Professional Development Short Course On:

Propagation Effects for Radar & Comm Systems

Instructor:

G. Daniel Dockery

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OUTLINE

• Part 1: Over-Sea Propagation
• Part 2: Scalar Parabolic Equation (PE) Algorithms
• Part 3: Over-Land Propagation
• Part 4: 3-D Vector PE Modeling
Part 1 Outline: Over-Sea Propagation

- Introduction & Radar Equation
- Surface Reflection
- Multipath
- Rough Sea Effects
- Spherical Earth Diffraction & Radio Horizon
- Physical Optics Models
- Atmospheric Refractivity
- Atmospheric Measurements
- Evaporation Ducting
- Synoptic Weather Factors
- Sea Clutter
- HF Propagation
Radar Equation

We begin by reviewing the basic monostatic radar range equation describing received power for a radar system:

\[ P_r = \frac{P_t G_t G_r \lambda^2 PF^4 \sigma_{RCS}}{(4\pi)^3 r^4 L} \]

Where
- \( P_t \) = Transmitted power
- \( G_t \) = Transmit antenna gain
- \( G_r \) = Receive antenna gain
- \( \lambda \) = Radar wavelength
- \( PF \) = Pattern Propagation Factor
- \( r \) = Slant range from radar to target
- \( \sigma_{RCS} \) = Target radar cross section (RCS)
- \( L \) = Miscellaneous system losses
Path Loss

Another quantity frequently used to describe propagation effects is path loss \((PL)\). The relation between \(PF\) and \(PL\) is

\[
PL = \frac{\lambda^2}{(4\pi)^2 r^2} PF^2
\]

This quantity is most useful for one-way communications problems, where the transmission equation can be written in terms of \(PL\) as

\[
P_r = P_t G_t G_r PF^2 \frac{\lambda^2}{(4\pi r)^2}
= P_t G_t G_r PL
\]

The results presented in this course will generally be presented in terms of \(PF^2\) or \(PF^4\).
Multipath Geometry

“Flat Earth”

Source

Earth’s Surface

$\theta = -\theta_g$

$r' = r_1 + r_2$

$\theta_g$

$r_1$

$r_2$

$r$

“Direct” Field

Specularly Reflected Field
Multipath, 3 GHz, $z_s = 20$ m V-pol
Multipath, 3 GHz, $z_s = 20$ m at height = 200 m

![Graph showing multipath effects with PF$^2$ dB vs range [km]. The graph includes two curves: H-pol (red) and V-pol (blue).]
Earth Horizon Geometry
4/3 earth horizon, $z_s = 20$ m, V-pol 3 GHz
4/3 earth horizon, \( z_s = 20 \) m, V-pol at height = 200 m

Horizon = 76.8 km
Effective Earth Radius (k-factor)

$k_{\text{eff}}$ is such that $h=h'$ at each range when ray is drawn straight. Since ray curvature depends on refraction, $k_{\text{eff}}$ also depends on refractive conditions.
Propagation Conditions
Horizontally Launched Rays

- **Subrefraction**
  \[ \frac{dN}{dz} > 0 \]

- **Free Space**
  \[ \frac{dN}{dz} = 0 \]

- **Standard**
  \[ \frac{dN}{dz} = -39 \]

- **Superrefraction**
  \[ \frac{dN}{dz} < -39 \]

- **Ducting**
  \[ \frac{dN}{dz} < -157 \]

- **Ducting Threshold**
  \[ \frac{dN}{dz} = -157 \]
Physical Optics Regions

interference region

PKF^2 [dB]

range [km]

Diffraction Region

Bold Interpolation Region
Physical Optics – PE Comparison

3 GHz, 100-ft Antenna Altitude, V-Pol.
Standard Atmosphere, 500 ft Altitude

Propagation Factor (dB)

Range (nmi)
Atmospheric refraction has a large effect on system performance – The “standard atmosphere” assumption is often inadequate.
Strong Surface-Based Ducting

Standard Atmosphere
$k_{eff} = 1.33$

One-Way Propagation Factor $F^2$
- S-Band
- 50-foot Antenna
- Narrow Beamwidth
  Sin(x)/x Pattern

Measured Surface-Based Duct Profile
Circulation Associated with Sea-Breeze

This situation results in the over-water conditions persisting some distance inland.
Advection Off Shore

This situation results in a surface duct increasing in height away from shore.
Helicopter Instrumentation

- Usual Aircraft: Bell Jet or Long Ranger
- Crew: Civilian Pilot & 2 APL Engineers
- Custom APL Instrumentation
Helicopter Vertical Profiles

Instrumented Helicopter

~600 m

Shipboard Radars

10 km
Helo Data Sample collected
September 2001 Near Camp Pendleton, CA

Outbound Run

STD

Land

Start:
2.07 9.90 15.43 22.73 29.66 37.19 44.38 51.10 56.90 69.75 62.79 65.04 nmi

Stop:
7.18 13.24 20.29 27.97 35.36 42.02 48.60 56.07 63.91 61.75 64.69 65.27 nmi
Propagation Diagram

- Measured Environment (all profiles)
Clutter Power Equation

Ignoring propagation effects, the monostatic radar equation for received clutter power by a pulsed radar may be written as

\[ P_r = \frac{P_t G^2 \lambda^2 f^4}{(4\pi)^3 r^3} \left( \sigma_o \theta_B \frac{c\tau}{2} \right) \]

where \( G \) is the antenna gain assumed for both transmit & receive, \( f^4 \) is the two-way antenna pattern factor in the direction of the surface, \( c \) is the speed of light, \( \theta_B \) is the azimuth beamwidth, and \( \tau \) is the pulse width. This is the equation that has historically been inverted to estimate \( \sigma_o \) using data from clutter measurement campaigns. Thus, in empirically based models for \( \sigma_o \), the propagation effects are embedded in the normalized cross section.
Sea Clutter Geometry

Monostatic Pulsed Radar

\[ c \tau / 2 \]

\[ \theta_g \]

\[ c \tau \sec \theta_g / 2 \]

\[ \theta_B \]

\[ r \theta_B \]
HF Propagation Mode Diagram

- Ionosphere
- Sky Wave
- Ground Wave
- Surface Wave
- Earth
## Ionosphere Effects Summary

<table>
<thead>
<tr>
<th>Effect</th>
<th>Freq. Dep.</th>
<th>0.5 GHz</th>
<th>1 GHz</th>
<th>3 GHz</th>
<th>10 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faraday Rotation (deg)</td>
<td>$1/f^2$</td>
<td>432</td>
<td>108</td>
<td>12</td>
<td>1.1</td>
</tr>
<tr>
<td>Propagation Delay (µsec)</td>
<td>$1/f^2$</td>
<td>1</td>
<td>0.25</td>
<td>0.028</td>
<td>0.0025</td>
</tr>
<tr>
<td>Excess Range Delay (m)</td>
<td>$1/f^2$</td>
<td>300</td>
<td>75</td>
<td>8.3</td>
<td>0.75</td>
</tr>
<tr>
<td>Refraction (‘ or “”)</td>
<td>$1/f^2$</td>
<td>$&lt;2.4’$</td>
<td>$&lt;0.6’$</td>
<td>$&lt;4.2”$</td>
<td>$&lt;0.36”$</td>
</tr>
<tr>
<td>RMS Dir. Of Arrival (“”)</td>
<td>$1/f^2$</td>
<td>48”</td>
<td>12”</td>
<td>1.32”</td>
<td>0.12”</td>
</tr>
<tr>
<td>Absorption (auroral/polar) (dB)</td>
<td>$~1/f^2$</td>
<td>0.2</td>
<td>0.05</td>
<td>0.006</td>
<td>$5\times10^{-4}$</td>
</tr>
<tr>
<td>Absorption (mid-latitude) (dB)</td>
<td>$1/f^2$</td>
<td>$&lt;0.04$</td>
<td>$&lt;0.01$</td>
<td>$&lt;0.001$</td>
<td>$&lt;10^{-4}$</td>
</tr>
<tr>
<td>Dispersion (psec/Hz)</td>
<td>$1/f^3$</td>
<td>0.004</td>
<td>0.0005</td>
<td>1.9$\times10^{-5}$</td>
<td>5$\times10^{-7}$</td>
</tr>
<tr>
<td>Scintillation (dB)</td>
<td></td>
<td>$&gt;20$</td>
<td>$\sim10$</td>
<td>$\sim4$</td>
<td></td>
</tr>
</tbody>
</table>

TEC=$1.86\times10^{18}$ m$^{-1}$; B=0.43 Gauss; Angle through ionosphere=30 deg
Part 2 Outline: Scalar PE Algorithms

• Summary of Modeling Approaches
• Vector & Scalar Wave Equations
• Parabolic Wave Equations
• Numerical Solution Approaches
• Basic and Mixed Fourier Split Step Solutions
• Source Modeling
• Surface Roughness
• Validation Examples
Part 3 Outline: Propagation Over Terrain

- Introduction
- Primary Terrain-related Effects
- Propagation Modeling Approaches
- Modeling Propagation Over Terrain With PE Models
- Refractivity Characteristics
- Land Clutter
Part 4 Outline:
3-D Vector PE Modeling

• Introduction

• 3-D Scalar PE Approaches (Brief Summary)

• 3-D Vector PE Modeling

• Modeling Propagation Over Terrain

• RCS Calculations (Brief Summary)
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