ECE 495 – Electromagnetic Warfare and Survivability

Block 1: Radar Fundamentals

Lesson 5: Doppler, MTI, and Pulse-Doppler

Juan Jurado, Col, USAF, Ph.D.
Permanent Professor and Head
Electrical and Computer Engineering

Fall 2026

Where We Left Off

L4 gave us the pulse train — a sampler in time.

Each pulse carries a phase. Across pulses, that phase moves whenever the target does.

Today: the Doppler shift, MTI filtering, and pulse-Doppler processing — the tools that separate the “movers” from clutter.

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Lesson Objectives

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

- Compute the **Doppler shift** from a radial velocity
- Explain how a **single delay-line MTI** rejects ground clutter
- Identify **blind speeds** and how PRF moves them around
- Describe **pulse-Doppler processing** as an FFT across pulses

The Doppler Effect on Radar Returns

A target moving radially at v_r shifts the carrier by:

$$\boxed{f_d = \frac{2\,v_r}{\lambda}}$$

The factor of 2 is the two-way path.

X-band ($\lambda = 3$ cm) examples:

- $v_r = 300$ m/s $\;\Rightarrow\;$ $f_d = 20$ kHz
- $v_r = 30$ m/s $\;\Rightarrow\;$ $f_d = 2.0$ kHz

Range tells you where; Doppler tells you what.

Clutter vs Targets

A radar looking down sees **everything**, not just the threat.

- **Ground clutter** — huge RCS, $f_d \approx 0$
- **Weather, sea, foliage** — distributed, small f_d
- **Aircraft** — modest RCS, f_d from hundreds of Hz to tens of kHz

The aircraft return is buried in clutter on the basis of *amplitude alone*. Doppler separates the two.

Clutter is a confidently stationary signal the radar must learn to ignore.

Single Delay-Line MTI Canceller

Subtract one pulse return from the next:

$$y[n] = x[n] - x[n-1]$$

Frequency response (with $T = \text{PRI}$):

$$|H(f)| = 2\,|\sin(\pi f T)|$$

- Notches at $f = 0$, PRF, $2\,$PRF, $\ldots$ — stationary clutter is killed
- Passes Doppler shifts away from those notches — movers survive
- Cheap to implement: one PRI of memory and a subtractor

(Higher-order cancellers and adaptive MTI go deeper)

Blind Speeds

A target whose Doppler shift lands on *any* MTI notch looks stationary.

$$\boxed{v_{\text{blind},n} = \frac{n \cdot \lambda \cdot \text{PRF}}{2}}$$

X-band, PRF $= 1$ kHz:

- $v_{\text{blind},1} = 15$ m/s, $v_{\text{blind},2} = 30$ m/s, $v_{\text{blind},3} = 45$ m/s, $\ldots$
- Ground vehicles and helicopters live right in this band

Raising PRF to 10 kHz pushes $v_{\text{blind},1}$ to 150 m/s — usually outside the clutter band.

That is why pulse-Doppler radars use medium-to-high PRF.

Pulse-Doppler Processing

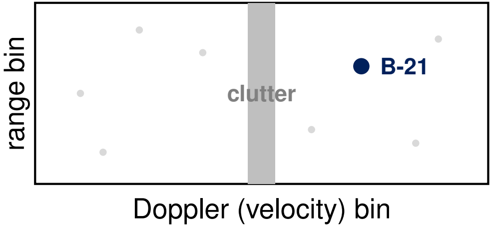
Collect N pulses in a coherent dwell. Take an N-point FFT *across pulses* at each range bin:

- Output is a **Doppler spectrum** per range bin
- Doppler bin width $=$ PRF $/N$ — finer with more pulses
- Each target lands in its own range-Doppler cell
- Coherent integration gives an SNR gain proportional to N

This is what modern AESA fire control radars are doing under the hood.

The Range-Doppler Map

The output of pulse-Doppler processing is a 2D matrix:



- Clutter forms a **vertical ridge** at zero Doppler
- Movers land away from the ridge — easy to threshold
- EW implication: *your* Doppler signature is hard to hide

Look-Down and Modern Clutter Rejection

A look-down radar competes with the entire **Earth** in its main beam.

- Main-beam clutter Doppler shifts with platform velocity and look angle
- Modern radars track and **cancel the main-beam clutter line** adaptively
- Side-lobe clutter is treated separately — this is where good antenna design pays off

EW relevance:

- Stealth aims to push your return into the clutter band
- Standoff jammers raise the noise floor across all Doppler bins

Today's Interactive Demo: Range-Doppler Map

Today's interactive demo.

- Read the map — clutter ridge at zero Doppler, mover in its own cell
- Slide the target velocity and watch the cell pull away from the ridge
- Toggle MTI: the ridge is nulled, the mover survives
- Put the target on a blind speed and watch it cancel with the clutter

Companion script: `L5_DopplerMTI.m`

In L6 we look at antennas as patterns — where the clutter actually enters.

Quick Exercise / Type-along: Land on the Notch

Type this with me — X-band, and the PRF from L4's exercise.

```
lambda = 0.03;                  % X-band, 3 cm
PRF    = 2e3;                   % L4's radar
v      = [20 30 60 250];        % closure velocities, m/s
fd     = 2*v/lambda;            % Doppler shift, Hz
vu     = lambda*PRF/4;          % L4 unambiguous velocity
vapp   = mod(v + vu, 2*vu) - vu;
vblind = (1:3)*lambda*PRF/2;
fprintf('  v(m/s)   fd(kHz)  v_app(m/s)\n');
fprintf('%8.0f %9.2f %11.1f\n', [v; fd/1e3; vapp]);
fprintf('\nv_u = %.1f m/s   blind = %s m/s\n', vu, mat2str(vblind));
```

Two of the four report 0 m/s. **Which two, and why?**

Then: a standoff jammer wants the B-21 to appear stationary in the R-D map. **What waveform property would it try to spoof?**

Wrap-Up

Key ideas:

- Doppler shift $f_d = 2v_r/\lambda$ — the second observable after range
- MTI kills zero-Doppler clutter; PRF picks where the blind speeds live
- Pulse-Doppler $=$ FFT across pulses $\to$ R-D map with movers in their own bins

Next lesson:

- **L6: Antennas, patterns, beamforming, ESA basics**
- Pre-flight quiz for L6 due before class