Radar Systems Engineering
Lecture 7 – Part 1
Radar Cross Section

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IEEE New Hampshire Section
Guest Lecturer
This lecture

Block Diagram of Radar System

Transmitter
- Power Amplifier
- Waveform Generation
- T / R Switch

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

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

User Displays and Radar Control

Data Recording

Target Radar Cross Section

Propagation Medium

Antenna

Receiver
- A / D Converter

IEEE New Hampshire Section
IEEE AES Society

Radar Systems Course
Radar Cross Section 1/1/2010

Photo Image
Courtesy of US Air Force
Used with permission.
Radar Cross Section (RCS) is the hypothetical area, that would intercept the incident power at the target, which if scattered isotropically, would produce the same echo power at the radar, as the actual target.

\[
\text{RCS} = \lim_{r \to \infty} 4\pi r^2 \frac{|E_s|^2}{|E_i|^2}
\]

(Unit: Area)

Figure by MIT OCW.
Factors Determining RCS

- Target, size, shape, material, orientation
- Scattering Direction (Bistatic)
- Far-Field
- Near-Field
- Monostatic
- Polarization
- Frequency

Figure by MIT OCW.
Threat’s View of the Radar Range Equation

Radar Range Equation

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

- Transmit Power \( P_t \)
- Antenna Gain \( G \)
- Target Cross Section \( \sigma \)
- Distance from Radar to Target \( R \)
- Cannot Control
  - Transmit Power \( P_t \)
  - Target Cross Section \( \sigma \)
- Can Control
  - Antenna Gain \( G \)
  - Bandwidth \( B_n \)
  - Detection Time \( T_S \)

Figure by MIT OCW.
• Radar cross section (RCS) of typical targets
  – Variation with frequency, type of target, etc.

• Physical scattering mechanisms and contributors to the RCS of a target

• Prediction of a target’s radar cross section
  – Measurement
  – Theoretical Calculation
Radar Cross Section of Artillery Shell

RCS vs. Aspect Angle of an Artillery Shell

Aspect Angle (degrees)

Radar Cross Section (dBsm)

0 20 40 60 80 100 120 140 160 180

0 -10 -20 -30 -40 -50 -60

Typical Artillery Shell

M107 Shell for 155mm Howitzer

Courtesy US Marine Corps
Radar Cross Section of Cessna 150L

Measured at RATSCAT (6585th Test Group) Holloman AFB for FAA

Radar Cross Section (dBsm)

Aspect Angle (degrees)

Cessna 150L (in takeoff)  Cessna 150L (in flight)

S Band
V V
Polarization

Courtesy of Federal Aviation Administration

Scott Studio Photography with permission
Aspect Angle Dependence of RCS

Cone Sphere Re-entry Vehicle (RV) Example

-20 dBm^2
Reflectivity pattern
0 dBm^2
+20 dBm^2

Forward aspect $\sigma \approx 0.001 \text{ m}^2$

Rear aspect $\sigma \approx 0.75 \text{ m}^2$

Peak $\sigma \approx 100 \text{ m}^2$

Radar A sees 0.001 m^2
Radar B sees 0.75 m^2

Figure by MIT OCW.
## Examples of Radar Cross Sections

<table>
<thead>
<tr>
<th>Target Description</th>
<th>Square meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional winged missile</td>
<td>0.1</td>
</tr>
<tr>
<td>Small, single engine aircraft, or jet fighter</td>
<td>1</td>
</tr>
<tr>
<td>Four passenger jet</td>
<td>2</td>
</tr>
<tr>
<td>Large fighter</td>
<td>6</td>
</tr>
<tr>
<td>Medium jet airliner</td>
<td>40</td>
</tr>
<tr>
<td>Jumbo jet</td>
<td>100</td>
</tr>
<tr>
<td>Helicopter</td>
<td>3</td>
</tr>
<tr>
<td>Small open boat</td>
<td>0.02</td>
</tr>
<tr>
<td>Small pleasure boat (20-30 ft)</td>
<td>2</td>
</tr>
<tr>
<td>Cabin cruiser (40-50 ft)</td>
<td>10</td>
</tr>
<tr>
<td>Ship (5,000 tons displacement, L Band)</td>
<td>10,000</td>
</tr>
<tr>
<td>Automobile / Small truck</td>
<td>100 - 200</td>
</tr>
<tr>
<td>Bicycle</td>
<td>2</td>
</tr>
<tr>
<td>Man</td>
<td>1</td>
</tr>
<tr>
<td>Birds (large -&gt; medium)</td>
<td>10^{-2} - 10^{-3}</td>
</tr>
<tr>
<td>Insects (locust -&gt; fly)</td>
<td>10^{-4} - 10^{-5}</td>
</tr>
</tbody>
</table>

Radar Cross Sections of Targets Span at least 50 dB

Adapted from Skolnik, Reference 2
Outline

• Radar cross section (RCS) of typical targets
  – Variation with frequency, type of target, etc.

• Physical scattering mechanisms and contributors to the RCS of a target

• Prediction of a target’s radar cross section
  – Measurement
  – Theoretical Calculation
• Types of RCS Contributors
  – Structural (Body shape, Control surfaces, etc.)
  – Avionics (Altimeter, Seeker, GPS, etc.)
  – Propulsion (Engine inlets and exhausts, etc.)
Single and Multiple Frequency RCS Calculations with the FD-FD Technique

• **RCS Calculations for a Single Frequency**
  – Illuminate target with incident sinusoidal wave
  – Sequentially in time, update the electric and magnetic fields, until steady state conditions are met
  – The scattered wave’s amplitude and phase can the be calculated

• **RCS Calculations for a Multiple Frequencies**
  – Illuminate target with incident Gaussian pulse
  – Calculate the transient response
  – Calculate to Fourier transforms of both:
    - Incident Gaussian pulse, and
    - Transient response
  – RCS at multiple frequencies is calculated from the ratios of these two quantities
Scattering Mechanisms for an Arbitrary Target

- Curvature Discontinuity Return
- Tip Diffraction at Aircraft Nose
- Backscatter from Creeping Wave
- Multiple Reflection
- Gap, Seam, or Discontinuity Echo
- Specular Surface Reflection
- Edge Diffraction
- Wave Echo from Traveling Wave
- Diffraction from Engine Cavity
- Tip Diffraction from Fuel Tank
- Tip Diffraction at Aircraft Nose
- Return From Engine Cavity
Measured RCS of C-29 Aircraft Model

1/12 Scale Model Measurement

Full Scale C-29
BAE Hawker 125-800

RCS (dBsm)

Aspect Angle (degrees)

Fuselage Specular
Wing Leading Edge
X-Band HH Polarization Waterline Cut

Adapted from Atkins, Reference 5
Courtesy of MIT Lincoln Laboratory

Courtesy of Arpingstone
Outline

• Radar cross section (RCS) of typical targets
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Techniques for RCS Analysis

Full Scale Measurements

Scaled Model Measurements

Theoretical Prediction

Courtesy of MIT Lincoln Laboratory
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Full Scale Measurements

Target on Support

• Foam column mounting
  – Dielectric properties of Styrofoam close to those of free space

• Metal pylon mounting
  – Metal pylon shaped to reduce radar reflections
  – Background subtraction can be used

Derived from: http://www.af.mil/shared/media/photodb/photos/050805-F-0000S-003.jpg
Full Scale Measurement of Johnson Generic Aircraft Model (JGAM)

RATSCAT Outdoor Measurement Facility at Holloman AFB

Courtesy of MIT Lincoln Laboratory
Used with Permission

- VV Polarization
- ELEV = 7
- 9.67 GHz
Compact Range RCS Measurement

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

[Diagram showing a target with main reflector, feed antenna, sub-reflector, and plane wave]

Courtesy of U. S. Navy.
Scale Model Measurement

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

Full Scale
Measure at frequency $f$

Scale Factor $S$ (Reduced Size)

Subscale
Measure at frequency $S \times F$

Courtesy of MIT Lincoln Laboratory
Used with Permission
## Scaling of RCS of Targets

- **Scale Factor**: $S$

### Quantity | Full Scale | Subscale
--- | --- | ---
Length | $L$ | $L' = L / S$
Wavelength | $\lambda$ | $\lambda' = \lambda / S$
Frequency | $f$ | $f' = S \cdot f$
Time | $t$ | $t' = t / S$
Permittivity | $\varepsilon$ | $\varepsilon' = \varepsilon$
Permeability | $\mu$ | $\mu' = \mu$
Conductivity | $g$ | $g' = S \cdot g$
Radar Cross Section | $\sigma$ | $\sigma' = \sigma / S^2$
Outline

• Radar cross section (RCS) of typical targets
  – Variation with frequency, type of target, etc.

• Physical scattering mechanisms and contributors to the RCS of a target

• Prediction of a target’s radar cross section
  – Measurement
  – Theoretical Calculation
• **Introduction**
  - A look at the few simple problems

• **RCS prediction**
  - **Exact Techniques**
    - Finite Difference- Time Domain Technique (FD-TD)
    - Method of Moments (MOM)
  - **Approximate Techniques**
    - Geometrical Optics (GO)
    - Physical Optics (PO)
    - Geometrical Theory of Diffraction (GTD)
    - Physical Theory of Diffraction (PTD)

• **Comparison of different methodologies**
Radar Cross Section of Sphere

Rayleigh Region
\( \lambda >> a \)
\( \sigma = \frac{k}{\lambda^4} \)

Mie or Resonance Region
Oscillations
Backscattered wave interferes with creeping wave

Optical Region
\( \lambda << a \)
\( \sigma = \pi a^2 \)
Surface and edge scattering occur

\[
\frac{\text{Circumference}}{\text{wavelength}} = \frac{2\pi a}{\lambda}
\]
Radar Cross Section Calculation Issues

• Three regions of wavelength
  - Rayleigh \((\lambda >> a)\)
  - Mie / Resonance \((\lambda \sim a)\)
  - Optical \((\lambda << a)\)

• Other simple shapes
  - Examples: Cylinders, Flat Plates, Rods, Cones, Ogives
  - Some amenable to relatively straightforward solutions in some wavelength regions

• Complex targets:
  - Examples: Aircraft, Missiles, Ships
  - RCS changes significantly with very small changes in frequency and / or viewing angle
    
    See Ref. 6 (Levanon), problem 2-1 or Ref. 2 (Skolnik) page 57

• We will spend the rest of the lecture studying the different basic methods of calculating radar cross sections
## High Frequency RCS Approximations

(Simple Scattering Features)

<table>
<thead>
<tr>
<th>Scattering Feature</th>
<th>Orientation</th>
<th>Approximate RCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corner Reflector</td>
<td>Axis of symmetry along LOS</td>
<td>$4\pi \frac{A_{\text{eff}}^2}{\lambda^2}$</td>
</tr>
<tr>
<td>Flat Plate</td>
<td>Surface perpendicular to LOS</td>
<td>$4\pi \frac{A^2}{\lambda^2}$</td>
</tr>
<tr>
<td>Singly Curved Surface</td>
<td>Surface perpendicular to LOS</td>
<td>$4\pi \frac{A^2}{\lambda^2}$</td>
</tr>
<tr>
<td>Doubly Curved Surface</td>
<td>Surface perpendicular to LOS</td>
<td>$\pi a_1 a_2$</td>
</tr>
<tr>
<td>Straight Edge</td>
<td>Edge perpendicular to LOS</td>
<td>$\frac{\lambda^2}{\pi}$</td>
</tr>
<tr>
<td>Curved Edge</td>
<td>Edge element perpendicular to LOS</td>
<td>$a \frac{\lambda}{2}$</td>
</tr>
<tr>
<td>Cone Tip</td>
<td>Axial incidence</td>
<td>$\lambda^2 \sin^4(\alpha/2)$</td>
</tr>
</tbody>
</table>

Where:  
- LOS = line of sight  
- $A_{\text{eff}}$ = effective area contributing to multiple internal reflections  
- $A$ = actual area of plate  
- $a$ = mean radius of curvature; $L$ = length of slanted surface  
- $a_1$ and $a_2$ = principal radii of surface curvature in orthogonal planes  
- $L$ = edge length  
- $a$ = radius of edge contour  
- $\alpha$ = half angle of the cone

Adapted from Knott is Skolnik Reference 3
Radar Cross Section Calculation Issues

• Three regions of wavelength
  Rayleigh \((\lambda >> a)\)
  Mie / Resonance \((\lambda \sim a)\)
  Optical \((\lambda << a)\)

• Other simple shapes
  – Examples: Cylinders, Flat Plates, Rods, Cones, Ogives
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RCS Calculation - Overview

- Electromagnetism Problem
  - A plane wave with electric field, $\vec{E}_1$, impinges on the target of interest and some of the energy scatters back to the radar antenna
  - Since, the radar cross section is given by: $\sigma = \lim_{r \to \infty} 4\pi r^2 \left( \frac{|E_s|^2}{|E_1|^2} \right)$
  - All we need to do is use Maxwell’s Equations to calculate the scattered electric field $\vec{E}_s$
  - That’s easier said that done
  - Before we examine in detail these different techniques, let’s review briefly the necessary electromagnetism concepts and formulae, in the next few viewgraphs
Maxwell’s Equations

• Source free region of space:

\[ \nabla \times \vec{E}(\vec{r}, t) = -\frac{\partial \vec{B}(\vec{r}, t)}{\partial t} \]

\[ \nabla \times \vec{H}(\vec{r}, t) = \frac{\partial \vec{D}(\vec{r}, t)}{\partial t} \]

\[ \nabla \cdot \vec{D}(\vec{r}, t) = 0 \]

\[ \nabla \cdot \vec{B}(\vec{r}, t) = 0 \]

• Free space constitutive relations:

\[ \vec{D}(\vec{r}, t) = \varepsilon_0 \vec{E}(\vec{r}, t) \quad \varepsilon_0 = \text{Free space permittivity} \]

\[ \vec{B}(\vec{r}, t) = \mu_0 \vec{H}(\vec{r}, t) \quad \mu_0 = \text{Free space permeability} \]
• Source free region:

\[ \nabla \times \vec{E}(\vec{r}) = i \omega \vec{B}(\vec{r}) \]
\[ \nabla \times \vec{H}(\vec{r}) = -i \omega \vec{D}(\vec{r}) \]
\[ \nabla \cdot \vec{D}(\vec{r}) = 0 \]
\[ \nabla \cdot \vec{B}(\vec{r}) = 0 \]

• Time dependence

\[ \vec{E}(\vec{r}, t) = \text{Re} \left\{ \vec{E}(\vec{r}) e^{-i\omega t} \right\} \]
\[ \vec{H}(\vec{r}, t) = \text{Re} \left\{ \vec{H}(\vec{r}) e^{-i\omega t} \right\} \]
Boundary Conditions

Medium 1  \( \mu_1 \)  \( \varepsilon_1 \)  \( \hat{n} \)  \( \vec{E}_1 \)  \( \vec{H}_1 \)  

Medium 2  \( \mu_2 \)  \( \varepsilon_2 \)  

- Tangential components of \( \vec{E} \) and \( \vec{H} \) are continuous:
  \[
  \hat{n} \times \vec{E}_1 = \hat{n} \times \vec{E}_2 \\
  \hat{n} \times \vec{H}_1 = \hat{n} \times \vec{H}_2
  \]

- For surfaces that are perfect conductors:
  \[
  \hat{n} \times \vec{E} = 0
  \]

- Radiation condition:
  \[
  \text{As } r \to \infty \quad \vec{E}(\vec{r}) \propto \frac{1}{r}
  \]
Scattering Matrix

• For a linear polarization basis

\[ \vec{E}_S = \left[ \begin{array}{c} \frac{E_{VS}}{E_{HS}} \\ e^{ikr}r S_{VV} & S_{VH} \\ S_{HV} & S_{HH} \end{array} \right] \begin{bmatrix} E_{VI} \\ E_{HI} \end{bmatrix} \]

• The incident field polarization is related to the scattered field polarization by this Scattering Matrix - \( S \)

\[ \sigma_{VV} = 4\pi \left| S_{VV} \right|^2 \]
\[ \sigma_{HH} = 4\pi \left| S_{HH} \right|^2 \]
\[ \sigma_{VH} = 4\pi \left| S_{VH} \right|^2 \]

• For and a reciprocal medium and for monostatic radar cross section:

\[ \sigma_{RR}, \sigma_{LL}, \sigma_{RL} \]

• For a circular polarization basis

\[ \sigma_{VH} = \sigma_{HV} \]
Radar Cross Section Calculation Methods

• Introduction
  – A look at the few simple problems

• RCS prediction
  – Exact Techniques
    Finite Difference- Time Domain Technique (FD-TD)
    Method of Moments (MOM)
  – Approximate Techniques
    Geometrical Optics (GO)
    Physical Optics (PO)
    Geometrical Theory of Diffraction (GTD)
    Physical Theory of Diffraction (PTD)

• Comparison of different methodologies
## Methods of Radar Cross Section Calculation

<table>
<thead>
<tr>
<th>RCS Method</th>
<th>Approach to Determine Surface Currents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Finite Difference-Time Domain (FD-TD)</strong></td>
<td>Solve Differential Form of Maxwell’s Equation’s for Exact Fields</td>
</tr>
<tr>
<td><strong>Method of Moments (MoM)</strong></td>
<td>Solve Integral Form of Maxwell’s Equation’s for Exact Currents</td>
</tr>
<tr>
<td><strong>Geometrical Optics (GO)</strong></td>
<td>Current Contribution Assumed to Vanish Except at Isolated Specular Points</td>
</tr>
<tr>
<td><strong>Physical Optics (PO)</strong></td>
<td>Currents Approximated by Tangent Plane Method</td>
</tr>
<tr>
<td><strong>Geometrical Theory of Diffraction (GTD)</strong></td>
<td>Geometrical Optics with Added Edge Current Contribution</td>
</tr>
<tr>
<td><strong>Physical Theory of Diffraction (PTD)</strong></td>
<td>Physical Optics with Added Edge Current Contribution</td>
</tr>
</tbody>
</table>
Finite Difference- Time Domain (FD-TD) Overview

• Exact method for calculation radar cross section

• Solve differential form of Maxwell’s equations
  – The change in the E field, in time, is dependent on the change in the H field, across space, and visa versa

• The differential equations are transformed to difference equations
  – These difference equations are used to sequentially calculate the E field at one time and the use those E field calculations to calculate H field at an incrementally greater time; etc. etc.
    Called “Marching in Time”

• These time stepped E and H field calculations avoid the necessity of solving simultaneous equations

• Good approach for structures with varying electric and magnetic properties and for cavities
Maxwell’s Equations in Rectangular Coordinates

- Examine 2 D problem – no y dependence: \( \frac{\partial}{\partial y} = 0 \)

- Equations decouple into H-field polarization and E-field polarization

\[
\begin{align*}
\frac{\partial}{\partial y} H_z - \frac{\partial}{\partial z} H_y &= \varepsilon_0 \frac{\partial}{\partial t} E_x \\
\frac{\partial}{\partial z} E_x - \frac{\partial}{\partial x} E_z &= -\mu_0 \frac{\partial}{\partial t} H_y \\
\frac{\partial}{\partial x} H_y - \frac{\partial}{\partial y} H_x &= \varepsilon_0 \frac{\partial}{\partial t} E_z
\end{align*}
\]

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\]

- H-field polarization
  \( H_y \quad E_x \quad E_z \)

- E-field polarization
  \( E_y \quad H_x \quad H_z \)
Maxwell’s Equations in Rectangular Coordinates

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  \( H_y \quad E_x \quad E_z \)

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\end{align*}
\]

- E-field polarization
  \( E_y \quad H_x \quad H_z \)
Discrete Form of Maxwell’s Equations

• H-field polarization:

\[ -\mu_0 \frac{\partial}{\partial t} H_y(x,y,t) = \frac{\partial}{\partial z} E_x(x,y,t) \]

\[ -\frac{\partial}{\partial x} E_z(x,y,t) \]

• Discrete form:

\[ -\frac{\mu_0}{\Delta T} \left[ H_y \left( x_0 + \frac{\Delta x}{2}, z_0 + \frac{\Delta z}{2}, t_0 + \frac{\Delta t}{2} \right) - H_y \left( x_0 + \frac{\Delta x}{2}, z_0 + \frac{\Delta z}{2}, t_0 - \frac{\Delta t}{2} \right) \right] \]

\[ = \frac{1}{\Delta z} \left[ E_x \left( x_0 + \frac{\Delta x}{2}, z_0 + \Delta z, t_0 \right) - E_x \left( x_0 + \frac{\Delta x}{2}, z_0, t_0 \right) \right] \]

\[ - \frac{1}{\Delta x} \left[ E_z \left( x_0 + \Delta x, z_0 + \frac{\Delta z}{2}, t_0 \right) - E_z \left( x_0, z_0 + \frac{\Delta z}{2}, t_0 \right) \right] \]

• Electric and magnetic fields are calculated alternately by the marching in time method
Absorbing Boundary Condition (ABC) Used to Limit Computational Domain

- Reflections at exterior boundary are minimized
- Traditional ABC’s model field as outgoing wave to estimate field quantities outside domain
- More recent perfectly matched layer (PML) model uses non-physical layer, that absorbs waves
RCS Calculations Using the FD-TD Method

• Single frequency RCS calculations
  – Excite with sinusoidal incident wave
  – Run computation until steady state is reached
  – Calculate amplitude and phase of scattered wave

• Multiple frequency RCS calculations
  – Excite with Gaussian pulse incident wave
  – Calculate transient response
  – Take Fourier transform of incident pulse and transient response
  – Calculate ratios of these transforms to obtain RCS at multiple frequencies

From Atkins, Reference 5
Courtesy of MIT Lincoln Laboratory
Description of Scattering Cases on Video

Finite Difference Time Domain (FDTD) Simulations

Case 1 – Plate I

Case 2 – Plate II

Case 3 – Plate III

Case 4 – Cylinder I

Case 5 – Cylinder II

Case 6 – Cavity

Courtesy of MIT Lincoln Laboratory Used with Permission
FD-TD Simulation of Scattering by Strip

Case 1

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

Courtesy of MIT Lincoln Laboratory
Used with Permission
FD-TD Simulation of Scattering by Strip

Case 1

Courtesy of
MIT Lincoln Laboratory
Used with Permission
Case 5

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

Courtesy of
MIT Lincoln Laboratory
Used with Permission
Case 5

Courtesy of MIT Lincoln Laboratory
Used with Permission
Backscatter of Short Pulse from Sphere

The figure illustrates the backscatter of a short pulse from a sphere, showing the electric field as a function of distance from the sphere.

- **Specular Return**
  - $\sigma / \lambda^2 = 3.14$

- **Creeping Wave Return**
  - $\sigma / \lambda^2 = 0.059$

The radius of the sphere is equal to the radar wavelength.

Figure by MIT OCW.