Fundamentals of Radar

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Outline

1. Definition and Principles of radar
2. Radar Frequencies
3. Radar Types and Applications
4. Radar Operation
5. Radar modes
What is Radar?

- **RADAR (Radio Detection And Ranging)** is a way to detect and study far-off targets by transmitting a radio pulse in the direction of the target and observing the reflection of the wave.

- It’s basically radio echo
RADAR Operation

RA dio Detection And Ranging

Antenna

Transmitted Pulse

Propagation

Reflected Pulse (“echo”)

Target Cross Section

Radar observables:

- Target range
- Target angles (azimuth & elevation)
- Target size (radar cross section)
- Target speed (Doppler)
- Target features (imaging)
A radar operator view [4]
<table>
<thead>
<tr>
<th>Mile</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>statute</strong></td>
<td><strong>nautical</strong></td>
</tr>
<tr>
<td>1.609344 km</td>
<td>1.852 km</td>
</tr>
<tr>
<td>1,609.344 m</td>
<td>1,852 m</td>
</tr>
</tbody>
</table>
Brief history of radar

- Conceived as early as 1880 by Heinrich Hertz
  - Observed that radio waves could be reflected off metal objects.
- Radio Aid to Detection And Ranging
- 1930s
  - Britain built the first ground-based early warning system called Chain Home.
- 1940
  - Invention of the magnetron permits high power transmission at high frequency, thus making airborne radar possible.
Brief history of radar

Currently

- Radar is the primary sensor on nearly all military aircraft.
- Roles include airborne early warning, target acquisition, target tracking, target illumination, ground mapping, collision avoidance, altimeter, weather warning.
- Practical frequency range 100MHz-100GHz.
THE ELECTROMAGNETIC SPECTRUM

Wavelength (in meters)

- Longer: Soccer Field, House, Baseball, This Period
- Shorter: Cell, Bacteria, Virus, Protein, Water Molecule

Common name of wave

- RADIO WAVES
- INFRARED
- ULTRAVIOLET
- "HARD" X RAYS
- "SOFT" X RAYS
- GAMMA RAYS

Sources

- AM Radio
- HF Cavity
- FM Radio
- Microwave Oven
- Radar
- People
- Light Bulb
- The ALS
- X-Ray Machines
- Radioactive Elements

Frequency (waves per second)

- $10^6$ to $10^10$

Radar Frequencies
Radar Frequency Bands

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
<td>1 km</td>
</tr>
<tr>
<td>1 GHz</td>
<td>1 m</td>
</tr>
<tr>
<td>$10^9$ Hz</td>
<td>1 mm</td>
</tr>
<tr>
<td>$10^{12}$ Hz</td>
<td>1 μm</td>
</tr>
<tr>
<td>IR</td>
<td>1 nm</td>
</tr>
</tbody>
</table>

| Visible   | 10 Hz      |
| IR        | 10 Hz      |

- **UHF**: Ultra High Frequency
- **VHF**: Very High Frequency
- **L-Band**: Lower Band
- **S-Band**: Lower Sideband
- **C-Band**: Center Band
- **X-Band**: Extended Band

Allocated Frequency (GHz):

<table>
<thead>
<tr>
<th>Band</th>
<th>Allocated Frequency</th>
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</thead>
<tbody>
<tr>
<td>UHF</td>
<td>0.2375 GHz - 0.3425 GHz</td>
</tr>
<tr>
<td>VHF</td>
<td>2.575 GHz - 3.875 GHz</td>
</tr>
<tr>
<td>L-Band</td>
<td>4.775 GHz - 5.25 GHz</td>
</tr>
<tr>
<td>S-Band</td>
<td>8.25 GHz - 9.75 GHz</td>
</tr>
<tr>
<td>C-Band</td>
<td>9.75 GHz - 12.75 GHz</td>
</tr>
<tr>
<td>X-Band</td>
<td>12.75 GHz - 15 GHz</td>
</tr>
</tbody>
</table>

Ku, K, Ka, W Bands:

- **Ku Band**: 12.75 GHz - 14.5 GHz
- **K Band**: 17 GHz - 27 GHz
- **Ka Band**: 26.5 GHz - 40 GHz
- **W Band**: Above 40 GHz
1.3 Airborne radar bands [1]

Figure 3.3 Airborne radar frequency coverage.
1.3.1 Airborne radar bands [1]


<table>
<thead>
<tr>
<th>Band designator&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Nominal frequency range</th>
<th>ITU assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>3–30 MHz</td>
<td>138–144 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>216–225 MHz</td>
</tr>
<tr>
<td>VHF</td>
<td>30–300 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>420–450 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>850–942 MHz</td>
</tr>
<tr>
<td>UHF</td>
<td>300–1000 MHz</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1–2 GHz</td>
<td>1215–1400 MHz</td>
</tr>
<tr>
<td>S</td>
<td>2–4 GHz</td>
<td>2300–2500 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2700–3700 MHz</td>
</tr>
<tr>
<td>C</td>
<td>4–8 GHz</td>
<td>5250–5925 MHz</td>
</tr>
<tr>
<td>X</td>
<td>8–12 GHz</td>
<td>8500–10 680 MHz</td>
</tr>
<tr>
<td>Ku</td>
<td>12–18 GHz</td>
<td>13.4–14.0 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.7–17.7 GHz</td>
</tr>
<tr>
<td>K</td>
<td>18–27 GHz</td>
<td>24.05–24.25 GHz</td>
</tr>
<tr>
<td>Ka</td>
<td>27–40 GHz</td>
<td>33.4–36 GHz</td>
</tr>
<tr>
<td>V</td>
<td>40–75 GHz</td>
<td>59–64 GHz</td>
</tr>
<tr>
<td>W</td>
<td>75–110 GHz</td>
<td>76–81 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92–100 GHz</td>
</tr>
<tr>
<td>mm</td>
<td>110–300 GHz</td>
<td>126–142 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>144–149 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>231–235 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>238–248 GHz</td>
</tr>
</tbody>
</table>

<sup>a</sup>IEEE Std 521–1984.
1.3.2 Airborne radar bands \[1\]

Figure 3.4  Effects of atmospheric attenuation.
The Range

- Distance from the radar
- Measured from time delay between transmitted pulse and returned signal received
The Range

- Remember, in general $v = \frac{d}{t}$ and $d = vt$
- The range is just a distance
- Since radio waves travel at the speed of light ($v = c = 300,000 \text{ km/sec}$)
  \[ \text{range} = c \cdot \text{time}/2 \]
- Why divided by 2?
The Range

- The “2” is because the measured time is for a round trip to and from the target. To determine the range, you only want the time to the object, so you take half!
Radar Range Measurement

Target range \( = \frac{ct}{2} \)

where \( c \) = speed of light
\( \tau \) = round trip time
Radar

- The range and the direction of the target determine its location. This is the job for many radar applications such as air traffic control.
The strength of the received echo can also be measured.

This will vary with the distance of the target, its size, its shape and its composition.
Types and Uses of Radar

- Search radars scan a large area with pulses of short radio waves.

- Targeting radars use the same principle but scan a smaller area more often.

- Navigational radars are like search radar, but use short waves that reflect off hard surfaces. They are used on commercial ships and long-distance commercial aircraft.
Types and Uses of Radar

- Mapping radar scans a large regions for remote sensing and geography applications.

- Wearable radar which is used to help the visually impaired as a substitute to eye.

- Air traffic control uses radar to reflect echoes off of aircraft.

- Weather radar uses radar to reflect echoes off of clouds.
Types and Uses of Radar

- Weather radars use radio waves with horizontal, dual (horizontal and vertical), or circular polarization.

- Some weather radars use the Doppler effect to measure wind speeds.
Incoherent Scatter Radar- A Radar Application

- Used to study the Earth's ionosphere and its interactions with the upper atmosphere, the magnetosphere, and the solar wind
Two Basic Types of Radar

- Continuous Wave
- Pulse Transmission
Continuous Wave Radar

- Employs continual RADAR transmission

- Separate transmit and receive antennas

- Relies on the “DOPPLER SHIFT”
Doppler Frequency Shifts

Motion Away:
Echo Frequency Decreases

Motion Towards:
Echo Frequency Increases
Continuous Wave Radar Components

Transmitter

CW RF Oscillator

Discriminator

AMP

Mixer

Indicator

Antenna

OUT

IN

Antenna
A pulsed radar is characterized by a high power transmitter that generates an endless sequence of pulses. The rate at which the pulses are repeated is defined as the pulse repetition frequency.

Parameters:
- pulse width, $\tau$, usually expressed in $\mu$sec
- pulse repetition frequency, $\text{PRF}$, usually in kHz
- pulse period, $T_p = 1/\text{PRF}$, usually in $\mu$sec
Pulse Transmission

Figure 2–1. Pulse transmission.
Pulse Transmission

- Pulse Width (PW)
  - Length or duration of a given pulse
- Pulse Repetition Time (PRT=1/PRF)
  - PRT is time from beginning of one pulse to the beginning of the next
  - PRF is frequency at which consecutive pulses are transmitted.
- PW can determine the radar’s minimum detection range; PW can determine the radar’s maximum detection range.
- PRF can determine the radar’s maximum detection range.
- **Pulse repetition frequency (PRF)**
  - a. Pulses per second
  - b. Relation to pulse repetition time (PRT)
  - c. Effects of varying PRF
    - (1) Maximum range
    - (2) Accuracy

- **Peak power**
  - a. Maximum signal power of any pulse
  - b. Affects maximum range of radar
- **Average power**
  - a. Total power transmitted per unit of time
  - b. Relationship of average power to PW and PRT

- **Duty cycle**
  - a. Ratio PW (time transmitting) to PRT (time of entire cycle, time transmitting plus rest time)
  - b. Also equal to ratio of average power to peak power
Minimum Range: If still transmitting when return received → RETURN NOT SEEN.

Max Range: \[
\frac{Average\ Power}{Peak\ Power} = \frac{PW}{PRT} = PW \times PRF
\]
Describe the components of a pulse radar system.

1. Synchronizer
2. Transmitter
3. Antenna
4. Duplexer
5. Receiver
6. Display unit
7. Power supply
Pulse Radar Block Diagram

- Synchronizer
- Power Supply
- Display
- Transmitter
- Duplexer (Switching Unit)
- Receiver
- Antenna

Connections:
- RF
- ATR
- Echo
- TR
- Video
- Antenna Bearing or Elevation
Pulsed radar architecture [1]

Figure 3.15 Top-level pulsed radar architecture.
A lab-based pulsed radar [4]
Pulsed modulation \[1\]

Figure 3.16 Pulsed radar transmission.
Pulsed Radar Bandwidth

In the frequency domain, the transmitted and received signals are composed of spectral components centered on the radar operating frequency, $f_0$, with a $\sin(x)/x$ shape.

The practical limits of the frequency response is $f_0 \pm 1/\tau$, and therefore the bandwidth of the receiver must be at least:

$$BWR_x \geq 2/\tau$$
Pulsed radar average power

- Since a pulsed radar only transmits for a small portion of the time, the average power of the radar is quite low:
  \[ P_{av} = P_{peak} \frac{\tau}{T_p} \]

- For example a pulsed radar with a 1 μsec pulse width and a medium PRF of 4 kHz that transmits at a peak power of 10kW transmits an average power of:
  \[ P_{av} = (10000 \text{ W}) (0.000001 \text{ sec}) (4000 /\text{sec}) \]
  \[ = _____ \text{ W} = _____ \text{ dBW} \]
Pulsed radar range resolution

The range resolution of a radar is its ability to distinguish two closely spaced targets along the same line of sight (LOS). The range resolution is a function of the pulse length, where pulse length, $L_p = c \tau$.

- For example, a 1 μsec pulse width yields a pulse length of 0.3 km.

- Two targets can be resolved in range if:
  \[ L_p < 2(R_2 - R_1) \]
Pulsed radar range resolution [4]

Figure 1-18. Range resolution - targets resolved.
Pulsed radar range resolution [4]

Figure 1-19. Range resolution - targets not resolved.
The PRF is another key radar parameter and is arguably one of the most difficult design decisions.

The range of a target becomes ambiguous as a function of half the pulse period; in other words targets that are further than half the pulse period yield ambiguous range results.

\[
R_{\text{amb}} = \frac{c}{(2 \text{ PRF})} = \frac{cT_p}{2}
\]
4.4 Pulsed radar range ambiguity \cite{1}

Figure 3.17 Effect of pulse period on target ambiguity.
A target whose range is:

- $R < R_{amb} = \frac{c}{2 \text{PRF}} = \frac{cT_p}{2}$
A target whose range is:

- \( R > R_{amb} = c / (2 \text{ PRF}) = cT_p / 2 \)
Range ambiguity

- Which target is which?
Angle resolution\textsuperscript{[4]}

Figure 1-38. Effect of beamwidth on angular resolution.
Pulse Vs. Continuous Wave

**Pulse Echo**
- Single Antenna
- Gives Range, usually Alt. as well
- Susceptible To Jamming
- Physical Range Determined By PW and PRF.

**Continuous Wave**
- Requires 2 Antennae
- Range or Alt. Info
- High SNR
- More Difficult to Jam But Easily Deceived
- Amp can be tuned to look for expected frequencies
RADAR Wave Modulation

- Amplitude Modulation
  - Vary the amplitude of the carrier sine wave

- Frequency Modulation
  - Vary the frequency of the carrier sine wave

- Pulse-Amplitude Modulation
  - Vary the amplitude of the pulses

- Pulse-Frequency Modulation
  - Vary the Frequency at which the pulses occur
Figure 2.8b. Electromagnetic energy modulation techniques.
Antennae

- **Two Basic Purposes:**
  - Radiates RF Energy
  - Provides Beam Forming and Focus
- **Must Be 1/2 of the Wave Length for the maximum wave length employed**
- **Wide Beam pattern for Search, Narrow for Track**
Beamwidth Vs. Accuracy

Beamwidth vs Accuracy

Ship A

Ship B
Azimuth Angular Measurement

Relative Bearing = Angle from ship’s heading.
True Bearing = Ship’s Heading + Relative Bearing
Determining Altitude

Altitude = slant range x sinθ elevation
Concentrating Radar Energy Through Beam Formation

- **Linear Arrays**
  - Uses the Principle of wave summation (constructive interference) in a special direction and wave cancellation (destructive interference) in other directions.
  - Made up of two or more simple half-wave antennas.

- **Quasi-optical**
  - Uses reflectors and “lenses” to shape the beam.
Figure 2–17. Broadside array.
Reflector Shape

- **Paraboloid** - Conical Scan used for fire control - can be CW or Pulse
- **Orange Peel Paraboliod** - Usually CW and primarily for fire control
- **Parabolic Cylinder** - Wide search beam - generally larger and used for long-range search applications - Pulse
Wave Shaping - Quasi-Optical Systems

Reflectors

Lenses

Reflector shapes.
Parabolic (dish) antenna

- Early airborne radars typically consisted of parabolic reflectors with horn feeds.
- The dish effectively directs the transmitted energy towards a target while at the same time "gathering and concentrating" some fraction of the returned energy.
Recent radars more likely employ a planar array
- It is electronically steerable as a transmit or receive antenna using phase shifters.
- It has the further advantage of being capable of being integrated with the skin of the aircraft ("smart skin").
Radar antenna beam patterns

- The main lobe of the radar antenna beam is central to the performance of the system.
- The side lobes are not only wasteful, they provide electronic warfare vulnerabilities.
Airborne radar modes

- Airborne radars are designed for and used in many different modes. Common modes include:
  - air-to-air search
  - air-to-air tracking
  - air-to-air track-while-scan (TWS)
  - ground mapping
  - continuous wave (CW) illumination
  - multimode
Air-to-air search \[1\]

Figure 3.11  Typical air-to-air search pattern.
Air-to-air tracking [1]

**Figure 3.12** Air-to-air tracking.
Air-to-air track-while-scan [1]

Figure 3.13  Air-to-air TWS.
Ground mapping [1]

Figure 3.14  Ground mapping.
Continuous wave illumination

Figure 3.26  CW illumination.
Multimode [1]

Figure 3.27  Simultaneous multimode operation.
In-class exercises
Quick response exercise

- Given a 10.5 GHz intercept radar and a transmitter capable of providing a peak power of 44 dBW at a PRF of 2 kHz:
  - What pulse width yields an average power of 50W?
  - What is the bandwidth in MHz and in % of this signal?
Pulsed radar calculations

- Design the pulse parameters so as to achieve maximum average power for an unspecified Ku band pulsed radar given the following component specifications and system requirements:
  - The receiver has a bandwidth of at least 0.5% across the band
  - The required range resolution is 50m
  - The required range ambiguity is 25 km
  - For cooling purposes, ensure that the duty cycle of the transmitter does not exceed 0.2%
References


5) Mark A. Hicks, "Clip art licensed from the Clip Art Gallery on DiscoverySchool.com"