



ECE 495 – Electromagnetic Warfare and Survivability

Block 1: Radar Fundamentals

Lesson 2: EM Spectrum and Propagation

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L1 framed the problem: kill chains, ES / EP / EA, the B-21 thread.

Before we can quantify any of it, we need the physics layer underneath.

Today: EM waves, propagation, polarization, and antenna basics — the building blocks of every equation in B1.

By the end of this lesson, you will be able to:

- Identify the **radar bands** across the EM spectrum and connect them to mission
- Compute **wavelength** and **free-space path loss** (FSPL)
- Explain why **polarization** matters in EW
- Relate antenna **gain** to **aperture** and **beamwidth**

The EM Spectrum: Radar Bands



Band	Frequency	Wavelength	Typical Use
L	1 – 2 GHz	30 – 15 cm	Long-range surveillance
S	2 – 4 GHz	15 – 7.5 cm	Surveillance, weather, ATC
C	4 – 8 GHz	7.5 – 3.75 cm	Weather, civil radar
X	8 – 12 GHz	3.75 – 2.5 cm	Fire control, airborne
Ku	12 – 18 GHz	2.5 – 1.7 cm	SAR, comm
K	18 – 27 GHz	1.7 – 1.1 cm	Short-range, high-res
Ka	27 – 40 GHz	11 – 7.5 mm	Missile seekers, mmW

- Lower frequency $\Rightarrow$ longer range, larger antennas, coarser resolution
- Higher frequency $\Rightarrow$ finer resolution, smaller antennas, more atmospheric loss
- Threat band tells you what mission it is doing

$$\lambda f = c, \quad c \approx 3 \times 10^8 \text{ m/s}$$

- λ sets antenna size, target interaction, and how the wave bends around obstacles
- Pick the frequency, the wavelength is fixed — no negotiating

Quick mental math:

- $f = 3 \text{ GHz} \Rightarrow \lambda = 10 \text{ cm}$ (S-band)
- $f = 10 \text{ GHz} \Rightarrow \lambda = 3 \text{ cm}$ (X-band)
- $f = 30 \text{ GHz} \Rightarrow \lambda = 1 \text{ cm}$ (Ka-band)

Wavelength sets antenna size, propagation, and target interaction.

A transmitter radiates power P_t isotropically. At range R , power spreads over a sphere of area $4\pi R^2$.

$$\text{Power density at } R : \quad S = \frac{P_t}{4\pi R^2}$$

A receiver with effective aperture A_e captures:

$$P_r = S \cdot A_e = \frac{P_t A_e}{4\pi R^2}$$

- One-way loss scales as $1/R^2$ — the **inverse square law**
- Radar is two-way and goes as $1/R^4$ — that is why L1's fourth-power law was harsh

FSPL between isotropic antennas, with R in km and f in GHz:

$$L_{fs,dB} = 20 \log_{10} R + 20 \log_{10} f + 92.45$$

- Doubling R adds 6 dB
- Doubling f adds 6 dB
- At 100 km, X-band is ~ 10 dB worse than S-band — before atmosphere

Every 6 dB matters: range and frequency both pay in 6 dB chunks.

Direction of the E-field as the wave propagates. Two flavors that matter:

- **Linear:** Vertical (V) or Horizontal (H)
- **Circular:** Right-hand (RHC) or Left-hand (LHC)

Why EW cares:

- Antennas only receive their matched polarization efficiently — mismatch loss can be 20–30 dB
- RAM and shaping behave differently for V vs. H — LO is polarization-dependent
- Polarization agility is an EP technique (own radar) and an EA target (threat radar)

Polarization is a survival angle.

Antennas: Gain, Aperture, and Beamwidth



$$G \approx \frac{4\pi A_e}{\lambda^2}, \quad \theta_{BW} \approx \frac{\lambda}{D}$$

- G is the focusing factor over isotropic — units: dBi
- A_e is the effective collecting area
- θ_{BW} is the angular extent of the main lobe
- More gain $\Leftrightarrow$ larger aperture $\Leftrightarrow$ narrower beam $\Leftrightarrow$ less coverage

Gain you buy with aperture; coverage you pay with beamwidth.

Four common shapes you will see this semester:

- **Omni** — nearly equal gain in all directions; low gain
- **Fan beam** — wide in one plane, narrow in the other; search radars
- **Pencil beam** — narrow in both planes; trackers and seekers
- **ESA (electronically scanned array)** — pencil beam that steers without moving the antenna

A real pattern has a main lobe, side lobes, and back lobes. Side lobes are an **EA vulnerability** (jam through them) and an **EP design target** (suppress them).

Today's Interactive Demo: Free-Space Path Loss



- Two log-scaled sliders: frequency (0.5–40 GHz) and range (1–500 km)
- Band chips (L through Ka) snap frequency to each band center
- Live readouts: wavelength λ and FSPL in dB
- A range cursor tracks your slider across the L/S/C/X curves
- Move either slider by $\times 2$ and the footer calls out the +6 dB step

Companion script: L2_FreeSpacePathLoss.m

In L3 we wrap FSPL into the full radar range equation.

Quick Exercise / Type-along: Where Did the 6 dB Go?



Same dish ($A_e = 1 \text{ m}^2$), same target at 50 km. Type this with me:

```
c = 3e8;                % m/s
Ae = 1.0;               % m^2 -- same physical antenna at every frequency
R_km = 50;              % fixed range to the target
f_GHz = [5 10 20];     % C-band, X-band, K-band
lam = c ./ (f_GHz*1e9);
G_dB = 10*log10(4*pi*Ae ./ lam.^2);
L_dB = 20*log10(R_km) + 20*log10(f_GHz) + 92.45;
net = G_dB - L_dB;
fprintf(' f(GHz)  lam(cm)  G(dBi)  FSPL(dB)  net(dB)\n');
fprintf('%8.1f %8.2f %8.2f %9.2f %10.2f\n', [f_GHz; lam*100; G_dB; L_dB; net]);
```

Read the last column. What do you notice?

Key ideas:

- EM spectrum is a menu — each band has a price and a benefit
- $\lambda f = c$ and $\text{FSPL} \propto (R/\lambda)^2$ underpin everything in B1
- Polarization and antenna gain are the levers we tune in B2 and B3

Next lesson:

- **L3: The radar range equation** — where FSPL, RCS, and gain all meet
- Pre-flight quiz for L3 due before class