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

Iwo Jima
1945

Courtesy of National Archives.

Courtesy of US Marine Corp.
Pre-Radar Aircraft Detection – Optical Systems

• 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
Prevalence of Cloud Cover

ISCCP - Total Cloud Cover 1983-1990

Infrared and Optical Radiation Opaque to Clouds

Courtesy of NASA
Pre-Radar Aircraft Detection – Acoustic Systems

Japanese Acoustic Detection System

• 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 Wikimedia

Courtesy of US Army Signal Corps.
Sound Mirrors Dunge, Kent, UK

- 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!

- 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.

\[ \tau = \frac{2R}{c} \]
How Radar Works- The Short Answer!

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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 (1920s and 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

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

Courtesy of Massachusetts Institute of Technology
Courtesy of Department of Defense
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• The basics / the big picture

• Course overview
Chain Home Radar System
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 MIT Lincoln Laboratory
Used with permission

Courtesy of Robert Cromwell
Used with permission
Chain Home Radar System

Typical Chain Home Radar Site

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°
- Peak Power
  - 350 kW
- Detection Range
  - ~160 nmi on JU-88 German Bomber

Courtesy of MIT Lincoln Laboratory
Used with permission
Chain Home Transmit & Receive Antennas

Two Transmitter Towers

λ/2

360'

λ/2

One Receiver Tower

240'

215'

95'

45'

0'

Main Antenna

Gap Filler Antenna

Transmit Antenna

Receive Antenna

Courtesy of MIT Lincoln Laboratory
Used with permission
Chain Home Radar System

Receiver / Detection Operator

Goniometer

Chain Home Transmitter

Chain Home Receiver Hut

Courtesy of United Kingdom Government.

Courtesy of J M Briscoe
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

- 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)

- 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

Courtesy of MIT Lincoln Laboratory
Used with permission
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• The basics / the big picture

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V-1 “Buzz Bomb” – The Threat

V-1 Cruise Missile

**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

Courtesy of Ben pcc
Used with permission.
# The SCR 584 Fire-Control Radar

## SCR-584 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>10 cm (S-Band)</td>
</tr>
<tr>
<td>Frequency</td>
<td>3,000 MHz</td>
</tr>
<tr>
<td>Magnetron</td>
<td>2J32</td>
</tr>
<tr>
<td>Peak Power</td>
<td>250 kW</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>0.8μsec</td>
</tr>
<tr>
<td>PRF</td>
<td>1707 Hz</td>
</tr>
<tr>
<td>Antenna</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>6 ft</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>4°</td>
</tr>
<tr>
<td>Azimuth Coverage</td>
<td>360°</td>
</tr>
<tr>
<td>Maximum Range</td>
<td>40 mi</td>
</tr>
<tr>
<td>Range Accuracy</td>
<td>75 ft</td>
</tr>
<tr>
<td>Azimuth Accuracy</td>
<td>0.06°</td>
</tr>
<tr>
<td>Elevation Accuracy</td>
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![SCR-584](image_url)  

*Courtesy of Department of Defense*
The SCR 584 Fire-Control Radar

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

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°

Courtesy of MIT Lincoln Laboratory
Radar Proximity Fuze

Modern Radar Proximity Fuze

V-53 Radar Proximity Fuze (Cutaway)

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
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
Instrumentation Radars
Civil Radars
More Civil Radars

Courtesy of NASA

Courtesy of NASA

Courtesy of Raymarine. Used with permission.

Courtesy of NASA
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Pulsed Radar
Terminology and Concepts

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

Average power = Peak power \( \times \) Duty cycle

Pulse repetition frequency (PRF) = \( \frac{1}{(PRI)} \)

Continuous wave (CW) radar: Duty cycle = 100% (always on)
Pulsed Radar Terminology and Concepts

- **Power**
  - **Peak power**: 1 MW
  - **Target Return**: 1 μW

- **Time**
  - **Pulse length**: 100 μsec
  - **Pulse repetition interval (PRI)**: 1 msec

- **Duty cycle**
  \[
  \text{Duty cycle} = \frac{\text{Pulse length}}{\text{Pulse repetition interval}} = 10\%
  \]

- **Average power**
  \[
  \text{Average power} = \text{Peak power} \times \text{Duty cycle} = 100 \text{ kW}
  \]

- **Pulse repetition frequency (PRF)**
  \[
  \text{PRF} = \frac{1}{\text{PRI}} = 1 \text{ kHz}
  \]

- **Continuous wave (CW) radar**: Duty cycle = 100% (always on)
Radar Observables

Transmitted Signal: \( s_T(t) = A(t) \exp(j 2\pi f_0 t) \)

Received Signal: \( s_R(t) = \alpha A(t - \tau) \exp[j 2\pi (f_0 + f_D) t] \)

- **Amplitude**: Depends on RCS, radar parameters, range, etc.
- **Angle**: Azimuth and Elevation
- **Time Delay**: \( \tau = \frac{2R_0}{c} \)
- **Doppler Frequency**: \( f_D = \frac{2Vf_0}{c} = \frac{2V}{\lambda} \)

\[ R(t) = R_0 - Vt \]
This peak leaves antenna at time \( t = 0 \), when aircraft at \( R_0 \)

- The peak A arrives at target at time \( \Delta t \)
- Aircraft moving with radial velocity \( V \)
- The period of the transmit pulse is \( T \), and \( f_0 = 1/T \) and \( c = \frac{\lambda}{T} = \lambda f_0 \)

- Note: \( c \Delta t = R_0 - V \Delta t \) or \( \Delta t = \frac{R_0}{c + V} \)

- Time when peak A arrives back at radar \( t_A = \frac{2R_0}{c + V} \)

- Time when peak B arrives back at radar \( t_B = T + \frac{2(R_0 - VT)}{c + V} \)
Doppler Shift (continued)

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

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

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

- For $V \ll c$ then

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

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

**Radial Velocity**

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

+ Approaching targets
- Receding targets

Christian Andreas Doppler (1803 - 1853)
Radar Observables

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

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- **Amplitude**: Depends on RCS, radar parameters, range, etc.
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• Course overview
Block Diagram of Radar System

- **Transmitter**
  - Power Amplifier
  - Waveform Generation

- **Signal Processor Computer**
  - Pulse Compression
  - Clutter Rejection (Doppler Filtering)

- **General Purpose Computer**
  - Tracking
  - Parameter Estimation
  - Thresholding
  - Detection

- **User Displays and Radar Control**

- **Antenna**

- **Target Radar Cross Section**

- **Propagation Medium**

Photograph Image: Courtesy of US Air Force
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Radar Frequency Bands

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Allocated Frequency (GHz)</th>
<th>VHF</th>
<th>L-Band</th>
<th>S-Band</th>
<th>C-Band</th>
<th>X-Band</th>
<th>Millimeter Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>~2 m</td>
<td>~435 cm</td>
<td>~23 cm</td>
<td>~10 cm</td>
<td>~5.5 cm</td>
<td>~3 cm</td>
<td>Ku</td>
<td>K</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>Ka</td>
<td>W</td>
</tr>
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Microwave Band

Allocated Frequency (GHz)

Frequency (Hz)

Wavelength

Linear Scale

Logarithmic Scales

Millimeter Bands

Ku
K
Ka
W

Microwave
Radio
TV

Infra-red
Visible
Light

Ultraviolet

Gamma-rays

X-rays
Standard Radar Bands* & Typical Usage

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
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<tr>
<td>UHF</td>
<td>300 MHz – 1 GHz</td>
</tr>
<tr>
<td>VHF</td>
<td>30 – 100 MHz</td>
</tr>
<tr>
<td>HF</td>
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<tr>
<td>W-Band</td>
<td>40 – 100+ GHz</td>
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*From IEEE Standard 521-2002

Search Radars

[Image of ALTAIR and UEWR – Fylingsdales, UK]

Courtesy of MIT Lincoln Laboratory
Used with permission

Courtesy of spliced.GNU
### Standard Radar Bands & Typical Usage

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*From IEEE Standard 521-2002

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**C-Band**

MOTR MQP-39

**X-Band**

Haystack Radar

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Courtesy of MIT Lincoln Laboratory
Used with permission

Courtesy of Lockheed Martin
Used with permission

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Tracking Radars

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*From IEEE Standard 521-2002
## Standard Radar Bands* & Typical Usage

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### Search & Track Radars
- **L-Band**
  - TPS-77
  - Courtesy of Lockheed Martin
  - Used with permission.
- **S-Band**
  - AEGIS SPY-1
  - Courtesy of US MDA
  - Used with permission.
- **C-Band**
  - Patriot MPQ-53
  - Courtesy of US MDA
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*From IEEE Standard 521-2002
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*From IEEE Standard 521-2002

![Missile Seekers](image)

Courtesy of US Army. Used with permission.
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Photo: Reagan Test Site, Kwajalein

Courtesy of MIT Lincoln Laboratory

Used with permission.
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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

• 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**
- Pulsed CW
- Frequency Modulated CW
- Phase Coded
- Pseudorandom Coded

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

**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
- Solid State
- Synthetic Aperture (SAR)
- MTI
- GMTI

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

---

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Introduction 10/1/2009
Classification Systems for Radars

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- FPS-85
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- TPQ-37
- MPQ-64

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- Phased Array (ESA)
- Hybrid-Scan

By Range
- Long Range
- Medium Range
- Short Range

By Frequency
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- UHF-Band
- L-Band
- S-Band
- C-Band
- X-Band
- Ku-Band
- Ka-Band
- Other
- Solid State
- Synthetic Aperture (SAR)
- MTI
- 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
## Joint Electronic-Type Designation System

<table>
<thead>
<tr>
<th>First Letter</th>
<th>Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Piloted Aircraft</td>
</tr>
<tr>
<td>B</td>
<td>Underwater Mobile (submarine)</td>
</tr>
<tr>
<td>D</td>
<td>Pilotless Carrier</td>
</tr>
<tr>
<td>F</td>
<td>Fixed Ground</td>
</tr>
<tr>
<td>G</td>
<td>General Ground Use</td>
</tr>
<tr>
<td>K</td>
<td>Amphibious</td>
</tr>
<tr>
<td>M</td>
<td>Ground Mobile</td>
</tr>
<tr>
<td>P</td>
<td>Human Portable</td>
</tr>
<tr>
<td>S</td>
<td>Water (surface ship)</td>
</tr>
<tr>
<td>T</td>
<td>Transportable (ground)</td>
</tr>
<tr>
<td>U</td>
<td>General Utility (multi use)</td>
</tr>
<tr>
<td>V</td>
<td>Vehicle (ground)</td>
</tr>
<tr>
<td>W</td>
<td>Water Surface and Underwater combined</td>
</tr>
<tr>
<td>Z</td>
<td>Piloted/Pilotless Airborne</td>
</tr>
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</table>

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

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

Highlighted in blue italics are typical radar Installations and Purposes AN/XYZ-1 or XYZ-1
## Joint Electronic-Type Designation System

<table>
<thead>
<tr>
<th>First Letter</th>
<th>Second Letter</th>
<th>Third letter</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>Type of Equipment</td>
<td>Purpose</td>
<td>AN/TPS-43 or TPS-43</td>
</tr>
<tr>
<td>A - Piloted Aircraft</td>
<td>A - Invisible Light, Infrared</td>
<td>A - Auxiliary Assembly</td>
<td></td>
</tr>
<tr>
<td>B - Underwater Mobile (submarine)</td>
<td>C - Carrier (electronic wave or signal)</td>
<td>B - Bombing</td>
<td></td>
</tr>
<tr>
<td>D - Pilotless Carrier</td>
<td>D - Radiac (Radioactivity Detection, ID, and Computation)</td>
<td>C - Communications (two way)</td>
<td></td>
</tr>
<tr>
<td>F - Fixed Ground</td>
<td>E - Laser</td>
<td>D - Direction Finding, Reconnaissance and Surveillance</td>
<td></td>
</tr>
<tr>
<td>G - General Ground Use</td>
<td>F - Fiber Optics</td>
<td>E - Ejection and/or Release</td>
<td></td>
</tr>
<tr>
<td>K - Amphibious</td>
<td>G - Telegraph or Teletype</td>
<td>G - Fire Control or Searchlight Directing</td>
<td></td>
</tr>
<tr>
<td>M - Ground Mobile</td>
<td>I - Interphone and Public Address</td>
<td>H - Recording and/or Reproducing</td>
<td></td>
</tr>
<tr>
<td>P - Human Portable</td>
<td>J - Electromechanical or inertial wire covered</td>
<td>K - Computing</td>
<td></td>
</tr>
<tr>
<td>S - Water (surface ship)</td>
<td>K - Telemetering</td>
<td>L - no longer used.</td>
<td></td>
</tr>
<tr>
<td>T - Transportable (ground)</td>
<td>L - Countermeasures</td>
<td>M - Maintenance or Test</td>
<td></td>
</tr>
<tr>
<td>U - General Utility (multi use)</td>
<td>M - Meteorological</td>
<td>P - no longer used.</td>
<td></td>
</tr>
<tr>
<td>V - Vehicle (ground)</td>
<td>N - Sound in Air</td>
<td>Q - Special or Combination</td>
<td></td>
</tr>
<tr>
<td>W - Water Surface and Underwater combined</td>
<td>P - Radar</td>
<td>R - Receiving or Passive Detecting</td>
<td></td>
</tr>
<tr>
<td>Z - Piloted/Pilotless Airborne</td>
<td>Q - Sonar and Underwater Sound</td>
<td>S - Detecting, Range and Bearing, Search</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R - Radio</td>
<td>T - Transmitting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S - Special or Combination</td>
<td>W - Automatic Flight or Remote Control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T - Telephone (Wire)</td>
<td>X - Identification or Recognition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V - Visual, Visible Light</td>
<td>Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W - Armament (not otherwise covered)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X - Fax or Television</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y - Data Processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z - Communications</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Installation** - T – Transportable (ground)

**Equipment Type** - P - Radar

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

Courtesy of US Air Force
## Joint Electronic-Type Designation System

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<thead>
<tr>
<th>First Letter</th>
<th>Second Letter</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>Type of Equipment</td>
<td>Purpose</td>
<td>AN/FPS-16 or FPS-16</td>
</tr>
<tr>
<td>A - Piloted Aircraft</td>
<td>A - Invisible Light, Infrared</td>
<td>A - Auxiliary Assembly</td>
<td>Installation - F – Fixed Ground</td>
</tr>
<tr>
<td>B - Underwater Mobile (submarine)</td>
<td>C - Carrier (electronic wave or signal)</td>
<td>B - Bombing</td>
<td>Equipment Type - P - Radar</td>
</tr>
<tr>
<td>D - Pilotless Carrier</td>
<td>D - Radiac (Radioactivity Detection, ID, and Computation)</td>
<td>C - Communications (two way)</td>
<td>Purpose - S – Detecting and/or range, and bearing, search</td>
</tr>
<tr>
<td>F - Fixed Ground</td>
<td>E - Laser</td>
<td>D - Direction Finding, Reconnaissance and Surveillance</td>
<td></td>
</tr>
<tr>
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<td>K - Amphibious</td>
<td>G - Telegraph or Teletype</td>
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<tr>
<td>M - Ground Mobile</td>
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<tr>
<td>P - Human Portable</td>
<td>J - Electromechanical</td>
<td>K - Computing</td>
<td></td>
</tr>
<tr>
<td>S - Water (surface ship)</td>
<td>or inertial wire covered</td>
<td>L - no longer used.</td>
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<tr>
<td>T - Transportable (ground)</td>
<td>K - Telemetering</td>
<td>M - Maintenance or Test</td>
<td></td>
</tr>
<tr>
<td>U - General Utility (multi use)</td>
<td>L - Countermeasures</td>
<td>P - no longer used.</td>
<td></td>
</tr>
<tr>
<td>V - Vehicle (ground)</td>
<td>M - Meteorological</td>
<td>Q - Special or Combination</td>
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</tr>
<tr>
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<td>S - Detecting, Range and Bearing, Search</td>
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<tr>
<td></td>
<td>Q - Sonar and Underwater Sound</td>
<td>T - Transmitting</td>
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</tr>
<tr>
<td></td>
<td>R - Radio</td>
<td>W - Automatic Flight or Remote Control</td>
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<td></td>
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<td>X - Identification or Recognition</td>
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<tr>
<td></td>
<td>T - Telephone (Wire)</td>
<td>Y - Surveillance (target detecting and tracking) and Control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V - Visual, Visible Light</td>
<td>(fire control and/or air control)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W - Armament (not otherwise covered)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X - Fax or Television</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Y - Data Processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z - Communications</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example: AN/FPS-16 or FPS-16

Installation - F – Fixed Ground

Equipment Type - P - Radar

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

[Image of a radar system] Courtesy of US Air Force
### Joint Electronic-Type Designation System

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<tr>
<th>First Letter</th>
<th>Second Letter</th>
<th>Third letter</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>Type of Equipment</td>
<td>Purpose</td>
<td>AN/SPY-1 or SPY-1 (a.k.a. AEGIS)</td>
</tr>
<tr>
<td>A - Piloted Aircraft</td>
<td>A - Invisible Light, Infrared)</td>
<td>A - Auxiliary Assembly</td>
<td>Installation - S – Water (Surface Ship)</td>
</tr>
<tr>
<td>B - Underwater Mobile</td>
<td>C - Carrier (electronic wave or signal)</td>
<td>B - Bombing</td>
<td>Equipment Type - P - Radar</td>
</tr>
<tr>
<td>(submarine)</td>
<td>D - Radiac (Radioactivity Detection, ID, and Computation)</td>
<td>C - Communications (two way)</td>
<td>Purpose - Y – Surveillance and Control (fire control and air control)</td>
</tr>
<tr>
<td>D - Pilotless Carrier</td>
<td>E - Laser</td>
<td>D - Direction Finding, Reconnaissance and Surveillance</td>
<td></td>
</tr>
<tr>
<td>F - Fixed Ground</td>
<td>F - Fiber Optics</td>
<td>E - Ejection and/or Release</td>
<td></td>
</tr>
<tr>
<td>G - General Ground Use</td>
<td>G - Telegraph or Teletype</td>
<td>G - Fire Control or Searchlight Directing</td>
<td></td>
</tr>
<tr>
<td>K - Amphibious</td>
<td>H - Interphone and Public Address</td>
<td>H - Recording and/or Reproducing</td>
<td></td>
</tr>
<tr>
<td>M - Ground Mobile</td>
<td>J - Electromechanical or inertial wire covered</td>
<td>K - Computing</td>
<td></td>
</tr>
<tr>
<td>P - Human Portable</td>
<td>K - Telemetering</td>
<td>L - no longer used.</td>
<td></td>
</tr>
<tr>
<td>S - Water (surface ship)</td>
<td>L - Countermeasures</td>
<td>M - Maintenance or Test</td>
<td></td>
</tr>
<tr>
<td>T - Transportable (ground)</td>
<td>M - Meteorological</td>
<td>N - Navigation Aid</td>
<td></td>
</tr>
<tr>
<td>U - General Utility (multi use)</td>
<td>N - Sound in Air</td>
<td>P - no longer used.</td>
<td></td>
</tr>
<tr>
<td>V - Vehicle (ground)</td>
<td>P - Radar</td>
<td>Q - Special or Combination</td>
<td></td>
</tr>
<tr>
<td>W - Water Surface and Underwater combined</td>
<td>Q - Sonar and Underwater Sound</td>
<td>R - Receiving or Passive Detecting</td>
<td></td>
</tr>
<tr>
<td>Z - Piloted/Pilotless Airborne</td>
<td>R - Radio</td>
<td>S - Detecting, Range and Bearing, Search</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S - Special or Combination</td>
<td>T - Transmitting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T - Telephone (Wire)</td>
<td>W - Automatic Flight or Remote Control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V - Visual, Visible Light</td>
<td>X - Fax or Television</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>Y - Data Processing</td>
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</tr>
<tr>
<td></td>
<td>X - Identification or Recognition</td>
<td>Z - Communications</td>
<td></td>
</tr>
</tbody>
</table>
### Joint Electronic-Type Designation System

<table>
<thead>
<tr>
<th>First Letter</th>
<th>Second Letter</th>
<th>Third Letter</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>Type of Equipment</td>
<td>Purpose</td>
<td>AN/MPQ-64 or MPQ-64 (a.k.a. Sentinel)</td>
</tr>
<tr>
<td>A - Piloted Aircraft</td>
<td>A - Invisible Light, Infrared</td>
<td>A - Auxiliary Assembly</td>
<td>Installation - M – Ground, Mobile</td>
</tr>
<tr>
<td>B - Underwater Mobile (submarine)</td>
<td>C - Carrier (electronic wave or signal)</td>
<td>B - Bombing</td>
<td>Equipment Type - P - Radar</td>
</tr>
<tr>
<td>D - Pilotless Carrier</td>
<td>D - Radiac (Radioactivity Detection, ID, and Computation)</td>
<td>C - Communications (two way)</td>
<td>Purpose - Q – Special or Combination of Purposes</td>
</tr>
<tr>
<td>F - Fixed Ground</td>
<td>E - Laser</td>
<td>D - Direction Finding, Reconnaissance and Surveillance</td>
<td></td>
</tr>
<tr>
<td>G - General Ground Use</td>
<td>F - Fiber Optics</td>
<td>E - Ejection and/or Release</td>
<td></td>
</tr>
<tr>
<td>K - Amphibious</td>
<td>G - Telegraph or Teletype</td>
<td>G - Fire Control or Searchlight Directing</td>
<td></td>
</tr>
<tr>
<td>M - Ground Mobile</td>
<td>I - Interphone and Public Address or Inertial Wire Covered</td>
<td>H - Recording and/or Reproducing</td>
<td></td>
</tr>
<tr>
<td>P - Human Portable</td>
<td>J - Electromechanical Telemetering</td>
<td>K - Computing</td>
<td></td>
</tr>
<tr>
<td>S - Water (surface ship)</td>
<td>L - Countermeasures</td>
<td>L - no longer used.</td>
<td></td>
</tr>
<tr>
<td>T - Transportable (ground)</td>
<td>M - Meteorological</td>
<td>M - Maintenance or Test</td>
<td></td>
</tr>
<tr>
<td>U - General Utility (multi use)</td>
<td>N - Sound in Air</td>
<td>P - no longer used.</td>
<td></td>
</tr>
<tr>
<td>V - Vehicle (ground)</td>
<td>P - Radar</td>
<td>Q - Special or Combination</td>
<td></td>
</tr>
<tr>
<td>W - Water Surface and Underwater combined</td>
<td>Q - Sonar and Underwater Sound</td>
<td>R - Receiving or Passive Detecting</td>
<td></td>
</tr>
<tr>
<td>Z - Piloted/Pilotless Airborne</td>
<td>R - Radio</td>
<td>S - Detecting, Range and Bearing, Search</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S - Special or Combination</td>
<td>T - Transmitting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T - Telephone (Wire)</td>
<td>W - Automatic Flight or Remote Control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V - Visual, Visible Light</td>
<td>X - Identification or Recognition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W – Armament (not otherwise covered)</td>
<td>Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X - Fax or Television</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y - Data Processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z - Communications</td>
<td></td>
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</tr>
</tbody>
</table>

*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

Maxwell’s Equations

Integral Form
\[ \iiint \vec{D} \cdot d\vec{S} = \iiint \rho \, dV \]
\[ \iiint \vec{B} \cdot d\vec{S} = 0 \]
\[ \oint \vec{E} \cdot d\vec{s} = -\iiint \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} \]
\[ \oint \vec{H} \cdot d\vec{s} = \iiint \left( \frac{\partial \vec{D}}{\partial t} + \vec{J} \right) \cdot d\vec{S} \]

Differential Form
\[ \nabla \cdot \vec{D} = 4\pi \rho \]
\[ \nabla \cdot \vec{B} = 0 \]
\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]
\[ \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \]

Plane Wave Solution
- **No Sources**
- **Vacuum**
- **Non-Conducting Medium**

\[ \vec{E}(\vec{r}, t) = E_0 e^{i(k \cdot \vec{r} - j\omega t)} \]
\[ \vec{B}(\vec{r}, t) = B_0 e^{i(k \cdot \vec{r} - j\omega t)} \]

Electric Field

Magnetic Field
Continuous-time System
\[ x(t) \]

Discrete-time System
\[ x[n] \]

Discrete Fourier Transform (DFT)
\[ X(\omega) = \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega n} \]

\[ x(t) \rightarrow \text{Continuous Linear Time Invariant System} \rightarrow y(t) \]
\[ y(t) = \int_{-\infty}^{\infty} x(\tau) h(t - \tau) d\tau \]

\[ x[n] \rightarrow \text{Discrete Linear Time Invariant System} \rightarrow y[n] \]
\[ y[n] = \sum_{k=-\infty}^{\infty} x[n - k] h[k] \]

Other Topics
- Fast Fourier Transform (FFT)
- Convolution
- Sampling Theorem - Aliasing
- Digital Filters
  - Low pass, High Pass, Transversal
- Filter Weighting
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

- Received Power
- Range (Time after Transmit Pulse)
- False Alarm Due to Noise
- Correctly Detected Target
- Missed Target Detection
- Noise Level
Radar Cross Section (RCS)

Radar Cross Section (RCS, or $\sigma$) is the effective cross-sectional area of the target as seen by the radar.

$$\text{Incident Power Density} \times \sigma = \text{Reflected Power}$$

Measured in $m^2$, or dBsm
Antennas – Fundamentals and Mechanical Scanning Techniques

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

Directional Antenna

ALTAIR Antenna

Courtesy of MIT Lincoln Laboratory
 Used with permission
Antennas – Electronic Scanning Techniques

Element Number

N

3

2

1

Scan Angle

Patriot Radar (MPQ-53)

AEGIS Radar (SPY-1)

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**

\[ T = \frac{1}{B} \]

\[ \Delta R = \frac{c}{2} \frac{T}{2} = \frac{c}{2B} \]

**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.
Radar Signal Processing I
Basics and MTI (Moving Target Indication) Techniques

Unprocessed Radar Backscatter

Two Pulse MTI Filter

Filter Input

\[ V_1, V_2, V_3, \ldots, V_N \]

Filter Output

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

Use low pass Doppler filter to suppress clutter backscatter

Radar A-Scope

Target

Target

Result of subtracting two successive pulses

Figure by MIT OCW.
Pulse Doppler Processing optimally rejects moving clutter with a number of pass band Doppler filters.
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.
• 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

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

Tracker Input

Tracker Output

Cross-Range

Range

Range

Courtesy of MIT Lincoln Laboratory
Used with permission
Transmitters

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

X-Band Traveling Wave Tube

Haystack Radar

PAVE PAWS UHF T/R Module

PAVE PAWS Radar

Courtesy of MIT Lincoln Laboratory. Used with permission.

Courtesy of Raytheon Used with permission.

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”

Radar Parameters

Power
Phased Array vs. Dish
Frequency
Aperture Size

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 m² 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

Courtesy of MIT Lincoln Laboratory
Used with permission
Synthetic Aperture Radar (SAR) Techniques

Spotlight Scan Mode

SAR Image of Golf Course

 Courtesy of MIT Lincoln Laboratory
Used with permission
Inverse Synthetic Aperture Radar (ISAR) Techniques

Photograph of Skylab

Simulated Range-Doppler Image of Skylab

Courtesy of NASA

Courtesy of MIT Lincoln Laboratory Used with permission
Over-the-Horizon Radars

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

Example
Relocatable OTH Radar (ROTHR)

 Courtesy of NOAA

 Courtesy of Raytheon.
Weather Radars

NEXRAD (aka WSR-88)  

Weather map for Hurricane Bertha 1996

Courtesy of NOAA
Space Based Remote Sensing Radars

Magellan Radar

SAR Map of Venus

Courtesy of NASA

Courtesy of NASA
Air Traffic Control & Other Civil Radars

[Images with captions: Courtesy of Target Corporation, Courtesy of FAA, Courtesy of neonbubble, Courtesy of Northrop Grumman. Used with permission.]
Ground Penetrating Radars (GPR)

Courtesy of seabird

Ground Penetrating Radar Data From Burial Ground

Horizontal Position (m)

Depth (m)

0
-3
0
10
20

Courtesy of Tapatio
Range Instrumentation Radars

- Courtesy of US Air Force
- Courtesy of Lockheed Martin. Used with permission.
- Courtesy of MIT Lincoln Laboratory. Used with permission.
Military Radar Systems
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
    Electromagnetics
  – Second Review Lecture
    Signals and Systems
    Digital Signal Processing
References