RADIOWAVE PROPAGATION: PHYSICS AND APPLICATIONS
I. Introduction

1. EM waves and propagation
2. Influence of frequency
3. Propagation mechanisms
II. EM Waves and propagation

- All of us are familiar with use of EM waves for information transmission
- All systems have three generalized components:
  - Transmitter: information carrying circuit level signal generated and converted to EM wave
  - Propagation: EM wave travels from transmitter to receiver through external environment
  - Receiver: EM wave converted to circuit signals and information extracted
- Environmental effects can have large influence on propagation component
• Use of EM waves eliminates need for wires: first predicted in 1865 by Maxwell
• Maxwell’s predictions verified experimentally by Hertz in 1880’s
• Demonstrated by Marconi in 1901 with wireless communications across the Atlantic
• Since then many studies of propagation have been conducted so there is a vast amount of experience and information available
• The complexity of most propagation environments makes exact predictions impossible, so usually only simple physical models combined with empirical data are available
Current technology exists to transmit and receive electromagnetic waves over a large range of frequencies: from 10 kHz to $10^{15}$ Hz!

A basic rule of thumb: EM waves tend to be affected most by structures comparable to or larger than one wavelength.

From this, we can see that since the Earth environment has structures on a wide range of scales, we should expect propagation phenomena to vary with frequency.

Example Earth scales: atmospheric particles, vegetation and forests, mountains, Earth curvature!

Because of this, frequency plays a large role in propagation effects, and names have been provided to specific frequency bands to illustrate this.
<table>
<thead>
<tr>
<th>Band name</th>
<th>Abbreviation</th>
<th>Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very-low frequency</td>
<td>VLF</td>
<td>3 to 30 kHz</td>
</tr>
<tr>
<td>Low frequency</td>
<td>LF</td>
<td>30 to 300 kHz</td>
</tr>
<tr>
<td>Medium frequency</td>
<td>MF</td>
<td>300 kHz to 3 MHz</td>
</tr>
<tr>
<td>High frequency</td>
<td>HF</td>
<td>3 MHz to 30 MHz</td>
</tr>
<tr>
<td>Very-high frequency</td>
<td>VHF</td>
<td>30 MHz to 300 MHz</td>
</tr>
<tr>
<td>Ultra-high frequency</td>
<td>UHF</td>
<td>300 MHz to 3 GHz</td>
</tr>
<tr>
<td>Super-high frequency</td>
<td>SHF</td>
<td>3 GHz to 30 GHz</td>
</tr>
<tr>
<td>Extremely-high frequency</td>
<td>EHF</td>
<td>30 GHz to 300 GHz</td>
</tr>
</tbody>
</table>

**Table:** IEEE Frequency Band Designations
<table>
<thead>
<tr>
<th>Band name</th>
<th>Frequencies (GHz)</th>
<th>Wavelengths (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1.0-2.0</td>
<td>15-30</td>
</tr>
<tr>
<td>S</td>
<td>2.0-4.0</td>
<td>7.5-15</td>
</tr>
<tr>
<td>C</td>
<td>4.0-8.0</td>
<td>3.75-7.5</td>
</tr>
<tr>
<td>X</td>
<td>8.0-12.0</td>
<td>2.5-3.75</td>
</tr>
<tr>
<td>$K_u$</td>
<td>12.0-18.0</td>
<td>1.67-2.5</td>
</tr>
<tr>
<td>$K$</td>
<td>18.0-27.0</td>
<td>1.11-1.67</td>
</tr>
<tr>
<td>$K_a$</td>
<td>27.0-40.0</td>
<td>0.75-1.11</td>
</tr>
<tr>
<td>V</td>
<td>40.0-75.0</td>
<td>0.40-0.75</td>
</tr>
<tr>
<td>W</td>
<td>75.0-110</td>
<td>0.27-0.40</td>
</tr>
</tbody>
</table>

**Table:** Microwave Frequency Band Designations
III. Propagation mechanisms

- Direct transmission - Ch 5
- Atmospheric refraction - Ch 6
- Ducting - Ch 6
- Direct plus ground reflections - Ch 7
- Terrain diffraction - Ch 7
- Empirical path loss and fading models - Ch 8
- Groundwave - Ch 9
- Ionospheric reflections - Ch 10-11
- Others - Ch 12
Virtual reflection point

Ionosphere

Actual path

Earth
# Propagation Mechanisms and Applications

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Applications</th>
</tr>
</thead>
</table>
| Direct                           | Most radar systems.  
<p>|                                  | SHF ground-to-satellite links.                                 |
| Direct plus Earth reflections    | UHF broadcast TV with high-gain antennas.                     |
|                                  | Ground-to-air and air-to-air communications.                   |
| Multipath environments           | VHF and higher ground-based point-to-point links (especially in urban areas). |
| Groundwave                       | Local standard broadcast (AM).                                 |
|                                  | Local HF links.                                                |
| Ionospheric waveguide ($D$ layer)| VLF and LF systems for long-range communications and navigation. |
| Ionospheric skywave ($E$, $F$ layers)| MF and HF broadcast and communications (including long-range amateur radio). |
| Tropospheric scatter             | UHF medium-range communications.                               |
| Ionospheric scatter              | Experimental medium-range communications in lower VHF band.    |
| Meteor scatter                   | VHF experimental long-range communications.                    |</p>
<table>
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<tr>
<th>Frequency Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLF to LF (10 to 200 kHz)</td>
<td>Waveguide mode between Earth and D-layer. Groundwave at short distances.</td>
</tr>
<tr>
<td>LF to MF (200 kHz to 2 MHz)</td>
<td>Transition between groundwave and waveguide mode predominance to skywave (ionospheric hops). Skywave especially pronounced at night.</td>
</tr>
<tr>
<td>HF (2 to 30 MHz)</td>
<td>Ionospheric hops. Very long-range communications with low power and simple antennas. The “short-wave” band.</td>
</tr>
<tr>
<td>VHF (30-100 MHz)</td>
<td>Low power and small antennas. Primarily for short-range using direct or direct-plus-Earth-reflected propagation (ducting can greatly increase the propagation range).</td>
</tr>
<tr>
<td>UHF (80-500 MHz)</td>
<td>Direct: early-warning radars, air-to-satellite and satellite-to-satellite communications.</td>
</tr>
<tr>
<td></td>
<td>Direct-plus-earth-reflected: air-to-ground communications, local television.</td>
</tr>
<tr>
<td></td>
<td>Tropospheric scatter: when large highly directional antennas and high power are used.</td>
</tr>
<tr>
<td>SHF (500 MHz to 10 GHz)</td>
<td>Direct: most radars, satellite communications.</td>
</tr>
<tr>
<td></td>
<td>Tropospheric refraction, terrain diffraction, and multipath become important in ground-to-ground links and in satellite communications at low elevation angles.</td>
</tr>
</tbody>
</table>
Characterization of Propagation Media

1. Information resources
2. Maxwell’s equations
3. Constitutive relations
4. Types of dielectric media
II. Information resources

- **International Telecommunication Union (ITU):** Regulates communications internationally. Holds an international meeting every 4 years, issues reports and recommendations.

- **Institute for Telecommunications Sciences (ITS):** Branch of U.S. Dept. of Commerce, National Telecommunications and Information Administration (NTIA).

- **Naval Command, Control, and Ocean Surveillance Center (NCCOSC).**

- **Federal Communications Commission.**

- **World Wide Web.**
III. Maxwell’s Equations

\[
\nabla \times \overrightarrow{H} = \frac{\partial \overrightarrow{D}}{\partial t} + \overrightarrow{J} \quad (1)
\]

\[
\nabla \times \overrightarrow{E} = -\frac{\partial \overrightarrow{B}}{\partial t} \quad (2)
\]

\[
\nabla \cdot \overrightarrow{D} = \rho \quad (3)
\]

\[
\nabla \cdot \overrightarrow{B} = 0 \quad (4)
\]

Eight scalar equations for twelve scalar unknown functions, not all independent

\[
\nabla \cdot \overrightarrow{J} = -\frac{\partial \rho}{\partial t} \quad (5)
\]

\[
\nabla \cdot \overrightarrow{J}_S = -\frac{\partial \rho_s}{\partial t} \quad (6)
\]
III. Maxwell’s Equations (cont’d)

\[ \hat{n} \times (\overline{H}_2 - \overline{H}_1) = \overline{J}_S \quad (7) \]
\[ \hat{n} \times (\overline{E}_2 - \overline{E}_1) = 0 \quad (8) \]
\[ \hat{n} \cdot (\overline{D}_2 - \overline{D}_1) = \rho_S \quad (9) \]
\[ \hat{n} \cdot (\overline{B}_2 - \overline{B}_1) = 0 \quad (10) \]
IV. Constitutive relations

A relationship between $D$ and $E$ and between $B$ and $H$ is required to make Maxwell’s equations solvable; these are the constitutive relations

The simplest possible constitutive relations:

$$D = \epsilon E$$  \hspace{1cm} (11) \\
$$B = \mu H$$  \hspace{1cm} (12)

but these are not always applicable!
IV. Constitutive relations (cont’d)

Model: fields in a material are those in free space plus fields produced by induced dipole moments in material

\[ \mathbf{D}(\mathbf{r}, t) = \epsilon_0 \mathbf{E}(\mathbf{r}, t) + \mathbf{P}(\mathbf{r}, t) \]  

(13)

where \( \mathbf{P} \) is the induced dipole moment per unit volume in the material. Note we still need a relationship between \( \mathbf{P} \) and \( \mathbf{E} \)!
V. Types of dielectric media

Relationship between applied field $\bar{E}$ and induced dipole moment density $\bar{P}$ will depend on the properties of the medium. There are many possible medium properties:

- **Nonlinearity** - $\bar{P}$ proportional to powers of $\bar{E}$ other than first
- **Anisotropy** - $\bar{P}$ depends on direction of $\bar{E}$
- **Dispersion** - $\bar{P}$ depends on the frequency of $\bar{E}$
- **Inhomogeneity** - $\bar{P}$ depends on $\bar{r}$
- **Time dependence** - $\bar{P}$ depends on $t$
V. Types of dielectric media (cont’d)

The simplest medium has none of the aforementioned properties, so

\[ \overline{P}(\vec{r}, t) = \chi \epsilon_0 \overline{E}(\vec{r}, t) \]  \hspace{1cm} (14) \]

and

\[ \overline{D}(\vec{r}, t) = \epsilon_0 (1 + \chi) \overline{E}(\vec{r}, t) = \epsilon_0 \epsilon_r \overline{E}(\vec{r}, t) = \epsilon \overline{E}(\vec{r}, t) \]  \hspace{1cm} (15) \]
Inhomogeneous and time-varying media can be handled through

\[ \overline{D}(\overline{r}, t) = \epsilon(\overline{r}, t)\overline{E}(\overline{r}, t) \] (16)

Anisotropic media can be handled through a tensor-valued permittivity

\[
\begin{bmatrix}
\epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\
\epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\
\epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz}
\end{bmatrix}
\] (17)
Dispersion results due to time response of medium

\[ \overline{P}(\bar{r}, t) = \varepsilon_0 \int_{-\infty}^{t} \overline{E}(\bar{r}, t') f(t - t') dt' \]  \hspace{1cm} (18)

or

\[ \overline{P}(\bar{r}, t) = \text{Re} \left[ \varepsilon_0 \overline{E}_0(\bar{r}) e^{j\omega t} \int_{0}^{\infty} e^{-j\omega u} f(u) du \right] \]  \hspace{1cm} (19)

for the sinusoidal steady state.
A relationship between phasors $\overline{P}_0$ and $\overline{E}_0$ is thus

$$\overline{P}_0(\bar{r}) = \chi(\omega)\epsilon_0 \overline{E}_0(\bar{r})$$  \hspace{1cm} (20)

for dispersive media, where

$$\chi(\omega) = \int_0^\infty e^{-j\omega u} f(u) du$$ \hspace{1cm} (21)

The last equation defines the complex susceptibility, $\chi(\omega)$, and

$$\overline{D}_0(\bar{r}) = \epsilon(\omega)\overline{E}_0(\bar{r})$$ \hspace{1cm} (22)

Imaginary part of $\epsilon$ indicates dielectric losses. Power lost in “frictional” motion of particles. Note that $\overline{D}(\bar{r}, t)$ and $\overline{E}(\bar{r}, t)$ may not be in the same direction!
Dielectric constant

Frequency (Hz)

Real

Imaginary

Molecular Orientational

Atomic Rotations/Vibrations
(Molecular Spectra)

Electronic Transitions
(Atomic Spectra)

Interfacial

Interfacial
(a) Distilled water, 25 C

(b) Carbon Tetrachloride, 25 C
Conductive media can be handled through Ohm’s law,

\[
\bar{J}(\vec{r}, t) = \sigma \bar{E}(\vec{r}, t)
\] (23)

and the phasor form of Ampere’s law,

\[
\nabla \times \bar{H}_0(\vec{r}) = \bar{J}_0(\vec{r}) + j \omega \bar{D}_0(\vec{r})
\] (24)

to get

\[
\nabla \times \bar{H}_0(\vec{r}) = (\sigma + j \omega \varepsilon) \bar{E}_0(\vec{r})
\] (25)

\[
= j \omega (\varepsilon - j \sigma / \omega) \bar{E}_0(\vec{r})
\] (26)
If one separates out the real and imaginary parts of the dielectric constant

\[ \epsilon = \epsilon_R - j\epsilon_I \]  

(27)

and rearranges the terms slightly, the result is

\[ \nabla \times \mathbf{H}_0(\mathbf{r}) = j\omega [\epsilon_R - j(\epsilon_I + \sigma/\omega)] \mathbf{E}_0(\mathbf{r}) \]  

(28)

showing that conduction and dielectric losses effects can be combined into a single imaginary part of the permittivity or into an "effective" conductivity. Be careful when using tables! We will define

\[ \epsilon^e = \epsilon_R - j(\epsilon_I + \sigma/\omega) \]  

(29)
A: sea water (average salinity), 20° C
B: wet ground
C: fresh water, 20° C
D: medium dry ground
E: very dry ground
F: pure water, 20° C
G: ice (fresh water)