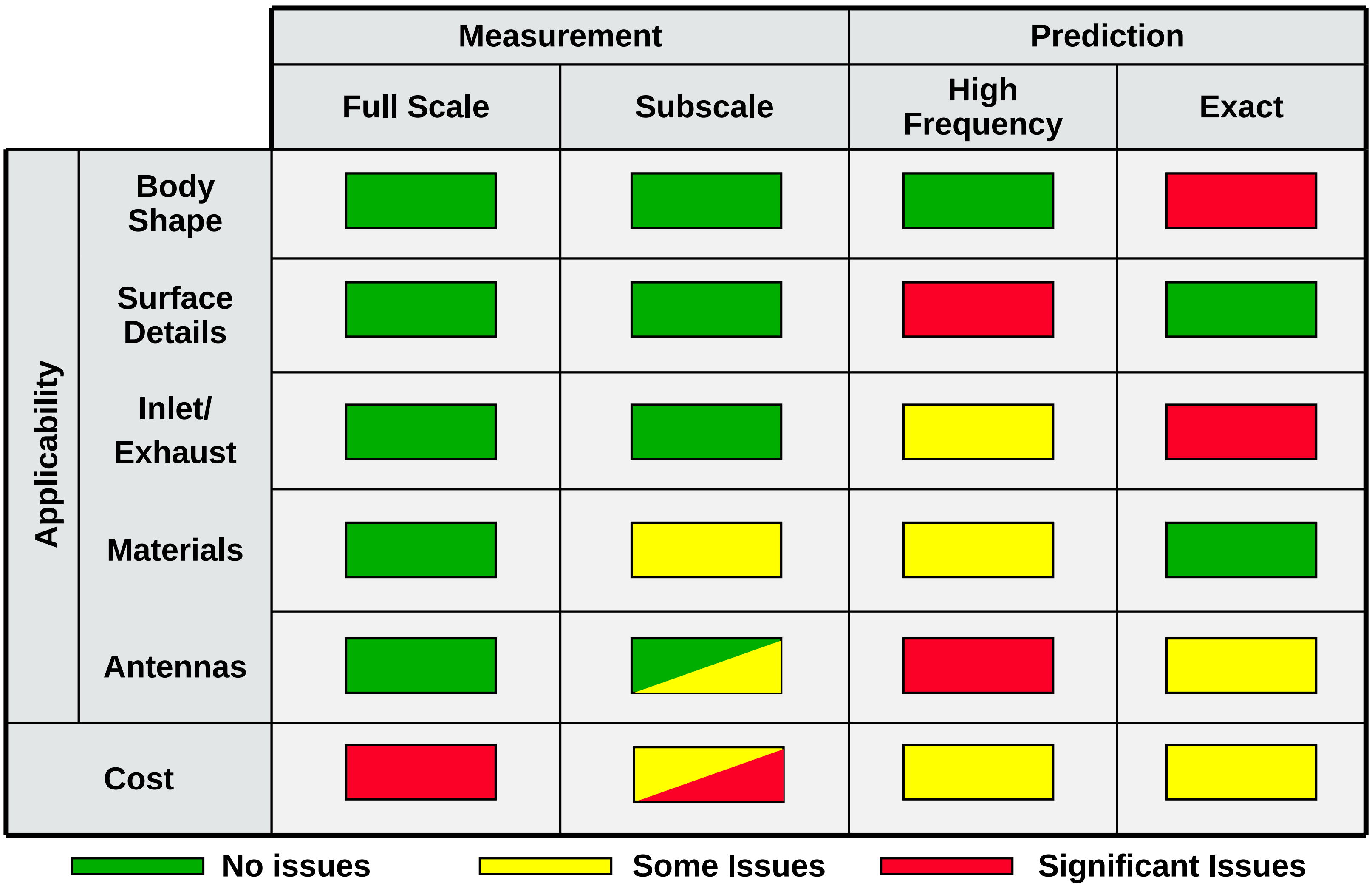
Measured and Calculated RCS of JGAM





Signature Analysis Approaches

• X-band air vehicle targets



Summary

- **Radar cross section varies significantly across targets of potential interest**
  - **Depends on target characteristics (shape, material, etc.)**
  - **Depends on radar parameters (frequency, polarization, etc.)**
- **Target signature contains several contributors**
  - **Structural (body shape, surface details, etc.)**
  - **Propulsion (inlets, exhaust)**
  - **Avionics (seekers, communication antennas, etc.)**
- **Accurate estimation of target signatures should draw upon all available tools (i.e. measurement and prediction)**
  - **Component based signature estimation allows use of multiple tools in coherent roll-up of overall vehicle signature**

References

- Atkins, R., Radar Cross Section Tutorial, 1999 IEEE National Radar Conference, 22 April 1999,
- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001

Detection of Targets in Noise
and
Pulse Compression Techniques

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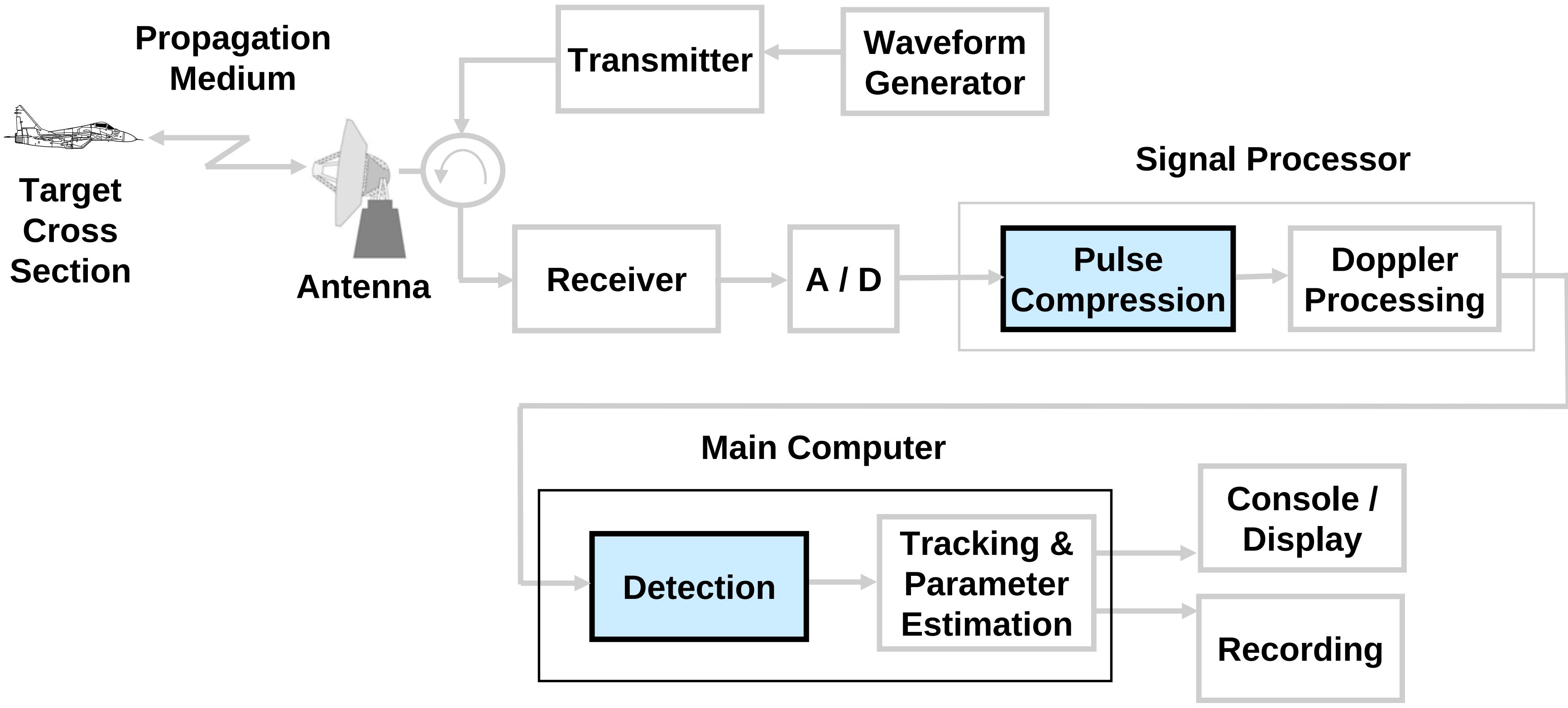
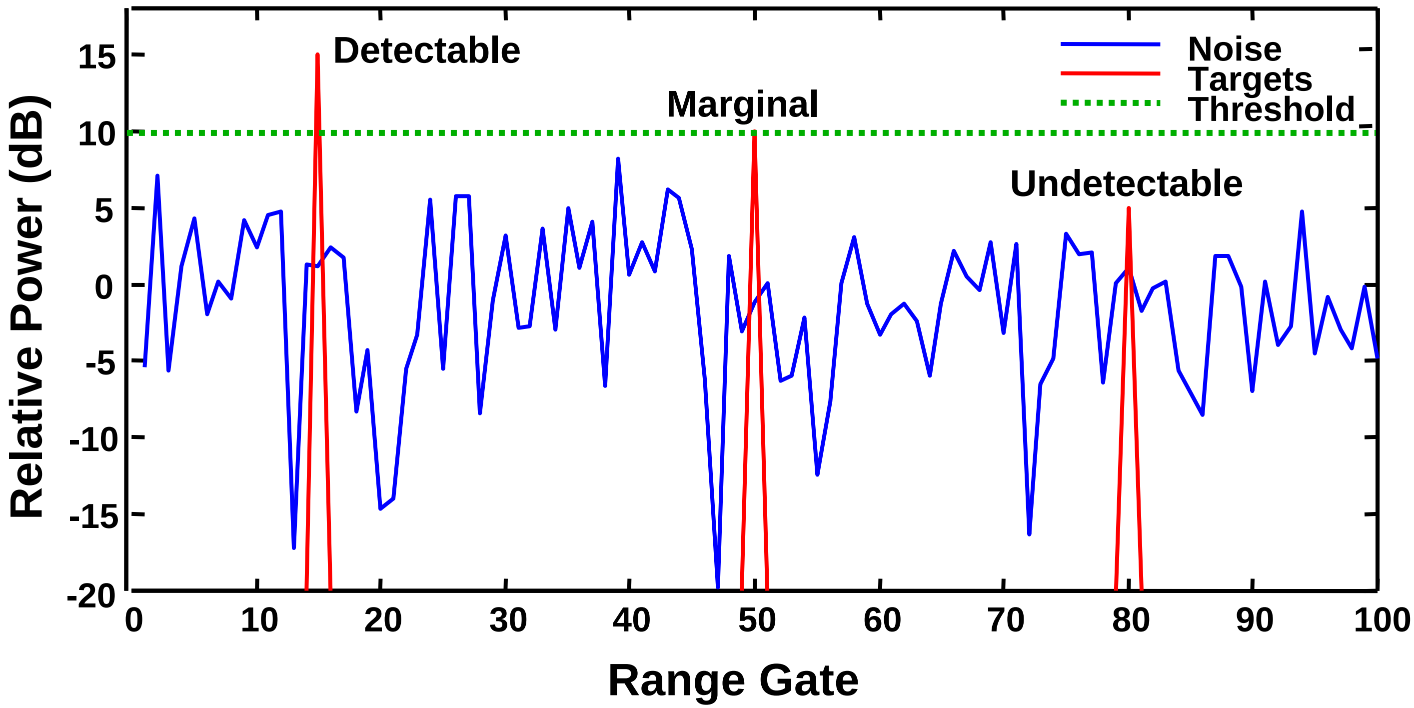
Detection and Pulse Compression



Outline

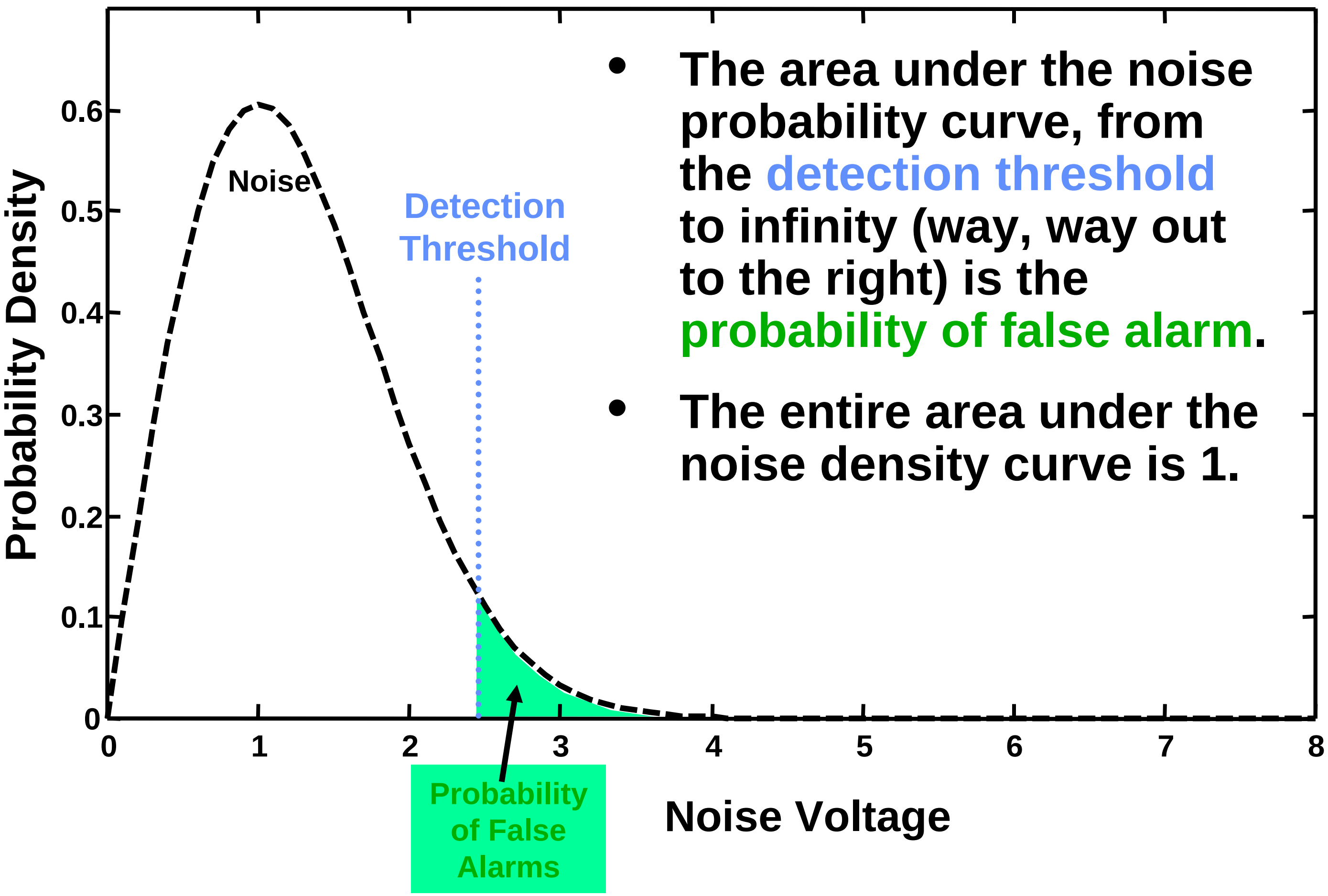
- **Detection of Target Echoes in Noise**
  - **Basic Concepts**
  - **Integration of Pulses**
  - **Fluctuating Targets Issues**
  - **Adaptive Thresholding Techniques**
- **Pulse Compression**

Target Detection in the Presence of Noise



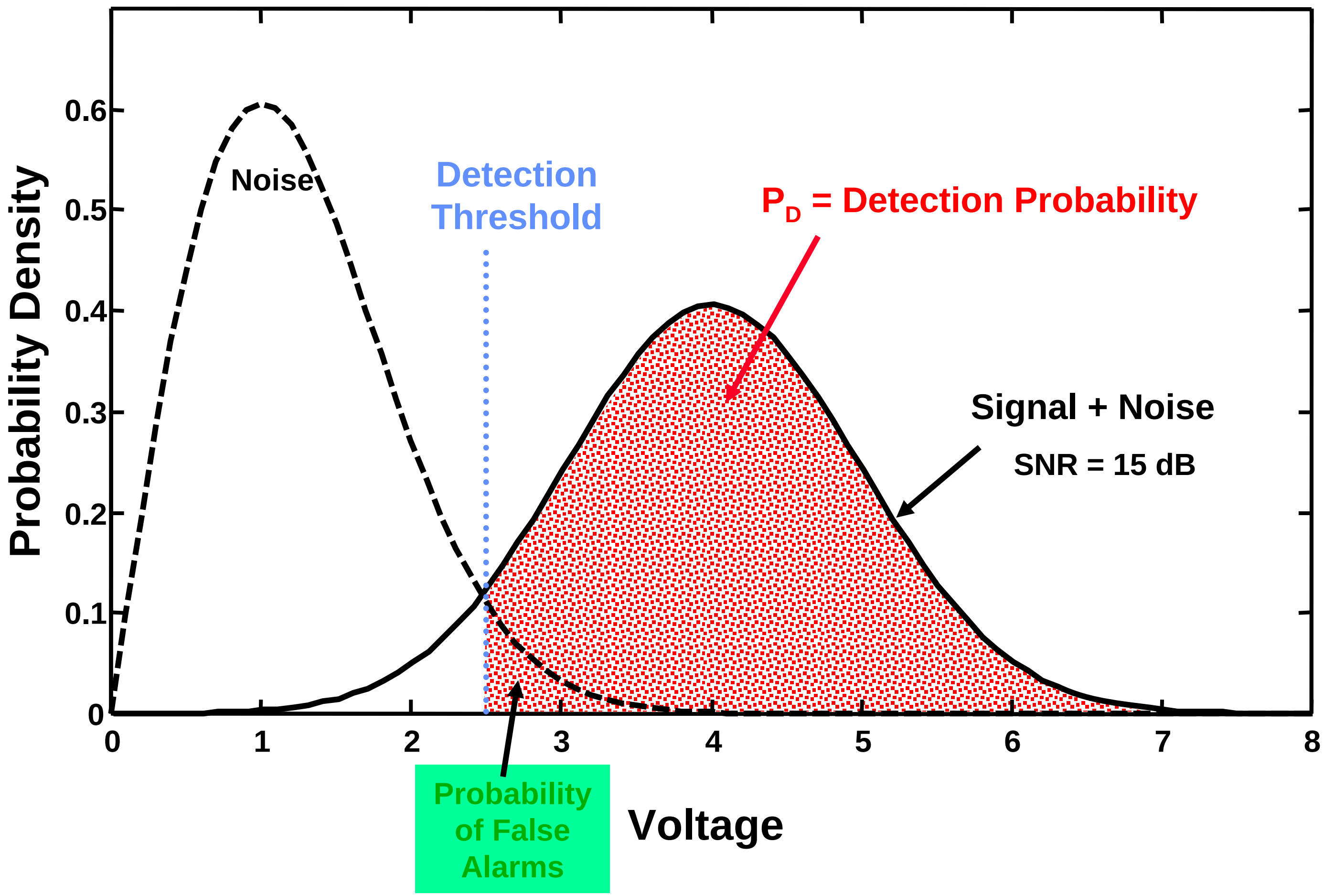
- The radar return is sampled at regular intervals with A/D (Analog to Digital) converters
- The sampled returns may include the target of interest and noise
- A threshold is used to reject noise

The Detection Problem

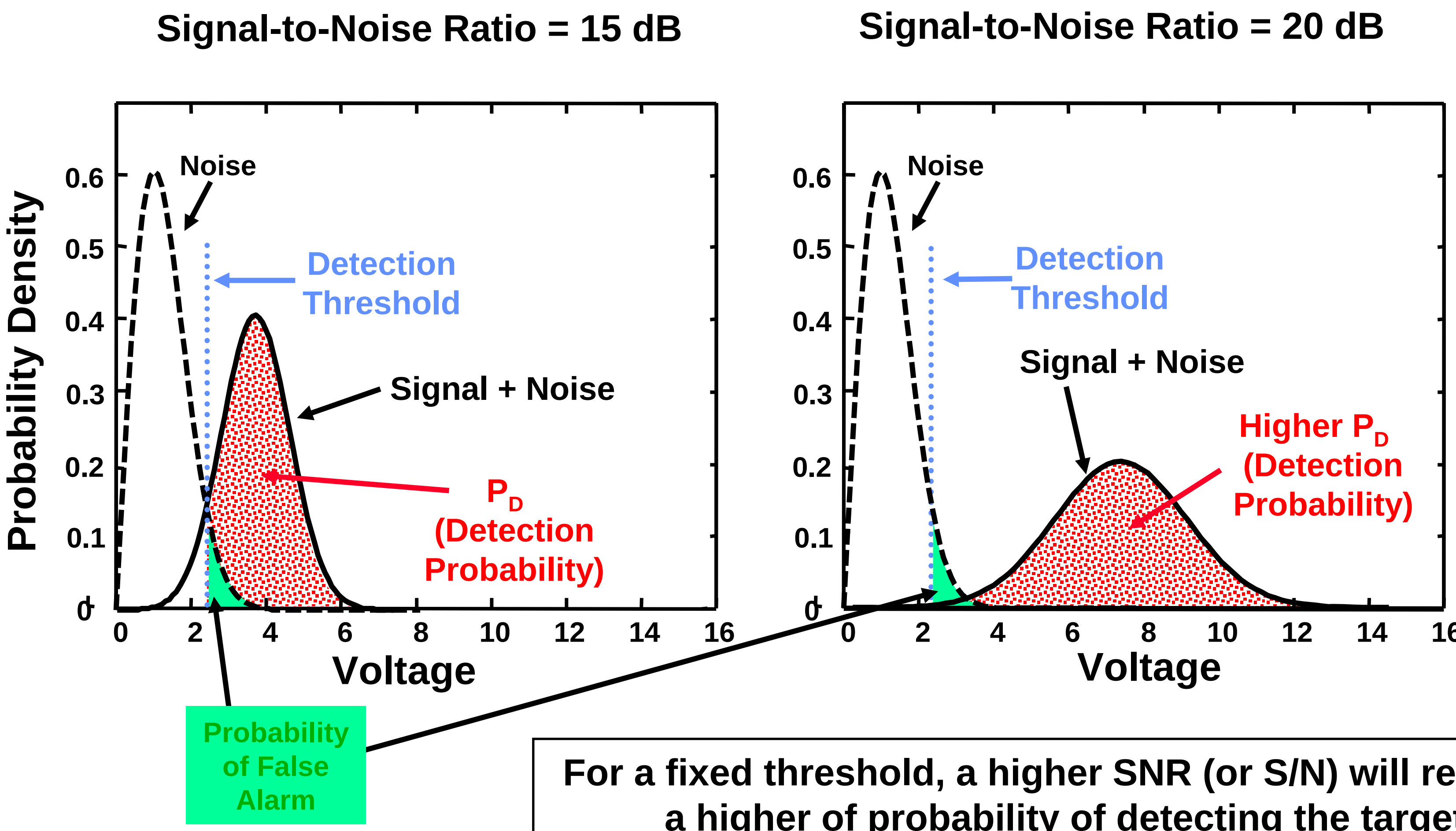


- The area under the noise probability curve, from the detection threshold to infinity (way, way out to the right) is the probability of false alarm.
- The entire area under the noise density curve is 1.

The Detection Problem



Detection Examples with Different SNR



For a fixed threshold, a higher SNR (or S/N) will result in a higher of probability of detecting the target

Probability of Detection vs. SNR

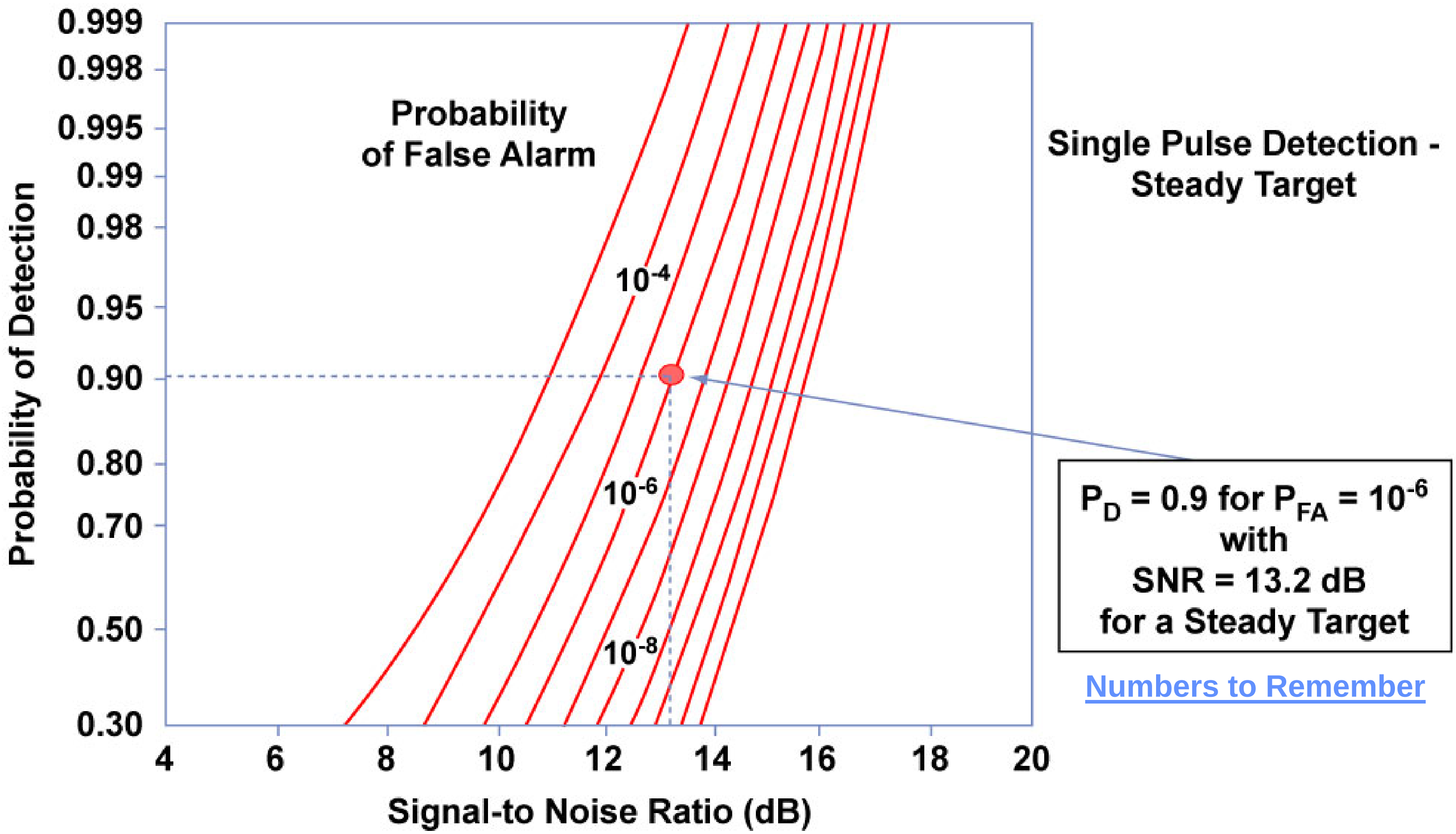


Figure by MIT OCW.

Outline

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Integration of Radar Pulses

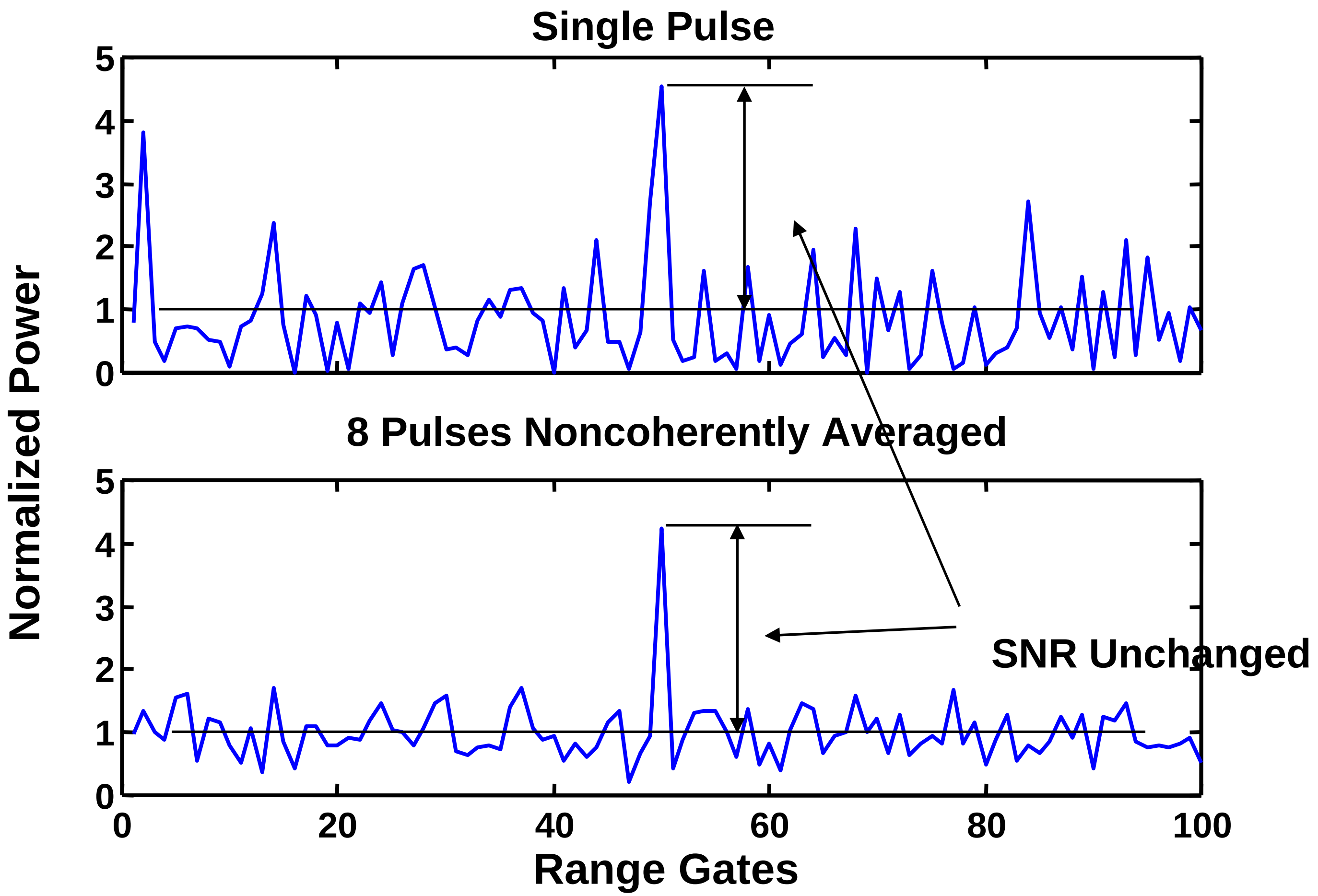
- Improve ability of radar to detect targets by combining the returns from multiple pulses
- Coherent Integration
  - No information lost (amplitude or phase)
- Non-coherent integration techniques
  - Some information lost (phase)
  - Non-coherent (video) Integration
  - Binary Integration
  - Cumulative detection
  - For most cases, coherent integration is more efficient than non-coherent integration

Coherent Integration

- Real and Imaginary (In-phase and Quadrature) parts of the complex radar return are added, and the magnitude of the voltage is calculated
  - $V=(I^2 + Q^2)^{1/2}$
- This quantity is then thresholded
- The coherent integration gain is equal to the number of pulses coherently integrated
  - 2 pulses 3 dB
  - 10 pulses 10 dB
  - 20 pulses 13 dB
- For this gain to be realized, the noise samples, from pulse to pulse must be independent
  - The background noise is white Gaussian noise

Noncoherent Integration

Steady Target



Noise Variance Reduced after Integration (Allows Lower Threshold)

Different Types of Non-Coherent Integration

- **Non Coherent Integration – General (aka video integration)**
  - Generate magnitude for each of N pulses
  - Add magnitudes and then threshold

- **Binary Integration**
  - Generate magnitude for each of N pulses and then threshold
  - Require at least M detections in N scans

- **Cumulative Detection**
  - Generate magnitude for each of N pulses and then threshold
  - Require at least 1 detection in N scans

Outline

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  - **Basic Concepts**
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  - **Adaptive Thresholding Techniques**
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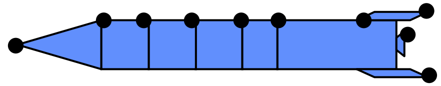
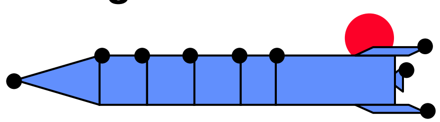
Target Fluctuations

Swerling Models

Fluctuation Interval

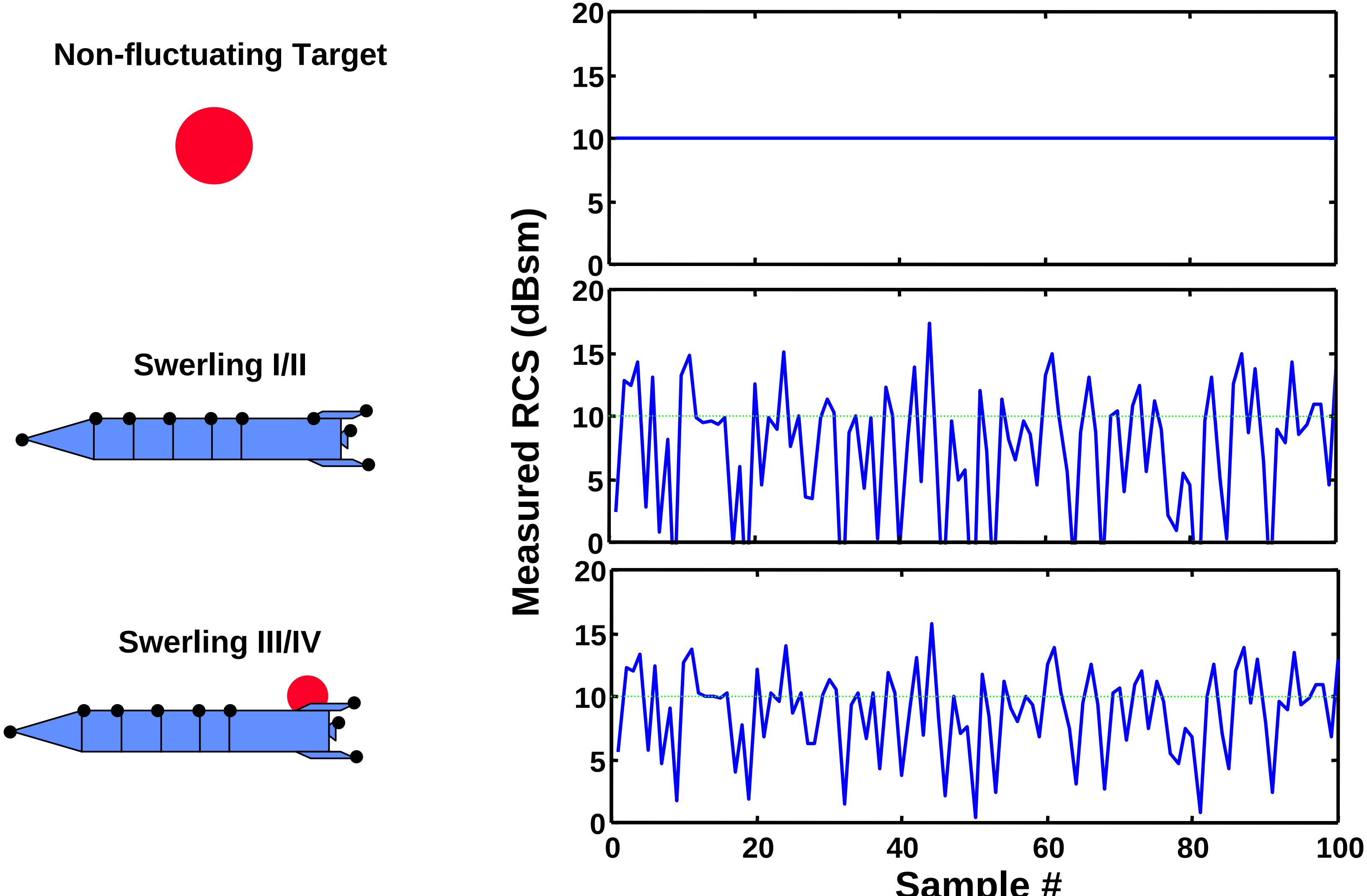
Nature of Scatterers		scan-to-scan (multiple pulses/scan)	pulse-to-pulse
	similar amplitudes  $p(\sigma) = \frac{1}{\sigma_{av}} e^{-\sigma/\sigma_{av}}$	**Swerling I**	**Swerling II**
	one amplitude much larger than others  $p(\sigma) = \frac{4\sigma}{\sigma_{av}^2} e^{-2\sigma/\sigma_{av}}$	**Swerling III**	**Swerling IV**

RCS Variability for Different Target Models

Non-fluctuating Target

Swerling I/II

Swerling III/IV



Detection Statistics for Fluctuating Targets

Single Pulse Detection

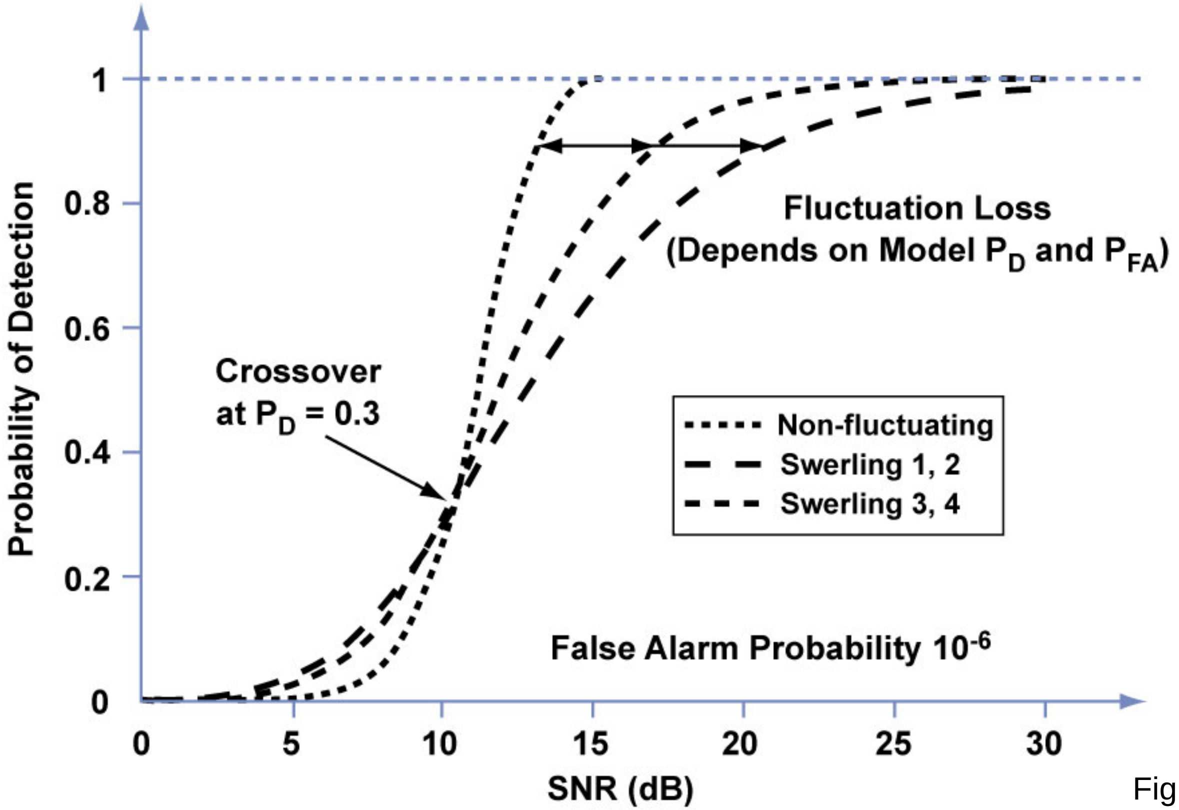


Figure by MIT OCW.

Fluctuating Targets Require More SNR than Non-fluctuating Targets to Maintain a High Probability of Detection

Outline

- **Detection of Target Echoes in Noise**
  - **Basic Concepts**
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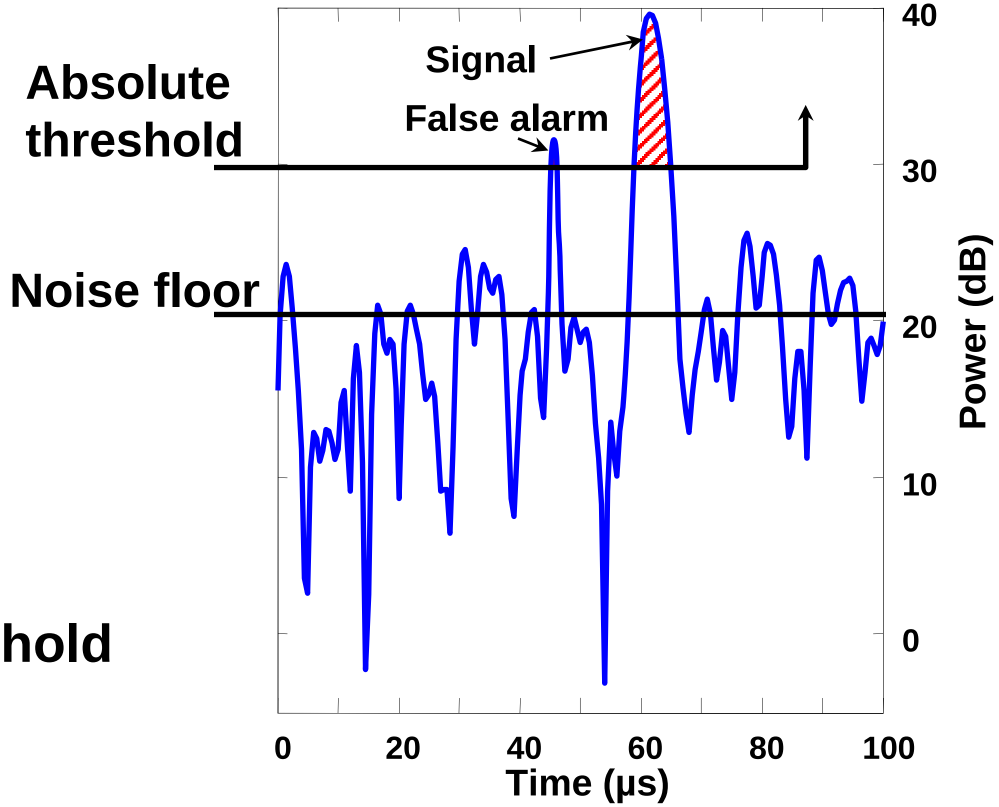
  - **Fluctuating Targets Issues**
  - **Adaptive Thresholding Techniques**
- **Pulse Compression**

Constant False Alarm Rate (CFAR) Thresholding

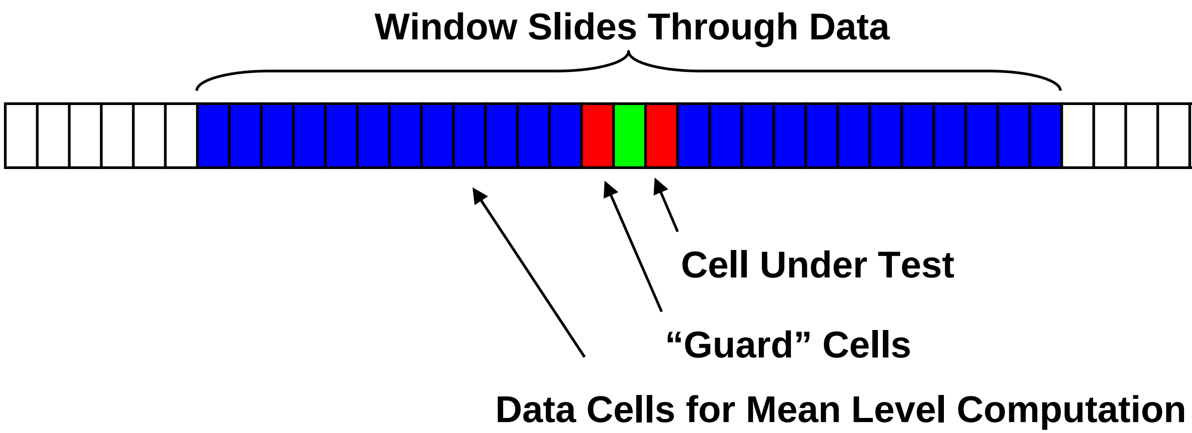
- **Problem: Must know (or estimate) noise floor to set threshold**
- **Solution: Estimate noise floor using noise-only samples**
  - **Adaptive thresholding**
- **CFAR thresholding:**

$$\frac{\text{test cell}}{\text{noise floor estimate}} > \text{threshold}$$



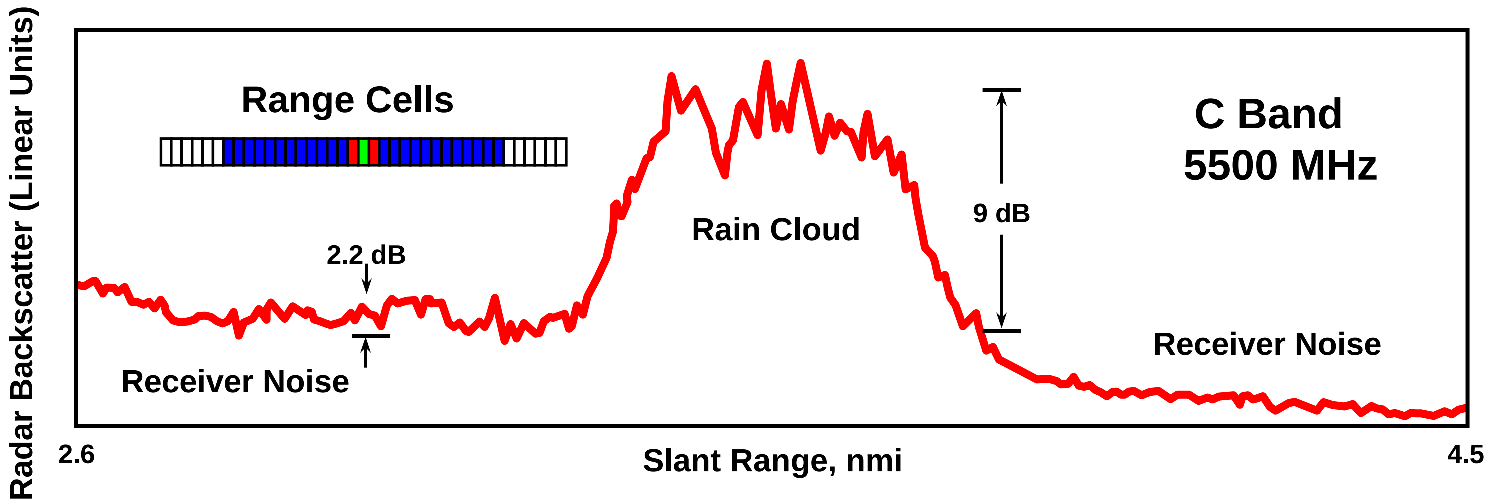
The Mean Level CFAR

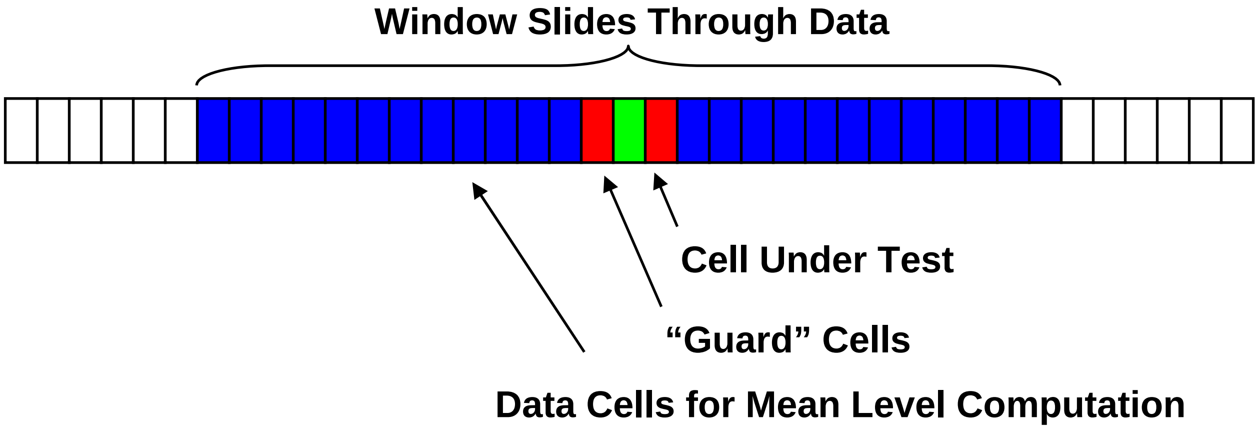
- **Use mean value of surrounding range cells to determine threshold for cell under test**



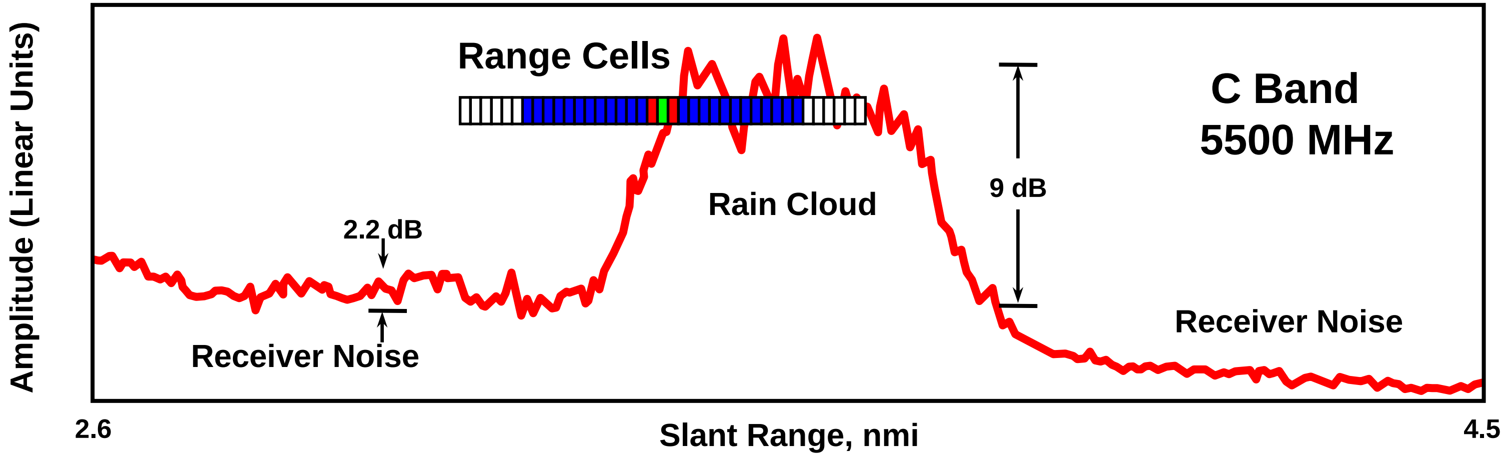
- **Nearby targets can raise threshold and suppress detection**

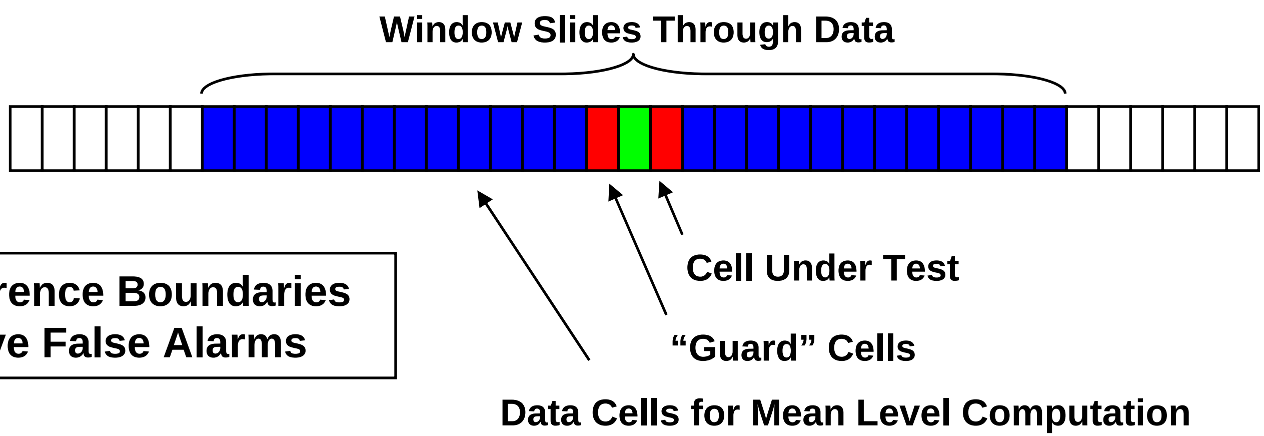
Effect of Rain on CFAR Thresholding





Effect of Rain on CFAR Thresholding

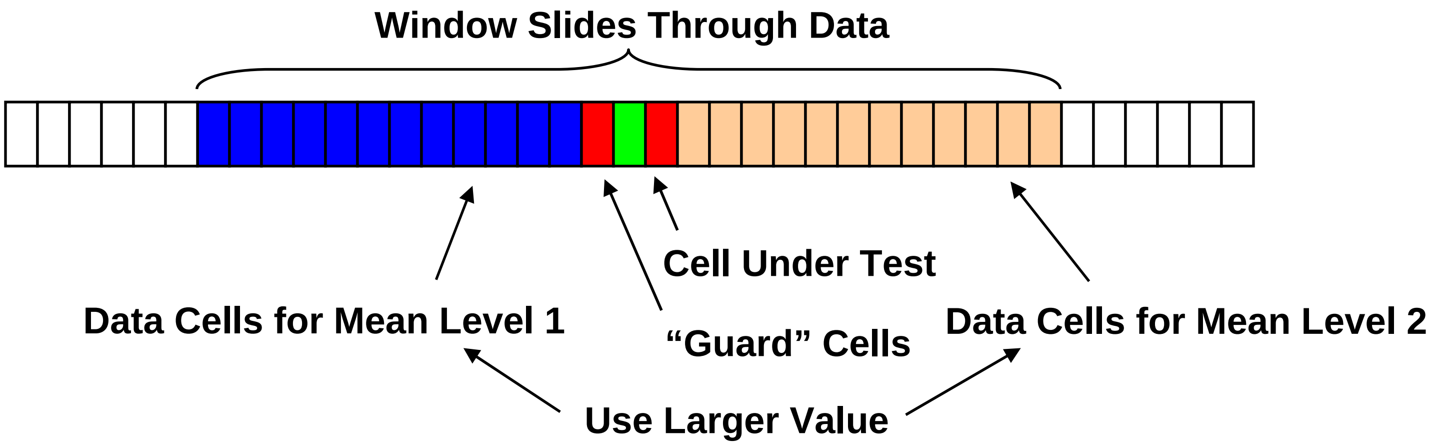




Sharp Clutter or Interference Boundaries Can Lead to Excessive False Alarms

Greatest-of Mean Level CFAR

- **Find mean value of N/2 cells before and after test cell separately**
- **Use larger noise estimate to determine threshold**



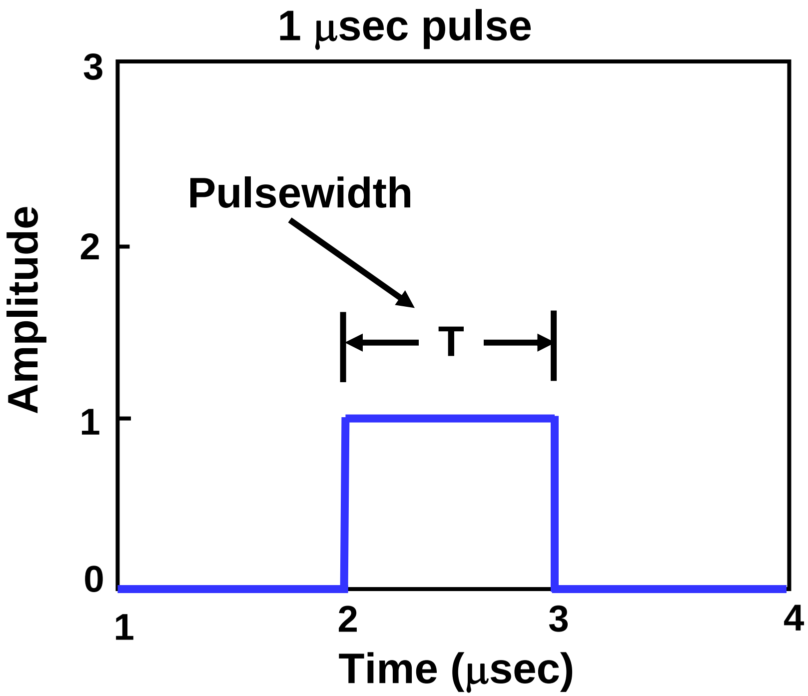
- **Helps reduce false alarms near sharp clutter or interference boundaries**
- **Nearby targets still raise threshold and suppress detection**

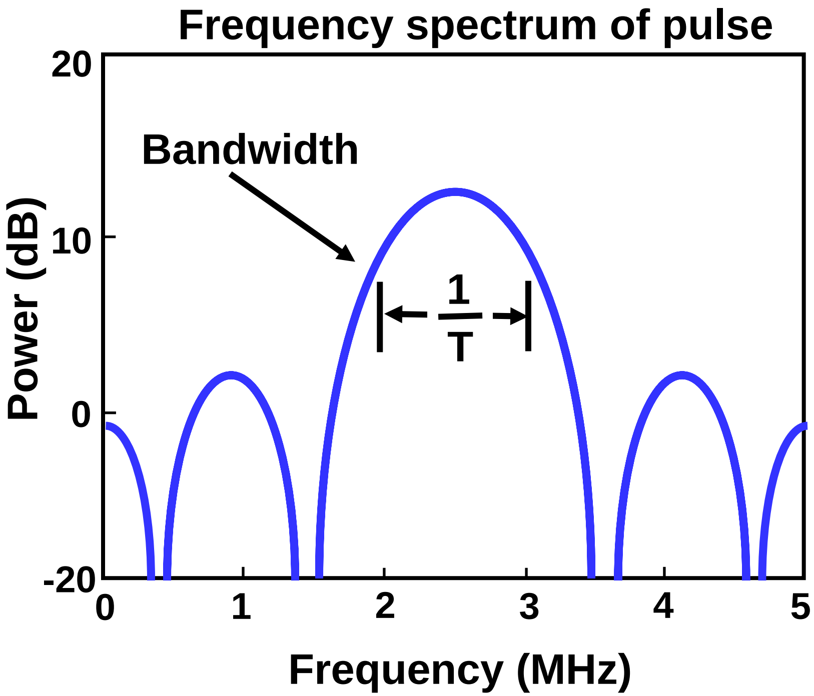
Outline

- Detection of Target Echoes in Noise
- Pulse Compression
  - Introduction
  - Phase Coded Waveforms
  - Linear Frequency Modulation Waveforms

Pulsed CW Radar Fundamentals

Range Resolution





- **Range Resolution (Δr)**
  - Proportional to pulse width (T)
  - Inversely proportional to bandwidth (B = 1/T)

    1 MHz Bandwidth => 150 m of range resolution

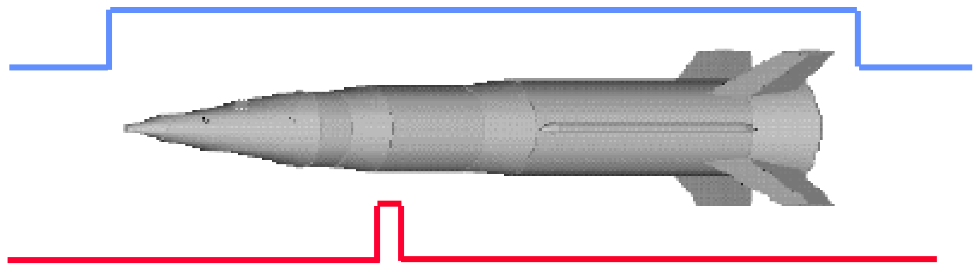
$$\Delta r = \frac{c\,T}{2}$$

$$\Delta r = \frac{c}{2B}$$

Pulse Width, Bandwidth and Resolution for a Square Pulse

Resolution: **Pulse Length is Larger than Target Length**

Cannot Resolve Features Along the Target



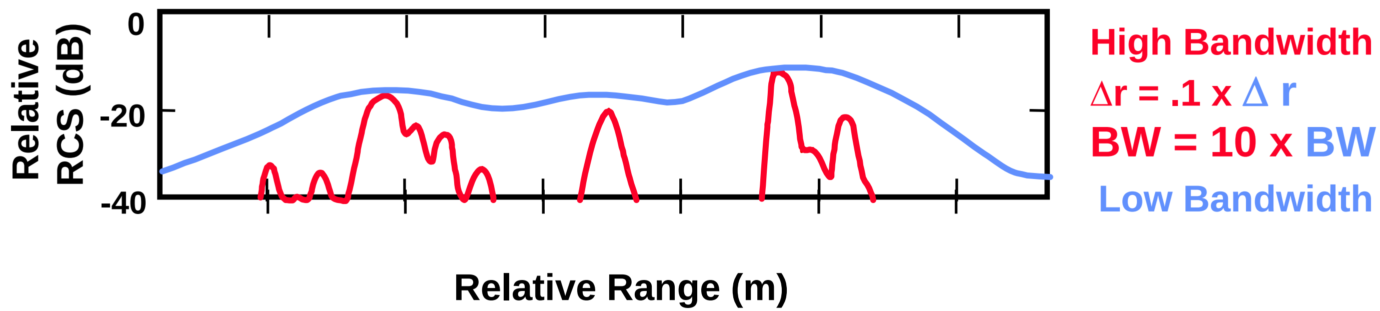
$$\Delta r = \frac{cT}{2}$$

$$\Delta r = \frac{c}{2B}$$

Pulse Length is Smaller than Target Length

Can Resolve Features Along the Target

Example :



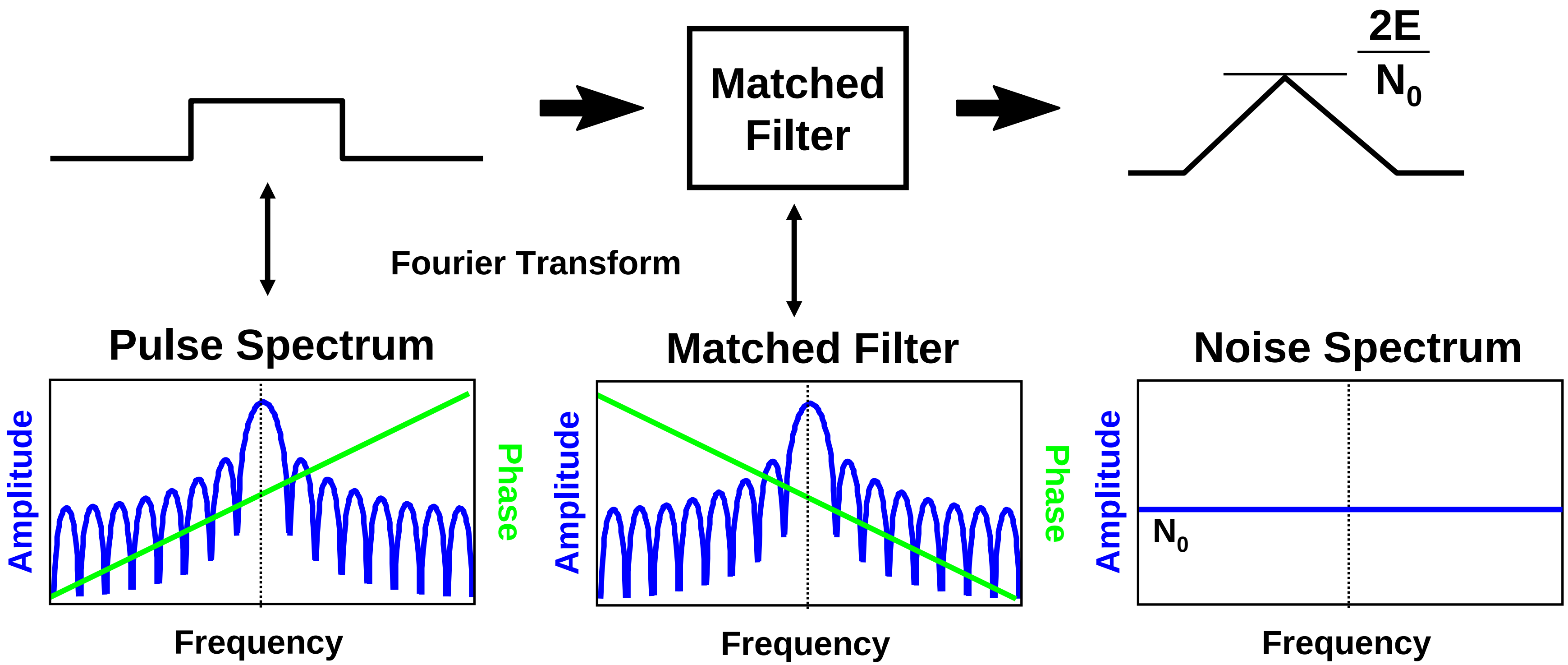
Shorter Pulses have Higher Bandwidth and Better Resolution

Motivation for Pulse Compression

- **Hard to get "good" average power and resolution at the same time using a pulsed CW system**
  - **Higher average power is proportional to pulse width**
  - **Better resolution is inversely proportional to pulse width**
- **A long pulse can have the same bandwidth (resolution) as a short pulse if the long pulse is modulated in frequency or phase**
- **These pulse compression techniques allow a radar to simultaneously achieve the energy of a long pulse and the resolution of a short pulse**

Matched Filter Concept

E = Pulse Energy (Power × Time)

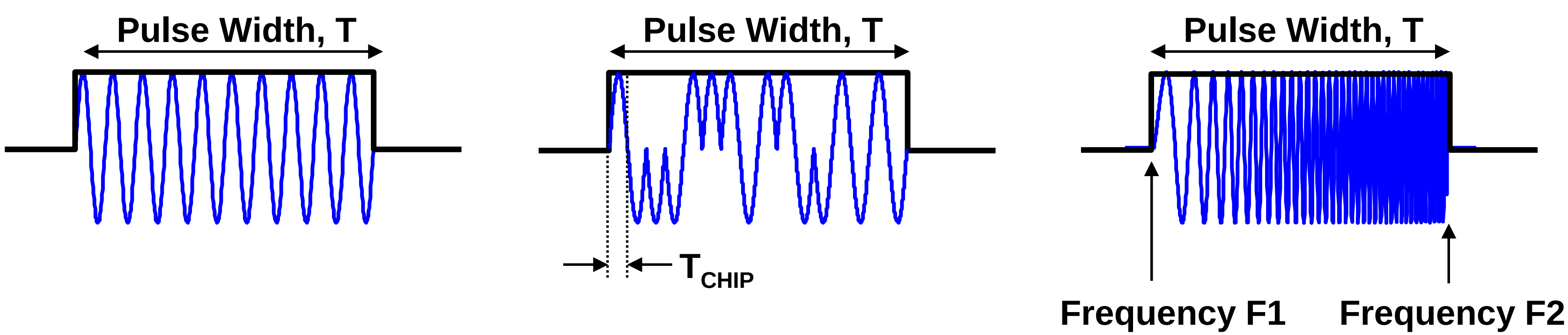


- Matched Filter maximizes the peak-signal to mean noise ratio
  - For rectangular pulse, matched filter is a simple pass band filter

Frequency and Phase Modulation of Pulses

- Resolution of a short pulse can be achieved by modulating a long pulse, increasing the time-bandwidth product
- Signal must be processed on return to "pulse compress"

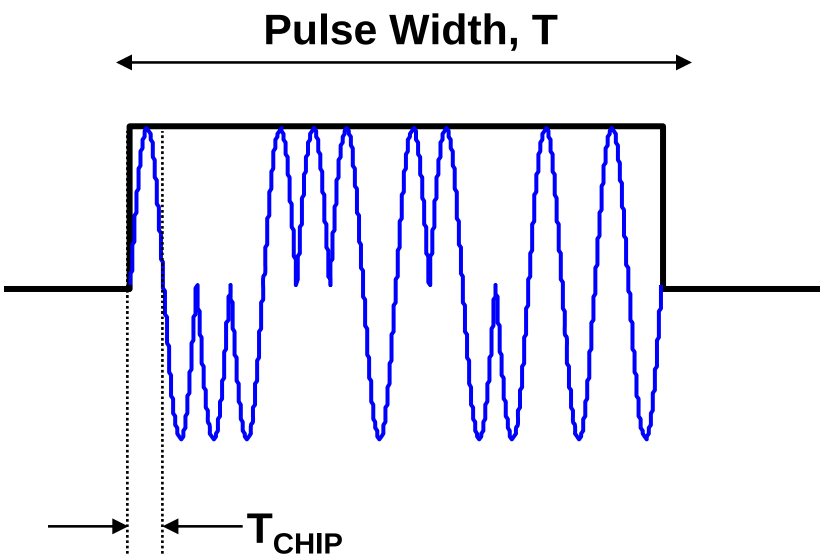
Square Pulse	Binary Phase Coded Waveform	Linear Frequency Modulated Waveform



Square Pulse	Binary Phase Coded Waveform	Linear Frequency Modulated Waveform
Bandwidth = 1/T	Bandwidth = $1/T_{CHIP}$	Bandwidth = ΔF = F2-F1
Time × Bandwidth = 1	Time × Bandwidth = T/T_{CHIP}	Time × Bandwidth = $T\Delta F$

Binary Phase Coded Waveforms

Binary Phase Coded Waveform



Bandwidth = 1/ T_{CHIP}

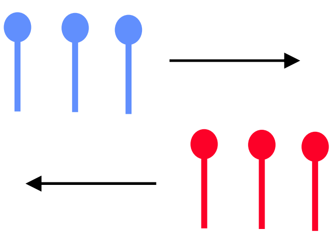
Pulse Compression Ratio = T/ T_{CHIP}

- Changes in phase can be used to increase the signal bandwidth of a long pulse
- A pulse of duration T is divided into N sub-pulses of duration T_{CHIP}
- The phase of each sub-pulse is changed or not changed, according to a binary phase code
- Phase changes 0 or π radians (+ or -)
- Pulse compression filter output will be a compressed pulse of width T_{CHIP} and a peak N times that of the uncompressed pulse

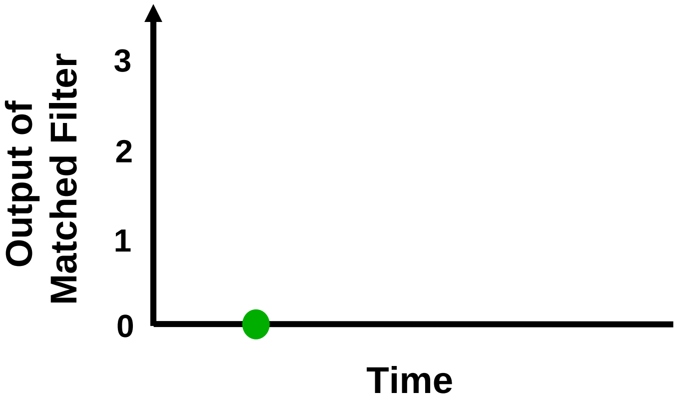
Implementation of Matched Filter

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

- **Convolution process:**
  - **Move digitized pulses by each other, in steps**
  - **When data overlaps, multiply samples and sum them up**



No overlap – Output 0



Implementation of Matched Filter

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Reflected echo **Time reversed pulse**

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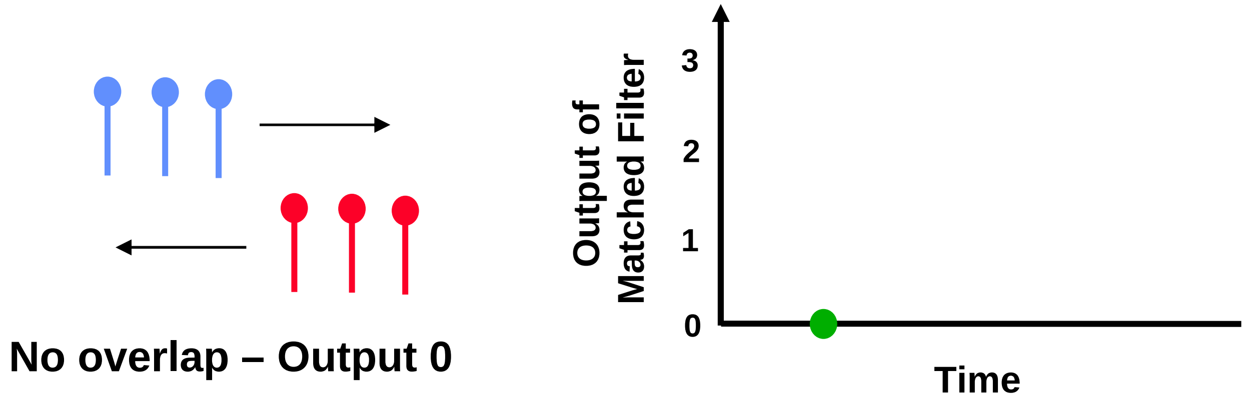

Implementation of Matched Filter

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Reflected echo   Time reversed pulse

- Convolution process:
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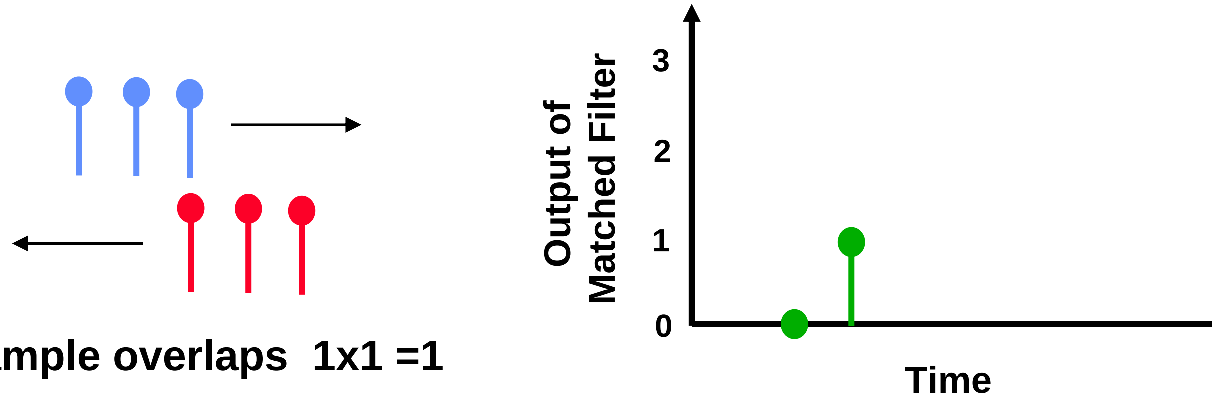
  - When data overlaps, multiply samples and sum them up



One sample overlaps 1x1 =1

Implementation of Matched Filter

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

Reflected echo **Time reversed pulse**

- **Convolution process:**
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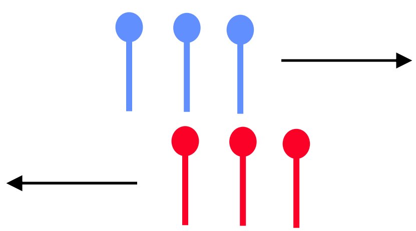
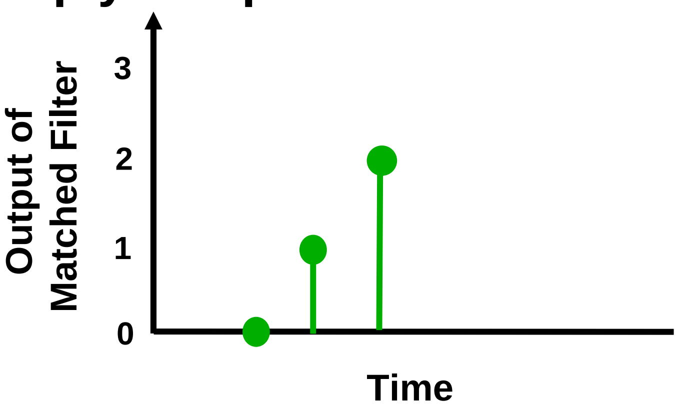




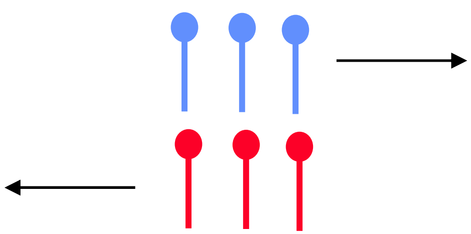
Two samples overlap (1x1) + (1x1) = 2

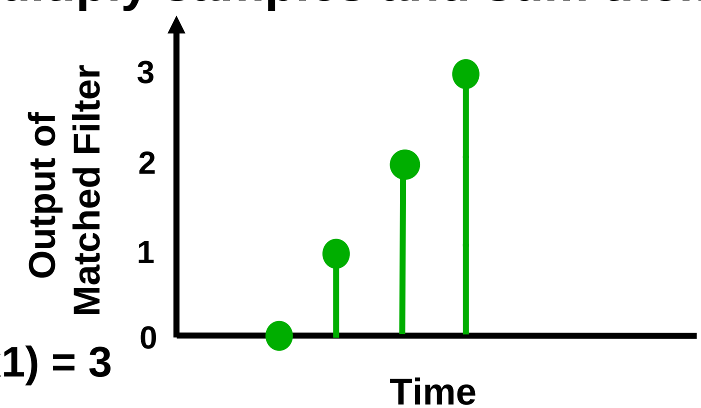
Implementation of Matched Filter

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

Reflected echo **Time reversed pulse**

- **Convolution process:**
  - **Move digitized pulses by each other, in steps**
  - **When data overlaps, multiply samples and sum them up**





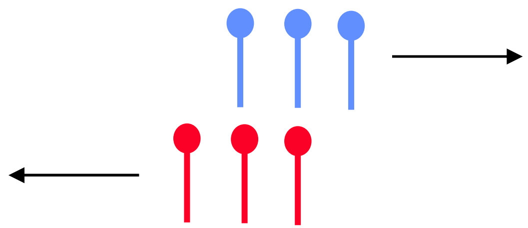
Three samples overlap (1x1) + (1x1) + (1x1) = 3

Implementation of Matched Filter

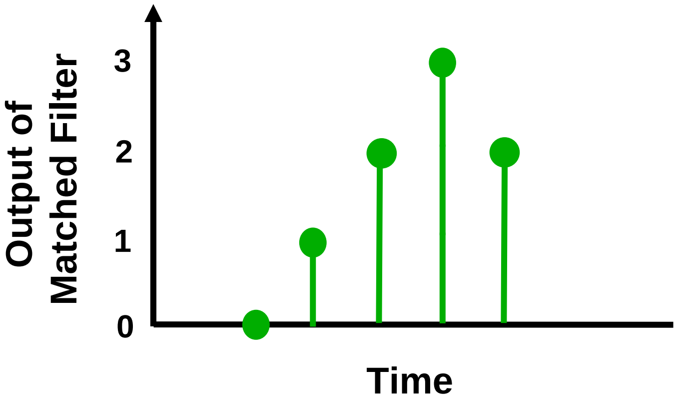
- Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse

Reflected echo   Time reversed pulse

- Convolution process:
  - Move digitized pulses by each other, in steps
  - When data overlaps, multiply samples and sum them up

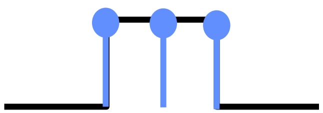


Two samples overlap (1x1) + (1x1) = 2

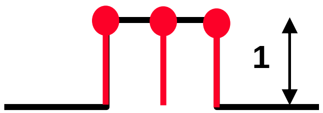


Implementation of Matched Filter

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

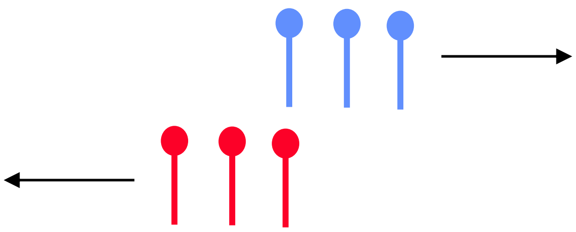


Reflected echo

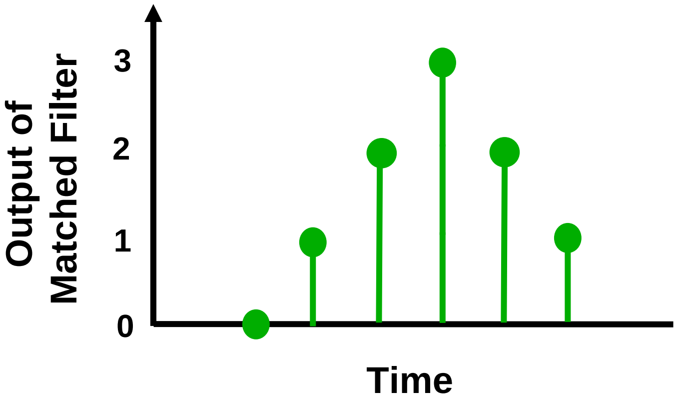


Time reversed pulse

- **Convolution process:**
  - Move digitized pulses by each other, in steps
  - When data overlaps, multiply samples and sum them up



One sample overlaps 1x1 =1

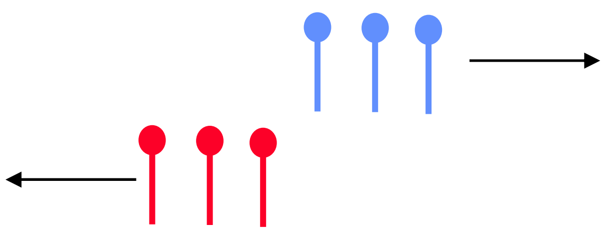


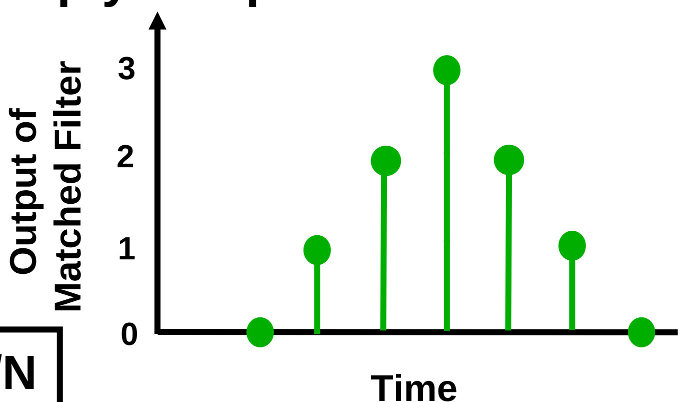
Implementation of Matched Filter

- **Matched filter is implemented by “convolving” the reflected echo with the “time reversed” transmit pulse**

Reflected echo Time reversed pulse

- **Convolution process:**
  - Move digitized pulses by each other, in steps
  - When data overlaps, multiply samples and sum them up





Use of Matched Filter Maximizes S/N

Pulse Compression

Binary Phase Modulation Example

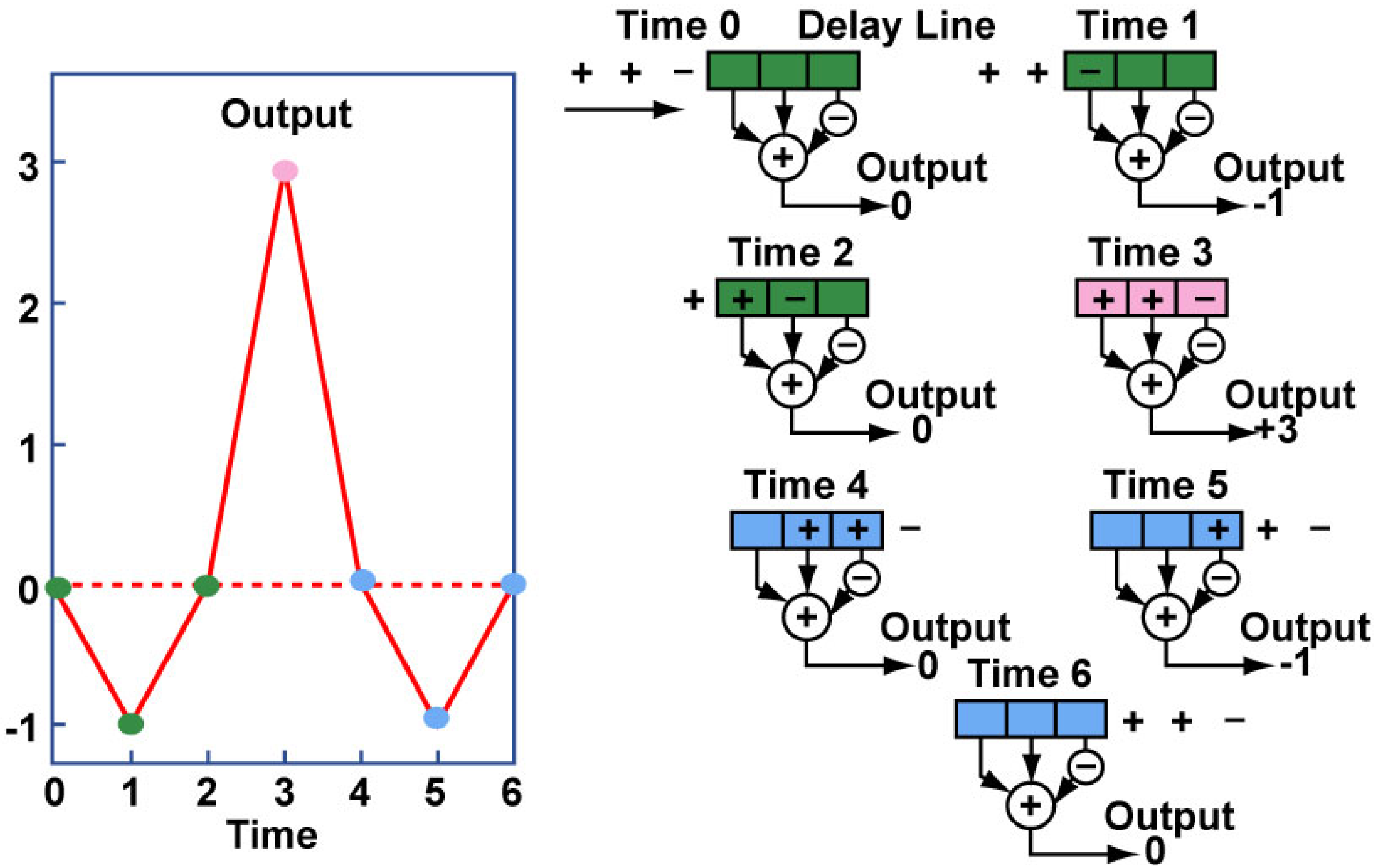
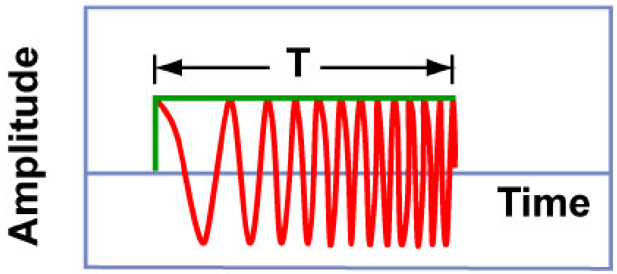


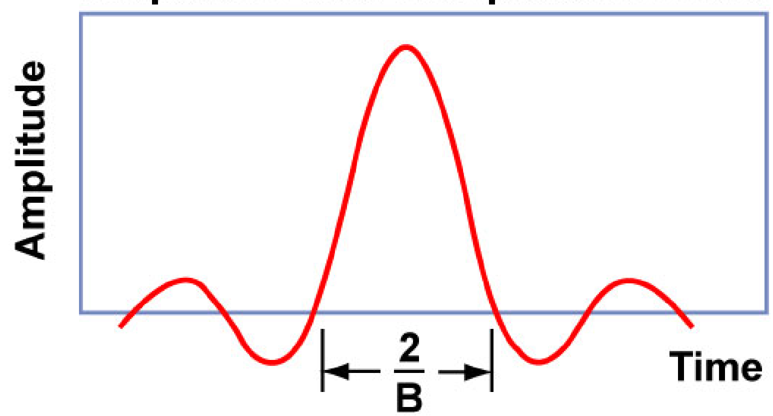
Figure by MIT OCW.

Linear FM Pulse Compression

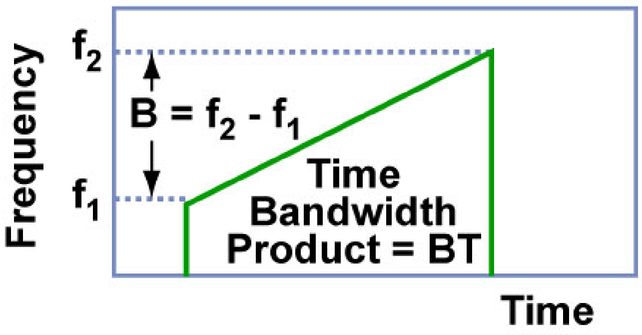
Linear FM waveform



Output of Pulse Compression Filter



Frequency of transmitted pulse as a function of time



Because range is measured by a shift in Doppler frequency, there is a coupling of the range and Doppler velocity measurement

Figure by MIT OCW.

Summary

- **Detection of Targets in Noise**
  - Both target properties and radar design features affect the ability to detect signals in noise
  - Coherent and non-coherent integration pulse integration can improve target detection
  - Adaptive thresholding (CFAR) techniques are needed in realistic environments
- **Pulse compression offers a means to simultaneous have high average power and good resolution**
  - A long pulse can have the same bandwidth (resolution) as a short pulse, if it is modulated in frequency or phase
  - Phase-encoded pulse compression divides long pulses into binary encoded sub-pulses
  - With frequency-encoded pulse compression, the radar frequency is increased linearly as the pulse is transmitted

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Toomay, J. C., Radar Principles for the Non-Specialist, New York, Van Nostrand Reinhold, 1989

Introduction to Radar Systems

Radar Antennas

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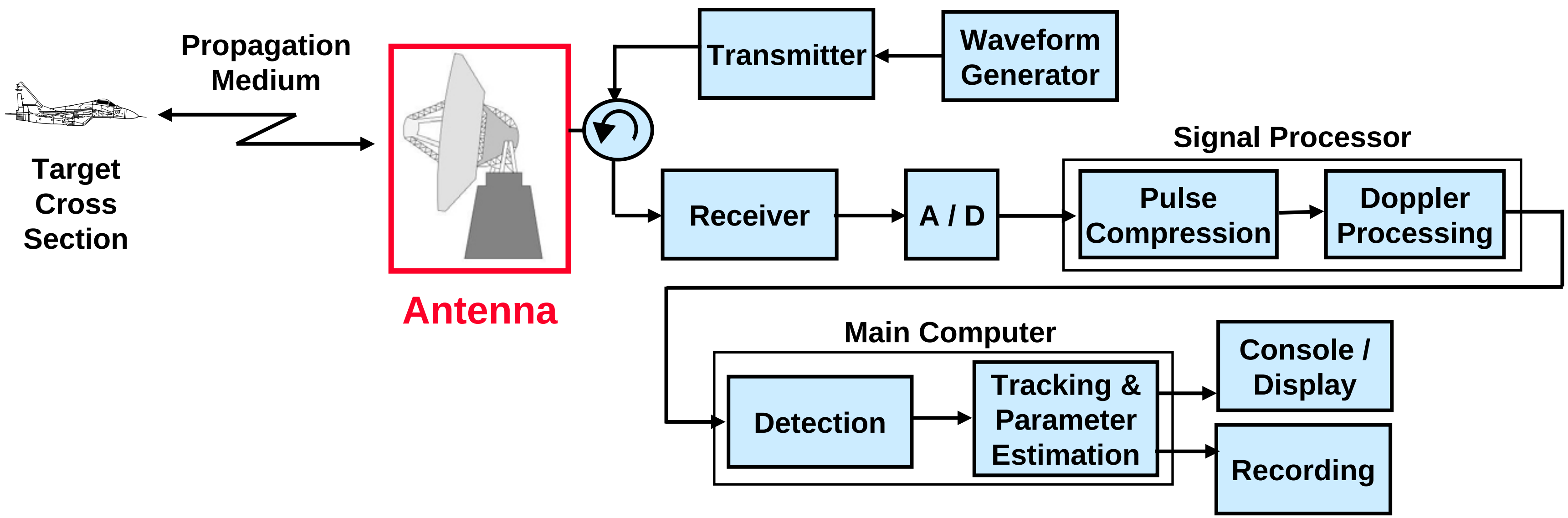
Focus



Track Radar Equation

$$S/N = \frac{P_t\, G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k\, T_s\, B_n\, L}$$

Search Radar Equation

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

G = Gain

A_e = Effective Area

This Lecture

T_s = System Noise Temperature

L = Losses

Radar Equation Lecture

Antenna Definition

- "Means for radiating or receiving radio waves"*
  – A radiated electromagnetic wave consists of electric and magnetic fields which jointly satisfy Maxwell's Equations
- Transitional structure between guiding device and free space

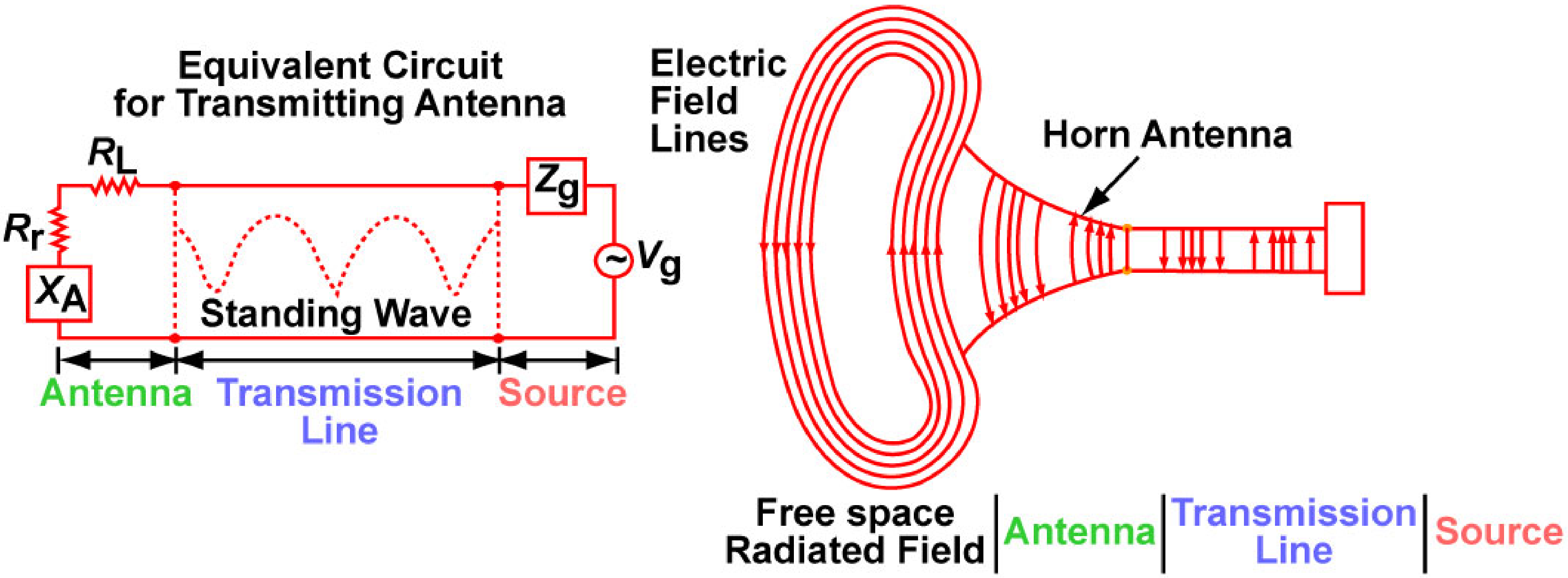
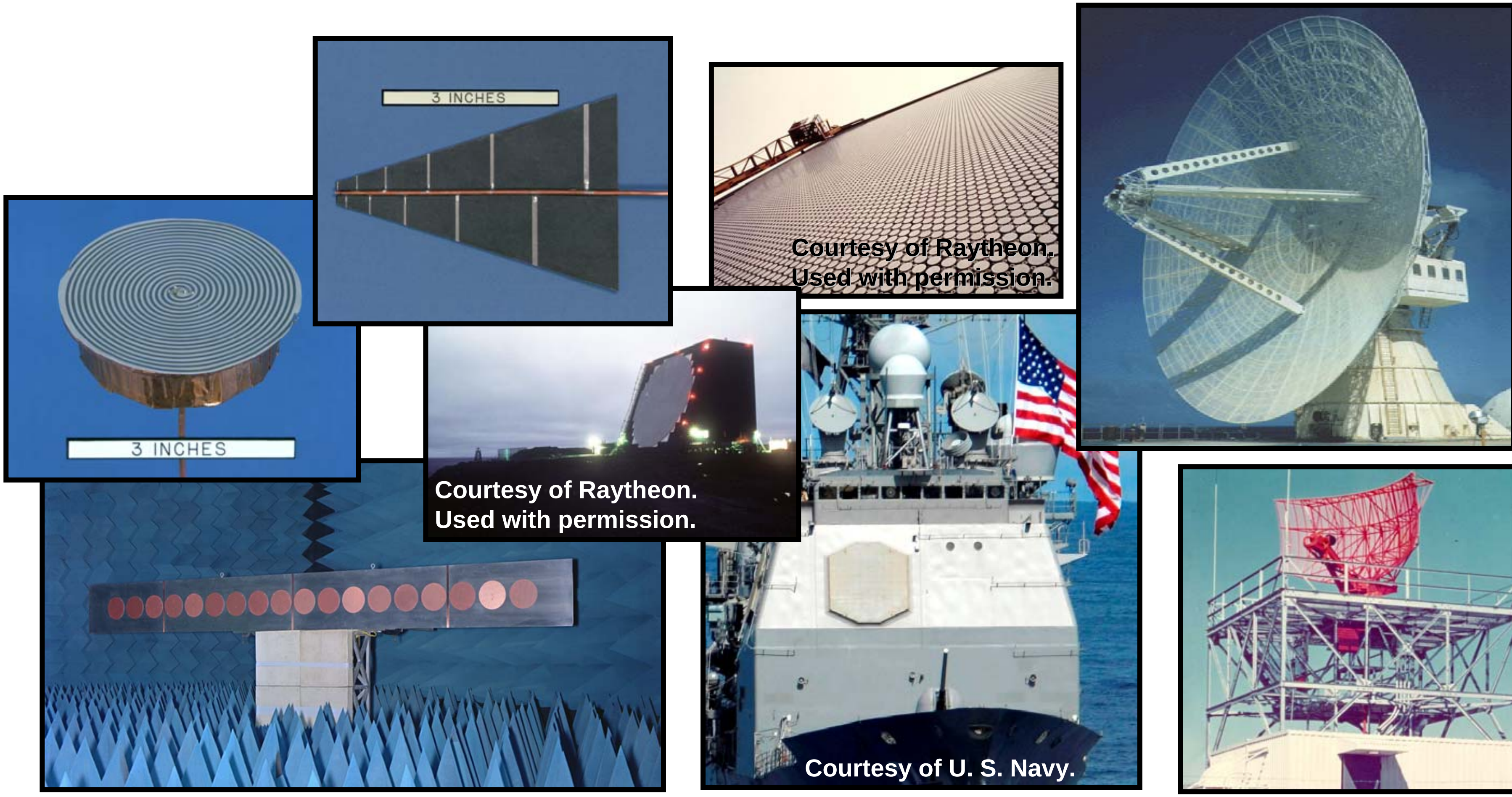


Figure by MIT OCW.

* IEEE Standard Definitions of Terms for Antennas (IEEE STD 145-1983)

Antenna Characteristics

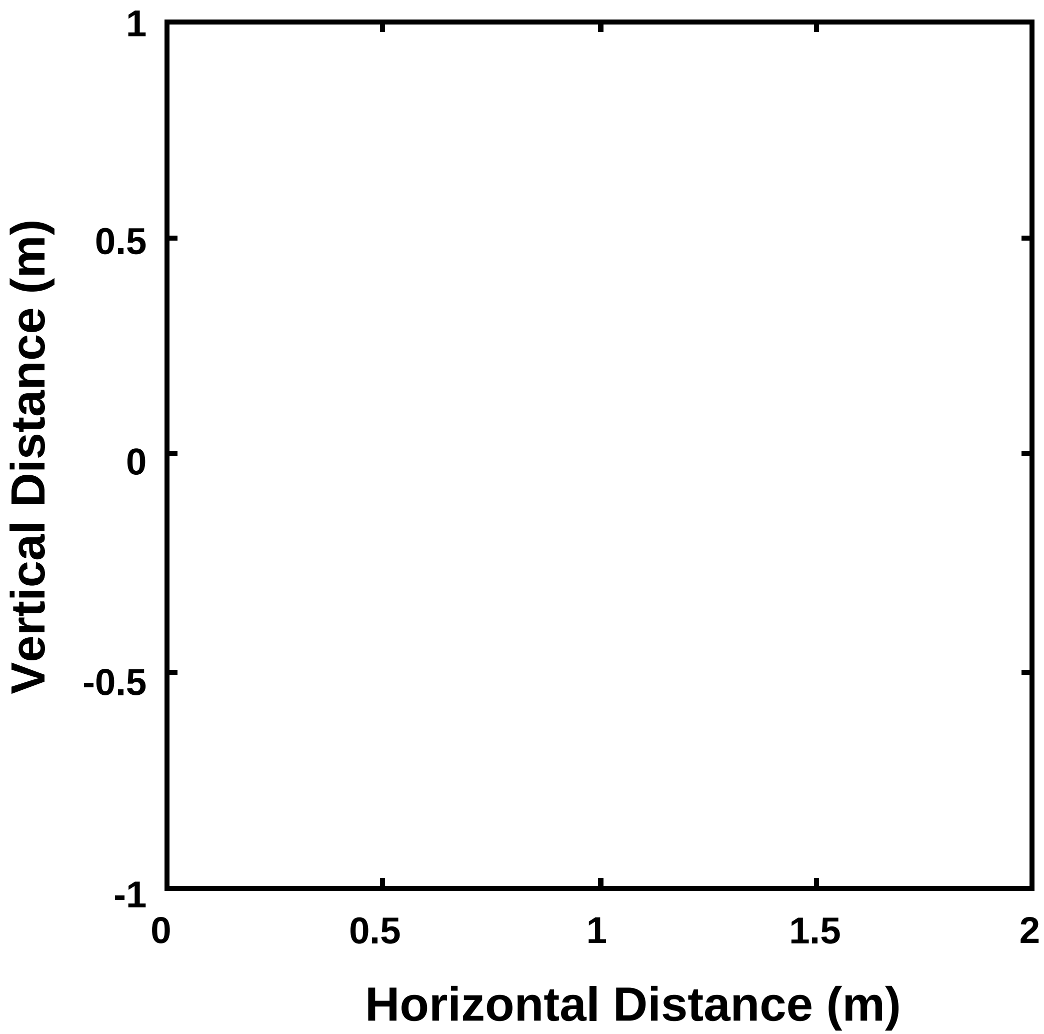
- **Accentuates radiation in some directions, suppresses in others**
- **Designed for both directionality and maximum energy transfer**



Outline

- Introduction
- Fundamental antenna concepts
- Reflector antennas
- Phased array antennas
- Summary

Radiation

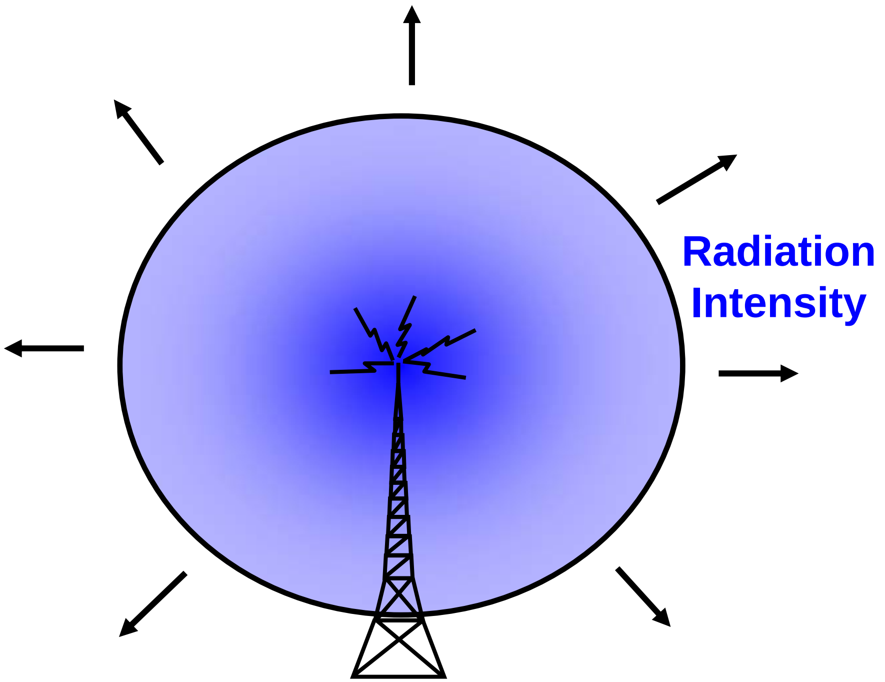


Dipole*

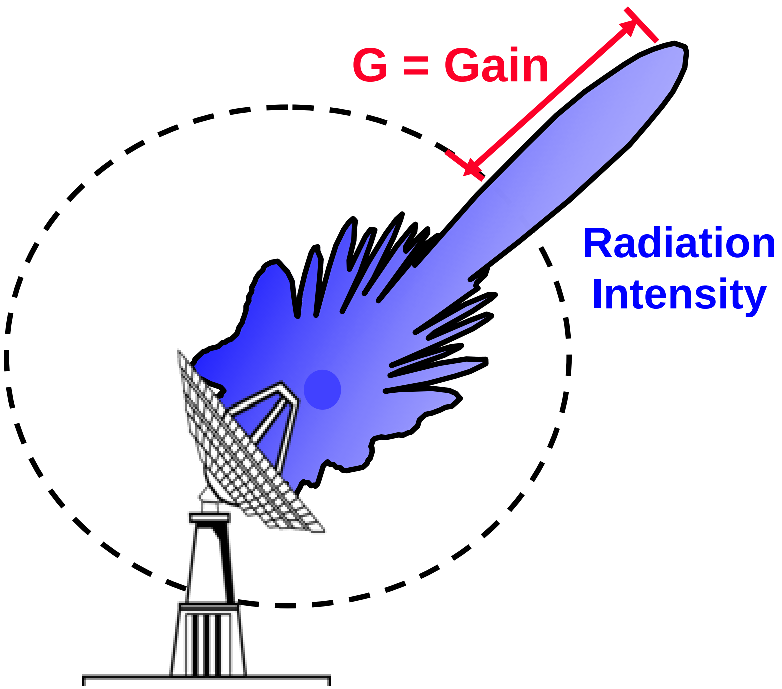
*driven by oscillating source

Antenna Gain

Isotropic Antenna



Directional Antenna



- **Same power is radiated**
- **Radiation intensity is power density over sphere (watt/steradian)**
- **Gain is radiation intensity over that of an isotropic source**

Antenna Pattern

- Pattern is a plot of gain versus angle
- Dipole example

$$G(\theta) = 1.643\left[\frac{\cos^2\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta}\right]$$

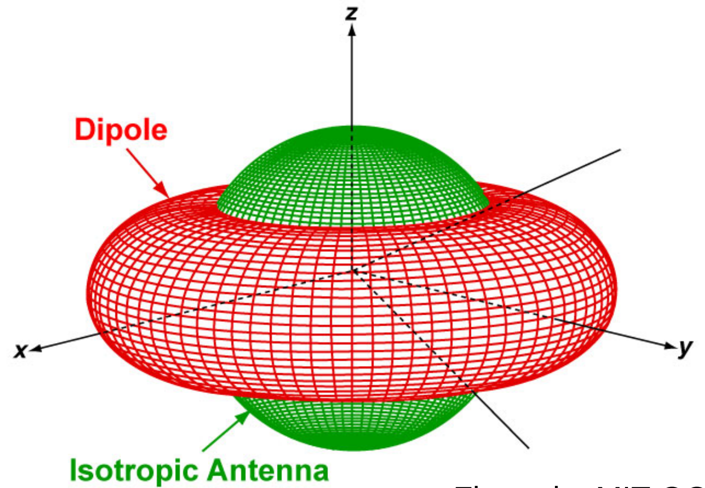
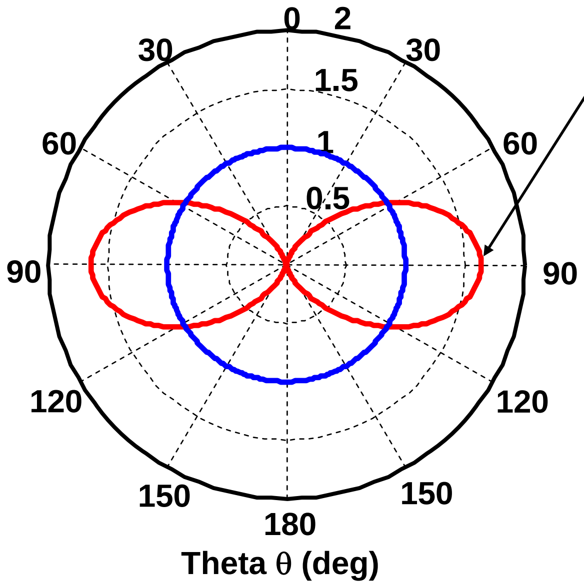


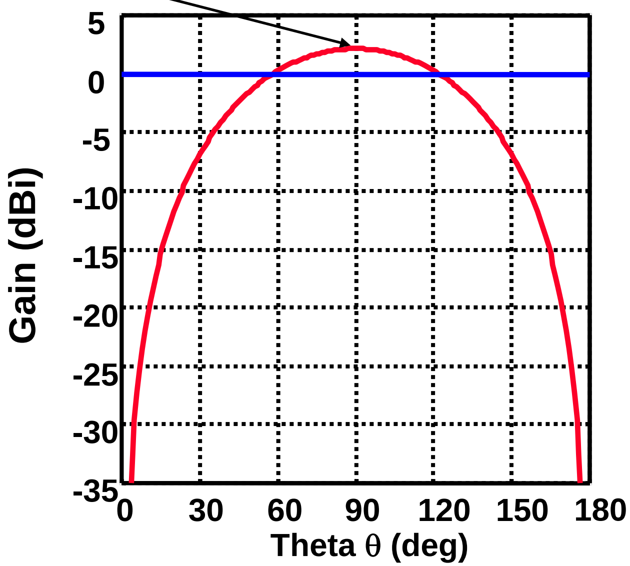
Figure by MIT OCW.

G_{max} = 1.64 = 2.15 dBi

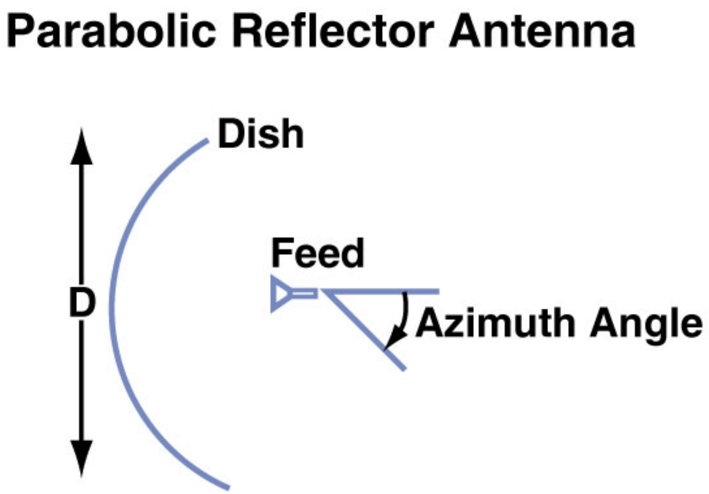
Polar Plot



Linear Plot



Antenna Pattern Characteristics



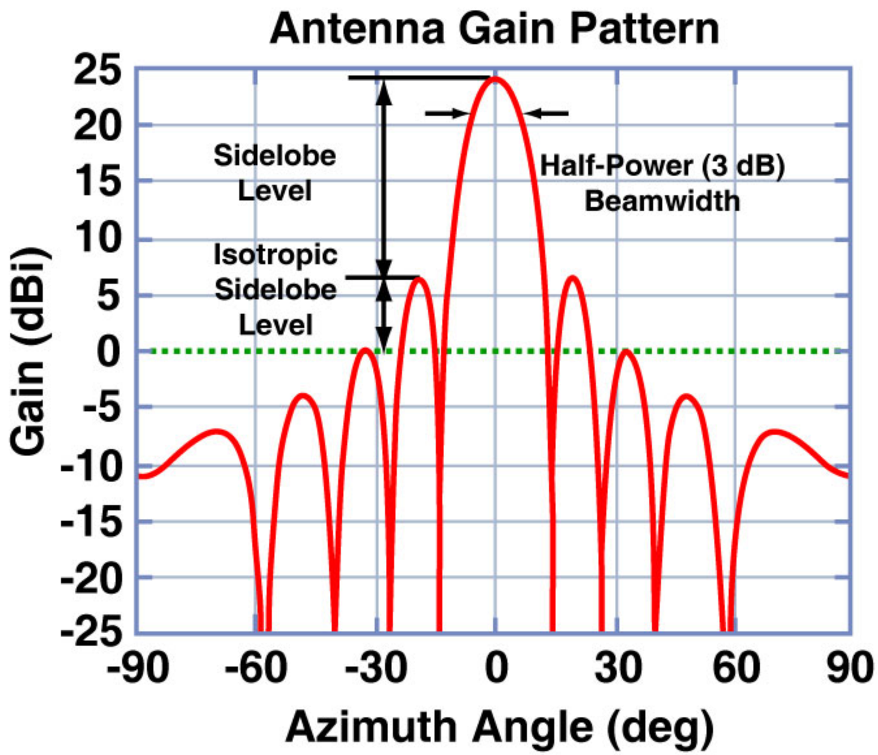


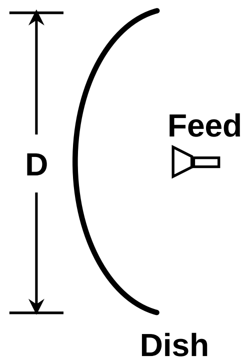
Figure by MIT OCW.

Aperture diameter D: 5 m
Frequency: 300 MHz
Wavelength: 1 m

Gain: 24 dBi
Isotropic Sidelobe Level: 6 dBi
Sidelobe Level: 18 dB
Half-Power Beamwidth: 12 deg

Effect of Aperture Size on Gain

Parabolic Reflector Antenna

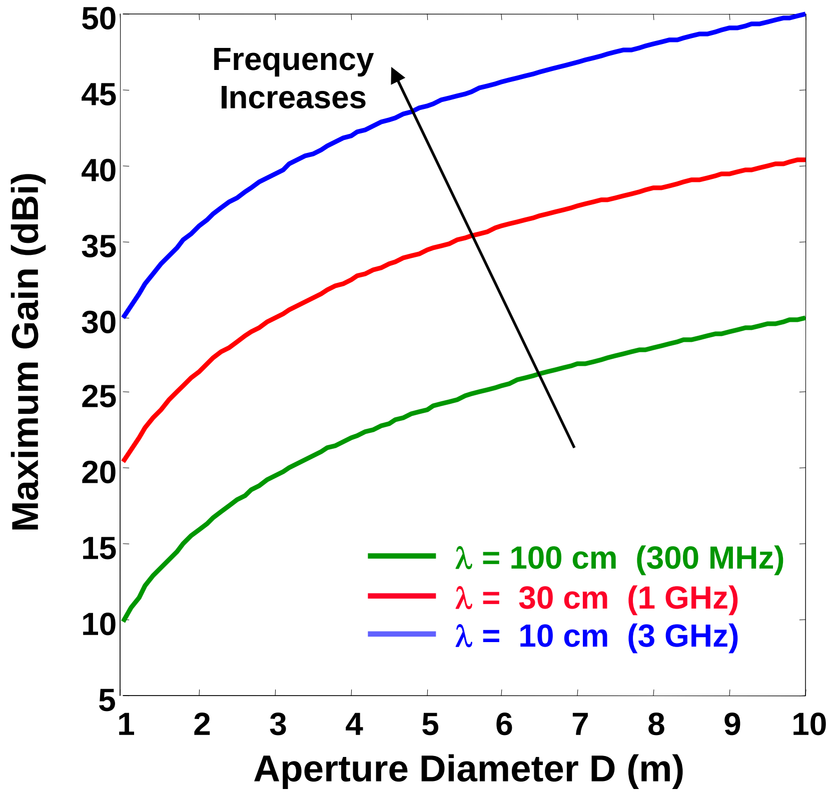


$$\text{Gain} = \frac{4\pi A_e}{\lambda^2}$$ ← Effective Area

$$\cong \frac{4\pi A}{\lambda^2}$$ ← Rule of Thumb (Best Case)

$$= \left(\frac{\pi D}{\lambda}\right)^2$$

Gain vs Diameter



Gain increases as aperture becomes electrically larger (diameter is a larger number of wavelengths)

Reflector Comparison
Kwajalein Missile Range Example

ALTAIR
45.7 m diameter

scale by 1/3

MMW
13.7 m diameter

Operating frequency: 162 MHz (VHF)
Wavelength λ: 1.85 m

Diameter electrical size: 25 λ

Gain: 34 dB
Beamwidth: 2.8 deg

Operating frequency: 35 GHz (Ka)
Wavelength λ: 0.0086 m

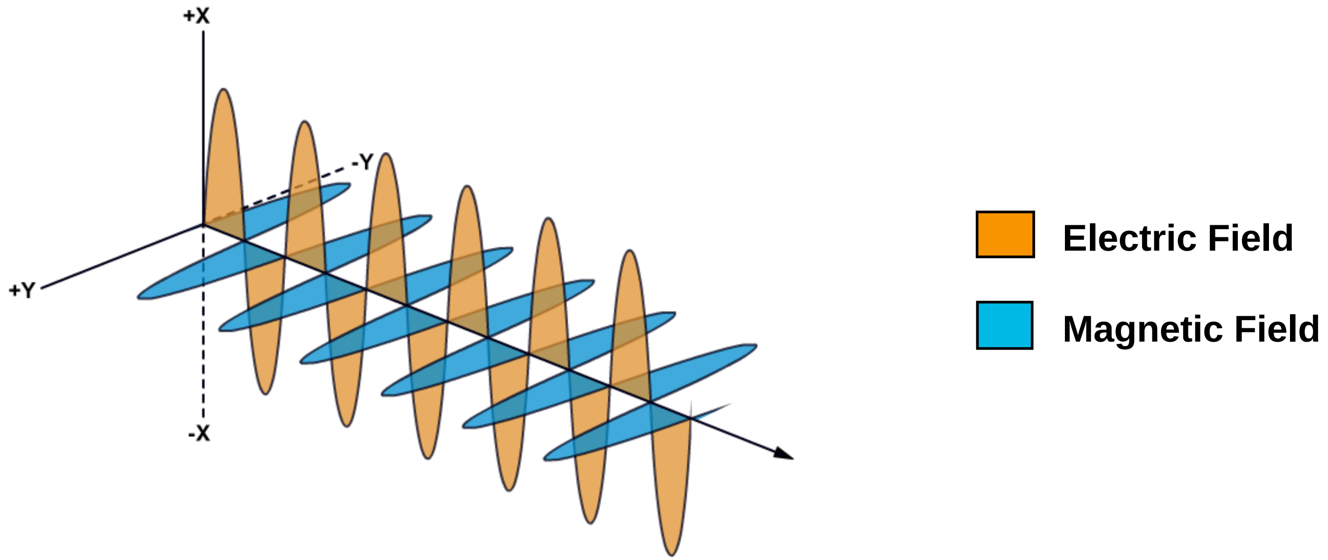
Diameter electrical size: 1598 λ

Gain: 70 dB
Beamwidth: 0.00076 deg

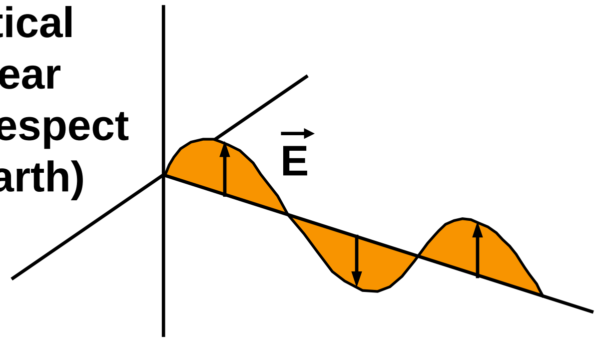
Polarization

- **Defined by behavior of the electric field vector as it propagates in time**

Electromagnetic Wave

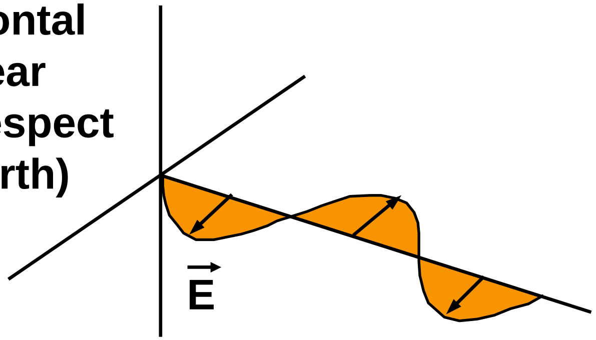


Vertical Linear (with respect to Earth)



(For over-water surveillance)

Horizontal Linear (with respect to Earth)



(For air surveillance looking upward)

Circular Polarization (CP)

- “Handed-ness” is defined by observation of electric field along propagation direction
- Used for discrimination, polarization diversity, rain mitigation

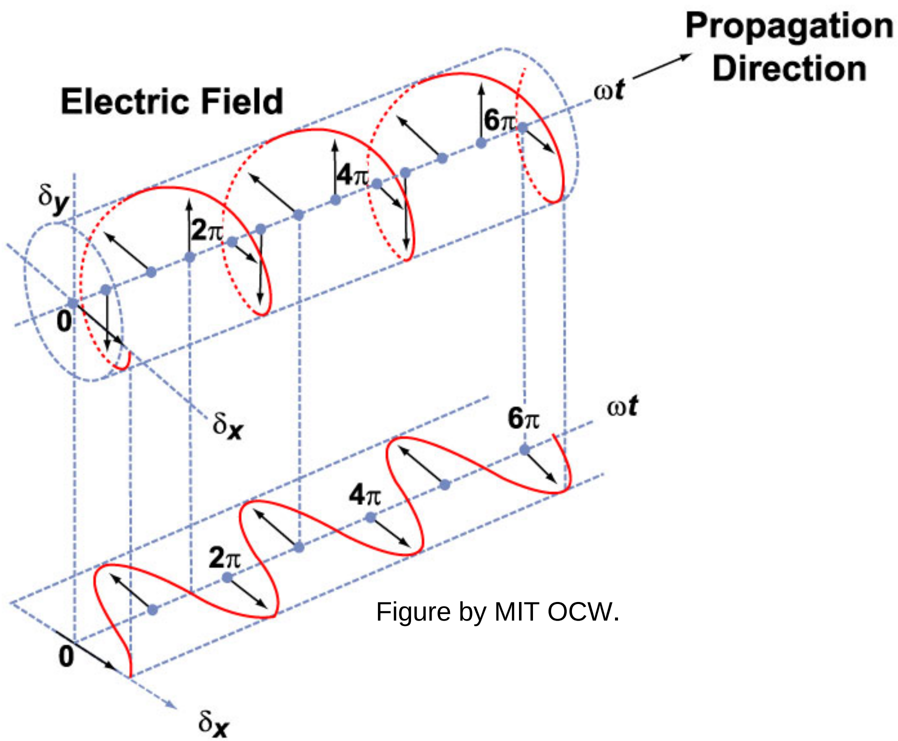
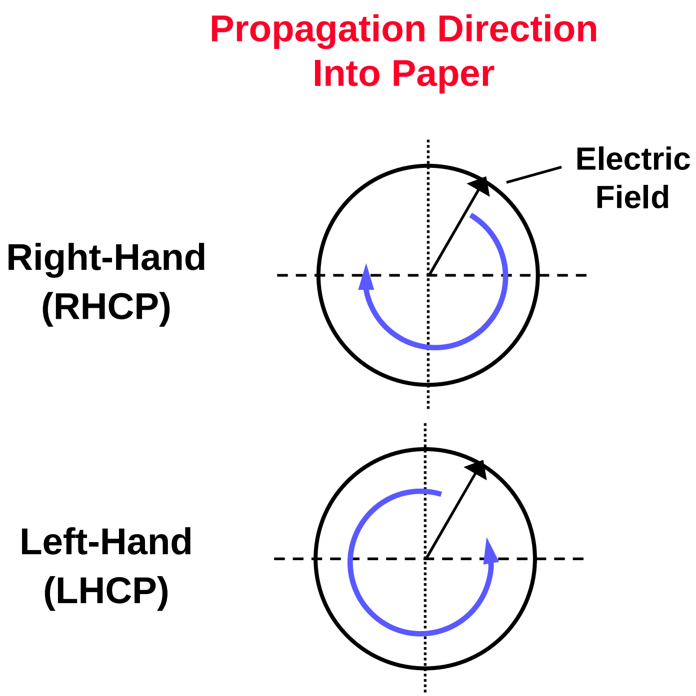


Figure by MIT OCW.



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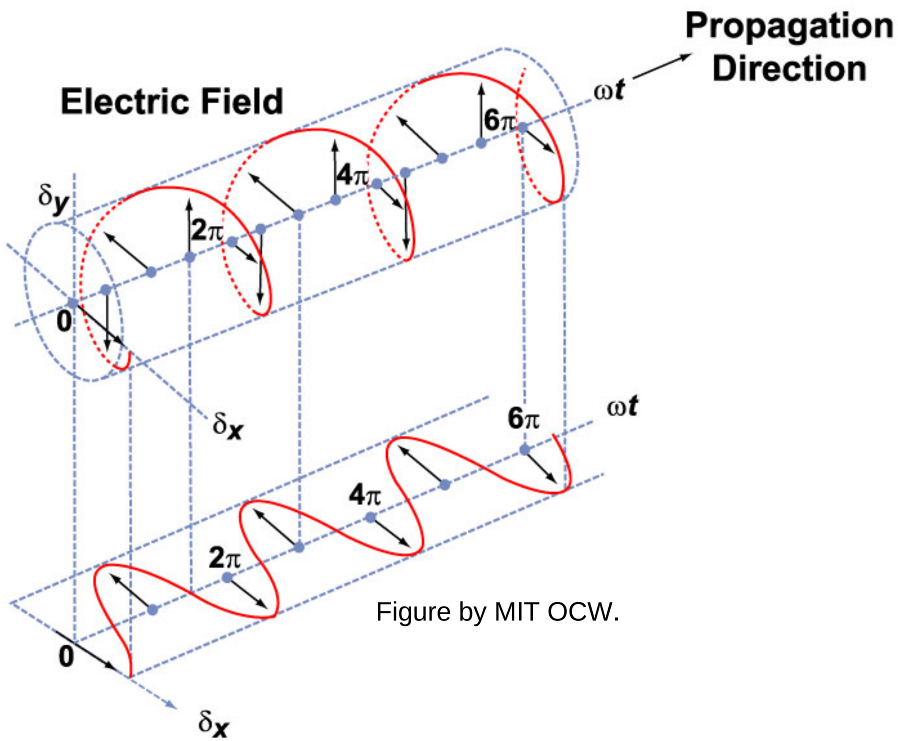
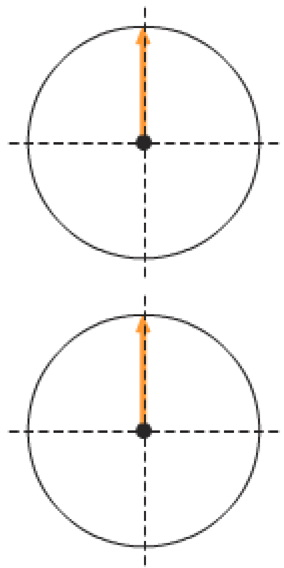


Figure by MIT OCW.

Propagation Direction Into Paper

Right-Hand (RHCP)

Left-Hand (LHCP)



Electric Field

Field Regions

Reactive Near-Field Region

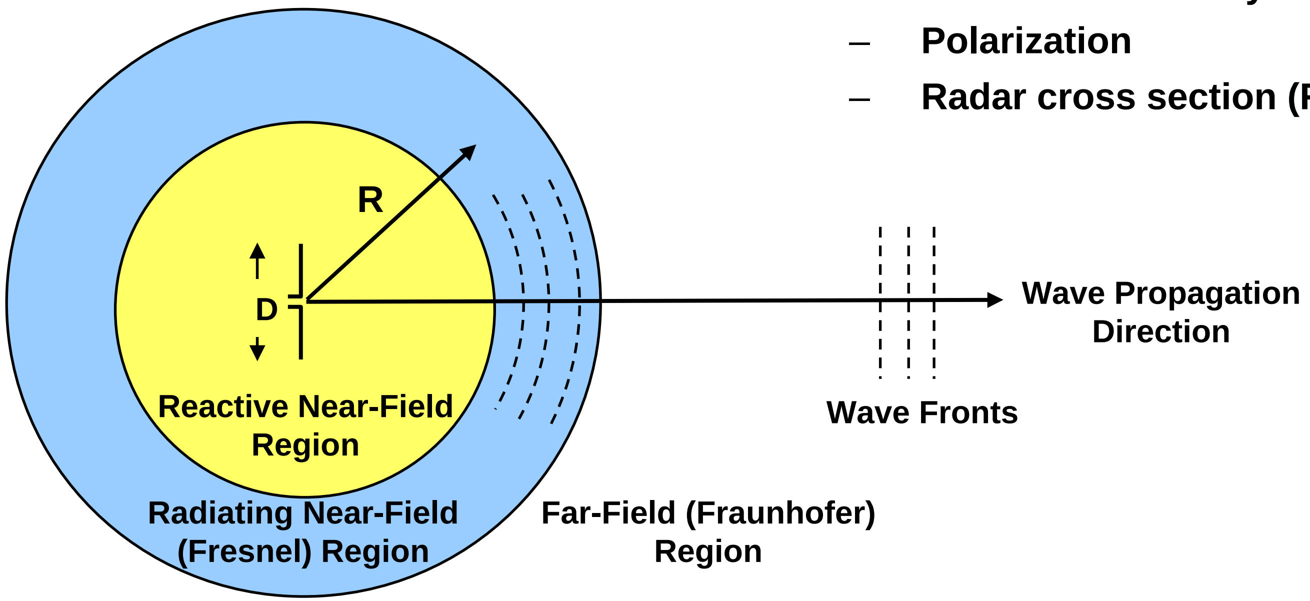
$$R < 0.62\sqrt{D^3/\lambda}$$

- Energy is stored in vicinity of antenna
- Near-field antenna quantities
  - Input impedance
  - Mutual coupling

Far-field (Fraunhofer) Region

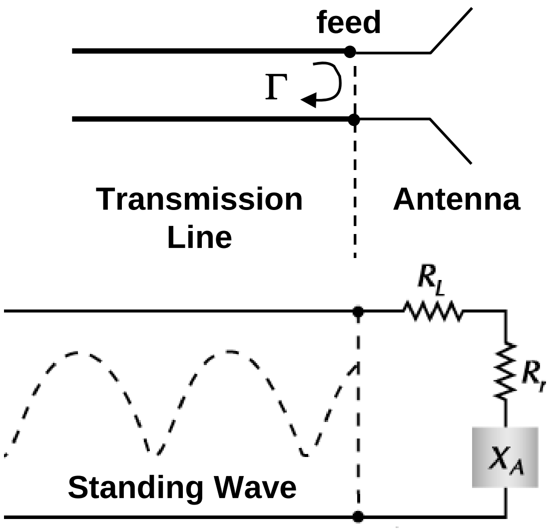
$$R > 2D^2/\lambda$$

- All power is radiated out
- Radiated wave is a plane wave
- Far-field antenna quantities
  - Pattern
  - Gain and directivity
  - Polarization
  - Radar cross section (RCS)



Antenna Input Impedance

- Antenna can be modeled as an impedance
  - Ratio of voltage to current at feed port
- Design antenna to maximize power transfer from transmission line
  - Reflection of incident power sets up standing wave
- Input impedance usually defines antenna bandwidth



$\Gamma = 0$	Incident Power is Delivered to Antenna
$\Gamma = 1$	All Incident Power is Reflected

Outline

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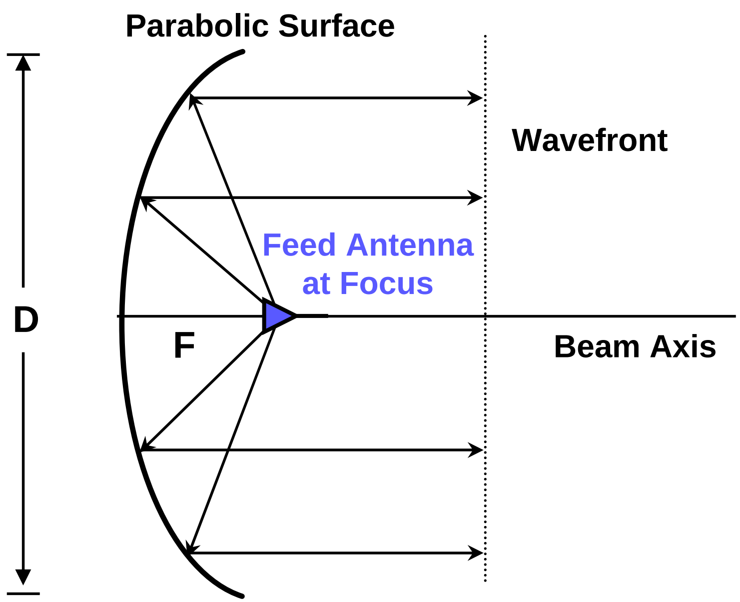
Parabolic Reflector Antenna



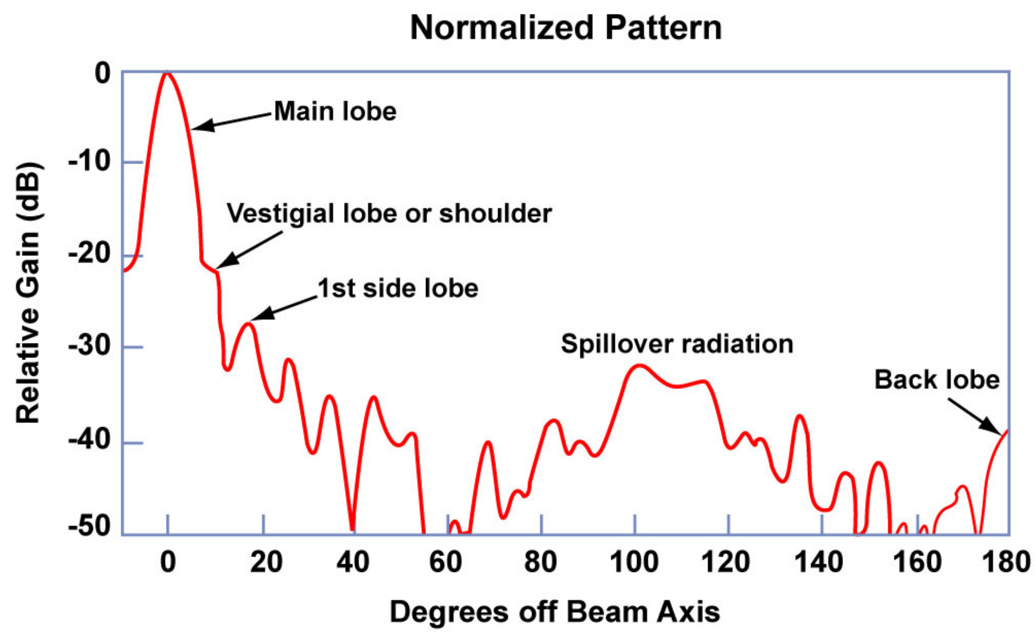


Figure by MIT OCW.

- **Design is a tradeoff between maximizing dish illumination and limiting spillover**
- **Feed antenna choice is critical**

Cassegrain Reflector Antenna

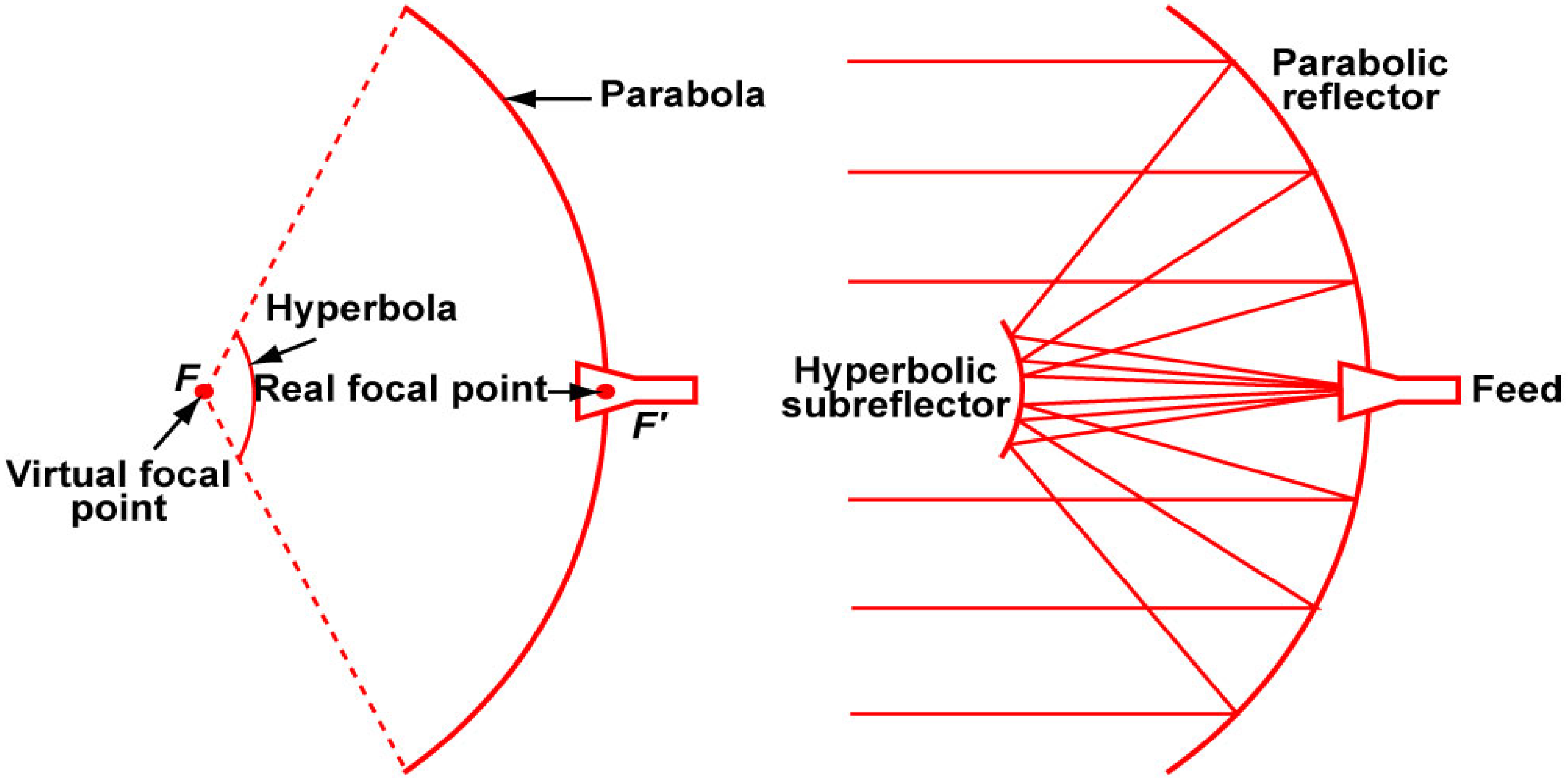


Figure by MIT OCW.

Geometry of Cassegrain Antenna

Ray Trace of Cassegrain Antenna

ALTAIR

Dual frequency

VHF Parabolic

UHF Cassegrain

FSS (Frequency Selective Surface) used for reflector

Outline

- Introduction
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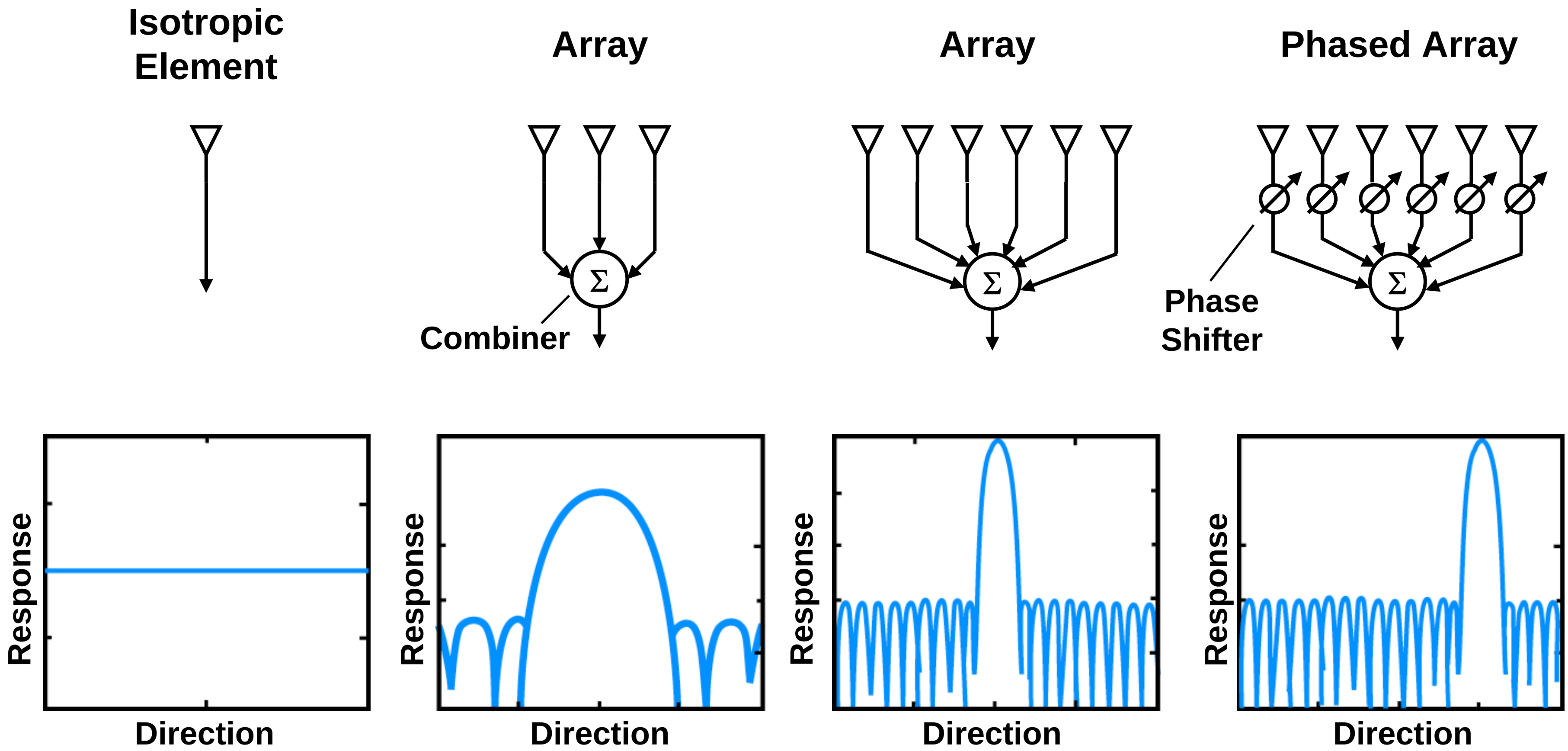
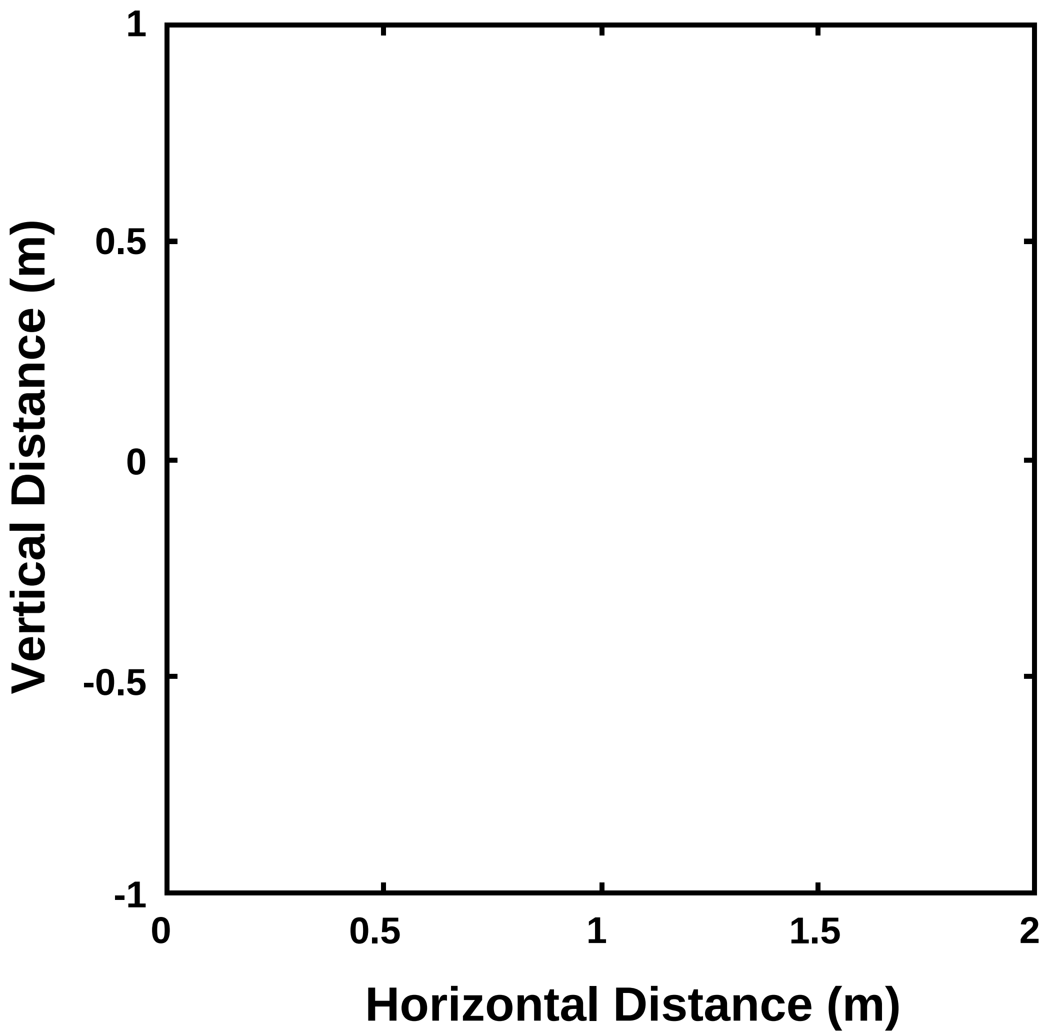
- Multiple antennas combined to enhance radiation and shape pattern



Two Antennas Radiating

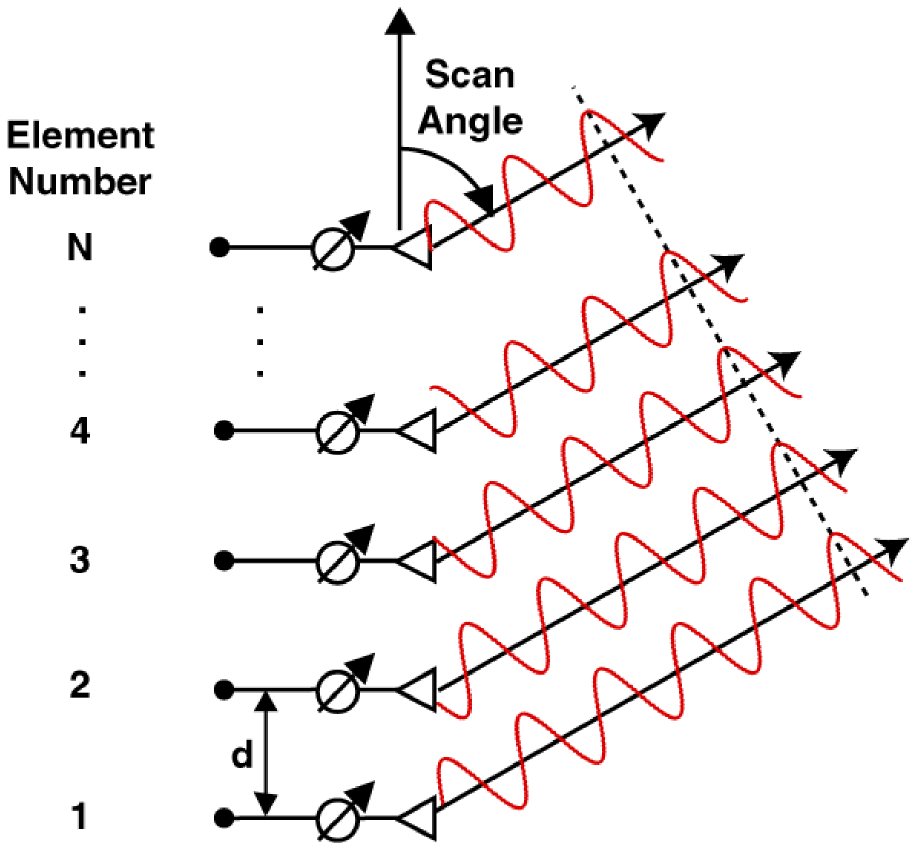
Dipole 1*

Dipole 2*



*driven by oscillating sources (in phase)

Array Controls



- **Geometrical configuration**
  - Linear, rectangular, triangular, circular grids
- **Element separation**
- **Phase shifts**
- **Excitation amplitudes**
  - For sidelobe control
- **Pattern of individual elements**
  - Isotropic, dipoles, etc.

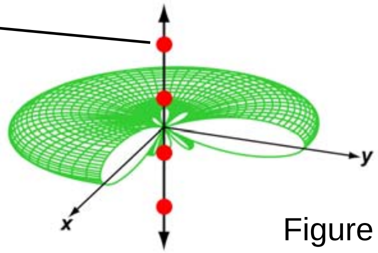
Increasing Array Size by Adding Elements

Linear Broadside Array

Isotropic Elements

λ/2 Separation

No Phase Shifting



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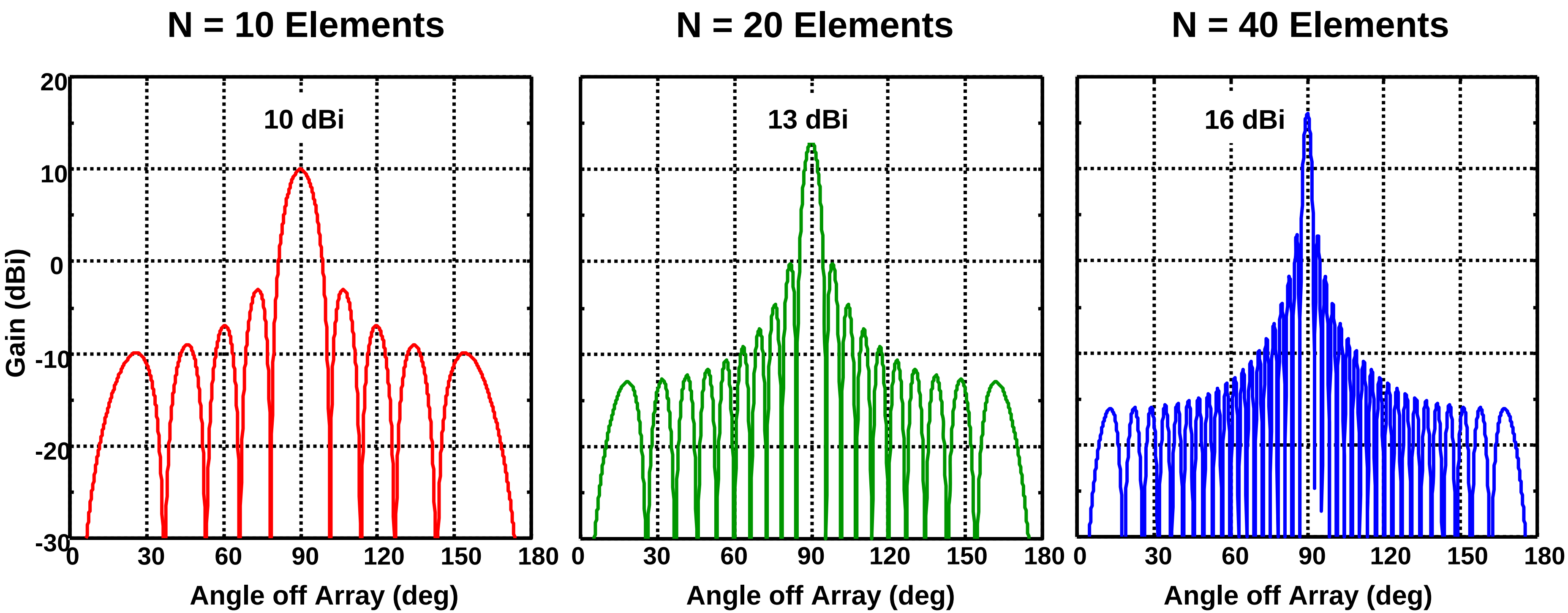


- Gain ~ 2N(d / λ) for long broadside array

Increasing Array Size by Separating Elements

- Linear Broadside Array
- N = 10 Isotropic Elements
- No Phase Shifting

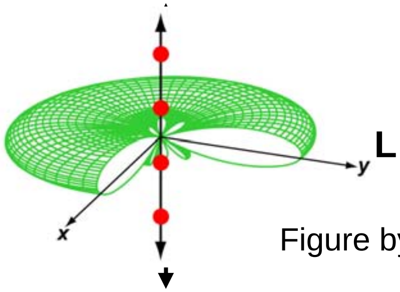
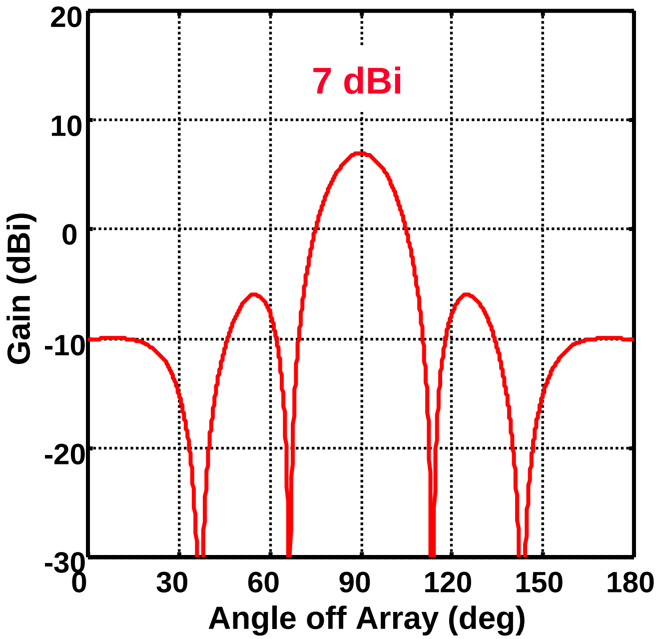
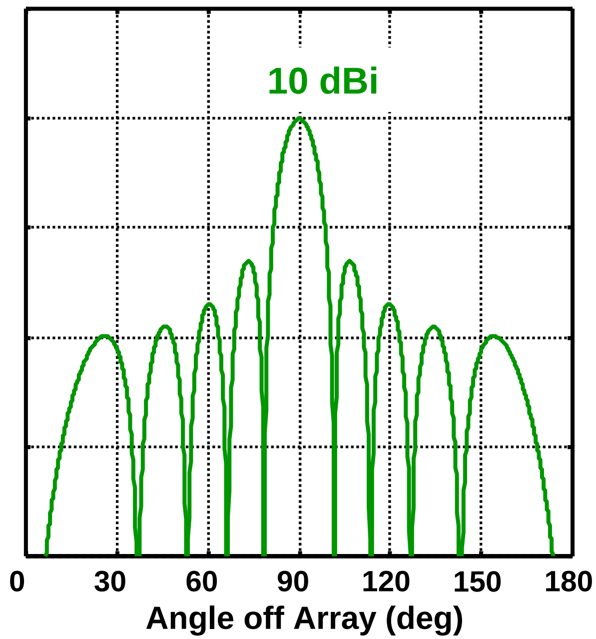


Figure by MIT OCW.

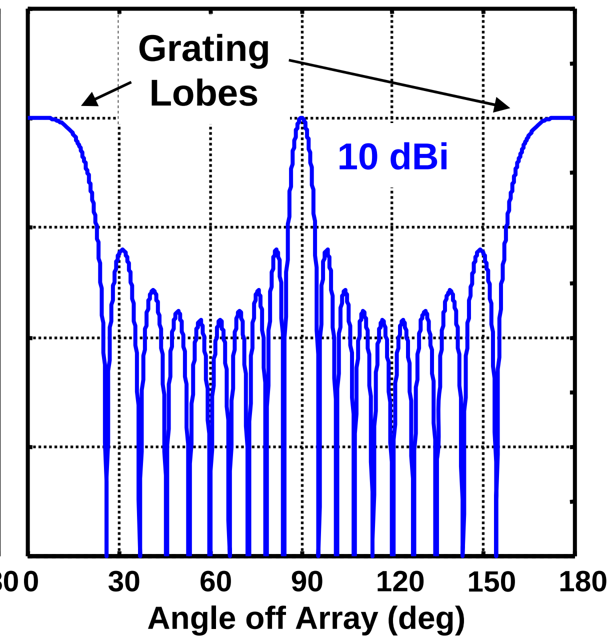
d = λ/4 separation



d = λ/2 separation



d = λ separation



Limit element separation to d < λ to prevent grating lobes for broadside array

Increasing Array Size of Scanned Array by Separating Elements

- **Linear Endfire Array**
- **N = 10 Isotropic Elements**
- **Phase Shifted to Point Up**

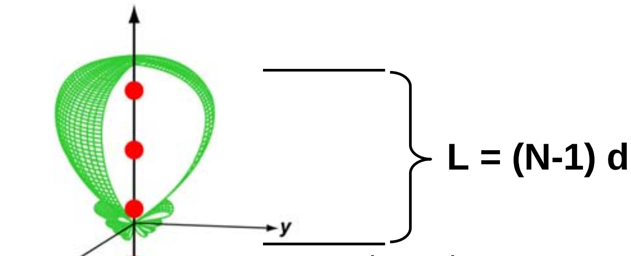
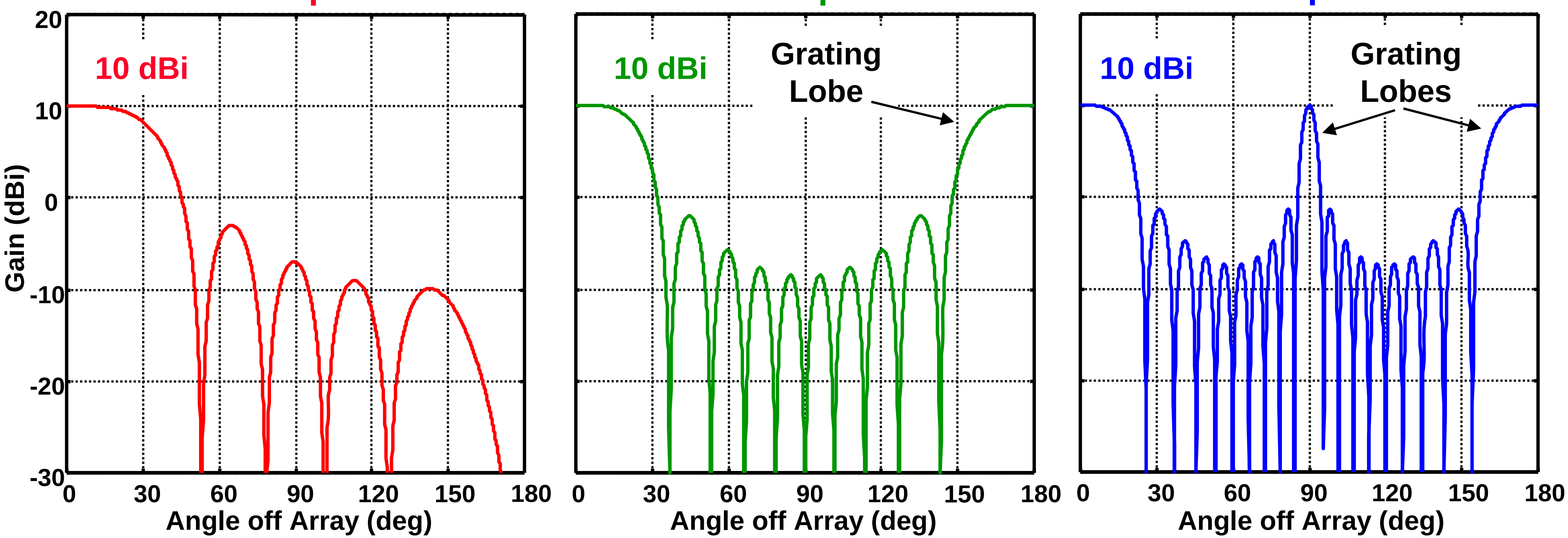


Figure by MIT OCW.

d = λ/4 separation | **d = λ/2 separation** | **d = λ separation**



- **No grating lobes for element separation d < λ / 2**
- **Gain ~ 4N(d / λ) ~ 4L / λ for long endfire array *without grating lobes***

Linear Phased Array
Scanned every 30 deg, N = 15, d = λ/4

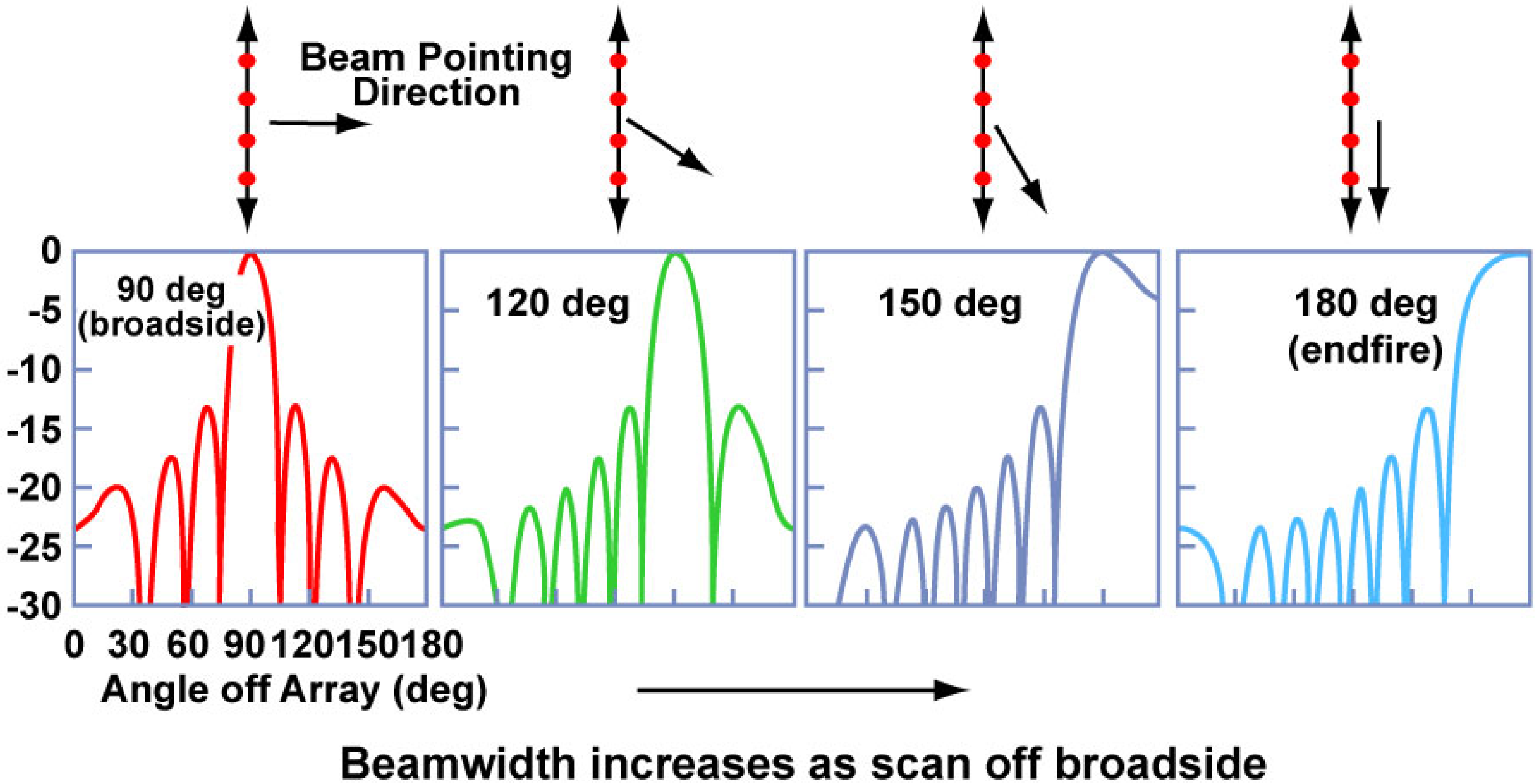
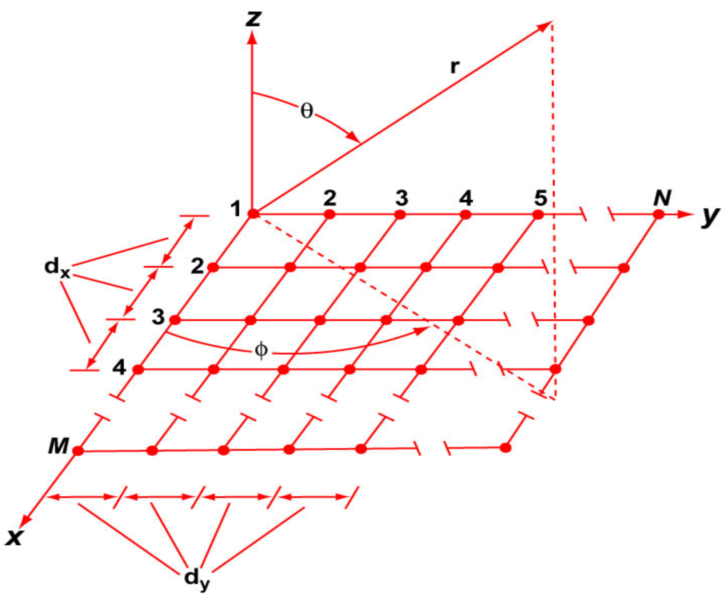


Figure by MIT OCW.

To scan over all space without grating lobes, keep element separation d < λ / 2

Planar Arrays



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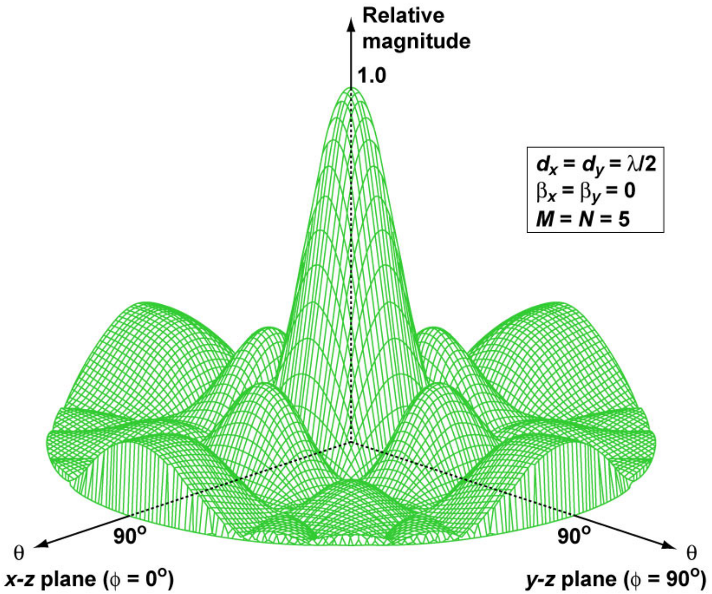


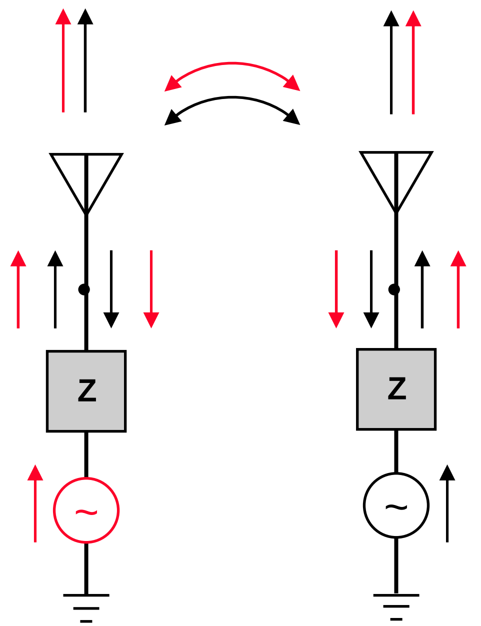
Figure by MIT OCW.

- **As scan to θ_o off broadside:**
  - **Beamwidth broadens by $1/\cos\theta_o$**
  - **Directivity decreases by $\cos\theta_o$**

To scan over all space without grating lobes, keep element separation in both directions < λ / 2

Mutual Coupling

Drive Both Antennas



- **Effect of one element on another**
  - Near-field quantity
  - Makes input impedance dependent on scan angle
- **Can greatly complicate array design**
  - Hard to deliver power to antennas for all scan angles
  - Can cause *scan blindness* where no power is radiated
- **Can limit scan volume and array bandwidth**

But... mutual coupling can sometimes be exploited to achieve certain performance requirements

Phased Arrays vs Reflectors

- **Phased arrays provide beam agility and flexibility**
  - **Effective radar resource management (multi-function capability)**
  - **Near simultaneous tracks over wide field of view**
- **Phased arrays are significantly more expensive than reflectors for same power-aperture**
  - **Need for 360 deg coverage may require 3 or 4 filled array faces**
  - **Larger component costs**
  - **Longer design time**

Outline

- Introduction
- Fundamental antenna parameters
- Reflectors
- Phased arrays
- Summary

Summary

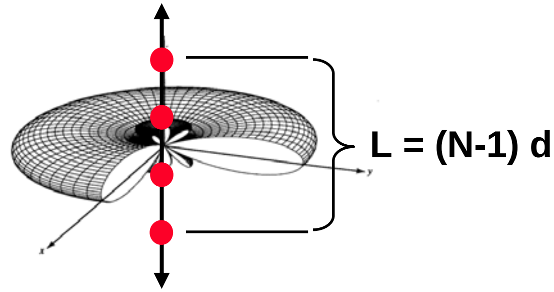
- **Fundamental antenna parameters and array topics have been discussed**
  - Radiation
  - Gain, pattern, sidelobes, beamwidth
  - Polarization
  - Far field
  - Input impedance
  - Array beamforming
  - Array mutual coupling
- **Reflector antennas offer a relatively inexpensive method of achieving high gain for a radar**
  - Parabolic reflectors
  - Cassegrain feeds
- **Phased array antennas offer beam agility and flexibility in use**
  - But much more expensive than reflector antennas

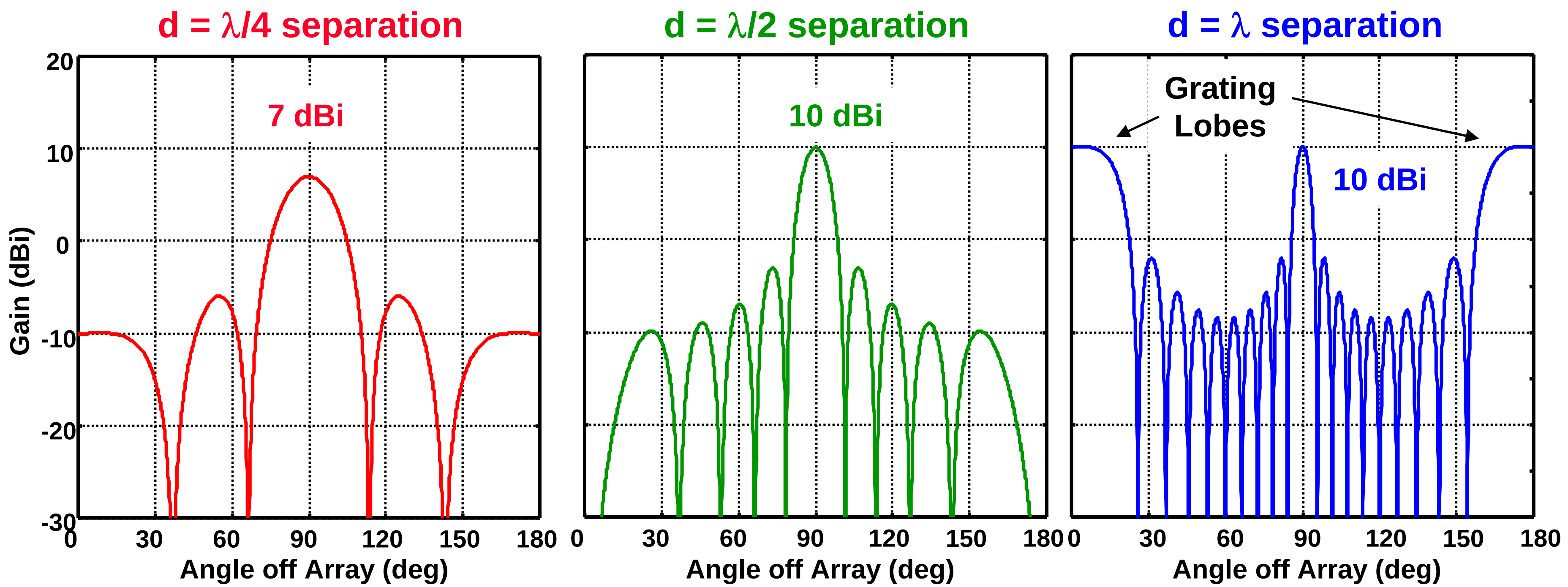
References

- Balanis, C. A., Antenna Theory: Analysis and design, 2nd Edition, New York, Wiley, 1997
- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Mailloux, R. J., Phased Array Antenna Handbook, Norwood, Mass., Artech House, 1994

Increasing Array Size by Separating Elements

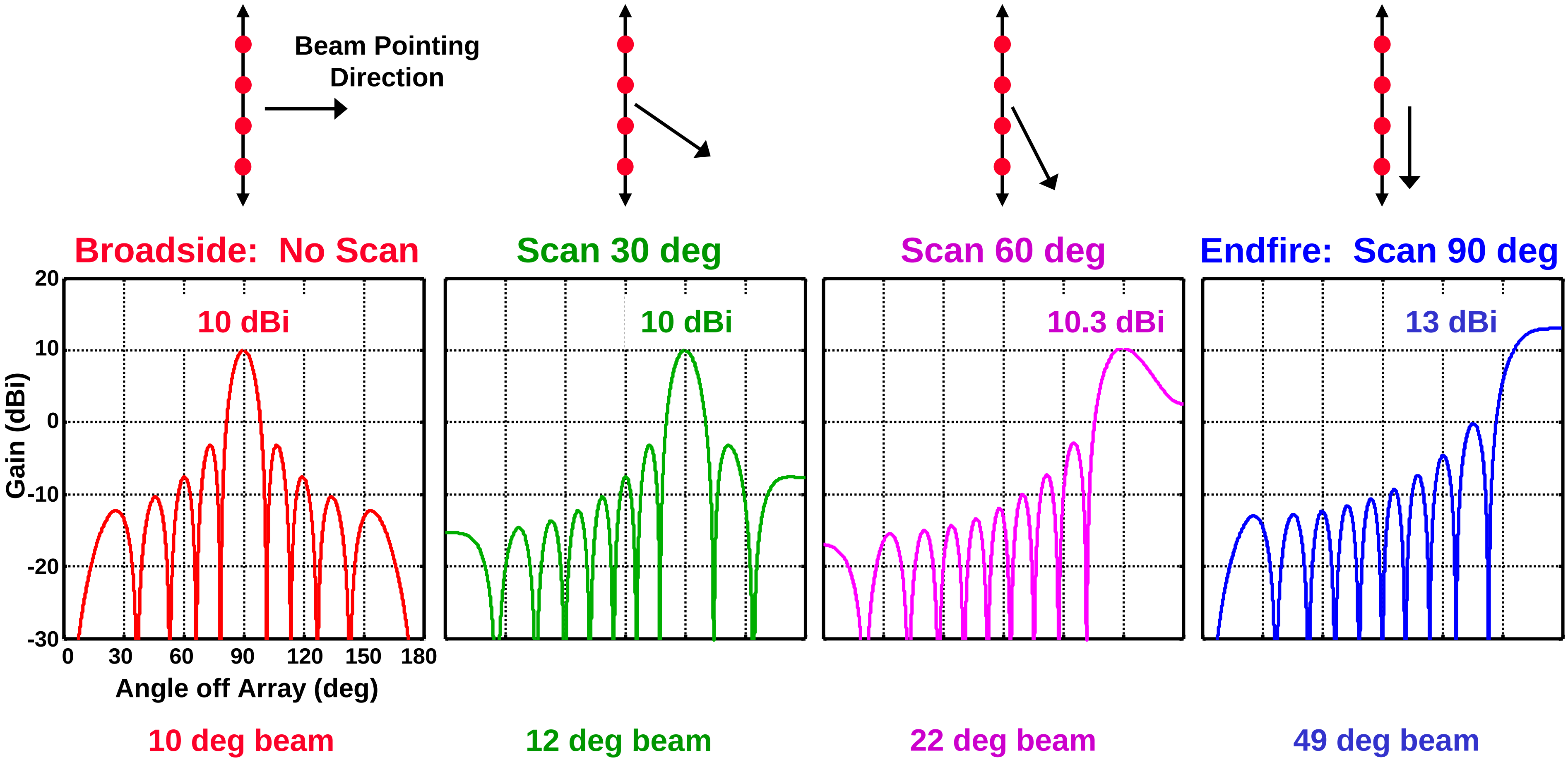
- Linear Broadside Array
- N = 10 Isotropic Elements
- No Phase Shifting





Limit element separation to d < λ to prevent grating lobes for broadside array

Linear Phased Array
Scanned every 30 deg, N = 20, d = λ/4



To scan over all space without grating lobes, keep element separation d < λ / 2

Introduction to Radar Systems

Radar Clutter and Chaff

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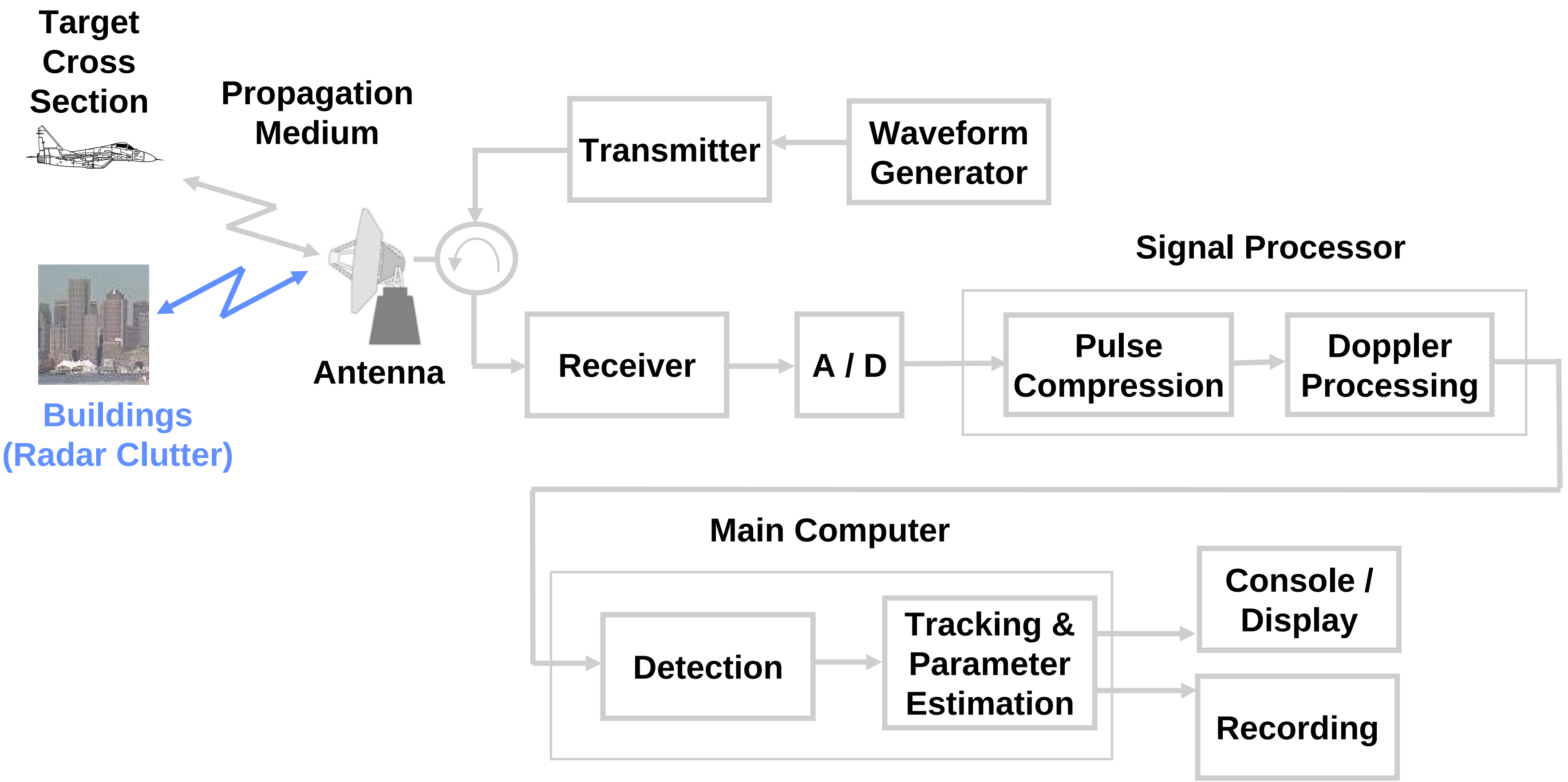
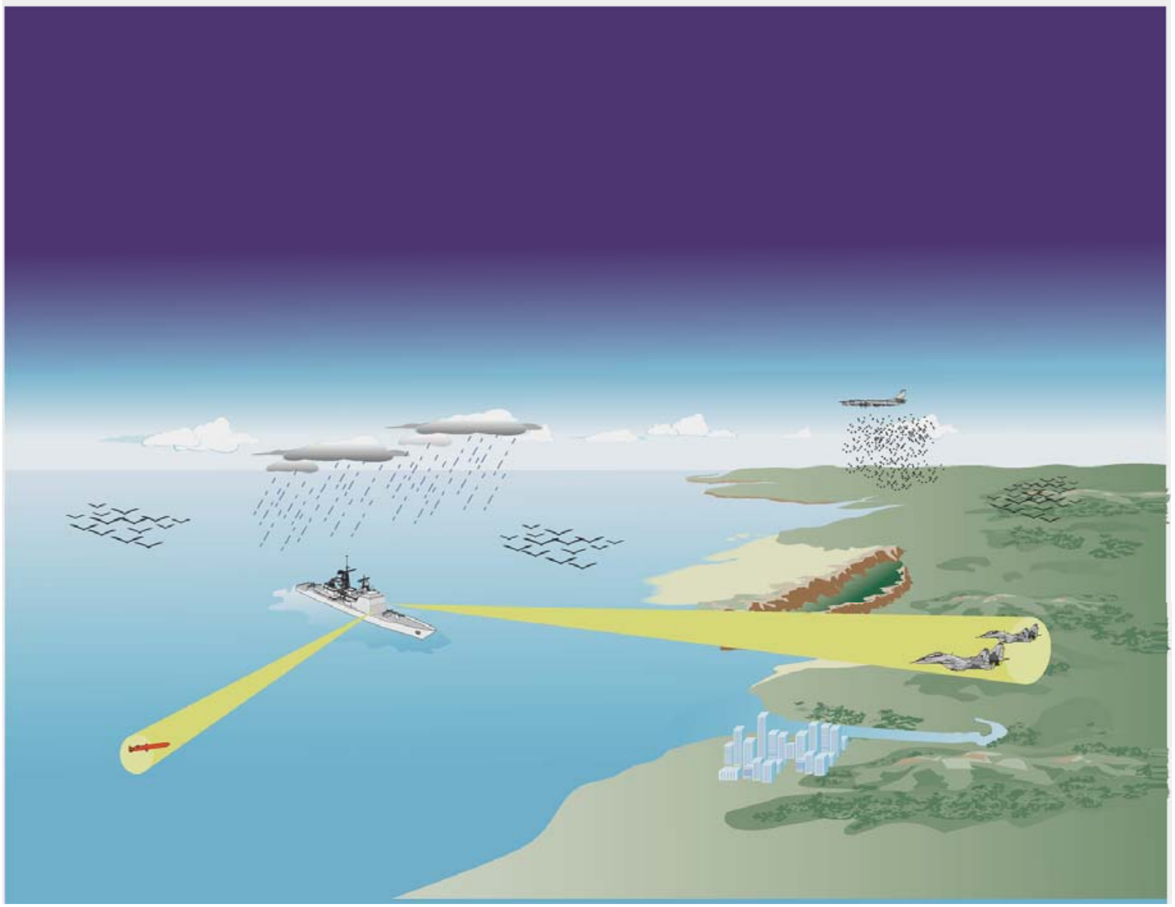
Radar Clutter



Why Understand Radar Clutter?

Naval Air Defense Scenario



Radar echo is composed of:

- **Backscatter from target of interest**
- **Receiver noise**
- **Atmospheric noise**
- **Interference**
  - **From other radars**
  - **Jammers**
- **Backscatter from unwanted objects**
  - **Ground**
  - **Sea**
  - **Rain**
  - **Chaff**
  - **Birds**
  - **Ground traffic**

Outline

- Motivation
- Ground Clutter
- Sea Clutter
- Rain
- Chaff
- Birds and Insects

Attributes of Ground Clutter

- **Mean value of backscatter from ground clutter**
  - **Very large size relative to aircraft**
  - **Varies statistically**
    - **Frequency, spatial resolution, geometry, terrain type**
- **Doppler characteristics of ground clutter return**
  - **Innate Doppler spread small (few knots)**
    - **Mechanical scanning antennas add spread to clutter**
  - **Relative motion of radar platform affects Doppler of ground clutter**
    - **Ship**
    - **Aircraft**

Photographs of Ground Based Radar's PPI
(Different Levels of Attenuation)

Mountainous Region of Lakehead, Ontario, Canada
PPI Set for 30 nmi.

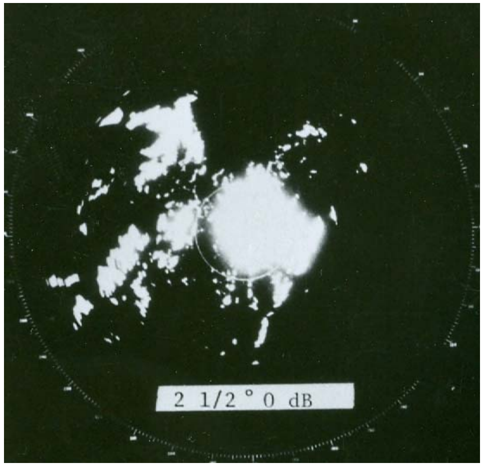
0 dB

60 dB

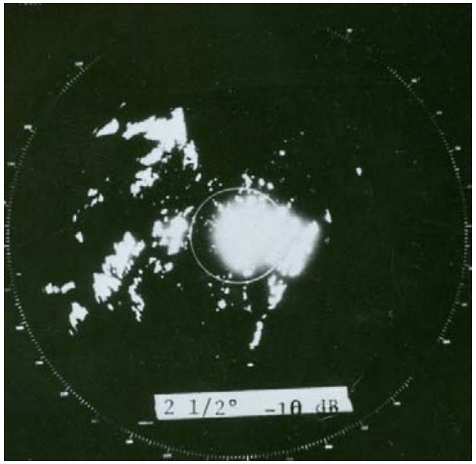
Source: Shrader, W. "Radar Technology Applied to Air Traffic Control," IEEE Transactions on Communications, Vol COM-21, No. 5, May 1973. © IEEE.

Photographs of Ground Based Radar's PPI
(Different Levels of Attenuation)

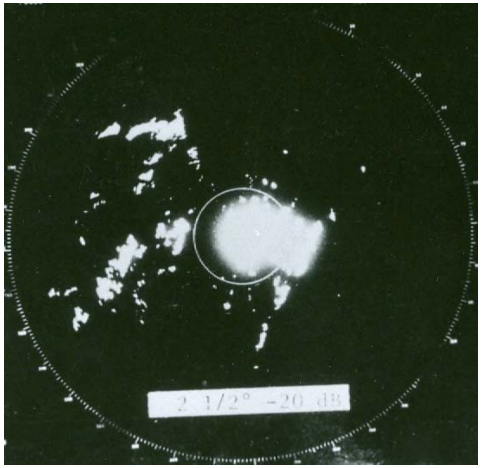
0 dB



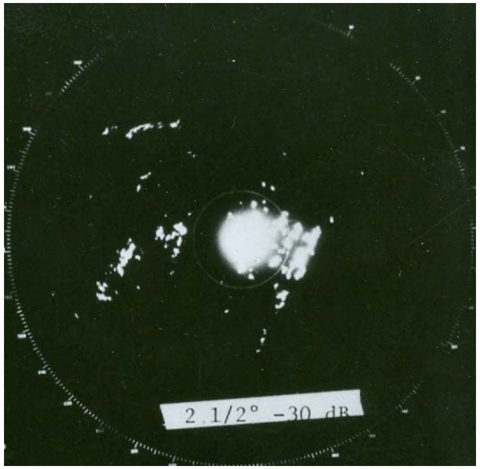
10 dB



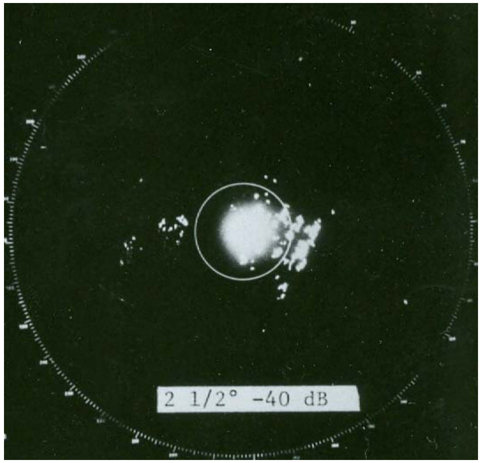
20 dB



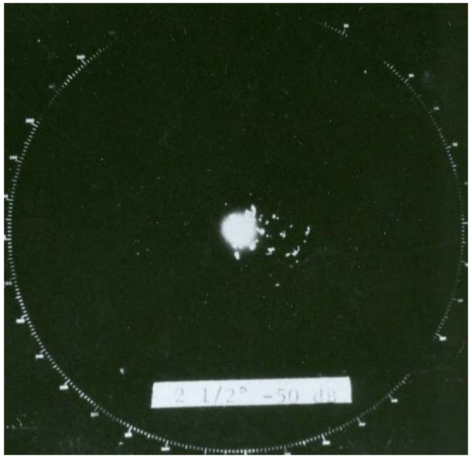
30 dB



40 dB

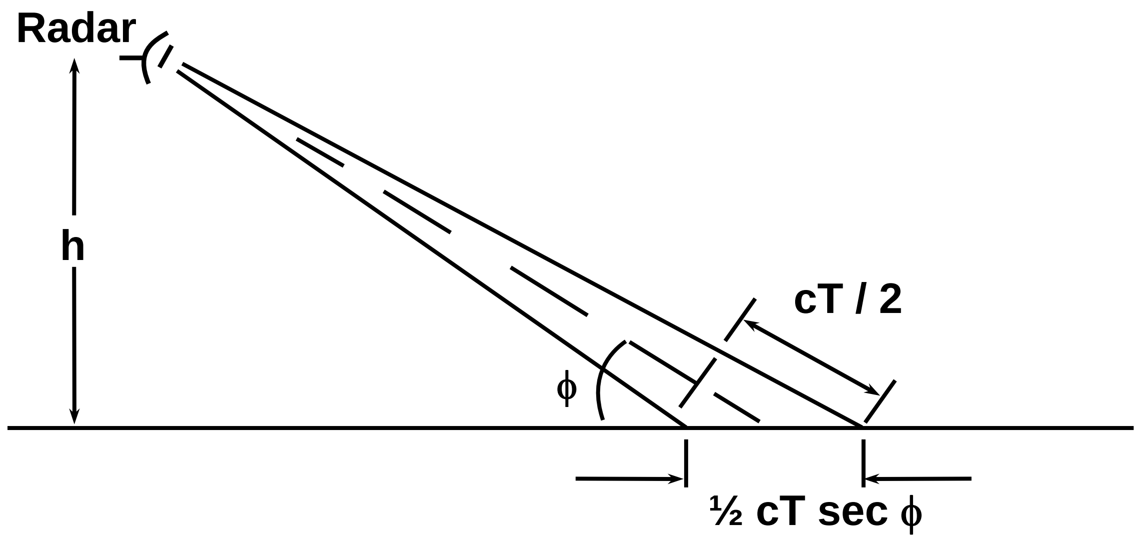


50 dB

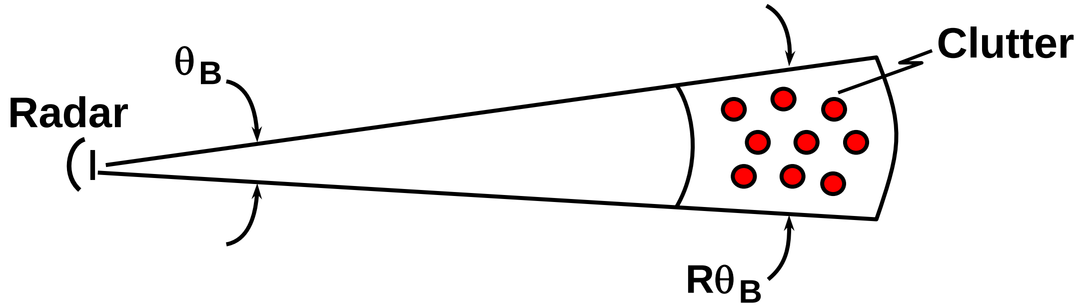


Geometry of Radar Clutter

Elevation View



Plan View



$$\sigma_0 = \frac{\sigma}{A} \qquad A = R\theta_B \left[\tfrac{1}{2}\, cT \sec\phi\right]$$

Calculation of Ground Clutter

- Typical Value of σ_o = -20 dB = $\dfrac{0.01\ m^2}{m^2}$
- $\sigma_{\text{Clutter}} = \sigma_o A = \sigma_o \dfrac{c\,T}{2} R\,\theta_B$
  - For ASR-9 (Airport Surveillance Radar)

$$\frac{c\,T}{2} = 100\text{m} \qquad R = 60\text{ km} \qquad \theta_B = 1.5^o = 0.026\text{ radians}$$

- $\sigma_{\text{Clutter}} = \dfrac{0.01\ m^2}{m^2} \times 100\text{ m} \times 60{,}000\text{ m} \times 0.026\text{ radians} = 1500\ m^2$

For $\sigma_{\text{Target}} = 1\ m^2$ ⇒ $\dfrac{\sigma_{\text{Target}}}{\sigma_{\text{Clutter}}} = \dfrac{1}{1500}$ ⇒ $\dfrac{\sigma_{\text{Target}}}{\sigma_{\text{Clutter}}} = 20$

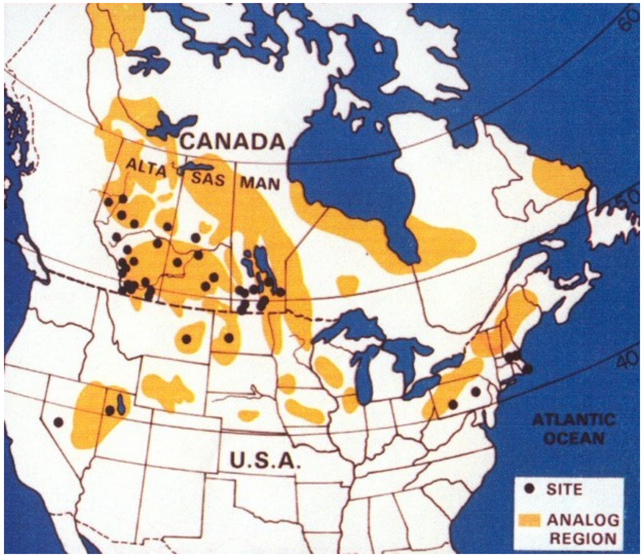
Small single-engine aircraft

For good detection

∴ Must suppress clutter by a factor of

1500 x 20 = 30,000 = 45 dB

Joint U.S./Canada Measurement Program



- **Phase One radar**
  - **VHF, UHF, L-, S-, X-bands**
- **Measurements conducted 1982 – 1984**
- **Archival data at Lincoln Laboratory**

- **42 sites**
- **Data shared with Canada and the United Kingdom**

Clutter Physics

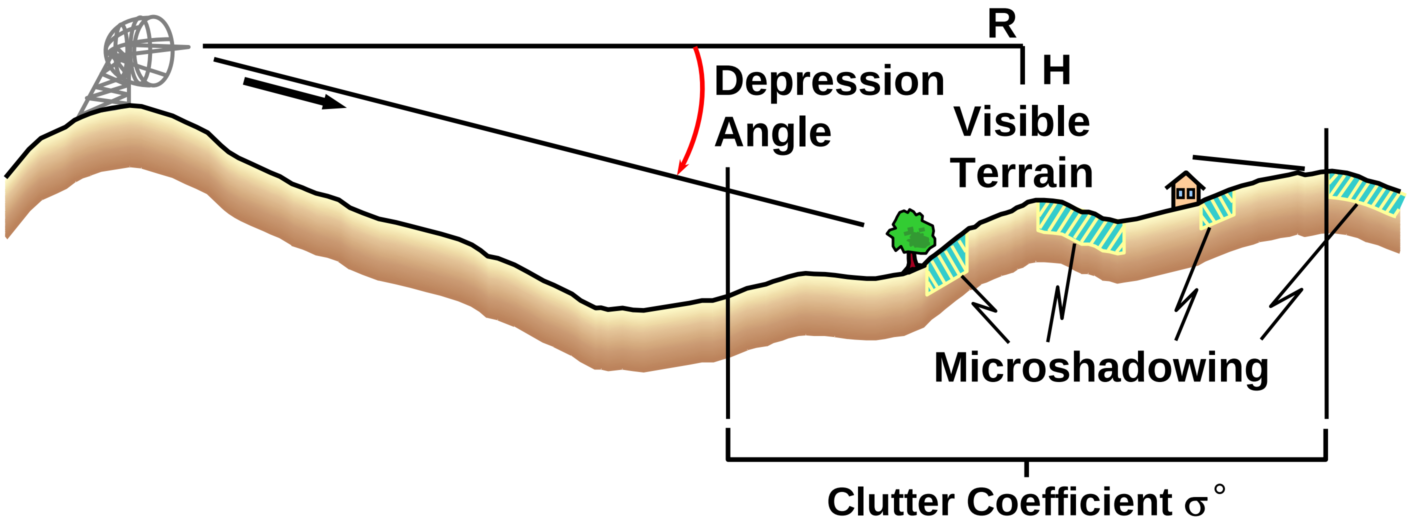


Image from Billingsley, J. B. *Ground Clutter Measurements for Surface Sited Radars*. Tech Report 786, Rev. 1. Lexington, MA: Lincoln Laboratory, February 1, 1993. Courtesy of Lincoln Laboratory

Clutter Physics

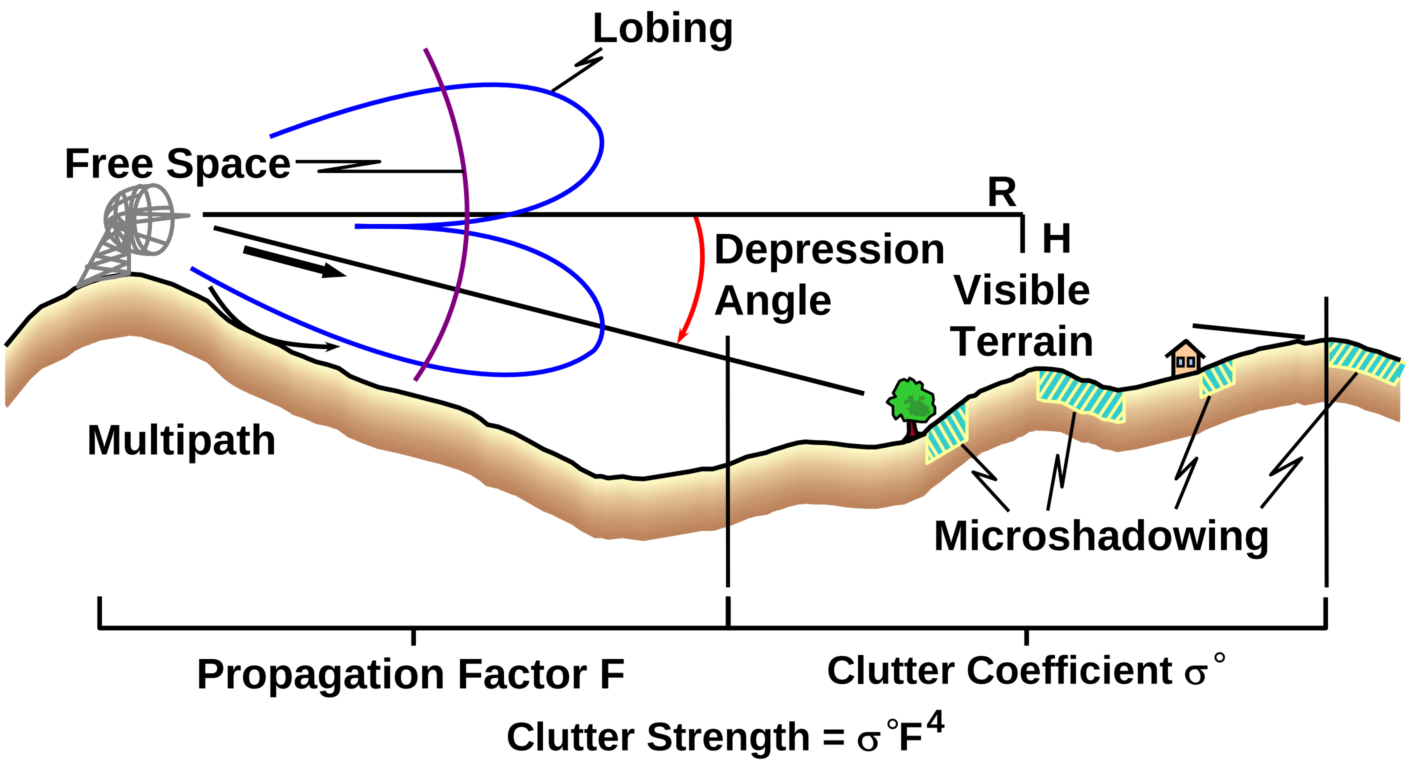


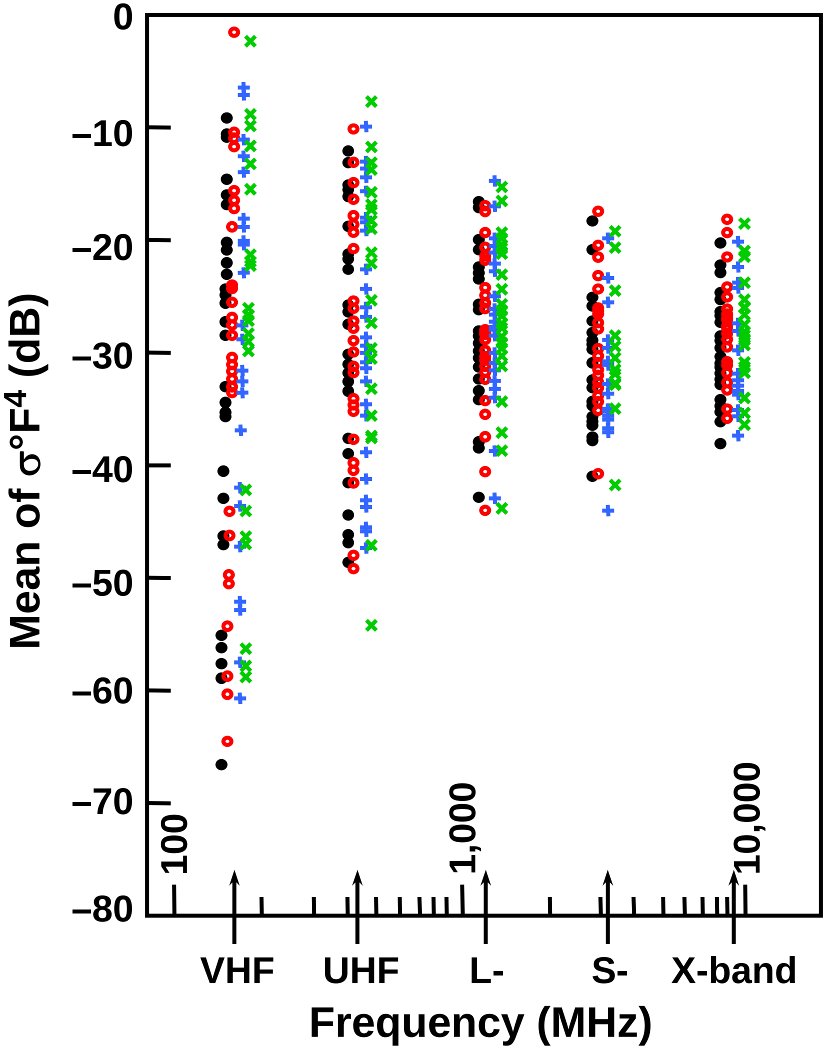
Image from Billingsley, J. B. *Ground Clutter Measurements for Surface Sited Radars*. Tech Report 786, Rev. 1. Lexington, MA: Lincoln Laboratory, February 1, 1993. Courtesy of Lincoln Laboratory

1) **Radar Parameters**
   - **Frequency, f**
   - **Spatial resolution, A**

2) **Geometry**
   - **Depression angle (Range R, Height H)**

3) **Terrain Type**
   - **Landform**
   - **Land cover**

Mean Ground Clutter Strength vs. Frequency



General Rural (36 Sites)

Key

Range Resolution (m)	Polarization	
150	H	•
150	V	∘
15/36	H	+
15/36	V	×

Outline

- Motivation
- Ground Clutter
- Sea Clutter
- Rain
- Chaff
- Birds and Insects

Attributes of Sea Clutter

- **Mean cross section of sea clutter depends on many variables**
  - Wind and weather
    - Sea State
  - Radar frequency
  - Radar Polarization
  - Range resolution
  - Cross range resolution
  - Grazing angle
  - Too many variables

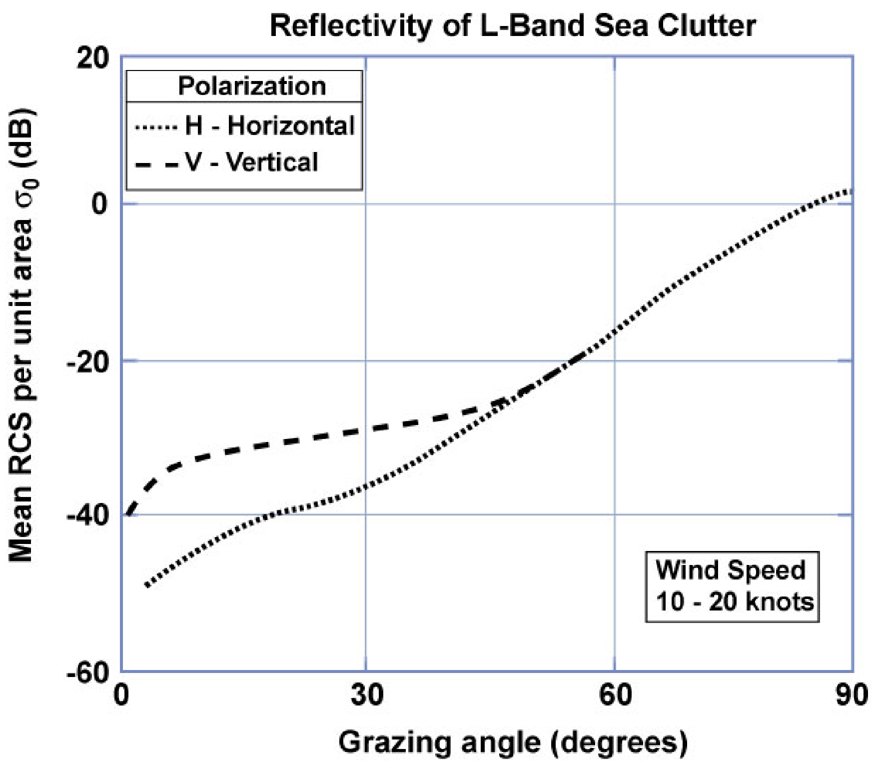


Figure by MIT OCW.

Mean sea backscatter is about 100 times less than ground backscatter

World Meteorological Organization
Sea State

Sea State	Wave Height (m)	Wind Velocity (knots)	Descriptive Term
0 to 1	0 to 0.1	0 to 6	Calm, Rippled
2	0.1 to 0.5	7 to 10	Smooth, Wavelets
3	0.6 to 1.2	11 to 16	Slight to Moderate
4	1.2 to 2.4	17 to 21	Moderate to Rough
5	2.4 to 4	22 to 27	Very Rough
6	4 to 6	28 to 47	High

Sea Spikes

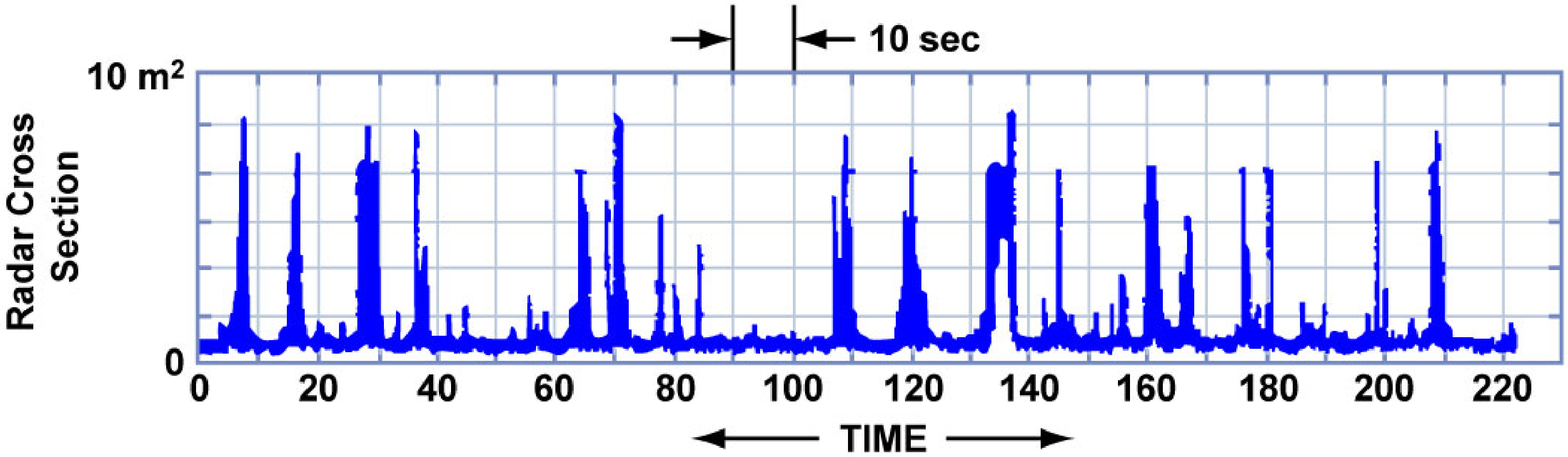


Figure by MIT OCW.

- Grazing angle   1.5 deg.
- Horizontal polarization

- **At low grazing angles, sharp sea clutter peaks, known as "sea spikes", begin to appear**
- **These sea spikes can cause excessive false detections**

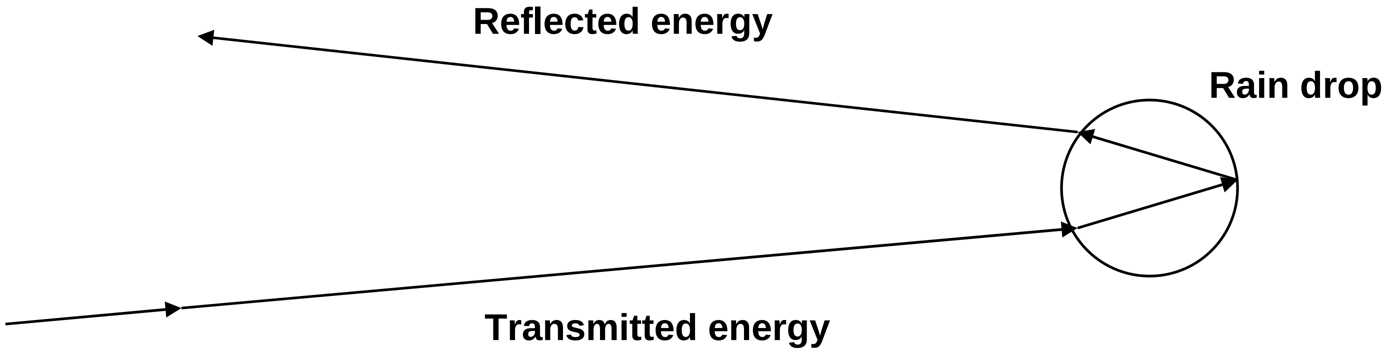
From Lewis and Olin, NRL

Outline

- Motivation
- Ground Clutter
- Sea Clutter
- Rain
- Chaff
- Birds and Insects

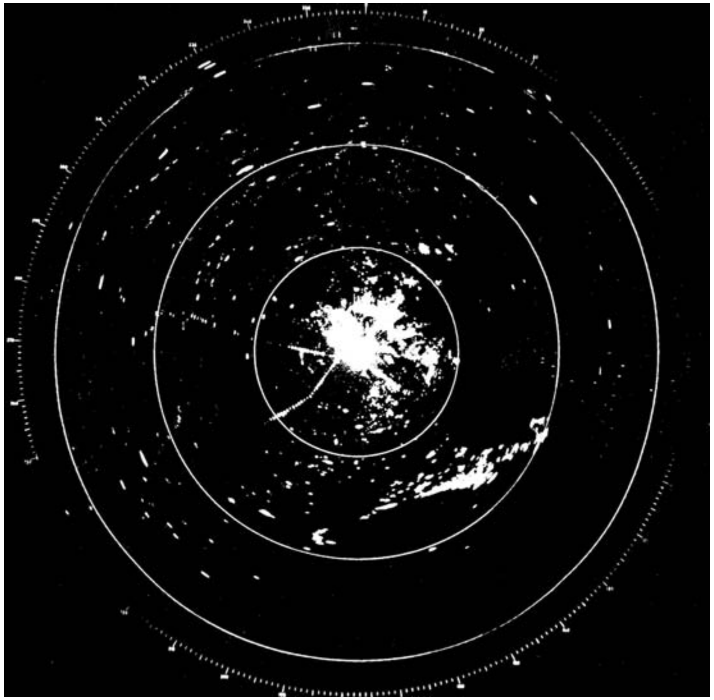
Attributes of Rain Clutter

- Rain both attenuates and reflects radar signals
- Problems caused by rain lessen dramatically with longer wavelengths (lower frequencies)
  – Much less of a issue at L-Band than X-Band
- Rain is diffuse clutter (wide geographic extent)
  – Travels horizontally with the wind
  – Has mean Doppler velocity and spread



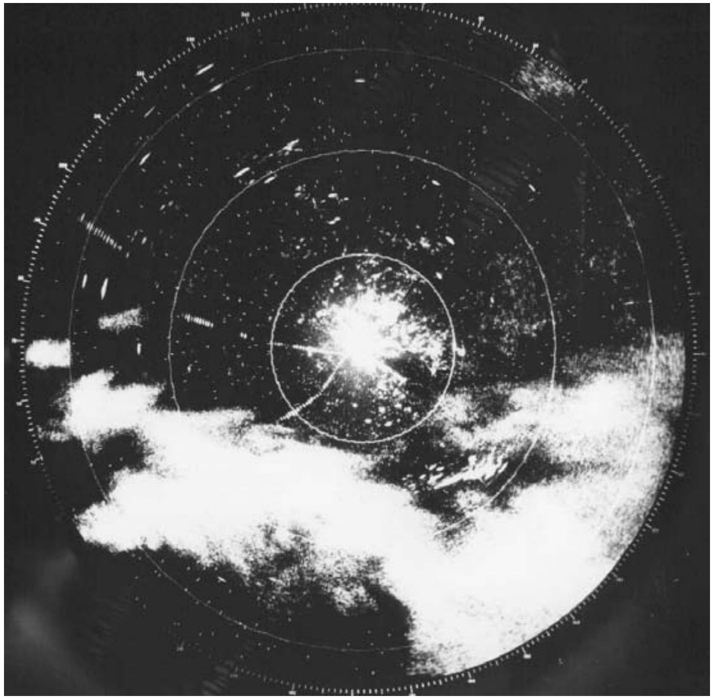
PPI Display Radar Normal Video

Clear Day (No Rain)



Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m^2 target

Day of Heavy Rain



10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

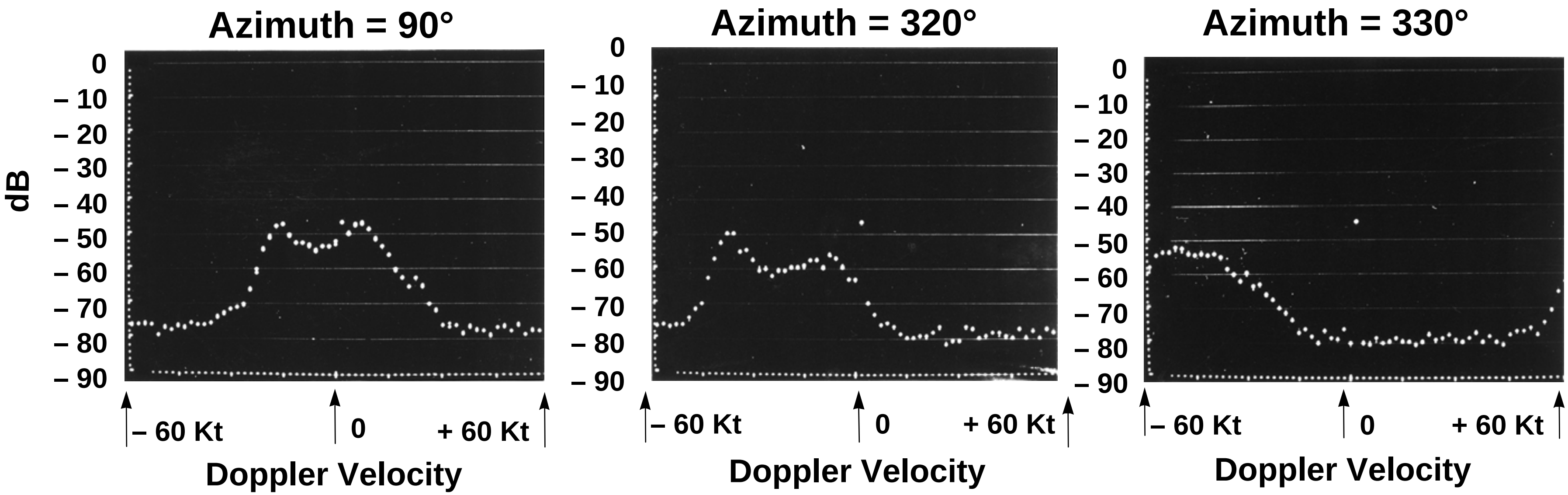
Reflectivity of Uniform Rain (σ in dBm^2/m^3)

Rain Type	Frequency			
	S 3.0 GHz	C 5.6	X 9.3	Ka 35
Drizzle, 0.25 mm/hr	–102	–91	–81	–58
Light Rain, 1 mm/hr	–92	–81.5	–72	–49
Moderate, 4 mm/hr	–83	–72	–62	–41
Heavy Rain, 16 mm/hr	–73	–62	–53	–33

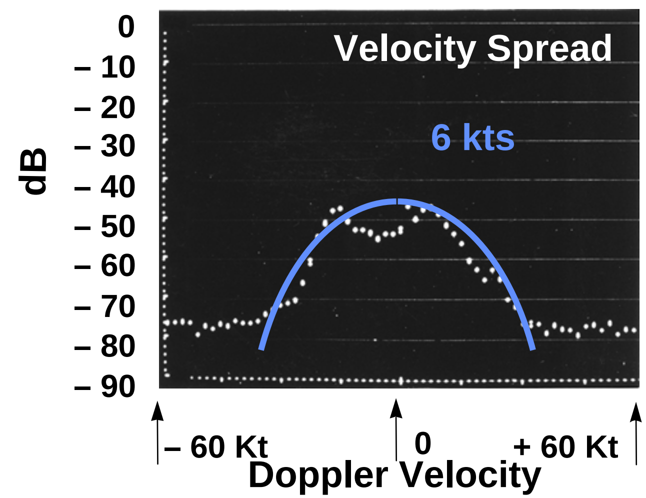
Figure by MIT OCW.

- **Rain reflectivity increases as f^4 (or $1 / \lambda^4$)**
  - **Rain clutter is an issue at S-Band and a significant one at X-Band or higher frequencies**

Measured S-Band Doppler Spectra of Rain



- Rain is not Gaussian
- Mean velocity varies as storm moves by radar
- In these examples the rainfall rate was approximately 20 mm/hr
- Winds 30 kts on ground, 50 kts at 6000 ft



Outline

- Motivation
- Ground Clutter
- Sea Clutter
- Rain
- Chaff
- Birds and Insects

Attributes of Chaff

- Large number of dipoles (metallic or metallic coated)
  - High reflectivity per pound
  - Optimum length 1/2 of radar wavelength
  - Moves with the wind
- Uses of chaff
  - Masking

    Large cloud can shield aircraft or missiles in or near the cloud
  - Deception

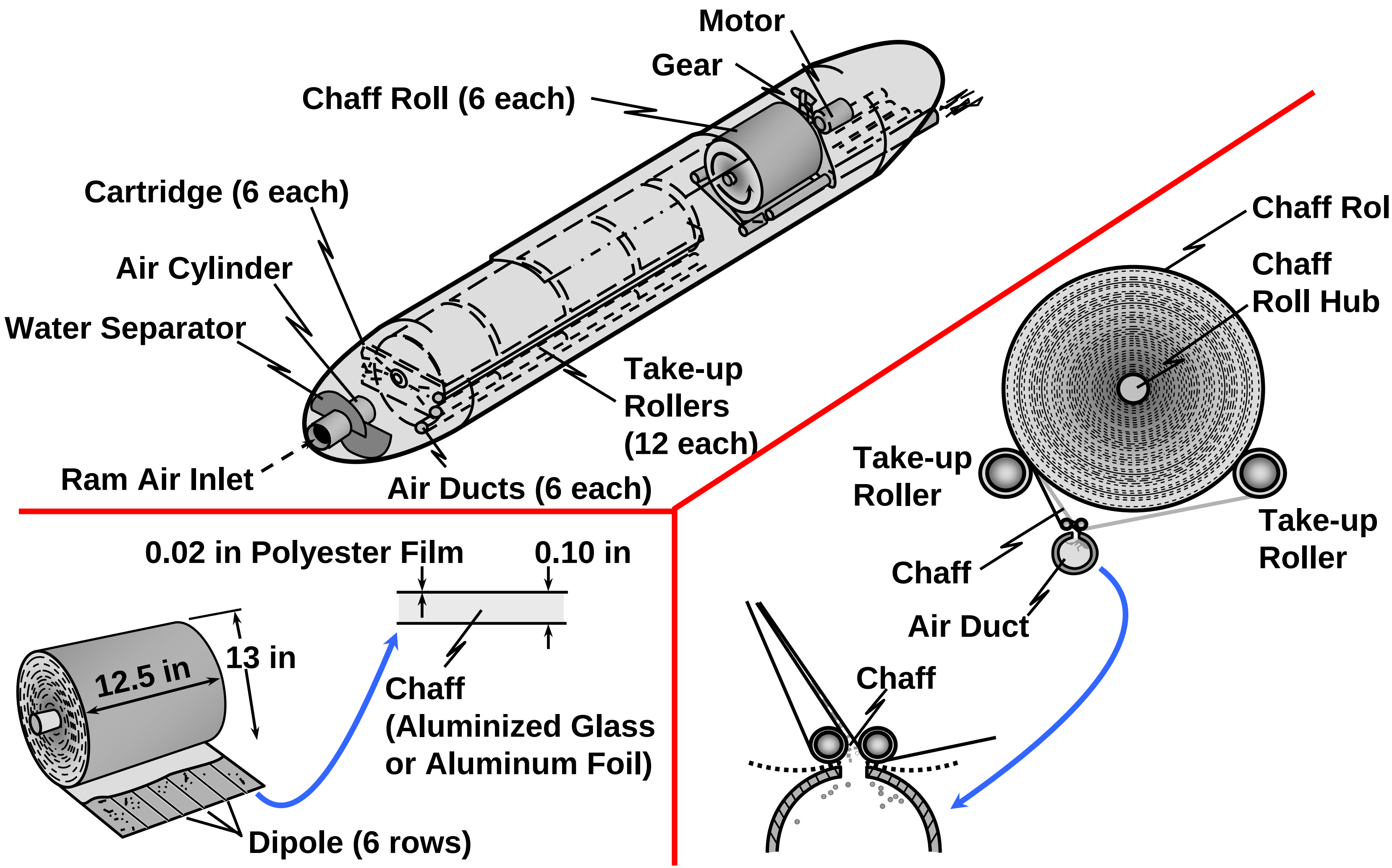
    Chaff “puff” can emulate a missile / aircraft and cause false detections

    Packets of chaff can divert radar tracker from target

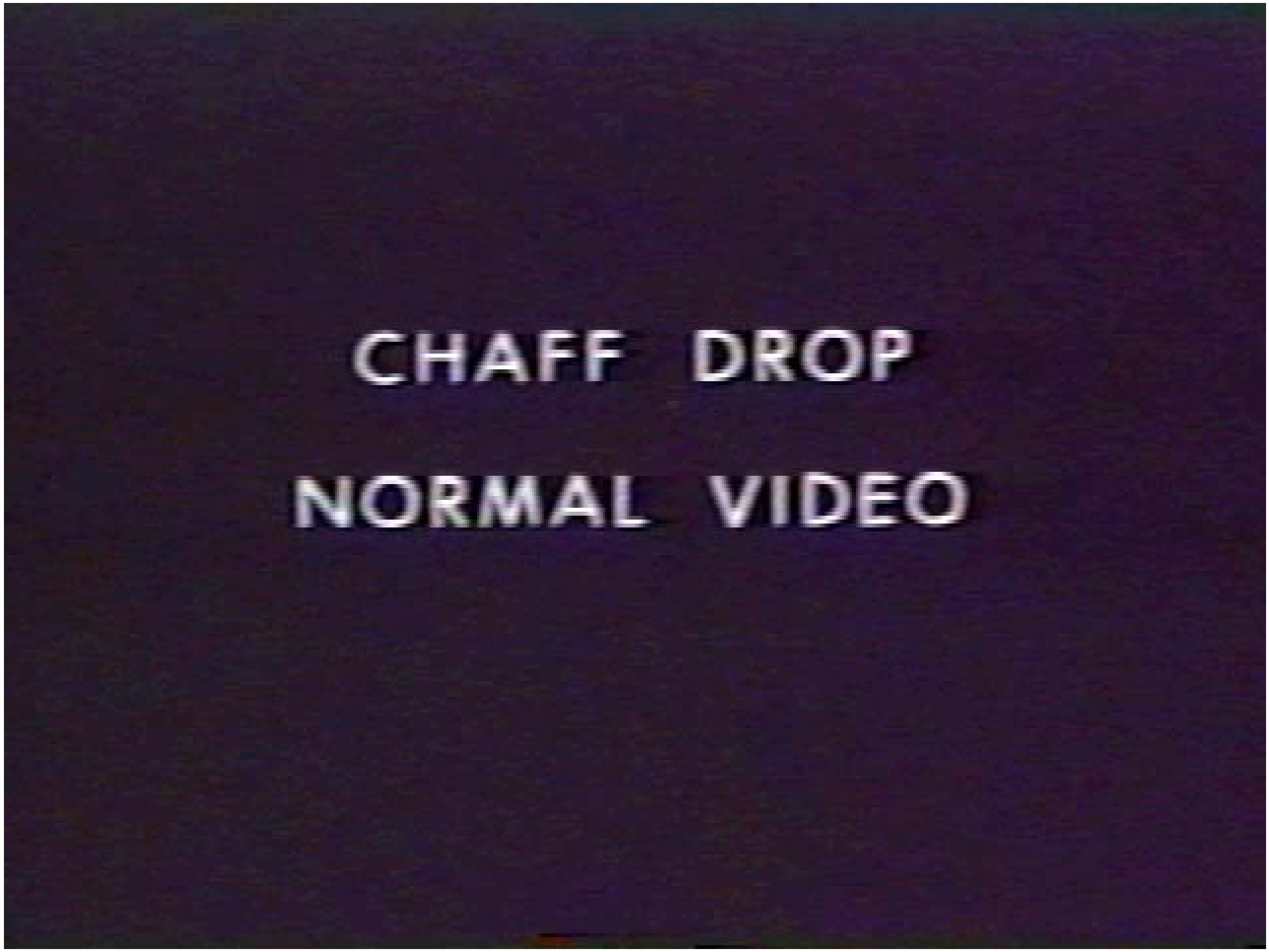
Chaff Reflectivity and Density

- **Resonant Metallic Dipoles**
  - **σ = .18 λ^2 (in m^2) Average Cross Section per Dipole**
  - **Bandwidth 10-15% of center frequency**
  - **Fall rates 0.5 to 3 m/s**
- **Aluminum foil dipoles (.001 in. x .01 in. x λ/2 long)**
  - **σ = 3000 W / f (in m^2)**
  - **W = weight in lb, f = frequency in GHz**
  - **At S-Band, 400 lb yields = 265,000 m^2 or 54.3 dBsm**

AN/ALE-38 Chaff-Dispensing System



Movie of Chaff



Outline

- Motivation
- Ground Clutter
- Sea Clutter
- Rain
- Chaff
- Birds and Insects

Bird Breeding Areas and Migration Routes

Gadwall

Northern Flicker

Virginia Rail

Photos courtesy of vsmithuk, sbmontana, and khosla.

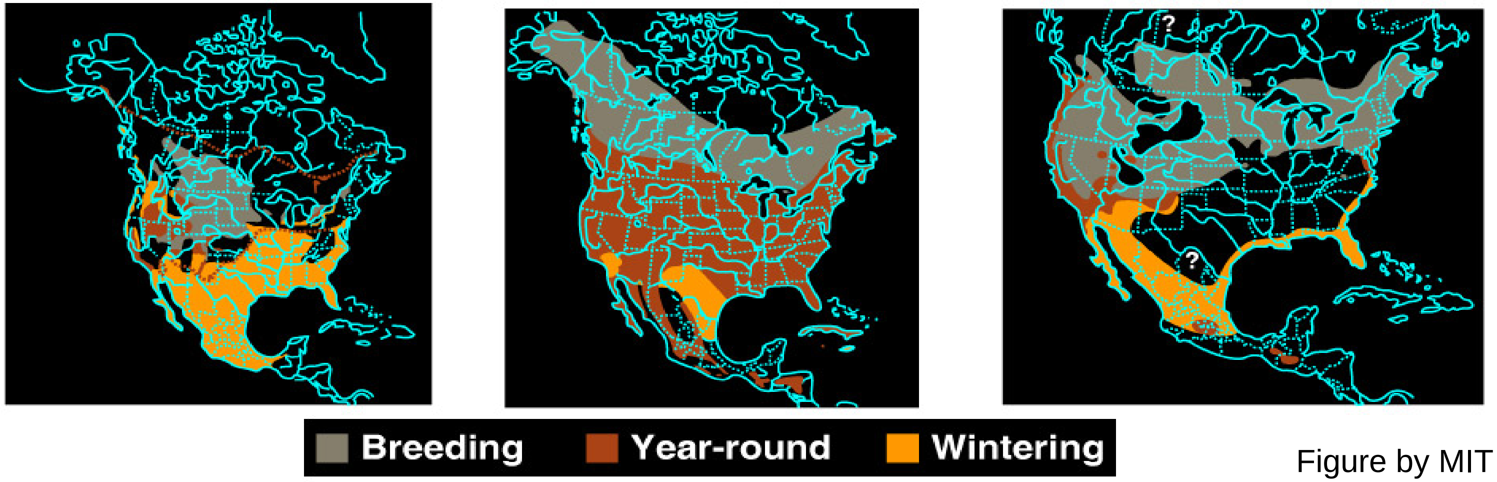


Figure by MIT OCW.

During the breeding season along the Gulf Coast, sea and wading bird colonies exist that have up to 60,000 birds. 10,000 birds are common. These birds are large; weighing up to 1 kg and having wingspreads from 0.75 to several meters.

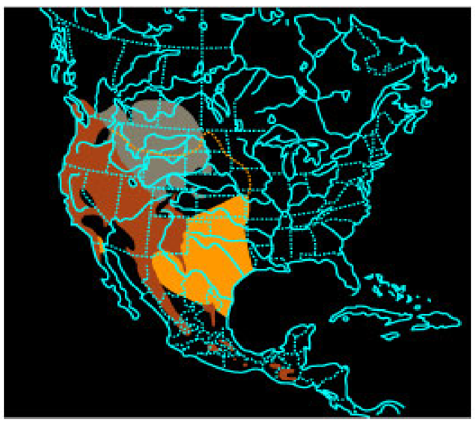
Bird Breeding Areas and Migration Routes

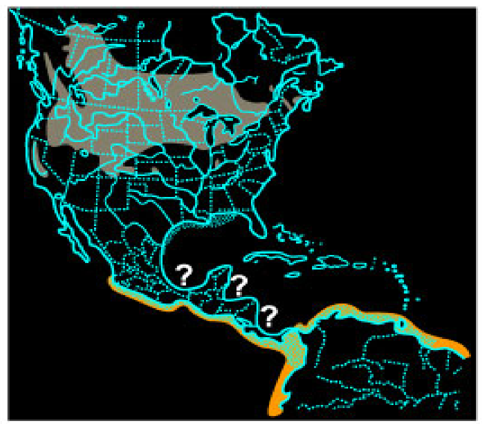
Spotted Towhee

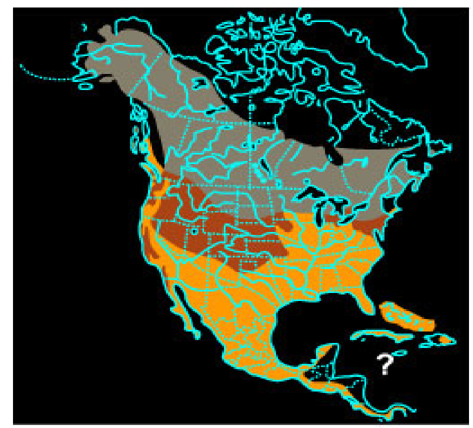
Black Tern

Northern Harrier

Photos courtesy amkhosla, Changhua Coast Conservation Action, and amkhosla.





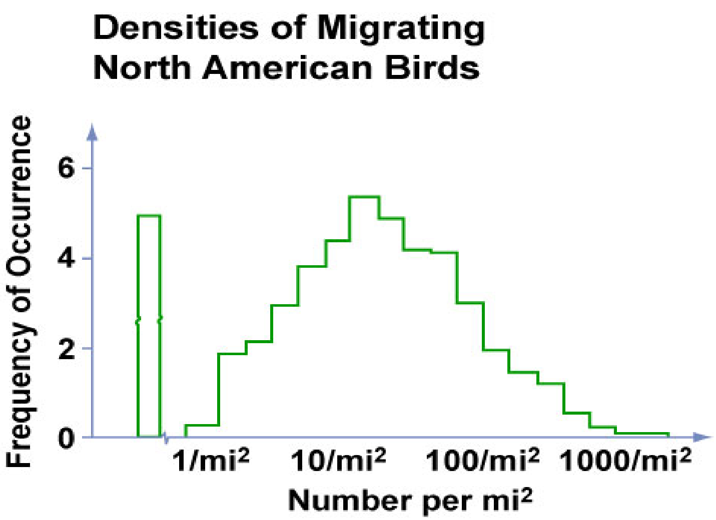


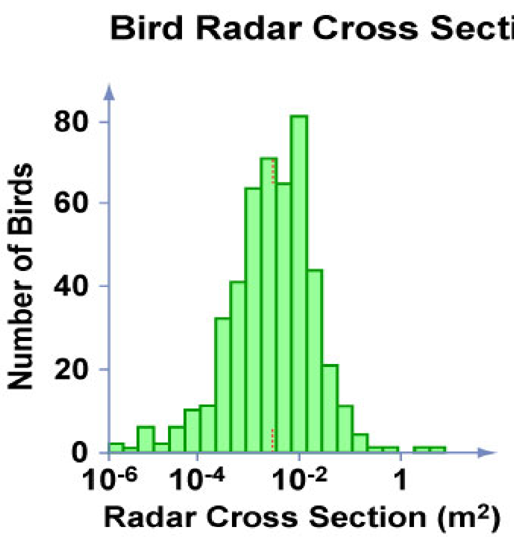
Breeding Summer Non-breeding Year-round Wintering

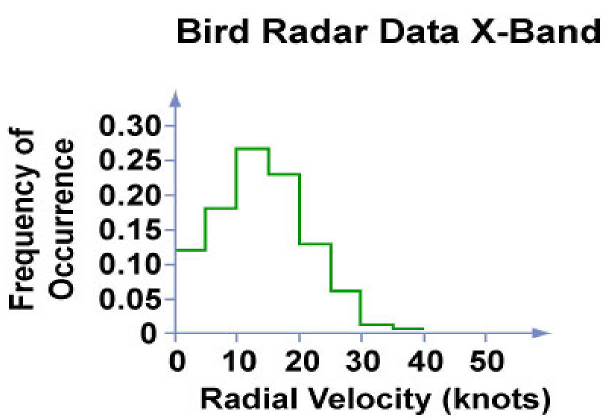
Figure by MIT OCW.

Within the lower Mississippi Valley, 63 blackbird roosts have been identified with over 1 million birds each. Many smaller roosts also exits. These birds disperse 30 miles for daily feeding.

Radar Properties of Birds



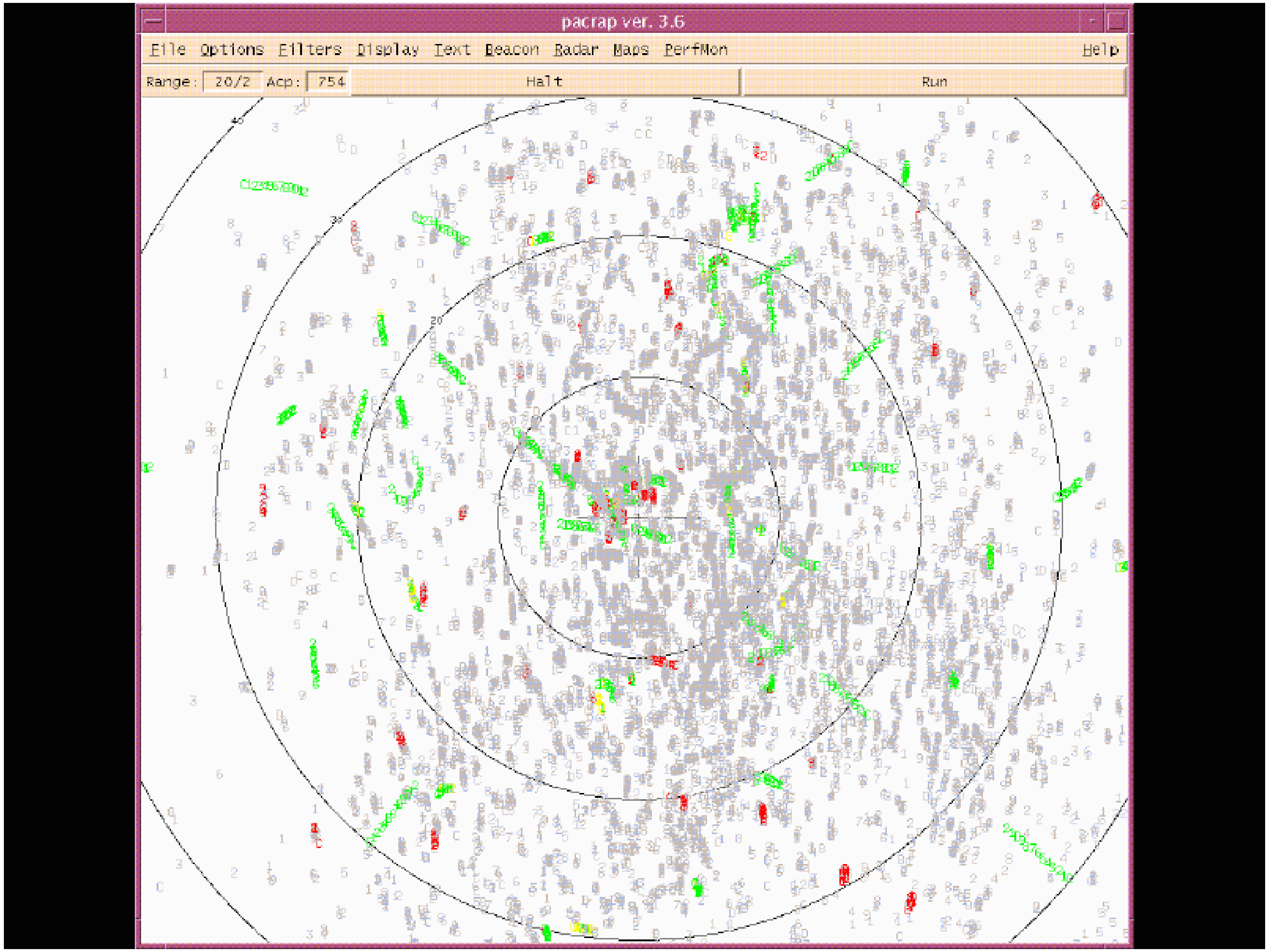




- Even though the radar echo of birds is relatively small, bird densities are so great that birds can often overload a radar with false targets
- Since birds move at relatively low velocities, their speed, if measured, can be used to preferentially threshold out the low velocity birds.

Figure by MIT OCW.

Bird Example from Dallas-Fort Worth



Radar&Beacon
Beacon-Only
Radar Uncorrelated
Radar Correlated

Attributes of Birds

- Birds are actually moving point targets
  - Velocity usually less than 60 knots
- Mean radar cross section is small, but a fraction of bird returns fluctuate up to a high level (aircraft like)
  - Cross section is resonant at S-Band and L-Band
- Lots of birds per square mile
  - 10 to 1000 bird / square mile
- Birds cause a false target problem in many radars
  - Significant issue for when detecting targets with low cross sections

Insects

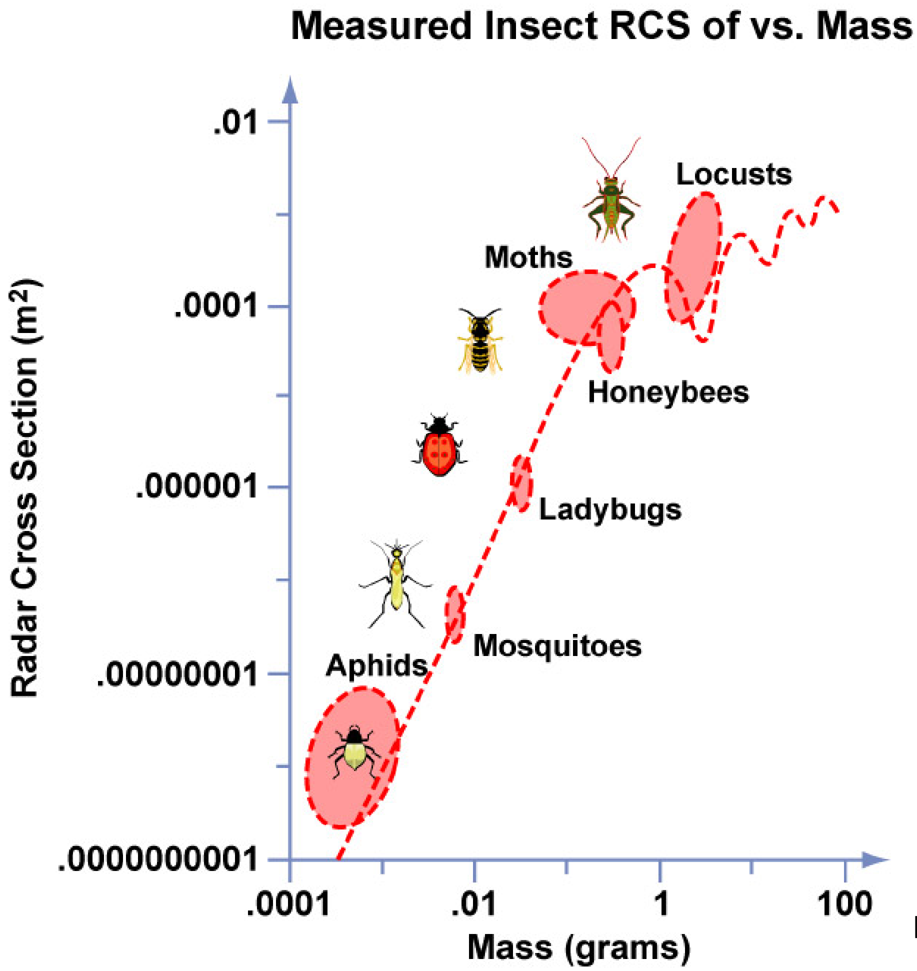


Figure by MIT OCW.

- Insects can clutter the display and prevent detection of desired targets
- Density of insects can be many orders of magnitude greater than that of birds
- Insect flight path generally follows that of the wind
- Cross section can be represented as a spherical drop of water of the same mass
- Insect echoes broad side are 10 to 1,000 times than when viewed end on

Summary

- **A number of different types of radar clutter returns have been described**
  - **Ground, sea, rain, and birds**
- **These environmental and manmade phenomena will produce a variety of discrete and diffuse, moving and stationary false targets, unless they are dealt with effectively**
- **A number of signal and data processing techniques can be used to suppress the effect of these radar clutter returns.**

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Nathanson, F. E., Radar Design Principles, New York, McGraw-Hill, 2nd Edition, 1991
- Eastwood, E., Radar Ornithology, London, Methuen, 1967

Introduction to Radar Systems

Clutter Rejection

MTI and Pulse Doppler Processing

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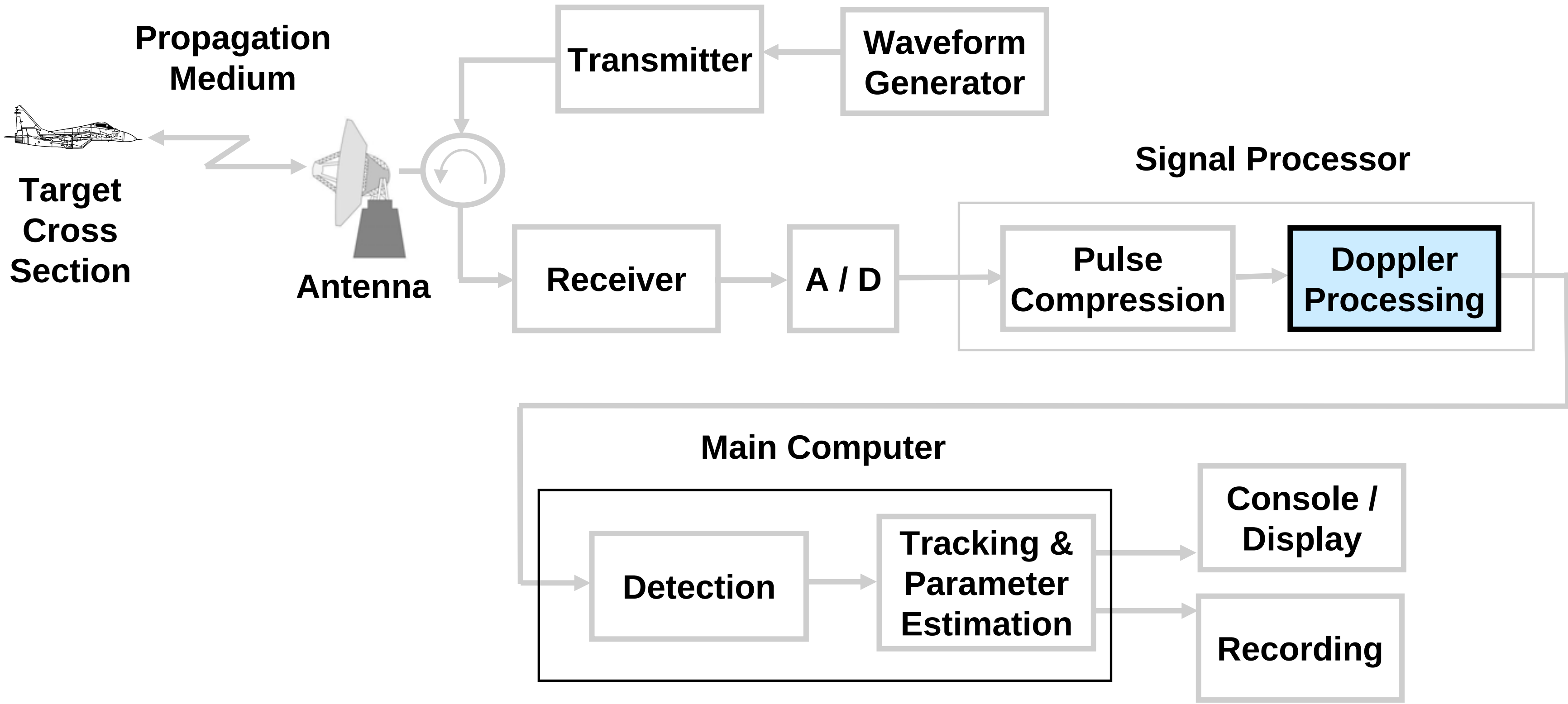
MTI and Doppler Processing



How to Handle Noise and Clutter

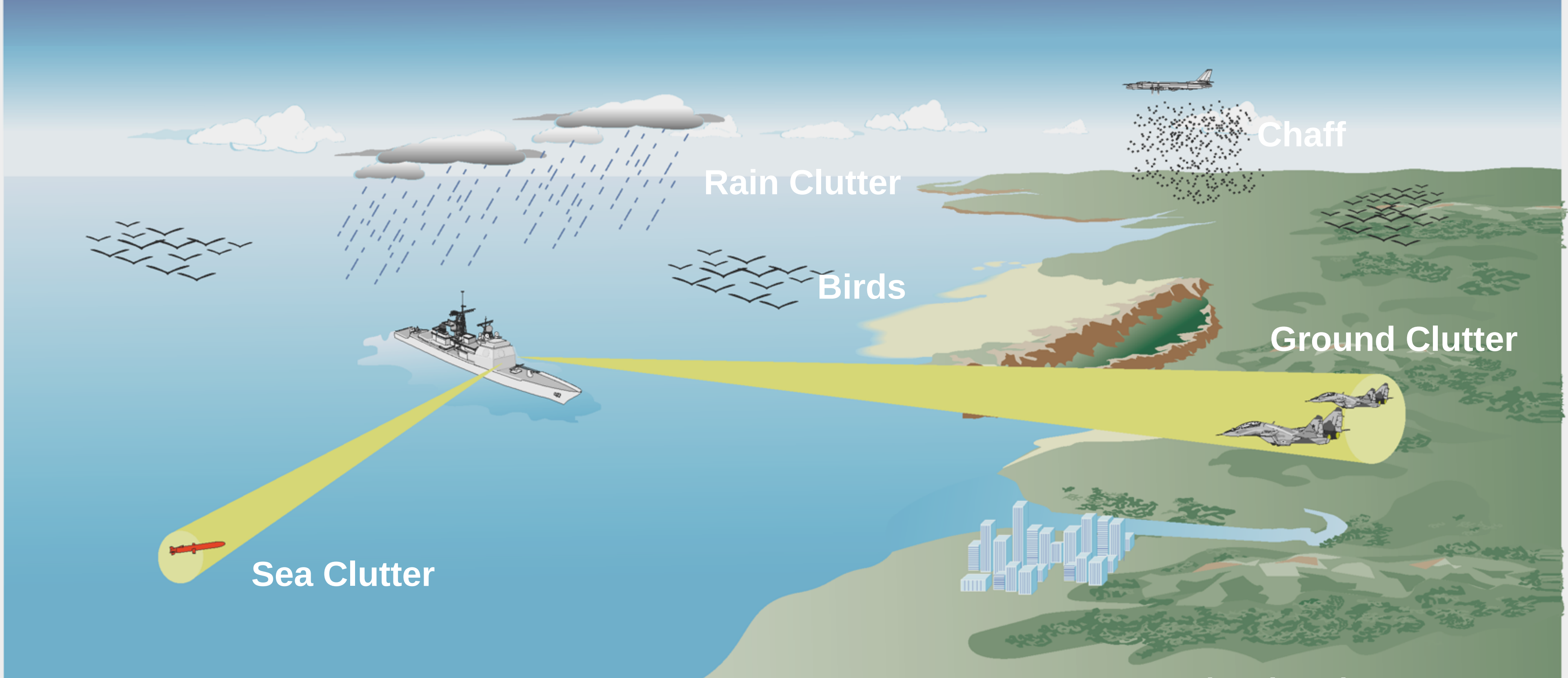
How to Handle Noise and Clutter

If he doesn't take his arm off my shoulder I'm going to hide his stash of Hershey Bars !!

Why does Steve always talk me into doing ridiculous stunts like this ?

Naval Air Defense Scenario

- Moving Target Indicator (MTI) and Pulse-Doppler (PD) processing use Doppler to reject clutter and enhance detection of moving targets
- Smaller targets require more clutter suppression



Outline

- Introduction
- Moving Target Indicator (MTI) Techniques
- Pulse Doppler Processing Techniques
- Summary

Terminology

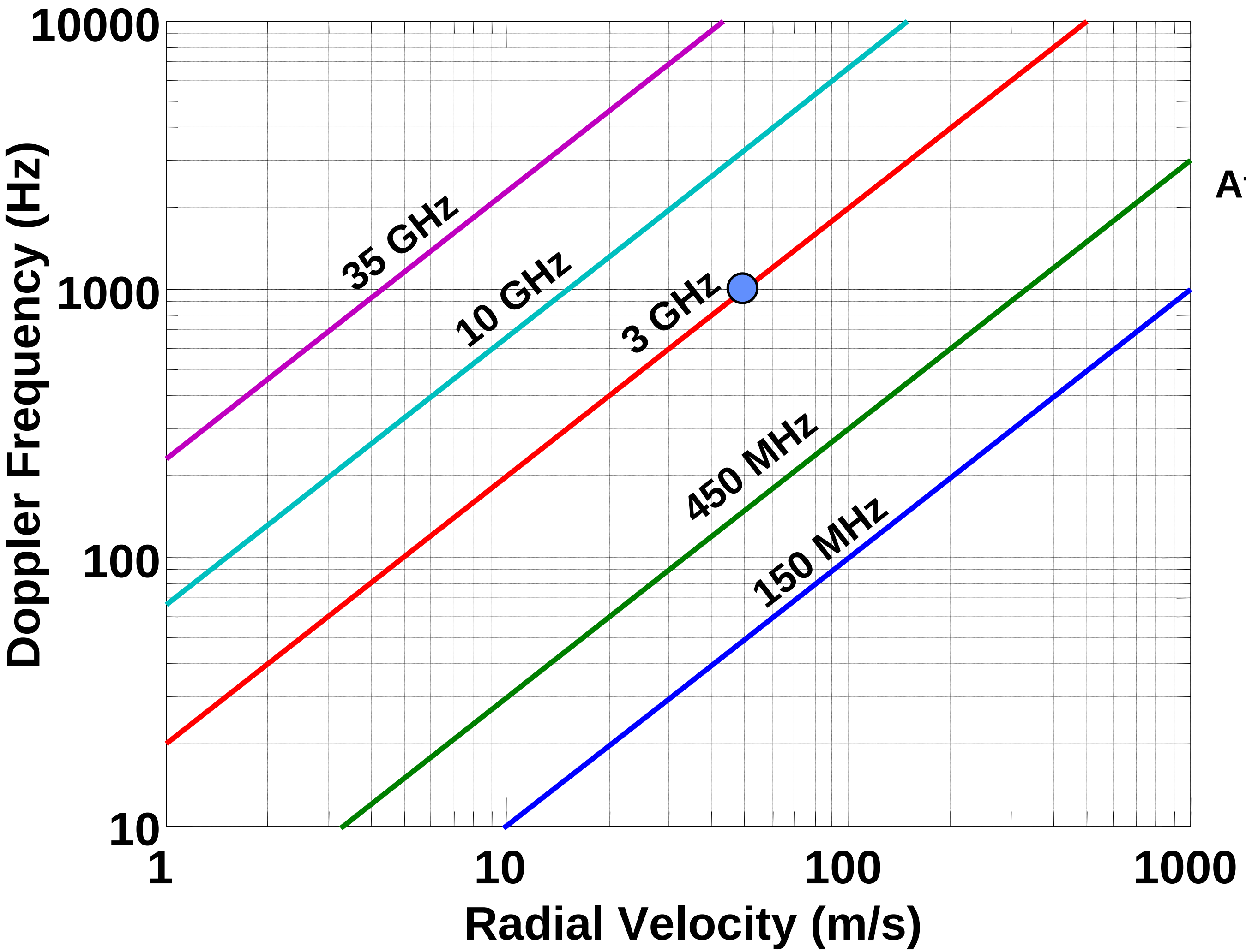
Moving Target Indicator (MTI) Techniques

- Just separate moving targets from clutter
- Use short waveforms   (two or three pulses)
- Do not provide target velocity estimation

Pulsed Doppler (PD) Techniques

- Separate targets into different velocity regimes in addition to canceling clutter
- Provide good estimates of target velocity
- Use long waveforms -- (many pulses, tens to thousands of pulses)

Doppler Frequency



At S-Band (2800 MHz)

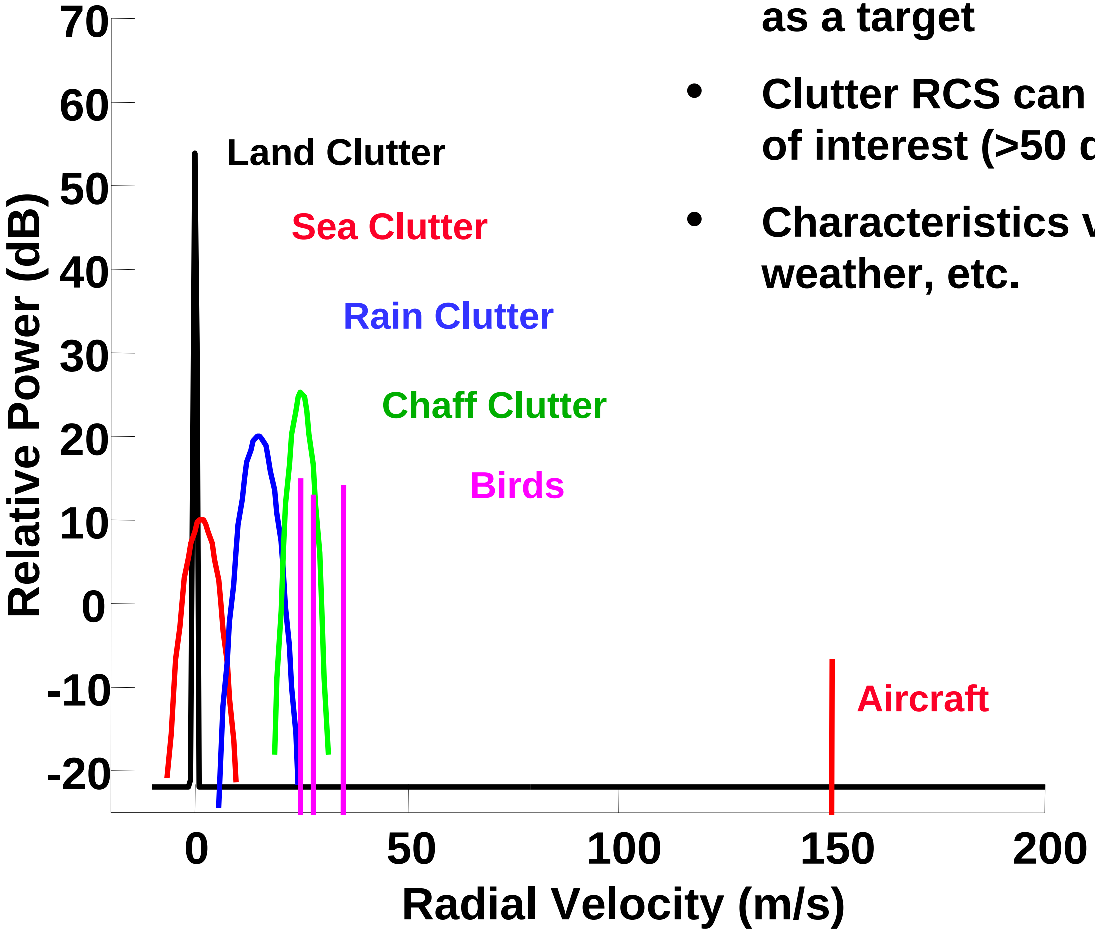
f_d ~ 1 kHz / 40 m/s

Doppler Frequency

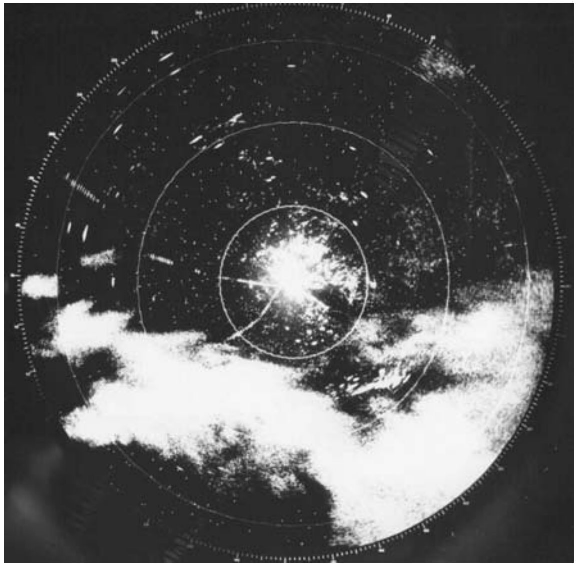
$$f_d = \frac{2V}{\lambda}$$

Example Clutter Spectra

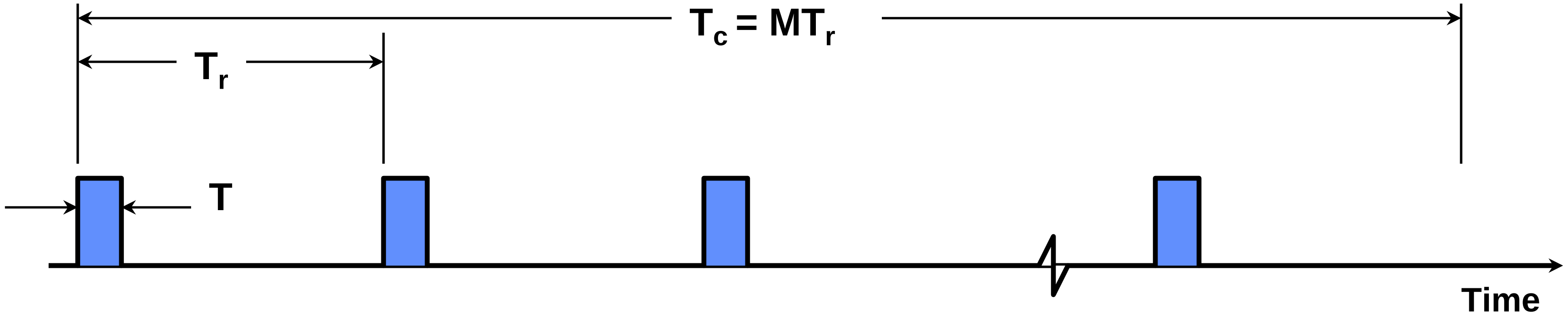
- Clutter comes from same range/angle cell as a target
- Clutter RCS can be much larger than targets of interest (>50 dB)
- Characteristics vary with terrain (land/sea), weather, etc.



PPI Display of Heavy Rain

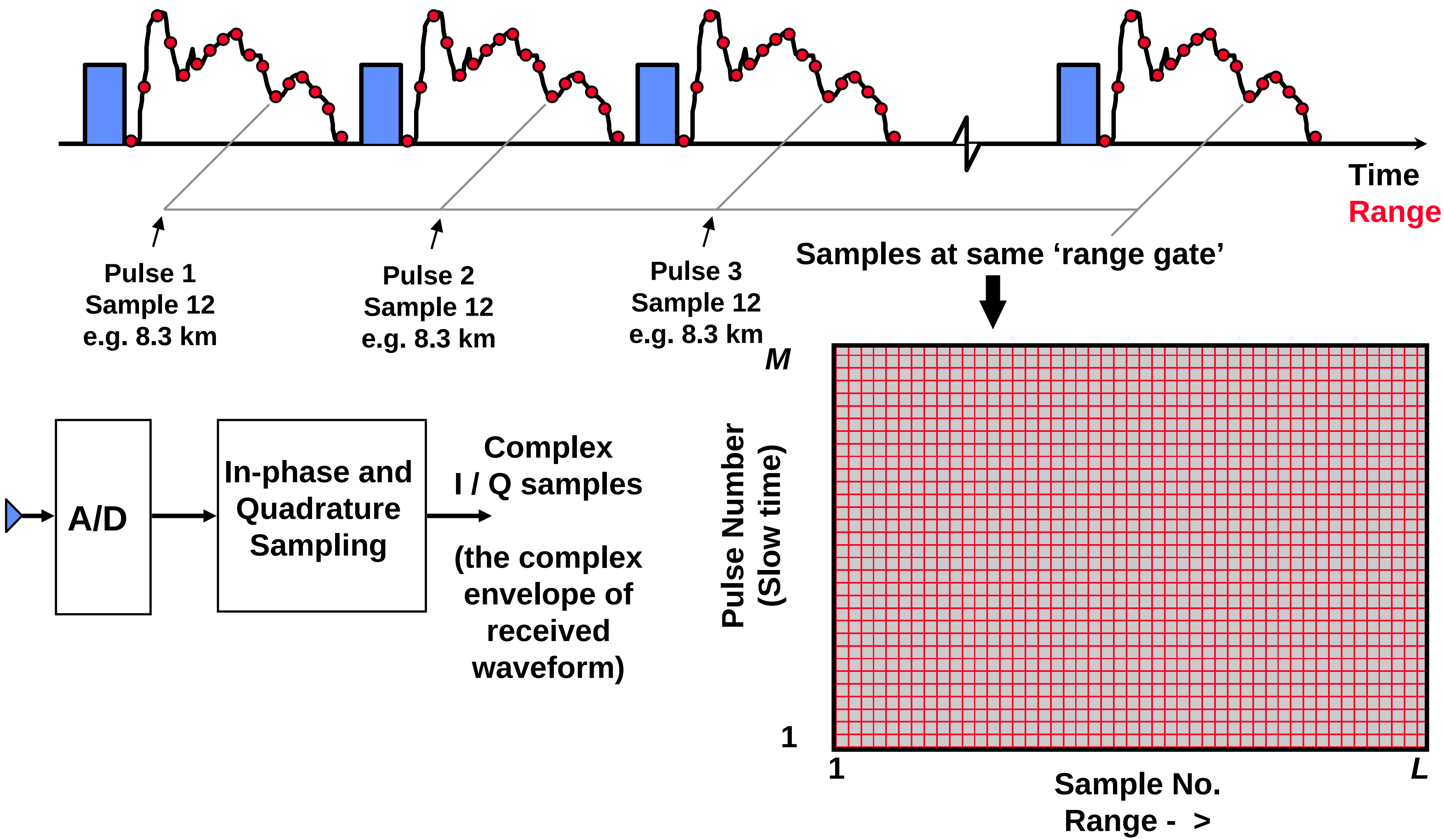


MTI and Pulse Doppler Waveforms



T	=	Pulse length
B	= 1/T	Bandwidth
T_r	=	Pulse repetition interval (PRI)
f_r	$= 1/T_r$	Pulse repetition frequency (PRF)
δ	$= T/T_r$	Duty Factor
T_c	$= MT_r$	Coherent processing interval (CPI)
M	=	Number of pulses in the CPI
		M = 2, 3, or sometimes 4 for MTI
		M usually much greater for Pulse Doppler

Data Collection for Doppler Processing

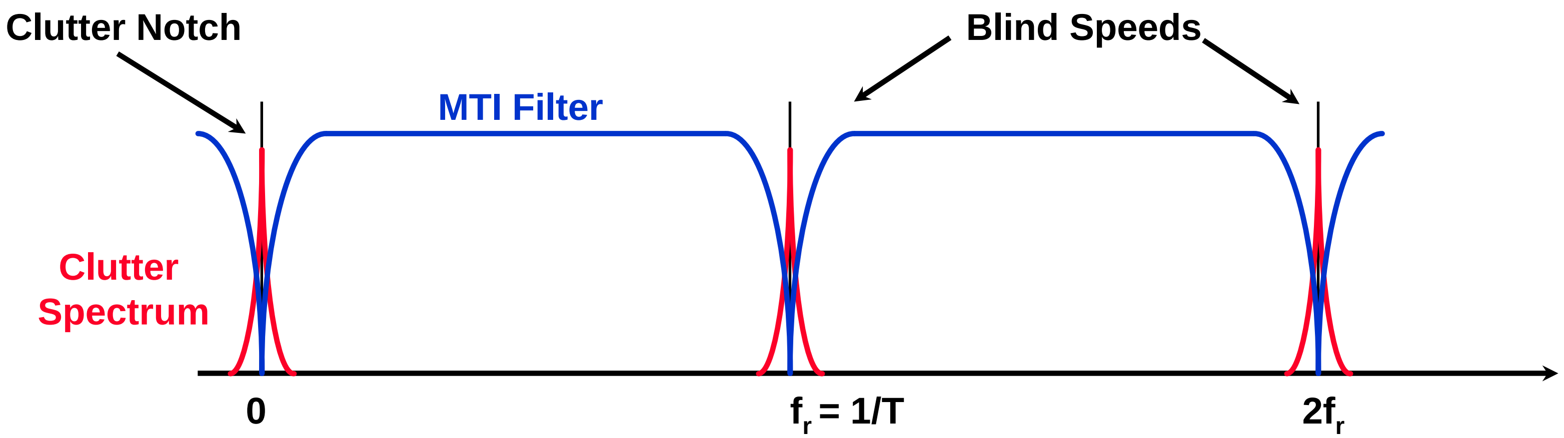


Outline

- Introduction
- Moving Target Indicator (MTI) Techniques
- Pulse Doppler Processing Techniques
- Summary

Moving Target Indicator (MTI) Processing

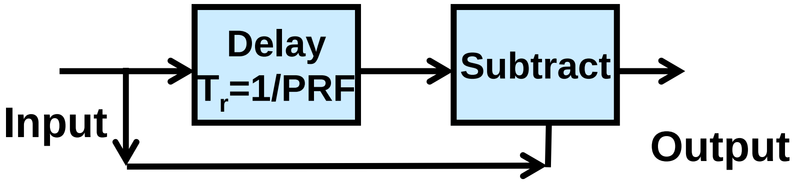
- **Notch out Doppler spectrum occupied by clutter**
- **Provide broad Doppler passband everywhere else**
- **Blind speeds occur at multiples of the pulse repetition frequency**
  - **When sample frequency (PRF) equals a multiple of the Doppler frequency**



Two Pulse MTI Canceller

- **Fixed Clutter echoes**
  - If one pulse is subtracted from the previous pulse, fixed clutter echoes will cancel and will not be detected
- **Moving targets**
  - Moving targets change in amplitude from one pulse to the next because of their Doppler frequency shift.
  - If one pulse is subtracted from the other, the result will be an uncancelled residue

Block Diagram



$$V_{output} = V_{i+1} - V_i$$

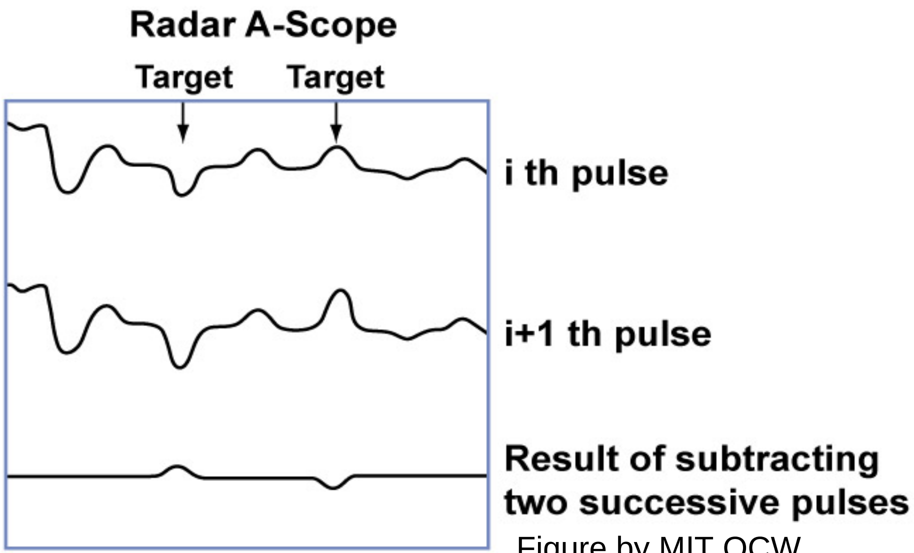
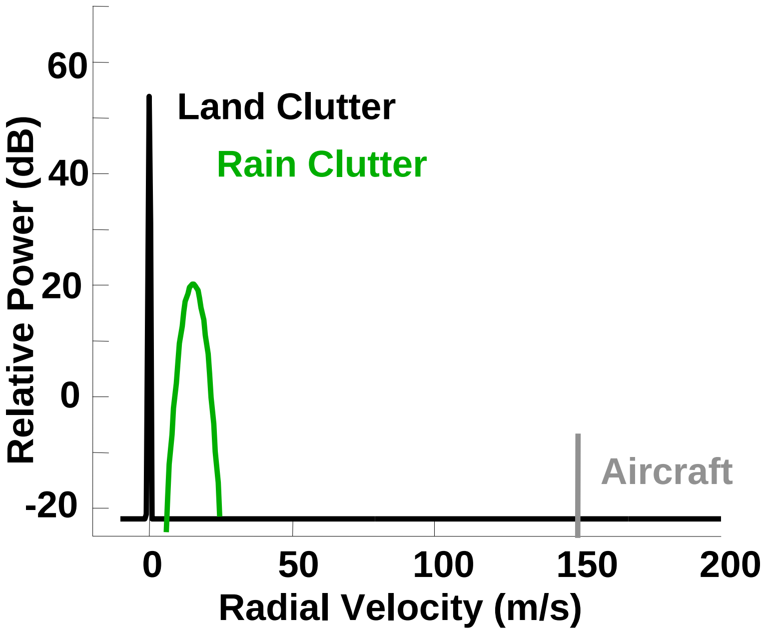


Figure by MIT OCW.

MTI Improvement Factor

- S_{in} and C_{in} - Input target and clutter power per pulse
- $S_{out}(f_d)$ and $C_{out}(f_d)$ – Output target and clutter power from processor at Doppler frequency, f_d
- MTI Improvement Factor = $I(f_d) = \left. \dfrac{(\text{Signal / Clutter})_{out}}{(\text{Signal / Clutter})_{in}} \right|_{f_d}$



MTI Improvement Factor

$$I(f_d) = \left. \frac{C_{in}}{C_{out}} \times \frac{S_{out}}{S_{in}} \right|_{f_d}$$

Clutter Attenuation

Signal Gain

MTI Improvement Factor Examples

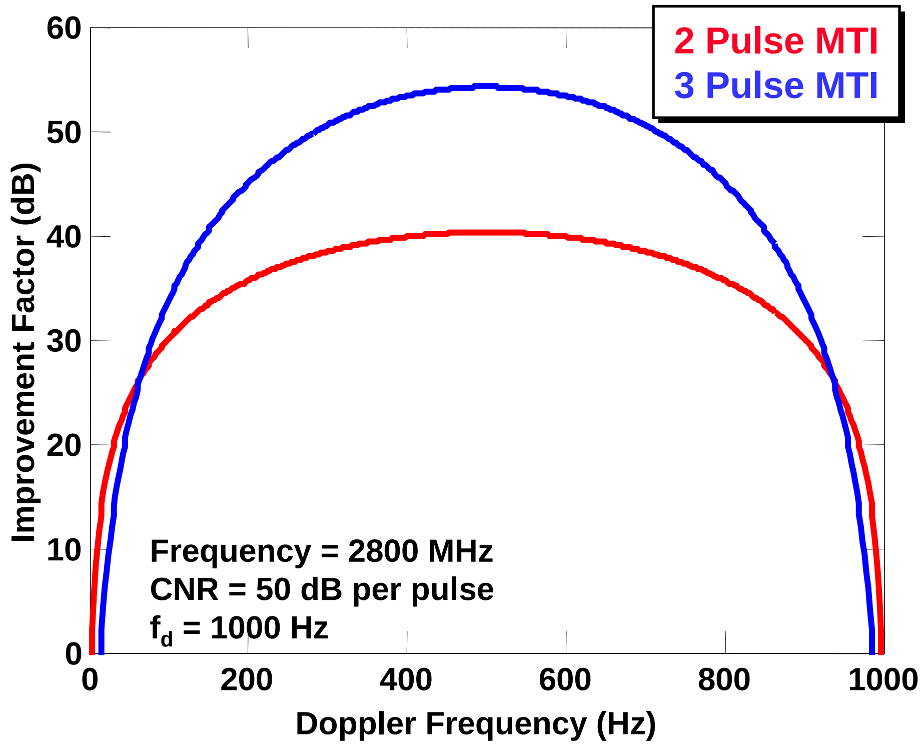
2-Pulse MTI

$$V_{output} = V_i - V_{i-1}$$

3-Pulse MTI

$$V_{output} = V_i - 2V_{i-1} + V_{i-2}$$

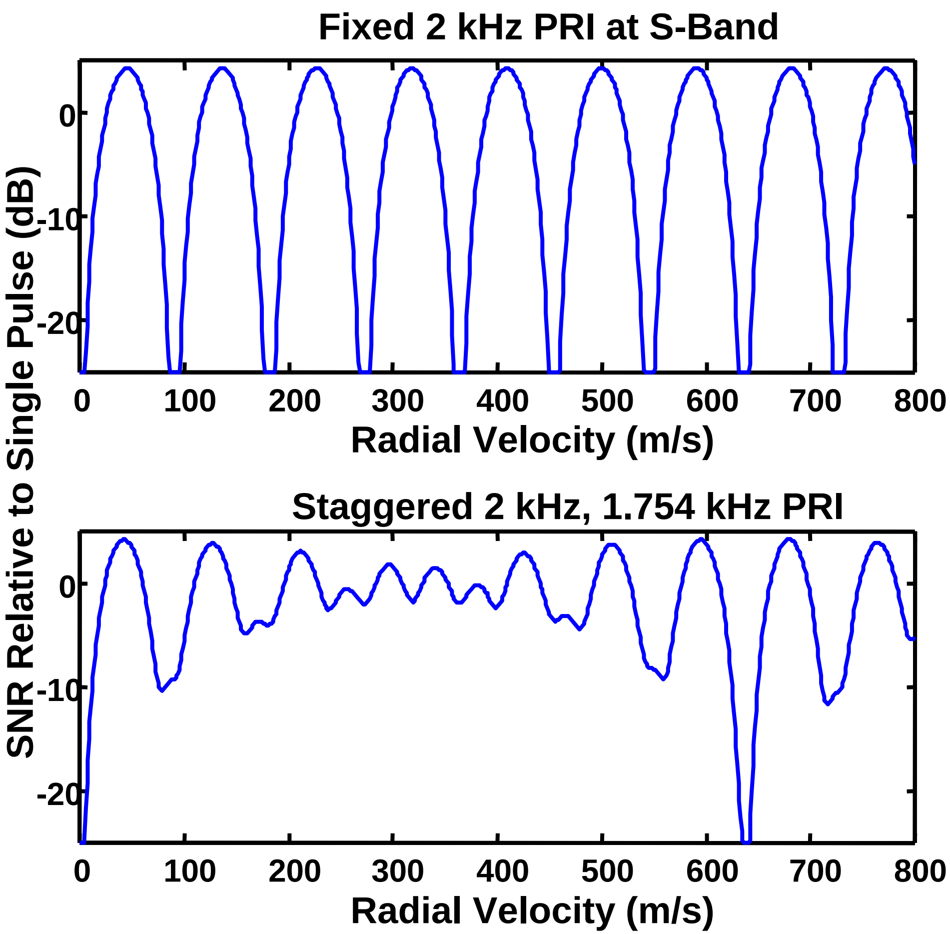
Spread Clutter (σ_v=1 m/s, σ_c=10 Hz)



Three-pulse canceller provides wider clutter notch and greater clutter attenuation

Staggered PRFs to Increase Blind Speed

MTI Frequency Response

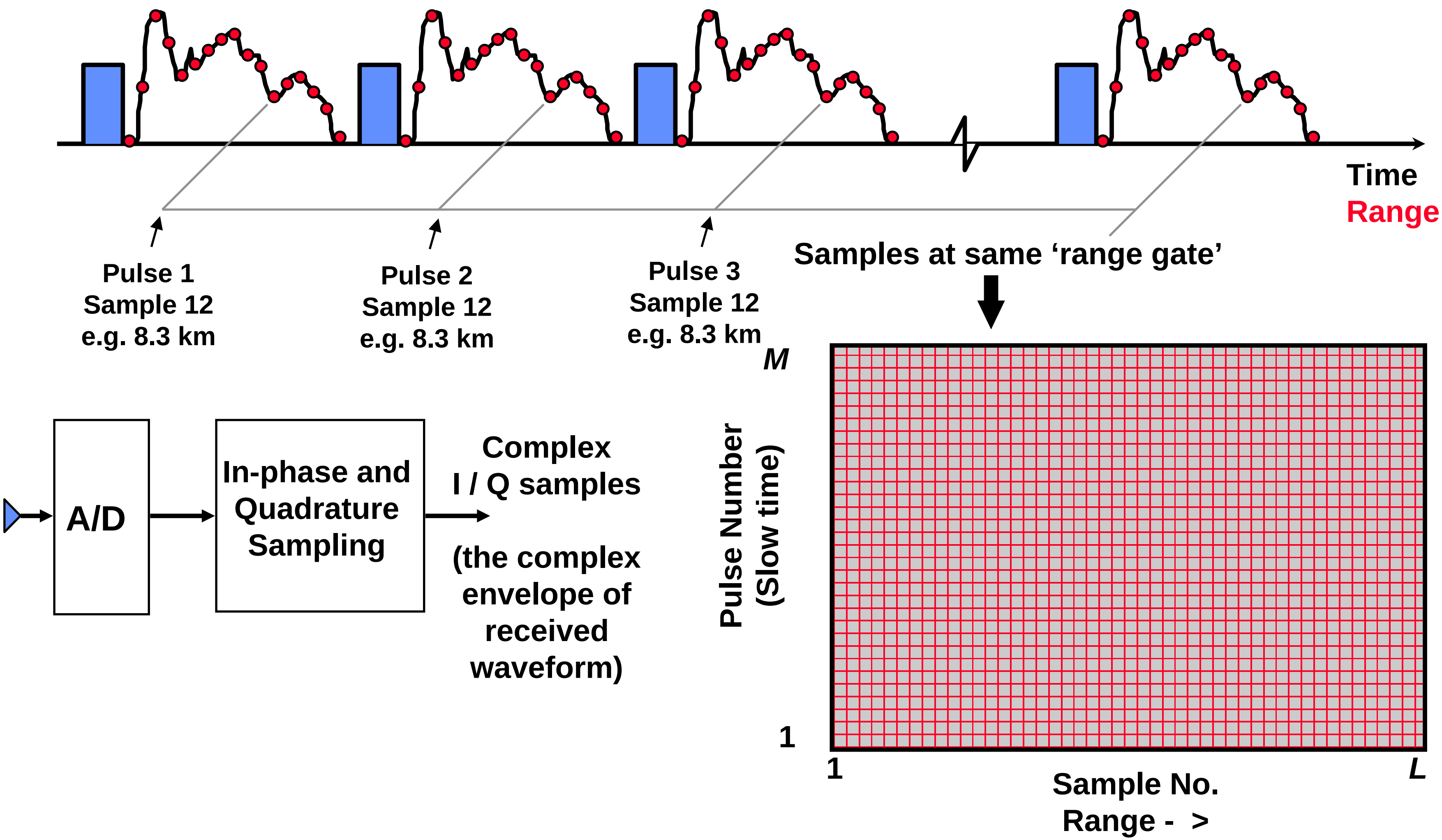


- Staggering or changing the time between pulses will raise the blind speed
- Although the staggered PRF's remove the blind speeds that would have been obtained with a constant PRF, there will be a new much higher blind speed

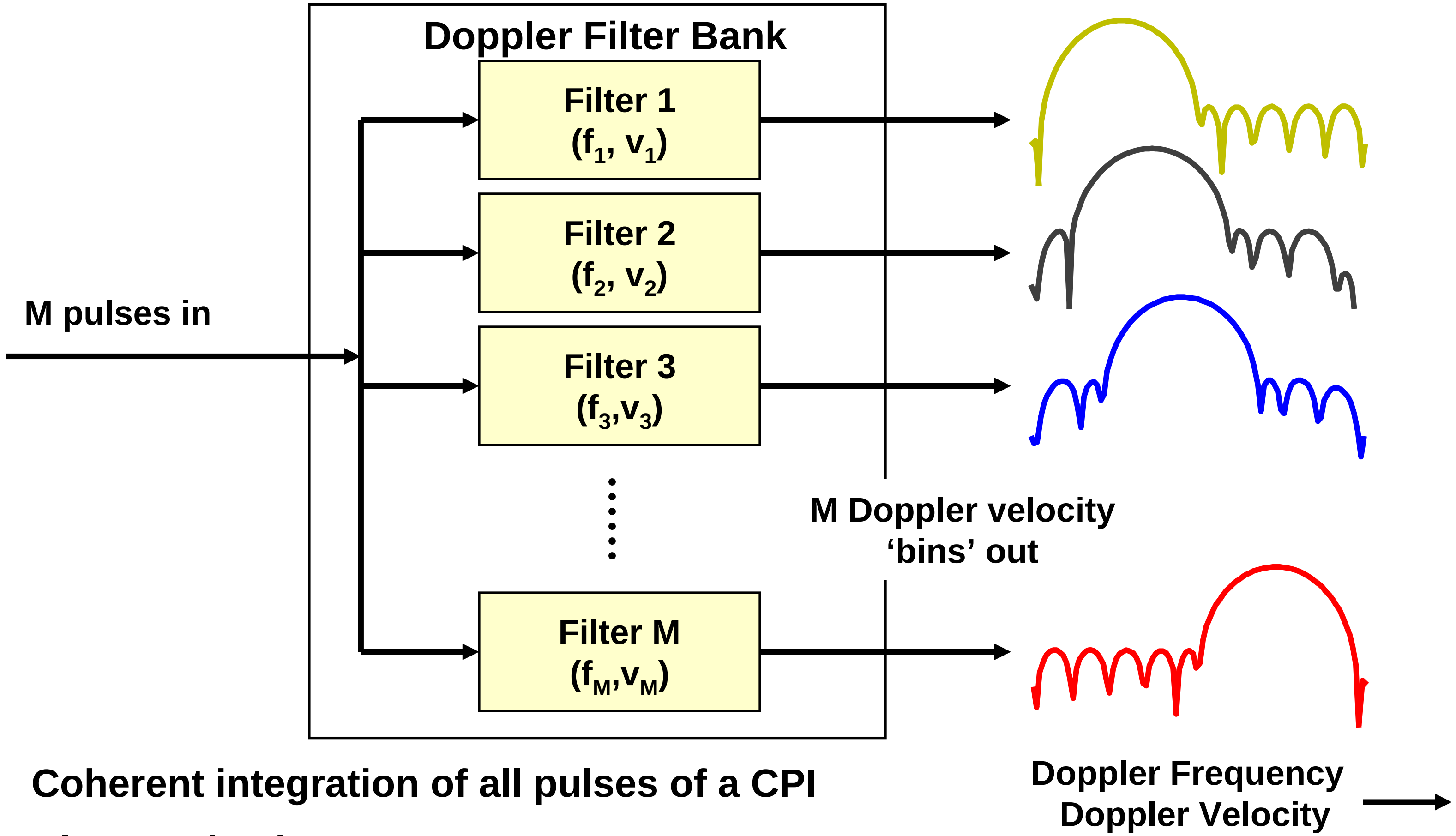
Outline

- Introduction
- Moving Target Indicator (MTI) Techniques
- Pulse Doppler Processing Techniques
  – Pulse Doppler Filtering Concept
    - Basic Concepts
    - Example - Moving Target Detector (MTD)
  – Range Doppler Ambiguities
  – Airborne Radar
- Summary

Data Collection for Doppler Processing

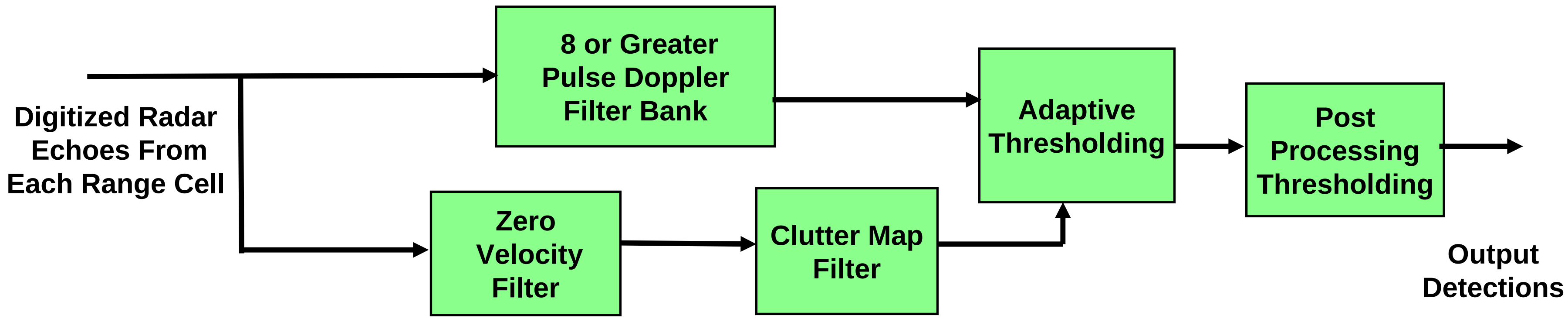


Pulse Doppler Processing



- Coherent integration of all pulses of a CPI
- Clutter rejection
- Resolving targets into different velocity segments and allowing for fine-grain target radial velocity estimation

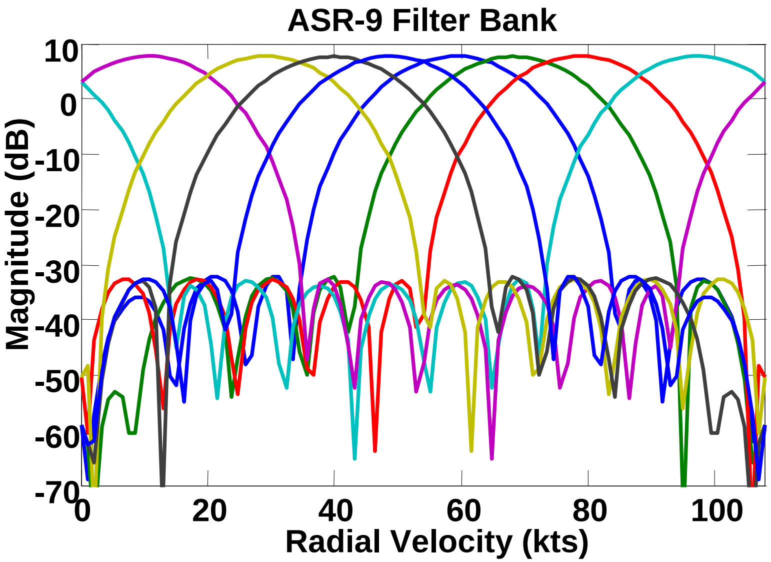
Moving Target Detector (MTD)

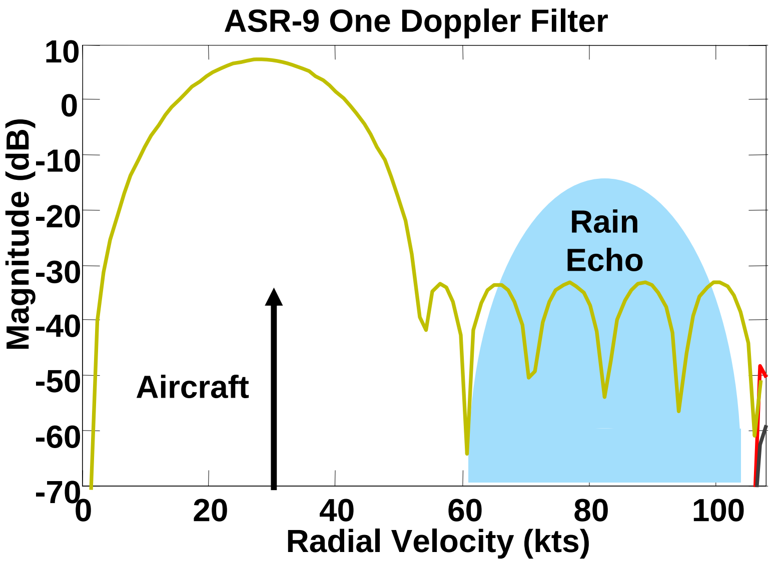


- Pulse Doppler filtering on groups of 8 or greater pulses with a fine grained clutter map.
- Aircraft are detected in ground clutter and / or rain with the Doppler filter bank & use of 2 PRFs.
- Birds and ground traffic are rejected in post processing, using Doppler velocity and a 2nd fine grained clutter map

ASR-9 8-Pulse Filter Bank

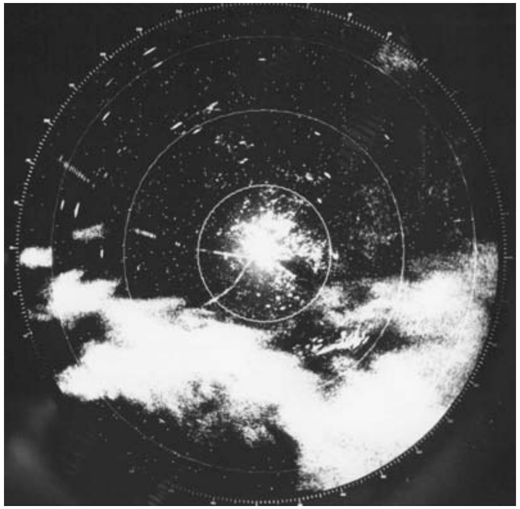
Courtesy of Northrop Grumman
Used with permission.



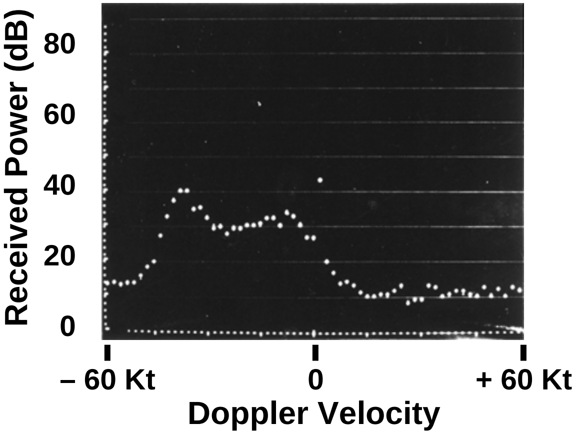


MTD Performance in Rain

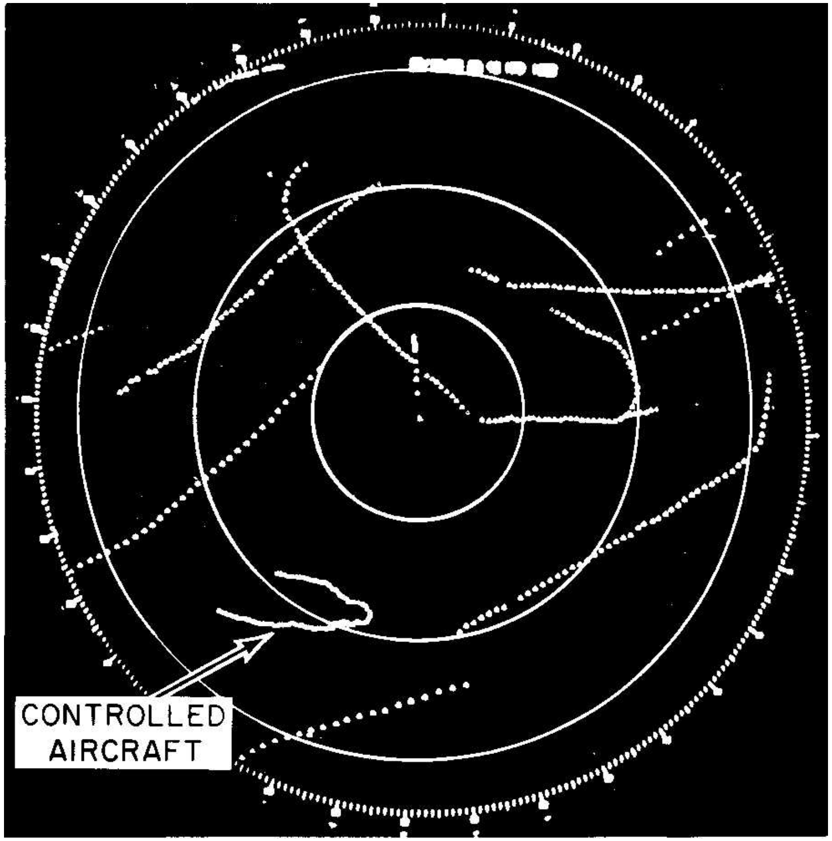
Unprocessed Radar Returns



Doppler Spectrum of Rain



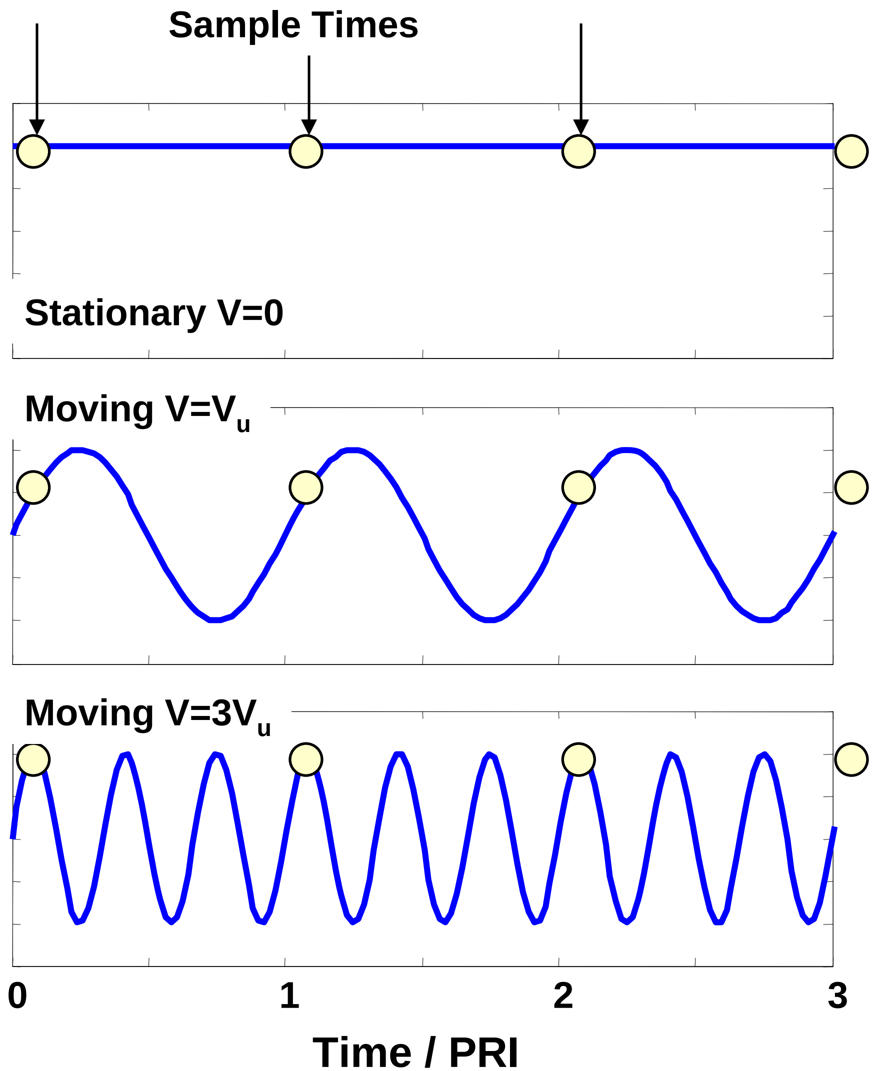
Time History of Radar Tracker Output
August 1975, FAA Test Center



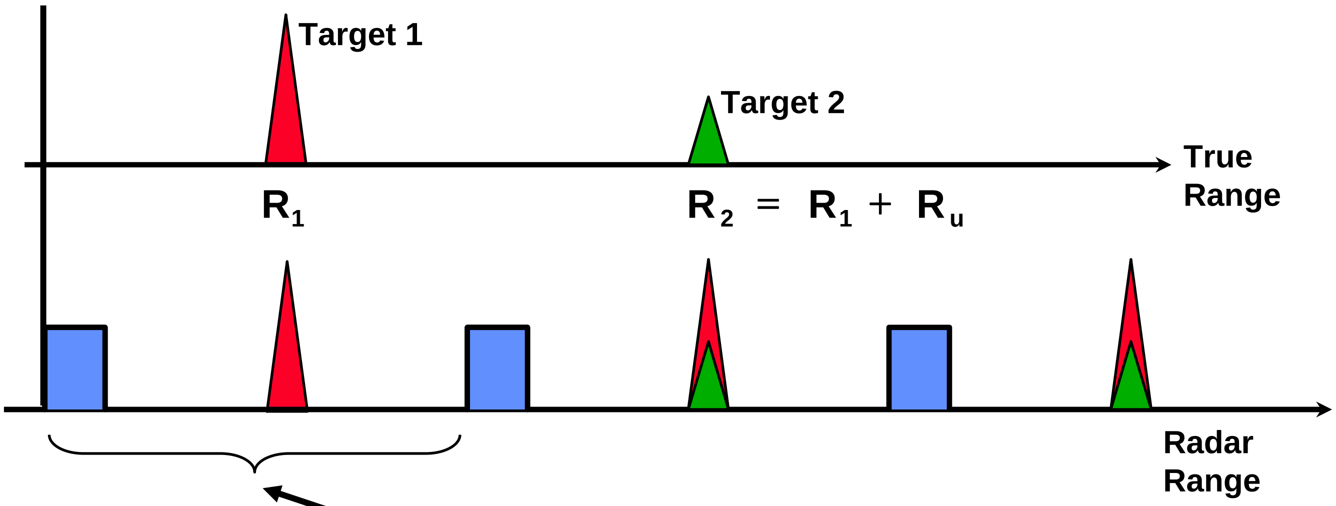
Doppler Ambiguities

- Pulse Doppler waveform samples target with sampling rate = PRF
- Sampling causes aliasing at multiples of PRF
- Two targets with Doppler frequencies separated by an integer multiple of the PRF are indistinguishable
- Unambiguous velocity

$$V_u = \frac{\lambda \, f_r}{2}$$



Range Ambiguities

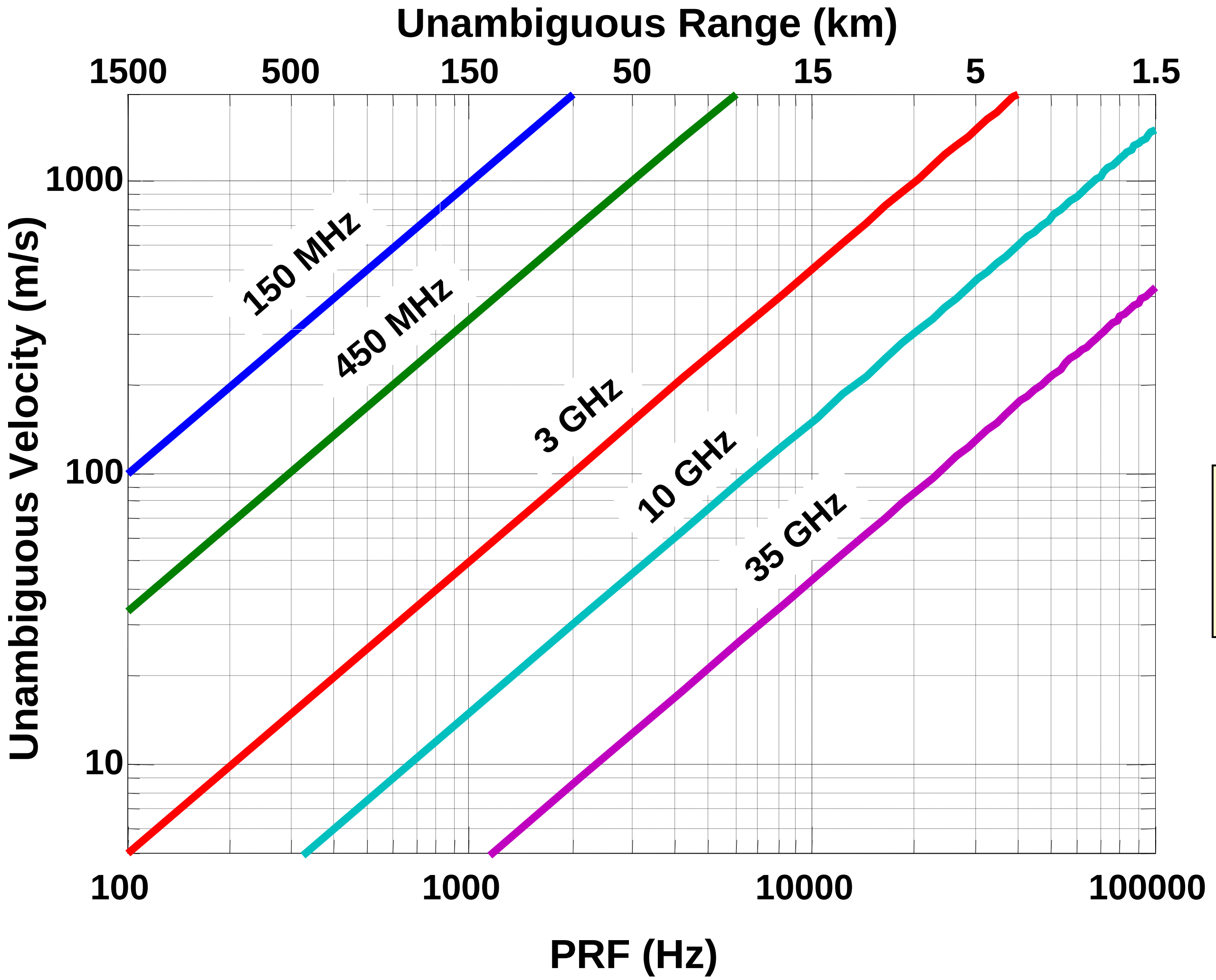


Unambiguous range

$$R_u = \frac{cT_r}{2}$$

- **Range ambiguities occur when echoes from one pulse are not all received before the next pulse**
- **Strong close targets (clutter) can mask far weak targets**

Unambiguous Range and Doppler Velocity



$$V_u = \frac{\lambda \, f_r}{2}$$

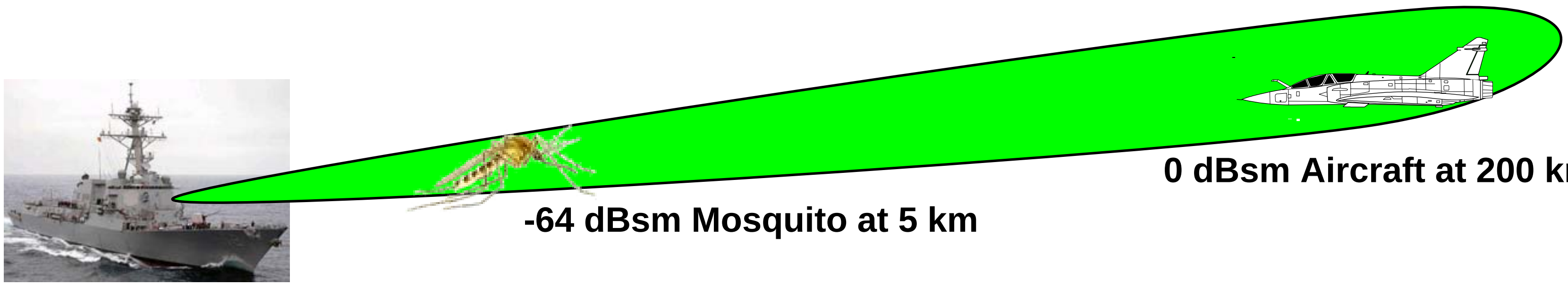
$$R_u = \frac{cT_r}{2} = \frac{c}{2 \, f_r}$$

Sensitivity Time Control (STC)

- **Deliberately reduce radar sensitivity at short ranges**

Why?

Both “Targets” Give Returns with Same Signal-to-Noise ratio



- **Attenuation of radar return by R^{-4} will result in constant SNR as a function of range for a constant cross section target**
- **STC cannot be used if the radar’s waveform is ambiguous in range**
  - **Targets which are beyond the ambiguous range of the radar will be attenuated, because they folded over to close ranges**

Classes of MTI and Pulse Doppler Radars

	Low PRF	Medium PRF	High PRF
Range Measurement	Unambiguous	Ambiguous	Very Ambiguous
Velocity Measurement	Very Ambiguous	Ambiguous	Unambiguous

Low PRF

- Wind blown clutter may be a problem
- Can use STC

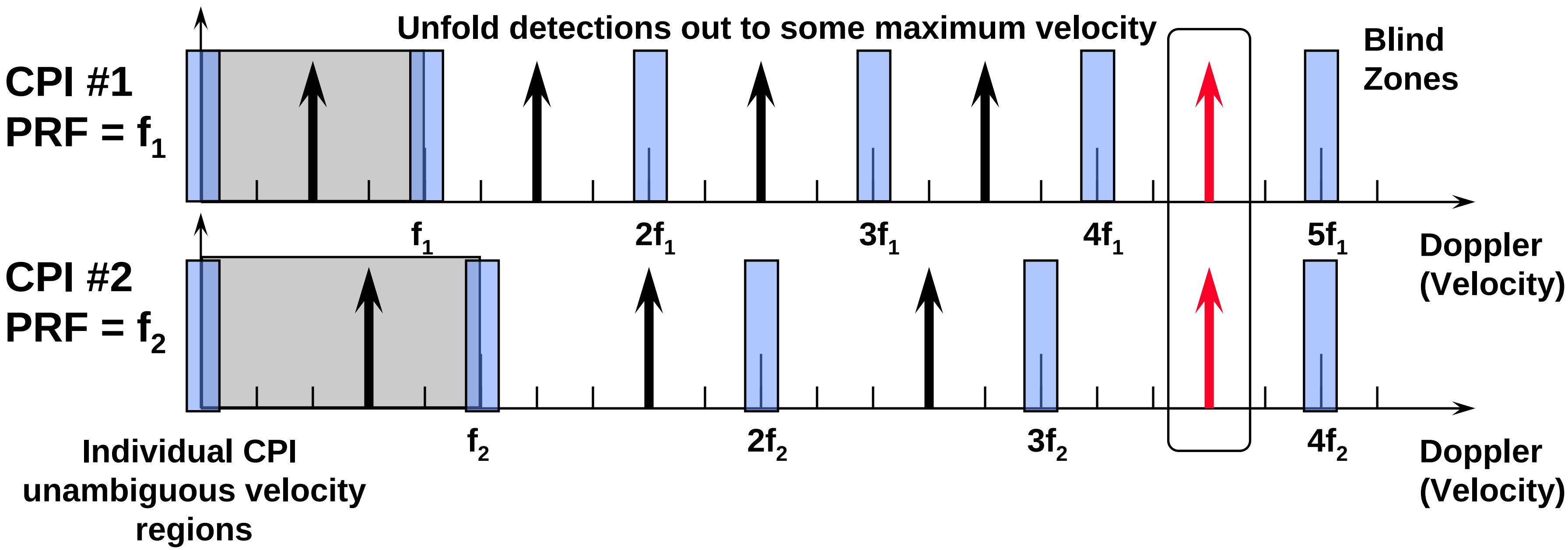
Medium PRF

- Wind blown clutter may be a problem
- Range eclipsing losses
- Far out targets compete with near in clutter
- Can't use STC
- Ambiguities hardest to remove

High PRF

- Range eclipsing losses
- Far out targets compete with near in clutter
- Can't use STC

Velocity Ambiguity Resolution

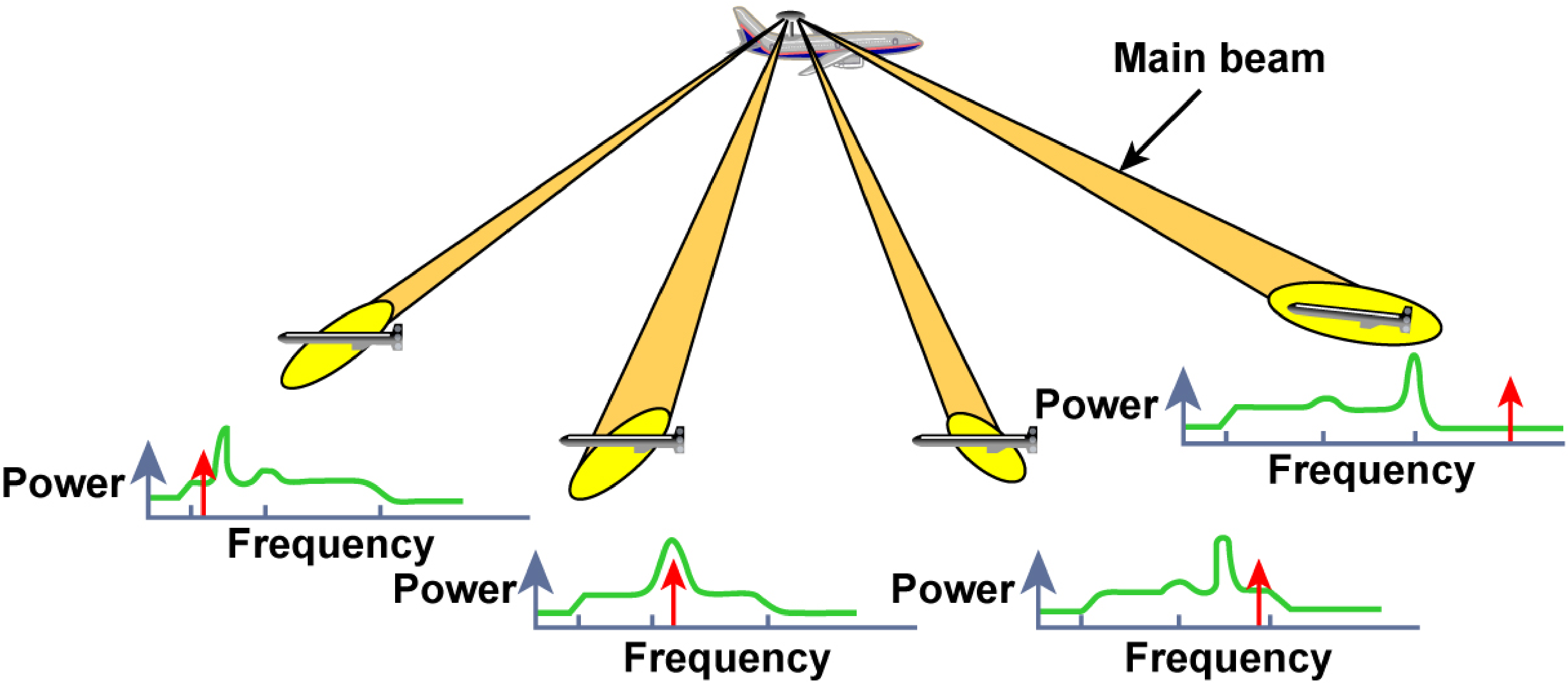


- Split dwell into multiple CPIs at different PRFs
  - Scan to scan, even pulse-to-pulse changes also possible
- Moves blind velocities to ensure detection of all non-zero velocity targets
- True target velocity is where best correlation across CPIs occurs
- Choose PRFs so that least common multiple occurs above desired maximum unambiguous velocity

Examples of Airborne Radar

Airborne Radar Clutter Characteristics

Illustrative example without Pulse-Doppler ambiguities



- Doppler frequency of mainbeam clutter depends on scan direction
- Doppler frequency of target depends on scan direction and target aspect angle

Figure by MIT OCW.

Airborne Radar Clutter Spectrum

Illustrative example without Pulse Doppler ambiguities

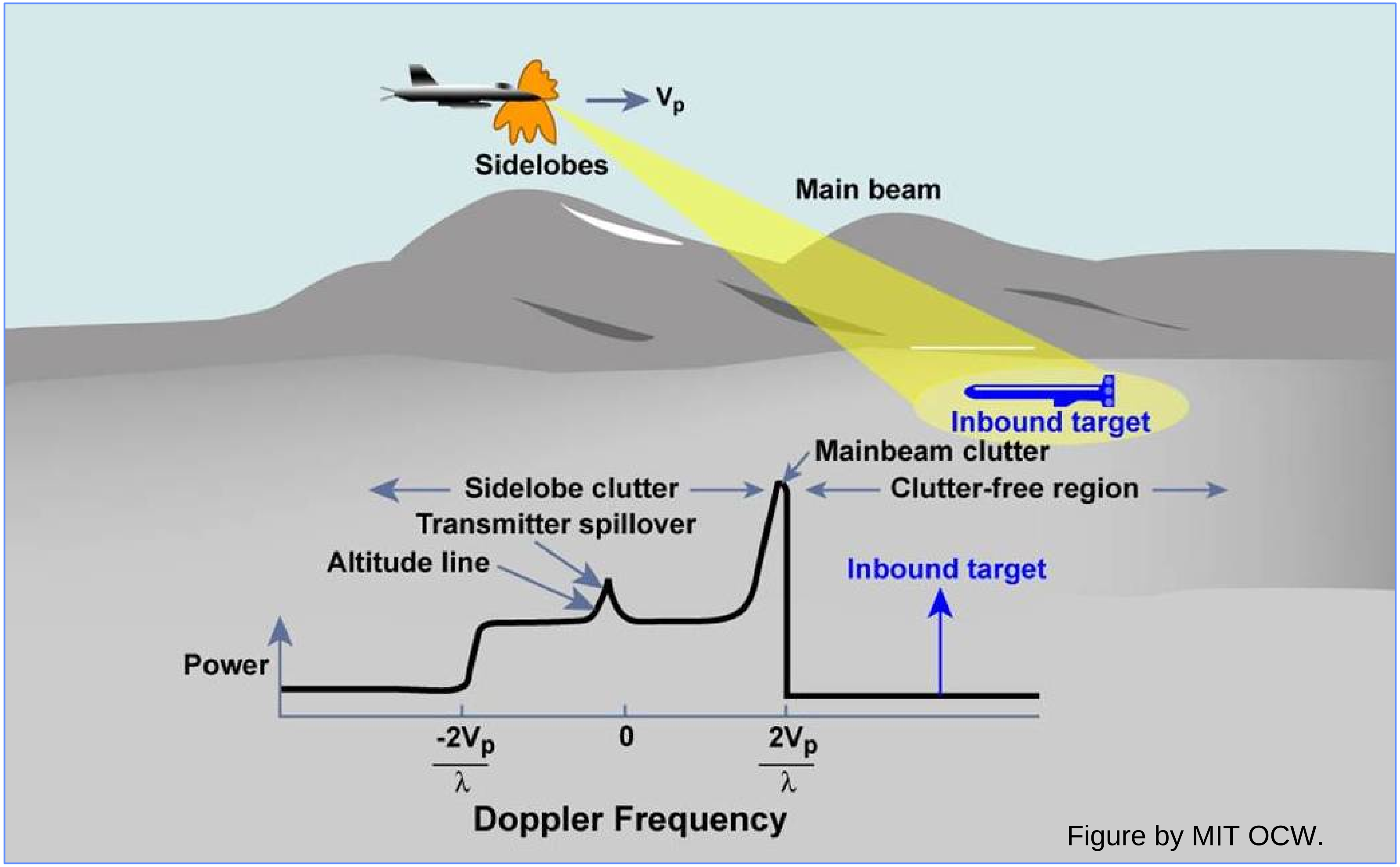


Figure by MIT OCW.

Airborne Radar Clutter Spectrum

Illustrative example without Pulse Doppler ambiguities

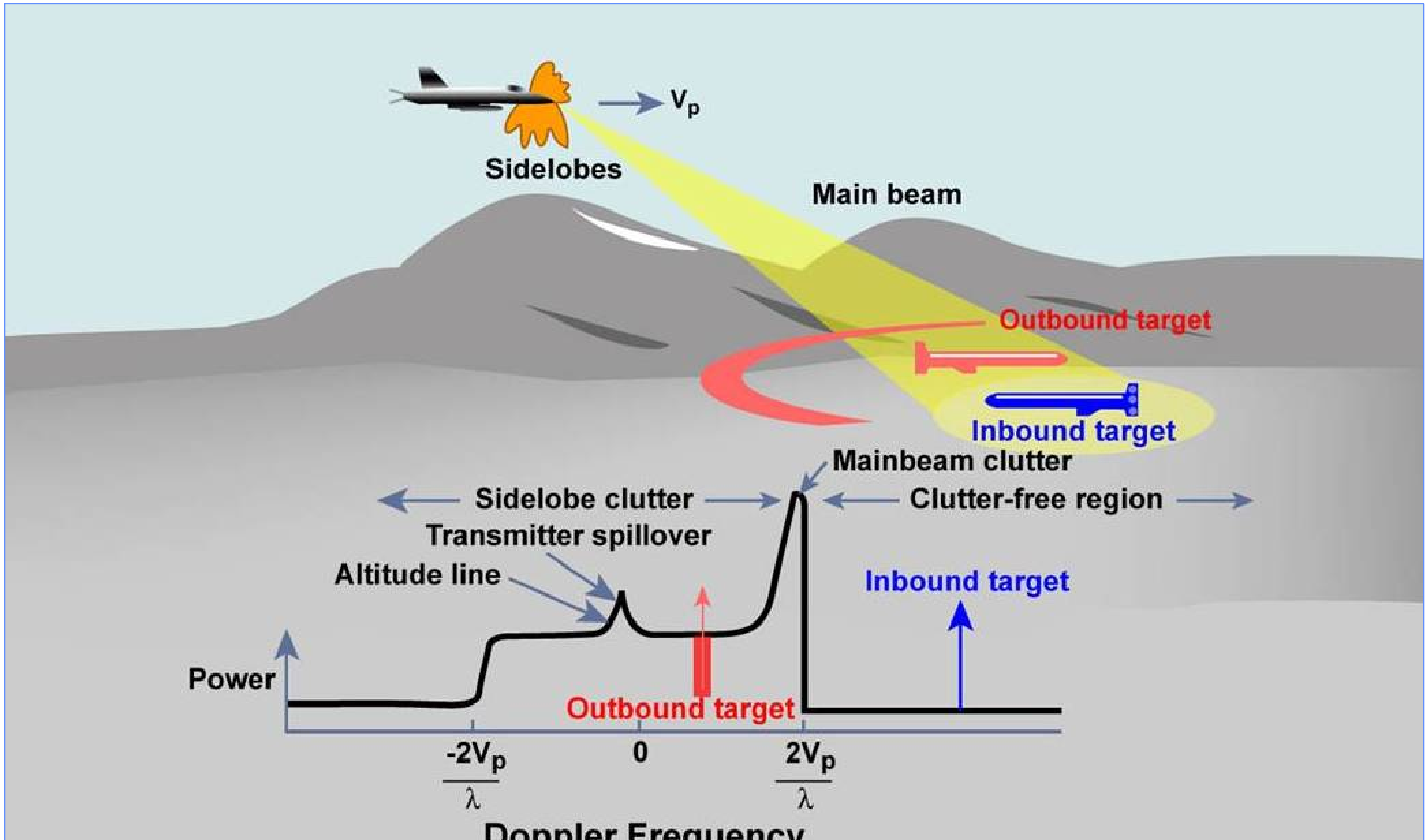
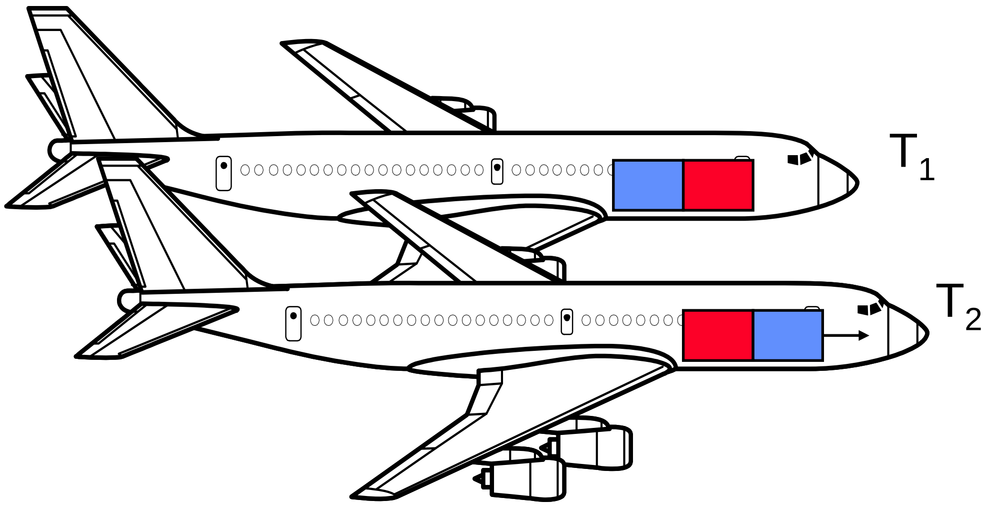


Figure by MIT OCW.

Displaced Phase Center Antenna (DPCA) Concept



If the aircraft motion is exactly compensated by the movement of the phase center of the antenna beam, then there will be no clutter spread due to aircraft motion, and the clutter can be cancelled with a two pulse canceller

Summary

- **Moving Target Indicator (MTI) techniques**
  - **Doppler filtering techniques that reject stationary clutter**
    - **No velocity measurement**
  - **Blind speeds are regions of Doppler space where targets with that Doppler velocity cannot be detected**
    - **Changing the PRF between sets of pulses can alleviate the blind speed problem**
  - **MTI techniques have a limited capability to suppress rain clutter**
- **Pulse Doppler techniques**
  - **Used to optimally reject various forms of radar clutter**
    - **Measurement of target radial velocity**
    - **Moving Target Detector techniques are an example of optimum Doppler processing and associated adaptive thresholding**
  - **Ambiguities in range and Doppler velocity can be resolved by transmitting multiple bursts of pulses with different PRF's**
  - **Airborne radars use multiple PRF waveforms to suppress clutter**

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001

Introduction to Radar Systems

Tracking and Parameter Estimation

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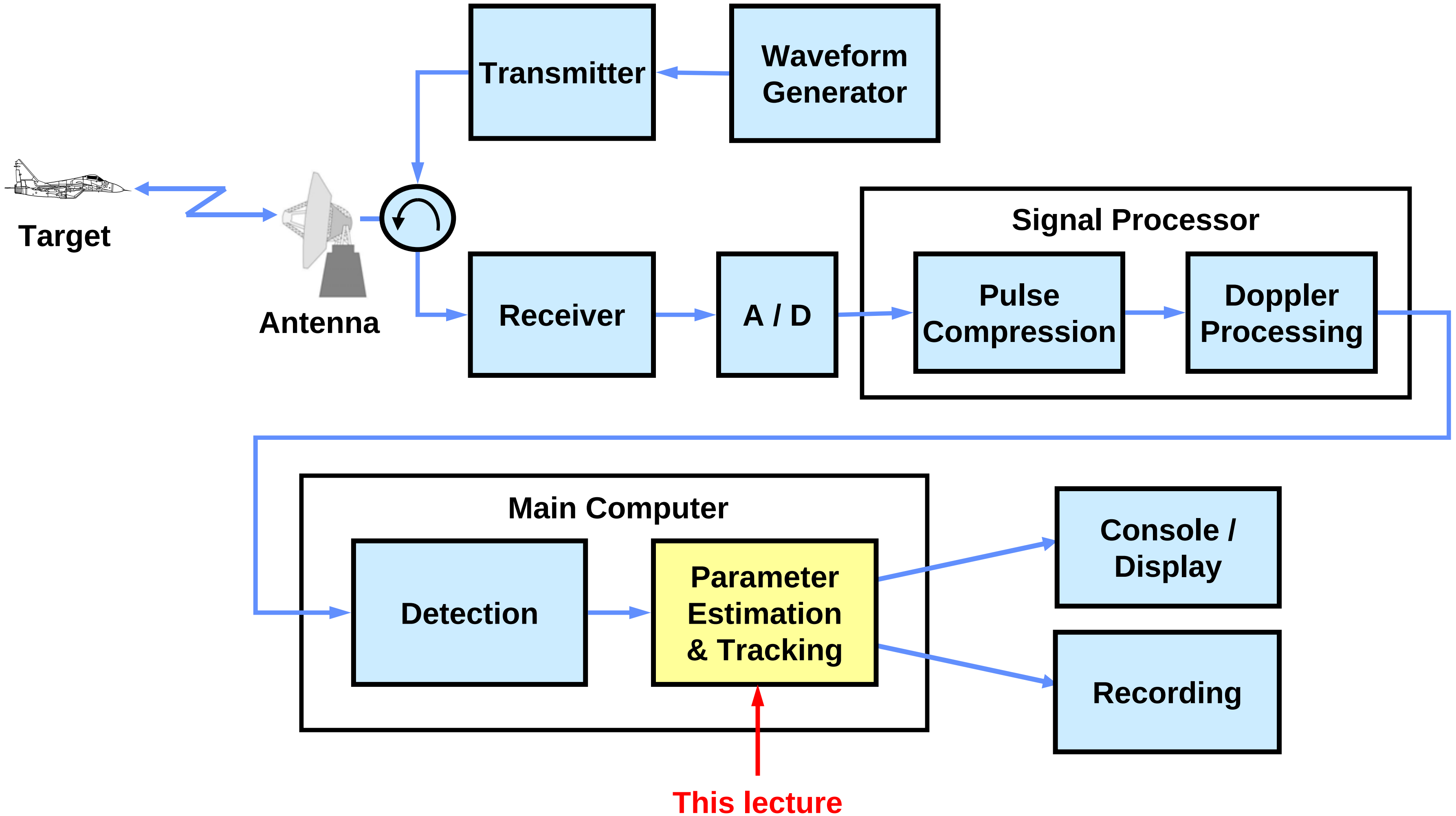
Generic Radar Block Diagram



Tracking Radars

MOTR

Courtesy of Lockheed Martin.
Used with permission.

BMEWS

Courtesy of Raytheon.
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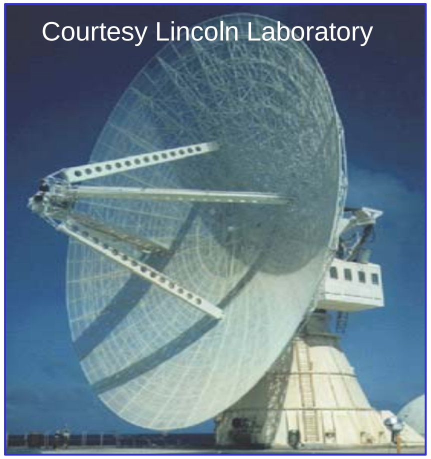
ASR

Courtesy Lincoln Laboratory

Courtesy of US Navy.

AEGIS



Courtesy Lincoln Laboratory

TRADEX

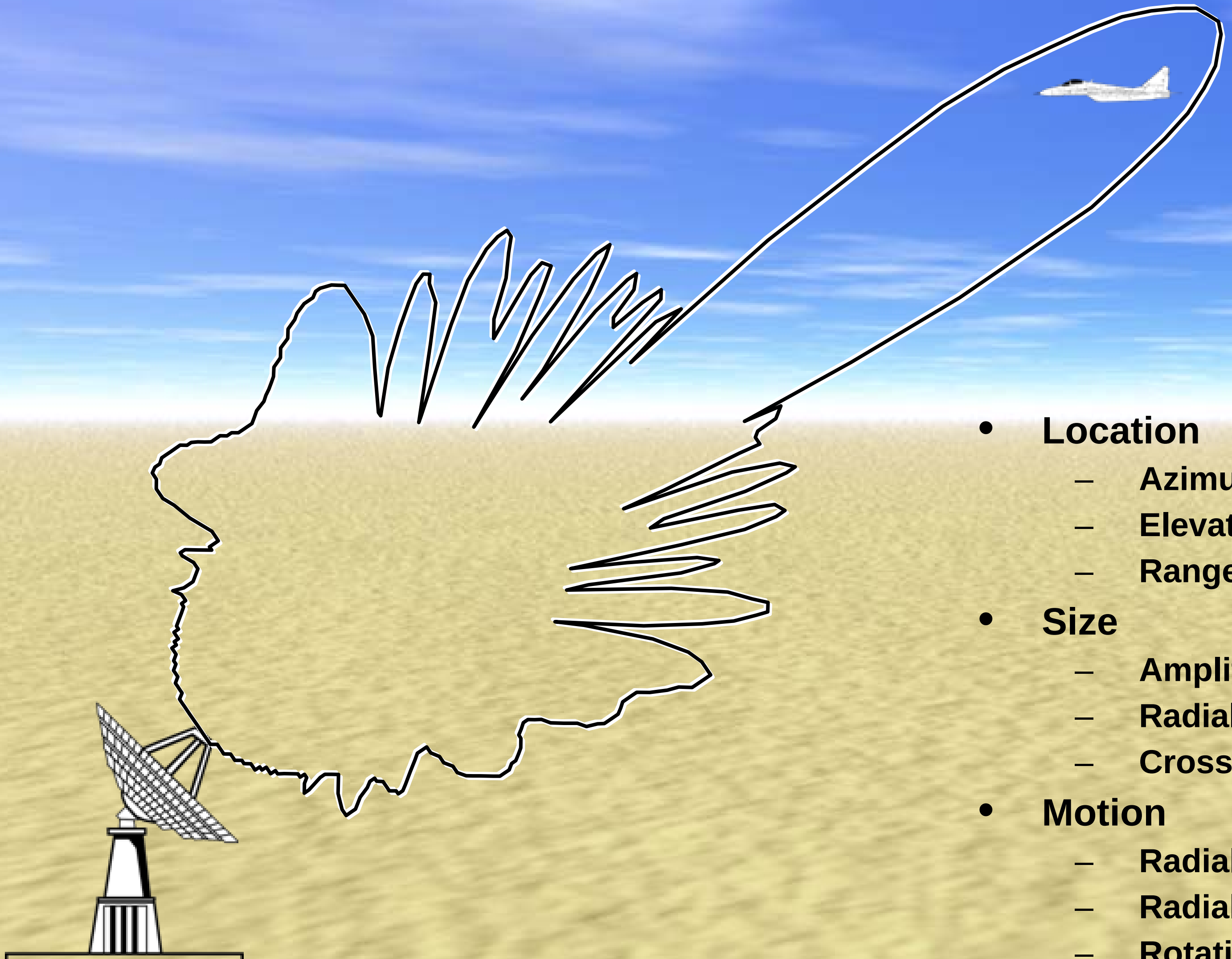
Parameter Estimation and Tracking Functions

- **After a target is initially detected, the radar must:**
  - Continue to detect the target
  - Estimate target parameters from radar observations
    - Position, size, motion, etc.
  - Associate detections with specific targets
    - Are all these nearby detections from the same target?
    - Use range, angle, Doppler measurements
  - Predict where the target will be in the future
  - Use multiple observations to develop a more accurate filtered estimate of the target track

Outline

- Introduction
- Estimation
  - Range Estimation
  - Angle Estimation
    - Monopulse
  - Estimation Performance
  - Velocity (Doppler) Estimation
- Tracking
- Summary

Radar Parameter Estimation



- **Location**
  - Azimuth Angle
  - Elevation Angle
  - Range
- **Size**
  - Amplitude (RCS)
  - Radial Extent (Length)
  - Cross Range Extent (Width)
- **Motion**
  - Radial Velocity
  - Radial Acceleration
  - Rotation, Precession
  - Ballistic Coefficient

Parameter Estimation

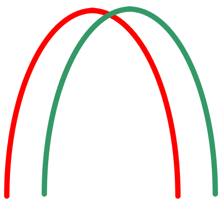
- **Primary metric parameters are range, angle, and Doppler velocity**

Parameter	Resolution	Key Characteristics
Range	1 / BW	Bandwidth
Angle	λ / D	Antenna size
Velocity (Doppler)	λ / Δt	Coherent Integration Time

  – **Accuracy improves as signal to noise ratio (SNR) increases**

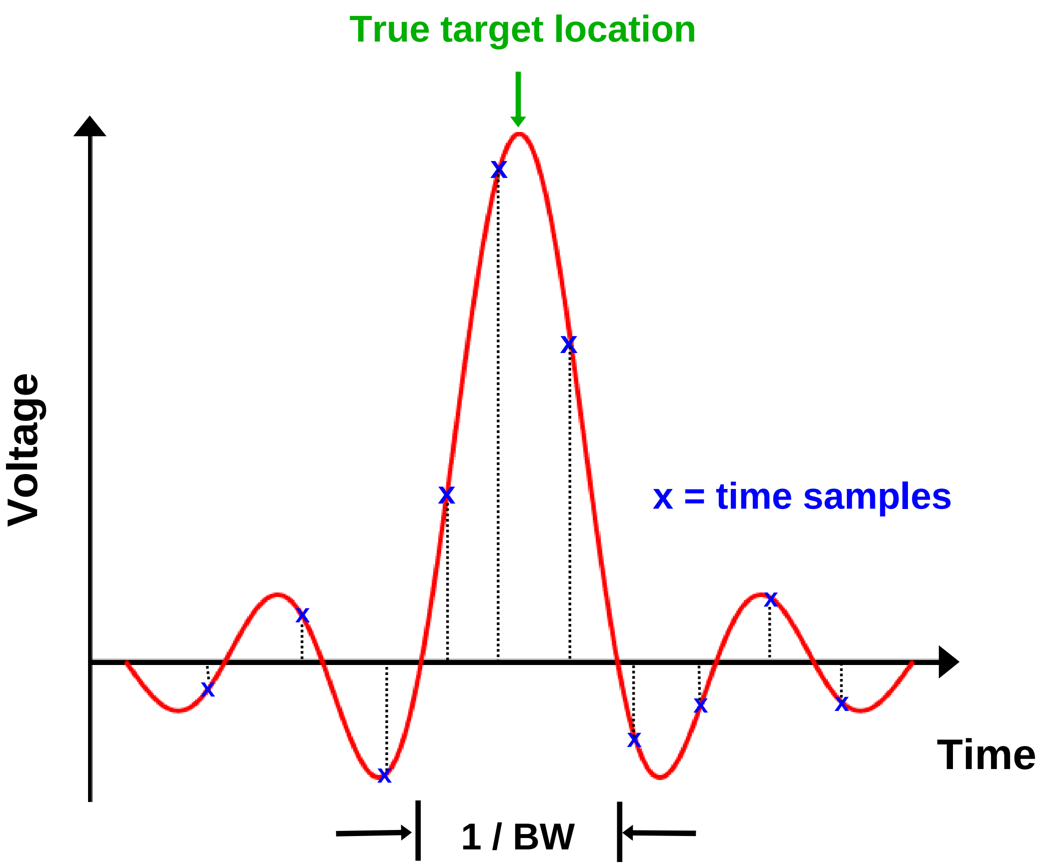
$$\sigma \propto \frac{\text{Resolution}}{\sqrt{\text{SNR}}}$$

- **Basic approach: Overlapped measurements**
  – **Range splitting**
  – **Monopulse techniques**
  – **Doppler bin splitting**



Range Estimation

Output of Pulse Compression

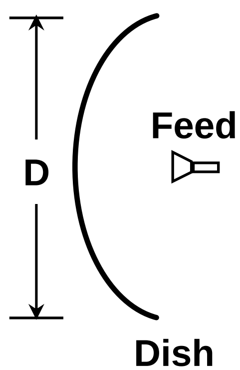


- **Range estimation** uses multiple time samples for peak fitting to achieve greater accuracy
- Range estimation accuracy improves with increasing bandwidth
- Range accuracy $\propto \dfrac{1}{BW} \cdot \dfrac{1}{\sqrt{SNR}}$

Increased Antenna Size Improves Beamwidth

- **Ability to resolve target directly impacts ability to estimate target location**

Parabolic Reflector Antenna

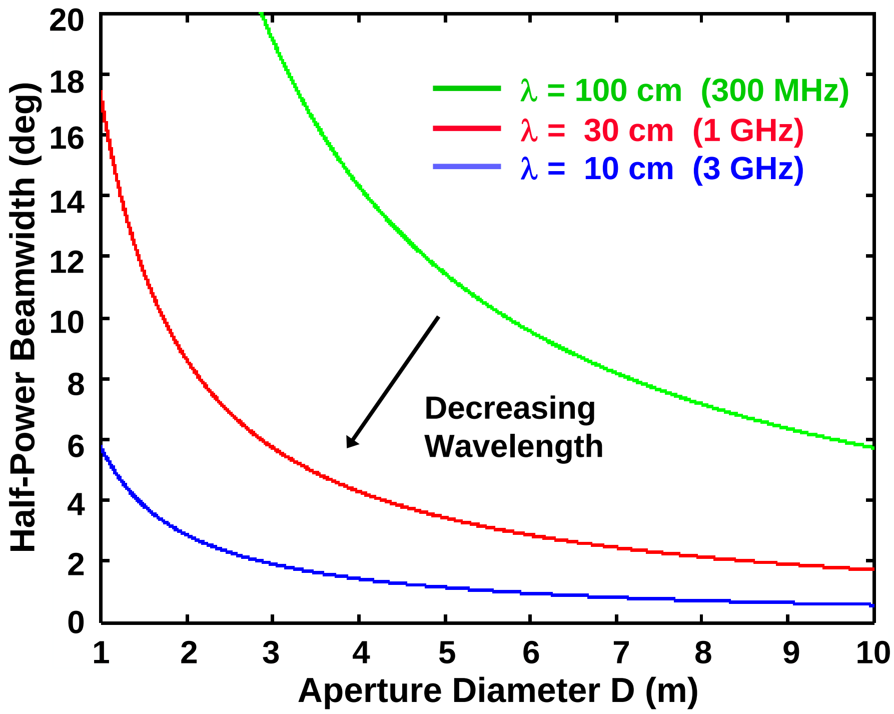


Beamwidth (deg) $\approx \frac{\lambda}{D} \cdot \frac{180}{\pi}$

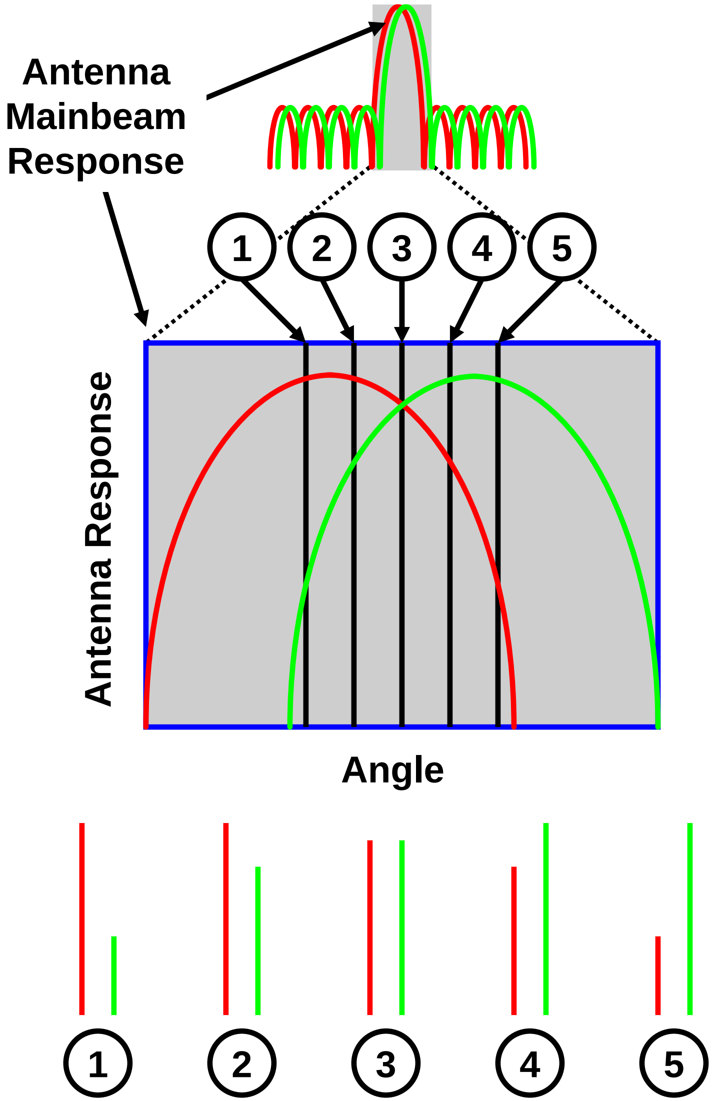
where D = aperture diameter

λ = wavelength

Antenna Beamwidth vs. Diameter

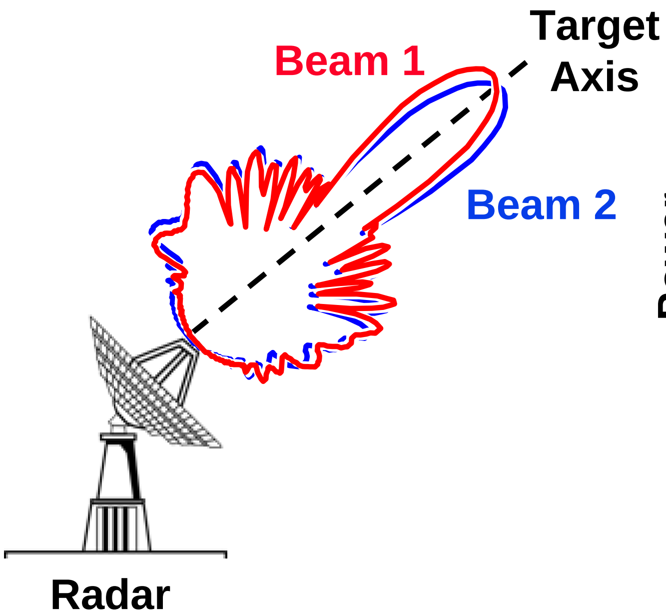


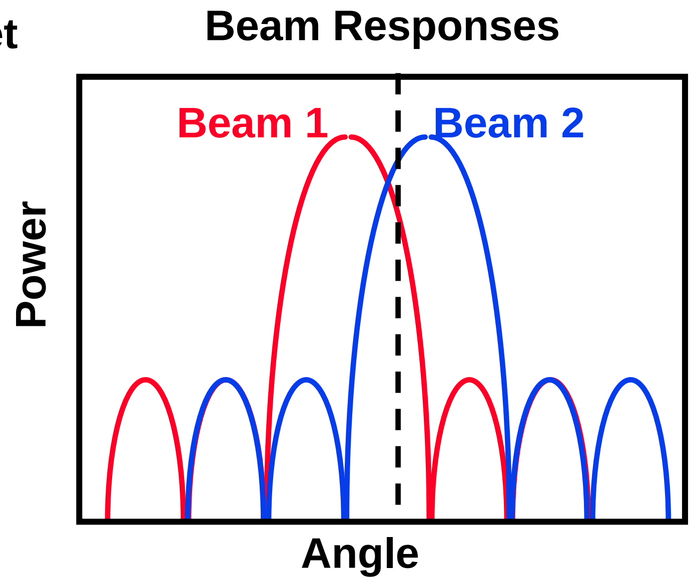
Angle Estimation

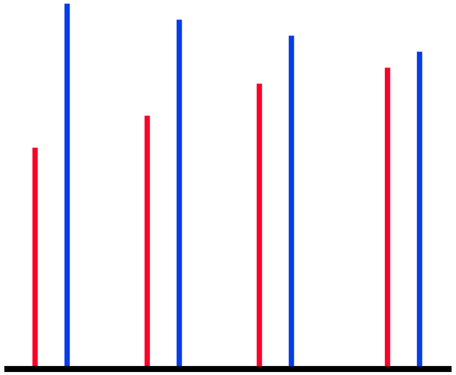


- **Detection provides coarse location in angle**
  - **Isolated within beamwidth of antenna**
- **Typically greater accuracy is required**
  - **1º beam at 100 km extends across 1,745 meters!**
- **Angle Estimation uses measurements at different beam positions for greater accuracy**

Sequential Lobing Radar

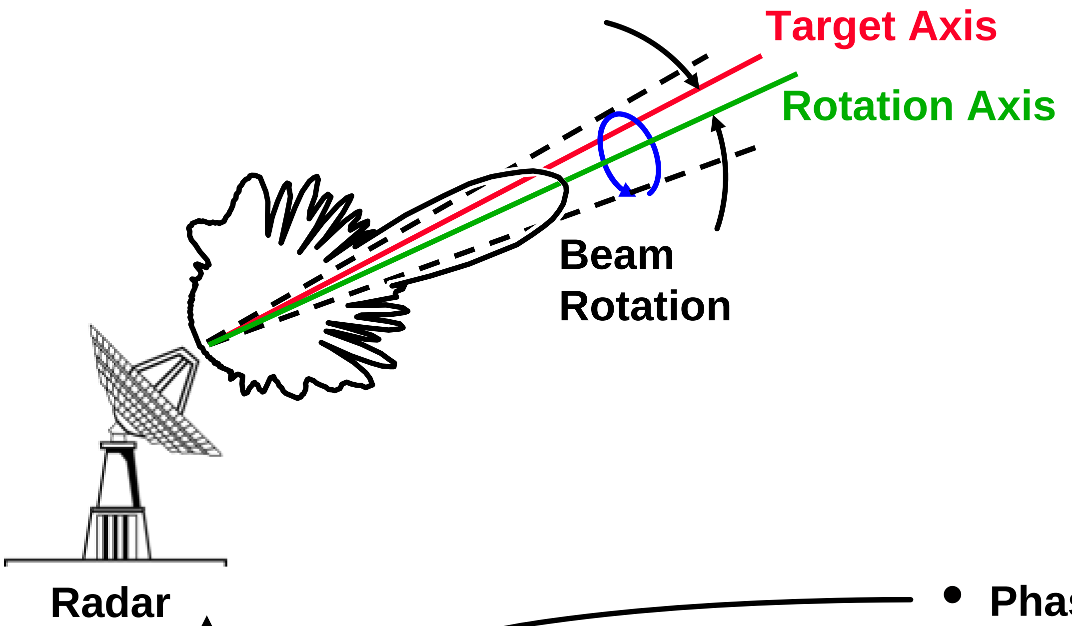


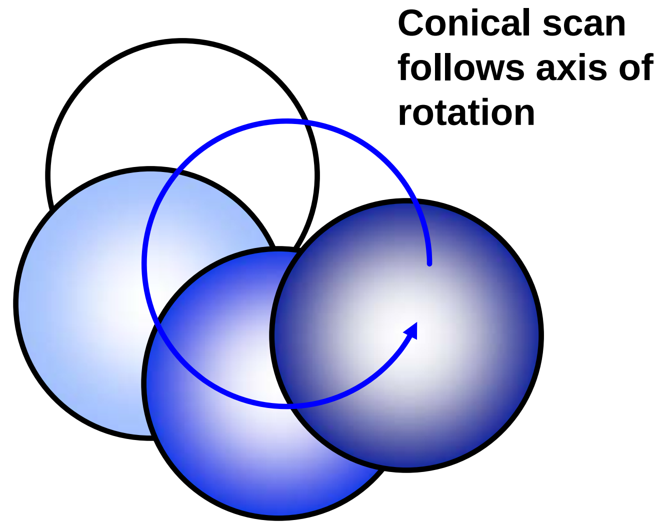


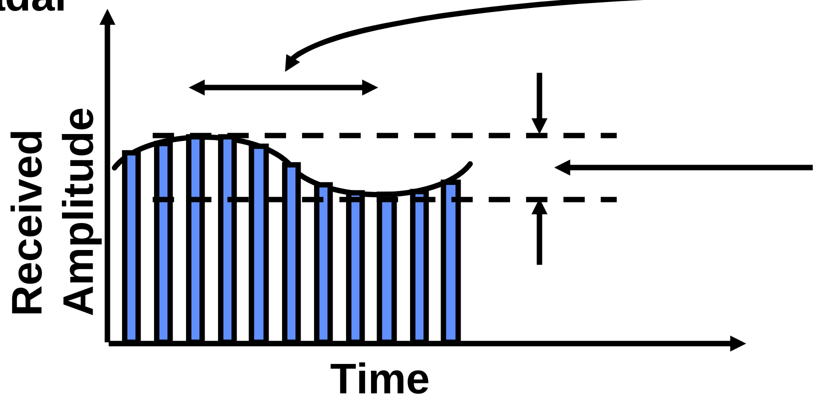


- Time sequence of beams directed around track location (two shown above)
- Reuses single receiver hardware for multiple beams
- Control loop redirects track location to equalize the beam response

Conical Scan Tracking





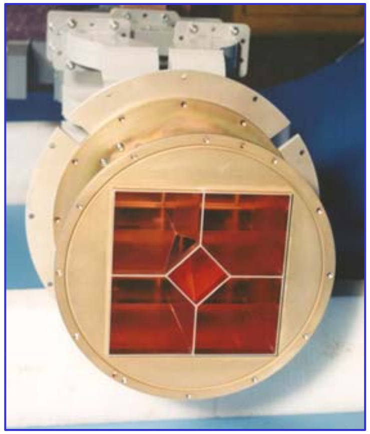


- Phase of modulation gives the angle error
- Amplitude of modulation gives the beam displacement

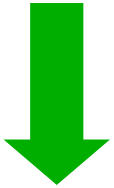
Monopulse Angle Estimation

- Monopulse angle estimation compares two or more simultaneous receive beams
- The sum and difference of the two squinted beams are used to generate the error signal
  - Each channel requires a separate receiver
- Monopulse improves performance over conical scan and sequential lobing whose performance degrade with time varying radar returns
- Monopulse measurements can be made via two methods
  - Amplitude-comparison (more commonly used)
  - Phase-comparison

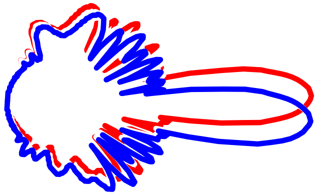
Monopulse Feed with Center Feed



Courtesy Lincoln Laboratory

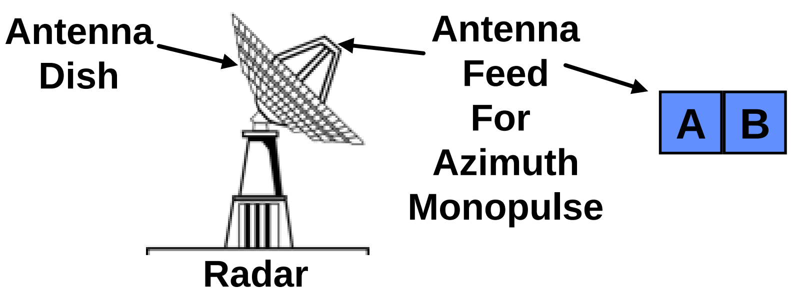


Multiple Simultaneous Receive Beams

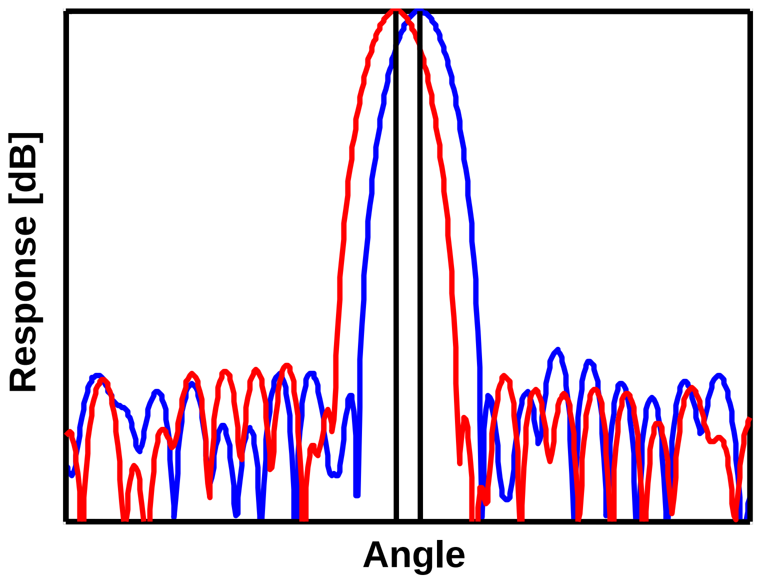


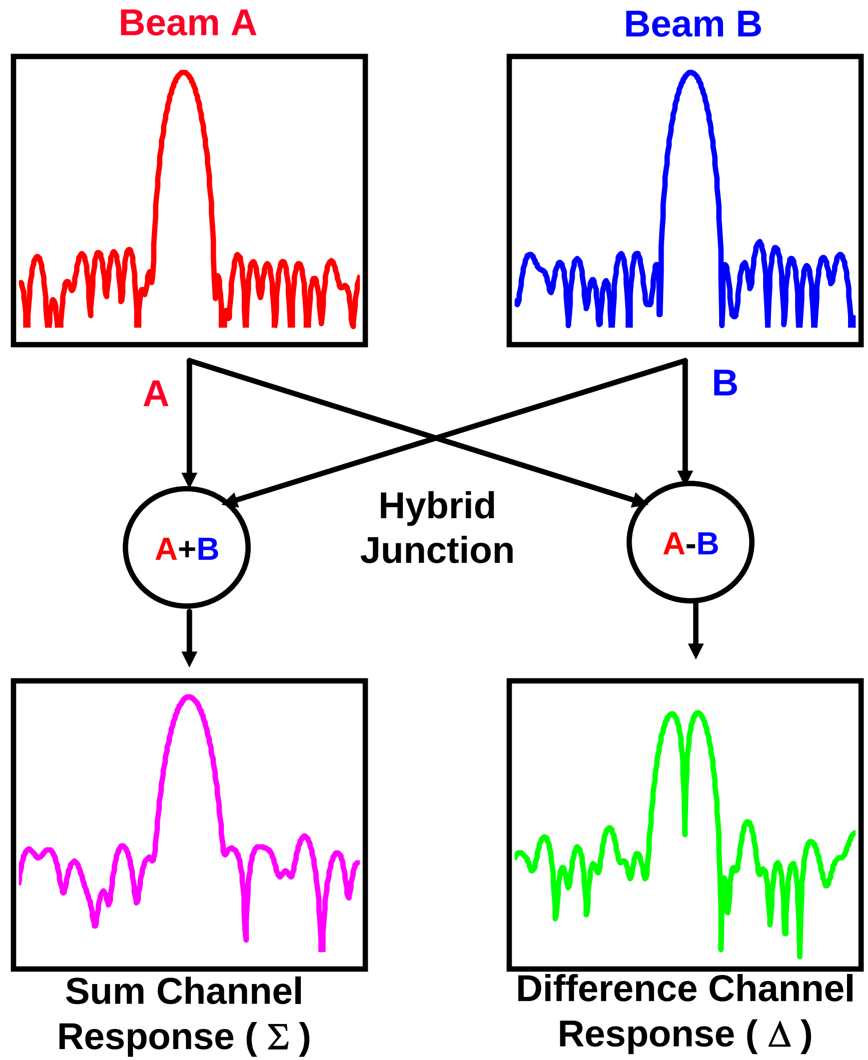
Amplitude Comparison Monopulse

- **Method:**
  - **Pairs of offset receive beams used to determine the location of the target relative to the antenna boresight (error signal)**
  - **Error signal used to re-steer the antenna boresight on to the target**
- **Typically, two offset receive beams are generated by using two feeds slightly displaced from the focus of a parabolic reflector**
- **The sum and difference of the two squinted beams are used to generate the error signal**
  - **Each channel requires a separate receiver**



Amplitude Comparison Monopulse

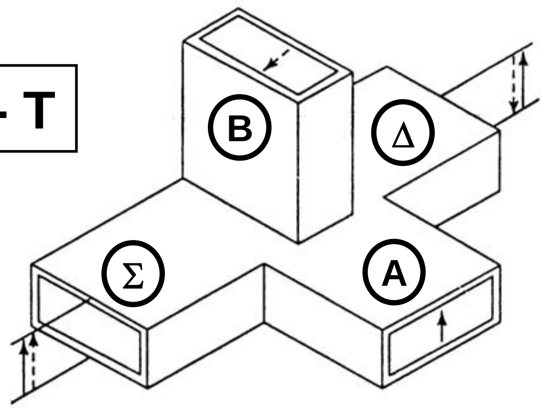


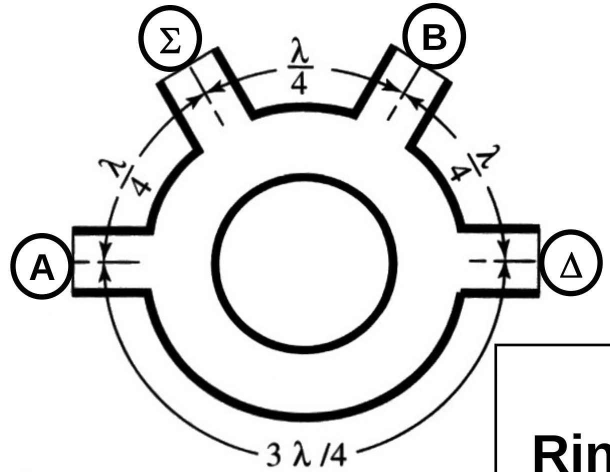


- **Receive two beams directed at slightly different angles**
  - **Typical offset 0.3 x beamwidth**
- **Generate Sum and Difference Signals**
  - **Sum = Σ = A + B**
  - **Difference = Δ = A - B**

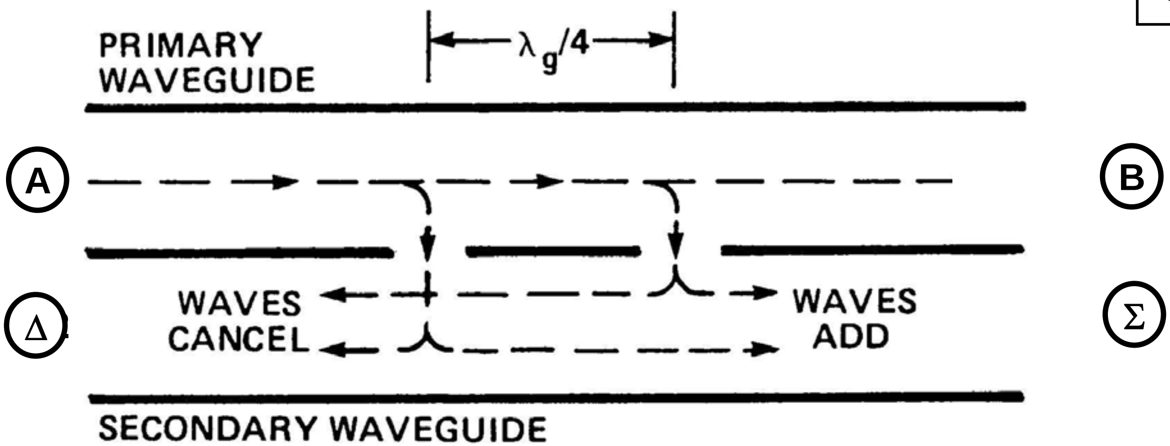
Hybrid Junctions Used in Monopulse Radar

Magic - T





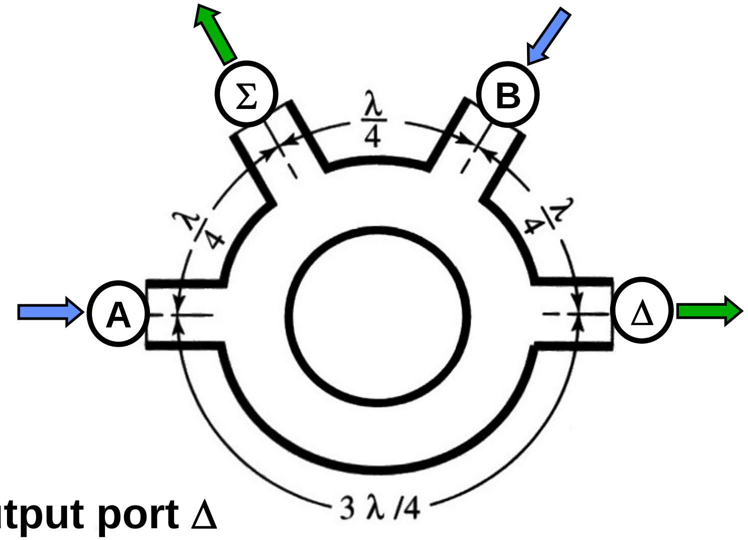
Hybrid Ring Junction or “Rat-Race”



3 dB Directional Coupler

Example of Hybrid Junction

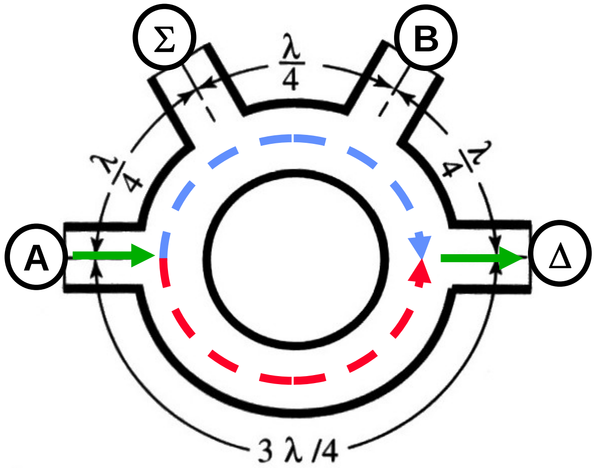
Hybrid Ring Junction or "Rat-Race"



- A signal input at port A reaches output port Δ by two separate paths, which have the same path length (3λ/4)
  - The two paths reinforce at port Δ
- An input signal at port B reaches output port Δ through paths differing by one wavelength (5λ/4 and λ/4)
  - The two paths reinforce at port Δ
- Paths from A to Δ and B to Δ differ by 1/2 wavelength
  - Signal at port A - signal at port B will appear at port Δ
- If signals of the same phase are entered at A and B, the outputs Σ and Δ are the sum and difference.

Example of Hybrid Junction

Hybrid
Ring Junction
or “Rat-Race”



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Example of Hybrid Junction

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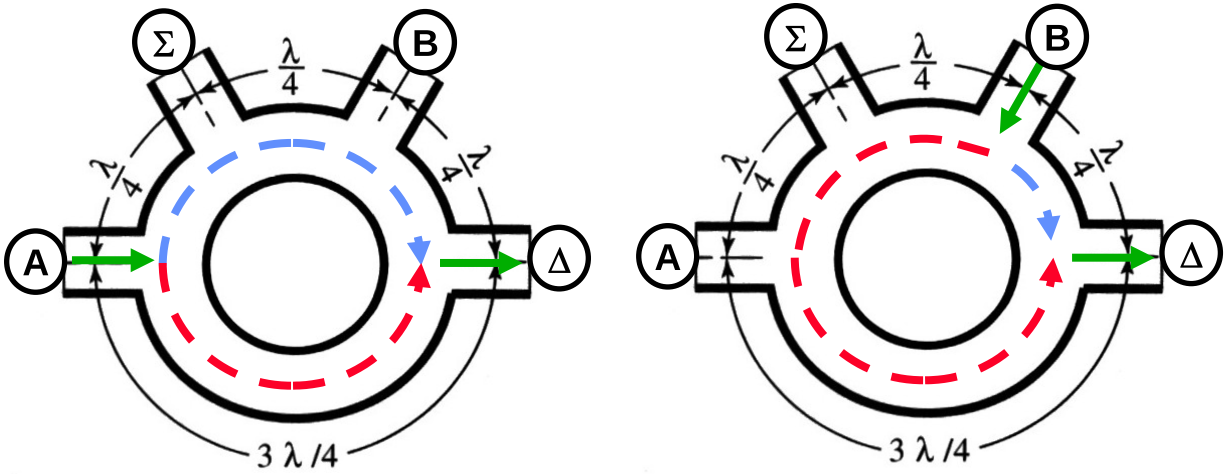

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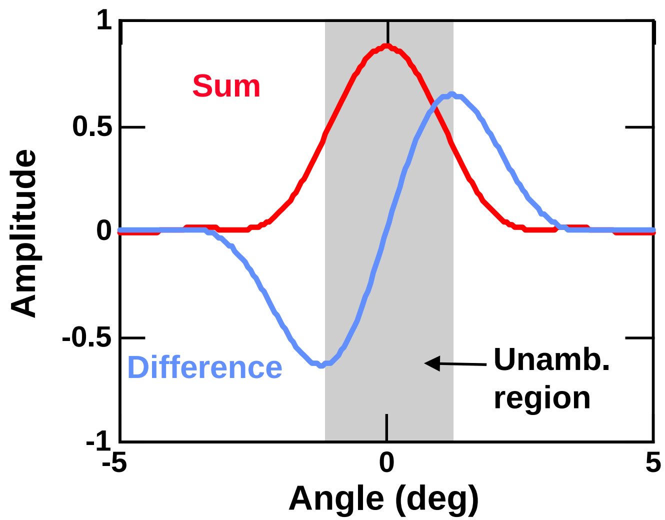
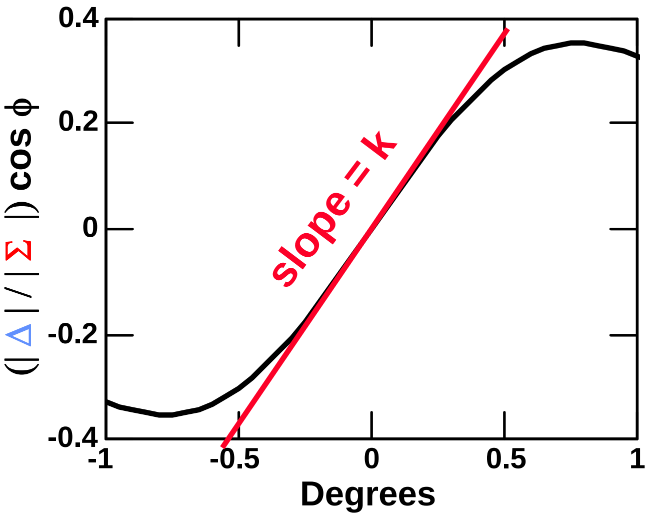
Monopulse Equations

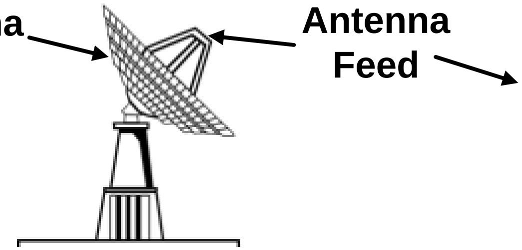




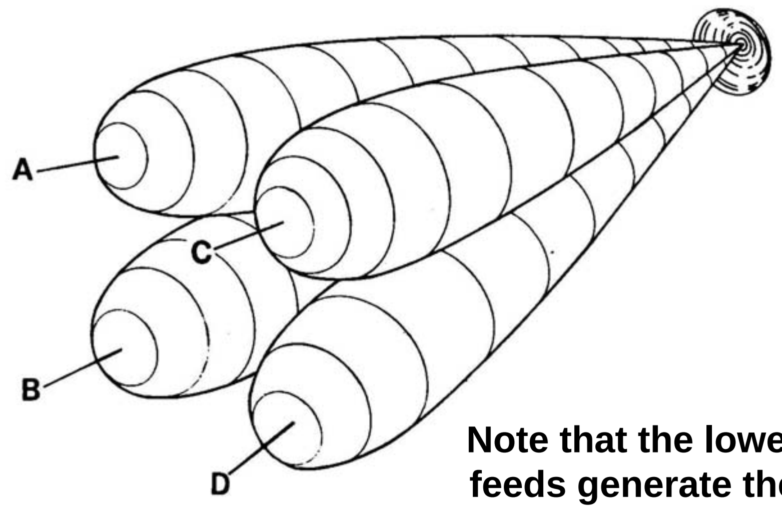
- Σ = Sum channel
- Δ = Difference channel
- ϕ = phase offset between Sum and Difference
- Error Signal $e = \dfrac{|\Delta| \cos\phi}{|\Sigma|}$

The Error Signal is a measure of how far the target is off-boresight

Two Dimensional Monopulse



B	D
A	C



Note that the lower feeds generate the upper beams

- Σ = Sum channel signal
  Δ = Difference channel signal
  ϕ = phase difference between Σ and Δ
- Error signal $e = \dfrac{|\Delta| \cos \phi}{|\Sigma|}$

Sum beam

Σ

B	D
A	C

A+B+C+D

Elevation difference beam

Δ_{EL}

B	D
A	C

B+D – (A+C)

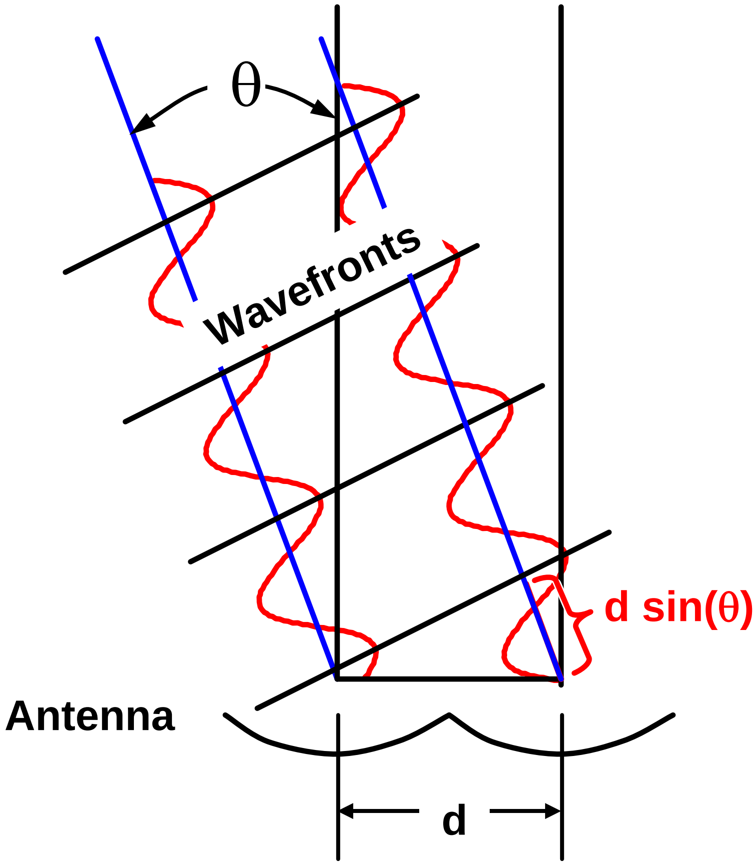
Azimuth difference beam

Δ_{AZ}

B	D
A	C

B+A – (C+D)

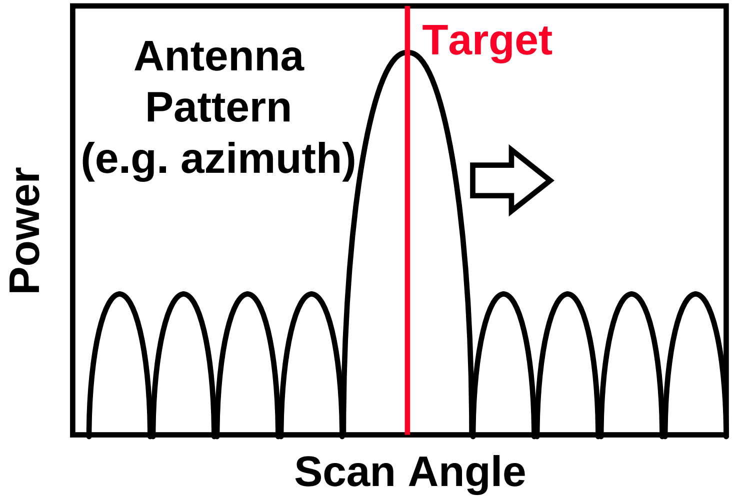
Phase Comparison Monopulse



- Phase comparison monopulse also known as "interferometer radar"
- Two antennas receive from the same target direction
  – Unlike amplitude comparison monopulse that receives beams in different directions
- Received target echo varies in phase
  – $\Delta\phi = 2\pi\,(d/\lambda)\sin\theta$

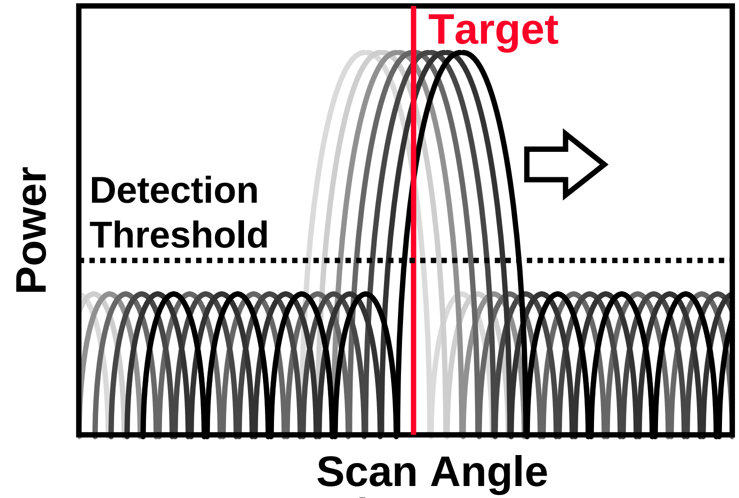
Angle Estimation with Scanning Radar
(Multiple Pulse Angle Estimation)

Antenna Pattern

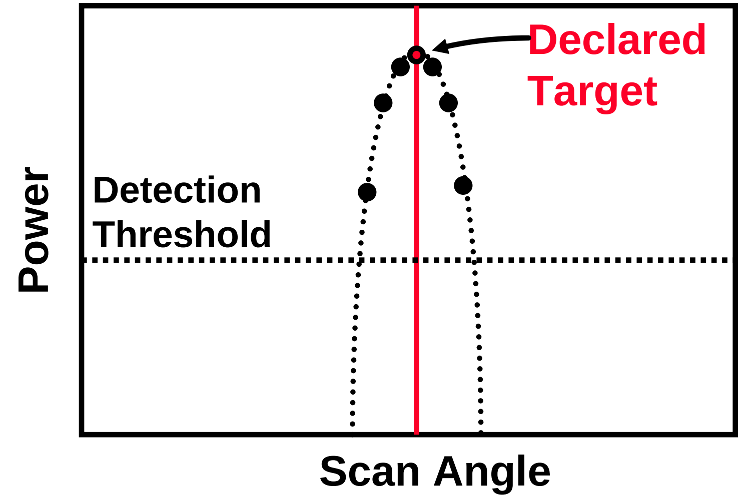


Airport Surveillance Radar

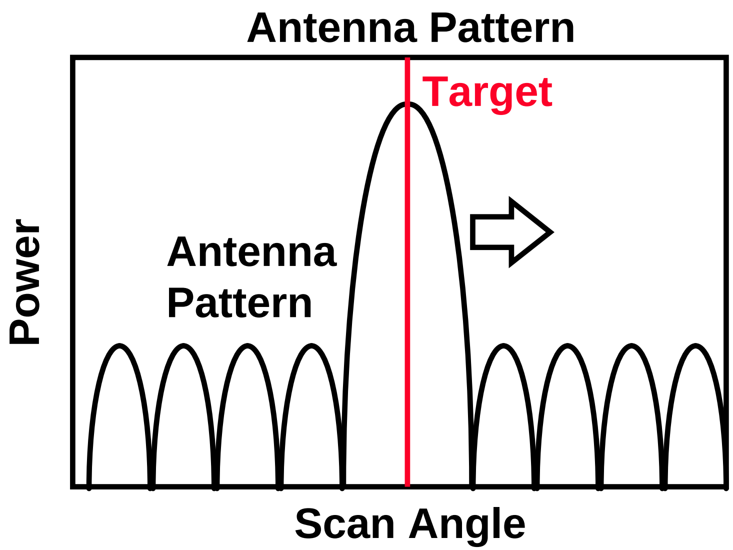
Antenna Pattern

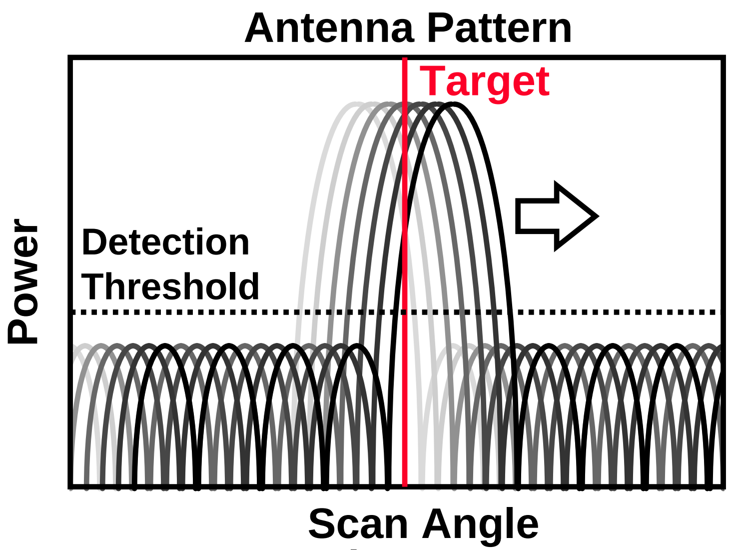


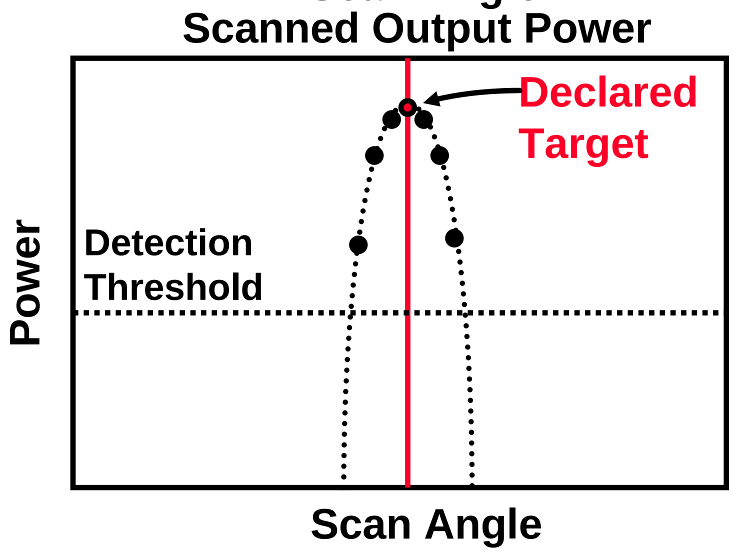
Scanned Output Power



Angle Estimation with Scanning Radar
(Multiple Pulse Angle Estimation)







- For a "track-while scan" radar, the target angle is measured by:
  - the highest target return, or
  - Interpolated angle measurement using known antenna pattern

Angle Estimation with Array Antennas

- **Phased array radars are well suited for monopulse tracking**
  - **Amplitude Comparison Monopulse**
    - **Radiating elements can be combined in 3 ways**
    - **Sum, azimuth difference, and elevation difference patterns**
  - **Phase Comparison Monopulse**
    - **Use top and bottom half of array for elevation**
    - **Use right and left half of array for azimuth**
- **Lens arrays (e.g. MOTR) would use amplitude monopulse**
  - **Four-port feed horn would be same as for dish reflector**

BMEWS

Courtesy of Raytheon.
Used with permission.

MOTR

Courtesy of Lockheed Martin.
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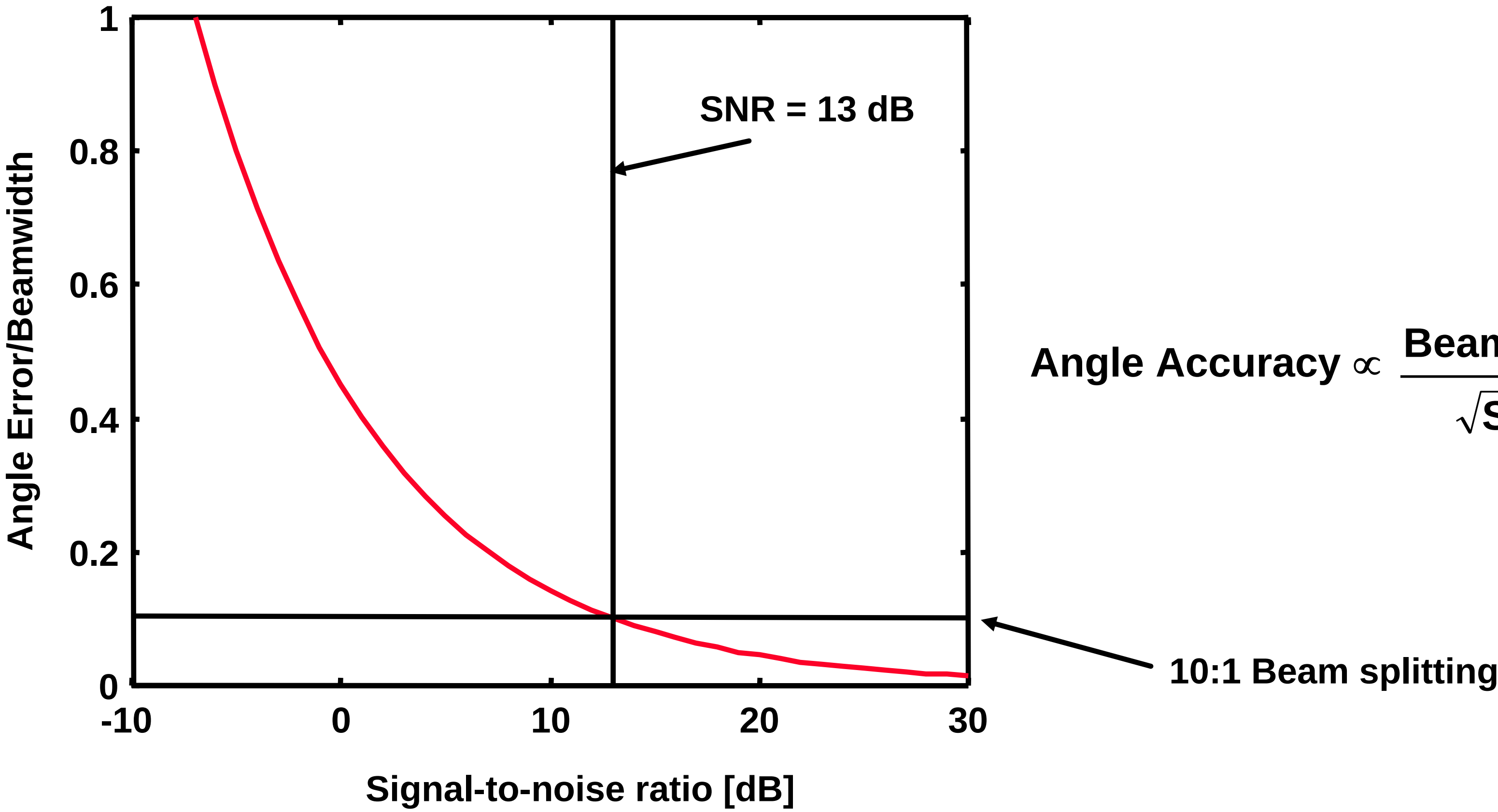
Monopulse Angle Estimation Accuracy



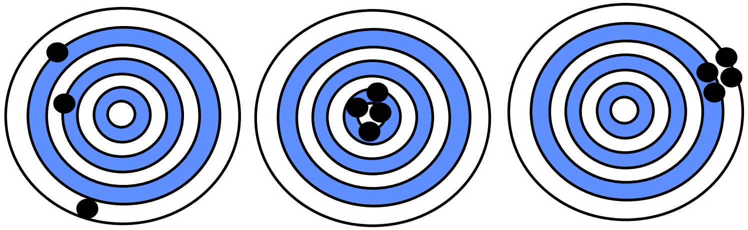
$$\text{Angle Accuracy} \propto \frac{\text{Beamwidth}}{\sqrt{\text{SNR}}}$$

At typical detection threshold levels (~13 dB) the beamwidth can be approximately split by a factor of ten; i.e. 10:1 antenna beam splitting

Accuracy, Precision and Resolution

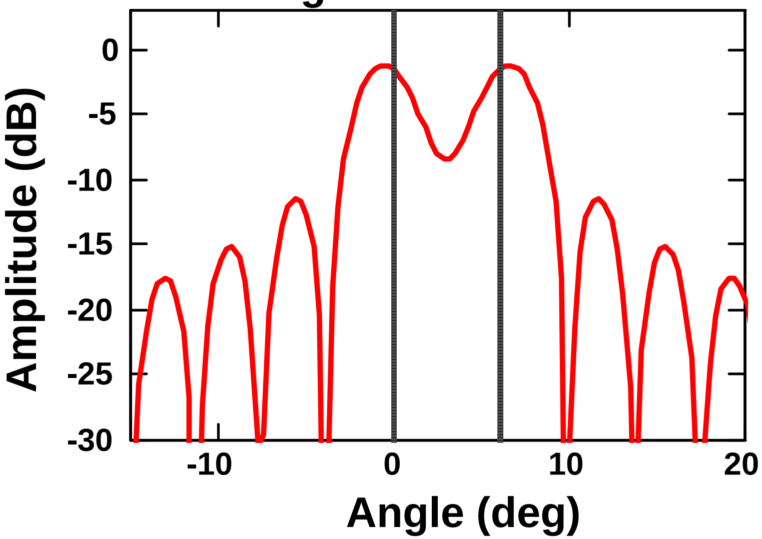
- **Accuracy:**
  - The degree of conformity of measurement to the true value
- **Precision:**
  - Repeatability of a measurement
  - Bias Error : True value- Average measured value
- **Resolution:**
  - Offset (angle or range) required for two targets to be recognized as separate targets

Example
Accuracy vs. Precision

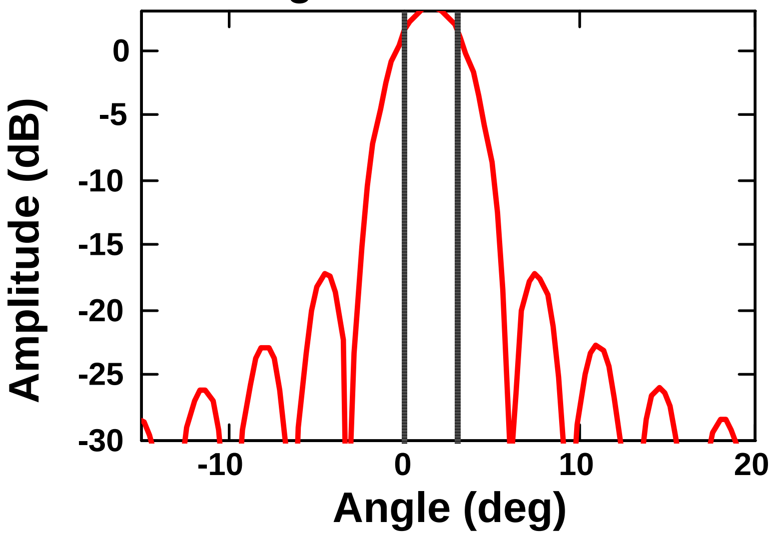


Low Accuracy Low Precision | High Accuracy High Precision | Low Accuracy High Precision

Targets at 0° and 6°



Targets at 0° and 3°

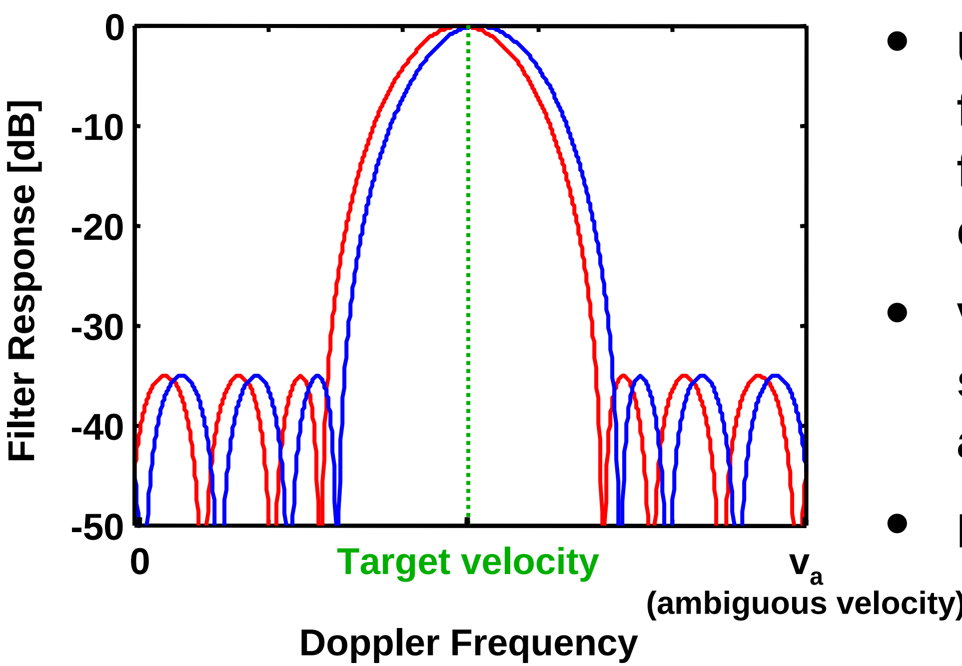


Doppler Velocity Estimation

Doppler Frequency → $f_d = \dfrac{2v_r}{\lambda}$

$2v_r$ ← Radial Velocity

λ ← Wavelength



- Use two closely spaced frequency filters offset from the center frequency of the Doppler filter containing the detection
- Velocity estimation procedure is similar to angle estimation with angle and frequency interchanged
- Doppler measurement accuracy $\propto \dfrac{\lambda}{\Delta t} \cdot \dfrac{1}{\sqrt{SNR}}$
  (Δt = coherent integration time)

Real-World Limitations

- Receiver noise
  - Adds variance to estimates
- Radar calibration
  - Poor calibration leads to poor estimation
- Amplitude fluctuations
  - Small effect on monopulse and array solutions
- Angle noise (angle scintillations, or target glint)
  - Complex target return biases angle estimate
- Multipath (low angle tracking)
  - Reflection off earth's surface combines with direct path return
  - Can cause biases in angle estimates for all techniques

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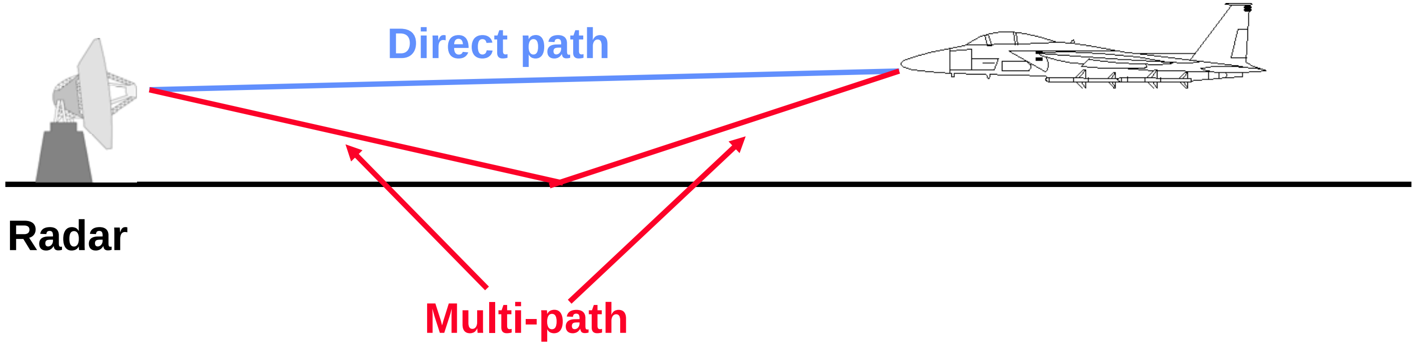
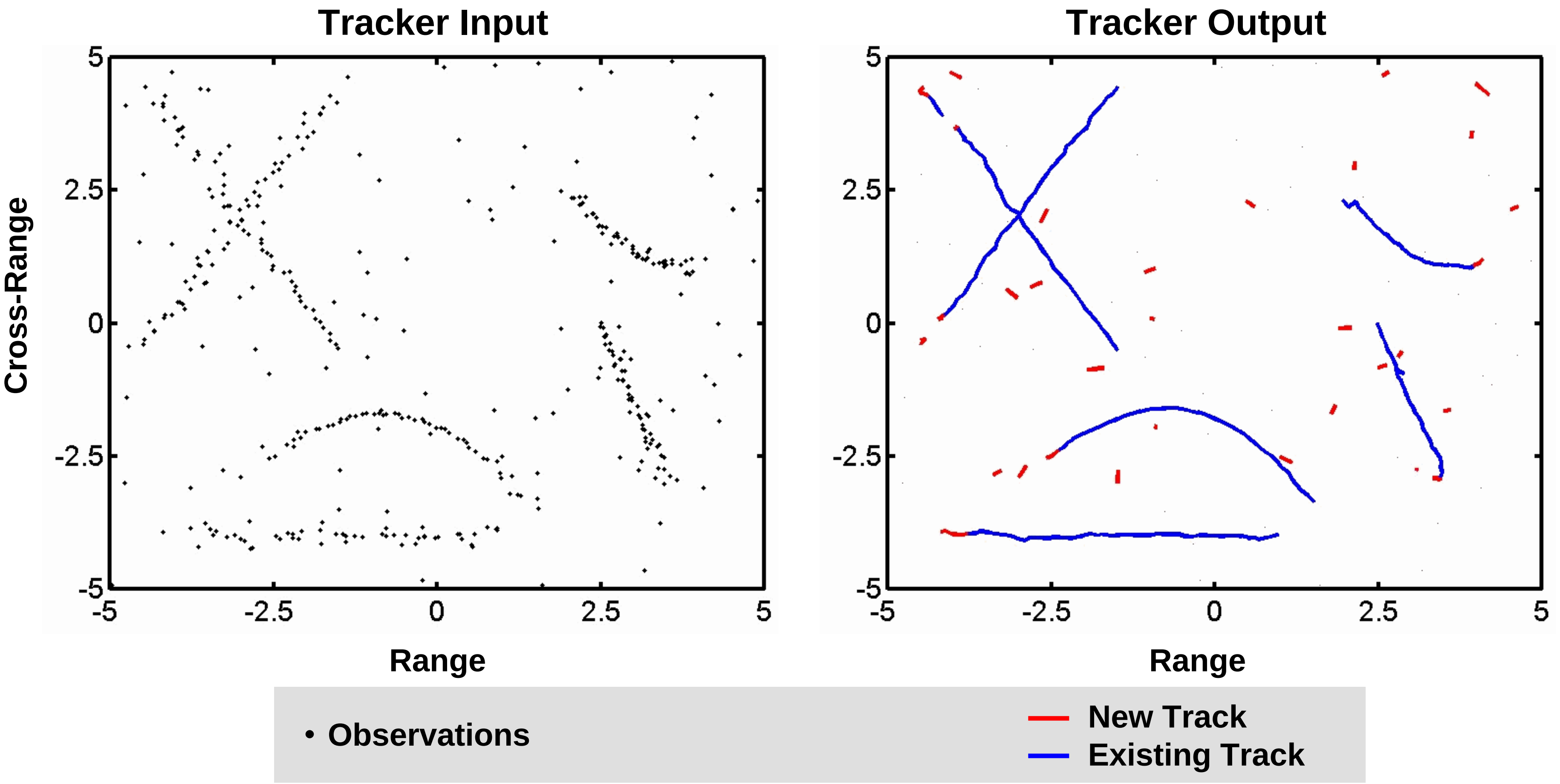


Outline

- Introduction
- Estimation
- Tracking
- Summary

Radar Tracking Example



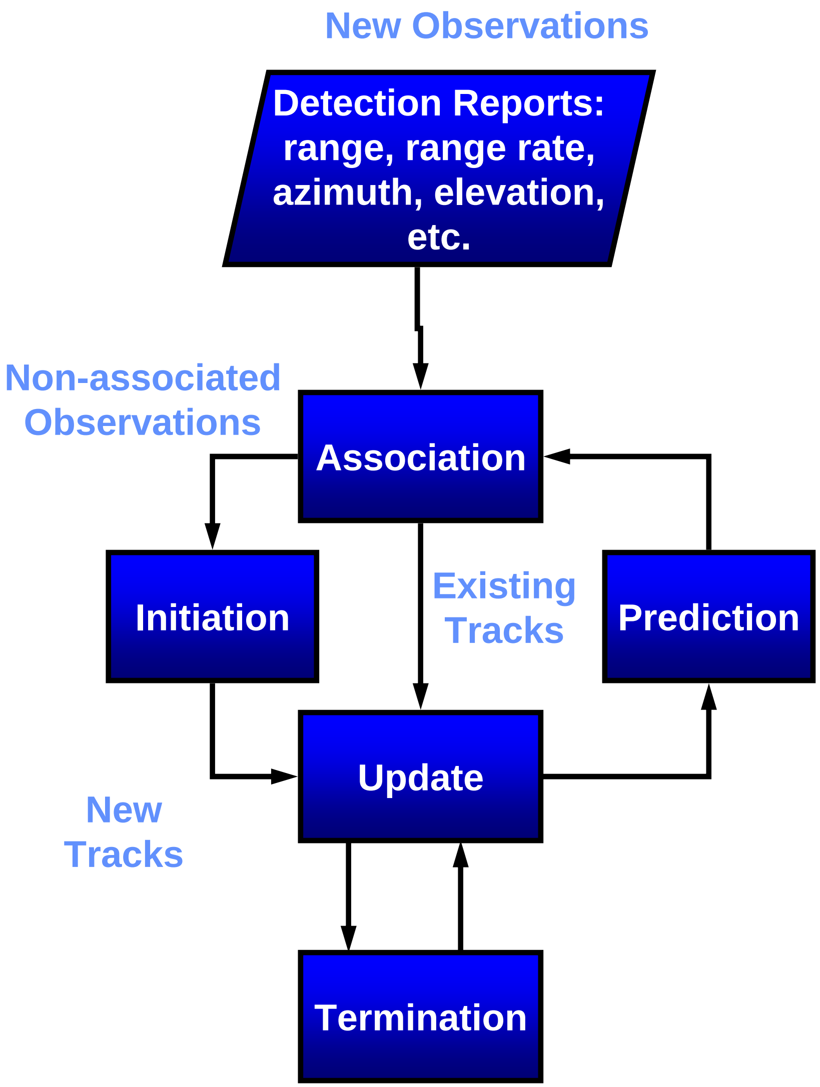
- Tracker receives new observations every scan
  - Target observations
  - False alarms
- New tracks are initiated
- Existing tracks are updated
- Obsolete tracks are deleted

Automatic Detection and Tracking Techniques

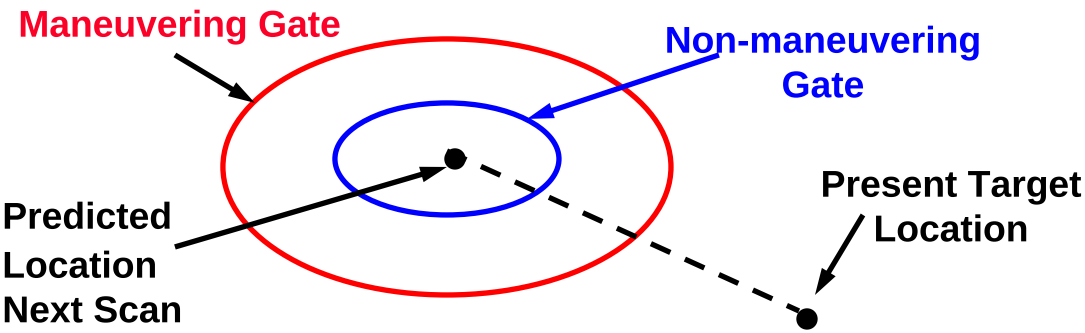
- Development of clutter rejection techniques and the digital revolution have enabled the successful development of these automatic detection and tracking techniques for Air Defense and Air Traffic Control radar systems
- Detection and Tracking Functions
  - Target Detection
    - Adaptive threshold (CFAR) applied to each range, angle, Doppler cell
  - Target Association
    - Adjacent (range, angle, and Doppler) threshold crossings, are associated
    - Range, angle(s), and Doppler of target are calculated from associated detections

Tracking Tasks

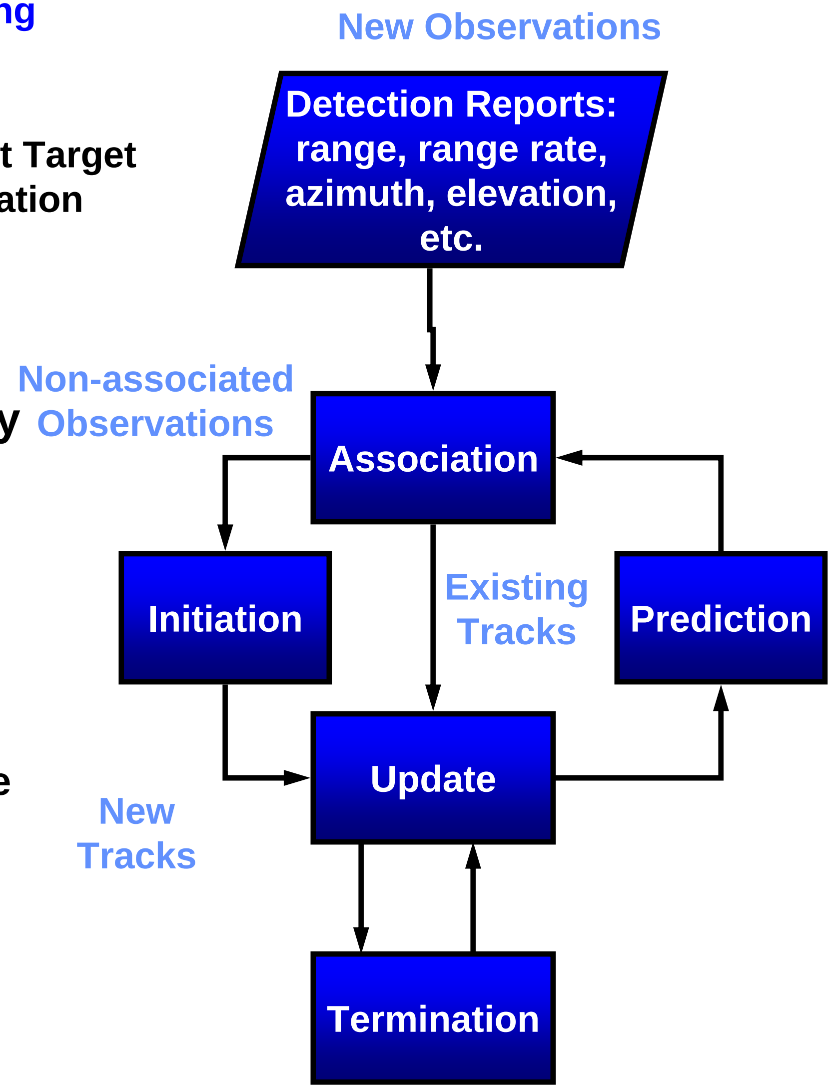
- **Track association and update**
  - Attempt made to correlate new detection with an existing tracks
  - Association is aided by seeing if the detections fall within a search window
- **Track initiation**
  - Track initiated from several scans of detection information
  - Track initiation in dense clutter environment can stress computer resources



Tracking Tasks



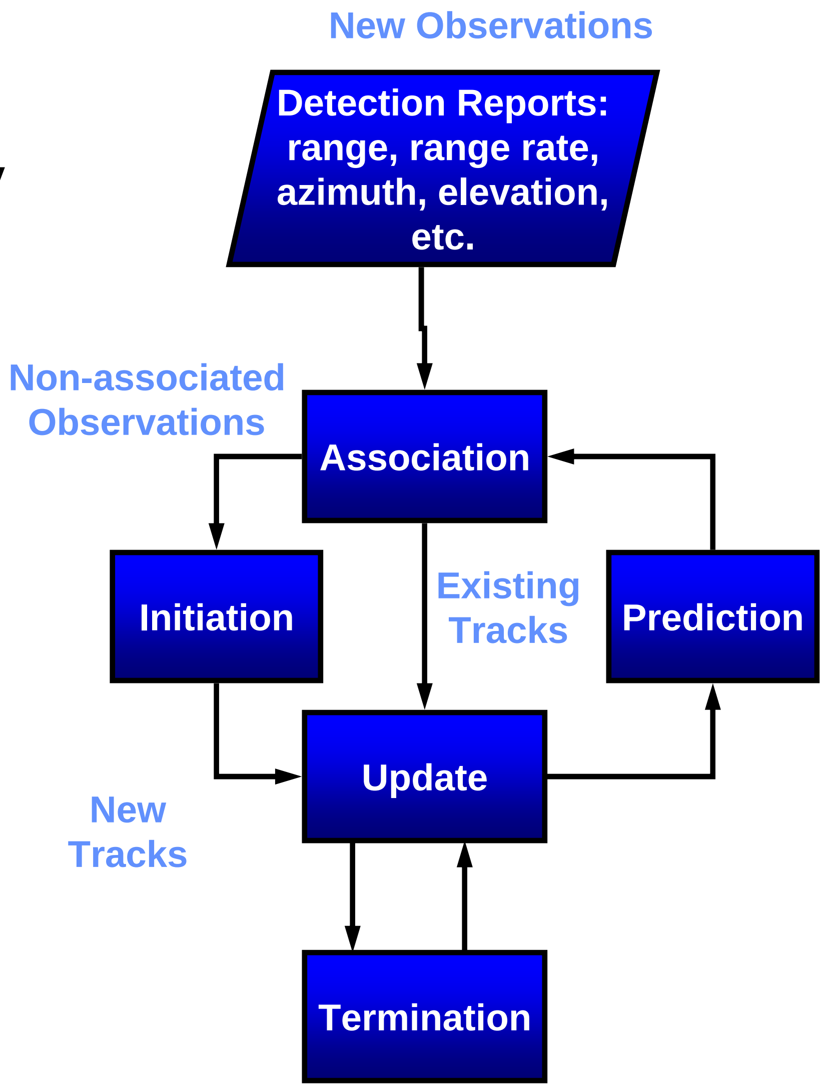
- **Track association and update**
  - The size of the gate is determined by
    - Estimated errors in the predicted position
    - Estimated errors in the speed and direction of the track
  - The gate should be :
    - Small in order to avoid having more than one detection fall within the gate
    - Large to follow target turns or maneuvers
  - If target association is successful, the track files are updated with the new target detection data



Tracking Tasks

- **Track prediction (filtering)**
  - Past detections used to estimate the target's present position and velocity
  - Estimate used to predict the location of the target on the next scan
  - Different methods of smoothing the detection data
    - $\alpha-\beta$ Filter
    - Kalman Filter

- **Track termination**
  - If data from target is missing on a scan of radar, track may be "coasted"
  - If data from target missing for a number of scans, the track is terminated



Tracking with Phased Array Radar

- **Tracking techniques are similar to automatic detection and tracking just described**
- **Advantages of phased array**
  - **Higher track update rate than radars with mechanically scanned antennas**
  - **Can simultaneously track multiple targets separated by many beamwidths**
- **There is no closed loop feedback controlling the radar beam**
  - **Computer controls the radar beam and track update rate**

Courtesy of U. S. Navy.

Courtesy of Raytheon. Used with permission.

Track Before Detect Techniques

- **Probability of detection may be improved by non-coherently integrating the radar echoes over multiple scans of the radar**
  - **Long integration times implies target may traverse many resolution cells during the integration time**
  - **Since target trajectory usually not known beforehand, integration must be performed assuming all possible trajectories**
    - **Computationally intensive problem**
  - **A correct trajectory is one that provides a realistic speed and direction for the type of target being observed**
  - **The target must be tracked before it is detected**
    - **Also called: Retrospective detection, long term integration**
  - **Higher single scan probability of false alarm can be tolerated**
    - **$P_{FA} = 10^{-3}$ rather than 10^{-5} or 10^{-6}**
  - **Requires :**
    - **Increased data processing capability**
    - **Longer observation time**

Summary

- **Parameter estimation techniques enable a radar to obtain accurate radar measurements**
  - **Range, angle, Doppler, etc.**
- **Monopulse angle estimation allows sub-beamwidth accuracy for a single radar pulse**
  - **Limitations due to multiple targets or interference**
- **Tracking algorithms find best fit between predicted target track and current observations**

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Toomay, J. C., Radar Principles for the Non-Specialist, New York, Van Nostrand Reinhold, 1989

Introduction to Radar Systems

Radar Transmitter/Receiver

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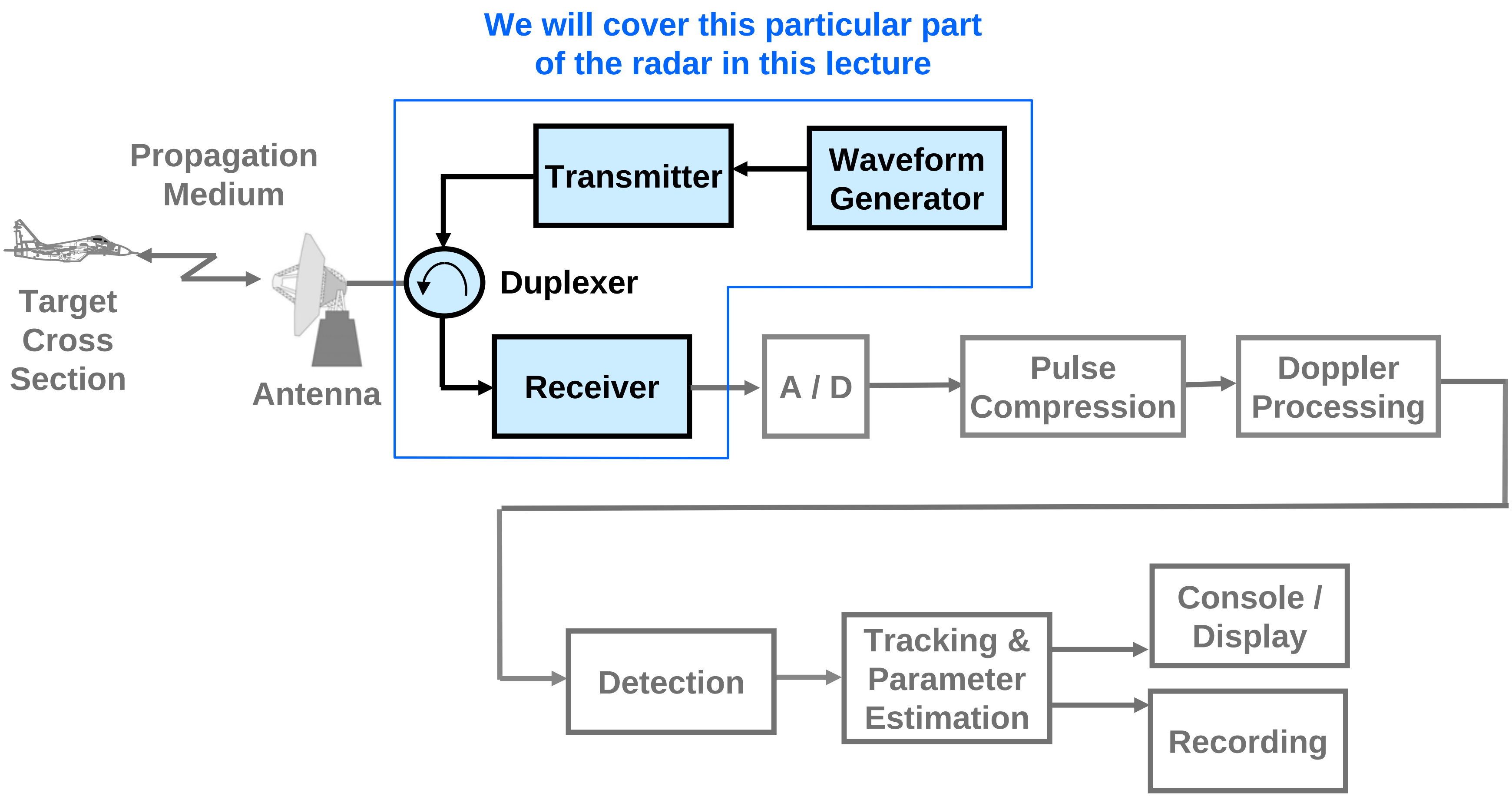
- The views and opinions expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or any of their contractors or subcontractors

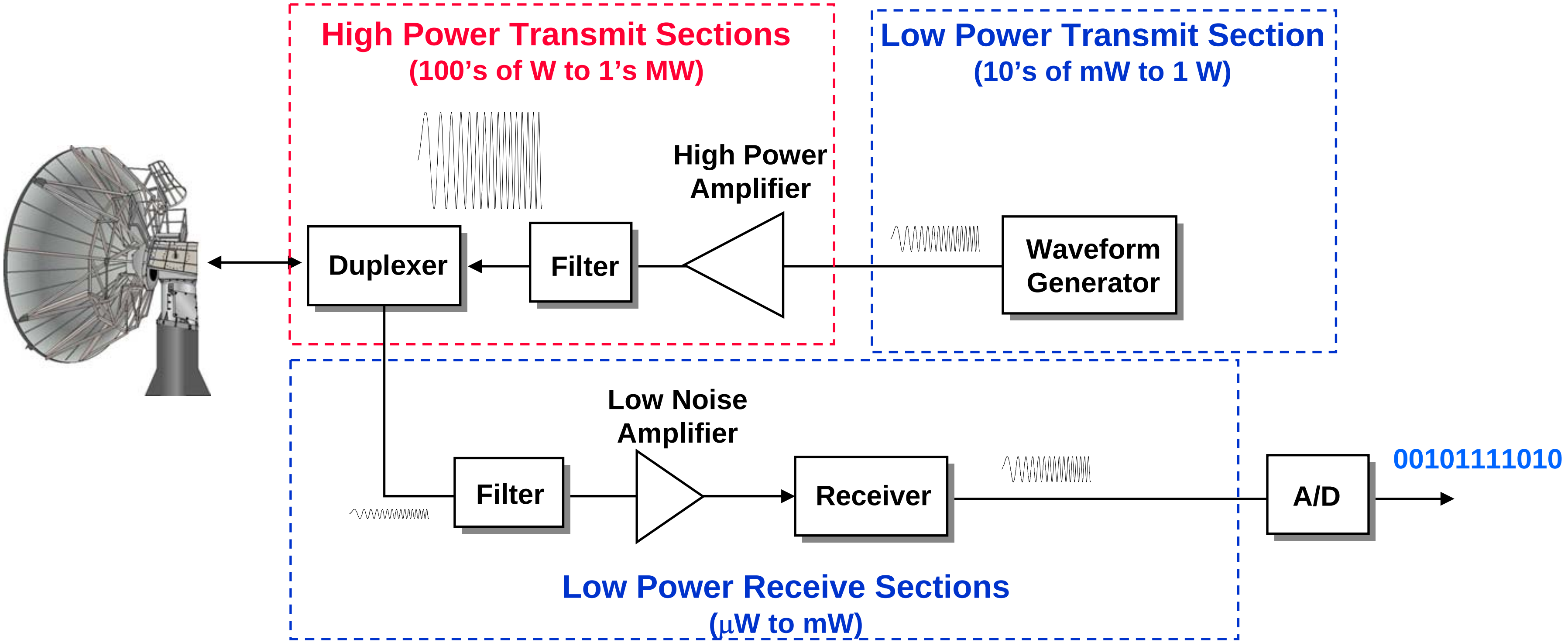
Outline

- **Introduction**
- **Radar Transmitter**
- **Radar Waveform Generator and Receiver**
- **Radar Transmitter/Receiver Architecture**
- **Summary**

Radar Block Diagram



Simplified Radar Transmitter/Receiver System Block Diagram



- Radar transmitter and receiver can be divided into two important subsystems
  - High power transmitter sections
  - Low power sections

    Radar waveform generator and receiver

Radar Range Equation Revisited

Parameters Affected by Transmitter/Receiver

- **Radar range equation for search (S/N = signal to noise ratio)**

$$S/N = \frac{\boxed{P_{av}}\, A_e\, t_s\, \sigma}{4\pi\, \Omega\, R^4\, k\, \boxed{T_s}\, \boxed{L}}$$

- **S/N of target can be enhanced by**
  – **Higher transmitted power P_{av}**
  – **Lower system losses L**
  – **Minimize system temperature T_s**

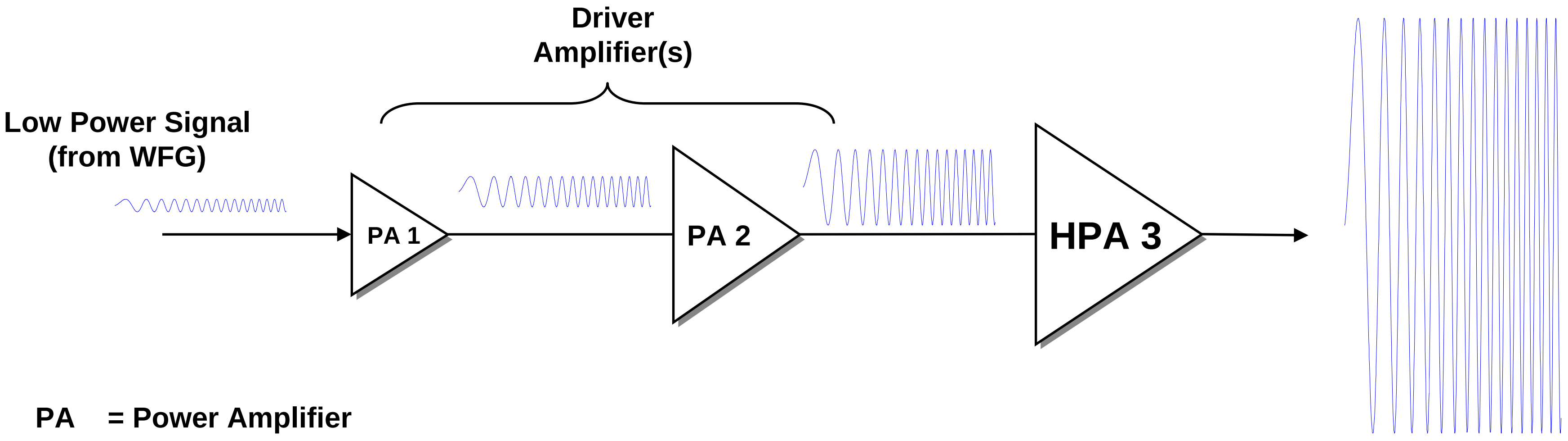
P_{av} = average power
A_e = antenna area
t_s = scan time for Ω
P_{av} = average power
σ = radar cross section
Ω = solid angle searched
R = target range
T_s = system temperature
L = system loss

The design of radar transmitter/receiver affects these three parameters directly

Outline

- **Introduction**
- **Radar Transmitter Overview**
  - **High Power Amplifier**
- **Radar Waveform Generator and Receiver**
- **Radar Transmitter/Receiver Architecture**
- **Summary**

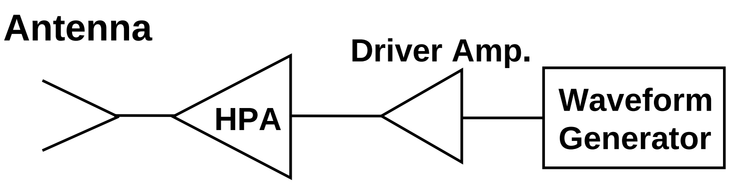
Power Amplification Process



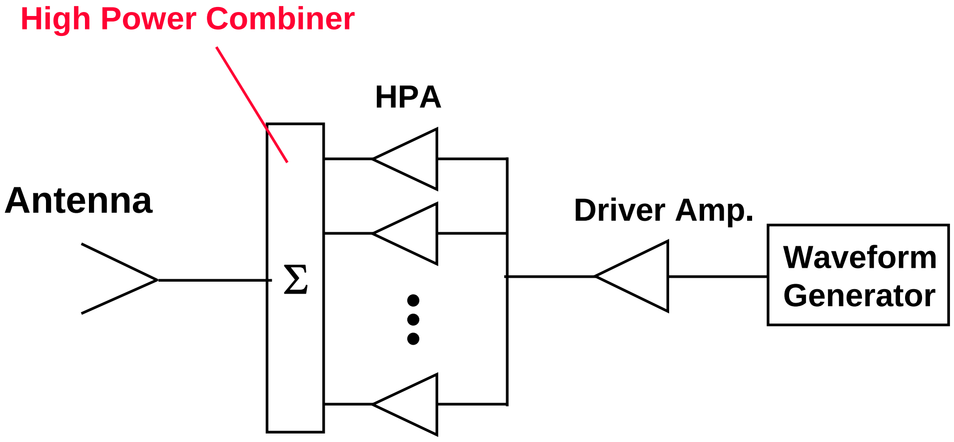
PA = Power Amplifier
HPA = High Power Amplifier

- **Amplification occurs in multiple stages**
  - Driver amplifiers
  - High power amplifier
- **Requirement for power amplifier**
  - Low noise
  - Minimum distortion to input signal

Method to Obtain Higher Power



1 – Single amplifier transmitter
Single antenna



2 – Parallel combining of HPA's
Single antenna

- **Higher transmitted power can be obtained by combining multiple amplifiers in parallel**
  - **Lower efficiency (due to combiner losses)**
  - **Increased complexity**

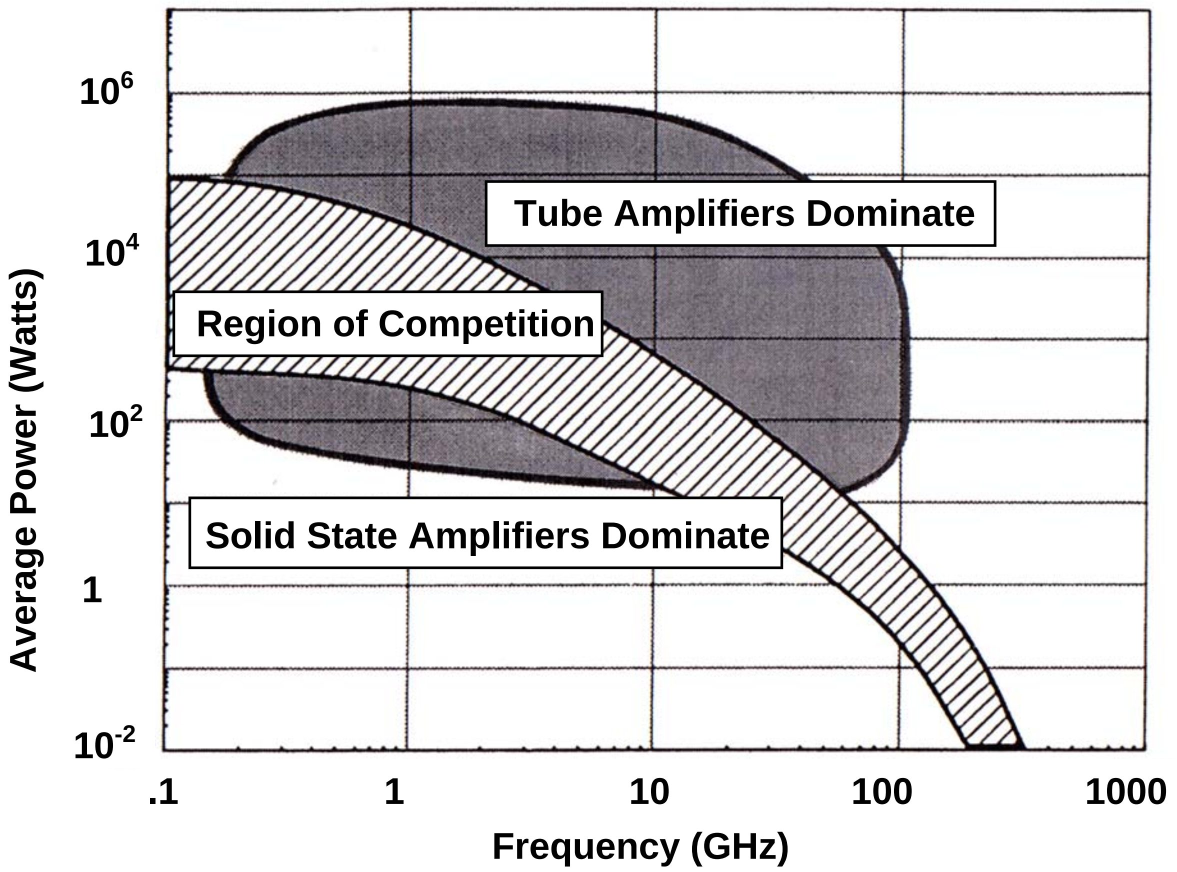
HPA = High Power Amplifier

Types of High Power Amplifiers

- **Vacuum tube amplifiers and solid state amplifiers**

	Vacuum Tube Amplifiers	Solid State Amplifiers
Output Power	High (10 kW to 1 MW)	Low (10's to 100's W)
Cost per Unit	High ($10's K to $300 K)	Low ($100's)
Cost per Watt	$1 – 3	Varied
Size	Bulky and heavy	Small foot print
Applications	• Dish antenna • Passive array	• Active array • Digital array

Average Power Output Versus Frequency
Tube Amplifiers versus Solid State Amplifiers



Power Amplifier Examples

- **Tube amplifiers**
  - **Klystrons**
  - **Travelling wave tubes**

- **Solid State amplifiers**
  - **Solid state power transistors**

Criteria for choosing high power amplifier
- **Average power output as a function of frequency**
- **Total bandwidth of operation**
- **Duty cycle**
- **Gain**
- **Mean time between failure (MTBF)**
- **etc…**

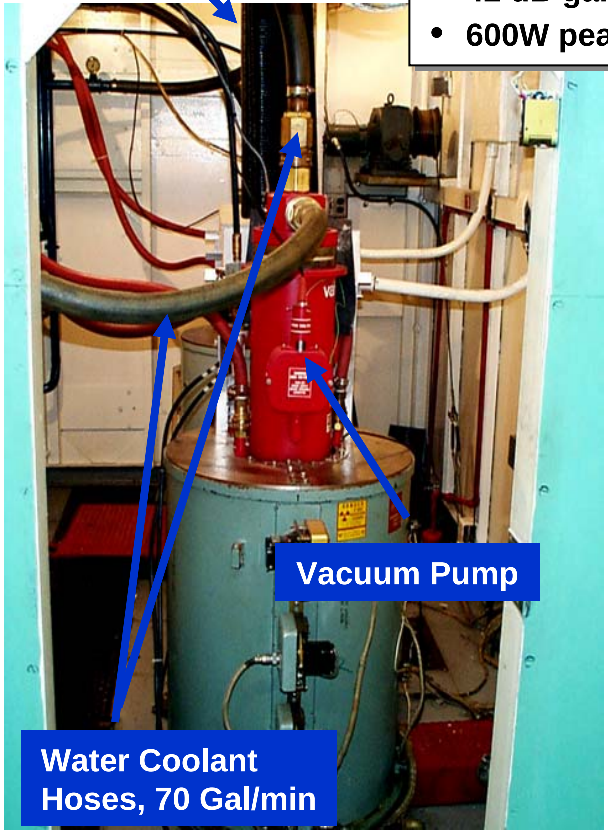
MIT/LL Millstone Hill Radar
Klystron Tubes (Vacuum Devices)

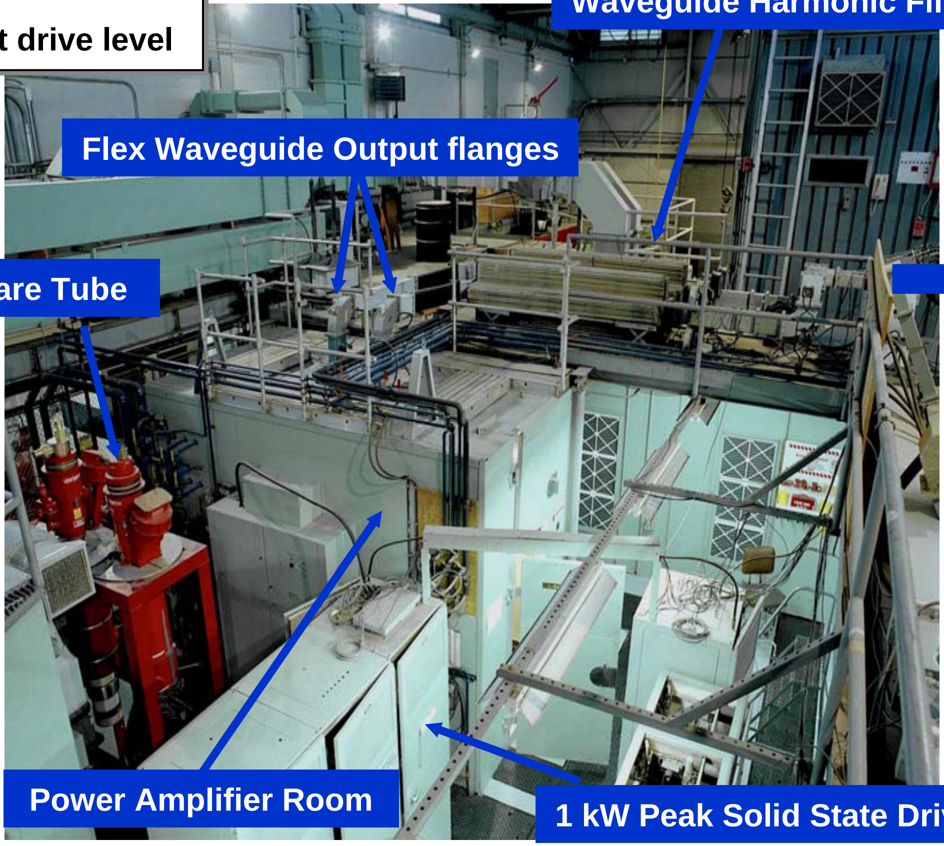
Output device	Klystrons (2)
Center Frequency	1295 MHz
Bandwidth	8 MHz
Peak Power	3 MW
Average Power	120 kW
Pulse Width	1 ms
Beam Width	0.6^o
Antenna Diameter	84 ft

- Originally designed in early 1960's

How Big are High Power Klystron Tubes ?
Millstone Hill Radar Transmitter Room

Varian X780 Klystron
- $400,000/tube
- 7 ft (height) x 1ft (diameter)
- 600 lbs
- 3% duty cycle
- 42 dB gain
- 600W peak input drive level





Photograph of Traveling Wave Tubes
Another Type of Tube Amplifiers

Center Freq : 3.3 GHz
Bandwidth : 400 MHz
Peak Power : 160 kW
Duty Cycle : 8 %
Gain : 43 dB

S Band
VTS-5753
COUPLED CAVITY
TWT

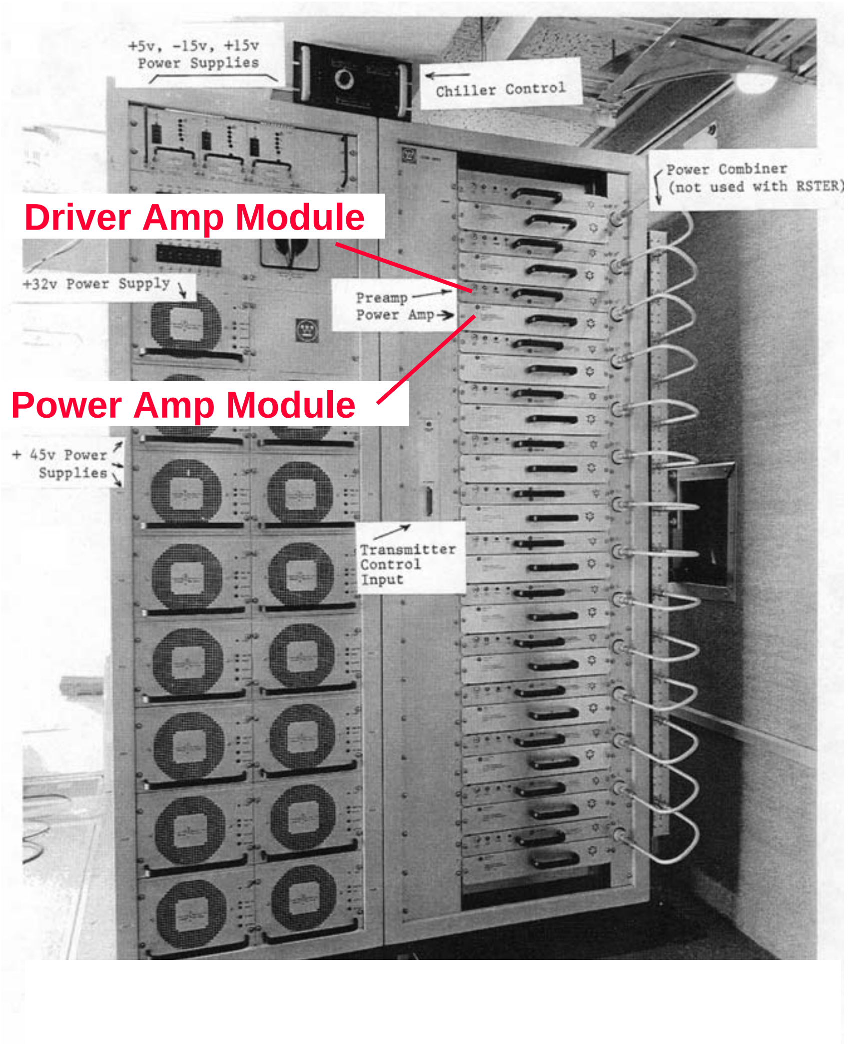
X Band
VTX-5681C
COUPLED CAVITY
TWT

Center Freq : 10.0 GHz
Bandwidth : 1 GHz
Peak Power : 100 kW
Duty Cycle : 35 %
Gain : 50 dB

S-Band Transmitter

Example of Solid State Transmitter

Radar Surveillance Technology Experimental Radar (RSTER)

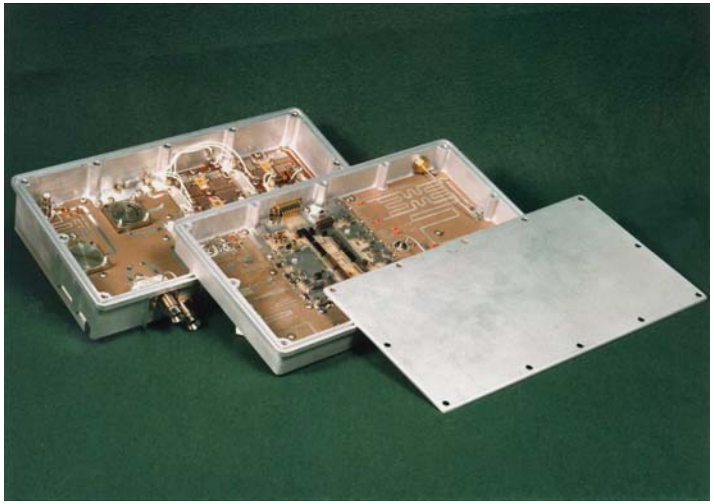


- 14 channels with 140 kW total peak power
  - 8 kW average power
- Each channel is supplied by a power amplifier module
  - 10 kW peak power

Solid State Active Phased Array Radar PAVE PAWS

- **PAVE PAWS**
  - **First all solid state active aperture electronically steered phased array radar**
  - **UHF Band**
  - **1792 active transceiver T/R modules, 340 W of peak power each**

Courtesy of Raytheon. Used with permission.

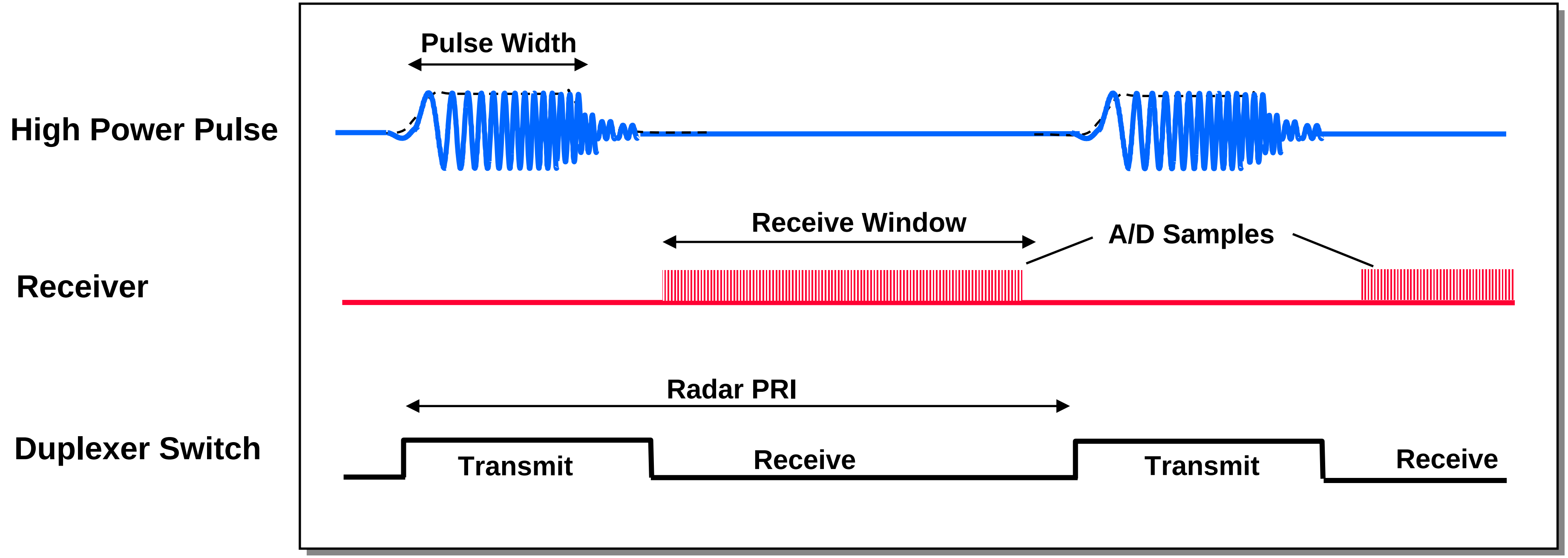


Courtesy of Raytheon. Used with permission.

Outline

- **Introduction**
- **Radar Transmitter Overview**
  - **High Power Amplifier**
  - **Duplexer**
- **Radar Waveform Generator and Receiver**
- **Radar Transmitter/Receiver Architecture**
- **Summary**

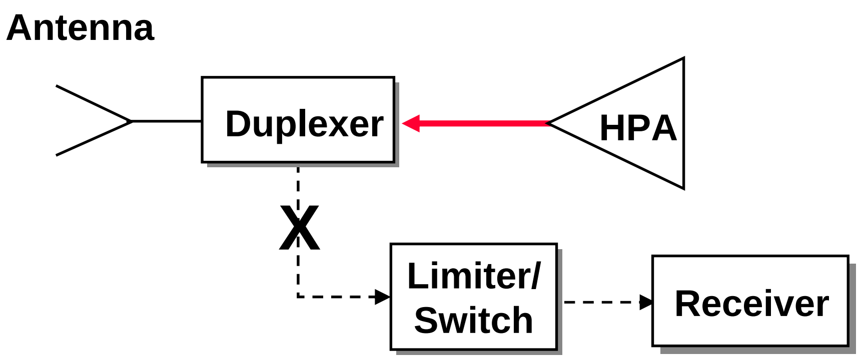
Radar Transmitter/Receiver Timeline



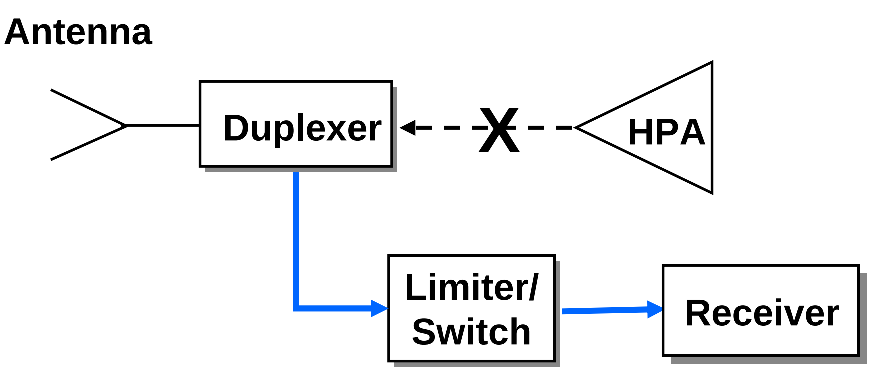
- Sensitive radar receiver must be isolated from the powerful radar transmitter
  - Transmitted power typically 10 kW – 1 MW
  - Receiver signal power in 10's μW – 1 mW
- Isolation provided by duplexer switching

PRI = Pulse Repetition Interval

Duplexer Function



Transmit Interval



Receive Interval

- Transmitter ON
  - Connect antenna to transmitter with low loss
  - Protect receiver during transmit interval
- Receiver ON
  - Connect Antenna to receiver with low loss
  - (transmitter must be turned off in this interval)
  - Limiter/switch is used for additional protection against strong interference

HPA = High Power Amplifier

Outline

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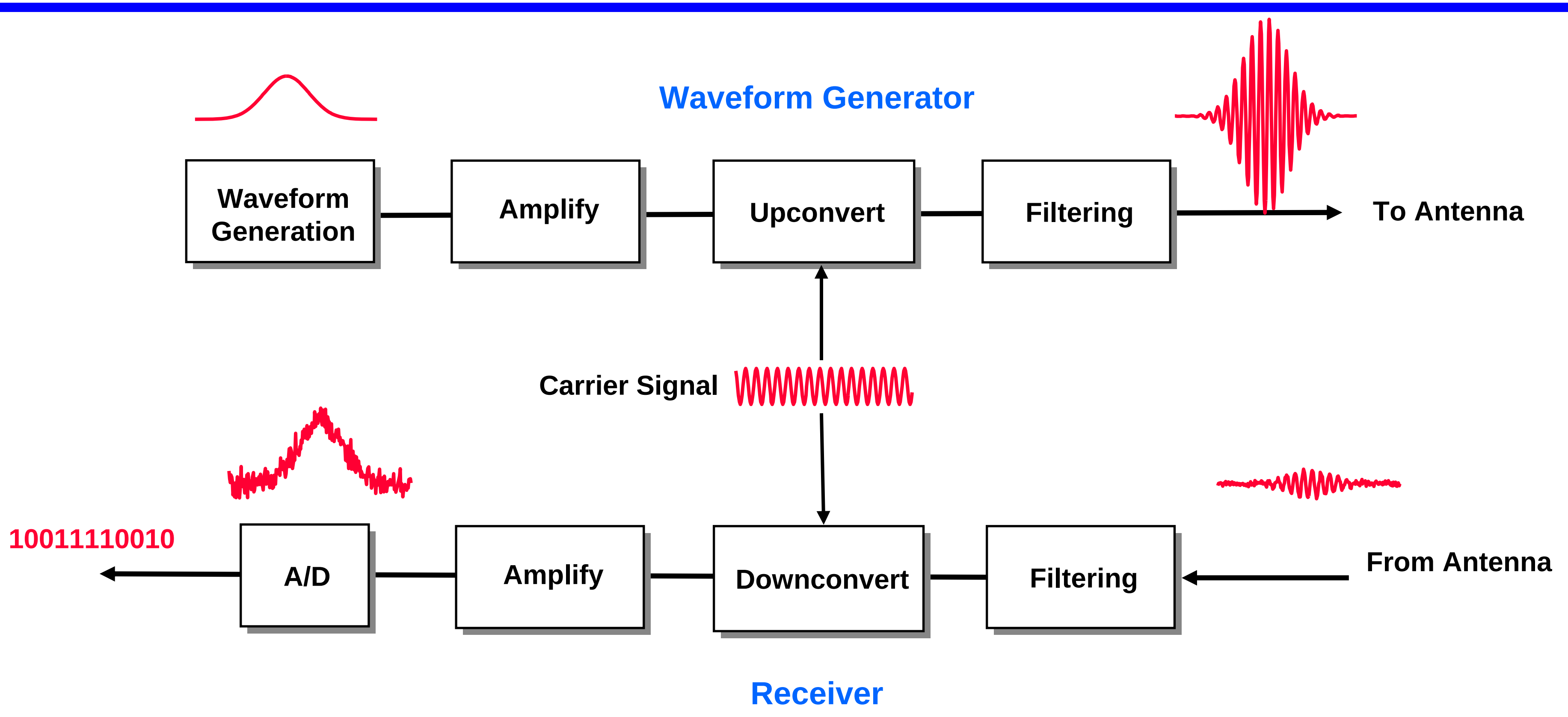
Simplified Functional Descriptions

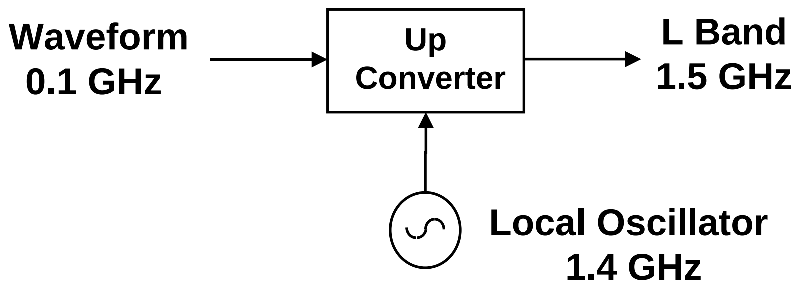


- **Waveform generator and receiver share several similar functions**
  - **Amplification, filtering and frequency conversion**

Frequency Conversion Concepts

Waveform Generator

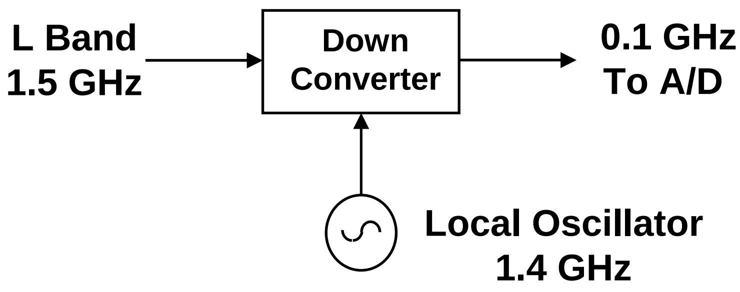
Frequency Upconversion
Baseband to L Band



- **Upconverter translates the waveform frequency to a higher frequency**
- **Reason:**
  - **Waveform generation less expensive at lower frequency**

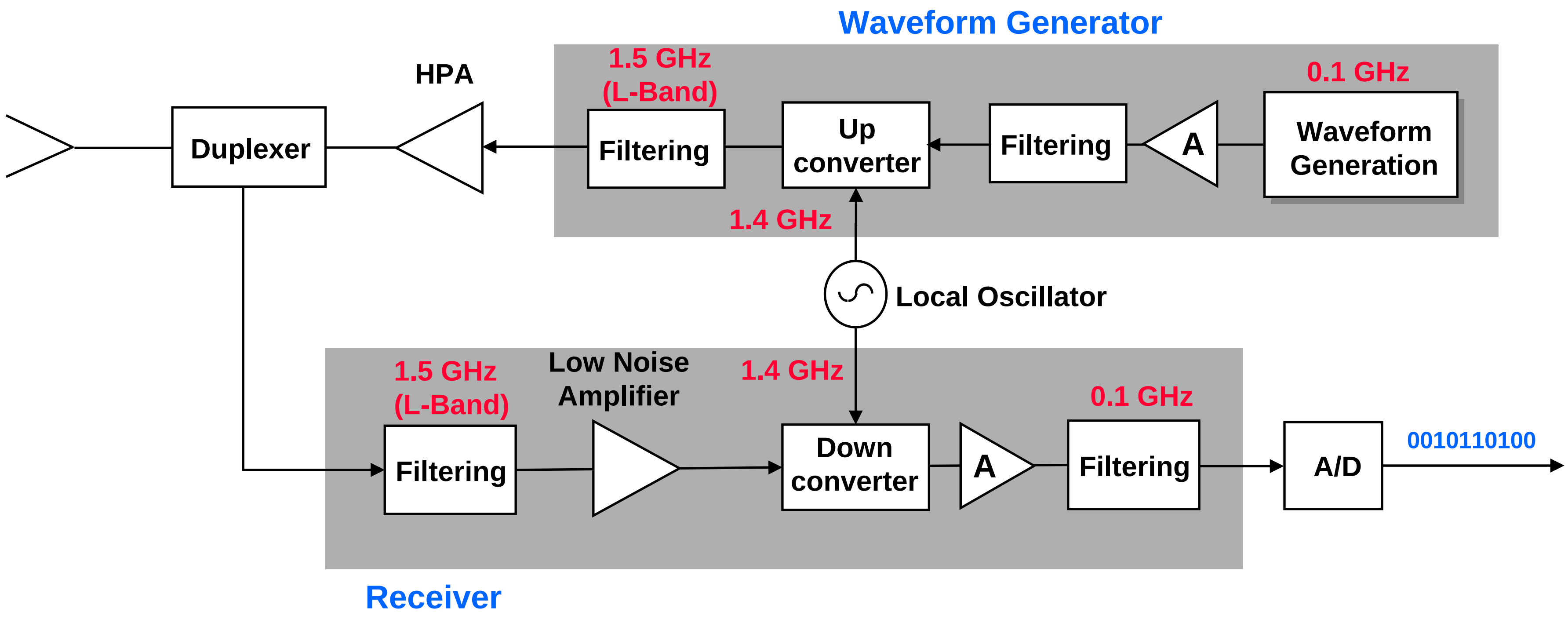
Receiver

Frequency Downconversion
L Band to Baseband



- **Downconverter translates the receive frequency to a lower frequency**
- **Reason:**
  - **Dynamic range of A/D converter higher at lower frequency**

Simplified System Block Diagram
Waveform Generator and Receiver



- This example shows only a single stage conversion
  – In general, design based on multiple stage of frequency conversion are employed
- Multiple stages of amplification and filtering are also used

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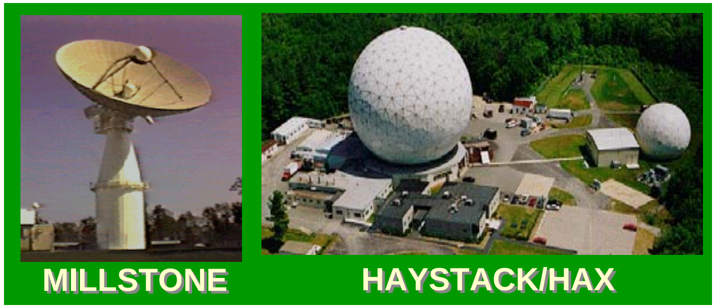
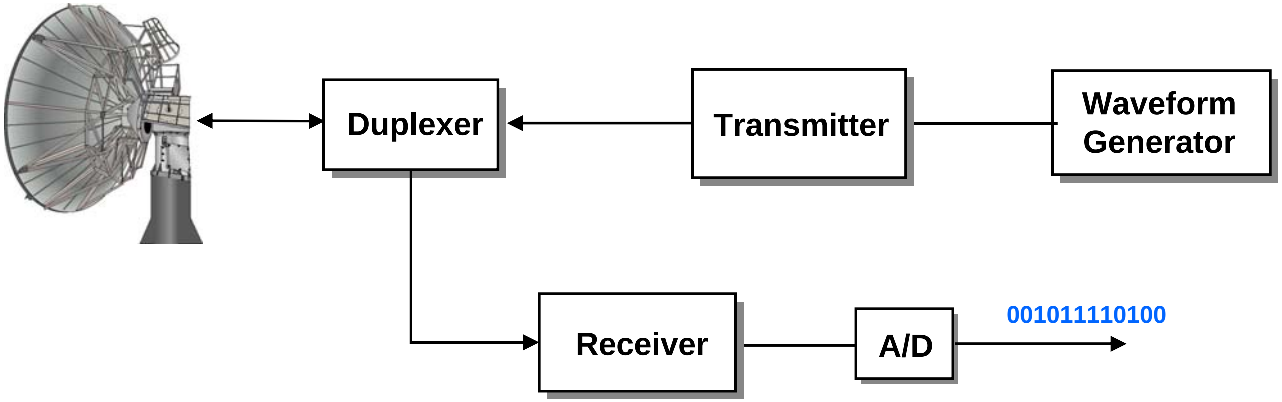
Dish Radars

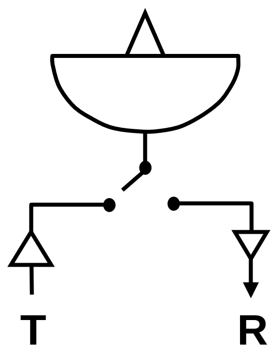
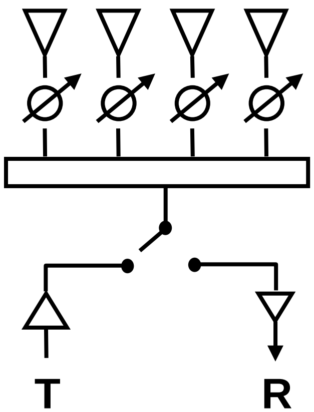
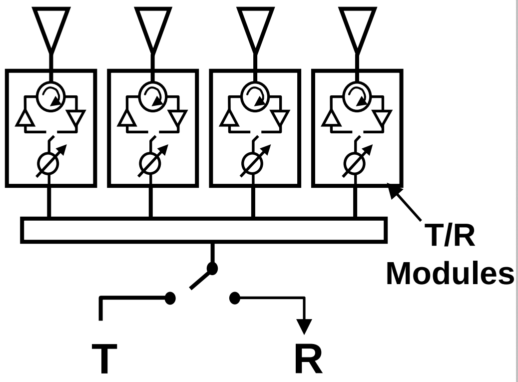
KWAJALEIN



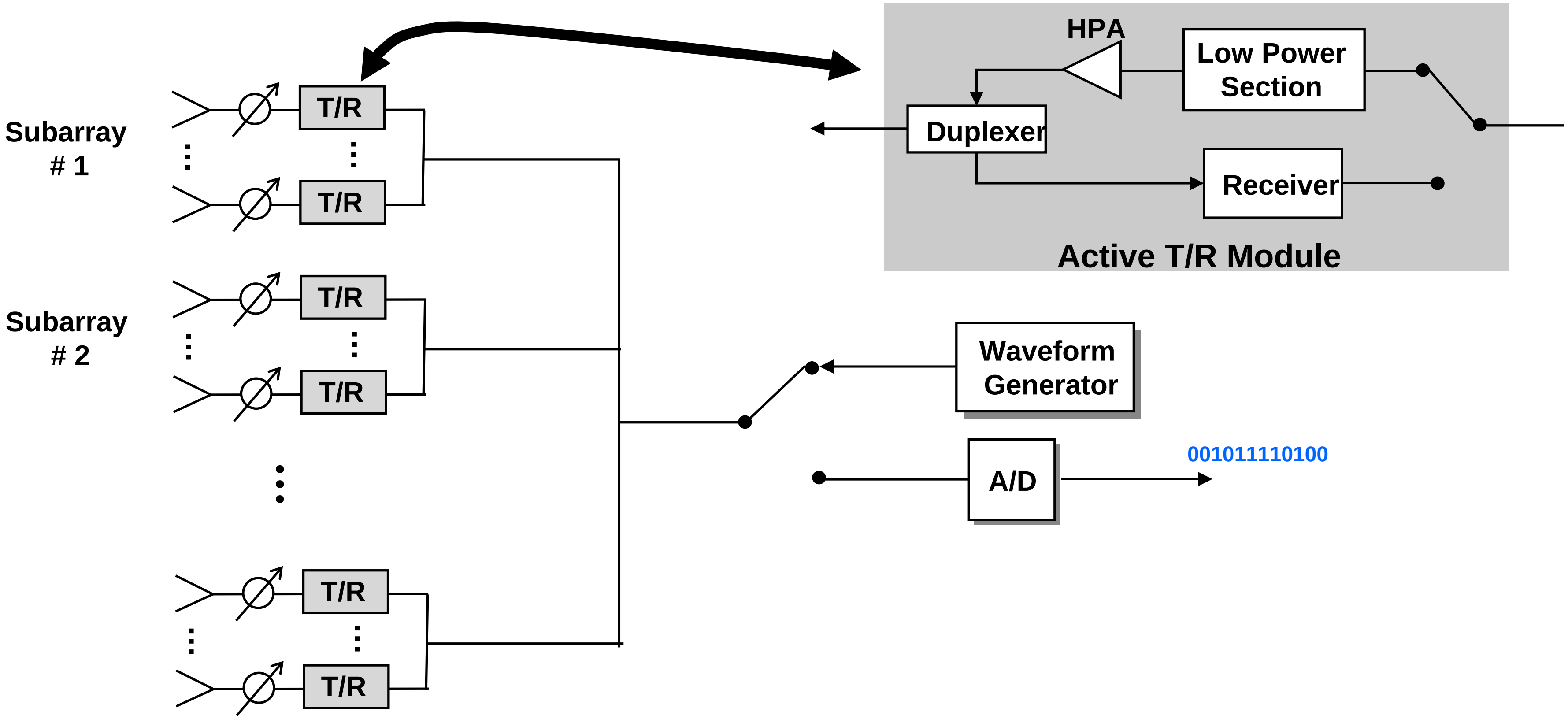


- Conventional radar transmitter/receiver design employed

Radar Antenna Architecture Comparison

	Dish Radar	Passive Array Radar	Active Array Radar
			
PRO	• Very low cost • Frequency diversity	• Beam agility • Effective radar resource management	• Beam agility • Effective radar resource management • Low loss
CON	• Dedicated function • Slow scan rate • Requires custom transmitter • High loss	• Higher cost • Requires custom transmitter and high-power phase shifters • High loss	• High cost • More complex cooling

Active Phased Array Radar



- **Transmit/Receive function distributed to each module on array**

Large Phased Arrays

Passive Array Radar

Active Array Radar

THAAD Radar
25,344 elements

Courtesy of Raytheon. Used with permission.

Passive Array Radar

Cobra Dane
15.3K active elements

Courtesy of Raytheon. Used with permission.

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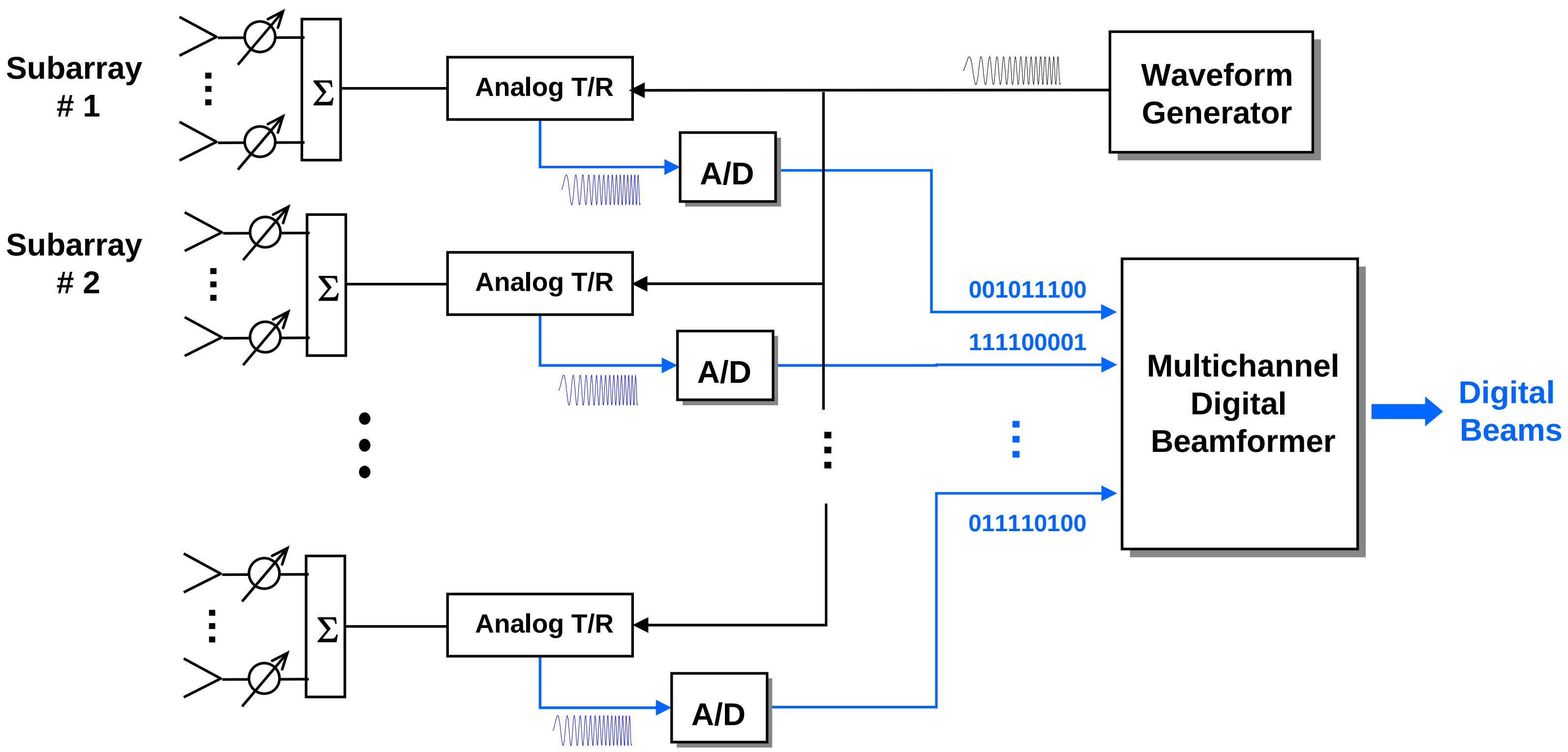
Digital Array Radar Architecture
Digital on Receive

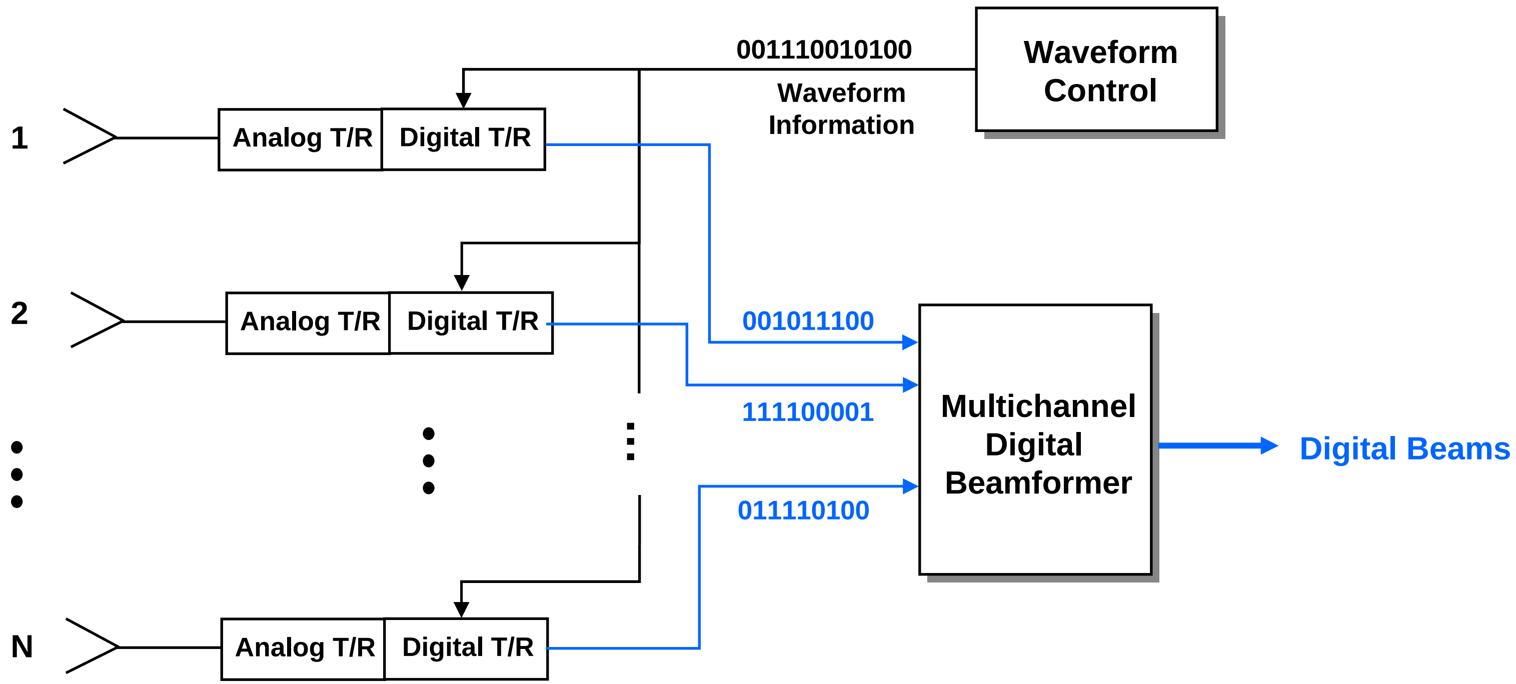


- **Each active analog T/R module is followed by an A/D for immediate digitization**
  – **Multiple received beams are formed digitally by the digital beamformer**

Digital Array Example
Digital On Receive

RSTER
(14 Digital Receivers)

Digital Array Radar Architecture II
Digital on Transmit & Receive



- Both waveform generation and receiver digitization are performed within each T/R module
  – Complete flexibility on transmit and receive

Summary

- **Radar transmit function is accomplished in two stages:**
  - **Waveform generator creates low power waveform signal and upconverts it to RF**
  - **Transmitter amplifies waveform signal**
- **Radar receiver performs filtering, amplification and downconversion functions**
  - **Final received signal is fed to an A/D for digitization**
- **Radar transmit/ receive architecture is highly dependent on the antenna type**
  - **Centralized architecture: dish radars, passive array radars**
  - **Distributed architecture: active array and digital array radars**

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Skolnik, M., Radar Handbook, New York, McGraw-Hill, 2nd Edition, 1990