ECE 495 – Electromagnetic Warfare and Survivability

Block 1: Radar Fundamentals

Lesson 4: Pulse Radars and Ambiguity

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Fall 2026

Where We Left Off

L3 gave us $R_{\max}$ — how *far* a radar can detect.

That assumes you can also *measure range*. Continuous-wave (CW) radars get power but not range. Pulse radars trade time for both.

Today: pulse width, PRF, duty cycle, and the tradeoffs that drive every radar design.

Lesson Objectives

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

- Define **PW, PRI, PRF, and duty cycle** for a pulse radar
- Compute **range resolution** and **unambiguous range** from PW and PRF
- Explain the **range-Doppler ambiguity tradeoff**
- Match a radar’s PRF regime (low / medium / high) to its mission

Why Pulses?

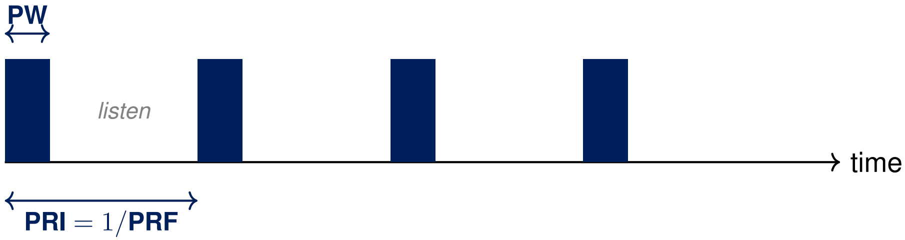
A CW radar always transmits — it can't tell where an echo came from.

Pulse radars transmit a short burst, then *listen*.

- Range is read directly from echo delay: $R = c \cdot t_{\text{echo}}/2$
- The Tx is off while the Rx listens — no self-interference
- Energy on target is shaped by duty cycle, not just peak power

Pulses gate time so we can read range from echo delay.

Anatomy of a Pulse Train



- **PW** — pulse width, the time the radar transmits
- **PRI** — pulse repetition interval; **PRF** $= 1/$PRI
- **Duty cycle** $=$ PW $\cdot$ PRF $=$ PW / PRI — average over peak

Pulse Width $\rightarrow$ Range Resolution

Two targets are resolvable only if their echoes do not overlap in time.

$$\boxed{\Delta R = \frac{c \cdot \text{PW}}{2}}$$

- $\text{PW} = 1\ \mu\text{s} \ \Rightarrow\ \Delta R = 150$ m
- $\text{PW} = 0.1\ \mu\text{s} \ \Rightarrow\ \Delta R = 15$ m
- Shorter PW gives finer range resolution — but less energy per pulse

(Pulse compression buys finer ΔR without giving up energy — a separate lesson.)

PRF $\to$ Unambiguous Range

The radar must hear the echo *before* it transmits the next pulse:

$$\boxed{R_u = \frac{c}{2 \cdot \text{PRF}}}$$

- PRF $= 1$ kHz $\;\Rightarrow\; R_u = 150$ km
- PRF $= 10$ kHz $\;\Rightarrow\; R_u = 15$ km
- Higher PRF gives more pulses per second — but shrinks R_u

What happens at $R > R_u$? The echo arrives *after* the next pulse goes out.

Range Ambiguity: Second-Time-Around Echoes

An echo from $R > R_u$ wraps into the next interval and **appears at**

$$R_{\text{apparent}} = R_{\text{true}} \bmod R_u.$$

Example: PRF $= 800$ Hz $\Rightarrow$ $R_u = 187.5$ km — one wrap.

A B-21 at **true range 200 km** shows up at:

$$R_{\text{apparent}} = 200 - 187.5 = 12.5 \text{ km}$$

- Looks like a short-range threat — wrong range, wrong tactical picture
- Mitigations: PRF jitter, multiple PRFs, pulse identification

Ambiguous returns are not noise; they are confidently wrong.

Doppler Ambiguity

Each pulse samples the target's Doppler shift. Sampling at the PRF means Nyquist limits unambiguous Doppler to $\pm$ PRF $/2$.

Translating Doppler to radial velocity:

$$\boxed{v_u = \frac{\lambda \cdot \text{PRF}}{4}}$$

- Doppler beyond $\pm v_u$ aliases into a different velocity bin
- Higher PRF buys more unambiguous Doppler — but it costs us range ambiguity

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The PRF Dilemma

Multiply the two ambiguity limits:

$$R_u \cdot v_u = \frac{c}{2\,\mathrm{PRF}} \cdot \frac{\lambda\,\mathrm{PRF}}{4} = \boxed{\frac{c\,\lambda}{8}}$$

- Product is **independent of PRF** — a hard physical limit
- Pick more R_u, you give up v_u at the same rate (and vice versa)
- The whole game is choosing which side of this tradeoff matches the mission

Range and Doppler can't both be unambiguous at the same PRF.

Three PRF Regimes (X-band example)

Regime	R_u	v_u	Typical use
Low PRF (1 kHz)	150 km	7.5 m/s	Long-range surveillance; ambiguous velocity
Medium PRF (10 kHz)	15 km	75 m/s	Multi-mode airborne fire control
High PRF (200 kHz)	0.75 km	1500 m/s	Look-down pulse-Doppler, fast inbound threats

- Modern radars dwell in **multiple** regimes within one scan
- EW implication: PRF tells you the radar's *intent*

Today's Interactive Demo: PRF Explorer

One knob, two limits — drive it yourself.

- **PRF and PW sliders**, with presets at 800 Hz / 1 / 10 / 200 kHz
- **Stat tiles** for PRI, duty cycle, R_u, and v_u
- **Invariant tile** holding $R_u \cdot v_u$ — watch what it does
- **Fold widget** — set a true range, read where it *appears*

Companion script: `L4_PulseTrainAndAmbiguity.m`

In L5 we use the pulse train as a Doppler sampler — pulse-Doppler, MTI, clutter.

Quick Exercise / Type-along: PRF Sweep

Type this with me. X-band threat radar, $\lambda = 3$ cm.

```
c = 3e8;  lambda = 0.03;                          % X-band
PRF = [800 2e3 5e3 1e4 2e4];                      % Hz, low -> high
Ru  = c ./ (2*PRF) / 1e3;                         % unambiguous range, km
vu  = lambda * PRF / 4;                           % unambiguous velocity, m/s
fprintf(' PRF(Hz)   Ru(km)  vu(m/s)    Ru*vu\n');
fprintf('%8.0f %8.1f %8.1f %8.0f\n', [PRF; Ru; vu; Ru.*vu]);
need_R = 200;  need_v = 250;   % B-21: see to 200 km, closing 250 m/s
ok = (Ru >= need_R) & (vu >= need_v);
fprintf('\nPRFs meeting both: %d of %d\n', sum(ok), numel(ok));
```

Read the last two columns, then the last line. What did the sweep just prove?

Wrap-Up

Key ideas:

- PW sets range resolution; PRF sets unambiguous range and velocity
- Range and Doppler ambiguity tradeoff: $R_u \cdot v_u = c\lambda/8$
- PRF regime $=$ mission — low for range, high for Doppler, medium for both badly

Next lesson:

- **L5: Doppler and pulse-Doppler processing** — MTI, clutter, blind speeds
- Pre-flight quiz for L5 due before class