Radar Systems Engineering
Lecture 5
Propagation through the Atmosphere

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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)

Receiver

A / D Converter

Propagation Medium

Target Radar Cross Section

Antenna

Receiver

A / D Converter

Propagation

Medium

Target Radar

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General Purpose Computer

Tracking

Parameter Estimation

Thresholding

Detection

Display / Consoles

Data Recording

Received Signal Energy

\[ R_{\text{signal}} = P_t \left[ \frac{4\pi A}{\lambda^2} \right] \left[ \frac{1}{4\pi R^2} \right] \left[ \frac{1}{L_s} \right] \left[ \frac{1}{L_p} \right] F^4 \left[ \sigma \right] \left[ \frac{1}{4\pi R^2} \right] [A] [t] \]
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

Display / Consoles
- Data Recording
- Tracking
- Parameter Estimation
- Thresholding
- Detection

Received Signal Energy
\[ E_{\text{received}} = P_t \left( \frac{4\pi A}{\lambda^2} \right) \left( \frac{1}{4\pi R^2} \right) \left( \frac{1}{L_s} \right) \]

Propagation Losses
- System Losses
- Propagation Loss
- Propagation Factor

Expected Signal
\[ \frac{E}{E_0} = \text{actual} \]

Waveform Generation

A / D Converter

T / R Switch

Antenna

Propagation Medium

Target Radar Cross Section

Received Signal Energy
\[ E_{\text{received}} = P_t \left( \frac{4\pi A}{\lambda^2} \right) \left( \frac{1}{4\pi R^2} \right) \left( \frac{1}{L_s} \right) \]

Propagation Loss
\[ F^4 \]

\[ [\sigma] \left[ \frac{1}{4\pi R^2} \right] [A][t] \]
Introduction and Motivation

- Ground based
- Sea based
- Airborne

Almost all radar systems operate through the atmosphere and near the Earth’s surface.
Effect of the Atmosphere on Radar Performance

- Attenuation of radar beam

- Refraction (bend) of the radar beam as it passes through the atmosphere

- “Multipath” effect
  - Reflection of energy from the lower part of the radar beam off of the earth’s surface
  - Result is an interference effect

- Over the horizon diffraction of the radar beam over ground obstacles

- Propagation effects vary with:
  - Changing atmospheric conditions and wavelength
  - Temporal and geographical variations
A Multiplicity of Atmospheric and Geographic Parameters

• Atmospheric parameters vary with altitude
  – Index of refraction
  – Rain rate
  – Air density and humidity
  – Fog/cloud water content

• Earth’s surface
  – Curvature of the earth
  – Surface material (sea / land)
  – Surface roughness (waves, mountains / flat, vegetation)
Outline

- Reflection from the Earth’s surface
  - Atmospheric refraction
  - Over-the-horizon diffraction
  - Atmospheric attenuation
  - Ionospheric propagation
Review of Interference Effect

- Two waves can interfere constructively or destructively
- Resulting field strength depends only on relative amplitude and phase of the two waves
  - Radar voltage can range from 0-2 times single wave
  - Radar power is proportional to \((\text{voltage})^2\) for 0-4 times the power
  - Interference operates both on outbound and return trips for 0-16 times the power

Courtesy of MIT Lincoln Laboratory
Used with Permission
Overview - Propagation over a Plane Earth

- Reflection from the Earth’s surface results in interference of the direct radar signal with the signal reflected off of the surface
  - Total propagation effect expressed by propagation factor $|F|^4$

- Surface reflection coefficient ($\Gamma$) determines relative signal amplitudes
  - Dependent on: surface material, roughness, polarization, frequency
  - Close to 1 for smooth ocean, close to 0 for rough land

- Relative phase determined by path length difference and phase shift on reflection
  - Dependent on: height, range and frequency

Courtesy of MIT Lincoln Laboratory
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Relative Phase Calculation

\[ R_1 = \sqrt{R^2 + (h_r - h_t)^2} \]
\[ R_2 = \sqrt{R^2 + (h_r + h_t)^2} \]

\[ \Delta \phi = \frac{2\pi}{\lambda} (R_1 - R_2) \approx \frac{4\pi h_r h_t}{\lambda R} \]

\[ F = 1 + |\Gamma| \exp(i \Delta \phi) \]

Two way propagation factor = \( |F|^4 \)
Propagation over a Plane Earth

Assume: $\Gamma = -1$, $R \gg h_R$, $h_t \gg h_R$

- The (reflected path) - (directed path): $\Delta = 2h_R \sin \theta$

- For small $\theta$, $\sin \theta = \frac{h_R + h_t}{R}$, $\Delta = \frac{2h_R h_t}{R}$

- The phase difference due to path length difference is:
  $$\phi = \left(\frac{2\pi}{\lambda}\right) \left(\frac{2h_R h_t}{R}\right)$$

- The total phase difference is
  $$\phi = \left(\frac{2\pi}{\lambda}\right) \left(\frac{2h_R h_t}{R}\right) + \pi$$
Propagation over a Plane Earth
(continued)

- The sum of two signals, each of unity amplitude, but with phase difference:
  \[ \eta = \sqrt{\left( (1 + \cos \phi)^2 + (\sin \phi)^2 \right)} = \sqrt{2 \left( 1 + \cos \left( \frac{4 \pi h_R h_t}{\lambda R} \right) \right)} \]

- The one way power ratio is:
  \[ \eta_{1\text{WAY}}^2 = 2 \left[ 1 - \cos \left( \frac{4 \pi h_R h_t}{\lambda R} \right) \right] = 4 \sin^2 \left( \frac{2 \pi h_R h_t}{\lambda R} \right) \]

- The two way power ratio is:
  \[ \eta_{1\text{WAY}}^4 = 16 \sin^4 \left( \frac{2 \pi h_R h_t}{\lambda R} \right) \]

- Maxima occur when \( (2n + 1) \frac{\pi}{2} \), minima when \( n \pi \)

- Multipath Maxima and Minima:
  \[
  \begin{align*}
  \text{Maxima} & : \frac{4 h_R h_t}{\lambda R} = 2n + 1 \\
  \text{Minima} & : \frac{2 h_R h_t}{\lambda R} = n
  \end{align*}
  \]
Multipath effect on radar detection range

- Multipath causes elevation coverage to be broken up into a lobed structure.
- A target located at the maximum of a lobe will be detected as far as twice the free-space detection range.
- At other angles the detection range will be less than free space and in a null no echo signal will be received.

Reflection Coefficient
\[ \Gamma = -1 \]
\[ \Gamma = -0.3 \]
\[ \Gamma = 0 \]

First maxima at angle

\[ \approx \frac{\lambda}{4h_R} \]

Courtesy of MIT Lincoln Laboratory
Used with Permission
Multipath is Frequency Dependent

Lobing density increases with increasing radar frequency

Reflection Coefficient
\( \Gamma = -1 \)
\( \Gamma = -0.3 \)

Courtesy of MIT Lincoln Laboratory
Used with Permission
• Reflection coefficient from a round earth is less than that from a flat earth
• Propagation calculations with a round earth are somewhat more complicated
  – Computer programs exist to perform this straightforward but tedious task
  – Algebra is worked out in detail in Blake (Reference 4)
• As with a flat earth, with a round earth lobing structure will occur

Adapted from Blake, Reference 4
Examples - L-Band Reflection Coefficient

Sea Water
\[ \varepsilon = 80 - 240 \lambda \ i \]

Very Dry Ground
\[ \varepsilon = 3 - 6 \times 10^{-3} \lambda \ i \]

\[ \Gamma_H = \frac{\sin \alpha - \sqrt{\varepsilon - \cos^2 \alpha}}{\sin \alpha + \sqrt{\varepsilon - \cos^2 \alpha}} \]
\[ \Gamma_V = \frac{\varepsilon \sin \alpha - \sqrt{\varepsilon - \cos^2 \alpha}}{\varepsilon \sin \alpha + \sqrt{\varepsilon - \cos^2 \alpha}} \]

\[ \varepsilon = \text{Complex dielectric constant} \]
\[ \varepsilon = \varepsilon_r - i\varepsilon_i = \varepsilon_r - i \ 60 \lambda \ \sigma \]

\[ \sigma = \text{Conductivity} \]
\[ \alpha = \text{Grazing angle} \]
\[ \lambda = \text{Wavelength} \]
SPS-49 Ship Borne Surveillance Radar

- **Radar Parameters**
  - Average Power 13 kW
  - Frequency 850-942 MHz
  - Antenna Gain 29 dB
    - Rotation Rate 6 RPM
  - Target $\sigma = 1 \text{ m}^2$
    - Swerling Case I
  - $P_D$ 0.5
  - PFA $10^{-6}$
  - Antenna Height 75 ft
  - Sea State 3

Courtesy of US Navy

USS Abraham Lincoln
Vertical Coverage of SPS-49 Surveillance Radar

Adapted from Gregers-Hansen’s work in Reference 1
Outline

- Reflection from the Earth’s surface
- Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation
Refraction of Radar Beams

- The index of refraction, \( n \), and refractivity, \( N \), are measures of the velocity of propagation of electromagnetic waves

\[
n = \frac{V_{\text{Vacuum}}}{V_{\text{Air}}}
\]

\[
N = (n - 1)10^{+6}
\]

\[
n = 1.000335
\]

\[
N = 335
\]

- The index of refraction depends on a number of environmental quantities:

\[
N = \frac{77.6}{T} \left[ p + \frac{4810e}{T} \right]
\]

\[
p = \text{barometric pressure (mbar)}
\]

\[
e = \text{partial pressure of water in (mbar)}
\]

\[
T = \text{absolute temperature, (°K)}
\]

(1 mm Hg = 1.3332 mbar)

Adapted from Skolnik, Reference 1
Refraction of Radar Beams

- The index of refraction (refractivity) decreases with increasing altitude

- Velocity of propagation increases with altitude

- The decrease is usually well modeled by an exponential

- Radar beam to bends downward due to decreasing index of refraction
Earth’s Radius Modified to Account for Refraction Effects

Atmospheric refraction can be accounted for by replacing the actual Earth radius \( a \), in calculations, by an equivalent earth radius \( k a \) and assuming straight line propagation

- A typical value for \( k \) is 4/3 (It varies from 0.5 to 6)
- Average propagation is referred to as a “4/3 Earth”

The distance, \( d \), to the horizon can be calculated using simple geometry as:

\[
d = \sqrt{2kh} \quad h = \text{height of radar above ground}
\]

Assuming 4/3 earth:

\[
d(\text{nmi}) = 1.23\sqrt{h(\text{ft})} \quad d(\text{km}) = 4.12\sqrt{h(\text{m})}
\]
Effects of Refraction of Radar Beam

Refraction causes an error in radar angle measurement.

For a target at an altitude of 20,000 ft and an elevation angle of 1°, the angle error ~3.5 milliradians.

Adapted from Skolnik, Reference 1
Non-Standard Propagation

- Using Snell’s law, it can be derived that \( k = \frac{1}{1 + a(\frac{dn}{dh})} \)
- Non standard propagation occurs when \( k \) not equal to 4/3
- Refractivity gradient for different propagation
  
<table>
<thead>
<tr>
<th>Condition</th>
<th>( N ) units per km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-refraction</td>
<td>positive gradient</td>
</tr>
<tr>
<td>No refraction</td>
<td>0</td>
</tr>
<tr>
<td>Standard refraction</td>
<td>-39</td>
</tr>
<tr>
<td>Normal refraction (4/3 earth radius)</td>
<td>0 to -79</td>
</tr>
<tr>
<td>Super-refraction</td>
<td>-79 to -157</td>
</tr>
<tr>
<td>Trapping (ducting)</td>
<td>-157 to -( \infty )</td>
</tr>
</tbody>
</table>
Anomalous Propagation

- Anomalous propagation occurs when effective earth radius is greater than 2. When $\frac{dn}{dh}$ is greater than $-1.57 \times 10^{-7}$ m$^{-1}$

- This non-standard propagation of electromagnetic waves is called anomalous propagation, superrefraction, trapping, or ducting.
  - Radar ranges with ducted propagation are greatly extended.
  - Extended ranges during ducting conditions means that ground clutter will be present at greater ranges
  - Holes in radar coverage can occur.

- Often caused by temperature inversion
  - Temperature usually decreases with altitude
  - Under certain conditions, a warm air layer is on top of a cooler layer
  - Typical duct thickness ~few hundred meters

\[
N = \frac{77.6}{T} \left[ p + \frac{4810e}{T} \right]
\]
Effect of Ducting on Target Detection

- **Ducting:**
  - Can cause gaps in elevation coverage of radar
  - Can allow low altitude aircraft detection at greater ranges
  - Increase the backscatter from the ground

Adapted from Skolnik, Reference 1
Anomalous Propagation

• Balloon borne radiosondes are often used to measure water vapor pressure, atmospheric pressure and temperature as a function of height above the ground to analyze anomalous propagation

• When ducting occurs, significant amounts of the radar’s energy can become trapped in these “ducts”
  – These ducts may be near the surface or elevated
  – “Leaky” waveguide model for ducting phenomena gives good results
    Low frequency cutoff for propagation

• Climactic conditions such as temperature inversions can cause ducting conditions to last for long periods in certain geographic areas.
  – Southern California coast near San Diego
  – The Persian Gulf
Ducted Clutter from New England

PPI Display

50 km range rings

Ducting conditions can extend horizon to extreme ranges

Courtesy of MIT Lincoln Laboratory
Used with Permission
Outline

• Reflection from the Earth’s surface
• Atmospheric refraction
• Over-the-horizon diffraction
• Atmospheric attenuation
• Ionospheric propagation
Propagation Over Round Earth

- **Interference region**
  - Located within line of sight radar
  - Ray optics assumed

- **Diffraction region**
  - Below radar line of sight
  - Direct solution to Maxwell’s Equations must be used
  - Signals are severely attenuated

- **Intermediate region**
  - Interpolation used

Adapted from Blake, Reference 2
Radar waves are diffracted around the curved Earth just as light is diffracted by a straight edge and ocean waves are bent by an obstacle (peninsula).


- The ability of radar to propagate beyond the horizon depends upon frequency (the lower the better) and radar height.

- For over the horizon detection, significant radar power is necessary to overcome the loss caused by diffraction.
Knife Edge Diffraction Model

F = Propagation factor

Radar height = 30 m
Target height = 135 m
Obstacle height = 100 m

Over the horizon propagation is enhanced at lower frequencies

Adapted from Meeks, Reference 6
Target Detection Near the Horizon

\[ R \approx \sqrt{2kaR} + \sqrt{2kaht} \]

\( a = \) radius of the Earth
\( k = 4/3 \) for normal atmosphere

- The expression relates, for a ray grazing the earth at the horizon, (radar beam tangential to earth): the maximum range that a radar at height, \( h_R \), may detect a target at height, \( h_t \).

- For targets below the horizon, there are always a target detection loss, due to diffraction effects, that may vary from 10 to > 30 dB, resulting in a signal to noise ratio below that of the free space value.
Frequency Dependence of Combined Diffraction and Multipath Effects

- Multipath effects result in good detection of low altitude targets at higher frequencies

- Diffraction Effects
  - Favors lower frequencies
  - Difficult at any frequency

- Loss
  - 80 dB at X-Band
  - 60 dB at L-Band
Outline

• Reflection from the Earth’s surface
• Atmospheric refraction
• Over-the-horizon diffraction
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Theoretical Values of Atmospheric Attenuation Due to H₂O and O₂

- The attenuation associated with the H₂O and O₂ resonances dominate the attenuation at short wavelengths
  - Attenuation is negligible at long wavelengths
  - It is significant in the microwave band
  - It imposes severe limits at millimeter wave bands

- At wavelengths at or below 3 cm (X-Band), clear air attenuation is a major issue in radar analysis

- At millimeter wavelengths and above, radars operate in atmospheric “windows”.

Adapted from Skolnik, Reference 1
Atmospheric Attenuation in the Troposphere

Adapted from Blake in Reference 1
Atmospheric Attenuation at 3 GHz

- Attenuation becomes constant after beam passes through troposphere

Adapted from Blake in Reference 1
Atmospheric Attenuation at 3 GHz

Adapted from Blake in Reference 1

- Attenuation 4.4 dB at 0° elevation vs. 1.0 dB at 5°
Atmospheric Attenuation at 10 GHz

- Attenuation: 6.6 dB at 10 GHz vs. 4.4 dB at 3 GHz

Adapted from Blake in Reference 1
Atmospheric Attenuation at 10 GHz

- For targets in the atmosphere, radar equation calculations require an iterative approach to determine the correct value of the atmospheric attenuation loss.

Adapted from Blake in Reference 1
Atmospheric Attenuation at Sea Level

- At high frequencies, oxygen and water vapor absorption predominate
- High attenuation obviates use of high frequencies for low altitude detection at long range

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Wavelength (cm)</th>
<th>Atmospheric Attenuation (dB/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>0.3</td>
<td>0.01</td>
</tr>
<tr>
<td>0.01</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0.001</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>0.3</td>
<td>1</td>
</tr>
</tbody>
</table>
Attenuation Due to Rain and Fog

Figure by MIT OCW.

Radar performance at high frequencies is highly weather dependent.
Radar Range - Height - Angle Chart
(Normal Atmosphere)

Assumes exponential model for atmosphere with N = 313

Adapted from Blake in Reference 4
Outline

• Reflection from the Earth’s surface
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• Ionospheric propagation
Over-the-Horizon Radars

OTH Radar Beam Paths

• 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)
Transmit Array

Courtesy of NOAA

Courtesy of Raytheon. Used with permission.
Frequency Spectrum
(HF and Microwave Bands)

Electromagnetic Propagation at High Frequencies (HF) is very different than at Microwave Frequencies

Adapted from Headrick and Skolnik in Reference 7
Ionospheric Propagation
(How it Works- What are the Issues)

- **Sky wave OTH radars:**
  - Refract (bend) the radar beam in the ionosphere,
  - Reflecting back to earth,
  - Scattering it off the target, and finally,
  - Reflect the target echo back to the radar

- **The performance of OTH radars vitally depends on the physical characteristics of the ionosphere, its stability and its predictability**

Adapted from Headrick and Skolnik in Reference 7
Physics of OTH Radar Propagation

Over the Horizon Propagation
Enabled by Ionospheric Refraction

Electron Concentration (N/cm$^3$)

Plasma Frequency $f_p = \frac{1}{2\pi} \sqrt{\frac{Ne^2}{m\varepsilon_0}}$

Maximum Usable Frequency (MUF)

Key for oblique incidence

$MUF = f_p \sec(\theta_{inc})$

MUF = Maximum Usable Frequency
Regular Variation in the Ionosphere

- Ultraviolet radiation from the sun is the principal agent responsible for the ionization in the upper ionosphere

Courtesy of NASA
Different Layers of the Ionosphere

- Ultraviolet radiation from the sun is the principal agent responsible for the ionization in the upper ionosphere.

- **D layer (~50 to 90 km altitude)**
  - Responsible for major signal attenuation during the day.
  - Absorption proportional to $1/f^2$.
  - Lower frequencies attenuated heavily.
  - D layer disappears at night.

- **E layer (~90 to 130 km altitude)**
  - Low altitude of layer => short range.
  - Sporadic-E layer – few km thick.

- **F layer (~200 to 500 km altitude)**
  - Most important layer for HF sky wave propagation.
  - During daylight, F region splits into 2 layers, the $F_1$ and $F_2$ layers.
    - The $F_1$ and $F_2$ layers combine at night.
    - $F_2$ layer is in a continual state of flux.

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Notional Graphic of Layer Heights

- **F_2**
- **F_1**
- **E**
- **D**

---

Ultraviolet radiation from the sun is the principal agent responsible for the ionization in the upper ionosphere.
Average Sun Spot Number (1750 – present)

- Within each week, of each month, of each year there is significant variation in the Sun Spot number (solar flux), and thus, the electron density in the ionosphere.

The solar cycle is 11 years.

Courtesy of NASA
Variability of Ionospheric Electron Density

Quiet Ionosphere  UT = 12h 00m  Ionospheric Storm  UT = 12h 00m

"Courtesy of Windows to the Universe, http://www.windows.ucar.edu"
Flare Emissions and Ionospheric Effects

- **Electromagnetic Radiation**
  - Delay: 8.3 minutes
  - Ultraviolet and X-Rays
  - D Layer Increase (SID)

- **Solar Cosmic rays**
  - Delay: 15 minutes to Several hours
  - High Energy Protons and a- particles
  - D Layer Increase (PCA)

- **Magnetic Storms**
  - Delay: 20-40 hours
  - Low Energy Protons and Electrons
  - Auroras
  - Sporadic E
  - Ionospheric Storms
  - D-Layer Increase (auroral absorption)
  - Geomagnetic Storms

SID: Sudden Ionospheric Disturbance
PCA: Polar Cap Absorption

May 19, 1998

Courtesy of NASA
Propagation Issues for OTH Radars

• OTH radar detection performance is dependent on many variables and is difficult to predict because of the variability and difficulty, of reliably predicting the characteristics of the ionosphere
  – Diurnal variations
  – Seasonal variations
  – Sun Spot cycle
  – Solar flares, coronal mass ejections, etc. from the sun

• Because OTH radars can detect targets at great ranges they have very large antennas and very high power transmitters
Summary

• The atmosphere can have a significant effect on radar performance
  – Attenuation and diffraction of radar beam
  – Refracting of the beam as it passes through the atmosphere
    Causes angle measurement errors
  – Radar signal strength can vary significantly due to multipath effects
    Reflections from the ground interfering with the main radar beam
  – Frequencies from 3 to 30 MHz can be used to propagate radar signals over the horizon
    Via refraction by the ionosphere
  – The above effects vary with the wavelength of the radar, geographic and varying atmospheric conditions
References

Homework Problems

  – Problem 8-1
  – Problem 8.8
  – Problem 8-11
Acknowledgements

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• Dr. Curt W Davis, III