Complex Systems Engineering: Radar Systems

Class 1 - Introduction

Class #1 Lecture

Instructor – Ingar Blosfelds

Class Logistics

- Schedule:
  - Wednesday, 6:30 – 9:00 pm, Rowan Hall Extension 319
  - 15 class periods, 1 final exam period
- Required Textbook:
  - "Principles of Modern Radar, Basic Principles"
  - www.amazon.com
- Class notes (pdf e-mailed prior to each class):
- Grading:
  - 50% final
  - 20% midterm (take-home)
  - 30% homework (none this week) (only Top 10 count, zero for late)
- Communications (e-mail preferred)
  - Ingar.T.Blosfelds@LMCO.com
  - 856 722-6161 work number

Class Schedule

Class		Subject	Date
1	**Overview**	Introduction	9/5/2018
2		Radar Equation	9/12/2018
3		Detection / Probability	9/19/2018
4	**External Factors**	Propagation Effects	9/26/2018
5		Clutter Characteristics	10/3/2018
6		Target Reflectivity / Fluctuation Models	10/10/2018
7	-Midterm distributed-	Doppler Phenomenology / Fourier Transform	10/17/2018
8	**Subsystems**	Antennas	10/24/2018
9	- Midterm due -	Transmitters / Solid State Antennas	10/31/2018
10		Receivers / Exciters	11/7/2018
11	**Signal/Data Processing**	Signal Processing	11/14/2018
12	- Thanksgiving -	Pulse Compression Waveforms	11/21/2018
13		Doppler Waveforms	11/28/2018
14	- Final distributed -	CFAR	12/5/2018
15		Radar Tracking	12/12/2018
	FINAL EXAM	Final Exam Due at 9 pm	12/19/2018

Instructor Biography

- **Education:**
  - BSEE, Duke University 1983
  - BS Comp Sci, Duke University 1983
  - MSEE Program, Drexel University
  - JD, Rutgers University, 1994
- **Early career, 1983 – 1994 (Associate Member – Senior Member)**
  - RCA/GE – Moorestown
  - Modeling, radar analysis
- **Mid career, 1994 – 2005 (Principal Member)**
  - Martin Marietta / LM – Moorestown
  - Radar design, combat system analysis, competitive assessment
  - Moonlighting as a patent attorney – ghost writing patent applications
- **Late career, 2006 – present (Lockheed Martin Fellow)**
  - Lockheed Martin – Moorestown
  - Sensor Lead (LCS, Deepwater, HCM, FFG(X), CSC), International pursuits

- **Family -** Born and raised in Huntington and Cold Spring Harbor, Long Island, he is a former high school athlete in football and lacrosse and is happily married to Patti and the proud father of Kira, Henry, and Emma. He was the Board of Education President in Delran in 2013 and served for seven years.

Class Overview

- Radar Concept
- Physics of EM Waves
- RF Interaction with Environment
  - Diffraction, Attenuation, Refraction, Reflection
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- Noise, SNR, Detection
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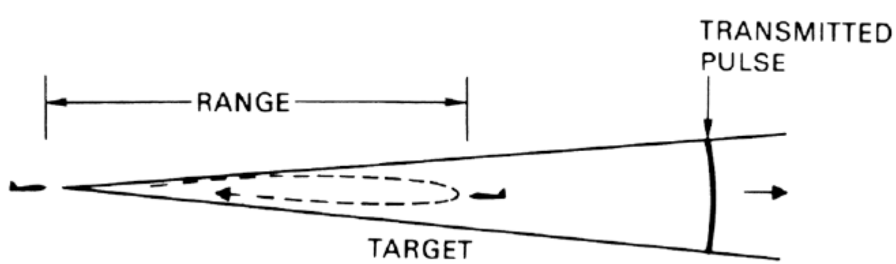
- Basic Radar Functions
- Radar Applications

Radar

- Radio Detection and Ranging
- Radio = electromagnetic waves in the radio frequency band with wavelengths ranging from 1 cm to 10s of meters.
- The principle of radar is that electromagnetic energy is radiated into space and when the energy intercepts an object, a small amount of the transmitted energy is reflected back to the antenna
- The time that it takes to make the round trip is directly related to the radar range. Thus, radar range is defined as the distance from the radiating antenna to the target that reflects the energy.



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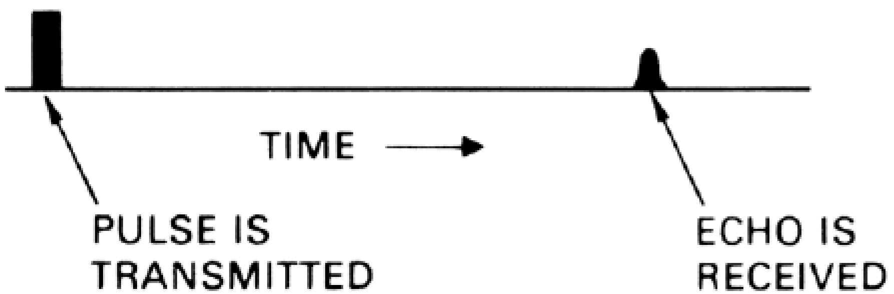
Range Derivation

- Information on the position of the target is the primary function of radars



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$$v = \frac{s}{t}$$

$$v = \frac{2 \cdot R}{t}$$ distance = round-trip

$$c = \frac{2 \cdot R}{t}$$ velocity = speed of light

$$c \cdot t = 2 \cdot R$$

$$R\,(in\ km) = \frac{c \cdot t}{2} = \frac{3.0E5\,km/\sec \cdot t}{2} = 1.5x10^5\,km/\sec \cdot t$$

Radar (or target) range = 150 km ➔ time = 1 ms

Range Derivation Examples

$$R\ (in\ km) = \frac{c \cdot t}{2} = \frac{3.0E5\, km/\sec \cdot t}{2} = 1.5x10^{5}\, km/\sec \cdot t$$

- t = 12x10-6 sec R = ?
- t = 1.258x10-3 sec R = ?

- R = 1000 m t = ?
- R = 250 miles t = ?

Please solve the problems

Basic Radar Block Diagram

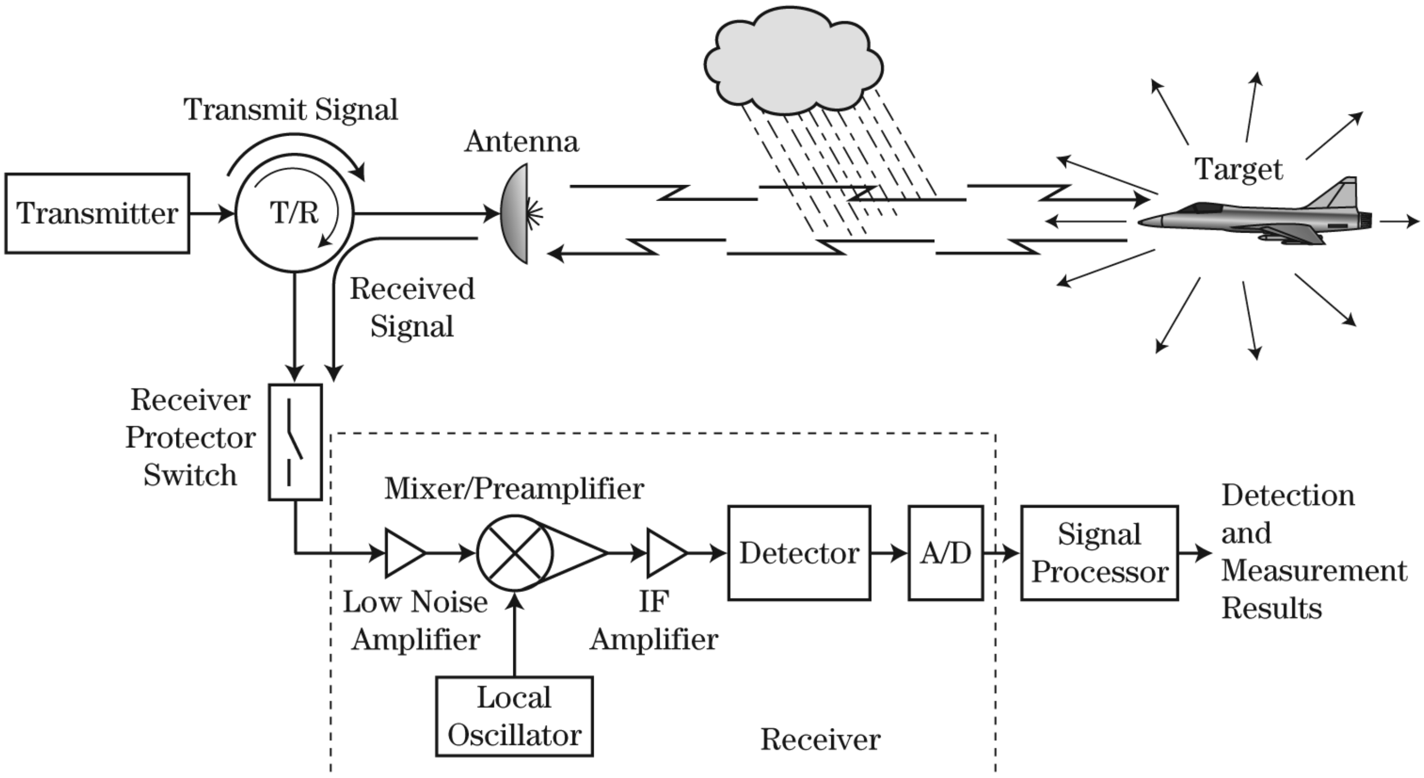


FIGURE 1-1 ■ Major elements of the radar transmission/ reception process.

"Used with Permission from Richards et al Principles of Modern Radar, Basic Principles (www.scitechpub.com)"

Basic Radar Equipment

- Control and Waveform Generator
  - Generates signals for transmitter and receiver
  - Distributes timing and control for radar
- Transmitter
  - Amplifies waveform for transmission
- Receiver
  - Down converts received signal and provides gain
  - Match filters
- Duplexer / Circulator
  - Allows use of one antenna for both transmit and receive
  - Protects receiver from high-powered transmit signals

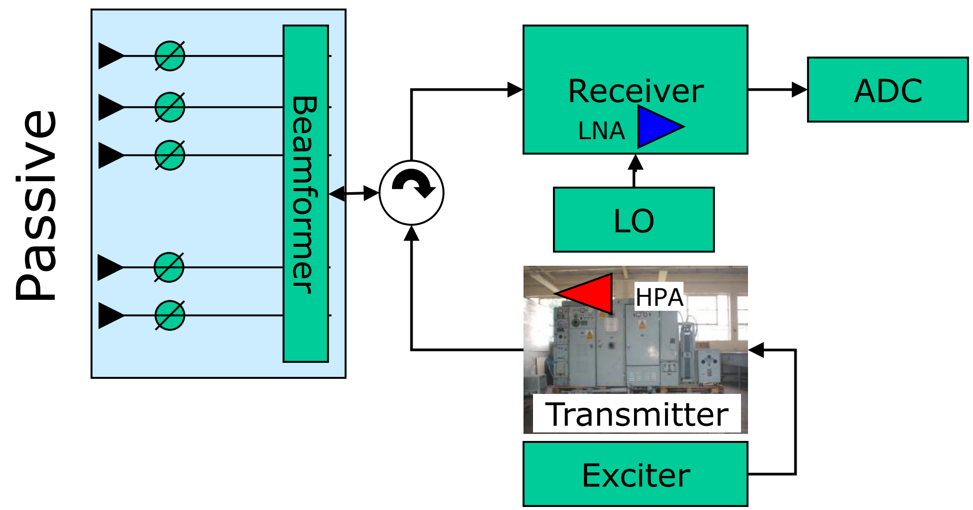
Basic Radar Equipment, II

- Antenna
  - Converts electrical energy to radio waves and vice versa
  - Forms beams and concentrates signal
- Signal Processor
  - Provides target detection processing
  - Processing for additional gain (coherent & noncoherent)
  - Clutter and noise processing
- Display
  - The human-machine interface
  - Displays radar output to an operator

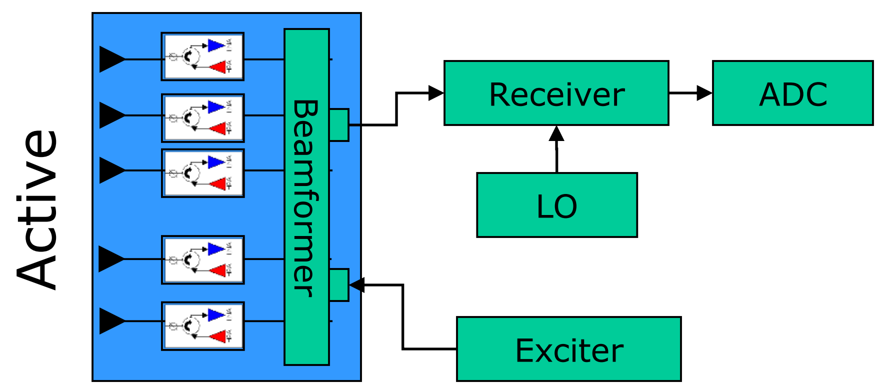
Radar Transmitters

- Old School Transmitters
  - Traveling-wave Transmitter (TWT)
    - High gain, efficiency, and power levels
    - Wide bandwidth (10% - 20% of transmitter frequency)
    - Can be used as final power amplifiers (SPY-1F)
    - Can be used to drive the final power amplifiers (SPY-1D)
    - Can achieve power levels in the hundreds of kW.
  - Cross-Field Amplifier (CFA)
    - Good phase stability (allows parallel operation)
    - Very high peak power (megawatts)
    - Long life (as seen in SPY-1D radars)
- New School Transmitters
  - Solid-state Devices (transmitter on the antenna face)
    - Semiconductor technology (no vacuum tubes)

Transmitter Configurations



- TWTs and CFAs are high power amplifiers that feed a passive array



- "Active" antennas include solid state transmit / receive (T/R) modules on the array face

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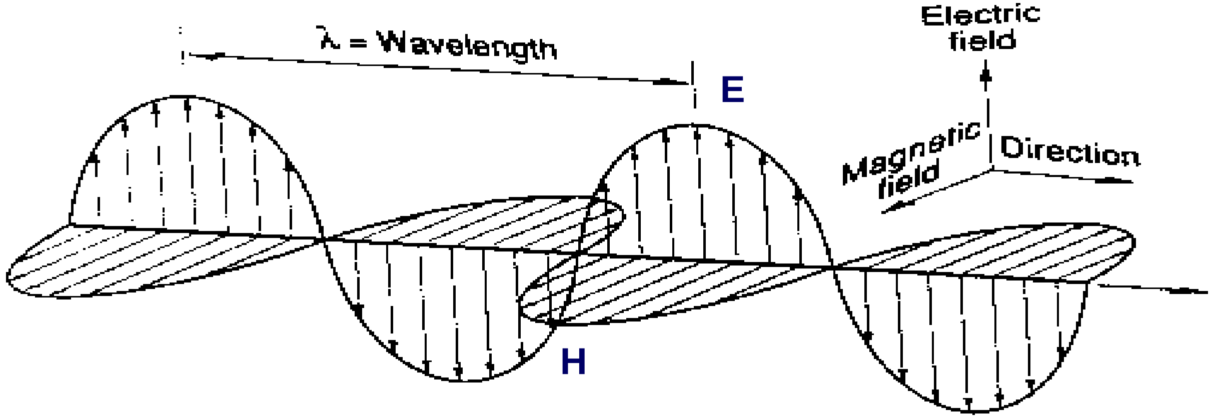
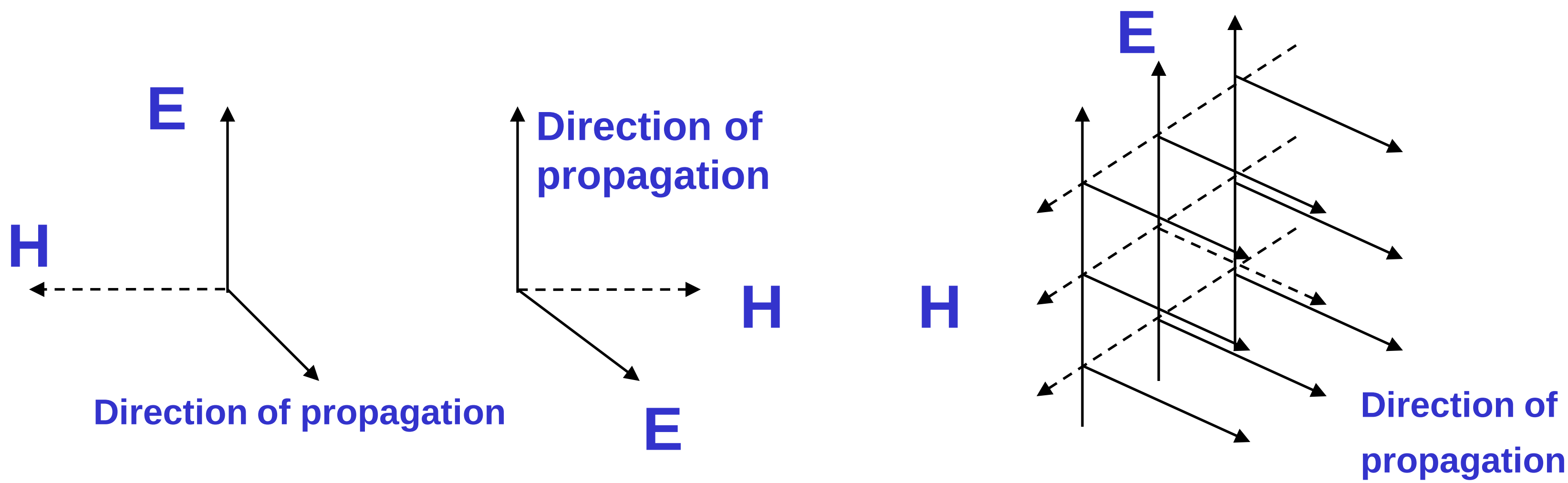
Electric and Magnetic fields

- To produce an electromagnetic field current must flow.
- Flowing electrons in current produces a magnetic field.
- A changing magnetic field produces an electric field and a changing electric field produces a magnetic field.
- This interdependent relationship gives rise to electromagnetic (EM) waves.
- The intensity of both fields may vary with time.



Direction of Propagation

- The direction of propagation of an EM wave is always perpendicular to both the E & H components.



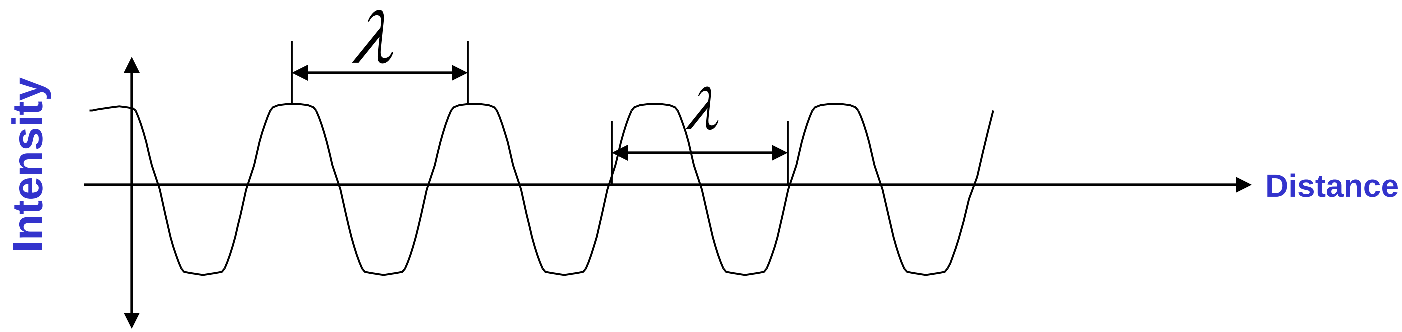
- The right hand rule is a method used to determine the direction of propagation
  - The thumb of your right hand represents direction of E field.
  - The fingers of you right hand represent direction of H field.
  - The normal to the palm represents direction of propagation of an EM wave.

Wave Transmission

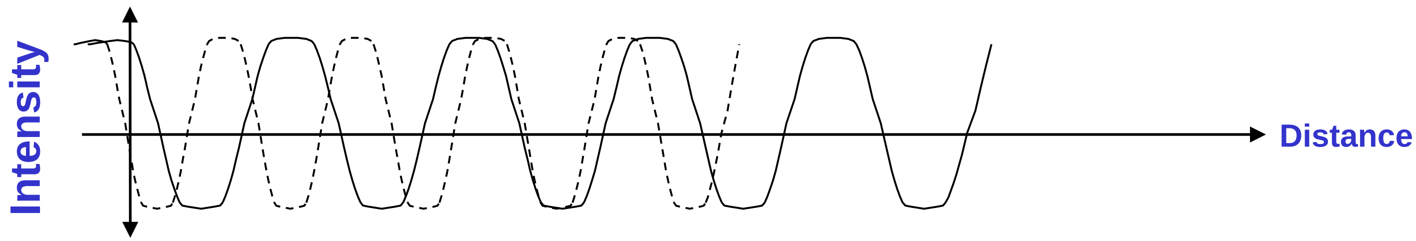
- Dropping a pebble in a pond causes waves to propagate, in all directions, through the water.
- If you strike a piano key a sound wave is propagated through the air.
- Both examples demonstrate the propagation of waves through a specific medium.
- Radar systems propagate radio waves & listen for echoes in order to determine target parameters including speed, range and elevation.
- RADAR is an acronym that stands for <u>Ra</u>dio <u>D</u>etection <u>A</u>nd <u>R</u>anging. This means radio waves are used to detect and analyze a target.
- Each type of wave has certain characteristics including wavelength, frequency and direction.

Wave Characteristics I

- Wavelength, λ , refers to the distance between successive parts of the wave.
- Waves are modeled by sine waves, as depicted below.

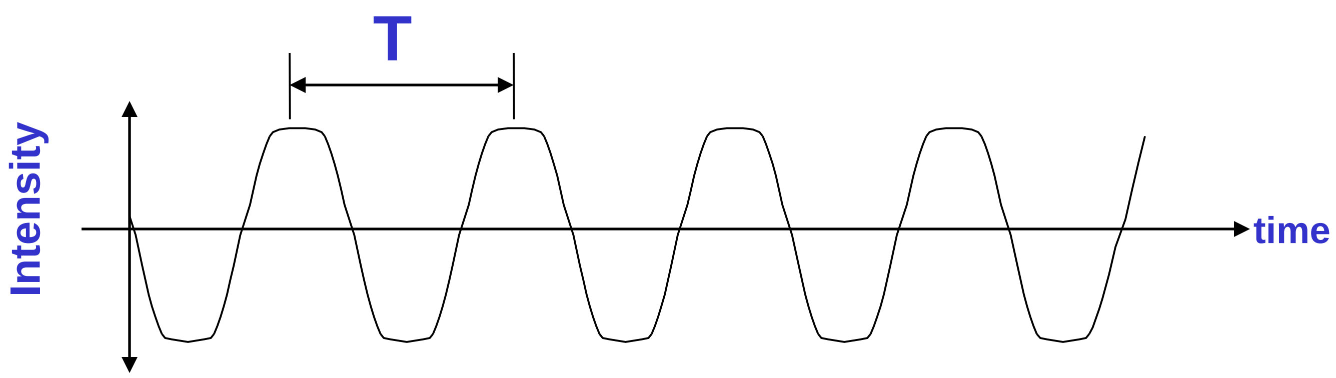


- Frequency, f , refers to the number of cycles the signal completes per second.
- The frequency of a wave is inversely proportional to the wavelength.
- The plot below represents 2 waves with different frequency.



Wave Characteristics II

- **The frequency of a signal is inversely proportional to the wavelength.**
- **In a vacuum radio waves travel at a constant speed, *c*, the speed of light.**
- $f = \frac{c}{\lambda}[Hz] = \frac{1}{T}$
- **Period, *T*, refers to the time taken to complete one cycle.**
- $Period = \frac{1}{f}[s]$
- **The graph below illustrates a wave's period.**



Wavelength / Frequency Problems

$$f = \frac{c}{\lambda}[Hz]$$

- f = 325 MHz λ = ?
- f = 2. 85 GHz λ = ?

- λ = 90 cm f = ?
- λ = 9 cm f = ?

Please solve the problems

Wave Characteristics – Phase I

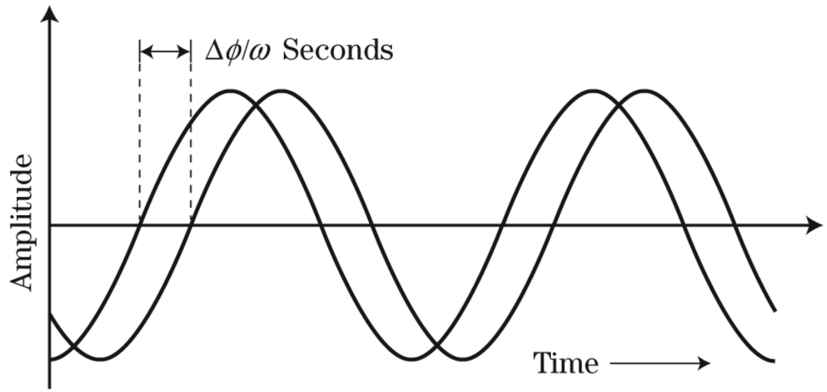


FIGURE 1-6 ■ Two sinusoidal waves with the same frequency but a phase difference $\Delta\phi$.

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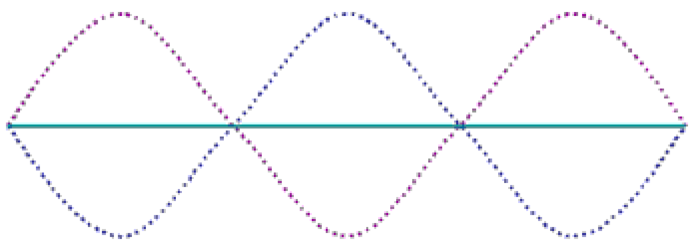
- **When two waves arrive at the same time and place, they combine such that the resultant wave is a complex sum, superposition, of the individual waves.**

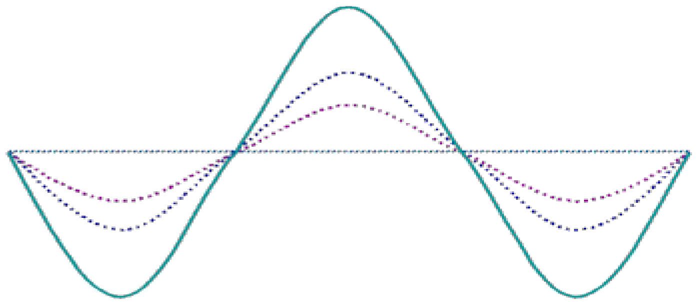
Wave Characteristics – Phase II

- The EM energy received at a point in space from two or more closely spaced radiating elements is a maximum when the energy from each radiating element arrives at the point in phase (constructive) and a minimum when it arrives out of phase (destructive).

Destructive Interference



Constructive Interference



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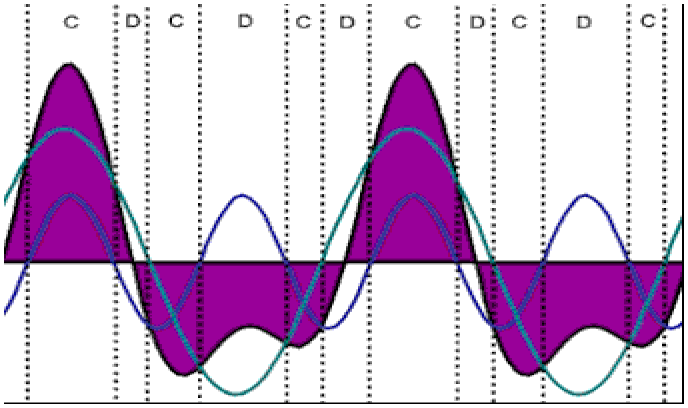
- Two waves at different frequencies can combine constructively and destructively



Wave Characteristics - Intensity

- Intensity is defined as the power per unit area of the wave
- As the wave propagates, it spreads and the intensity decreases

FIGURE 1-7 ■ Intensity of spherical waves.

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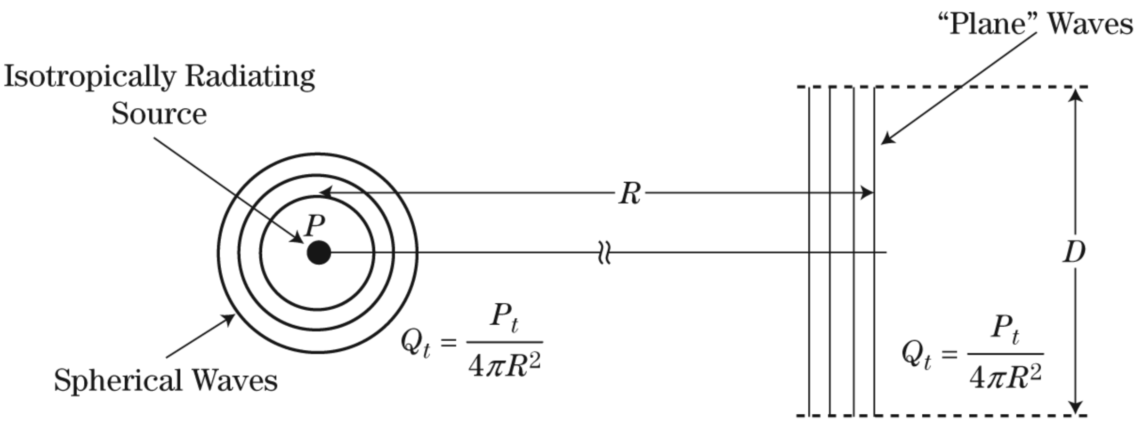

Wave Characteristics - Polarization

- Polarization describes the motion and orientation of the E vector
- E is oriented on the Y-axis ➔ Vertical Polarization
- E is oriented on the X-axis ➔ Horizontal Polarization
- $E_y = E_x$ & phase differs by odd multiples of $\pi/2$ ➔ Circular Polarization

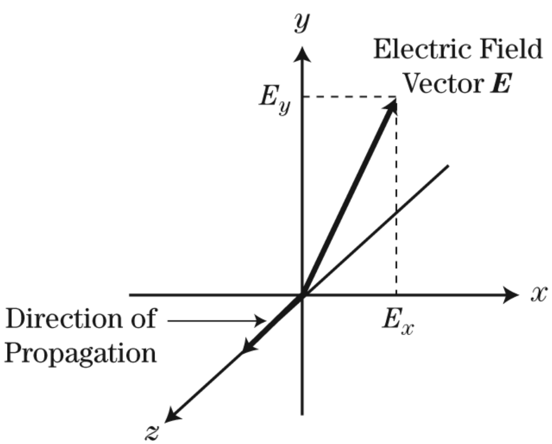

FIGURE 1-8 ■ Polarization components of a transverse EM wave propagating in the $+z$ direction.

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Specific Radar Frequency Bands

- Below are some lower-frequency bands used in Radar:

Band	Frequency [MHz]
UHF	300 – 900
VHF	30 – 300
HF	3 – 30

- The US standard for remaining bands are listed below:

Band	Frequency [GHz]
millimeter	40 – 100
Ka	26.5 – 40
K	18 – 26.5
Ku	12.5 – 18
X	8 – 12.5
C	4 – 8
S	2 – 4
L	1 – 2

Frequency Trade-offs

Search	*Lower Frequencies*	*Wider Beams to Cover Volume*	*VHF, UHF, L,S*
Track	*Higher Frequencies*	*Narrow Beams to get Good Angle Accuracy*	*S,C,X*
Multifunctions, search, and track	*Middle Frequencies*	*Lower Frequencies*	*S,C*
Low Elevation Applications	*Higher Frequencies*	*To get Narrow Beams*	*S,C,X*
Wide Bandwidth Applications	*Higher Frequencies*	*Since BW $\leq$ 10% Carrier Frequency*	*C, X*
Seeing through weather	*Lower Frequencies Best*		*UHF, L,S*
Mapping weather	*Higher Frequencies Best*		*C,X, Ku*
Airborne Radar	*Higher Frequencies Best*	*To get Narrow Beams with Small Apertures*	*X, Ku*
Over-The-Horizon Radar	*Very low frequencies*		*HF*

S-Band Radars Make Excellent Multi-Function Radars

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Radar Diffraction

- Diffraction is the bending of EM waves as they propagate through an aperture or around the edge of an object

FIGURE 1-9 ■ Extreme cases of diffraction.

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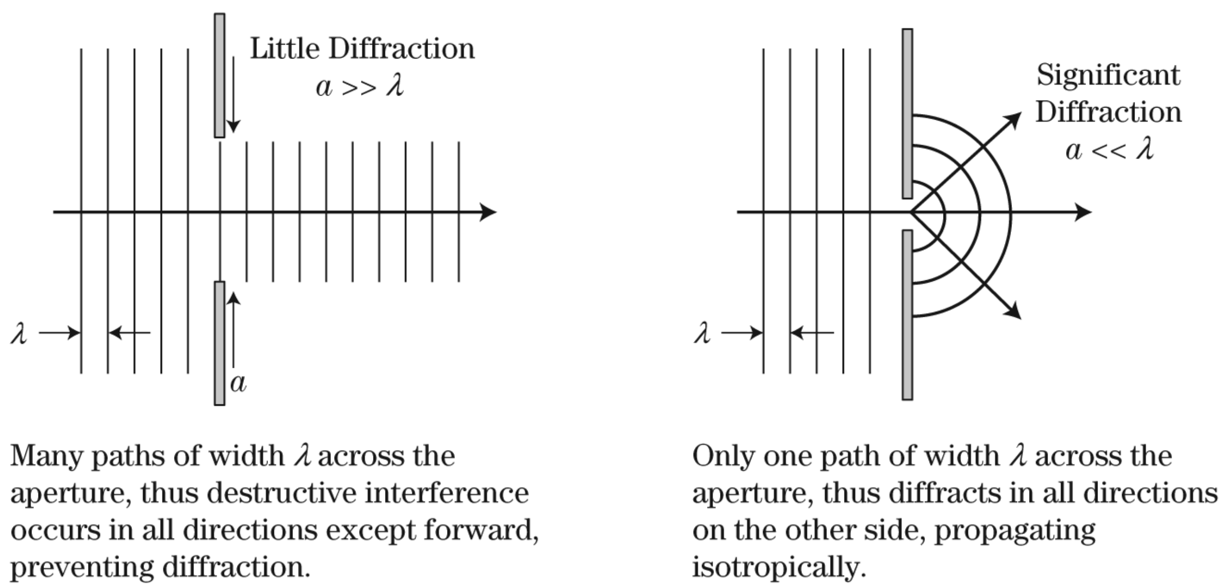
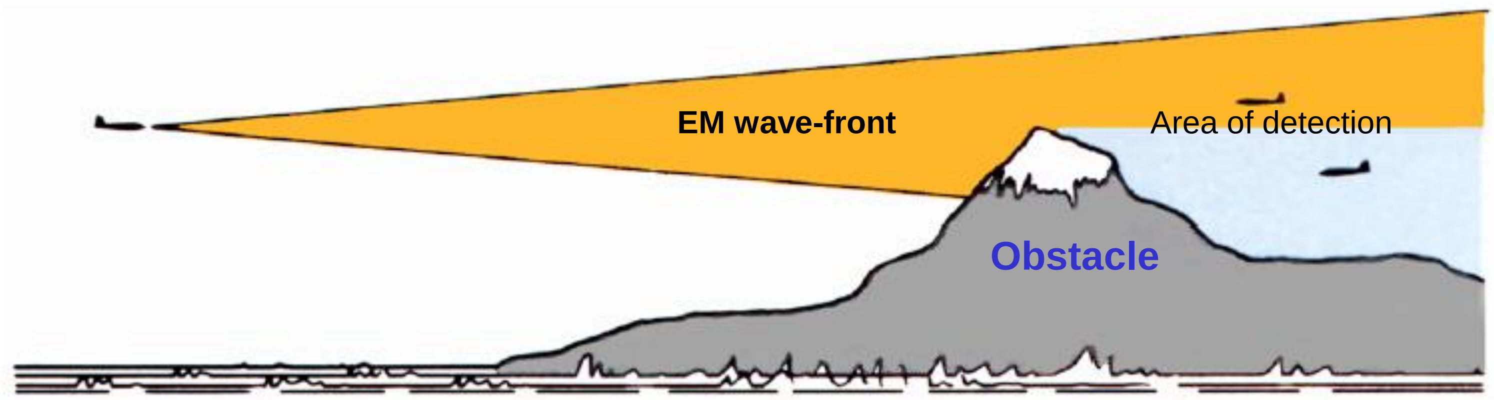


Radar Diffraction – Earth / Ocean

- While diffraction can severely attenuate the intensity of the signal, some target returns may still be large enough to detect



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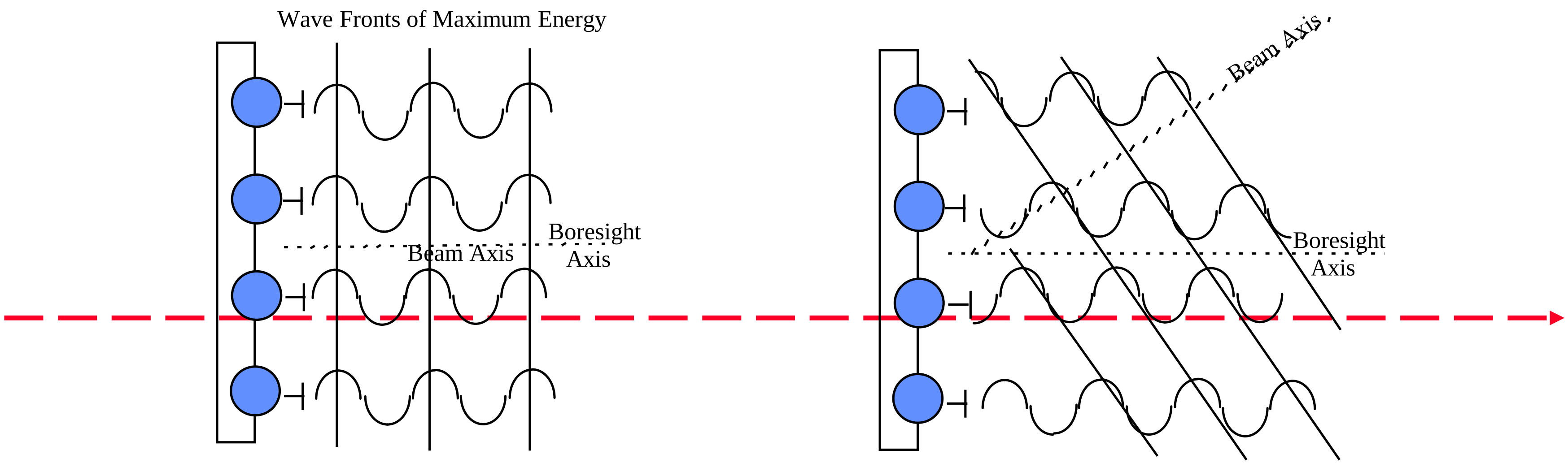
Generating Antenna Beams

- Individual radiators across a structure is called an antenna and forms the basis for how phased array radars form beams.



Radiating in Phase

Altering the Phase to Change the Axis

Beam is formed straight ahead (broadside)

Beam is formed at an angle from broadside

Antenna Gains

- Waves travel the same distance to a point perpendicular to the array
- If the waves exit the array in phase, then they will combine constructively at the point and form a maximum gain
- As you move angularly away from the perpendicular, the distance that each wave travels changes along with phase, resulting in destructive interference

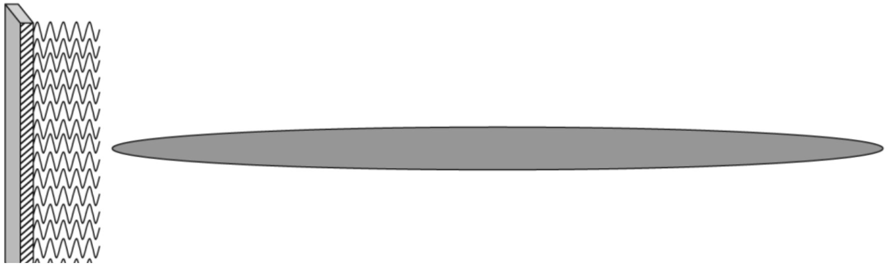


FIGURE 1-11 ■ A multi-element linear array of radiating elements with in-phase signals and resulting main beam pattern.

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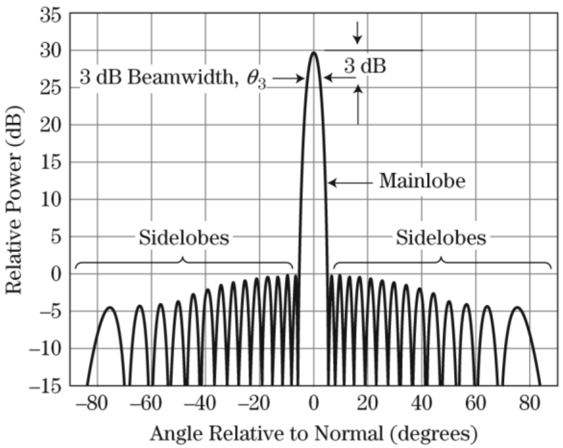

FIGURE 1-12 ■ Idealized one-dimensional antenna pattern.

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$$\theta_3 \approx \frac{1.3\lambda}{D}$$

D = diameter

Beamwidth in radians

Antenna Beamwidth Calculations

Freq	Wavelength	Ant Dia	Beamwidth	
			Rad	deg
10 GHz		1.0 m		
3 GHz		1.0 m		

$$\theta_3 \approx \frac{1.3\lambda}{D}$$

D = diameter

Beamwidth in radians

Please solve the problems

Atmospheric Attenuation

- Radar waves traveling through space interact with particles (dust, rain, fog, smog, etc.)
- Particles in the atmosphere can absorb, deflect, and scatter the radar waves, thereby decreasing or attenuating the amount of energy reaching the target (absorbed energy converts into heat energy which is why one gets warm quickly when parked in front of a SPY-1 radar)
- Higher frequency radar waves (shorter wave length) are scattered and attenuated more than lower frequency radar waves

Attenuation

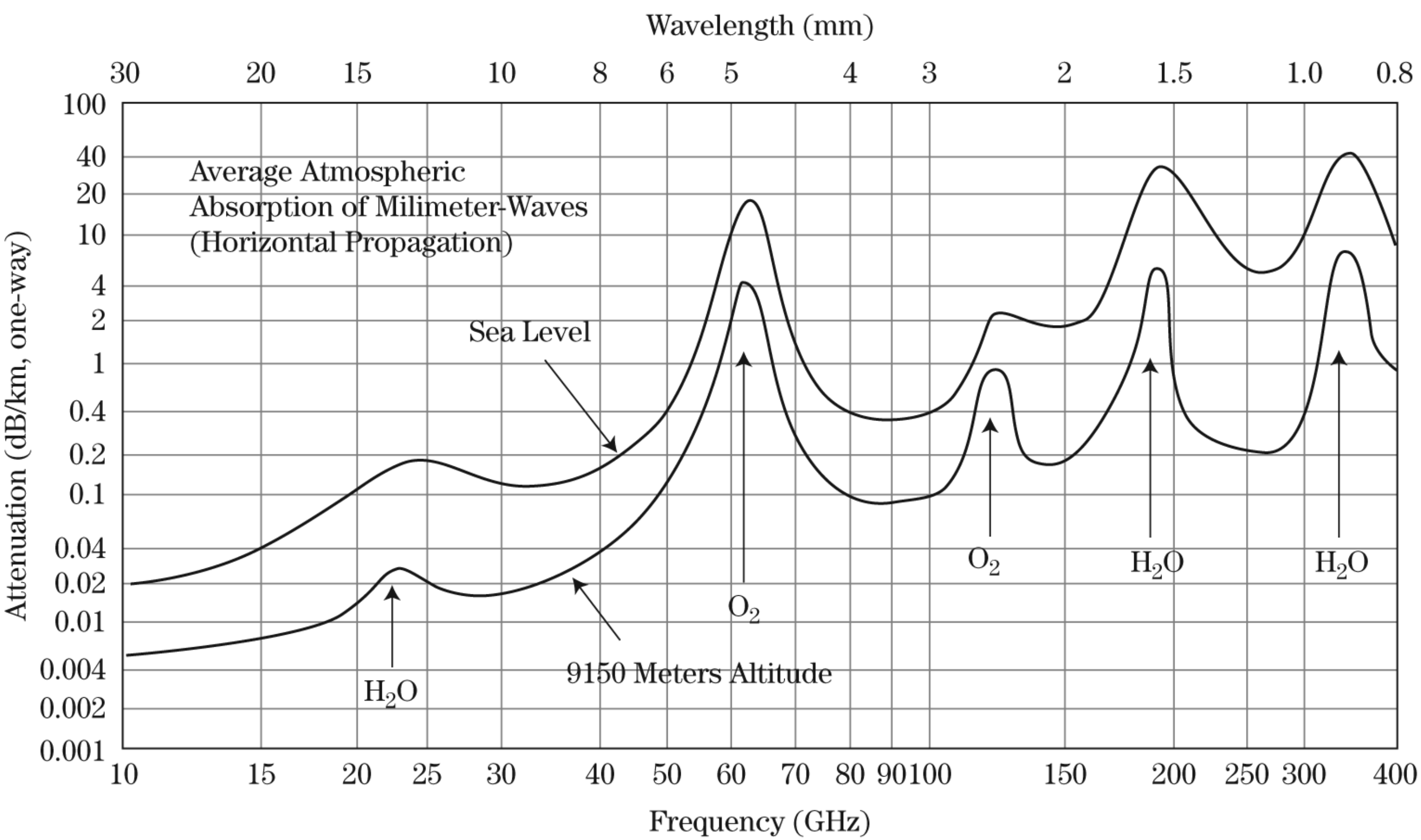

FIGURE 1-13 ■ One-way atmospheric attenuation as a function of frequency at sea level and at 9150 meters altitude. (From U. S. Government work.)

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Rain Attenuation

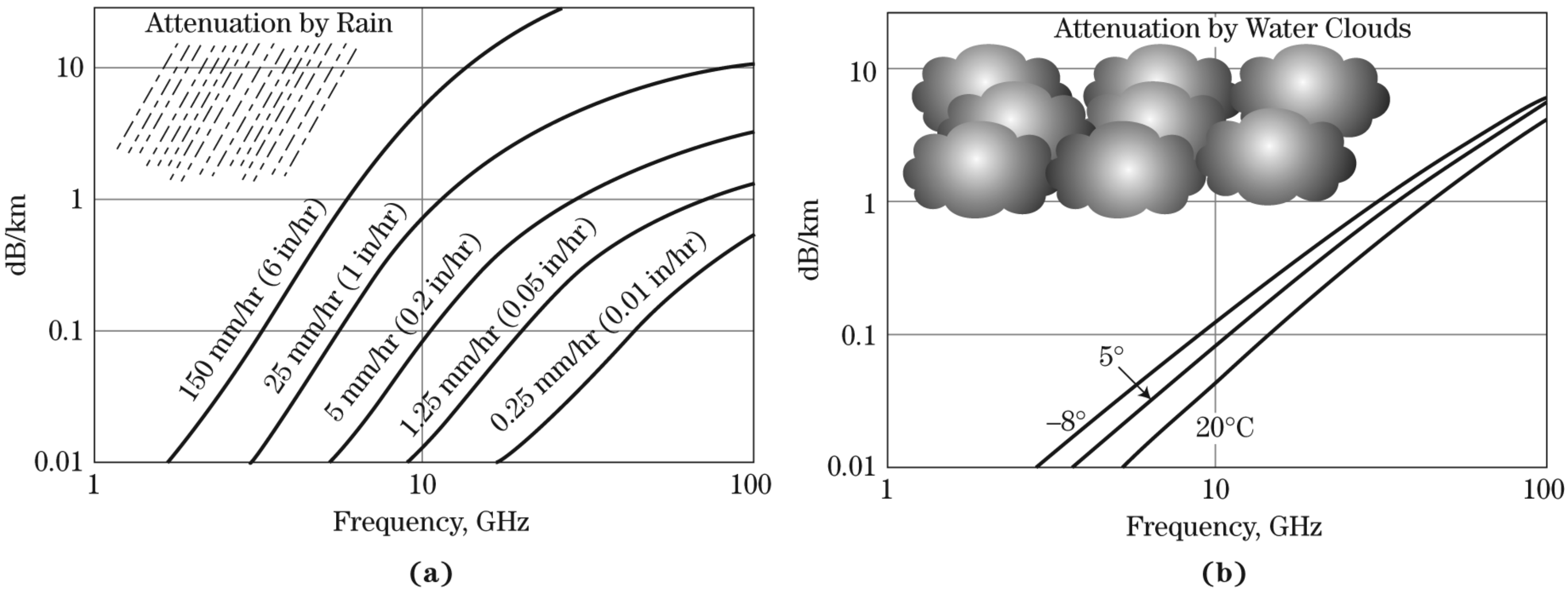

FIGURE 1-14 ■ One-way rain and cloud attenuation as a function of frequency. (a) Rain. (b) Clouds.

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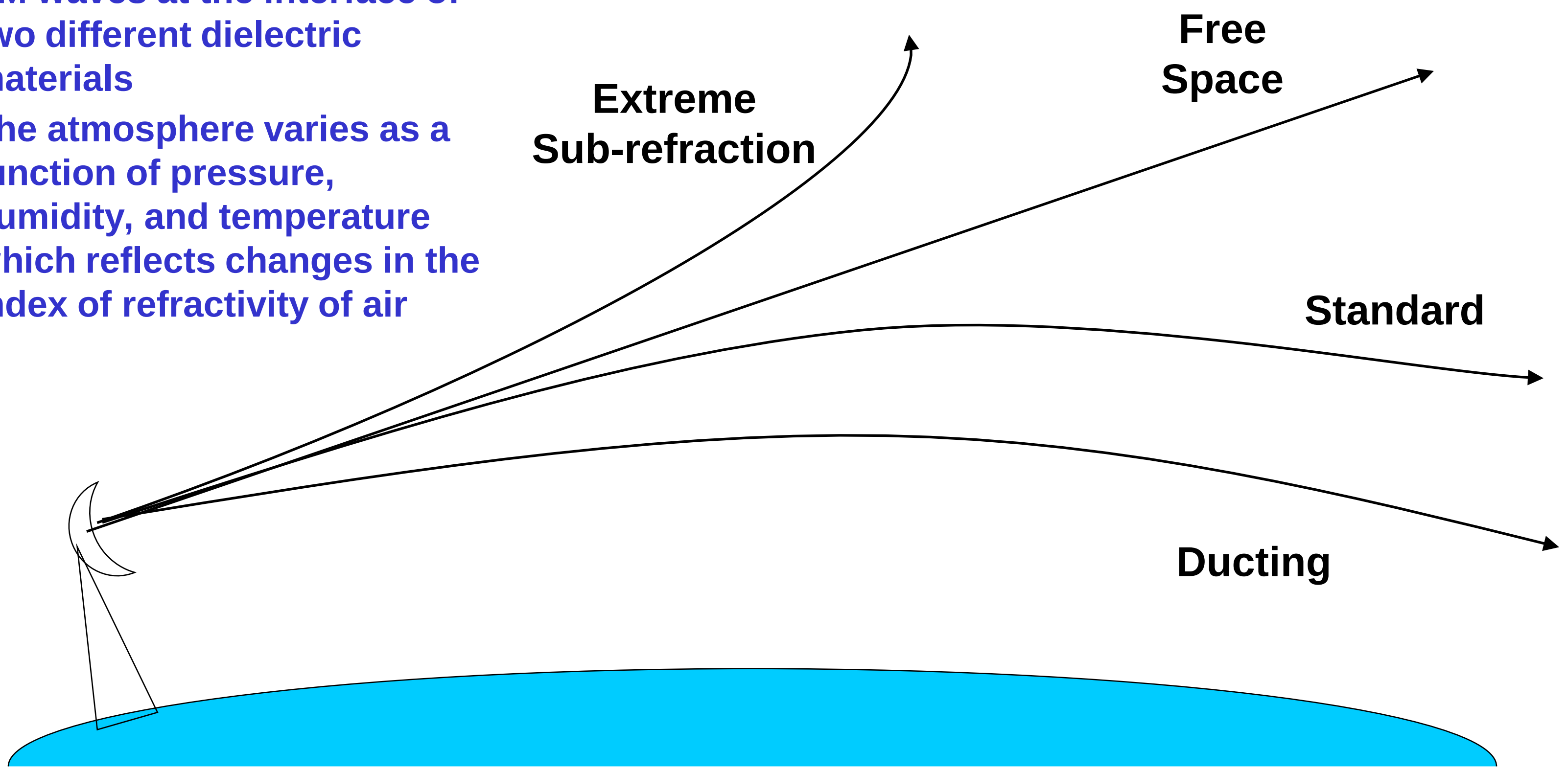
Refraction Overview

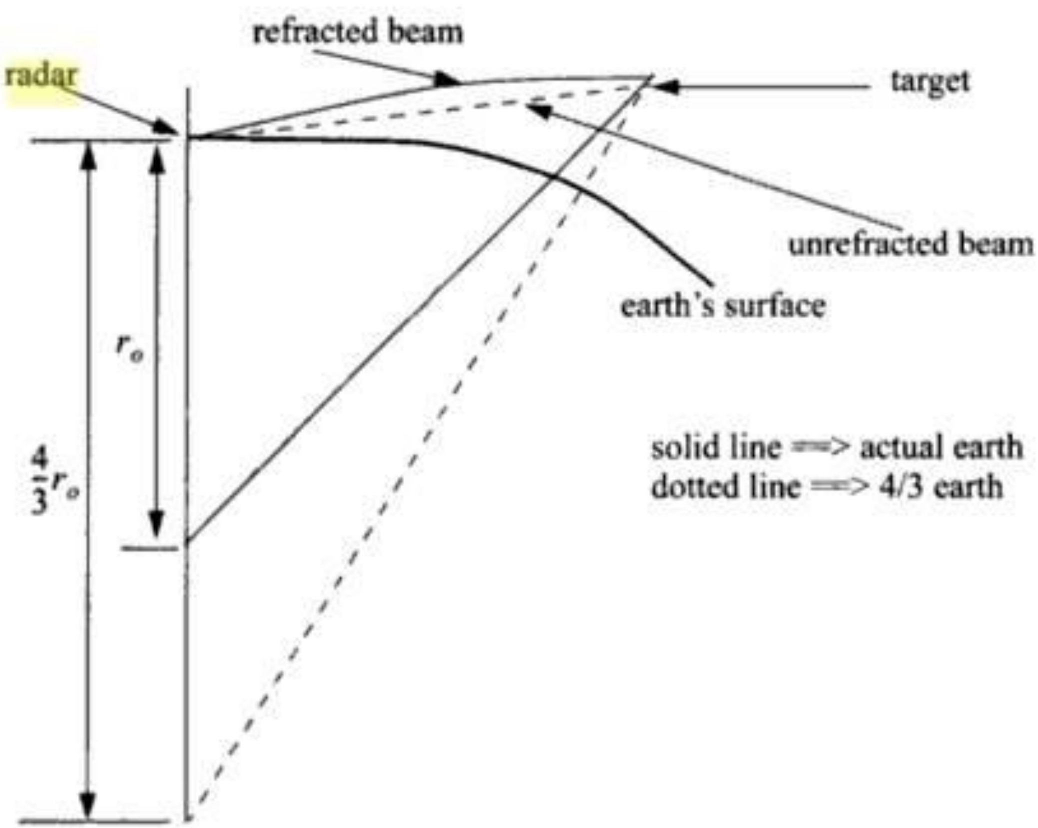
- Refraction is the bending of EM waves at the interface of two different dielectric materials
- The atmosphere varies as a function of pressure, humidity, and temperature which reflects changes in the index of refractivity of air

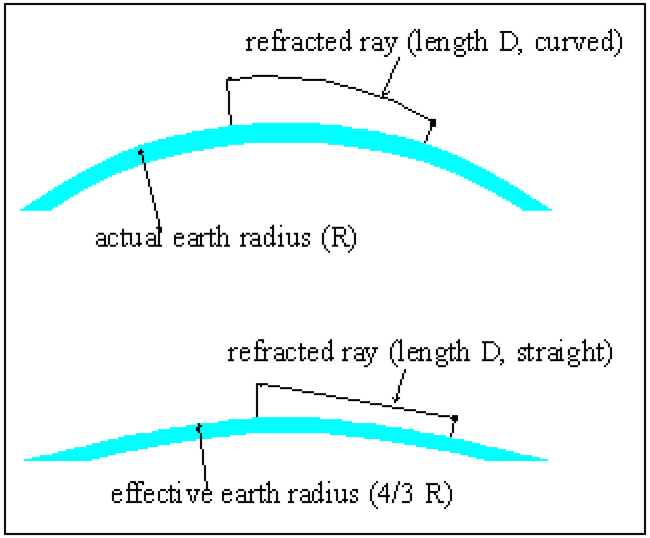


RF waves react differently to varied environmental conditions

Standard Propagation / Refraction
aka "4/3 Earth"

- The first radar engineers collecting atmospheric data and how it impacts transmissions were from Europe and the cold waters there created atmospheric conditions that became known as "standard atmosphere" or 4/3 earth.
- In these conditions, the radar energy propagating through this atmosphere refracts or bends downwards. By assuming an effective earth's radius of 4/3, the radar horizon can be measured with straight lines as opposed to having to model the radar refraction with the actual earth's radius.





effective Earth radius

Reflection or Scattering

- When RF waves strike objects, the wave can re-radiated forwards or backwards, depending upon the type of surface and the roughness of the surface.

FIGURE 1-17 ■ Specular scattering.

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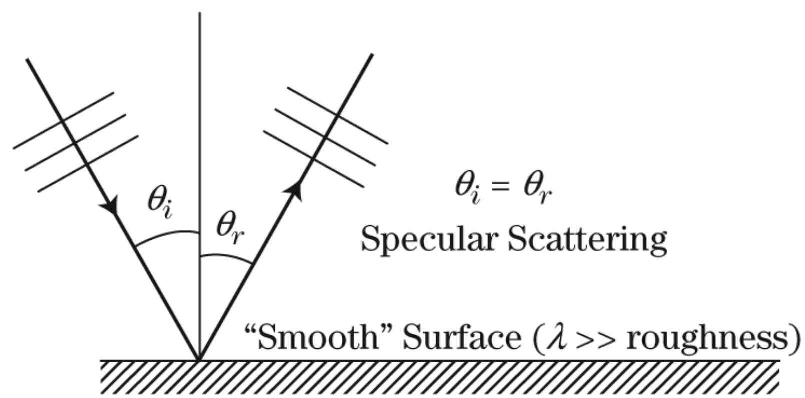
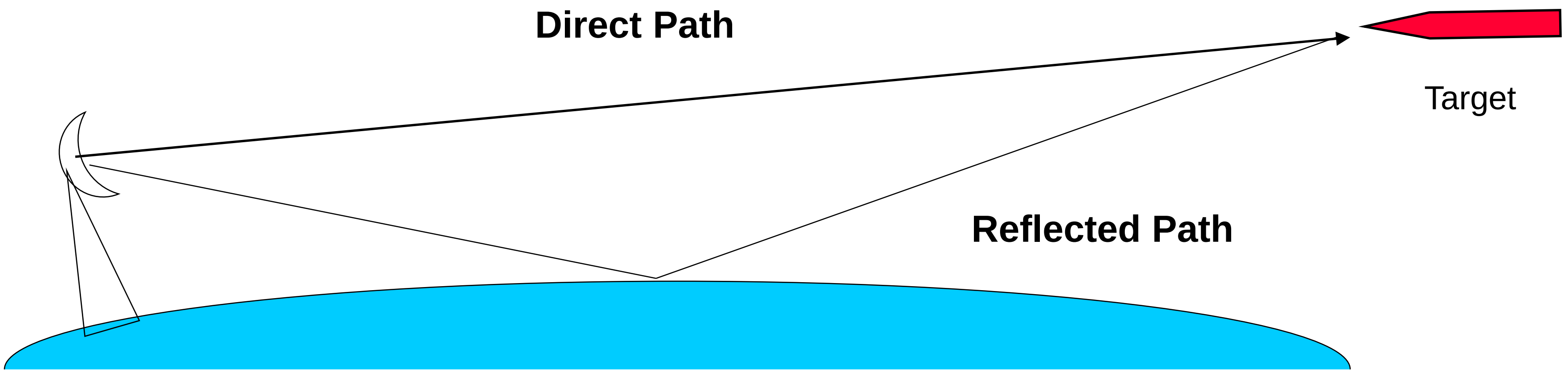


Multipath Reflections



The radar transmissions can reflect off the ocean surface and illuminate the target. The path traveled off the ocean is different than the direct path; consequently, the energy received at the target can be in phase or out of phase. Thus, the two paths can add constructively, leading to multipath peaks, or can add destructively, leading to multipath nulls.

Diffuse Reflection or Scattering

- On rough surfaces or high seas, the RF reflections can be coming from all different angles which can lessen the impact of specular multipath

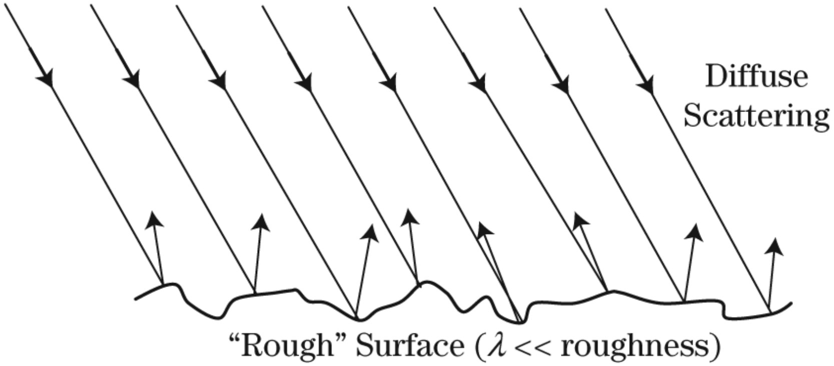


FIGURE 1-18 ■ Diffuse scattering.

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Radar Configurations

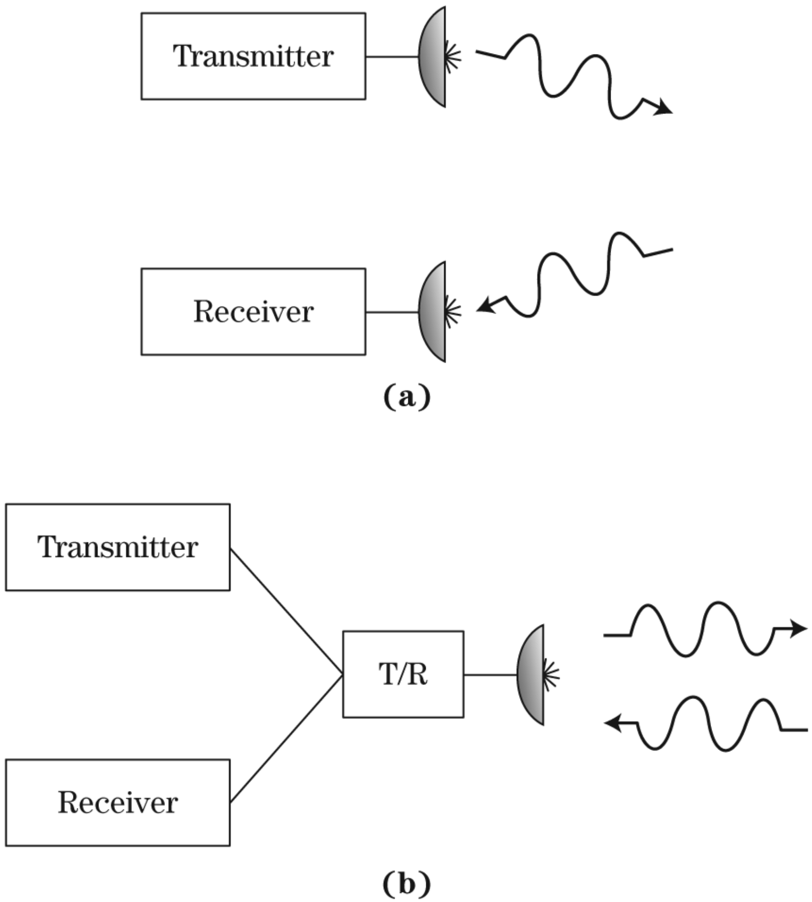

FIGURE 1-19 ■ Basic radar configurations: (a) Bistatic. (b) Monostatic.

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Monostatic v. Bistatic Radars

- Advantages of Bistatic Radar

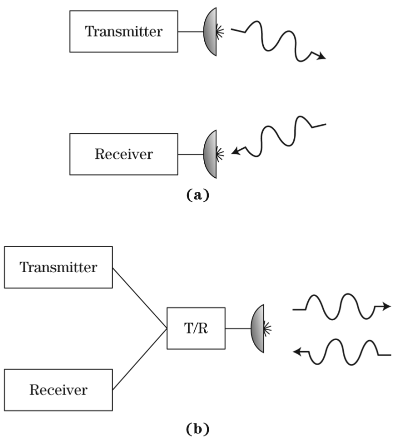

FIGURE 1-19 ■ Basic radar configurations: (a) Bistatic. (b) Monostatic.

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- Advantages of Monostatic Radar

Radar Configurations – CW vs. Pulsed

Differences between Pulse and Continuous Wave Radars

- **Transmission**
  - **Pulse Radar: delay between transmitting and receiving periods so that the time between transmitted pulse and received pulse is different**
  - **CW Radar: transmits continuously**
- **Antennas**
  - **Pulse Radar: may use same antenna for transmitting and receiving, "blanking" the receiver during transmission and vice-versa. This is done by the duplexer / circulator.**
  - **CW Radar: typically uses two antennas, one for transmit and one for receive since there are no delays to receive**
- **Extracting Range Information**
  - **Pulse Radar: uses "pulse delay ranging" to provide range measurements**
  - **CW Radar: FM ranging – linearly increasing frequency as a function of time**

Pulsed Radar Waveform

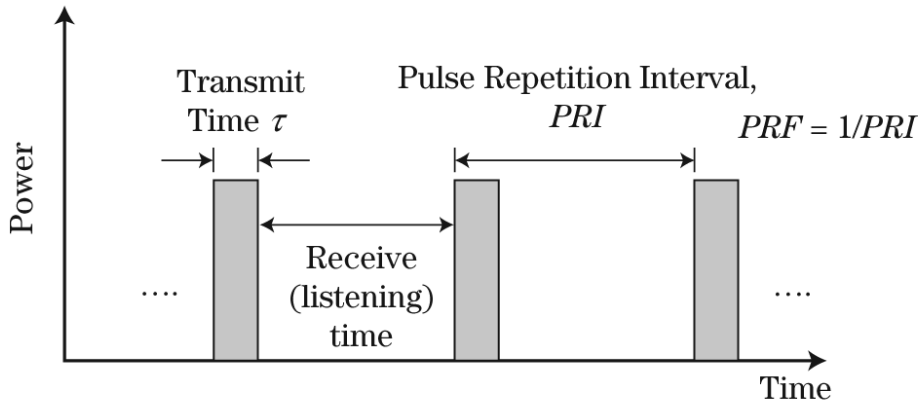

FIGURE 1-20 ■ Pulsed radar waveform.

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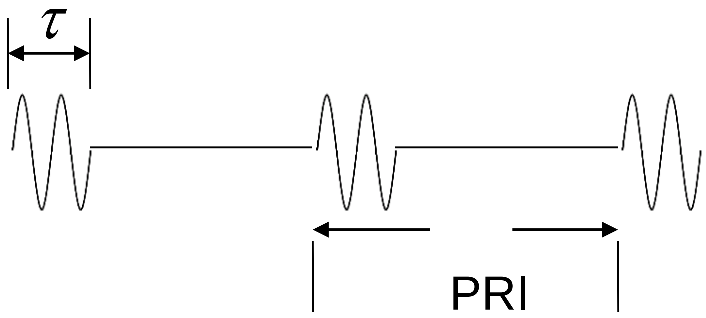
Pulsed Waveform – Duty Factor

- Duty Cycle (Duty Factor) = $\tau \div PRI$
- Peak Power = P_P
- Average Power = $P_A = P_P$ * Duty Factor



Unambiguous Range Measurement

- When the round-trip delay for the pulse to return from the target is greater than the pulse repetition interval (PRI), then ambiguities occur

FIGURE 1-22 ■ Pulsed radar range ambiguity.

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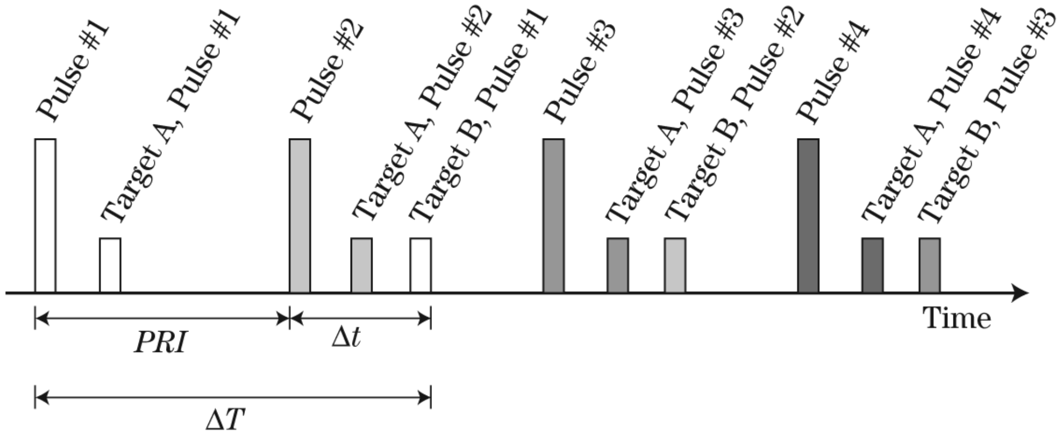
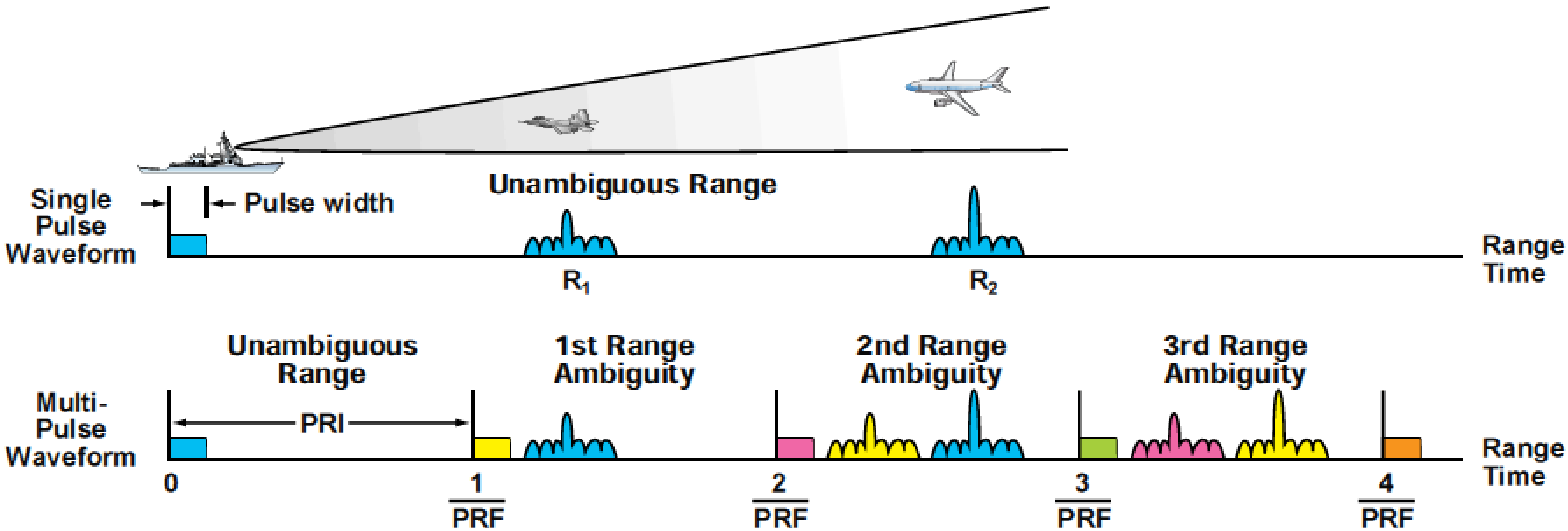


Range Ambiguities



- *No detections during transmit pulses*
- *Range ambiguity removal difficulty proportional to number of ambiguity zones*

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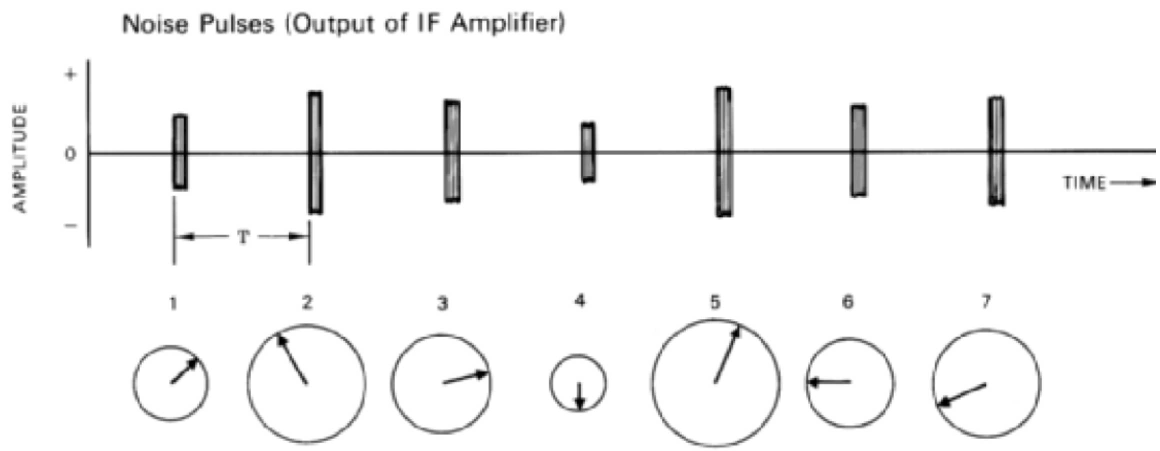
$$R_{unambig} = \frac{c}{2 \cdot PRF}$$

Signal Integration, I

- Maximum detection range is a key in radar design
- If one pulse does not provide enough detection range, then you can transmit additional pulses to increase Signal-to-Noise (S/N) levels

Noise and clutter will be random in phase and will not add together



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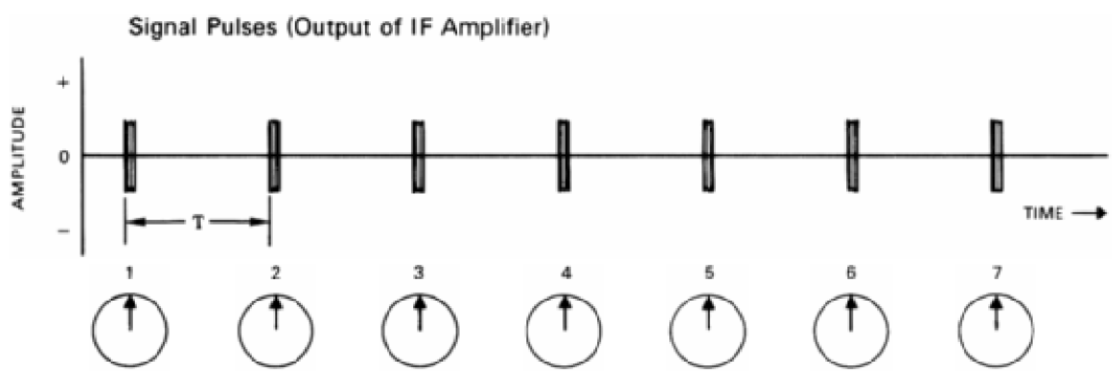
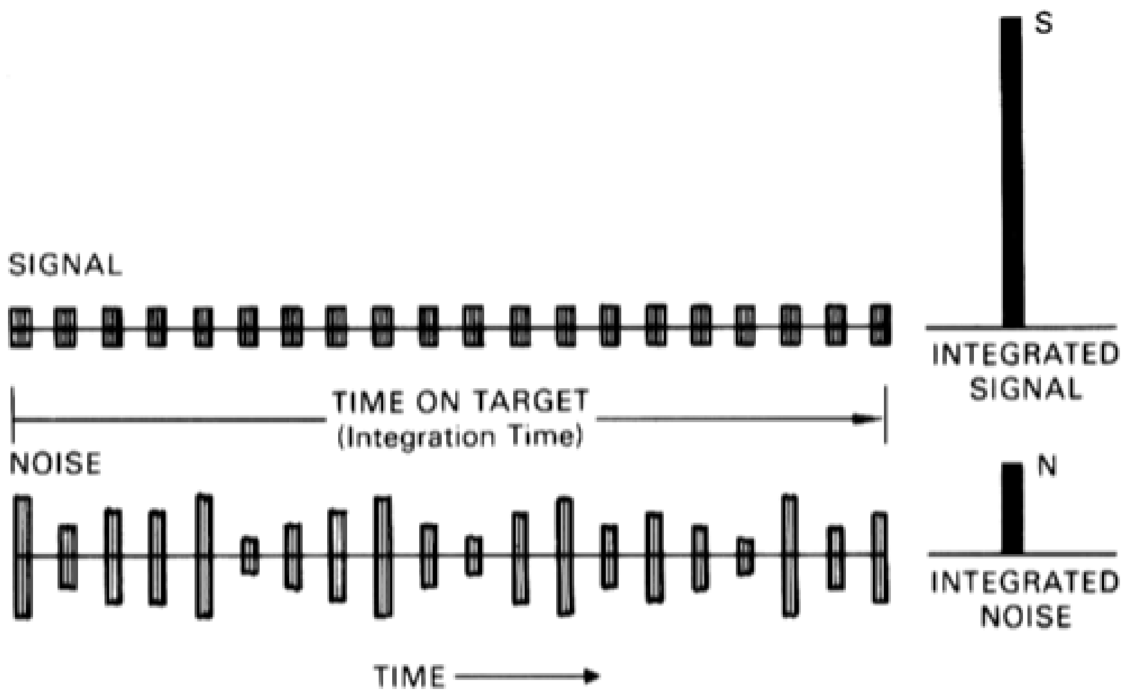
Targets basically present the same image from pulse to pulse, thereby the returns tend to be in phase and add up



Signal Integration, II

- Target signals (in phase) add together, increasing the signal level
- Noise signals (random) do not add together, so integrating multiple pulses can increase Signal-to-Noise (S/N) levels



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Doppler Shift

- *The Doppler effect causes the signal reflected by a moving target to be shifted by an amount*

$$f_d = \frac{2v_r}{\lambda} = 2\,\frac{v_r}{c}\,f_t$$

f_d = Doppler frequency in Hz

v_r = relative radial velocity between radar and target

λ = wavelength of carrier frequency

f_t = transmit frequency

- *The Doppler effect forms the basis of techniques used to discriminate between moving targets and stationary targets (clutter) such as MTI (Moving Target Indicator)*

Targets Moving Perpendicular (Crossing) Produce No Doppler Shift

Class Overview

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- Radar Applications

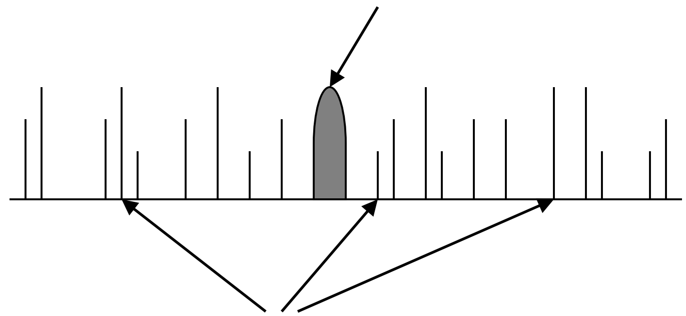
How far can a radar see?

- One of the fundamental considerations in radar design is the maximum range.
- Amongst the limiting factors affecting radar range are:
  - Line of Sight
  - Clutter
  - Weather
  - Jamming or other electromagnetic interference
  - Noise

Electrical Background Noise

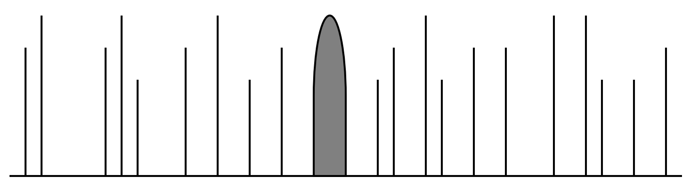
- The main problem with detection is finding the echo of the transmitted signal from the noise.

Target Echo



Noise

- Since the noise is amplified along with the signal in the gain stages of the receiver, more gain does not help find an echo.



Noise still as prominent after gain

Electrical Background Noise

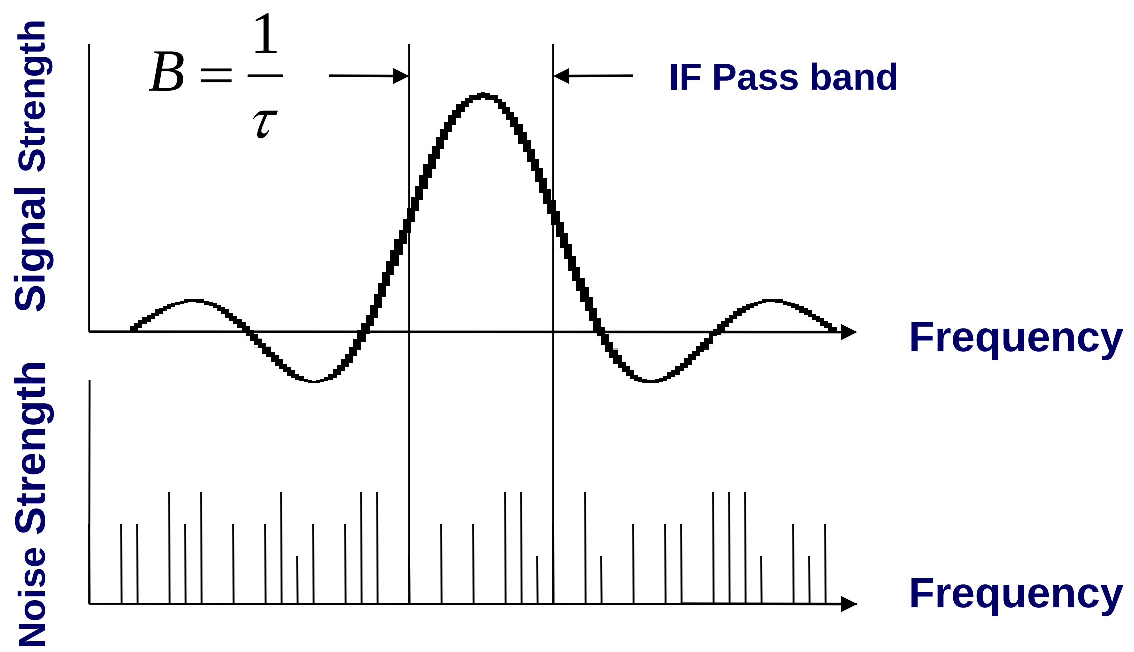
- Thermal noise is the dominant source of noise in the receiver.
- It has the same spectral characteristics as the noise resulting from thermal agitation in a conductor.
- Ideal noise is approximated by the following equation:

$$\text{Ideal Mean Noise Power} = kT_0B$$

- Actual noise will include a noise figure factor, F_n
  - Where:
    - k is Boltzmann's constant, $1.38*10^{-23}$ W s/K.
    - T_0 is the absolute temperature of the conductor representing the external noise, in Kelvin. (We generally approximate 290 K at room temperature)
    - B is the receiver bandwidth, in Hz.

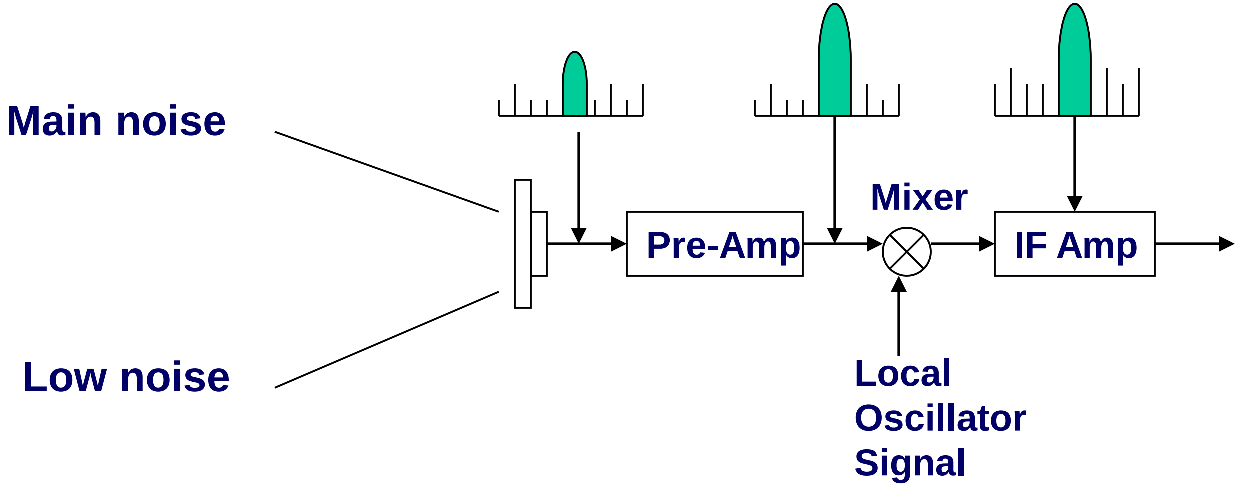
Electrical Background Noise

- Noise can be reduced by reducing the receiver bandwidth.
- This is called matched filter design.
- The optimum bandwidth is very close to $1/\tau$.



Electrical Background Noise

- The dominant source of noise is in the input stages of the receiver.
- A low-noise preamplifier and low-noise mixer can help reduce receiver noise.



Electrical Background Noise

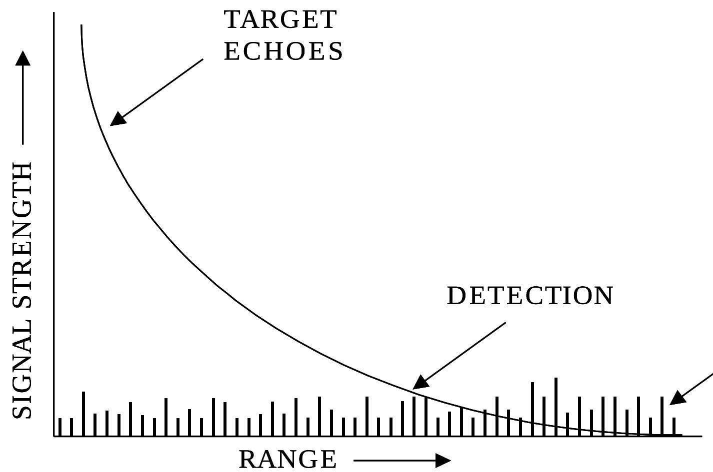
- The main sources of noise apart from the receiver include:
  - Ground (temperature and absorption)
  - Atmospheric conditions & operating frequency
  - Solar conditions

Signal Energy

- Four basic factors determine how much energy a radar will receive from a target.
  - Average Power which is the rate of flow of energy.
  - Scattered Power which is the fraction of the wave's power which in intercepted by the target and scattered back in the radar's direction.
  - Captured Power which is the fraction of that power that is captured by the radar's antenna.
  - Time on Target which is the length of time that the antenna beam is trained on the target.

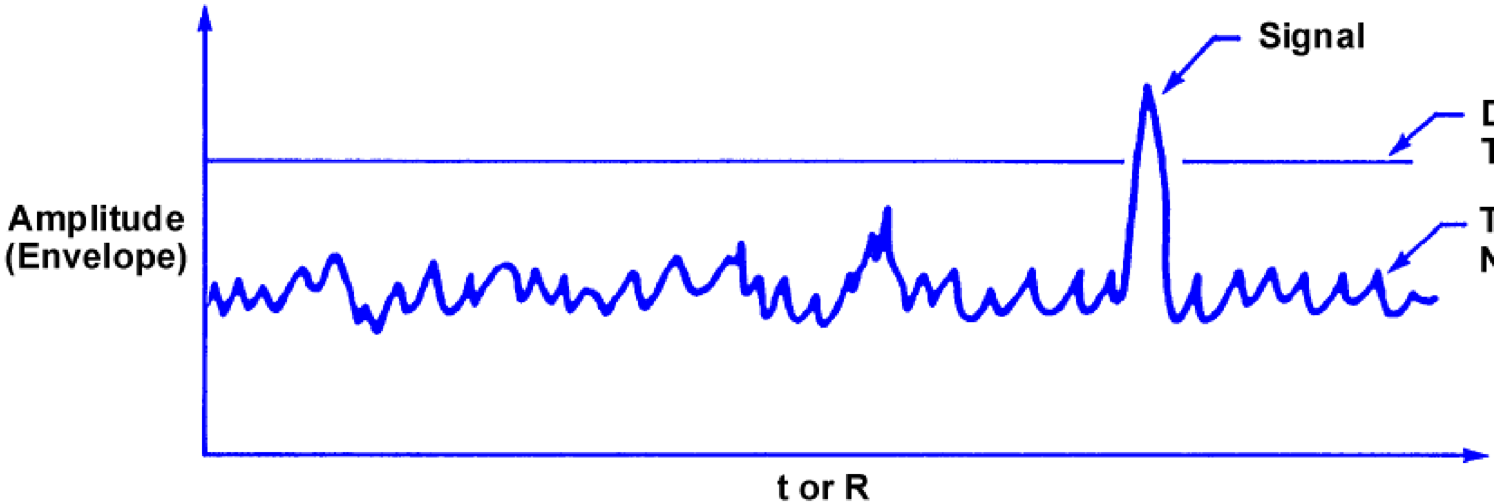
Signal Detection

- Detection threshold – a user or system defined level to determine whether a target is present.
- This threshold can be approximated by an experienced radar operator, or calculated, with greater accuracy, using probability.



AS A DISTANT TARGET APPROACHES, IT ECHOES RAPIDLY GROW STRONGER, BUT ONLY AS THEY EMERGE FROM THE BACKGROUND OF NOISE AND/OR GROUND CLUTTER WILL THEY BE DETECTED.

Detection Processing

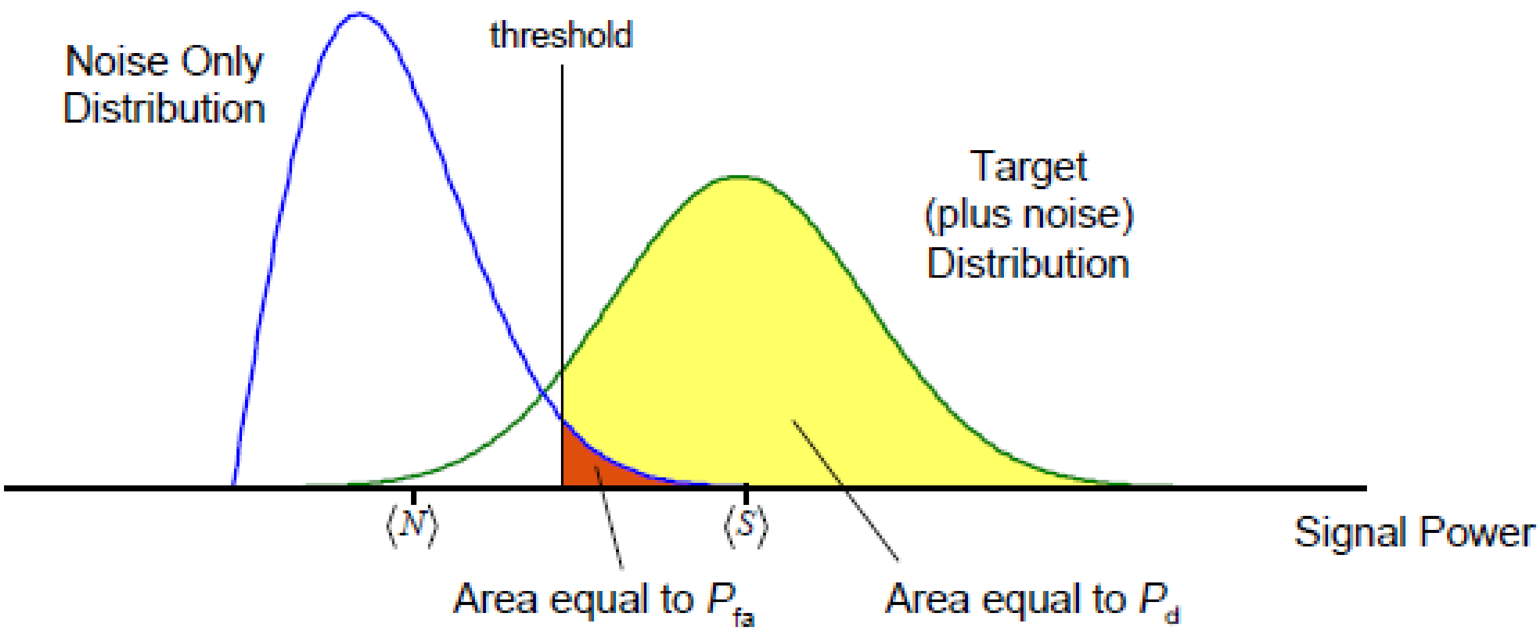


- *One objective is to set the detection threshold low so that small signals can be detected*
- *Another objective, but contradictory one, is to set the detection threshold high so few false alarms can occur due to thermal noise*

If a signal is large enough, it is detected and passed on to the Radar Control Computer to Schedule Confirmation and Track Dwells

Probability of False Alarm, I

- Detection threshold attempts to minimize the area of the probability distribution function for noise beyond the threshold while maximizing the area for the target return



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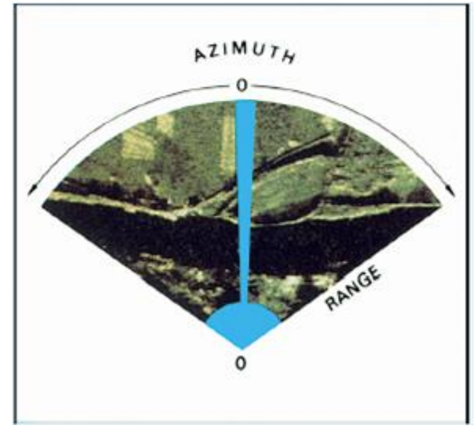
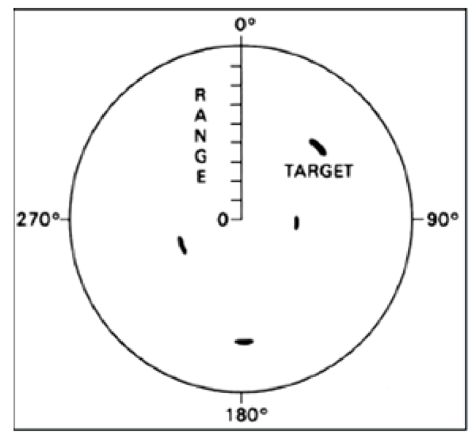
Bearing

- True Bearing
  - Referenced to true north
- Relative Bearing
  - Referenced to direction of platform



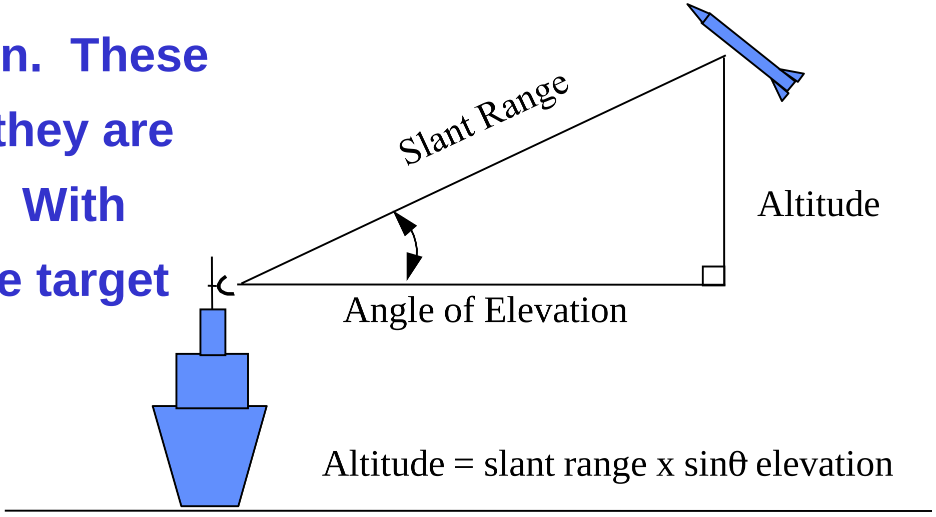


Radars Can Provide Azimuth Angle Information

Determining 3D Position

- All fixed and rotating radars know their azimuth (horizontal) position when they transmit and receive energy.

- Some radars are mechanically or electronically steered in elevation. These radars additionally know where they are pointing in elevation (vertically). With these systems, we can determine target position with more accuracy.



3D Radars Provide Azimuth, Elevation, and Range

Radar Resolution

FIGURE 1-26 ■ Concept of resolution in range. (a) Transmitted pulse and two targets. (b) Receiver output for resolved targets. (c) Receiver output for unresolved targets. (d) Receiver output for defining range resolution.

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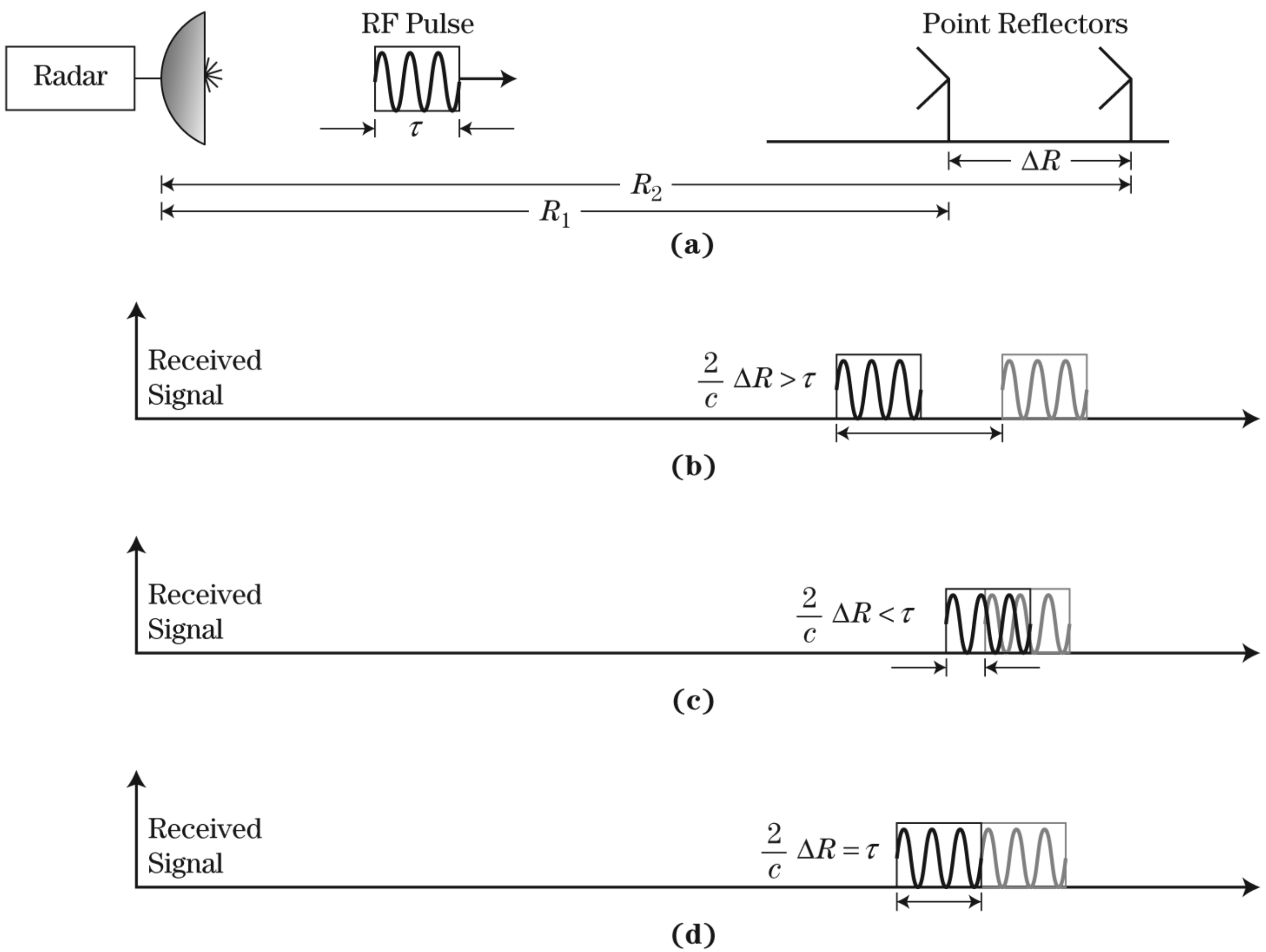
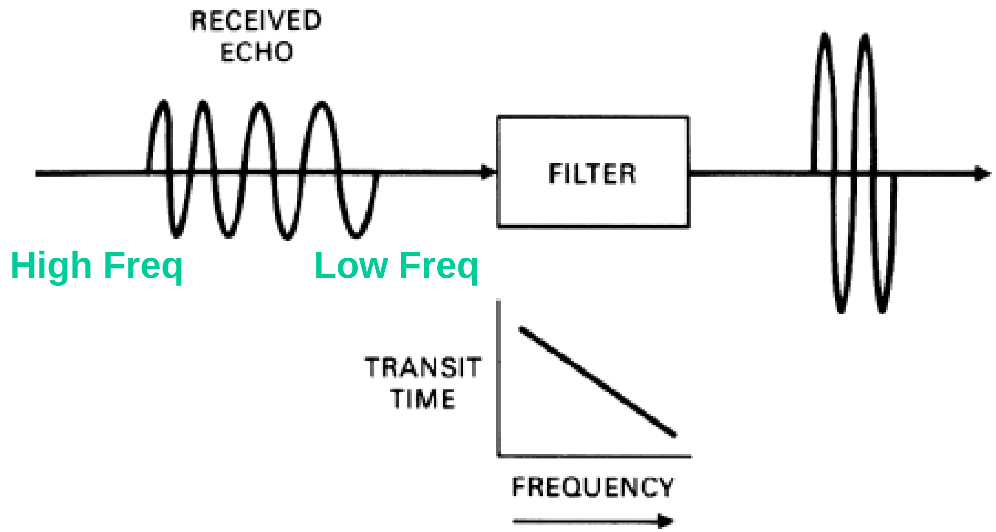


Pulse Compression, LFM (Chirp)

- Transmitted pulse is increased at a constant rate in frequency throughout its length (linear frequency modulation or LFM)
- Increase in frequency is not enough to effect the phase shifters and antenna pattern



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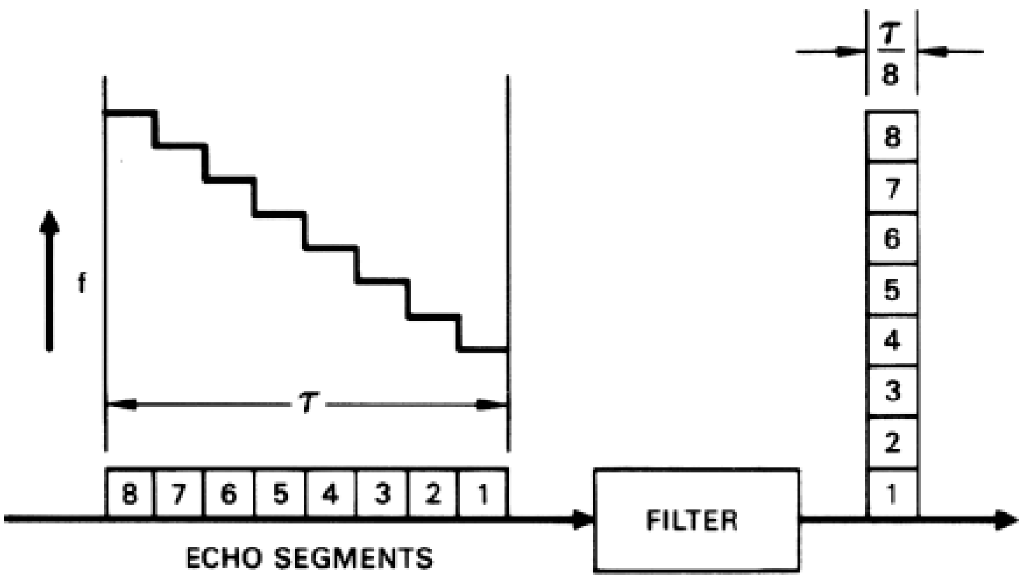
LFM Provides a Simple Means for Pulse Compression

LFM (Chirp), II

- Pulse compression filter delays signals inversely with frequency
- The leading edge (lower frequency) of the received pulse is delayed longer than trailing edge (higher frequency) so that the pulse effectively compresses on top of itself



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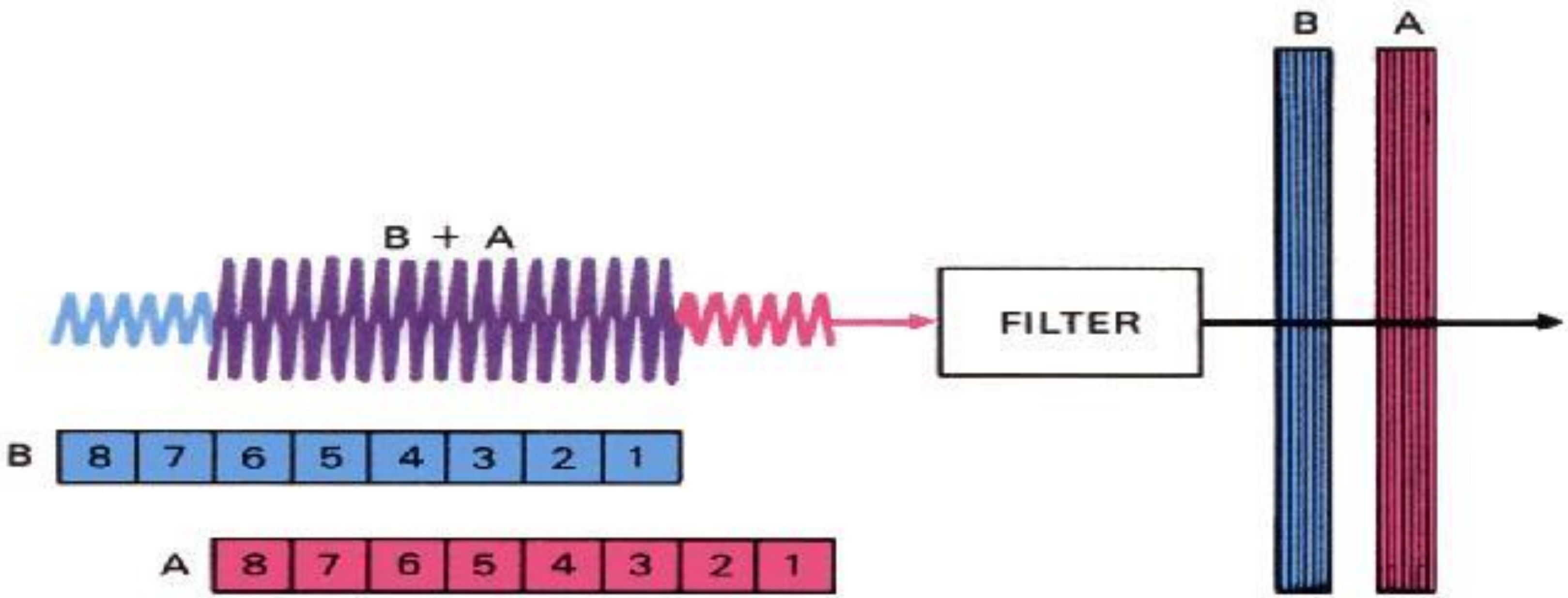
Pulse Compression Improves Range Resolution

Resolving Targets in Range

- Pulse Compression Ratio =
  Uncompressed pulsewidth / Compressed pulsewidth
  (Below, the ratio is 8:1)



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Common Waveform Pulse Types

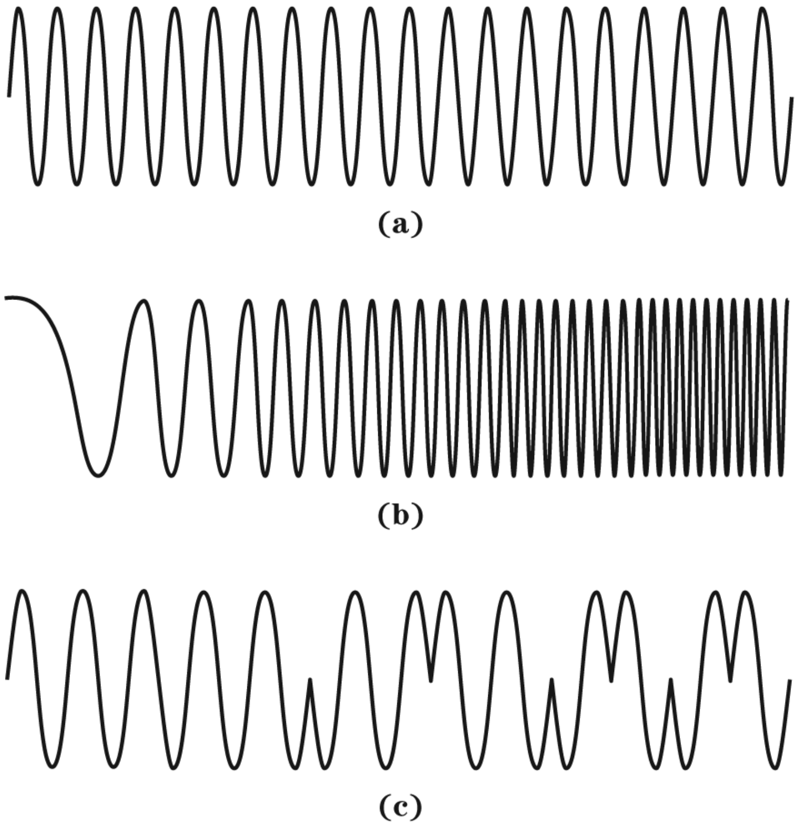

FIGURE 1-27 ■ Three common choices for a single pulse in a pulsed radar waveform. (a) Simple pulse. (b) Linear FM or chirp pulse. (c) Biphase coded pulse.

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Accuracy

- How accurate are the range measurements?
- Accuracy is a statistical measure of how well a measurement can be estimated within its resolution
- Accuracy expressions can be derived within a few percent of the maximum likelihood estimate

$$\delta_R = \frac{\Delta R}{\sqrt{2\frac{S}{N}}} = \frac{c\tau}{2\sqrt{2\frac{S}{N}}} = \frac{c}{2B\sqrt{2\frac{S}{N}}}$$

τ, Pulse Width

RMS range accuracy

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Search

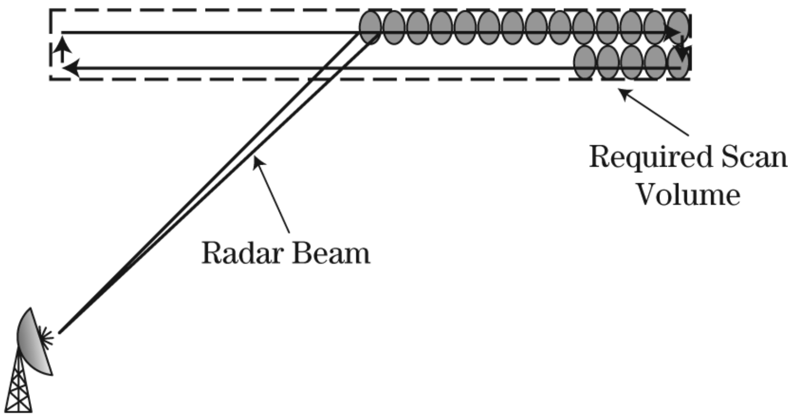

FIGURE 1-29 ■ Coverage of a search volume using a series of discrete beam positions.

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- **Number of beam positions:** $$\frac{\theta_{el}\theta_{az}}{(\theta_{3dB})^2}$$

Search Coverage

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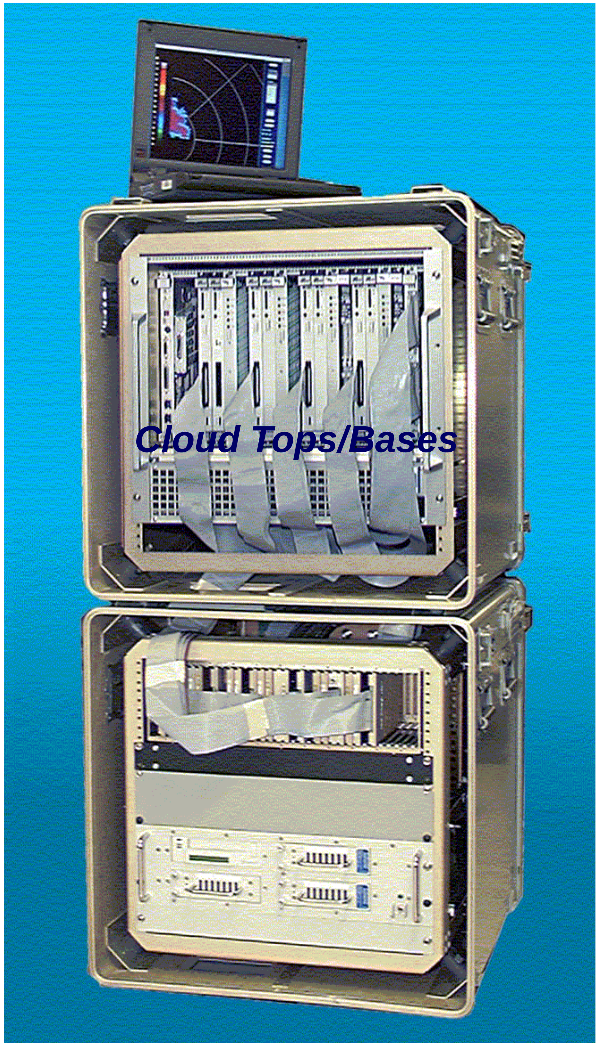
Radar Applications

1. Air radars for air traffic control and detection of enemy aircraft and/or missiles
2. Space radars used to track objects in space
3. Marine radars, used on boats to aid navigation during the night or under low visibility conditions such as fog
4. Radars used inside the airplane, to detect other airplanes, to scan clouds ahead, or to guide weapons from military aircraft
5. Police radars, used by cops to catch speeding vehicles
6. Traffic radars, similar to police radars, detect speeding vehicles, detect wrong-way driving, alert the drivers about their speed, and are used to count vehicles
7. Car radars, used for anti-collision detection, automatic cruise control, and are much used in autonomous vehicles to detect surroundings
8. Automatic door openers - used to detect when someone approaches the door
9. Tank level meters, use radar technology to measure the level of fluids in tanks
10. Speed/velocity meters used in industry (to measure speed of conveyor belt, to measure speed of water flow, etc.)
11. Ground-penetrating radars are used to analyze the ground where the analysis of the echo results in a very detailed soil profile. GPR-systems are also used in civil engineering to create the profile of an excavation area. This is particularly helpful for street and tunnel constructions.
12. Radars for ground surveillance, used in border control and perimeter security systems
13. Weather radars that detect clouds and turbulences inside clouds
14. Distance meters that use radar technology to measure distances

Meteorology

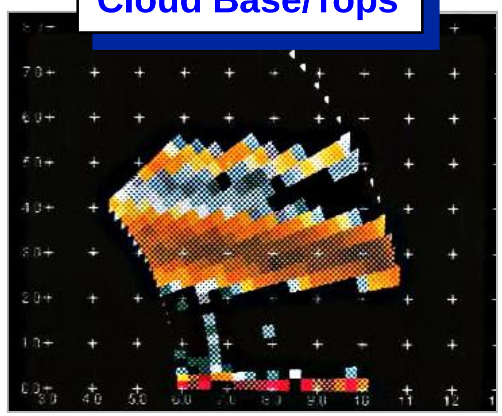
- Radar is used to detect weather patterns & for storm avoidance.
- Recall that most objects reflect waves.
- Radar can actually 'see' through clouds. This ability allows radar to detect rain.
- Weather patterns are determined by measuring the rate of change of echo strength.
- Larger rain drops have a stronger echo. The larger rain drops indicate heavier showers and by monitoring the trend of a weather front, its future location can be predicted.
- Radar is similarly used to detect aerosols, pollution levels and free electrons.

Tactical Environmental Processor

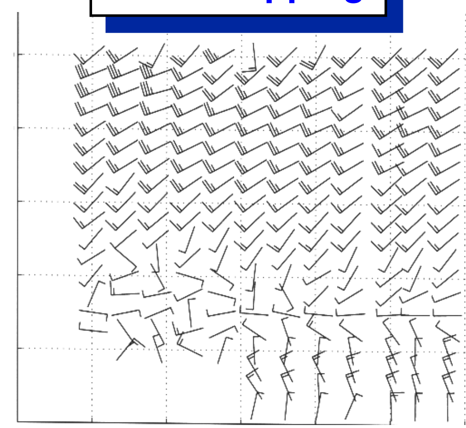


- ❑Converts raw I/Q data from radar into spectral moments
- ❑ Tactical waveforms
  - ❑Single Pulse → Reflectivity (dBZ)
  - ❑Three Pulse → Reflectivity, Radial Velocity (m/s), and Spectrum Width (m/s)
- ❑ Pulse Doppler waveforms
  - ❑Provide greater sensitivity for cloud/wind detection

Cloud Base/Tops



Wind Mapping



Winds off JAX

Airborne Radar

- Radar has several applications in the airborne environment
- Radar is used extensively as a navigational aid
- Radar beacons
  - Transponders are part of the navigation system
  - Transponders receive radar pulses but reply with a different frequency
  - No clutter with return pulse
- Radar is used to measure altitude. To do this a downward looking radar is used to measure the distance to the ground.
- Continuous or pulsed wave depending on application.
- Radar is an essential component of all Air Traffic Control systems.
- Most aircraft carry transponders. On approach to an airport, a beacon is used to determine an aircraft's speed and identity.

Military

- Radar is also used extensively in the military.
- Radar is an important component for reconnaissance and surveillance of the battlefield.
- Radar’s ability to ‘see’ through cloud and pollution allows long range detection and the tracking of multiple targets.
- Early warning radar allows long range detection. The radar horizon increases with altitude suiting this type of radar to be airborne.
- Airborne radar can provide multiple target tracking to 200 nm at 30 000 ft.
- Radar is also used in the delivery of munitions. Once the radar has identified an enemy target, the fire control unit is notified. These munitions are guided by radar.