Radar Systems Engineering
Lecture 1
Introduction

Dr. Robert M. O’Donnell
IEEE New Hampshire Section
Guest Lecturer

Outline

- **Background**
- **Radar basics**
- **Course overview**

Outline

- **Background**
  - **Some pre-radar history**
  - **How radar works**
    - **The one viewgraph, no math answer!**
  - **The early days of radar**
  - **Two examples from World War II**
    - **Air defense in "The Battle of Britain"**
      - **Summer 1940**
    - **The role of radar in stopping the German V-1 "Buzz Bomb" attacks on Britain**
      - **V-1 The first cruise missile**
      - **About 9,000 V_1's fired at Britain**
- **Radar basics**
- **Course overview**

The Uncertainty of Warfare

Omaha Beach
1944


Courtesy of National Archives.


Courtesy of National Archives.

Iwo Jima
1945


Courtesy of US Marine Corp,

Pre-Radar Aircraft Detection – Optical Systems


Courtesy of US Army Signal Corps.

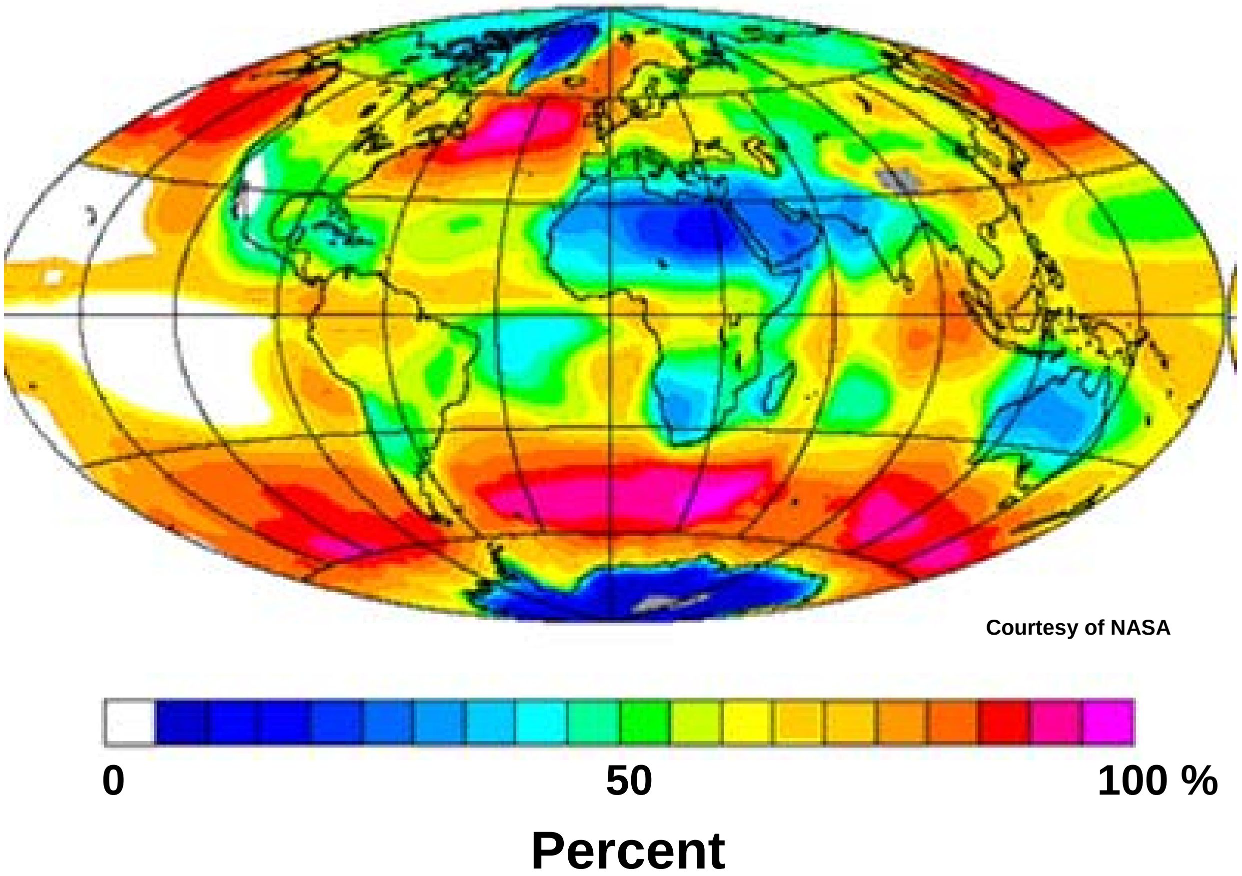

Courtesy of UK Government

- **Significant range limitation**
  - **Attenuation by atmosphere**
- **Narrow field of view**
  - **Caused by very small wavelength**
- **Clouds Cover limits operational usefulness**
  - **Worldwide - 40-80% of the time**


Courtesy of National Archives.

Prevalence of Cloud Cover

ISCCP - Total Cloud Cover 1983-1990

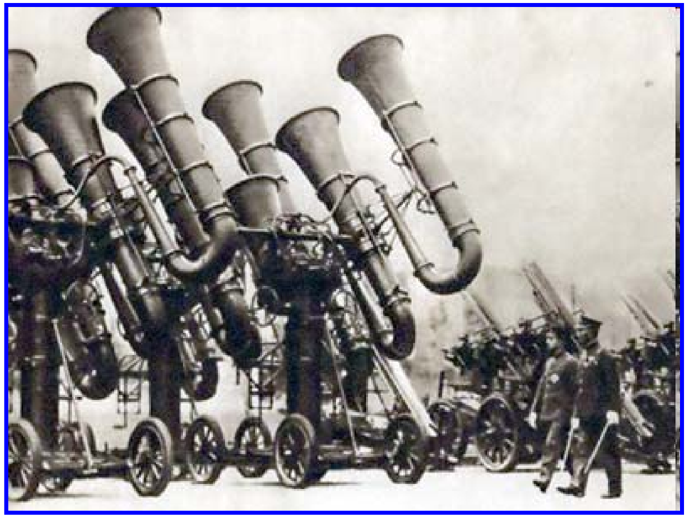


Courtesy of NASA

Infrared and Optical Radiation Opaque to Clouds

Pre-Radar Aircraft Detection – Acoustic Systems

Japanese Acoustic Detection System

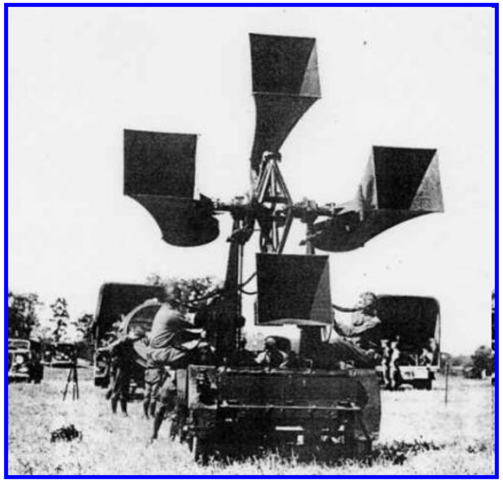


Courtesy of Wikimedia

- **Developed and used in first half of 20th century**
- **Attributes**
  - **Limited Range**
    - **approximately 10+ miles**
  - **Limited field of view**
  - **Ambient background noise limited (weather, etc)**
- **Used with searchlights at night**

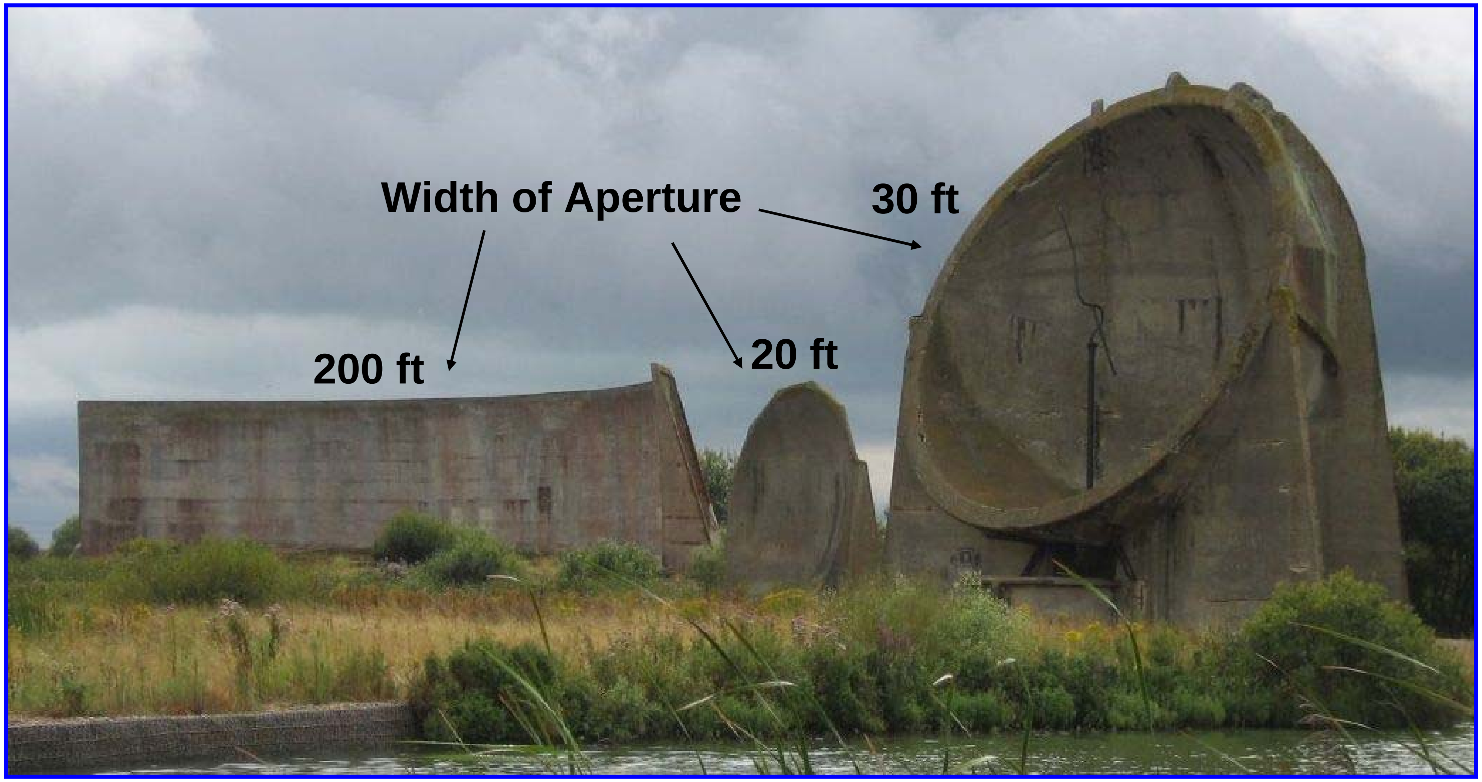
US Acoustic Detection Systems

Courtesy of US Army Signal Corps.



Courtesy of US Army Signal Corps.

Sound Mirrors Dunge, Kent, UK



Courtesy of s__i in Wikimedia

- **Used for aircraft detection (pre-World War II)**
- **Short detection range (less than 15 miles)**
  - **Tactically useful for detecting slow WW1 Zeppelins**
  - **Not useful for detecting faster WW2 German bombers**

How Radar Works- The Short Answer!

Courtesy of NOAA

- **An electromagnetic wave is transmitted by the radar.**
- **Some of the energy is scattered when it hits a distant target**
- **A small portion of the scattered energy, the radar echo, is collected by the radar antenna.**
- **The time difference between:**

  when the pulse of electromagnetic energy is transmitted, and
  when the target echo is received,
  is a measure of how far away the target is.

$$\tau = \frac{2R}{c}$$

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Trust me, its going to get a lot more complicated !

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The Early Days of Radar

- Sir Robert Watson-Watt
  - Considered by many “the inventor of radar”
  - Significant early work occurred in many other countries, including the United States (1920sand 1930s)
  - After experimental verification of the principles, Watson-Watt was granted a patent in 1935
  - Leader in the development of the Chain Home radar systems
    - Chain Home, Chain Home Low
    - Ground Control Intercept and Airborne Intercept Radar

Sir Robert Watson-Watt

Courtesy of Wikimedia

- Tizard Mission
- MIT Radiation Laboratory

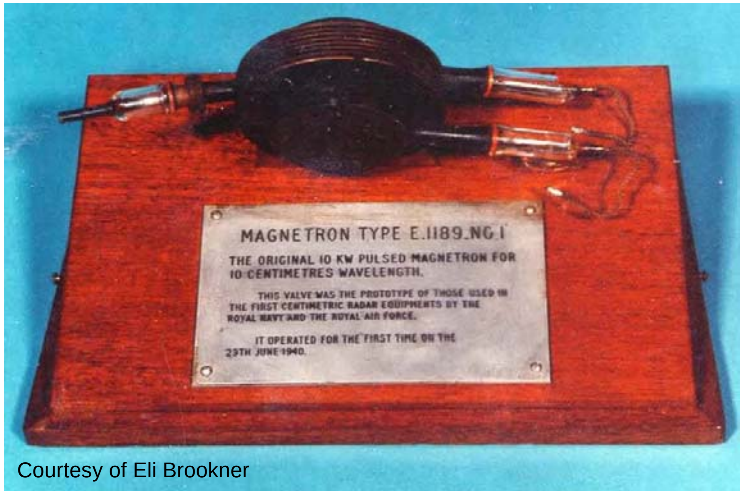
The Early Days of Radar

- **Sir Robert Watson-Watt**

- **"Tizard Mission" (British Technical & Scientific Mission to US)**
  - **Seven British radar experts and a "Black Box" sent to US in Fall of 1940**
  - **Contained cavity magnetron and "nearly everything Britain knew about radar"**
  - **Possession of cavity magnetron technology was critical to Allied war radar development**

- **MIT Radiation Laboratory**

Original British 10 cm 10 kW Pulsed magnetron



Courtesy of Eli Brookner

The Early Days of Radar

- Sir Robert Watson-Watt
- Tizard Mission
- MIT Radiation Laboratory (operated between 1940 & 1945)
  - Developed and fielded advanced radar systems for war use
  - Exploited British 10 cm cavity magnetron invention
  - Grew to almost 4000 persons (9 received the Nobel Prize)
  - Designed almost half of the radars deployed in World War II
  - Created over 100 different radar systems ($1.5B worth of radar)

Building 20- Home of MIT Radiation Laboratory

Courtesy of Massachusetts Institute of Technology

SCR-584 (circa World War 2) Fire Control Radar

Courtesy of Department of Defense

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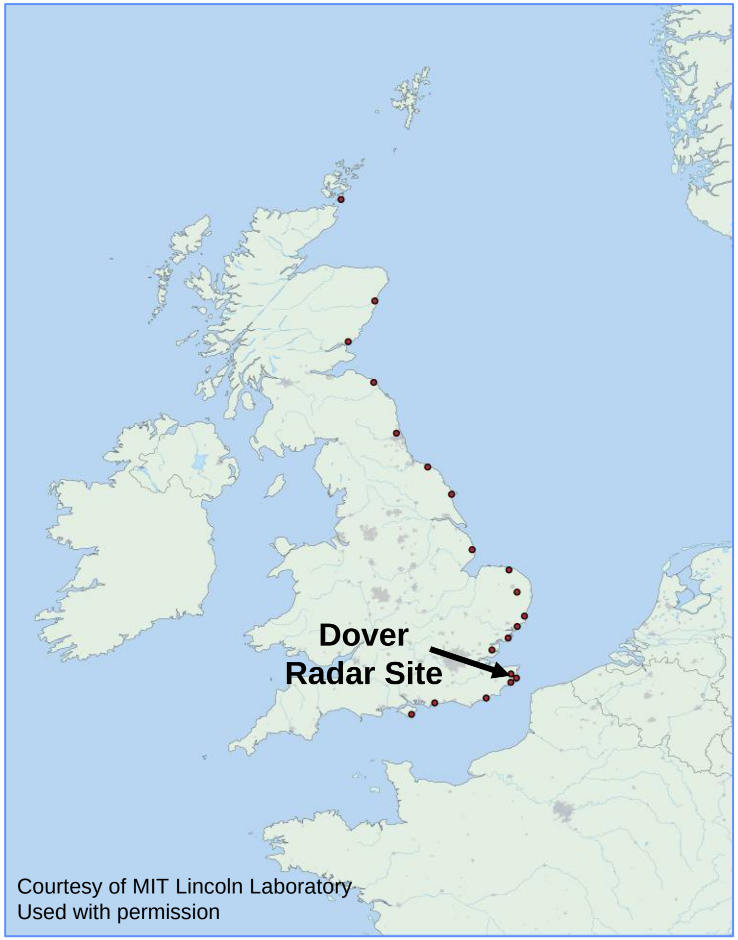
Chain Home Radar System
Deployment Began 1936

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



Courtesy of MIT Lincoln Laboratory
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Sept 2006 Photograph of Three Chain Home Transmit Towers, near Dover

Courtesy of Robert Cromwell.
Used with permission.

Chain Home Radar System

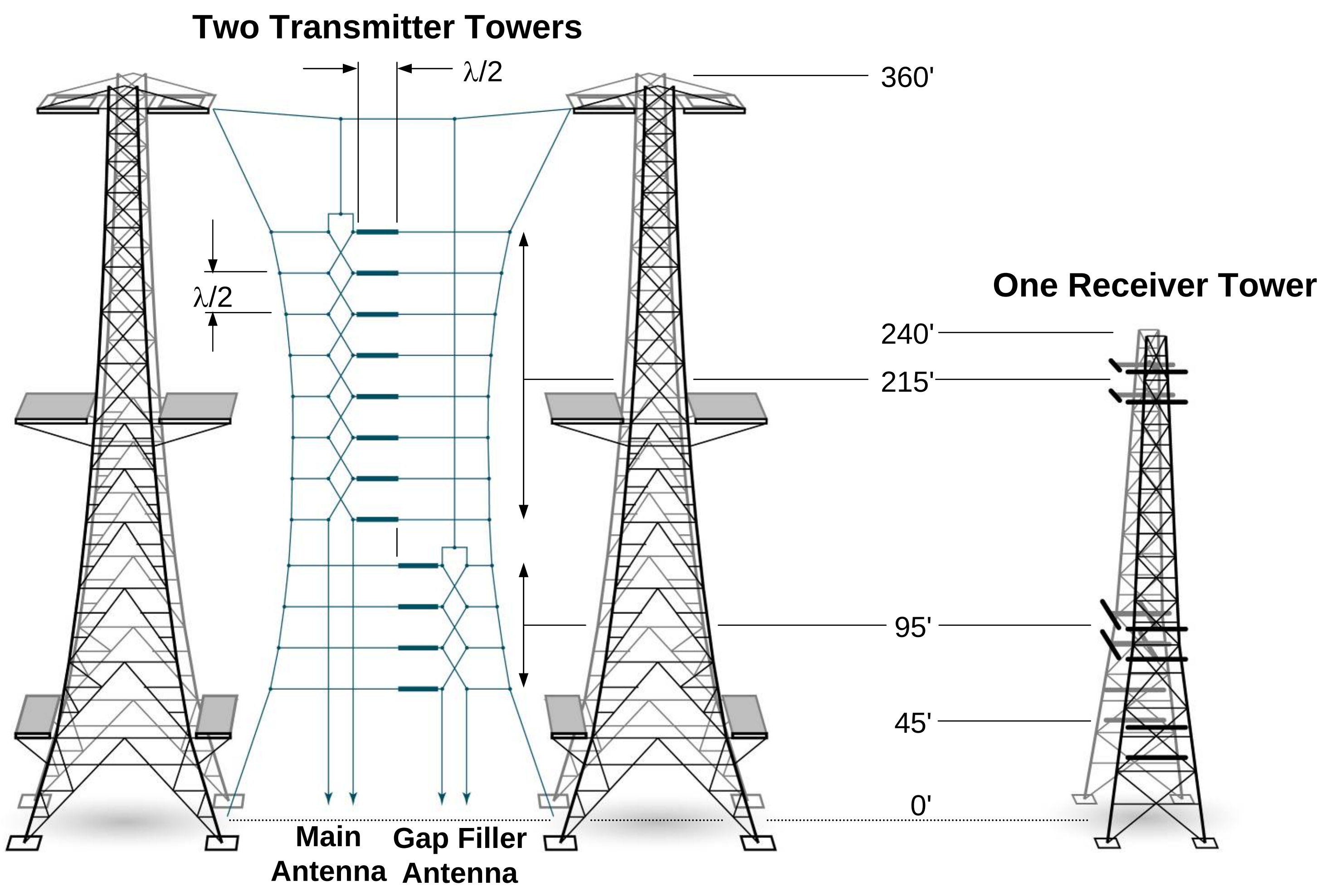
Typical Chain Home Radar Site

Courtesy of MIT Lincoln Laboratory
Used with permission

Chain Home Radar Parameters

- **Wavelength**
  - **10 to 15 m**
- **Frequency**
  - **20 to 30 MHz**
- **Antenna**
  - **Dipole Array on Transmit**
  - **Crossed Dipoles on Receive**
- **Azimuth Beamwidth**
  - **~ 100^{o}**
- **Peak Power**
  - **350 kW**
- **Detection Range**
  - **~160 nmi on JU-88 German Bomber**

Chain Home Transmit & Receive Antennas



Transmit Antenna

Receive Antenna

Chain Home Radar System

Receiver / Detection Operator

Goniometer

Courtesy of United Kingdom Government.

Chain Home Transmitter

Courtesy of J M Briscoe

Chain Home Receiver Hut

Chain Home Radar Operations

Plotting Area in Chain Home Radar Receiver Room

Operation Room at Air Group 10

Courtesy of United Kingdom Government.

"Chain Home Low" Radar

Chain Home Low Antenna

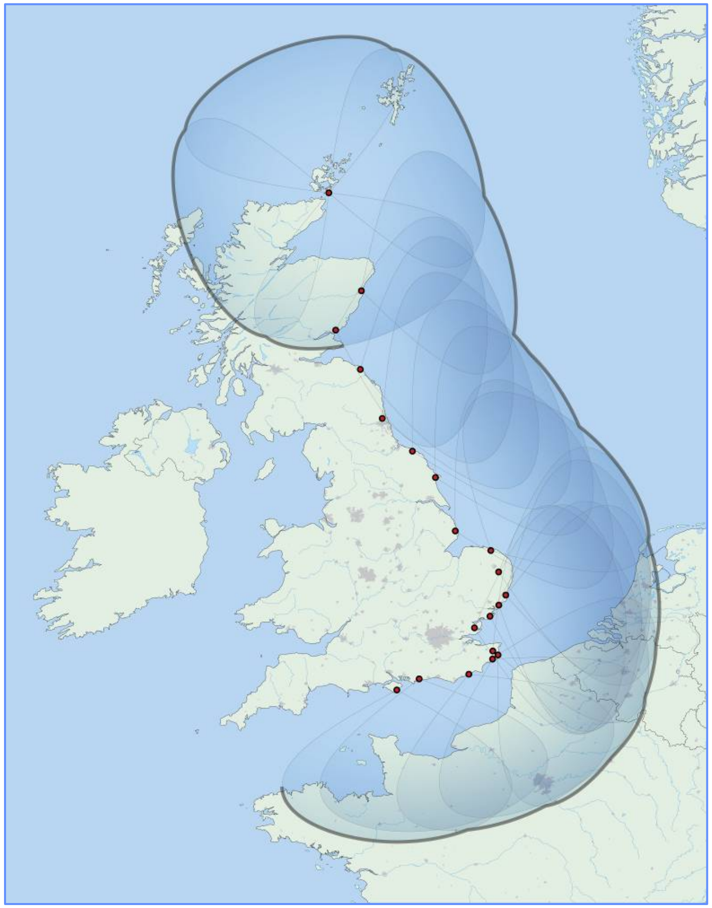
Chain Home Low Transmitter

- **Twenty four Chain Home Low radar's were added to fill coverage gaps at low elevation angles (< 2°)**
  - **Their low frequency 200 MHz lessened multipath lobing effects relative to Chain Home (20-30 MHz)**
- **Detection range 25 mi at 500 ft**

Courtesy of United Kingdom Government.

Radar and “The Battle of Britain”

Approximate Chain Home Radar Coverage
Sept 1940
(21 Early Warning Radar Sites)



Courtesy of MIT Lincoln Laboratory
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- **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**

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- **The basics / the big picture**

- **Course overview**

V-1 "Buzz Bomb" – The Threat

V-1 Cruise Missile

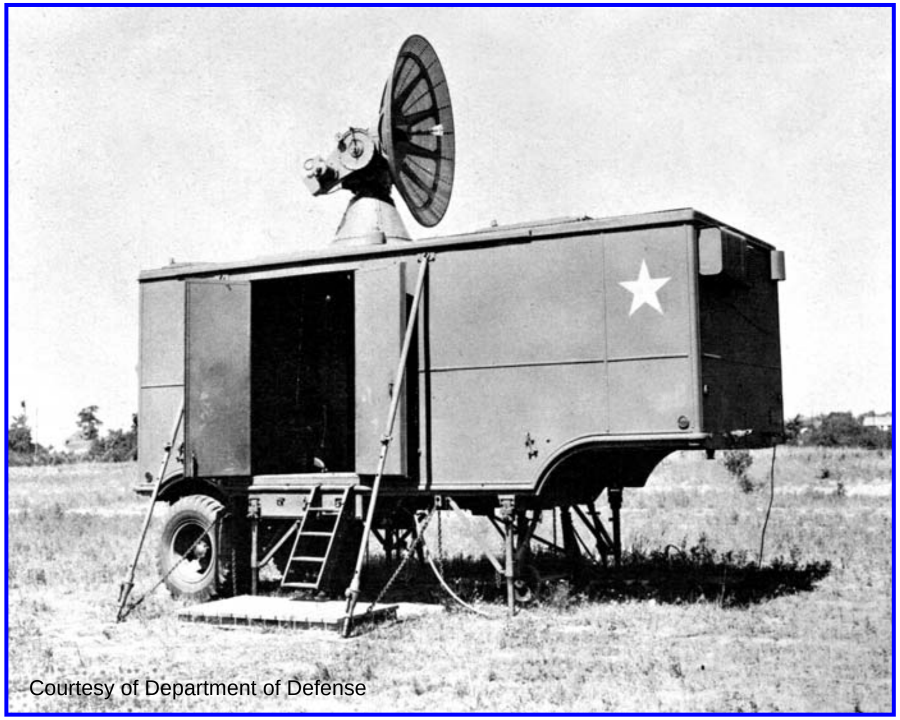
Courtesy of Ben pcc
Used with permission.

Characteristics

Propulsion	Ramjet
Speed	390 mph
Altitude	2-3000 ft
Range	250 km
Guidance	gyrocompass / autopilot
Warhead	850 kg HE
No. Launched	9,000
No. Impacted London Area	2,400

The SCR 584 Fire-Control Radar

SCR-584



Courtesy of Department of Defense

SCR-584 Parameters

Wavelength	10 cm (S-Band)
Frequency	3,000 MHz
Magnetron	2J32
Peak Power	250 kW
Pulse Width	0.8µsec
PRF	1707 Hz
Antenna	
Diameter	6 ft
Beamwidth	4°
Azimuth Coverage	360°
Maximum Range	40 mi
Range Accuracy	75 ft
Azimuth Accuracy	0.06°
Elevation Accuracy	0.06°

The SCR 584 Fire-Control Radar

SCR-584 (40th Anniversary of MIT Rad Lab)

Courtesy of MIT Lincoln Laboratory

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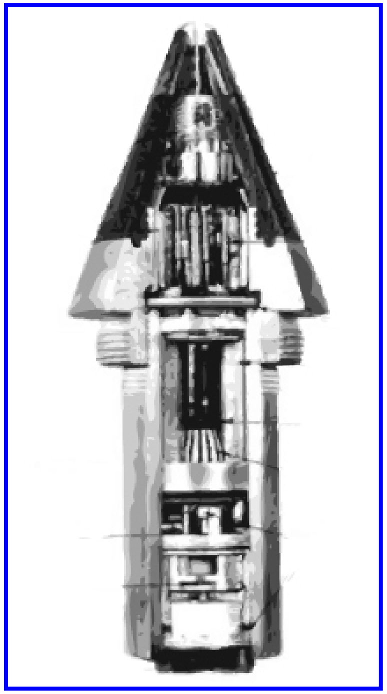
Radar Proximity Fuze

Modern Radar Proximity Fuze

Courtesy of Robert O'Donnell

Circa 1985

V-53 Radar Proximity Fuze (Cutaway)



Courtesy of US Navy

Circa mid 1940s

Operation of Radar Proximity Fuze

- Must operate under very high g forces
- Micro transmitter in fuze emits a continuous wave of ~200 MHz
- Receiver in fuze detects the Doppler shift of the moving target
- Fuze is detonated when Doppler signal exceeds a threshold
- Direct physical hit not necessary for destruction of target

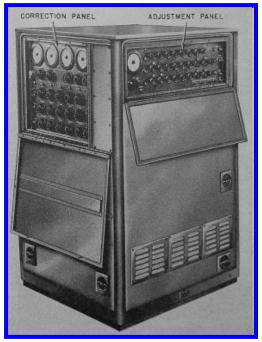
Radar Proximity Fuze Revolutionized AAA and Artillery Warfare

World War 2 Air Defense System

SCR-584 Fire Control Radar

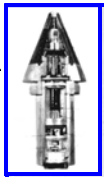

Courtesy of Department of Defense

M9 Predictor

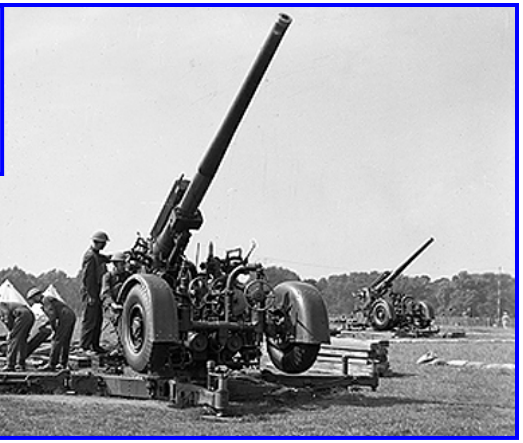


Courtesy of US Army

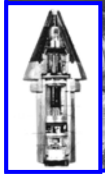
Radar Proximity Fuze


Courtesy of US Navy

British 3.7” AAA Gun



US 90 mm AAA Gun


Courtesy of US Navy

Courtesy of US Army

When deployed on British coast, V-1 “kill rate” jumped to 75%, when this integrated system was fully operational in 1944

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  - What radars measure
  - Block diagram of a radar system
  - Different Radar wavelengths / frequencies
  - Descriptive classifications of radars
    - Military, civilian, other
- Course overview

Utility and Positive Attributes of Radar

- **Long range detection and tracking of targets**
  - 1000's of miles
- **All weather and day/night operation**
- **Wide area search capability**
- **Coherent operation enables**
  - Simultaneous reliable target detection and rejection of unwanted "clutter" objects
  - Target imaging (fixed and moving)
  - Very fast beam movement with electronic scanning of antennas (microseconds)
  - Ability to adaptively shape antenna beam to mitigate interference and jamming
- **"Relatively lossless, straight line propagation at microwave frequencies**

Negative Attributes / Challenges of Radar

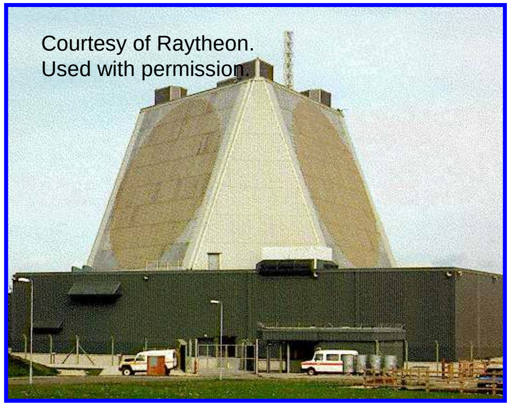
- **Long range detection requires**
  - Large and heavy antennas
  - High power transmitters
  - Significant power usage
  - $$$$$
- **Radar beams not propagate well**
  - through the Earth, water, or heavy foliage
  - around obstacles
- **Vulnerable to jamming, and anti-radiation missiles**
- **Target can detect that it is being illuminated**
- **Target can locate the radar in angle-space**
- **The echo from some targets is becoming very small**
  - Low observable technology

Surveillance and Fire Control Radars


Courtesy of US Air Force
Used with permission.


Courtesy of NATO.


Photo courtesy of ITT Corporation. Used with permission.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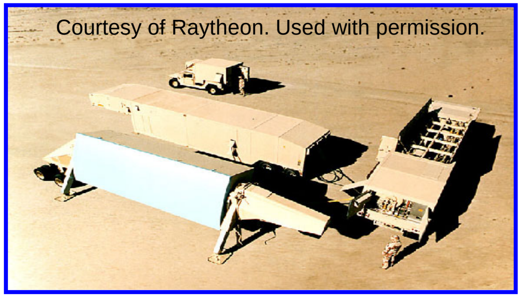
Courtesy of US Navy.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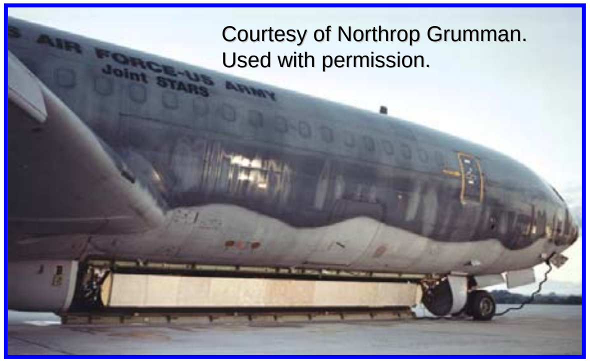
Airborne Radars


Courtesy of US Air Force.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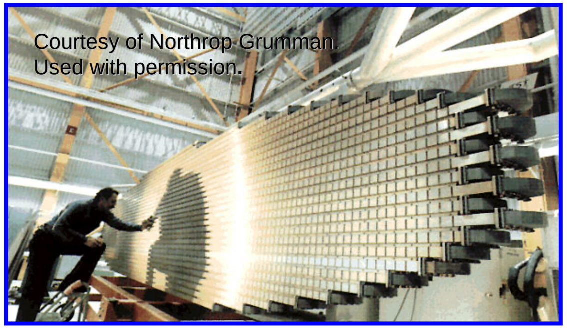
Courtesy of US Air Force.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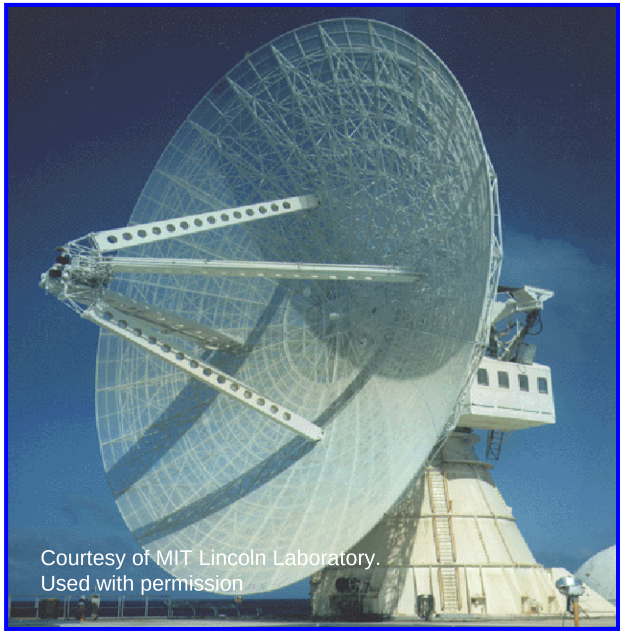
Courtesy of US Air Force.

Instrumentation Radars



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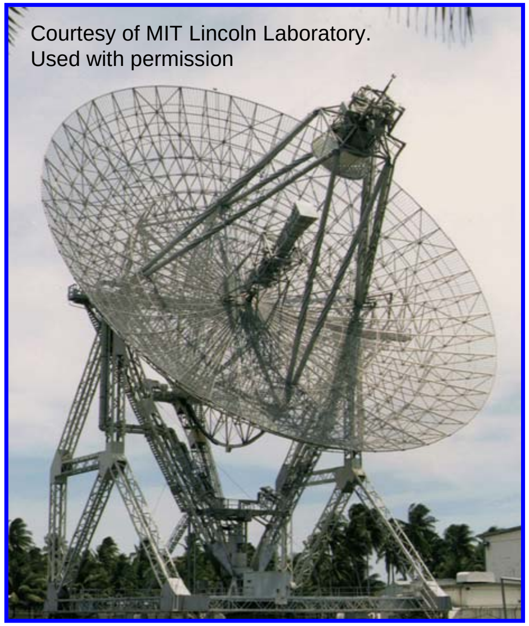

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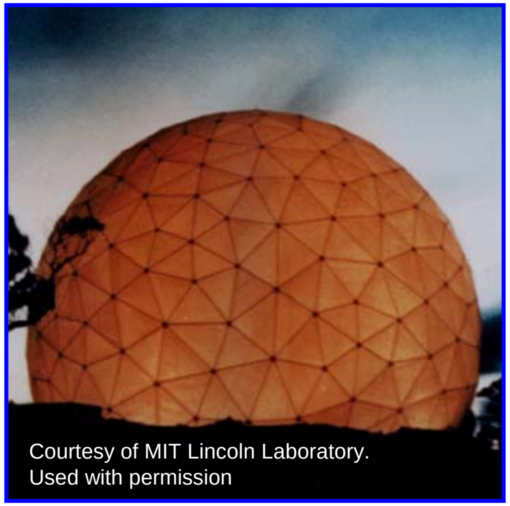

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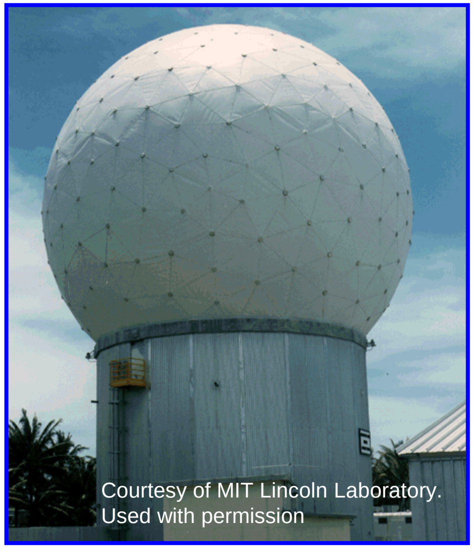

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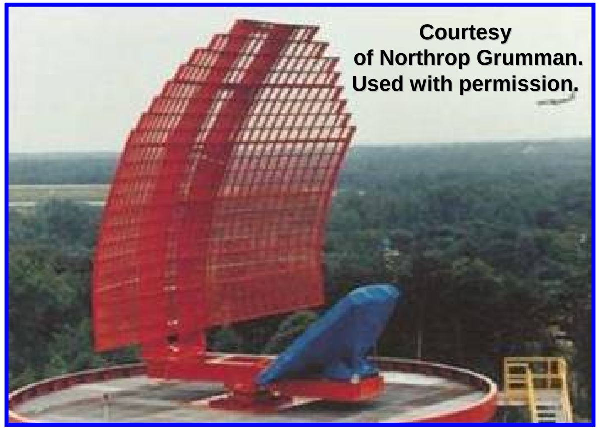
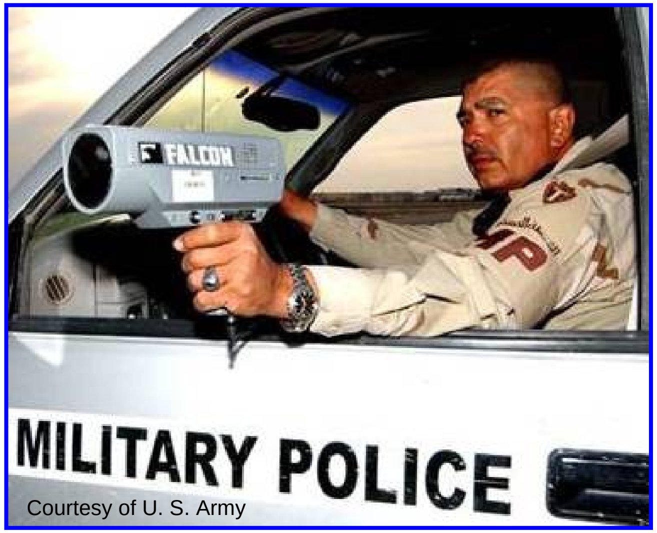
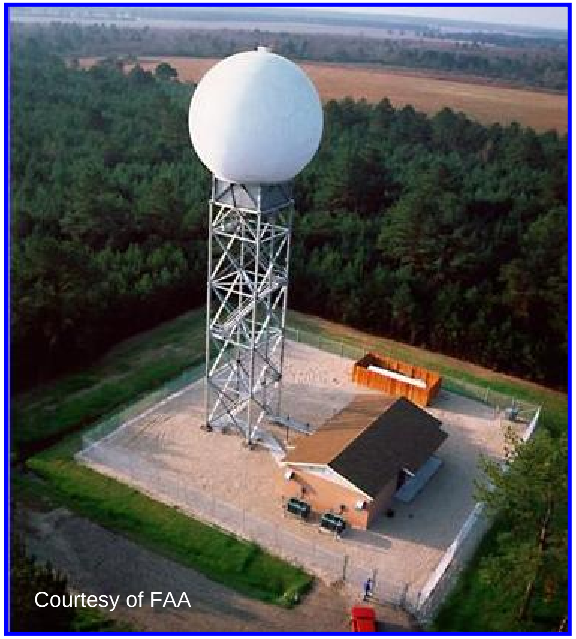
Civil Radars







More Civil Radars

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  - **Utility and positive / negative attributes of radar**
  - **What radars measure**
  - **Block diagram of a radar system**
  - **Different Radar wavelengths / frequencies**
  - **Descriptive classifications of radars**
    Military, civilian, other

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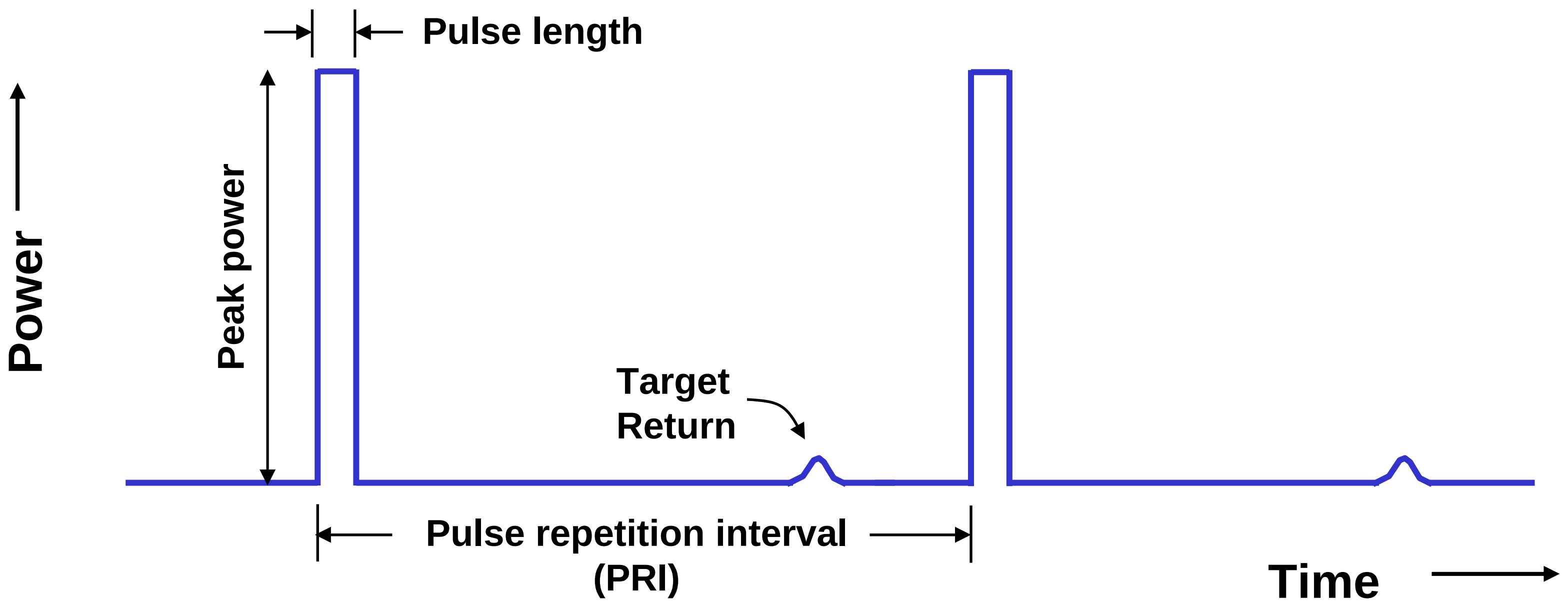
Pulsed Radar
Terminology and Concepts



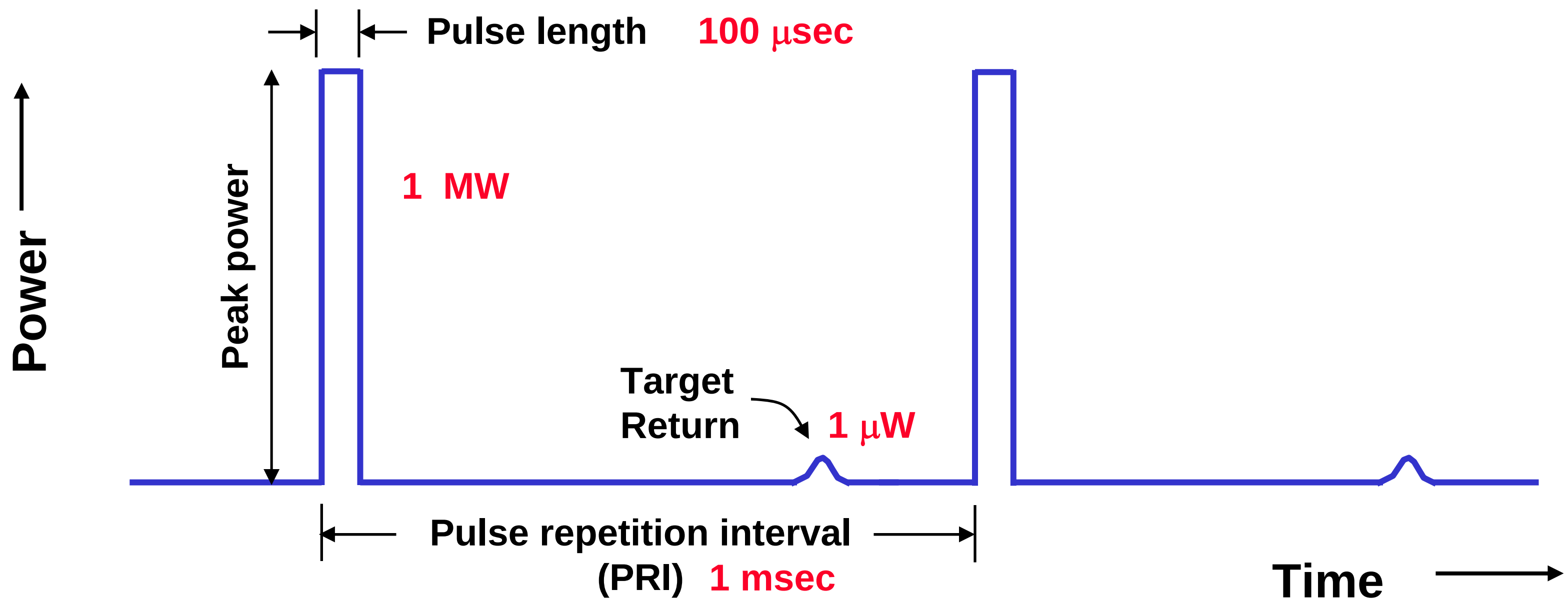
Duty cycle = $\frac{\text{Pulse length}}{\text{Pulse repetition interval}}$

Average power = Peak power * Duty cycle

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

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

Pulsed Radar
Terminology and Concepts



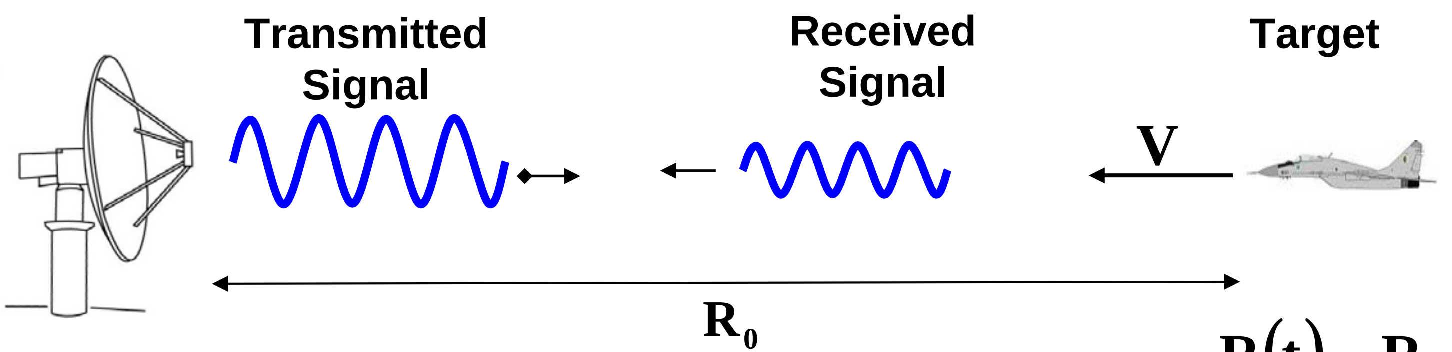
Duty cycle = $\frac{\text{Pulse length}}{\text{Pulse repetition interval}}$ 10%

Average power = Peak power * Duty cycle 100 kW

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

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

Radar Observables



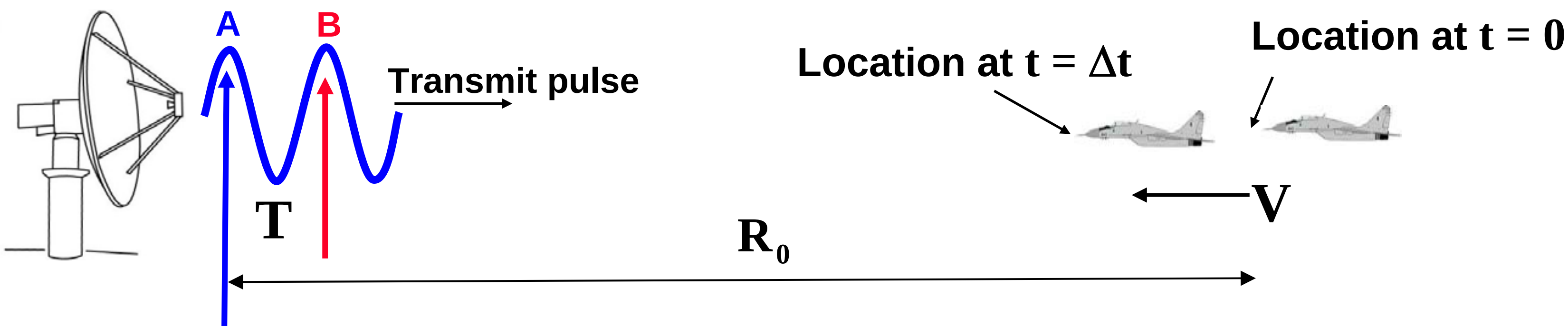
$$R(t) = R_0 - Vt$$

Transmitted Signal: $s_T(t) = A(t)\exp(j2\pi f_0 t)$

Received Signal: $s_R(t) = \alpha A(t-\tau)\exp[j2\pi(f_0 + f_D)t]$

<u>Amplitude</u>	<u>Angle</u>	<u>Time Delay</u>	<u>Doppler Frequency</u>
Depends on RCS, radar parameters, range, etc.	Azimuth and Elevation	$\tau = \frac{2R_0}{c}$	$f_D = \frac{2Vf_0}{c} = \frac{2V}{\lambda}$

Doppler Shift



T
- **This peak** leaves antenna at time $t = 0$, when aircraft at R_0
- The **peak A** arrives at target at time Δt
- Aircraft moving with **radial velocity** V
- The period of the transmit pulse is T, and $f_0 = 1/T$ and $c = \lambda/T = \lambda f_0$
- Note: $c\Delta t = R_0 - V\Delta t$ or $\Delta t = \dfrac{R_0}{c+V}$
- Time when **peak A** arrives back at radar $t_A = \dfrac{2R_0}{c+V}$
- Time when **peak B** arrives back at radar $t_B = T + \dfrac{2(R_0 - VT)}{c+V}$

- The period of the transmitted signal is T and the received echo is $T_R = T_B - T_A$ or

$$T_R = T\left[\frac{c - V}{c + V}\right] \qquad f_R = f_0\left[\frac{c + V}{c - V}\right] = f_0\left[\frac{1 + \frac{V}{c}}{1 - \frac{V}{c}}\right]$$

- For $V << c$ then $\frac{1}{1 - \frac{V}{c}} = 1 + \frac{V}{c} - \left(\frac{V}{c}\right)^2 + \ldots$

$$f_R \approx f_0 + \frac{2V}{c/f_0}$$

Radial Velocity

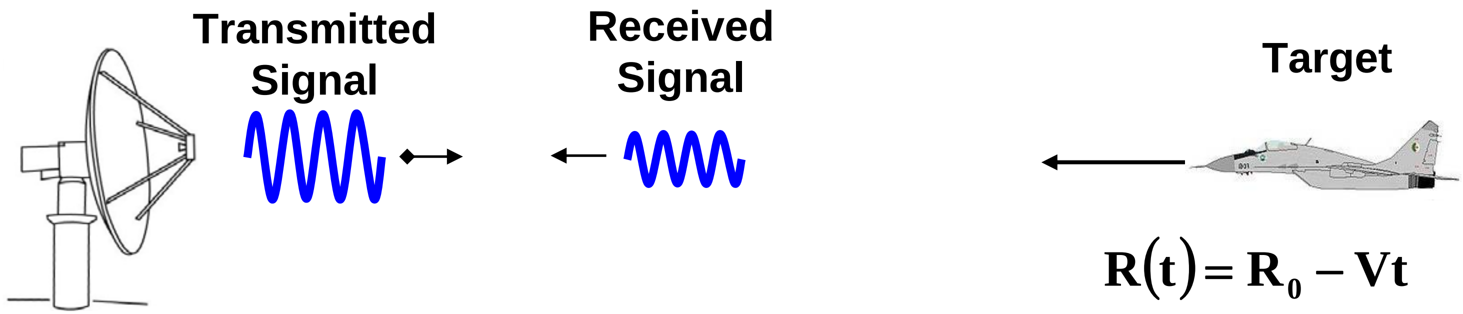
$$f_D = +\frac{2V}{c/f_0} = +\frac{2V}{\lambda}$$

+ Approaching targets

- Receding targets

Christian Andreas Doppler (1803 - 1853)

Radar Observables



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<u>Amplitude</u>

Depends on RCS, radar parameters, range, etc.

<u>Angle</u>

Azimuth and Elevation

<u>Time Delay</u>

$$\tau = \frac{2R_0}{c}$$

<u>Doppler Frequency</u>

$$f_D = \frac{2Vf_0}{c} = \frac{2V}{\lambda}$$

+ Approaching targets
- Receding targets

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Block Diagram of Radar System

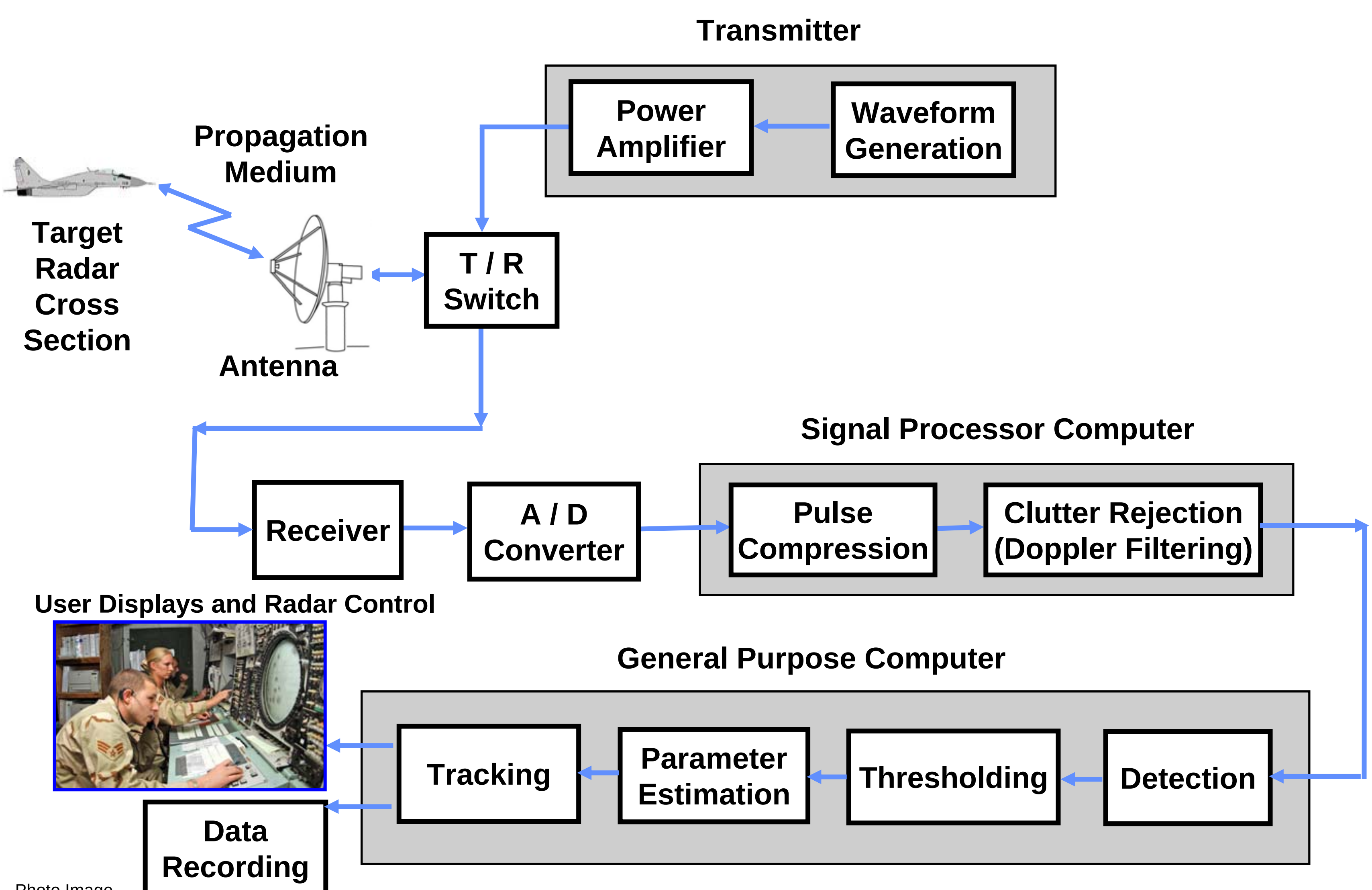

Photo Image
Courtesy of US Air Force

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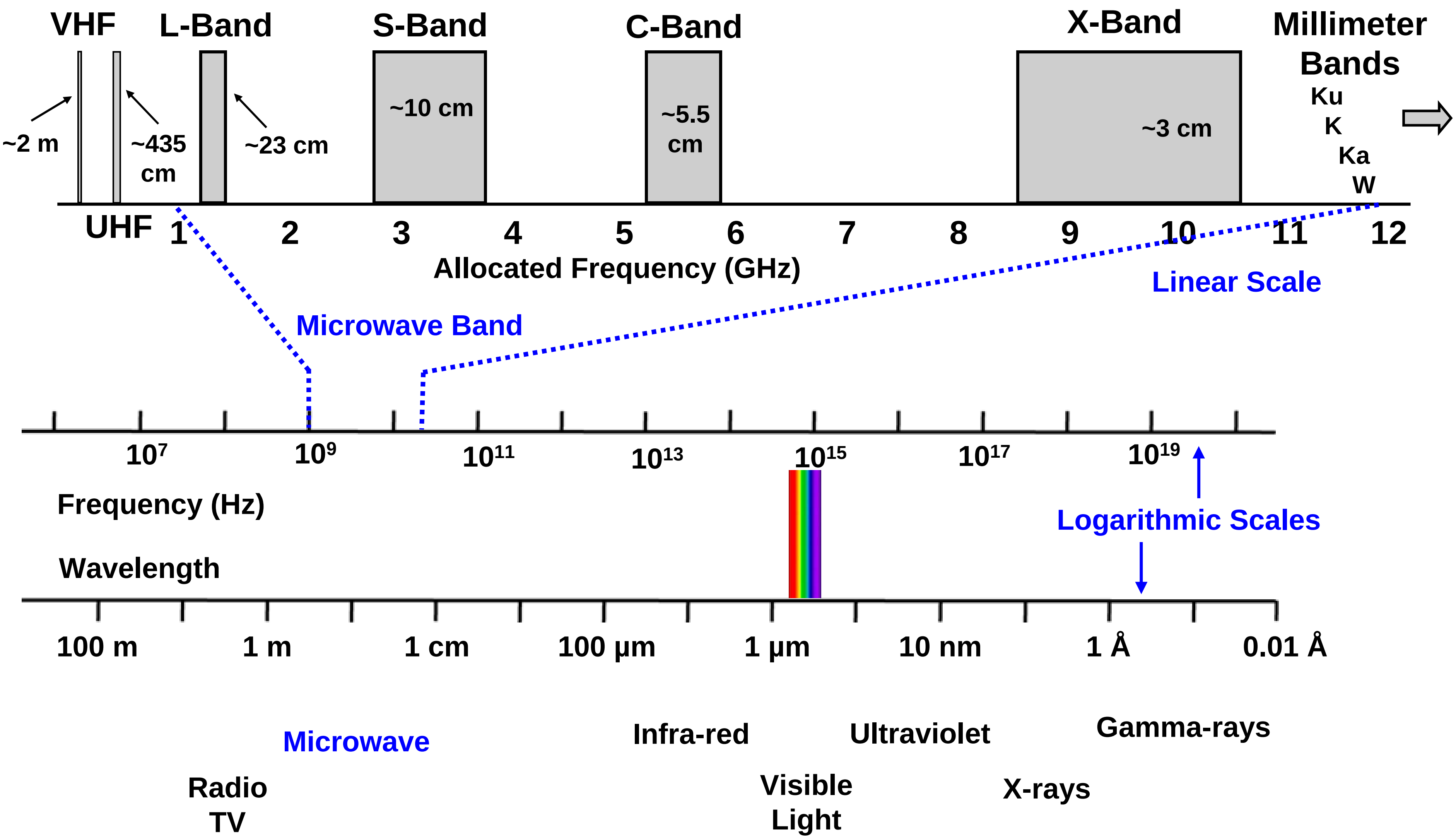
- **Background**

- **Radar basics**
  - **Utility and positive / negative attributes of radar**
  - **What radars measure**
  - **Block diagram of a radar system**
  - **Different Radar wavelengths / frequencies**
  - **Descriptive classifications of radars**

    Military, civilian, other

- **Course overview**

Radar Frequency Bands



Standard Radar Bands* & Typical Usage

UHF - VHF
ALTAIR

UHF
UEWR – Fylingsdales, UK

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

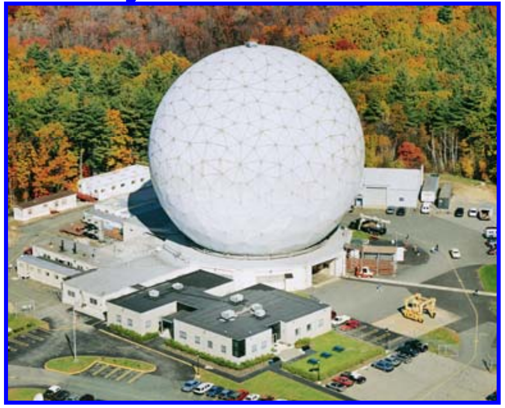
*From IEEE Standard 521-2002

Standard Radar Bands* & Typical Usage

C-Band
MOTR MQP-39

Courtesy of Lockheed Martin
Used with permission

X-Band
Haystack Radar



Courtesy of MIT Lincoln Laboratory
Used with permission

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

*From IEEE Standard 521-2002

Standard Radar Bands* & Typical Usage

L-Band

TPS-77

S-Band

AEGIS SPY-1

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

Search & Track Radars (L-Band through X-Band)

*From IEEE Standard 521-2002

C-Band

Patriot MPQ-53

Standard Radar Bands* & Typical Usage

Courtesy of US Army.
Used with permission.

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

Missile Seekers (C-Band through Ka-Band)

*From IEEE Standard 521-2002

Standard Radar Bands* & Typical Usage

Reagan Test Site Kwajalein

Courtesy of MIT Lincoln Laboratory
Used with permission

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

Range Instrumentation Radars (VHF through W-Band)

*From IEEE Standard 521-2002

Outline

- **Background**

- **Radar basics**
  - **Utility and positive / negative attributes of radar**
  - **What radars measure**
  - **Block diagram of a radar system**
  - **Different Radar wavelengths / frequencies**
  - **Descriptive classifications of radars**
    - **Military, civilian, other**

- **Course overview**

Classification Systems for Radars

By Function
Surveillance
Track
Fire Control – Guidance
Discrimination

By Mission
Air Traffic Control
Air Defense
Ballistic Missile Defense
Space Surveillance
Airborne Early Warning (AEW)
Ground Moving Target Indication (GMTI)

By Name
Pave Paws
Cobra Dane
Sentinel
Patriot
Improved Hawk
Aegis
ALCOR
Firefinder
TRADEX
Haystack
Millstone

By Platform
Ground
Ship
Airborne
Space

By Waveform Format
Low PRF
Medium PRF
High PRF
CW (Continuous Wave)

By Waveform
Pulsed CW
Frequency Modulated CW
Phase Coded
Pseudorandom Coded

By Military Number
FPS-17
FPS- 85
FPS-118
SPS-48
APG-68
TPQ-36
TPQ-37
MPQ-64

By Antenna Type
Reflector
Phased Array (ESA)
Hybrid-Scan

By Range
Long Range
Medium Range
Short Range

By Frequency
VHF-Band
UHF-Band
L-Band
S-Band
C-Band
X-Band
K_U-Band
K_A-Band

Other
Solid State
Synthetic Aperture (SAR)
MTI
GMTI

Classification Systems for Radars

By Function
Surveillance
Track
Fire Control – Guidance
Discrimination

By Mission
Air Traffic Control
Air Defense
Ballistic Missile Defense
Space Surveillance
Airborne Early Warning (AEW)
Ground Moving Target Indication (GMTI)

By Name
Pave Paws (FPS-115)
Cobra Dane(FPS-108)
Sentinel (MPQ-64)
Patriot (MPQ-53)
Improved Hawk (MPQ-48)
Aegis (SPY-1)
ALCOR
Firefinder (TPQ-37)
TRADEX
Haystack
Millstone

By Platform
Ground
Ship
Airborne
Space

By Waveform Format
Low PRF
Medium PRF
High PRF
CW (Continuous Wave)

By Waveform
Pulsed CW
Frequency Modulated CW
Phase Coded
Pseudorandom Coded

By Military Number
FPS-17
FPS- 85
FPS-118
SPS-48
APG-68
TPQ-36
TPQ-37
MPQ-64

By Antenna Type
Reflector
Phased Array (ESA)
Hybrid-Scan

By Range
Long Range
Medium Range
Short Range

By Frequency
VHF-Band
UHF-Band
L-Band
S-Band
C-Band
X-Band
K_U-Band
K_A-Band

Other
Solid State
Synthetic Aperture (SAR)
MTI
GMTI

Joint Electronic-Type Designation System

First Letter Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
P - Human Portable
S - Water (surface ship)
T - Transportable (ground)
U - General Utility (multi use)
V - Vehicle (ground)
W - Water Surface and Underwater combined
Z - Piloted/Pilotless Airborne

Second Letter Type of Equipment

A - Invisible Light, Infrared)
C - Carrier (electronic wave or signal)
D - Radiac (Radioactivity Detection, ID, and Computation)
E - Laser
F - Fiber Optics
G - Telegraph or Teletype
I - Interphone and Public Address
J - Electromechanical or inertial wire covered
K - Telemetering
L - Countermeasures
M - Meteorological
N - Sound in Air
P - Radar
Q - Sonar and Underwater Sound
R - Radio
S - Special or Combination
T - Telephone (Wire)
V - Visual, Visible Light
W - Armament (not otherwise covered)
X - Fax or Television
Y - Data Processing
Z - Communications

Third letter Purpose

A - Auxiliary Assembly
B - Bombing
C - Communications (two way)
D - Direction Finding, Reconnaissance and Surveillance
E - Ejection and/or Release
G - Fire Control or Searchlight Directing
H - Recording and/or Reproducing
K - Computing
L - no longer used.
M - Maintenance or Test
N - Navigation Aid
P - no longer used.
Q - Special or Combination
R - Receiving or Passive Detecting
S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

AN/XYZ-1 or XYZ-1

Highlighted in *blue italics* are typical radar Installations and Purposes

Joint Electronic-Type Designation System

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Example

AN/TPS-43 or TPS-43

Installation - T – Transportable (ground)

Equipment Type - P - Radar

Purpose - S – Detecting (and/or range and bearing), search

Courtesy of US Air Force

IEEE New Hampshire Section

Joint Electronic-Type Designation System

First Letter Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
P - Human Portable
S - Water (surface ship)
T - Transportable (ground)
U - General Utility (multi use)
V - Vehicle (ground)
W - Water Surface and Underwater combined
Z - Piloted/Pilotless Airborne

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C - Carrier (electronic wave or signal)
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Third letter Purpose

A - Auxiliary Assembly
B - Bombing
C - Communications (two way)
D - Direction Finding, Reconnaissance and Surveillance
E - Ejection and/or Release
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S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

Example

AN/FPS-16 or FPS-16

Installation - F – Fixed Ground

Equipment Type - P - Radar

Purpose - S – Detecting and/or range, and bearing, search

Courtesy of US Air Force

Joint Electronic-Type Designation System

First Letter
Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
P - Human Portable
S - Water (surface ship)
T - Transportable (ground)
U - General Utility (multi use)
V - Vehicle (ground)
W - Water Surface and Underwater combined
Z - Piloted/Pilotless Airborne

Second Letter
Type of Equipment

A - Invisible Light, Infrared)
C - Carrier (electronic wave or signal)
D - Radiac (Radioactivity Detection, ID, and Computation)
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P - Radar
Q - Sonar and Underwater Sound
R - Radio
S - Special or Combination
T - Telephone (Wire)
V - Visual, Visible Light
W - Armament (not otherwise covered)
X - Fax or Television
Y - Data Processing
Z - Communications

Third letter
Purpose

A - Auxiliary Assembly
B - Bombing
C - Communications (two way)
D - Direction Finding, Reconnaissance and Surveillance
E - Ejection and/or Release
G - Fire Control or Searchlight Directing
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S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

Example

AN/SPY-1 or SPY-1 (a.k.a. AEGIS)

Installation - S – Water (Surface Ship)

Equipment Type - P - Radar

Purpose - Y – Surveillance and Control (fire control and air control)

Courtesy of US Navy

Joint Electronic-Type Designation System

First Letter Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
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Third letter Purpose

A - Auxiliary Assembly
B - Bombing
C - Communications (two way)
D - Direction Finding, Reconnaissance and Surveillance
E - Ejection and/or Release
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S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

Example

AN/MPQ-64 or MPQ-64 (a.k.a. Sentinel)

Installation - M – Ground, Mobile

Equipment Type - P - Radar

Purpose - Q – Special or Combination of Purposes

Courtesy of Raytheon
Used with permission.

Outline

- **Background**
- **Radar basics**
- **Course overview**
  - **One viewgraph for each lecture topic**

Course Outline - Part 1

- Prelude
- Introduction
- Review of Electromagnetism
- Review of Signals and Systems, and Digital Signal Processing
- The Radar Equation
- Atmospheric Propagation Effects
- Detection of Signals in Noise
- Radar Cross Section
- Antennas – Basics and Mechanical Scanning Techniques
- Antennas – Electronic Scanning and Hybrid Techniques
- Radar Clutter

Course Outline – Part 1 (continued)

- Radar Waveforms and Pulse Compression Techniques
- Clutter Rejection Techniques – Basics and MTI (Moving Target Indication)
- Clutter Rejection Techniques – Pulse Doppler Processing
- Adaptive Processing
- Airborne Pulse Doppler Radar
- Radar Observable Estimation
- Target Tracking
- Transmitters
- Receivers

Course Outline - Part 2

- Electronic Counter Measures (ECM)
- Radar Design Considerations
- Radar Open Systems Architecture (ROSA)
- Synthetic Aperture Radar (SAR) Techniques
- Inverse Synthetic Aperture Radar (ISAR) Techniques
- Over-the-Horizon Radars
- Weather Radars
- Space Based Remote Sensing Radars
- Air Traffic Control, Civil, and Marine Radars
- Ground Penetration Radars
- Range Instrumentation Radars
- Military Radar Systems

The total length of each topic will vary from about 30 minutes to up to possibly 2 hours. The video stream for most topics will be broken up into a few "easily digestible" pieces, each 20-30 minutes in length.

Review - Electromagnetism

James Clerk Maxwell

Maxwell's Equations

Integral Form

$$\oiint \vec{D} \cdot d\vec{S} = \iiint \rho \, dV$$

$$\oiint \vec{B} \cdot d\vec{S} = 0$$

$$\oint \vec{E} \cdot d\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$$

$$\oint \vec{H} \cdot d\vec{s} = \iint \left(\frac{\partial \vec{D}}{\partial t} + \vec{J} \right) \cdot d\vec{S}$$

Differential Form

$$\nabla \cdot \vec{D} = 4\pi\rho$$

$$\nabla \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

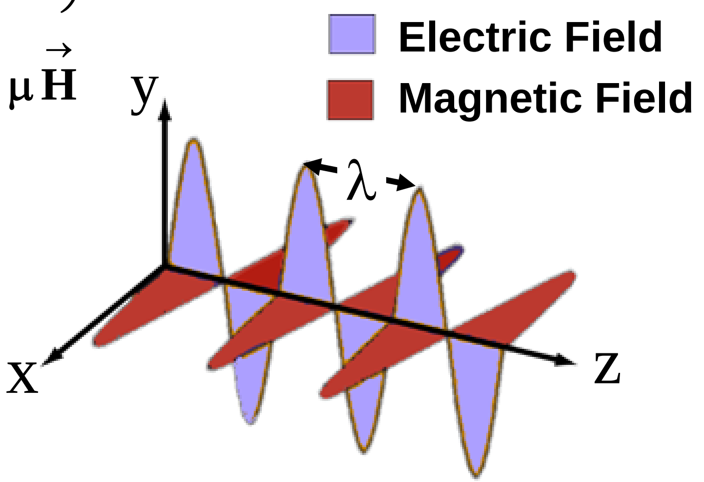
$$\vec{D} = \varepsilon \vec{E} \qquad \vec{B} = \mu \vec{H}$$

Plane Wave Solution

No Sources
Vacuum
Non-Conducting Medum

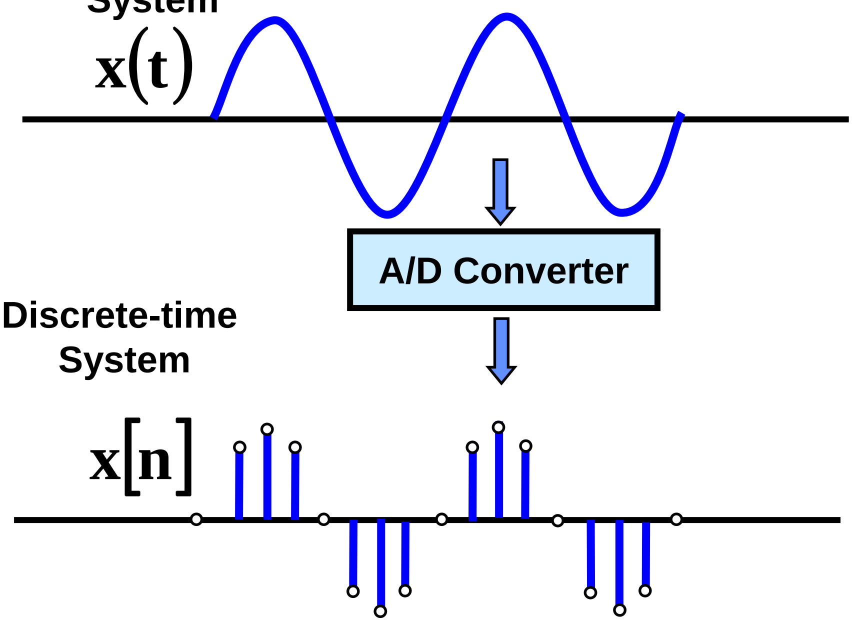
$$\vec{E}(\vec{r}, t) = E_{\circ} e^{j(\vec{k} \cdot \vec{r} - jwt)}$$

$$\vec{B}(\vec{r}, t) = B_{\circ} e^{j(\vec{k} \cdot \vec{r} - jwt)}$$

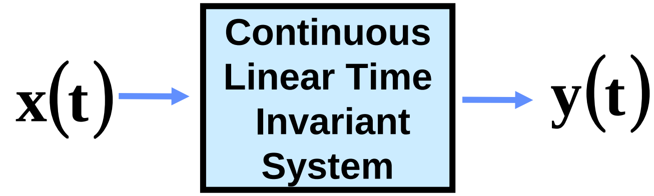


Review – Signals and Systems, and Digital Signal Processing

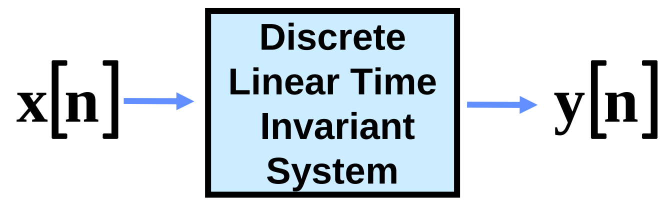
Continuous-time System



Discrete-time System



$$y(t) = \int_{-\infty}^{\infty} x(\tau) h(t-\tau) d\tau$$



$$y[n] = \sum_{k=-\infty}^{\infty} x[n-k] h[k]$$

Discrete Fourier Transform (DFT)

$$X(\omega) = \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega n}$$

Other Topics

Fast Fourier Transform (FFT)

Convolution

Sampling Theorem - Aliasing

Digital Filters

Low pass, High Pass, Transversal)

Filter Weighting

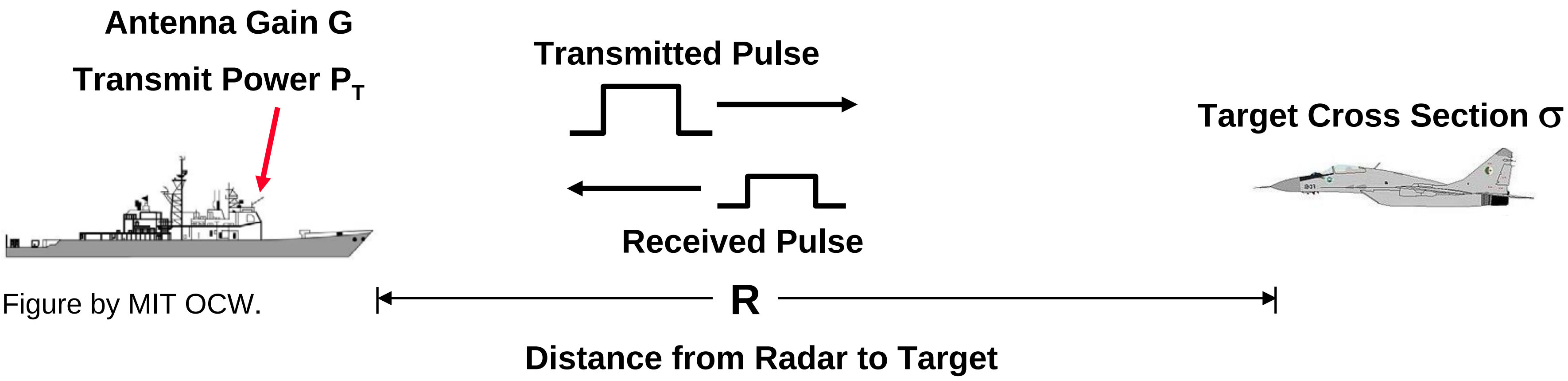


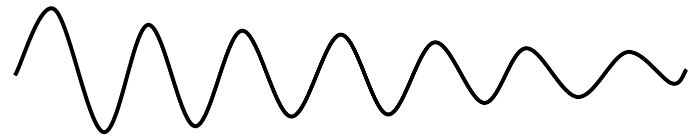
Figure by MIT OCW.

Radar Range Equation

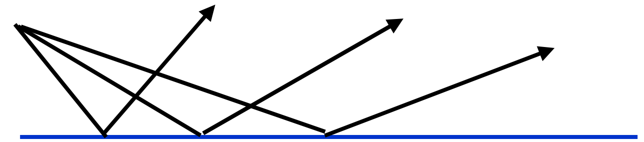
$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}$$

Propagation Effects on Radar Performance

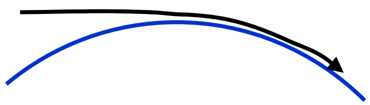
- **Atmospheric attenuation**



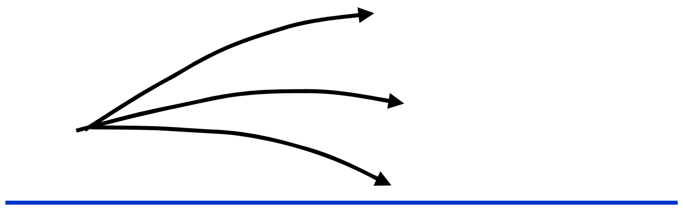
- **Reflection off of Earth's surface**



- **Over-the-horizon diffraction**



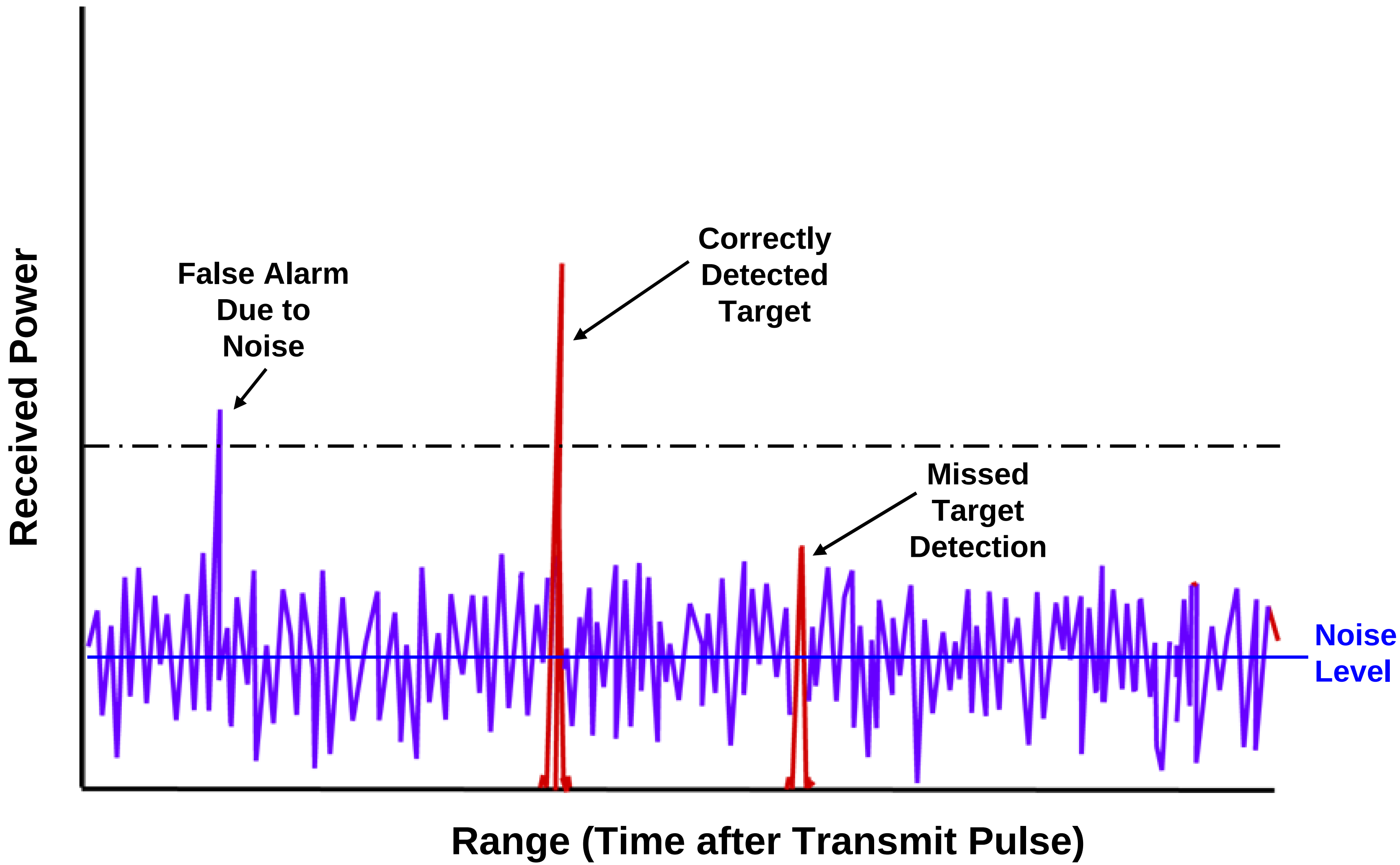
- **Atmospheric refraction**



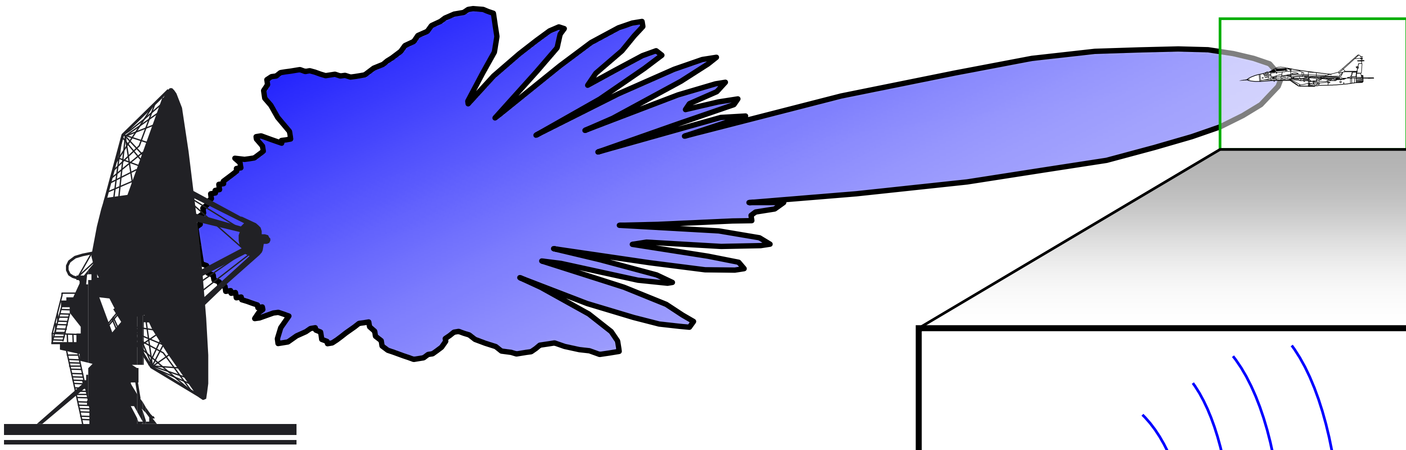
Radar beams can be attenuated, reflected and bent by the environment

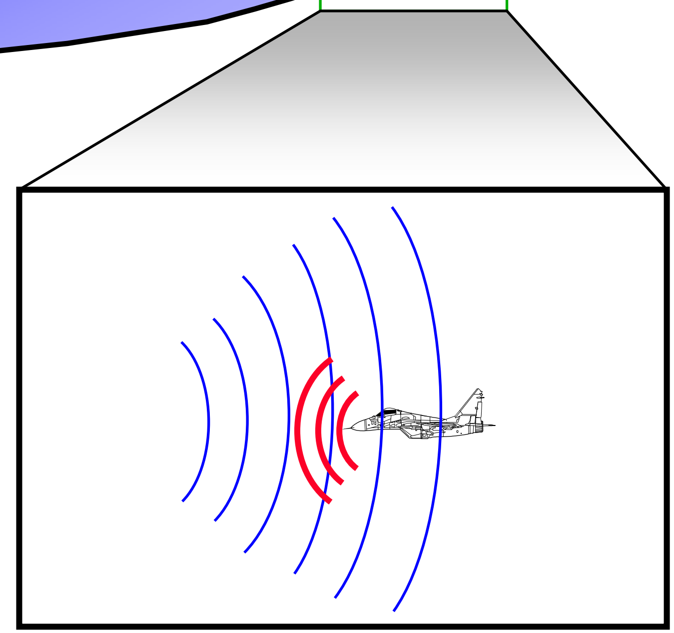
Courtesy of MIT Lincoln Laboratory
Used with permission

Detection of Signals in Noise



Radar Cross Section (RCS)





RCS

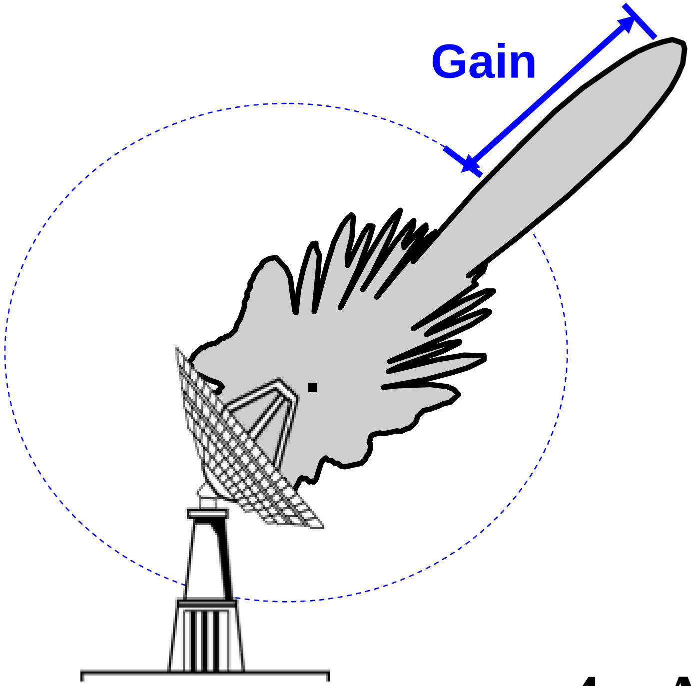
Incident Power Density	x	σ	=	Reflected Power
(Watts/m^2		m^2		Watts)

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

Measured in m^2, or dBsm

Antennas – Fundamentals and Mechanical Scanning Techniques

Directional Antenna

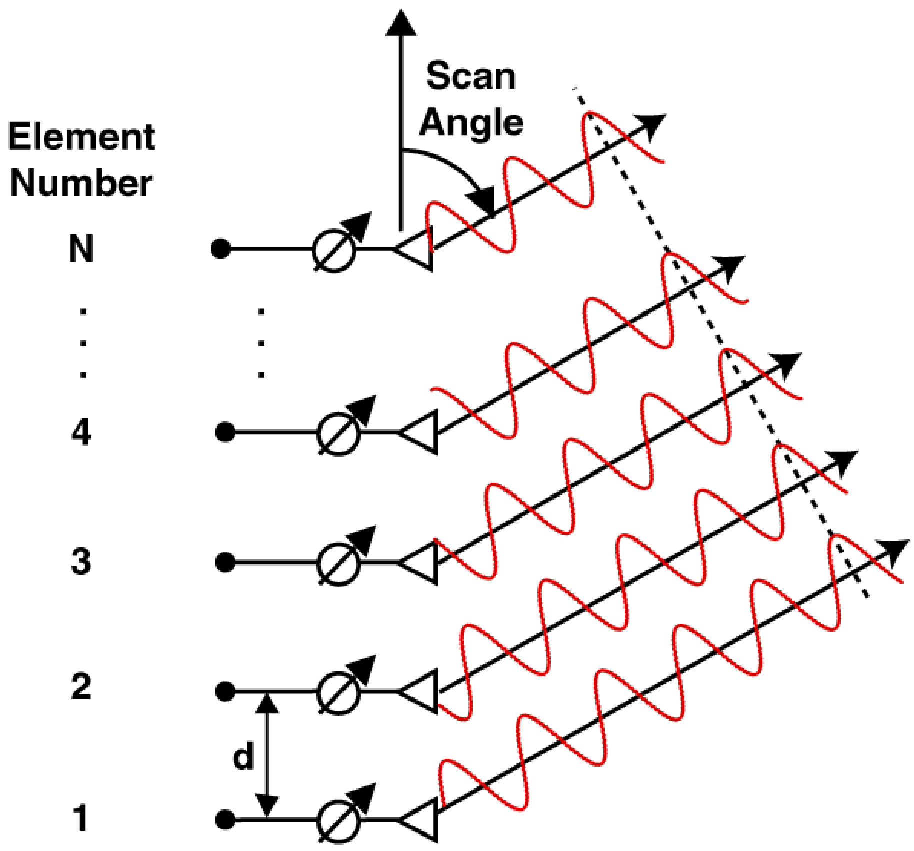


$$G = \frac{4 \pi A}{\lambda^2}$$

ALTAIR Antenna

Courtesy of MIT Lincoln Laboratory
Used with permission

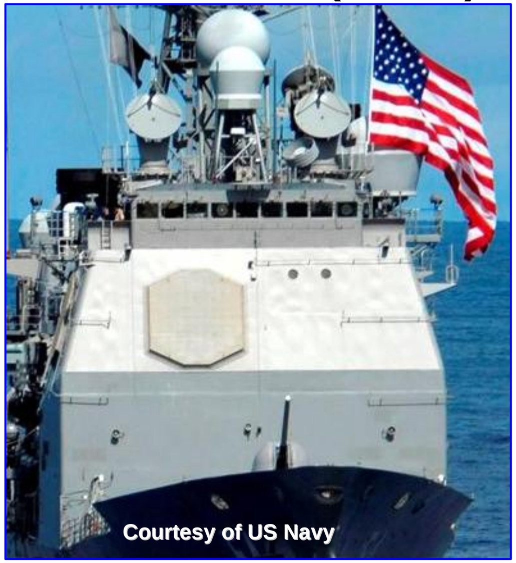
Antennas – Electronic Scanning Techniques



Courtesy of MIT Lincoln Laboratory
Used with permission

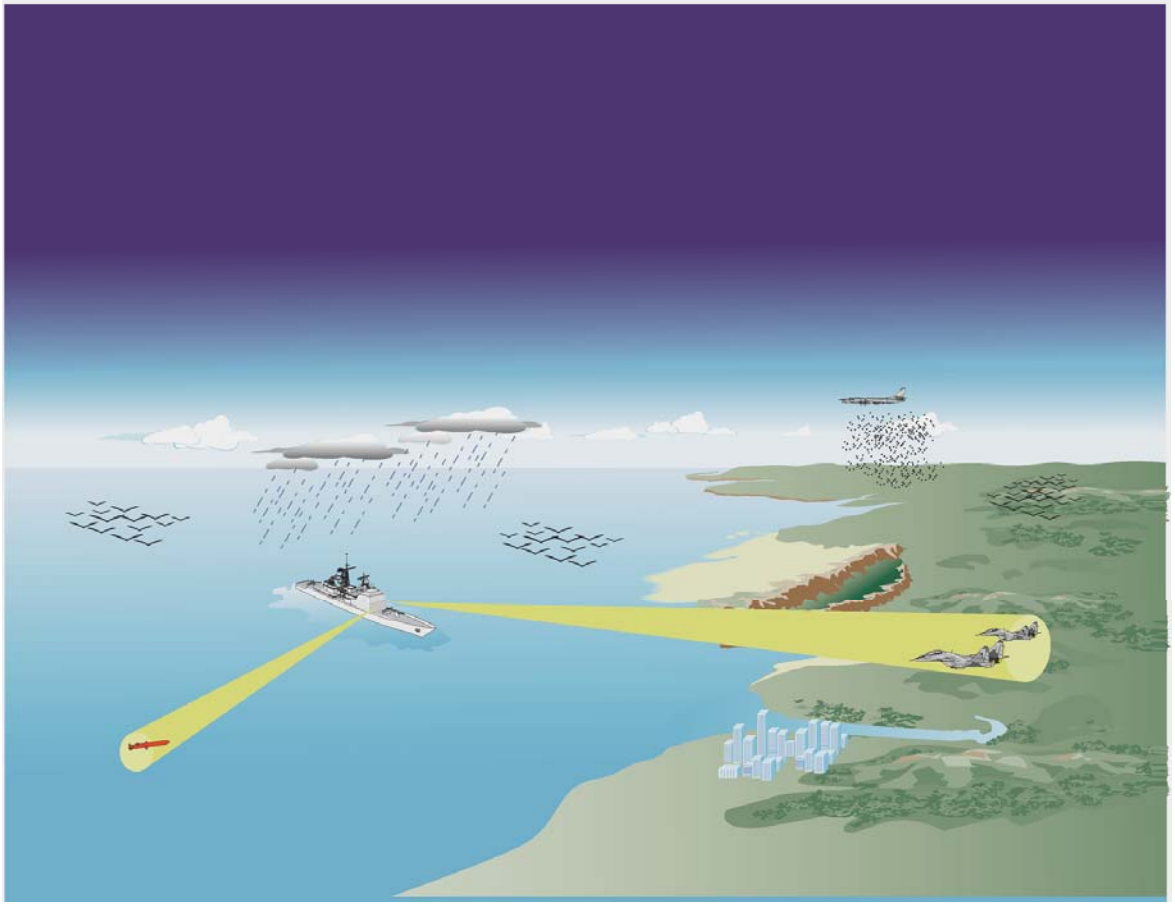
Patriot Radar (MPQ-53)

AEGIS Radar (SPY-1)



Radar Clutter

Naval Air Defense Scenario



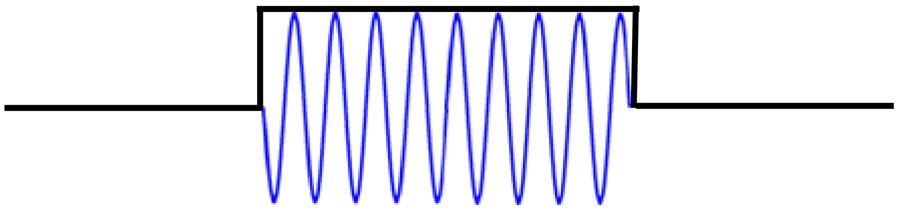
Courtesy of MIT Lincoln Laboratory
Used with permission

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

Radar Waveforms and Pulse Compression Techniques

Basic Pulsed CW Waveform

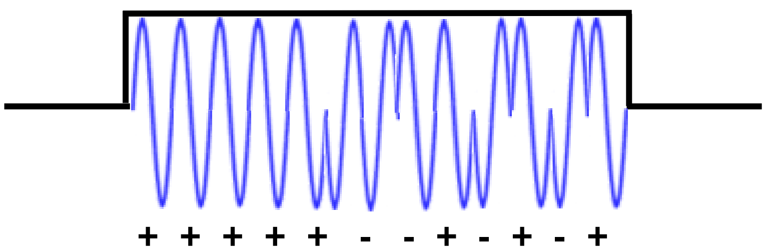


$$T = \frac{1}{B}$$

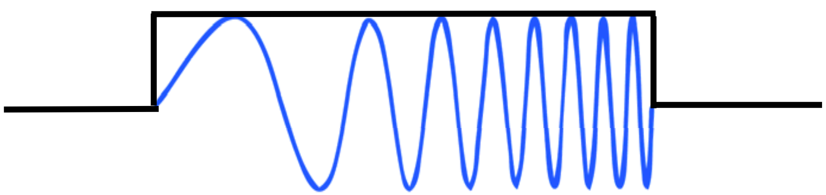
$$\Delta R = \frac{c\,T}{2} = \frac{c}{2B}$$

Pulse Compression Waveforms

Binary Phase Coded Waveform

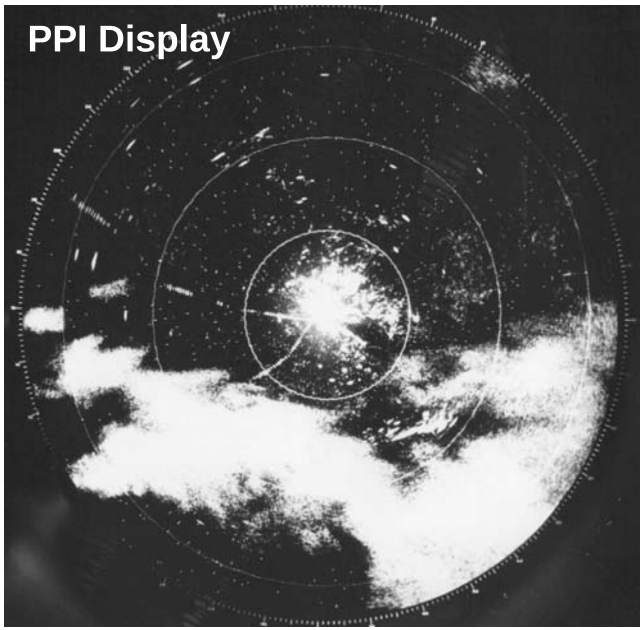


Linear Frequency Modulated Waveform



The spectral bandwidth (resolution) of a radar pulse can be increased, if it is modulated in frequency or phase

Unprocessed Radar Backscatter



Courtesy of FAA

Use low pass Doppler filter to suppress clutter backscatter

Two Pulse MTI Filter

Filter Input

$$V_1, V_2, V_3, \ldots V_N$$

Filter Output

$$V_2 - V_1, V_3 - V_2, V_4 - V_3, \ldots V_N - V_{N-1}$$

Radar A-Scope

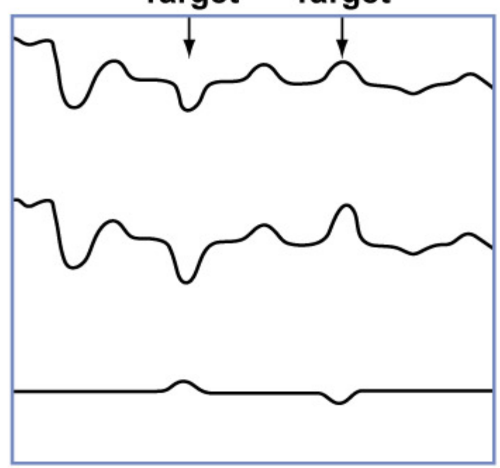
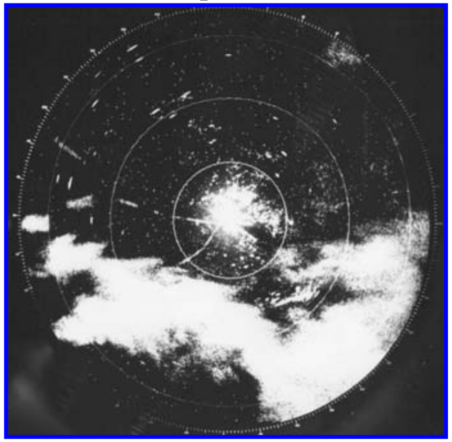


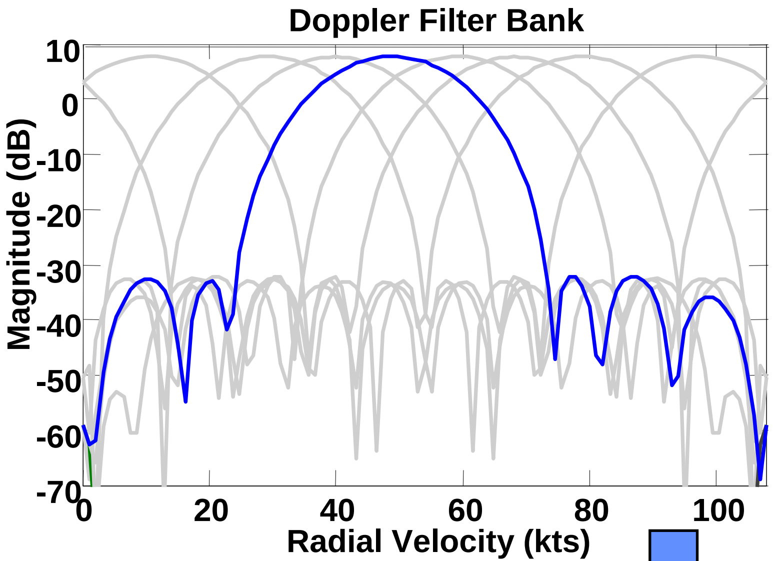
Figure by MIT OCW.

Pulse Doppler Processing

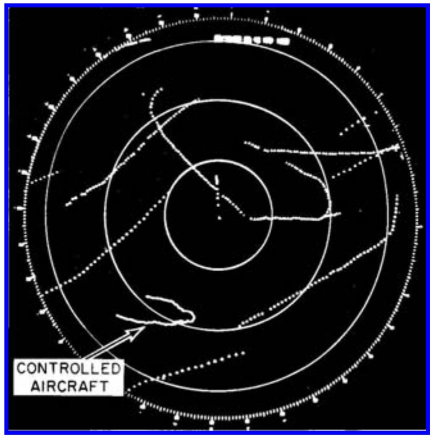
Input



Courtesy of FAA



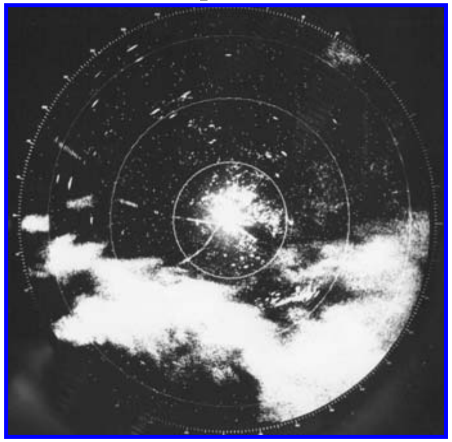
Output



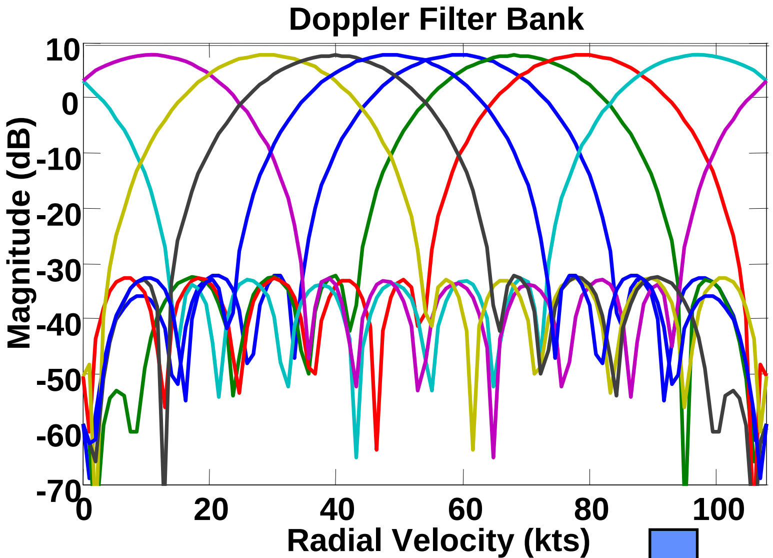
Courtesy of FAA

Pulse Doppler Processing optimally rejects moving clutter with a number of pass band Doppler filters

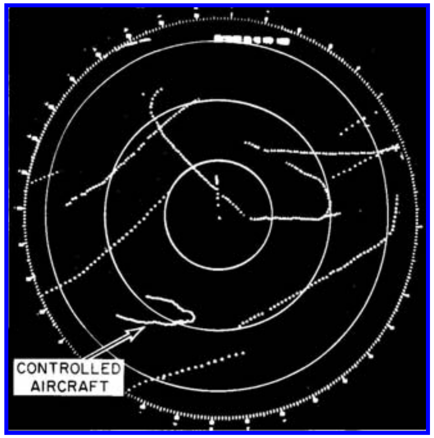
Input



Courtesy of FAA

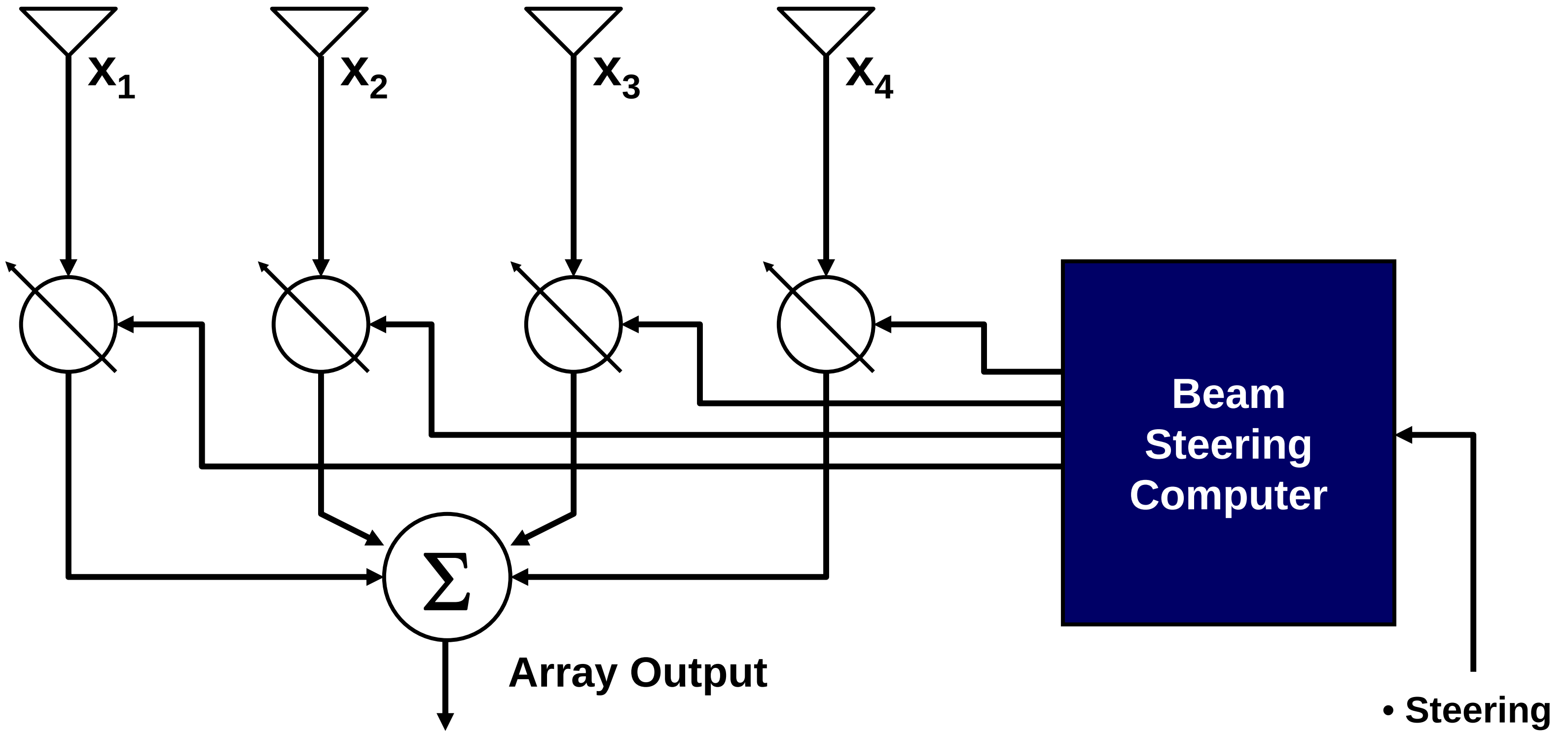


Output



Courtesy of FAA

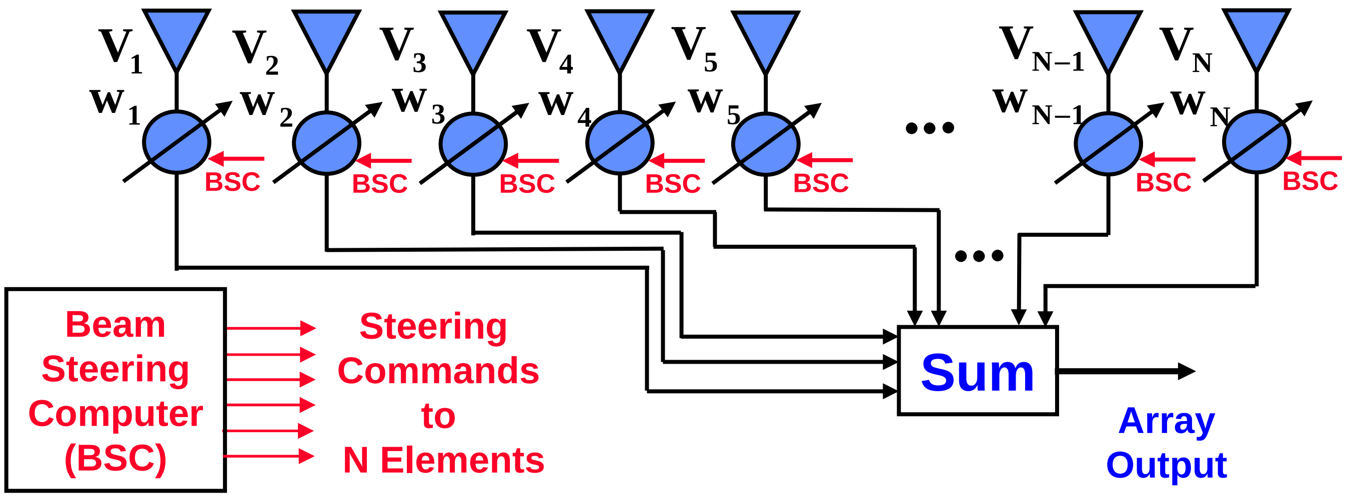
Pulse Doppler Processing optimally rejects moving clutter with a number of pass band Doppler filters



- Want to adjust antenna steering weights to maximize detection in the direction of the wanted target, while putting nulls in the direction of jamming and clutter?

- The same methods may be used to weight the received signal in the time domain, so that targets are optimally detected and the unwanted clutter (rain, chaff, etc) are rejected by low Doppler filter sidelobes.

Adaptive Processing

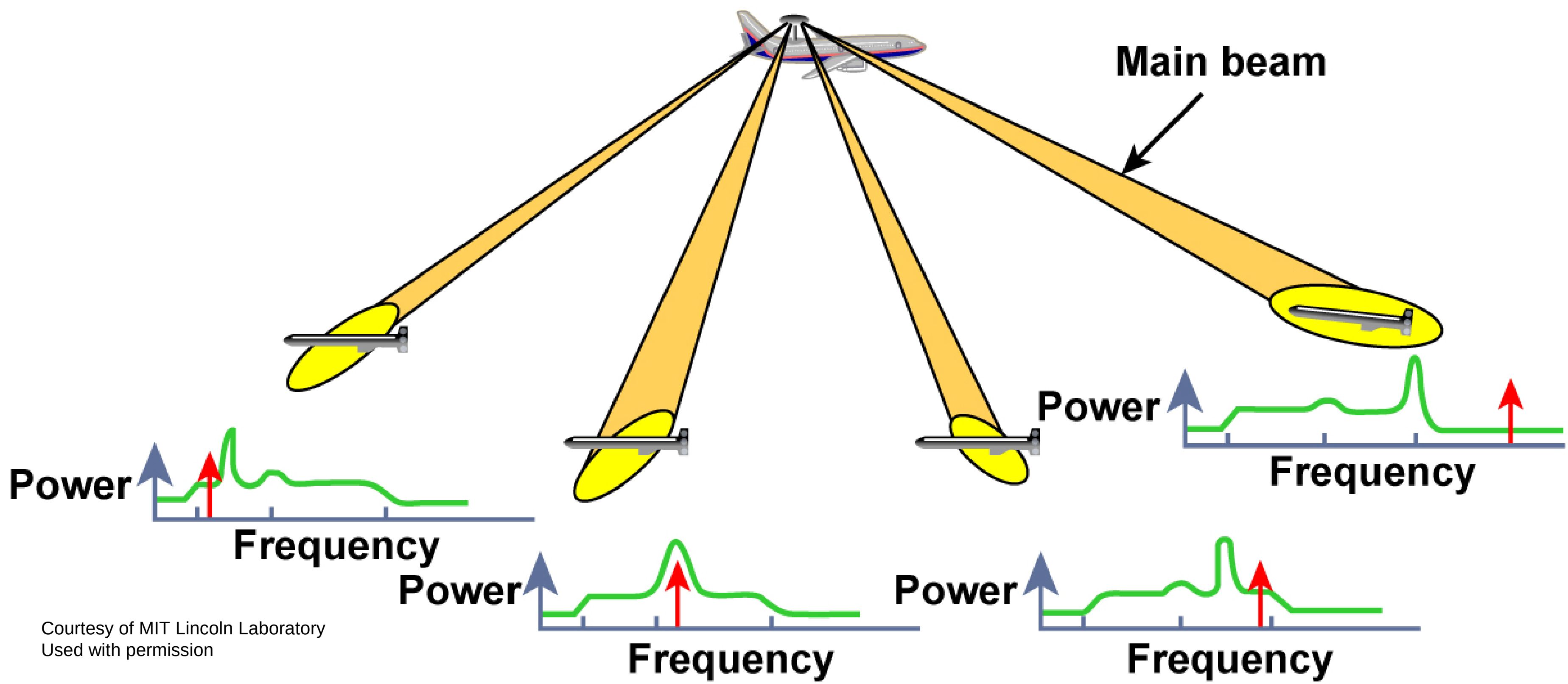


- **Goal: calculate and set antenna weights so that Antenna gain in the target's direction is maximized, while antenna sidelobes are minimized (nulls) in the direction of jamming and clutter**

- **Doppler processing uses these techniques to maximize detection at the Doppler of the target, while placing low sidelobes at the Doppler frequencies of clutter**

Airborne Pulse Doppler Processing

Illustrative example without Pulse-Doppler ambiguities



Courtesy of MIT Lincoln Laboratory
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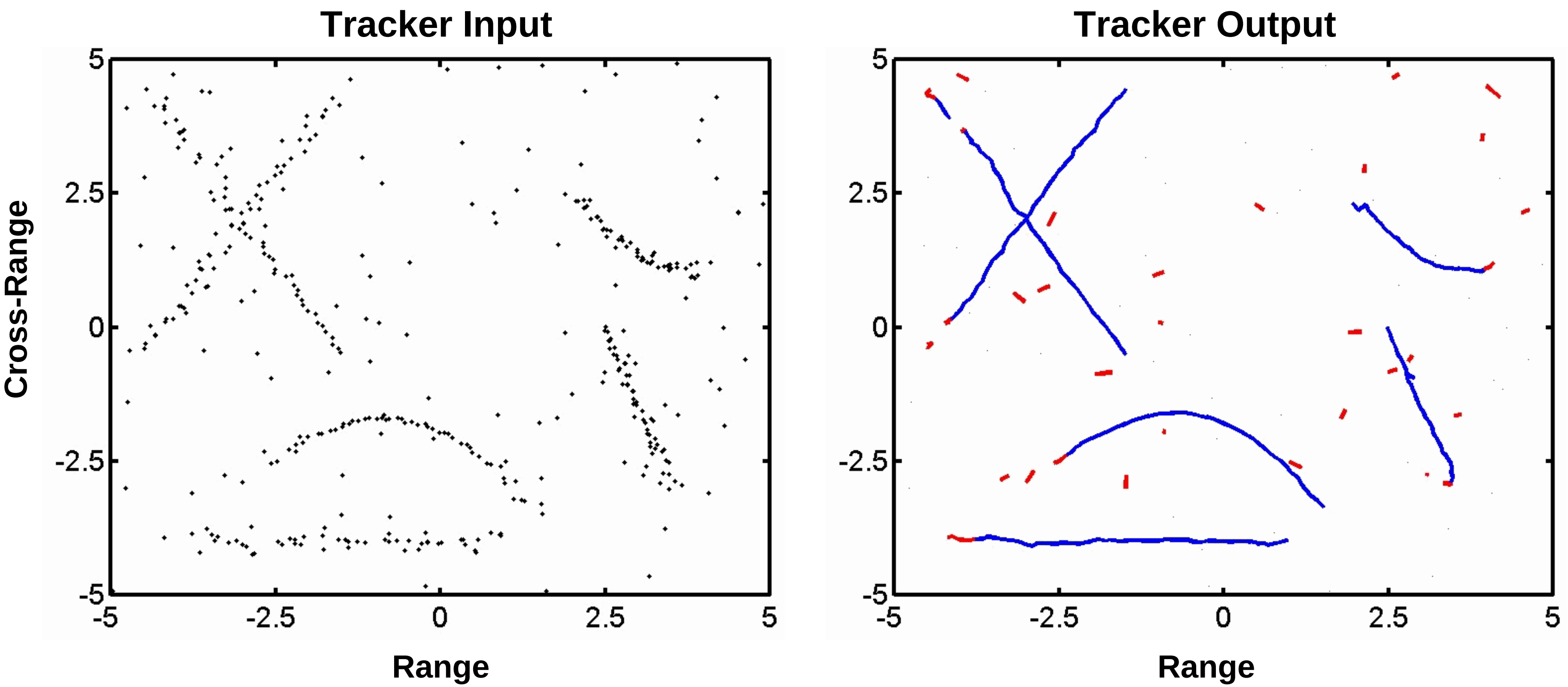
- Doppler frequency of mainbeam clutter depends on scan direction
- Doppler frequency of target depends on scan direction and target aspect angle

Tracking



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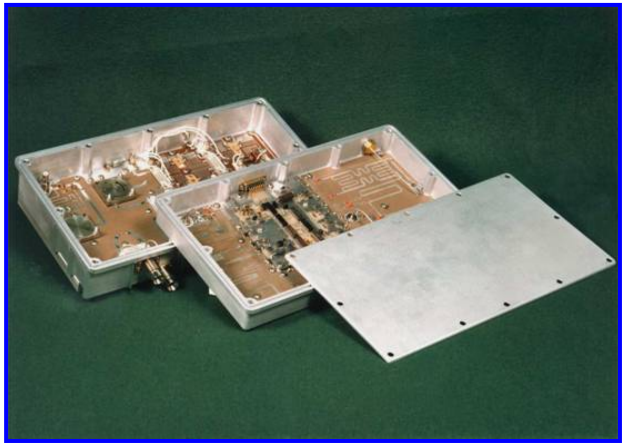
Transmitters

Tubes or T/R Modules ?   Answer: Both have their place!

X-Band Traveling Wave Tube

Courtesy of MIT Lincoln Laboratory. Used with permission.

PAVE PAWS UHF T/R Module



Courtesy of Raytheon Used with permission.

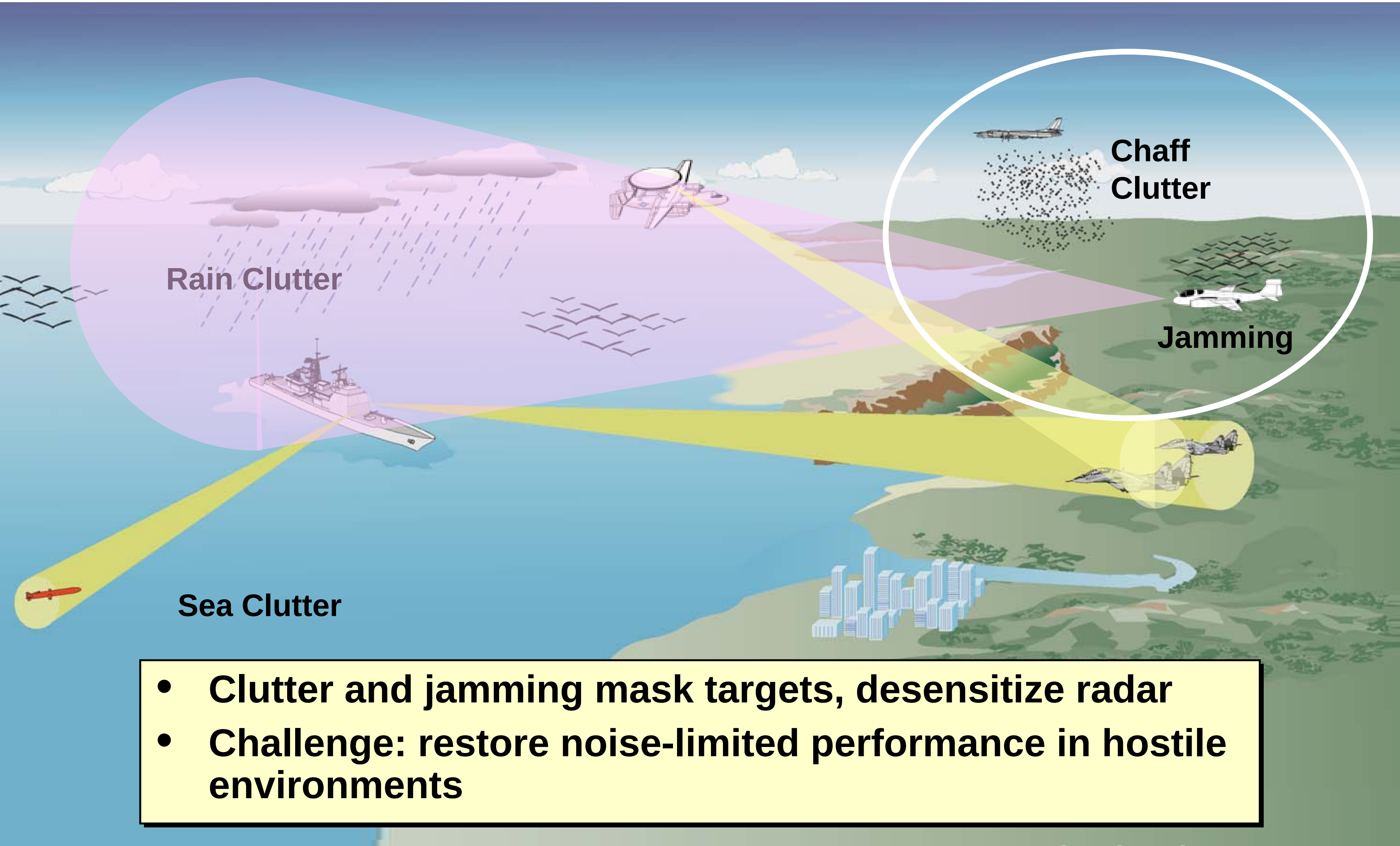
Haystack Radar

Courtesy of MIT Lincoln Laboratory. Used with permission.

PAVE PAWS Radar

Courtesy of Raytheon. Used with permission.

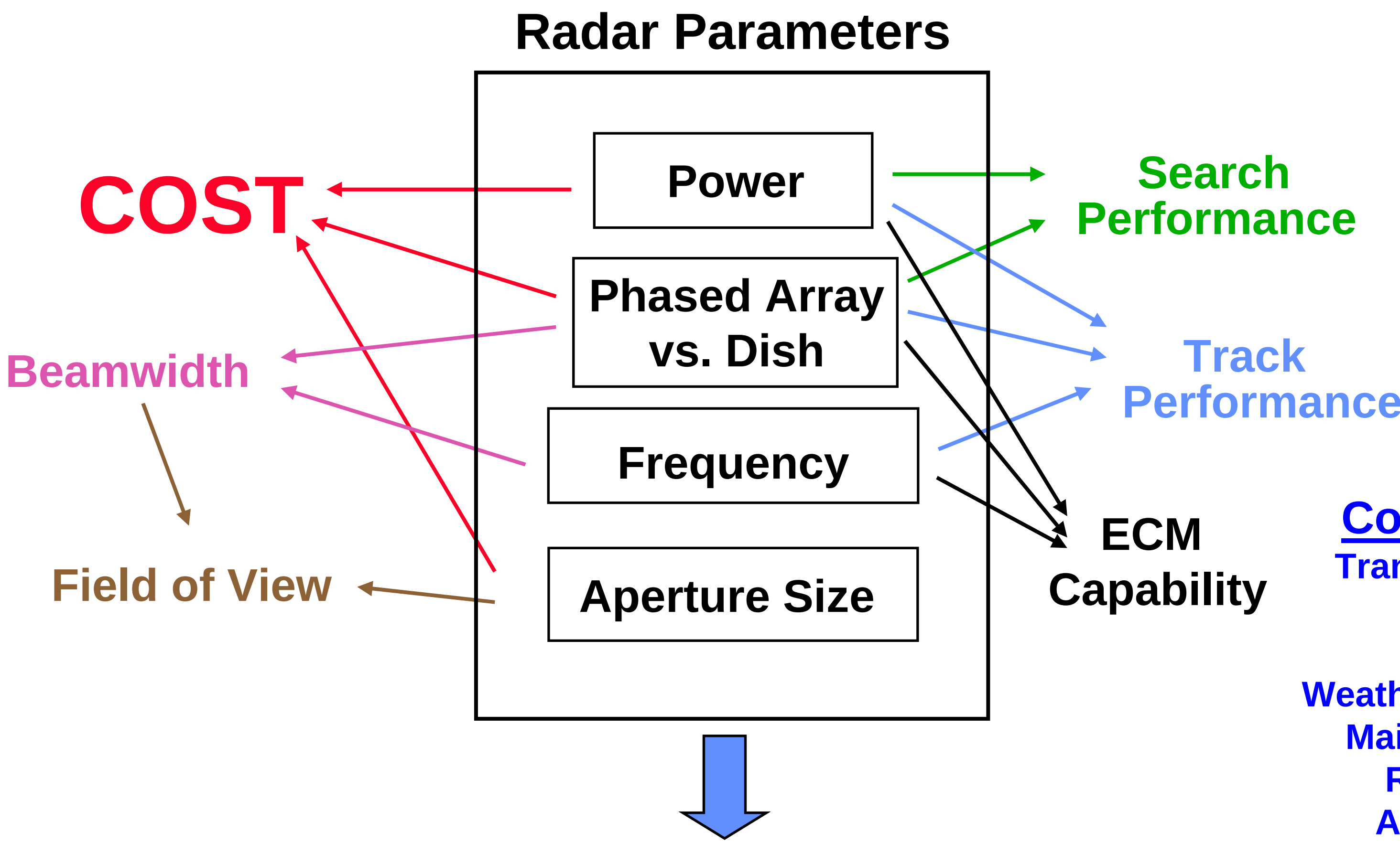
Electronic Counter Measures (ECM)



- Clutter and jamming mask targets, desensitize radar
- Challenge: restore noise-limited performance in hostile environments

Radar Design Considerations

"A Curse of Dimensionality"



Constraints

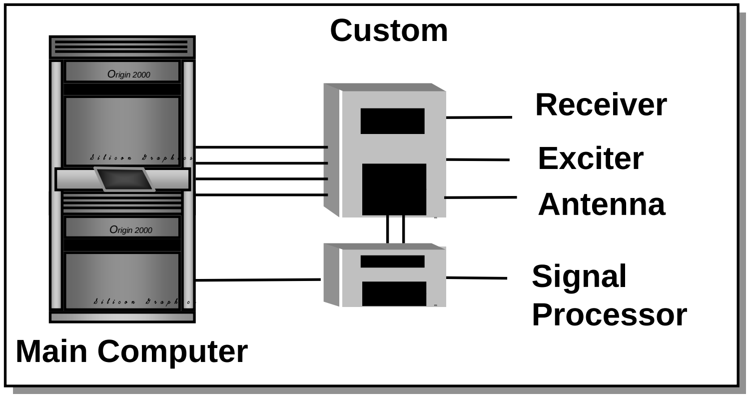
Transportability
Volume
Weight
Weather (Sea State)
Maintainability
Reliability
Availability
Life Cycle Cost
Upfront Cost

Example : 90% P_D, $P_{FA} = 10^{-6}$ at 1000 km on 1 m^2 target

Radar Open Systems Architecture (ROSA)

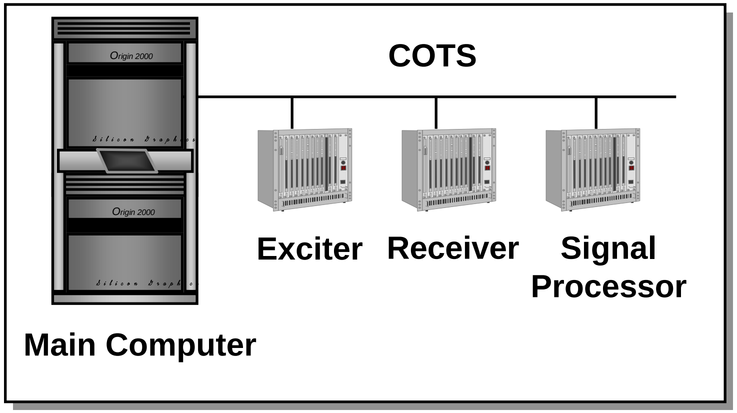
- Traditional Radar System Architecture
  - Custom development
  - Proprietary HW, SW and interfaces

Software rehost
Hardware obsolescence



- Radar Open Systems Architecture (ROSA)
  - Radar functions are organized as rational, accessible, modular subsystems
  - Industry standard interfaces
  - COTS HW, open source operating system and S/W

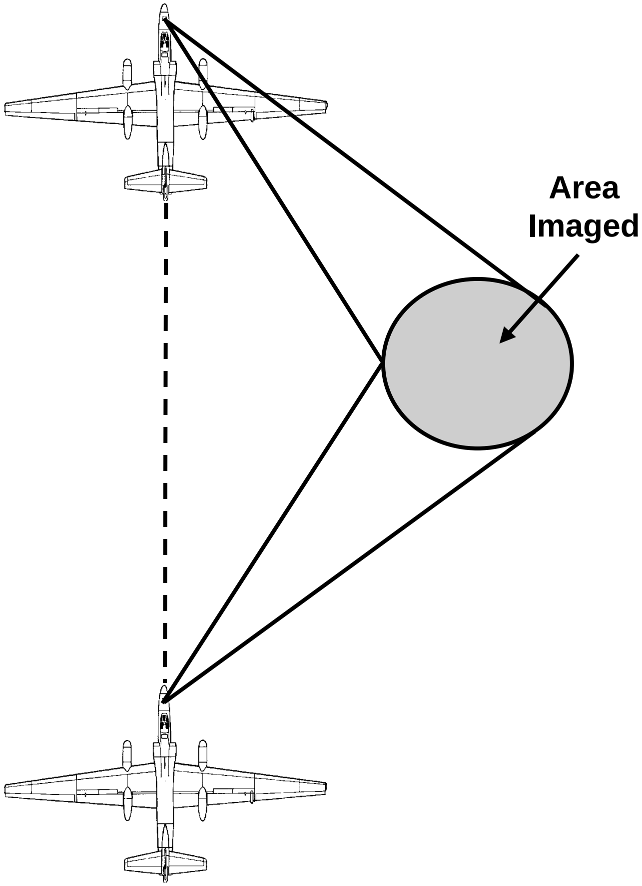
Evolutionary product improvements



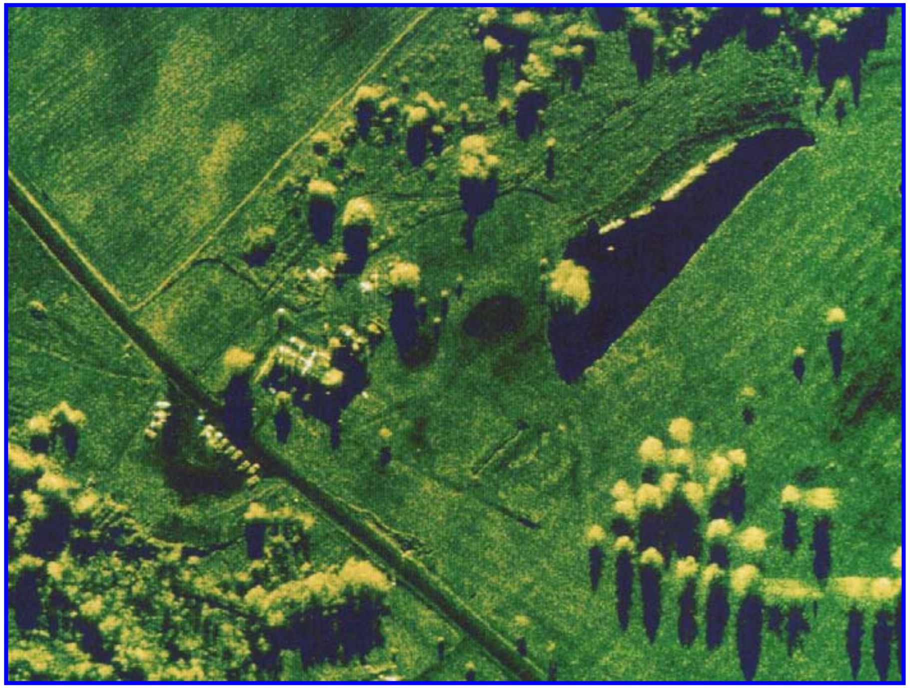
Architecture based on modular independent functions connected through well defined open systems interfaces

Synthetic Aperture Radar (SAR) Techniques

Spotlight Scan Mode



SAR Image of Golf Course



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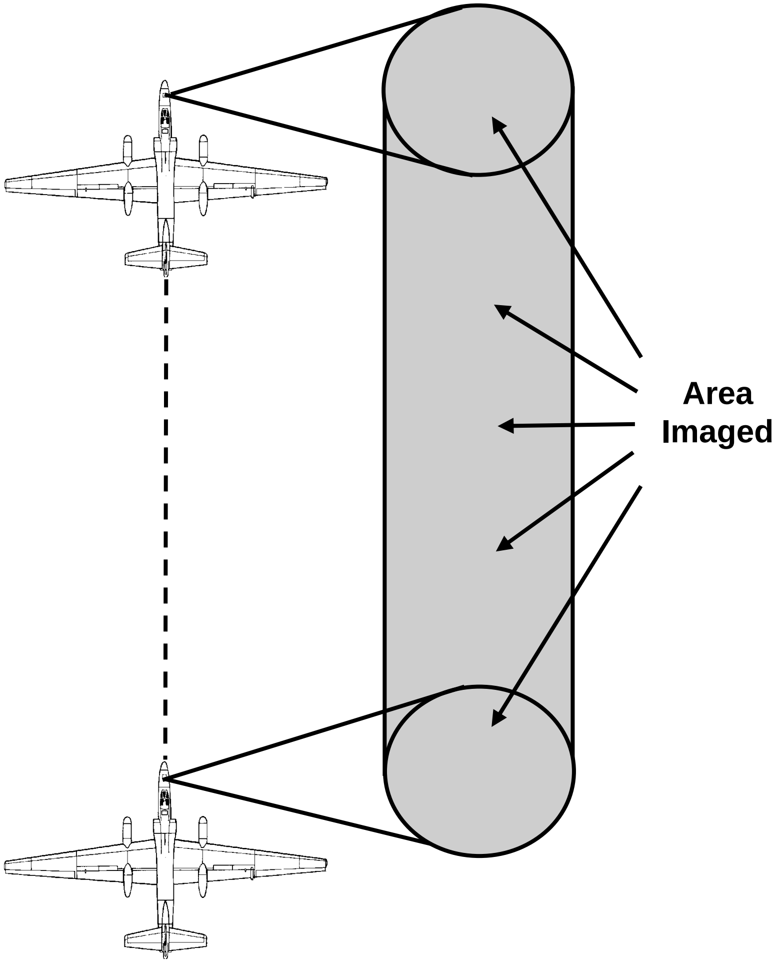
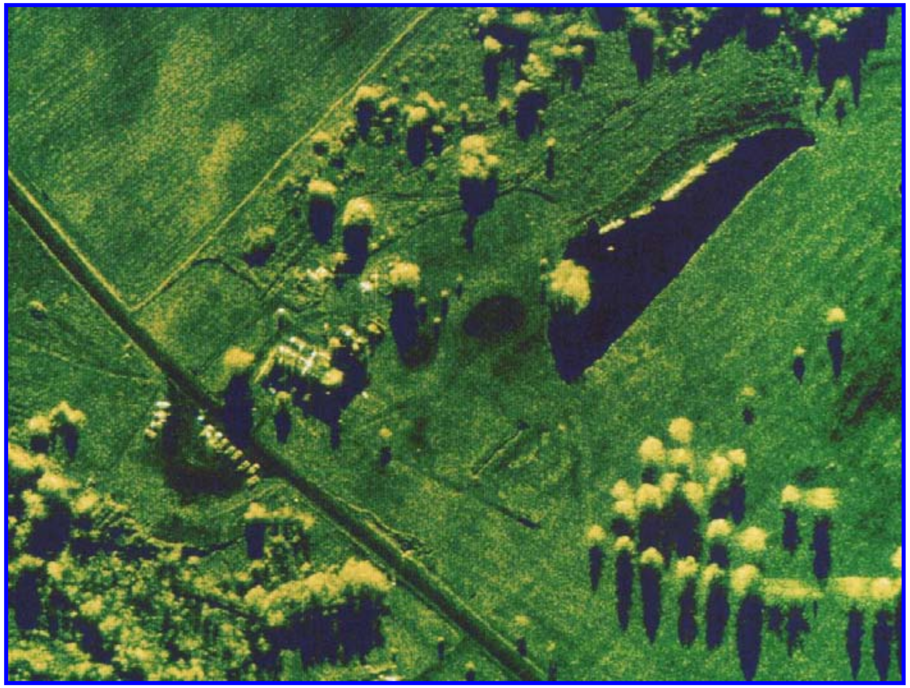
Spotlight Scan Mode



SAR Image of Golf Course



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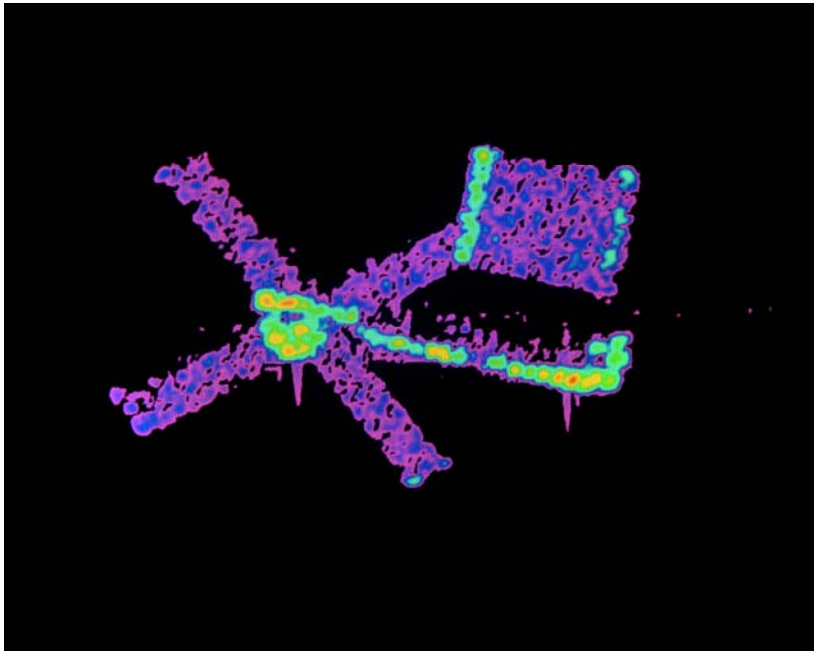
Inverse Synthetic Aperture Radar (ISAR) Techniques

Photograph of Skylab

Courtesy of NASA

Simulated Range-Doppler Image of Skylab



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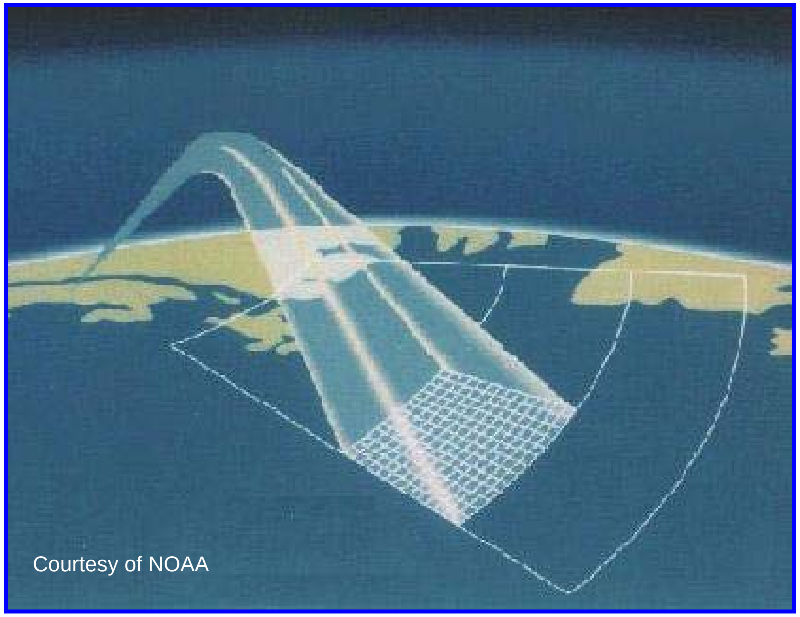
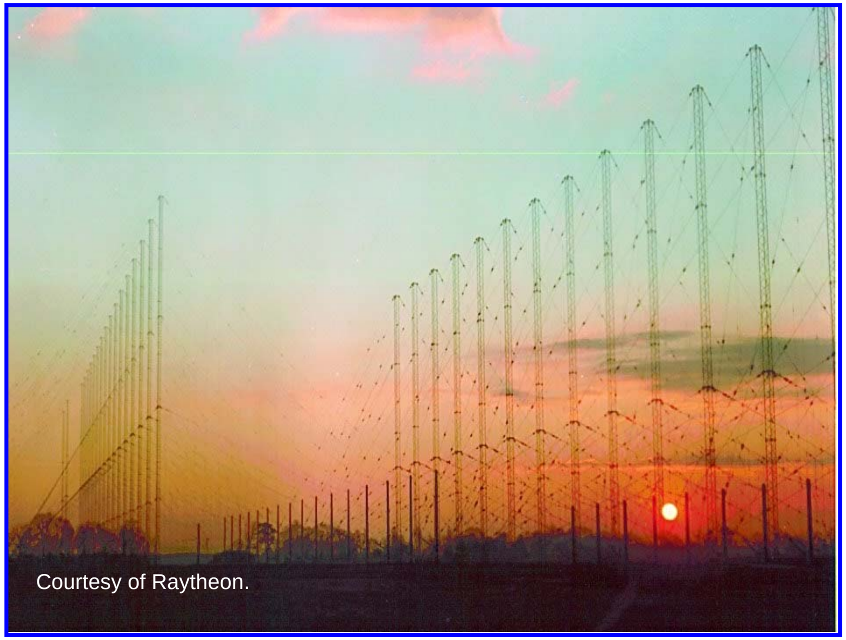
Over-the-Horizon Radars

OTH Radar Beam Paths



Example
Relocatable OTH Radar (ROTHR)

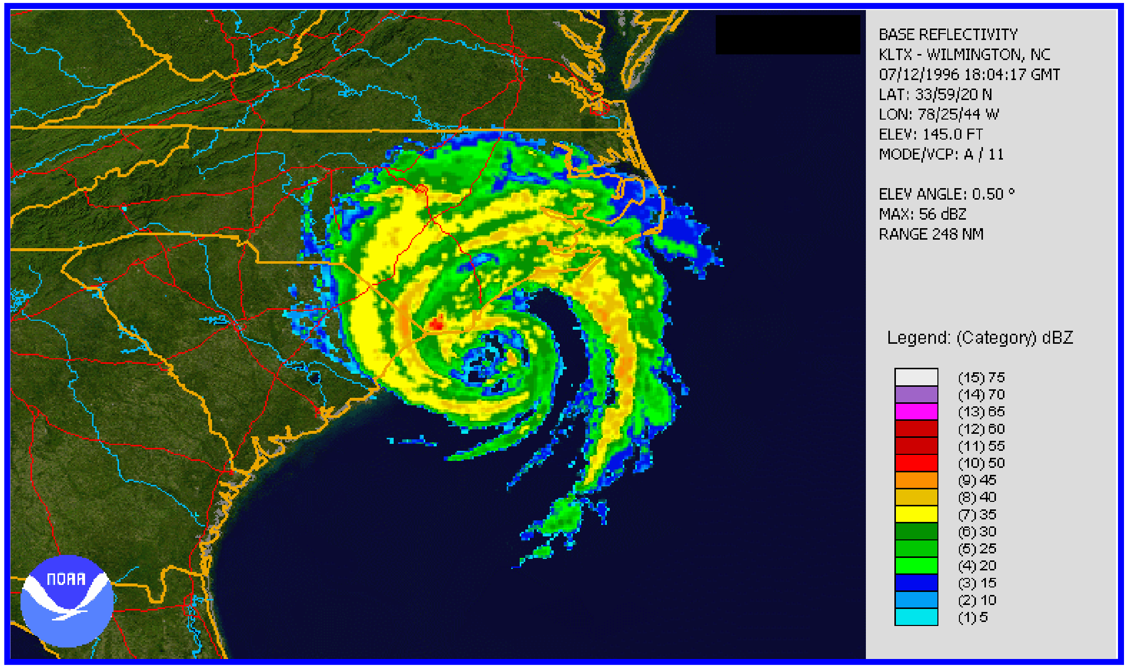


- **Typically operate at 10 – 80 m wavelengths (3.5 – 30 MHz)**
- **OTH Radars can detect aircraft and ships at very long ranges (~ 2000 miles)**

NEXRAD (aka WSR-88)

Courtesy of NOAA

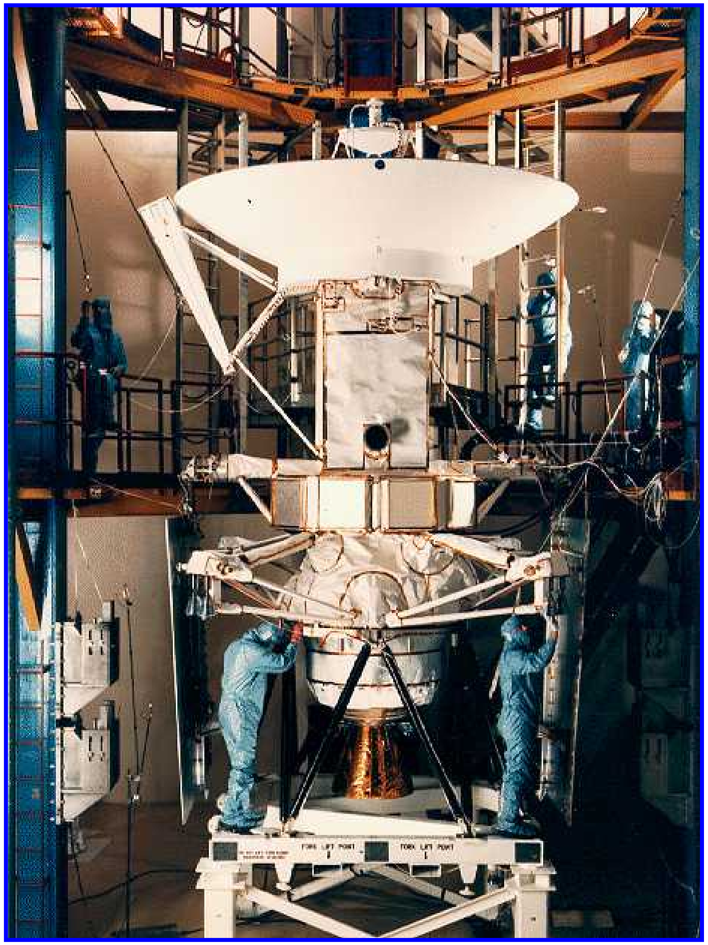
Weather map for Hurricane Bertha 1996



Courtesy of NOAA

Space Based Remote Sensing Radars

Magellan Radar



Courtesy of NASA

SAR Map of Venus

Courtesy of NASA

Air Traffic Control & Other Civil Radars

Courtesy of Target Corporation

Courtesy of neonbubble

Courtesy of FAA

Courtesy of Northrop Grumman.
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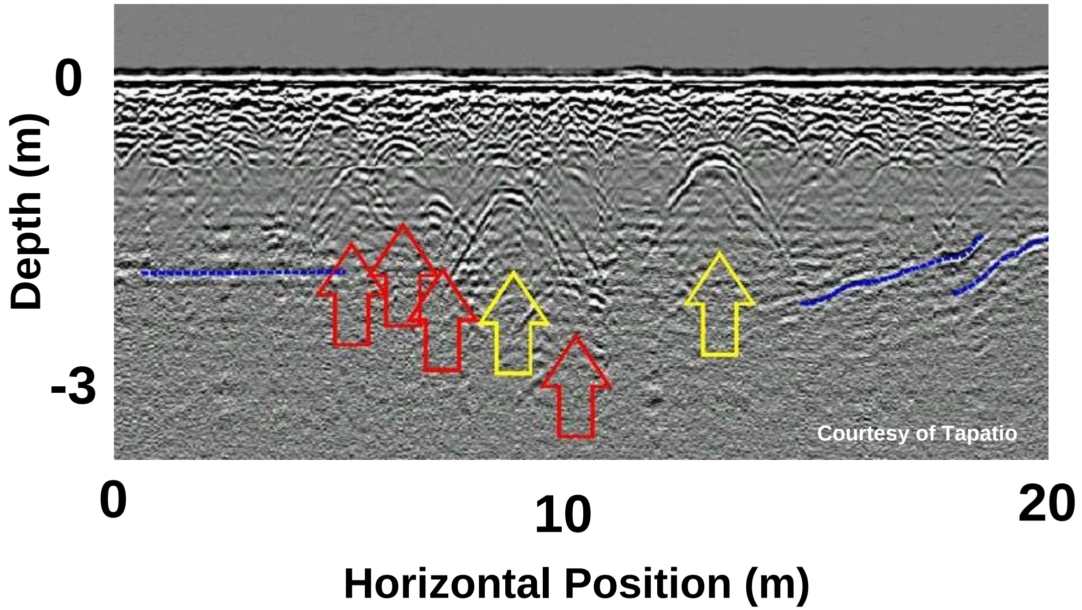
Ground Penetrating Radars

Ground Penetrating Radar (GPR)

Courtesy of seabird

Ground Penetrating Radar Data From Burial Ground



Range Instrumentation Radars


Courtesy of US Air Force


Courtesy of Lockheed Martin. Used with permission.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Military Radar Systems

Courtesy of US Air Force.


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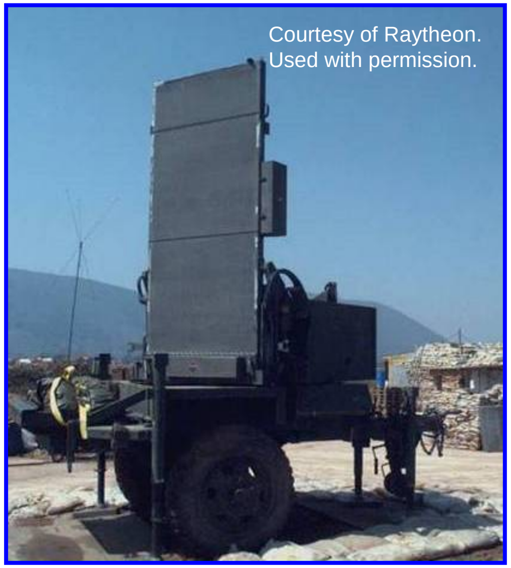
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Problems

- **A radar sends a short pulse of microwave electromagnetic energy directed towards the moon. Some of the energy scatters off of the moon's surface and returns to the radar. What is the round trip time? If the target was an aircraft 150 nmi. distant, what is the round trip time?**

- **A radar transmits a pulse of width of 2 microseconds. What is the closest 2 targets can be and still be resolved?**

- **You are traveling 75 mph in your new bright red Ferrari. A nearby policeman, using his hand held X-Band (frequency = 9,200 MHz) speed radar, transmits a CW signal from his radar, which then detects the Doppler shift of the echo from your car. Assuming that you are speeding directly towards his speed trap, how many Hz is the frequency of the received signal shifted by the Doppler effect? Is the Doppler shift positive or negative?**

Summary

- **As I hope you can see, we are going to cover a lot of ground in the course**

- **Good Luck in the journey !**

- **The next 2 lectures will be rather quick reviews of some topics that you should have facility with to get the most out of this course**
  - **First Review lecture**
    - **Electomagnetics**
  - **Second Review Lecture**
    - **Signals and Systems**
    - **Digital Signal Processing**

References

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