Radar Systems Engineering
Lecture 8
Antennas
Part 1 - Basics and Mechanical Scanning

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Guest Lecturer
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

Data Recording

Target Radar Cross Section
Antenna

Propagation Medium

Transmitter Components
- T/R Switch

Receiver

A/D Converter

Clutter Rejection (Doppler Filtering)

IEEE New Hampshire Section
IEEE AES Society
• “Means for radiating or receiving radio waves”*
  – A radiated electromagnetic wave consists of electric and magnetic fields which jointly satisfy Maxwell’s Equations
• Direct microwave radiation in desired directions, suppress in others
• Designed for optimum gain (directivity) and minimum loss of energy during transmit or receive

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

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

\[G = \text{Gain}\]
\[A_e = \text{Effective Area}\]
\[T_s = \text{System Noise Temperature}\]
\[L = \text{Losses}\]

Radar Antennas Come in Many Sizes and Shapes

Electronic Scanning Antenna

Mechanical Scanning Antenna

Hybrid Mechanical and Frequency Scanning Antenna

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Outline

- Introduction
- Antenna Fundamentals
- Reflector Antennas – Mechanical Scanning
- Phased Array Antennas
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics
Outline

• Introduction

• Antenna Fundamentals
  – Basic Concepts
  – Field Regions
    Near and far field
  – Electromagnetic Field Equations
  – Polarization
  – Antenna Directivity and Gain
  – Antenna Input Impedance

• Reflector Antennas – Mechanical Scanning
Tree of Antenna Types

Adapted from Kraus, Reference 6
Tree of Antenna Types

- End Fires
  - Polyrods
  - Helices
  - Yagi-Udas
  - Log Periodics
  - Conical Spirals

- Loops
  - Dipoles
  - Stubs
  - Apertures

- Dipoles
  - Folded Dipoles
  - Arrays
  - Curtains
  - W8JKs

- Arrays
  - Twin Lines
  - Curtains
  - Vees
  - Long Wires
  - Biconical
  - Beverage
  - Rhombic

- Apertures
  - Lenses
  - Spirals
  - Reflectors
  - Horns
  - Flat
  - Parabolic
  - Corner
  - Radomes
  - Frequency Selective Surfaces

Adapted from Kraus, Reference 6
Generation of Electromagnetic Fields & Calculation Methodology

- **Radiation mechanism**
  - Radiation is created by an acceleration of charge or by a time-varying current
  - Acceleration is caused by external forces
    - Transient (pulse)
    - Time-harmonic source (oscillating charge)

- **EM wave is calculated by integrating source currents on antenna / target**
  - Electric currents on conductors or magnetic currents on apertures
    - (transverse electric fields)

- **Source currents can be modeled and calculated using numerical techniques**
  - (e.g. Method of Moments, Finite Difference-Time Domain Methods)
Harmonic Time Variation is assumed: $e^{j\omega t}$

$$\vec{E}(x,y,z;t) = \text{Real} \left[ \vec{E}(x,y,z)e^{j\omega t} \right]$$

**Instantaneous Electric Field**

**Phasor**

Calculate Phasor: $$\vec{E}(x,y,z) = \hat{e} \left| \vec{E}(x,y,z) \right| e^{j\alpha}$$

**Instantaneous Harmonic Field is:**

$$\vec{E}(x,y,z;t) = \hat{e} \left| \vec{E}(x,y,z) \right| \cos (\omega t + \alpha)$$

**Any Time Variation can be Expressed as a Superposition of Harmonic Solutions by Fourier Analysis**
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Regions of Radiation

Adapted from Kraus, Reference 6

Field Regions

Reactive Near-Field Region

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

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

Far-field (Fraunhofer) Region

\[ R > 2D^2/\lambda \]

- All power is radiated out
- Radiated wave is a plane wave
- Far-field EM wave properties
  - Polarization
  - Antenna Gain (Directivity)
  - Antenna Pattern
  - Target Radar Cross Section (RCS)

Equiphase Wave Fronts

Plane Wave Propagates Radially Out

Adapted from Balanis, Reference 1

Courtesy of MIT Lincoln Laboratory, Used with permission
Far-Field EM Wave Properties

- In the far-field, a spherical wave can be approximated by a plane wave.
- There are no radial field components in the far field.
- The electric and magnetic fields are given by:

\[
E^{ff}(r, \theta, \phi) \approx E^o(\theta, \phi) \frac{e^{-jkr}}{r} \\
H^{ff}(r, \theta, \phi) \approx H^o(\theta, \phi) \frac{e^{-jkr}}{r} = \frac{1}{\eta} \hat{r} \times \vec{E}^{ff}
\]

where \( \eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377 \, \Omega \) is the intrinsic impedance of free space

\( k = \frac{2\pi}{\lambda} \) is the wave propagation constant.
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• Reflector Antennas – Mechanical Scanning
Propagation in Free Space

- Plane wave, free space solution to Maxwell’s Equations:
  - No Sources
  - Vacuum
  - Non-conducting medium
  \[
  \mathbf{E}(\vec{r}, t) = E_0 e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}
  \]
  \[
  \mathbf{B}(\vec{r}, t) = B_0 e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}
  \]

- Most electromagnetic waves are generated from localized sources and expand into free space as spherical wave.

- In the far field, when the distance from the source great, they are well approximated by plane waves when they impinge upon a target and scatter energy back to the radar.
Modes of Transmission For Electromagnetic Waves

- **Transverse electromagnetic (TEM) mode**
  - Magnetic and electric field vectors are transverse (perpendicular) to the direction of propagation, \( \hat{k} \), and perpendicular to each other.
  - Examples (coaxial transmission line and free space transmission).
  - TEM transmission lines have two parallel surfaces.

- **Transverse electric (TE) mode**
  - Electric field, \( \vec{E} \), perpendicular to \( \hat{k} \).
  - No electric field in \( \hat{k} \) direction.

- **Transverse magnetic (TM) mode**
  - Magnetic field, \( \vec{H} \), perpendicular to \( \hat{k} \).
  - No magnetic field in \( \hat{k} \) direction.

- **Hybrid transmission modes**
• The Poynting Vector, \( \vec{S} \), is defined as:

\[
\vec{S} \equiv \vec{E} \times \vec{H} \quad (W/m^2)
\]

• It is the power density (power per unit area) carried by an electromagnetic wave.

• Since both \( \vec{E} \) and \( \vec{H} \) are functions of time, the average power density is of greater interest, and is given by:

\[
\left\langle \vec{S} \right\rangle = \frac{1}{2} \text{Re} \left( \vec{E} \times \vec{H}^* \right)
\]

• For a plane wave in a lossless medium

\[
\left\langle \vec{S} \right\rangle = \frac{1}{2\eta} \left| \vec{E} \right|^2 \equiv W_{AV}
\]

where \( \eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} \)
Radiation Intensity and Radiated Power

- **Radiation Intensity** = Power radiated per unit solid angle

  \[ U(\theta, \phi) \approx r^2 W_{rad}(\theta, \phi) = \frac{r^2}{2\eta} \left| \vec{E}(r, \theta, \phi) \right|^2 \]

  \[ \approx \frac{r^2}{2\eta} \left[ \left| \vec{E}_\theta(r, \theta, \phi) \right|^2 + \left| \vec{E}_\phi(r, \theta, \phi) \right|^2 \right] \]

  \[ \approx \frac{1}{2\eta} \left[ \left| \vec{E}_\theta^0(r, \theta, \phi) \right|^2 + \left| \vec{E}_\phi^0(r, \theta, \phi) \right|^2 \right] \quad \text{(W/steradian)} \]

  where \( \vec{E}(r, \theta, \phi) = \vec{E}^0(\theta, \phi) \frac{e^{-jkr}}{r} = \) far field electric field intensity

  \( \vec{E}_\theta, \vec{E}_\phi = \) far field electric field components

  \[ \eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} \]

- **Total Power Radiated**

  \[ P_{rad} = \int_0^{2\pi} \int_0^{\pi} U(\theta, \phi) \sin \theta \, d\theta \, d\phi \quad \text{(W)} \]
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• Reflector Antennas – Mechanical Scanning
Antenna Polarization

- Defined by behavior of the electric field vector as it propagates in time as observed along the direction of radiation
- Circular used for weather mitigation
- Horizontal used in long range air search to obtain reinforcement of direct radiation by ground reflection

![Electric Field Diagram](Image)

- **Linear**
  - Vertical or Horizontal
- **Circular**
  - Two components are equal in amplitude, and separated in phase by 90 deg
  - Right-hand (RHCP) is CW above
  - Left-hand (LHCP) is CCW above
- **Elliptical**

Courtesy of MIT Lincoln Laboratory, Used with permission
Polarization

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

**Vertical Linear (with respect to Earth)**

(For over-water surveillance)

**Horizontal Linear (with respect to Earth)**

(For air surveillance looking upward)

*Courtesy of MIT Lincoln Laboratory, Used with permission*
Circular Polarization (CP)

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

![Diagram of Circular Polarization](image)

**Figure by MIT OCW.**
Circular Polarization (CP)

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

![Circular Polarization Diagram](Figure by MIT OCW.)

- Right-Hand (RHCP)
- Left-Hand (LHCP)

Equations:
- $\epsilon_{\theta}$
- $\epsilon_{\phi}$
- $\omega t$

Propagation Direction
- Into Paper

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Antenna Gain

**Gain** = Radiation intensity of antenna in given direction over that of isotropic source

\[
G = \frac{4\pi A_{\text{eff}}}{\lambda^2} = \frac{4\pi \eta A}{\lambda^2}
\]

- Difference between gain and directivity is **antenna loss**

- "Rules of Thumb"

\[
G = \frac{26,000}{\theta_B \phi_B} \quad \text{(degrees)}
\]

\[
\theta_B = \frac{65 \lambda}{D} \quad \text{(degrees)}
\]

\[
\Phi = \frac{D}{\lambda} \quad \text{(degrees)}
\]
Radiation Intensity $= U(\theta, \phi) = \text{Power radiated / unit solid angle}$

Directivity $= \frac{\text{Radiation intensity of antenna in given direction}}{\text{Radiation intensity of an isotropic source radiating same power}}$

\begin{align*}
D(\theta, \phi) &= \frac{4\pi U(\theta, \phi)}{P_{\text{rad}}} \\
&= \text{(dimensionless)}
\end{align*}

Gain $= \frac{\text{Radiation intensity of antenna in given direction}}{\text{Radiation intensity of isotropic source radiating available power}}$

- Difference between gain and directivity is antenna loss
- Gain $\leq$ Directivity

\begin{align*}
G(\theta, \phi) &= \frac{4\pi U(\theta, \phi)}{P_{\text{in}}} \\
&= \text{(dimensionless)}
\end{align*}

Maximum Gain $= \text{Radiation intensity of antenna at peak of beam}$

\begin{align*}
G &= \frac{4\pi A_{\text{eff}}}{\lambda^2} = \frac{4\pi \eta A}{\lambda^2} \\
A &= \text{Area of antenna aperture} \\
\eta &= \text{Efficiency of antenna}
\end{align*}
Example – Half Wavelength Dipole

Far Field

\[ \mathbf{E}^f(\theta) = \hat{\theta} j \eta \frac{I_o}{2\pi} e^{-jkr} \left[ \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{r \sin \theta} \right] \]

\[ \mathbf{H}^f(\theta) = \hat{\phi} j \frac{I_o}{2\pi} e^{-jkr} \left[ \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{r \sin \theta} \right] \]

Adapted from Balanis, Reference 1, pp182 - 184

Radiation Intensity

\[ U(\theta) = \eta \left| \frac{I_o}{8\pi^2} \right|^2 \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{\sin^2 \theta} \]

Gain / Pattern

\[ G(\theta) = \frac{4\pi U(\theta)}{P_{in}} = 1.643 \left[ \frac{\cos^2\left(\frac{\pi}{2} \cos \theta\right)}{\sin^2 \theta} \right] \]

\[ G_o = \frac{4\pi U_{\text{max}}}{P_{in}} = 1.643 \]

Radiated Power

\[ P_{\text{rad}} = \eta \left| \frac{I_o}{8\pi\lambda} \right|^2 C_{\text{in}}(2\pi) \]

\[ C_{\text{in}}(2\pi) = \int_{\theta}^{2\pi} \frac{1 - \cos \phi}{\lambda} d\phi \approx 2.435 \]

Effective Area

\[ A_e = \frac{\lambda^2 D_o}{4\pi} \approx 0.13\lambda^2 \]

\[ \theta = \text{angle down from z-axis} \]
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• Reflector Antennas – Mechanical Scanning
Antenna Input Impedance

- Antenna can be modeled as an impedance (ratio of voltage to current at feed port)
  - Antenna “resonant” when impedance purely real
  - Microwave theory can be applied to equivalent circuit
- Design antenna to maximize power transfer from transmission line
  - Reflection of incident power sets up standing wave on line
  - Can result in arcing under high power conditions

\[
\Gamma \quad feed \\
\begin{array}{c}
\text{Transmission Line} \\
\text{Antenna}
\end{array}
\]

\[
\begin{align*}
V_{\text{Max}} & \quad V_{\text{Min}} \\
R_{\text{A}} & \quad R_{\text{L}}
\end{align*}
\]

\[
P_{\text{rad}} = \frac{1}{2} |I_0|^2 R_r
\]

Courtesy of MIT Lincoln Laboratory, Used with permission
Antenna Input Impedance

- Antenna can be modeled as an impedance (ratio of voltage to current at feed port)
  - Antenna “resonant” when impedance purely real
  - Microwave theory can be applied to equivalent circuit
- Design antenna to maximize power transfer from transmission line
  - Reflection of incident power sets up standing wave on line
  - Can result in arching under high power conditions
- Usually a 2:1 VSWR is acceptable

\[
VSWR = \frac{V_{\text{Max}}}{V_{\text{Min}}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}
\]

| \( |\Gamma| = 0 \) | \( VSWR = 1 \) |
---|---|
| All Incident Power is Delivered to Antenna |

| \( |\Gamma| = 1 \) | \( VSWR \rightarrow \infty \) |
---|---|
| All Incident Power is Reflected |

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  – Aperture Illumination
  – Different Reflector Feeds and Reflector Geometries
Antenna Pattern Characteristics

**Parabolic Reflector Antenna**

- Aperture diameter $D = 5$ m
- Frequency = 300 MHz
- Wavelength = 1 m

**Graph: Antenna Gain vs. Angle**

- Gain = 24 dBi
- Isotropic Sidelobe Level = 6 dBi
- Sidelobe Level = 18 dB
- Half-Power Beamwidth = 12 deg
Parabolic Reflector Antenna

- Reflector antenna design involves a tradeoff between maximizing dish illumination while limiting spillover and blockage from feed and its support structure.

- Feed antenna choice is critical.

Normalized Antenna Gain Pattern

Figure By
MIT OCW

Relative Gain (dB)

Angle off Beam Axis (degrees)
Effect of Aperture Size on Gain

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

Gain = \frac{4\pi A_e}{\lambda^2}

\approx \frac{4\pi A}{\lambda^2}

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

\text{Effective Area}

\text{Rule of Thumb (Best Case)}

\text{Wavelength Decreases}

\lambda = 10 \text{ cm (3 GHz)}
\lambda = 30 \text{ cm (1 GHz)}
\lambda = 100 \text{ cm (300 MHz)}
Effect of Aperture Size on Beamwidth

Beamwidth decreases as aperture becomes electrically larger (diameter larger number of wavelengths)

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

Parabolic Reflector Antenna

Wavefront

Antenna Feed at Focus

Beam Axis

Antenna Beamwidth vs. Diameter

- $\lambda = 100 \text{ cm (300 MHz)}$
- $\lambda = 30 \text{ cm (1 GHz)}$
- $\lambda = 10 \text{ cm (3 GHz)}$

Wavelength Increases

Half-Power Beamwidth (deg)

Aperture Diameter $D$ (m)

1 3 5 7 9
Parabolic Reflector Antenna

- Point source is evolves to plane wave (In the Far Field)
- Feed can be dipole or open-ended waveguide (horn)
- Feed structure reduces antenna efficiency

Examples of Parabolic Antenna Feed Structure

Adapted from Skolnik, Reference 2
Different Types of Radar Beams

- **Pencil Beam**
  - Courtesy of MIT Lincoln Laboratory
  - Used with permission

- **Stacked Beam**
  - Courtesy of US Air Force

- **Fan Beam**
  - Courtesy of MIT Lincoln Laboratory
  - Used with permission

- **Shaped Beam**
  - Courtesy of Northrop Grumman
  - Used with Permission
Reflector Comparison
Kwajalein Missile Range Example

**ALTAIR**
45.7 m diameter

- Operating frequency: 162 MHz (VHF)
- Wavelength $\lambda$: 1.85 m
- Diameter electrical size: 25 $\lambda$
- Gain: 34 dB
- Beamwidth: 2.8 deg

**MMW**
13.7 m diameter

- Operating frequency: 35 GHz (Ka)
- Wavelength $\lambda$: 0.0086 m
- Diameter electrical size: 1598 $\lambda$
- Gain: 70 dB
- Beamwidth: 0.00076 deg

Scale by 1/3

Courtesy of MIT Lincoln Laboratory, Used with permission
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Antenna Spillover

- Even when the feed is at the exact focus of the parabolic reflector, a portion of the emitted energy at the edge of the beam will not impinge upon the reflector.

- This is called “beam spillover”

- Tapering the feed illumination can mitigate this effect

- As will be seen, optimum antenna performance is a tradeoff between:
  - Beam spillover
  - Tapering of the aperture illumination
  - Antenna gain
  - Feed blockage

Adapted from Skolnik, Reference 5
Effect of Aperture Blocking in a Parabolic Reflector Antenna

The effect of aperture blockage can be approximated by:

Antenna pattern of undisturbed aperture – Antenna pattern produced by shadow of the obstacle

Examples of Aperture Blockage

Feed and its supports
Masts onboard a ship
FPS-16

Courtesy of US Air Force
Effect of Aperture Blocking in a Parabolic Reflector Antenna

This procedure is possible because of the linearity of the Fourier transform that relates the antenna aperture illumination and the radiation pattern.

Examples of Aperture Blockage

- Feed and its supports
- Masts onboard a ship

TRADEX

Courtesy of MIT Lincoln Laboratory, Used with permission
Examples of Antenna Blockage

- USS Abraham Lincoln (SPS-49)
- USS Theodore Roosevelt (SPS-48)
- SPG-51
- NASA Tracking Radar
- P-15 Flatface

Courtesy of US Navy

Courtesy of NASA

Courtesy of US Air Force
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Antenna Radiation Pattern from a Line Source

- The aperture Illumination, \( A(z) \), is the current a distance \( Z \) from the origin \((0,0,0)\), along the \( z \) axis.
- Assumes \( E(\phi) \) is in the far field, \( a >> \lambda \) and \( R >> a^2 / \lambda \).
- Note that the electric field is the Inverse Fourier Transform of the Aperture Illumination.

\[
E(\phi) = \int_{-a/2}^{a/2} A(z) \exp \left( j 2\pi \frac{z}{\lambda} \sin \phi \right) dz
\]
Effect of Source Distribution on Antenna Pattern of a Line Source

**Uniform Aperture Distribution**

\[
A(z) = 1
\]

\[
E(\phi) = \frac{a}{2} \int_{-a/2}^{a/2} \exp\left(j 2\pi \frac{z}{\lambda} \sin \phi \right) dz
\]

\[
= A_0 \sin\left(\pi \left(\frac{a}{\lambda}\right) \sin \phi \right) \frac{\sin\left(\pi \left(\frac{a}{\lambda}\right) \sin \phi \right)}{\left(\pi \left(\frac{a}{\lambda}\right) \sin \phi \right)}
\]

**Cosine Aperture Distribution**

\[
A(z) = \cos \pi \left(\frac{a}{z}\right)
\]

\[
E(\phi) = \frac{\pi}{4} \left[ \frac{\sin(\psi + \pi/2)}{(\psi + \pi/2)} + \frac{\sin(\psi - \pi/2)}{(\psi - \pi/2)} \right]
\]

where \( \psi = \pi \left(\frac{a}{\lambda}\right) \sin \phi \)
Antenna Pattern of a Line Source
(with Uniform and Cosine Aperture Illumination)

- Weighting of Aperture Illumination
  - Increases Beamwidth
  - Lowers Sidelobes
  - Lowers Antenna Gain

Curves Normalized to 0 dB at Maximum

Adapted from Skolnik, Reference 1

\[ |E(\phi)|^2 \]

Relative Radiation Intensity (dB)

\[ \pi \left( \frac{D}{\lambda} \right) \sin \phi \]

~0.9 dB Loss
Illumination of Two-Dimensional Apertures

- Calculation of this integral is non-trivial
  - Numerical techniques used
- Field pattern separable, when aperture illumination separable
  \[ A(x, y) = A_x(x)A_y(y) \]
- Problem reduces to two 1 dimensional calculations

\[ E(\theta, \phi) = \int \int A(x, y) e^{\left(\frac{2\pi j}{\lambda}\sin \theta (x \cos \phi + y \sin \phi)\right)} dx \, dy \]
Uniformly Illuminated Circular Aperture

- **Field Intensity of circular aperture of radius a:**

\[
E(\theta) = 2\pi \int_{0}^{a} A(r) J_0 \left[ 2\pi \left( \frac{r}{\lambda} \right) \sin \phi \theta \right] r \, dr
\]

- **For uniform aperture illumination:**

\[
E(\theta) = 2\pi a^2 J_1(\xi) / \xi
\]

where \( \xi = 2\pi \left( \frac{a}{\lambda} \right) \sin \theta \) and \( J_1(\xi) = 1^{st} \) order Bessel Function

- Use cylindrical coordinates, field intensity independent of

- Half power beamwidth (degrees) = \( 58.5 \left( \frac{\lambda}{a} \right) \), first sidelobe = - 17.5 dB

- Tapering of the aperture will broaden the beamwidth and lower the sidelobes

Adapted from Skolnik, Reference 1
# Radiation Pattern Characteristics for Various Aperture Distributions

| Type of Distribution | $|z| < 1$ | Gain Relative to Uniform (dB) | Beamwidth Half-Power (dB) | Intensity, 1st Sidelobe (dB below Maximum) |
|----------------------|---------|-------------------------------|---------------------------|-------------------------------------------|
| Uniform: $A(z) = 1$  | 1.0     | 51 $\lambda/D$               | 13.2                      |                                           |
| Cosine: $A(z) = \cos^n(\pi z / 2)$ |
| n=0                  | 1.0     | 51 $\lambda/D$               | 13.2                      |                                           |
| n=1                  | 0.810   | 69 $\lambda/D$               | 23                        |                                           |
| n=2                  | 0.667   | 83 $\lambda/D$               | 32                        |                                           |
| n=3                  | 0.515   | 95 $\lambda/D$               | 40                        |                                           |
| Parabolic: $A(z) = 1 - (1 - \Delta) z^2$ |
| $\Delta=1.0$        | 1.0     | 51 $\lambda/D$               | 13.2                      |                                           |
| $\Delta=0.8$        | 0.994   | 53 $\lambda/D$               | 15.8                      |                                           |
| $\Delta=0.5$        | 0.970   | 56 $\lambda/D$               | 17.1                      |                                           |
| $\Delta=0$          | 0.833   | 66 $\lambda/D$               | 20.6                      |                                           |
| Triangular: $A(z) = 1 - |z|$ | 0.75 | 73 $\lambda/D$ | 26.4 | |
| Circular: $A(z) = \sqrt{1 - z^2}$ | 0.865 | 58.5 $\lambda/D$ | 17.6 | |
| Cosine-squared + pedestal |
| $0.33 + 0.66 \cos^2(\pi z / 2)$ | 0.88 | 63 $\lambda/D$ | 25.7 | |
| $0.08 + 0.92 \cos^2(\pi z / 2)$ (Hamming) | 0.74 | 76.5 $\lambda/D$ | 42.8 | |

Heavier Taper
- Lowers sidelobes
- Increases beamwidth
- Lowers directivity

Uniform distribution always has 13 dB sidelobe.

Adapted from Skolnik, Reference 1.
Taper Efficiency, Spillover, Blockage, and Total Loss vs. Feed Pattern Edge Taper

Reflector Design is a Tradeoff of Aperture Illumination (Taper) Efficiency, Spillover and Feed Blockage

Adapted from Cooley in Skolnik, Reference 4
Outline

• Introduction

• Antenna Fundamentals

• Reflector Antennas – Mechanical Scanning
  – Basic Antenna (Reflector) Characteristics and Geometry
  – Spillover and Blockage
  – Aperture Illumination
  – Different Reflector Feeds and Reflector Geometries
    Feed Horns
    Cassegrain Reflector Geometry
    Different Shaped Beam Geometries
    Scanning Feed Reflectors
Feed Horns for Reflector Antennas

- Simple flared pyramidal (TE$_{01}$) and conical (TE$_{11}$) horns used for pencil beam, single mode applications
- Corrugated, compound, and finned horns are used in more complex applications
  - Polarization diversity, ultra low sidelobes, high beam efficiency, etc.
- Segmented horns are used for monopulse applications

Adapted from Cooley in Skolnik, Reference 4
Cassegrain Reflector Antenna

Geometry of Cassegrain Antenna

Ray Trace of Cassegrain Antenna

Figure by MIT OCW.
Advantages of Cassegrain Feed

- Lower waveguide loss because feed is not at the focus of the paraboloid, but near the dish.

- Antenna noise temperature is lower than with conventional feed at focus of the paraboloid
  - Length of waveguide from antenna feed to receiver is shorter
  - Sidelobe spillover from feed see colder sky rather than warmer earth

- Good choice for monopulse tracking
  - Complex monopulse microwave plumbing may be placed behind reflector to avoid the effects of aperture blocking
**ALTAIR- Example of Cassegrain Feed**

**ALTAIR Antenna**

**ALTAIR Antenna Feed**

**Dual Frequency Radar**

- Antenna size - 120 ft.
- VHF parabolic feed
- UHF Cassegrain feed
- Frequency Selective Surface (FSS) used for reflector at UHF

- This “saucer” is a dichroic FFS that is reflective at UHF and transparent at VHF. The “teacup” to its right is the cover for a five horn VHF feed, located at the antenna’s focal point.

- The FSS sub-reflector is composed of two layers of crossed dipoles

*Courtesy of MIT Lincoln Laboratory, Used with permission*
Antennas with Cosecant-Squared Pattern

- Air surveillance coverage of a simple fan beam is usually inadequate for aircraft targets at high altitude and short range
  - Simple fan beam radiates very little energy at high altitude

- One technique - Use fan beam with shape proportional to the square of the cosecant of the elevation angle
  - Gain constant for a given altitude

- Gain pattern:
  - $G(\theta) = G(\theta_1) \csc^2 \theta / \csc^2 \theta_1$ for $\theta_1 < \theta < \theta_2$
  - $G(\theta) \sim G(\theta_1) (2 - \cot \theta_2)$
Antenna Pattern with Cosecant-Squared Beam Shaping

Ray Trace for $\csc^2$ Antenna Pattern

FAA ASR Radars Use $\csc^2$ Antenna Reflector Shaping

ASR-9 Antenna

Courtesy of US Dept of Commerce
Patterns for Offset Feeds

Notice that a vertical array of feeds results in a set of “stacked beams”
- Can be used to measure height of target
Example of Stacked Beam Antenna

- Stacked beam surveillance radars can cost effectively measure height of target, while simultaneously performing the surveillance function.
- This radar, which was developed in the 1970s, underwent a number of antenna upgrade in the 1990s (TPS-70, TPS-75).
  - Antenna was replaced with a slotted waveguide array, which performs the same functions, and in addition has very low sidelobes.
Example of Stacked Beam Antenna

• Stacked beam surveillance radars can cost effectively measure height of target, while simultaneously performing the surveillance function.
• This radar, which was developed in the 1970s, was replaced in the 1990s with a technologically modern version of the radar.
  – New antenna, a slotted waveguide array, has all of the same functionality as TPS-43 dish, but in addition, has very low antenna sidelobes.
Scanning Feed Reflector Antennas

• Scanning of the radar beam over a limited angle with a fixed reflector and a movable feed
  – Paraboloid antenna cannot be scanned too far without deterioration
    Gain of antenna, with f/D=.25, reduced to 80% when beam scanned 3 beamwidths off axis

  – Wide angle scans in one dimension can be obtained with a parabolic torus configuration
    Beam is generated by moving feed along circle whose radius is 1/2 that of torus circle
    Scan angle limited to about 120 deg
    Economical way to rapidly scan beam of very large antennas over wide scan angles

  – Organ pipe scanner
    Mechanically scan feed between many fixed feeds
Examples of Scanning Feed Reflector Configuration

Parabolic Torus Antenna

Organ Pipe Scanner Feed

\[ R = \text{Radius of Torus} \]
\[ f = \text{Focal Length of Torus} \]

The output feed horns of the organ pipe scanner are located along this arc.

The length of each waveguide is equal.
Radar Example – Organ Pipe Scanner

Courtesy of MIT Lincoln Laboratory, Used with permission
Radar Example – Organ Pipe Scanner

BMEWS Site, Clear, Alaska

Courtesy of MIT Lincoln Laboratory, Used with permission
Summary – Part 1

• Discussion of antenna parameters
  – Gain
  – Sidelobes
  – Beamwidth
    Variation with antenna aperture size and wavelength
  – Polarization
    Horizontal, Vertical, Circular

• Mechanical scanning antennas offer an inexpensive method of achieving radar beam agility
  – Slow to moderate angular velocity and acceleration

• Different types of mechanical scanning antennas
  – Parabolic reflectors
  – Cassegrain and offset feeds
  – Stacked beams

• Antenna Issues
  – Aperture illumination
  – Antenna blockage and beam spillover
Homework Problems

- From Skolnik, Reference 2
  - Problem 2.20
  - Problems 9.2, 9.4, 9.5, and 9.8
Outline

- Introduction
- Antenna Fundamentals
- Reflector Antennas – Mechanical Scanning
- Phased Array Antennas
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics
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References