OUTLINE

More history
Index of Refraction
More basic radar
It is frequently said that, although the atomic bomb ended World War II, it was radar that won the war.
The primary technical barrier to developing UHF systems was the lack of a usable source for generating high-power microwaves.

In February 1940, John Randall and Harry Boot at Birmingham University in the UK built a resonant cavity magnetron.

Bombing of London Sept 1940 – May 1941 (The Blitz)

Britain was interested in developing practical applications for airborne microwave radar, but did not have the large-scale manufacturing ability to mass produce magnetrons.

In 1940, Britain partnered with the US National Defense Research Committee (NDRC)
Over the course of five years, MIT researchers designed 50 percent of the radar used in World War II and invented over 100 different radar systems.

Including:
- Airborne bombing radars
- Shipboard search radars
- Harbor and coastal defense radars
- Interrogate-friend-or-foe beacon systems
- Long-range navigation (LORAN) system
- Critical contributions of the Radiation Laboratory were:
  - the microwave early-warning (MEW) radars, which effectively nullified the V-1 threat to London, and
  - air-to-surface vessel (ASV) radars, which turned the tide on the U-boat threat to Allied shipping.
Millstone

The BMEWS Prototype

Millstone Radar
1957

First in Space Surveillance

Sputnik
A-Scope Trace
Until 1976, it was almost unknown that Appleton had collaborated with the Austrian physicist Wilhelm Altar on magneto-ionic theory in 1925-26. Altar wrote a paper which contains the magneto-ionic equations in so-called “dielectric tensor” form, and in general terms contains what would today be called the dispersion relation in cold plasma theory.
Radar Range Measurement

Target range = \( \frac{c \tau}{2} \)

where c = speed of light
\( \tau \) = round trip time
Phase Velocity, Group Velocity, Index of Refraction

\[ v_p = \frac{\omega}{k} \]

\[ v_g = \frac{\partial \omega}{\partial k} \]

\[ n = \frac{c}{v_p} \]
Illustration of Atmospheric Effects

- Troposphere
- Ionosphere
- Observed bearing
- True bearing
- Total refraction error in elevation
- True range
- Observed range
- Total refraction error in range
Index of Refraction in the Ionosphere

\[ n^2 = 1 - \frac{X(1 - X)}{(1 - X) - \frac{1}{2} Y_T^2} \pm \left( \frac{1}{4} Y_T^4 + (1 - X)^2 Y_L^2 \right)^{\frac{1}{2}} \]

\[ X = \frac{\omega_N^2}{\omega^2}, \quad Y = \frac{\omega_H}{\omega}, \quad \omega_N = \left( \frac{N e^2}{\varepsilon_0 m_e} \right)^{\frac{1}{2}}, \quad \omega_H = \frac{e|B|}{m_e} \]

\( \omega \) = the angular frequency of the radar wave,
\( Y_L = Y \cos \theta, \quad Y_T = Y \sin \theta, \)
\( \theta \) = angle between the wave vector \( \vec{k} \) and \( \vec{B} \),
\( \vec{k} \) = wave vector of propagating radiation,
\( \vec{B} \) = geomagnetic field,
\( N \) = electron density
\( e \) = electronic charge,
\( m_e \) = electron mass,
and \( \varepsilon_0 \) = permittivity constant.
Outline

• More History
• Index of Refraction
More Basic Radar
RADAR
Radio Detection And Ranging

Radar observables:
- Target range
- Target angles (azimuth & elevation)
- Target size (radar cross section)
- Target speed (Doppler)
- Target features (imaging)
Radar Block Diagram

MIT Haystack Observatory
Radar Range Equation

\[ \text{Received Signal Energy} = \left[ \frac{4\pi A}{\lambda^2} \right] \left[ \frac{1}{4\pi R^2} \right] \left[ \frac{1}{L} \right] \left[ \sigma \right] \left[ \frac{1}{4\pi R^2} \right] \left[ A \right] \left[ \tau \right] \]
Pulsed Radar Terminology and Concepts

Duty cycle = \( \frac{\text{Pulse length}}{\text{Pulse repetition interval}} \)

\[ 10\% \]

Average power = Peak power \* Duty cycle

\[ 100 \text{ kWatt} \]

Pulse repetition frequency (PRF) = \( \frac{1}{\text{PRI}} \)

\[ 1 \text{ kHz} \]

Continuous wave (CW) radar: Duty cycle = 100% (always on)
What do radars transmit?

- Waves?
- Waves, modulated by “on-off” action of pulse envelope
- or Pulses?
Properties of Waves

Relationship Between Frequency and Wavelength

\[ \text{Speed of light, } c \\
= 3 \times 10^8 \text{ m/sec} \\
= 300,000,000 \text{ m/sec} \]

\[ \text{Frequency (1/s)} = \frac{\text{Speed of light (m/s)}}{\text{Wavelength } \lambda (\text{m})} \]

Examples:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 MHz</td>
<td>3 m</td>
</tr>
<tr>
<td>1 GHz</td>
<td>30 cm</td>
</tr>
<tr>
<td>3 GHz</td>
<td>10 cm</td>
</tr>
<tr>
<td>10 GHz</td>
<td>3 cm</td>
</tr>
</tbody>
</table>
Properties of Waves
Phase and Amplitude

Amplitude (volts)

Phase, $\theta$

$A \sin(\theta)$

$90^\circ$ phase offset

Amplitude (volts)

Phase, $\theta$

$A \sin(\theta - 90^\circ)$
Properties of Waves
Constructive vs. Destructive Addition

<table>
<thead>
<tr>
<th>Constructive (in phase)</th>
<th>Destructive (180° out of phase)</th>
<th>Partially Constructive (somewhat out of phase)</th>
<th>Non-coherent signals (noise)</th>
</tr>
</thead>
</table>

- Constructive waves add to produce a larger, more intense wave.
- Destructive waves cancel each other out, resulting in a null effect.
- Partially constructive waves produce a wave of intermediate intensity.
- Non-coherent signals are random and do not interfere constructively.
Polarization

Electromagnetic Wave

Vertical Polarization

Horizontal Polarization
Doppler Shift Concept

\[ f = \frac{c}{\lambda} \]

\[ f' = f \pm \frac{2v}{\lambda} \]
Resolving Doppler

Tx signal: \( \cos(2\pi f_0 t) \)
Doppler shifted: \( \cos[2\pi(f_0 + f_D)t] \)

Multiply by \( \cos(2\pi f_0 t) \) -> Low pass filter -> \( \cos(2\pi f_D t) \)

BUT, the sign of \( f_D \) is lost (cosine is an even function)

So, instead use
\[
\exp(j2\pi f_D t) = \cos(2\pi f_D t) + j\sin(2\pi f_D t)
\]

Generate this signal by mixing cos and sin via two oscillators (same frequency, 90° out of phase)

Components are called I (In phase) and Q (Quadrature): \( A\exp(j2\pi f_D t) = I + jQ \)