Radar Systems Engineering
Lecture 12
Clutter Rejection
Part 1 - Basics and Moving Target Indication

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

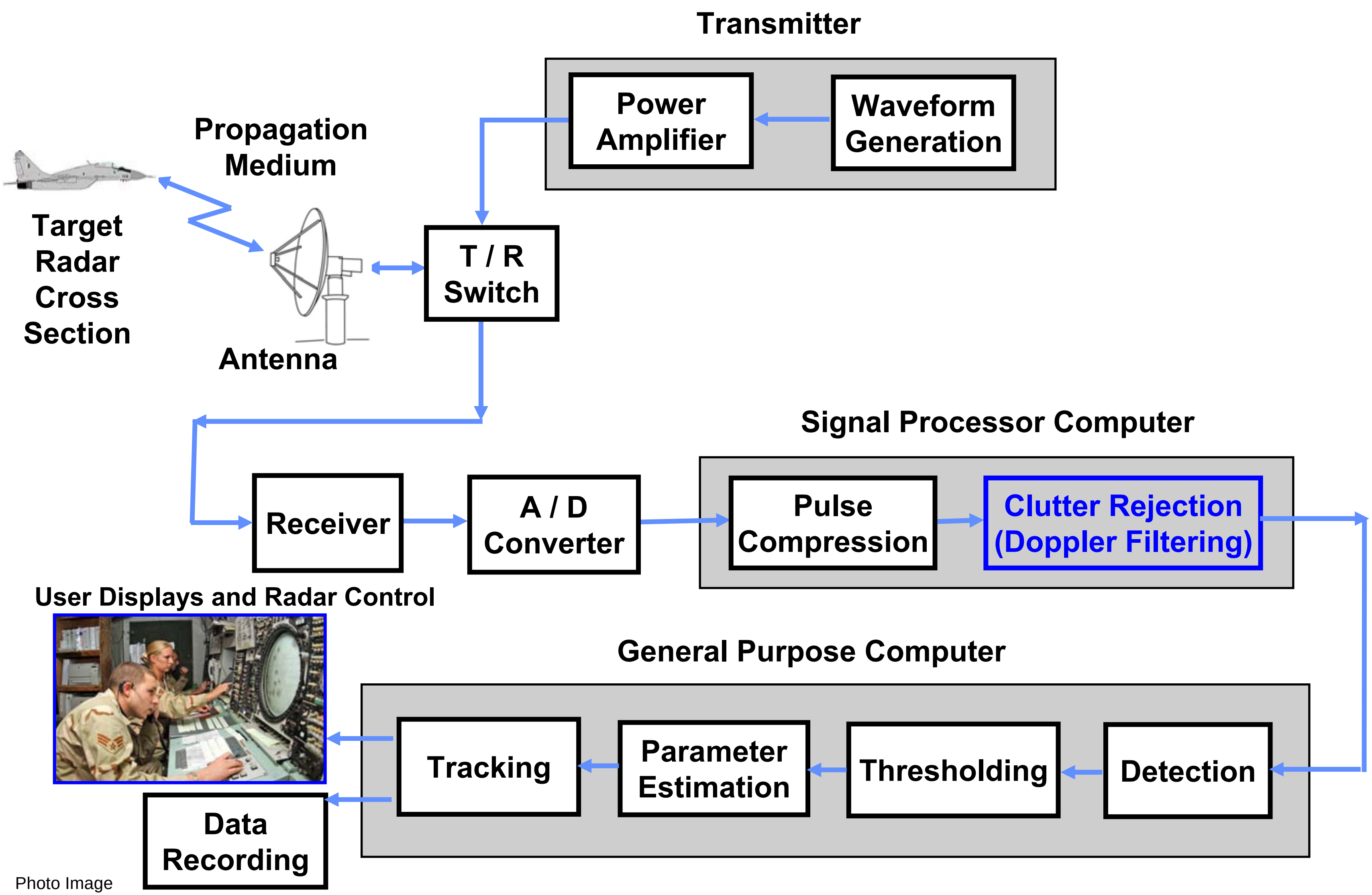

Photo Image
Courtesy of US Air Force

How to Handle Noise and Clutter

Viewgraph courtesy of MIT Lincoln Laboratory
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How to Handle Noise and Clutter

If he doesn't take his arm off my shoulder I'm going to hide his stash of Hershey Bars !!

Why does Steve always talk me into doing ridiculous stunts like this ?

Viewgraph courtesy of MIT Lincoln Laboratory
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Outline

- Introduction

- History of Clutter Rejection
  - Non-coherent MTI

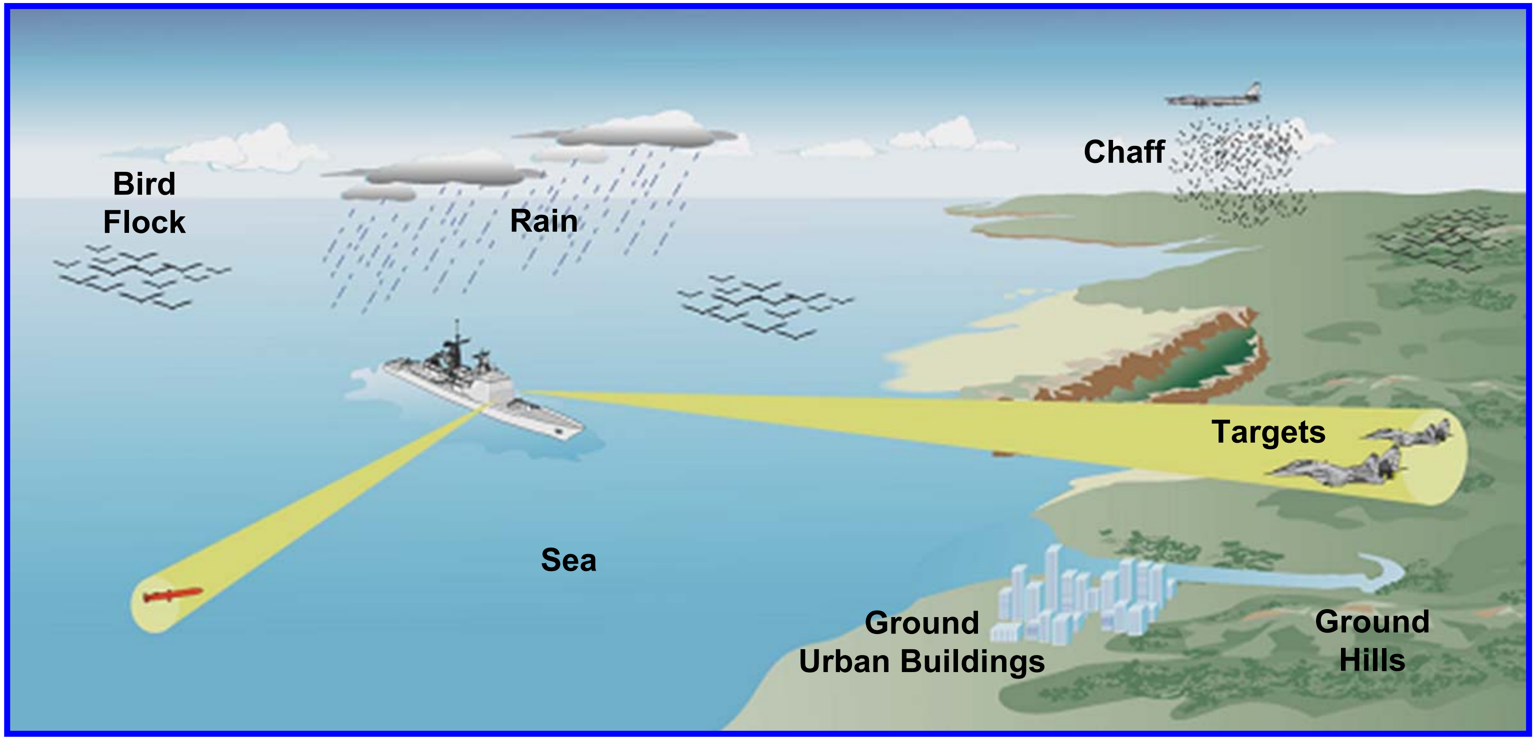
- Impact of the Digital Revolution – Moore's law

- MTI Clutter Cancellation
  - General description
    - Doppler ambiguities and blind speed effects
    - MTI Improvement factor
  - MTI cancellers
    - Two pulse, three pulse, etc.
    - Feedback
  - Effect of signal limiting on performance
  - Multiple and staggered PRFs

- Summary

Clutter Problems – The Big Picture

- **Ground Clutter**
  - Can be intense and discrete
  - Can be 50 to 60 dB > than target
  - Doppler velocity zero for ground based radars
    - Doppler spread small
- **Sea Clutter**
  - Less intense than ground echoes
    - By 20 to 30 dB
    - Often more diffuse
  - Doppler velocity varies for ship based radars (ship & wind velocity)
    - Doppler spread moderate



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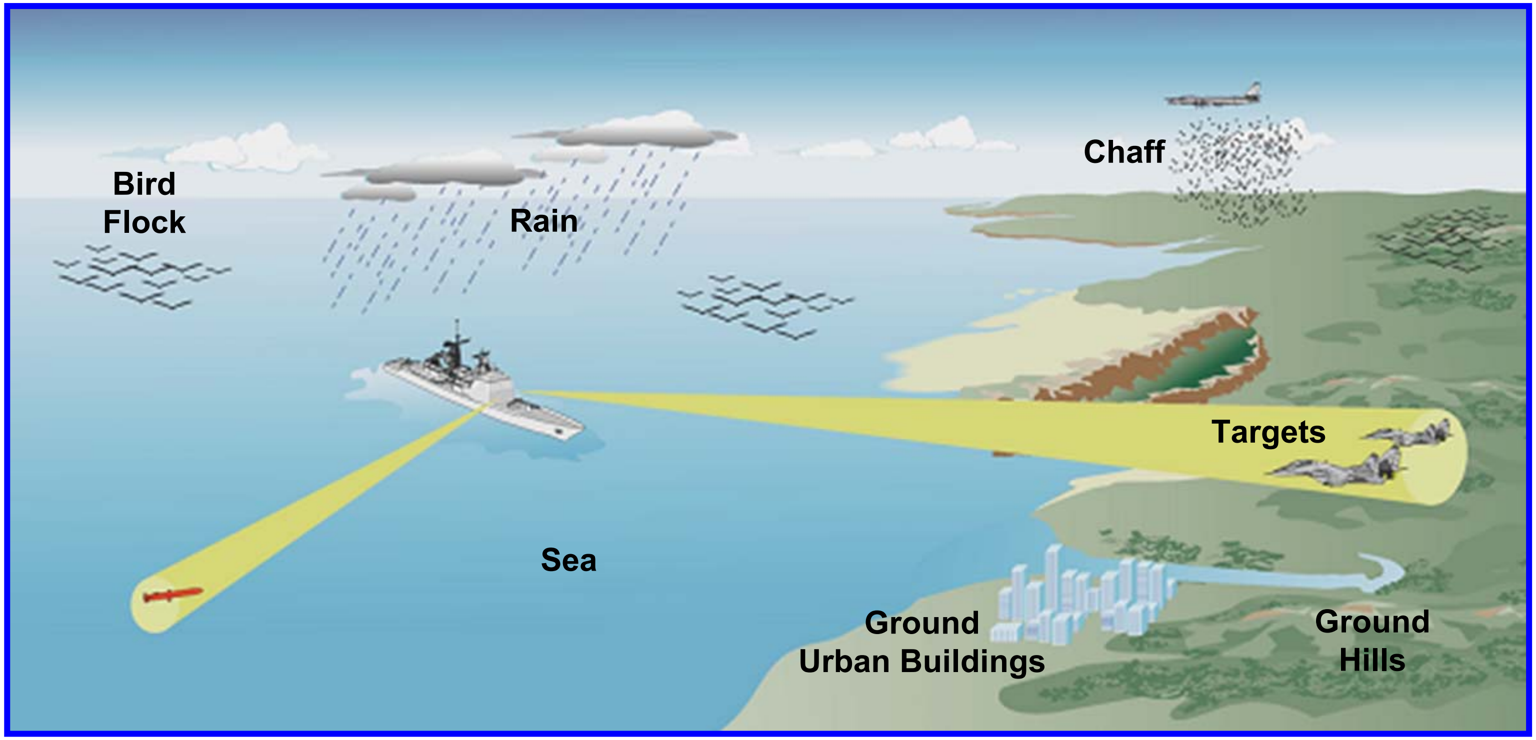
Clutter Problems – The Big Picture (cont.)

- **Rain Clutter**
  - Diffuse and windblown
  - Can be 30 dB > than target
    - Strength frequency dependant
  - Mean Doppler varies relative to wind direction & radar velocity
    - Doppler spread moderate
- **Bird Clutter**
  - 100s to 10,000s of point targets
  - Doppler velocity - 0 to 60 knots
    - Flocks of birds can fill 0 to 60 knots of Doppler space
    - Big issue for very small targets



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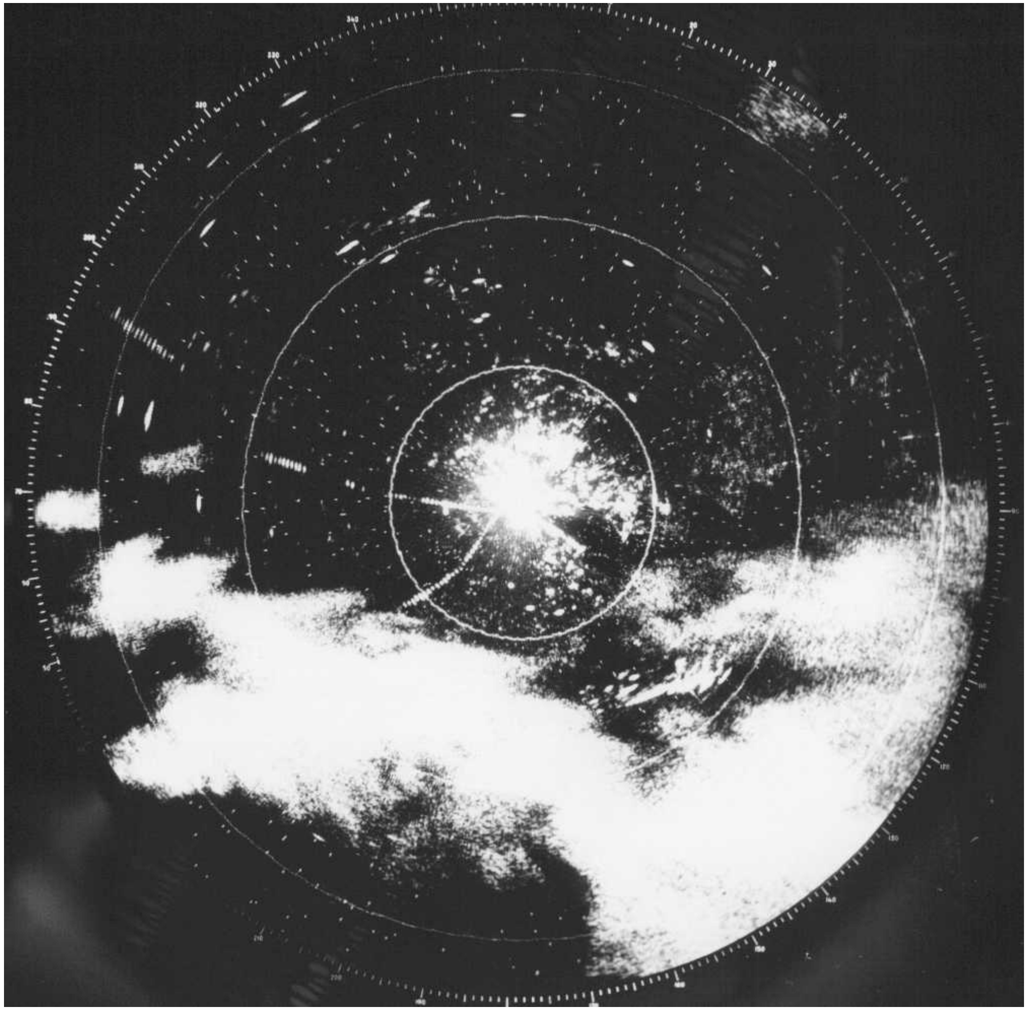
Example – Radar Display with Clutter

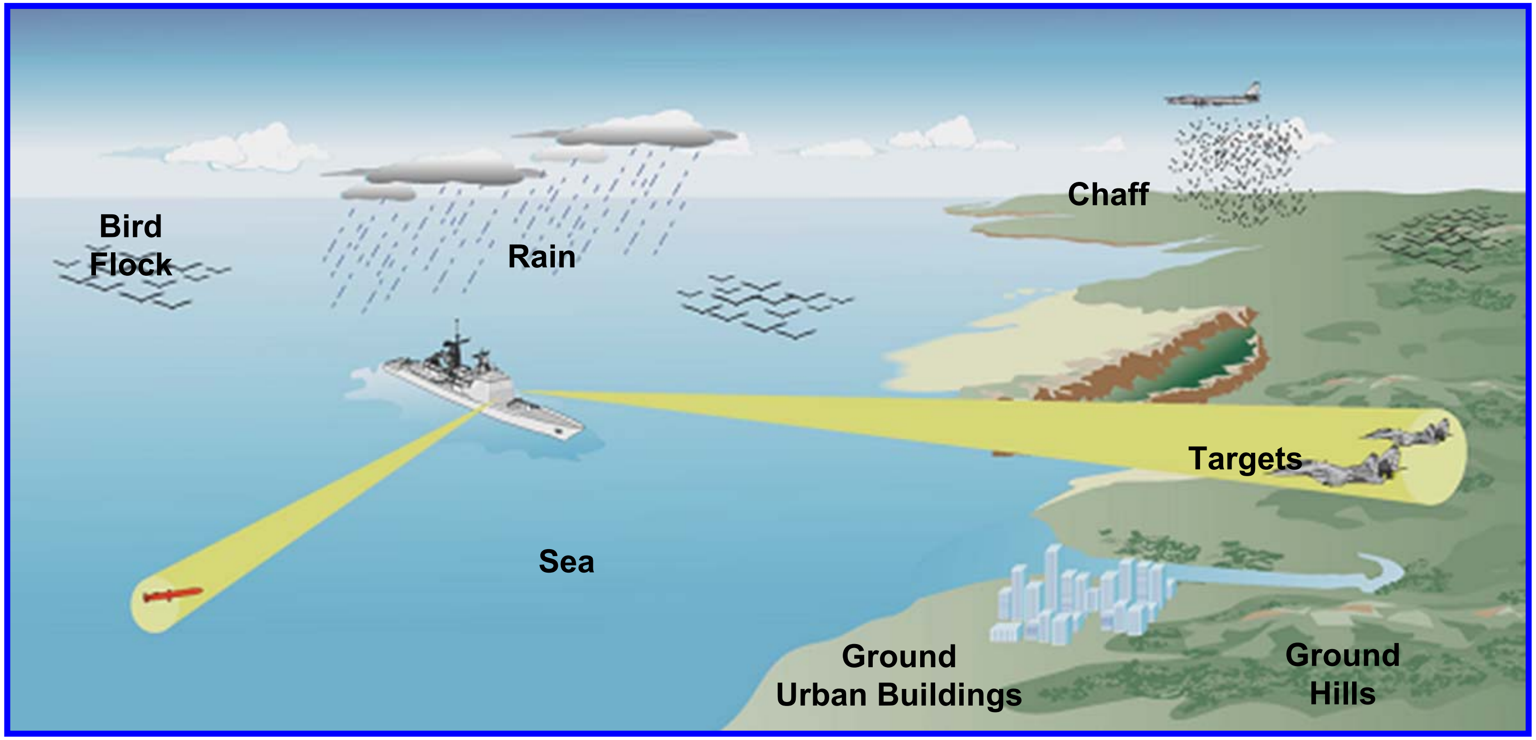
PPI Display of Heavy Rain



Courtesy of FAA

The Solution

- **Moving Target Indicator (MTI) and Pulse-Doppler (PD) processing use the Doppler shift of the different signals to enhance detection of moving targets and reject clutter.**
  - **The total solution is a sequential set of Doppler processing and detection / thresholding techniques**
- **Smaller targets require more clutter suppression**



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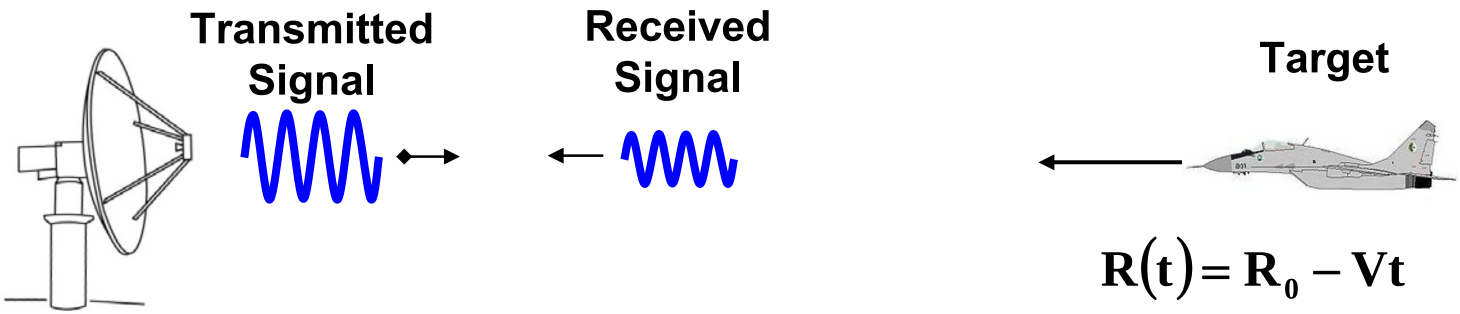
The Doppler Effect



$$R(t) = R_0 - Vt$$

Transmitted Signal: $$s_T(t) = A(t)\exp(j 2\pi f_0 t)$$

Received Signal: $$s_R(t) = \alpha\, A(t-\tau)\exp[j 2\pi (f_0 + f_D) t]$$

- The amplitude of the backscattered signal is very weak
- The delay of the received echo is proportional to the distance to the target
- The frequency of the received signal is shifted by the Doppler Effect

Time Delay

$$\tau = \frac{2R_0}{c}$$

Doppler Frequency

$$f_D = \frac{2Vf_0}{c} = \frac{2V}{\lambda}$$

+ Approaching targets
- Receding targets

Terminology & Basics

- Moving Target Indicator (MTI) Techniques
  - Suppress clutter with a low pass Doppler filter
    - Reject slow moving clutter
    - Detect moving targets
  - Small number of pulses typically used
    - Two to three pulses
  - No estimate of target's velocity

- Pulsed Doppler (PD) Techniques
  - Suppress clutter with a set pass band Doppler filters
  - Targets sorted into one or more Doppler filters
    - Targets radial velocity estimated
  - A large number of pulses are coherently processed to generate optimally shaped Doppler filters
    - From 10s to 1000s of pulses

- **In this lecture Moving Target Indicator (MTI) techniques will be studied**

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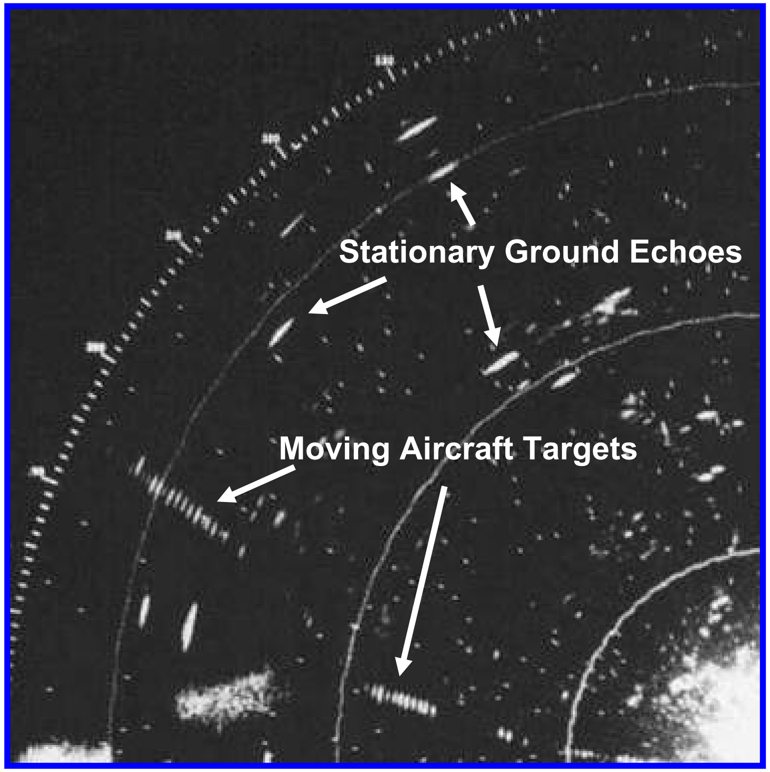
Early Non Coherent MTI

Plan Position Indicator (PPI) Display



Courtesy of FAA

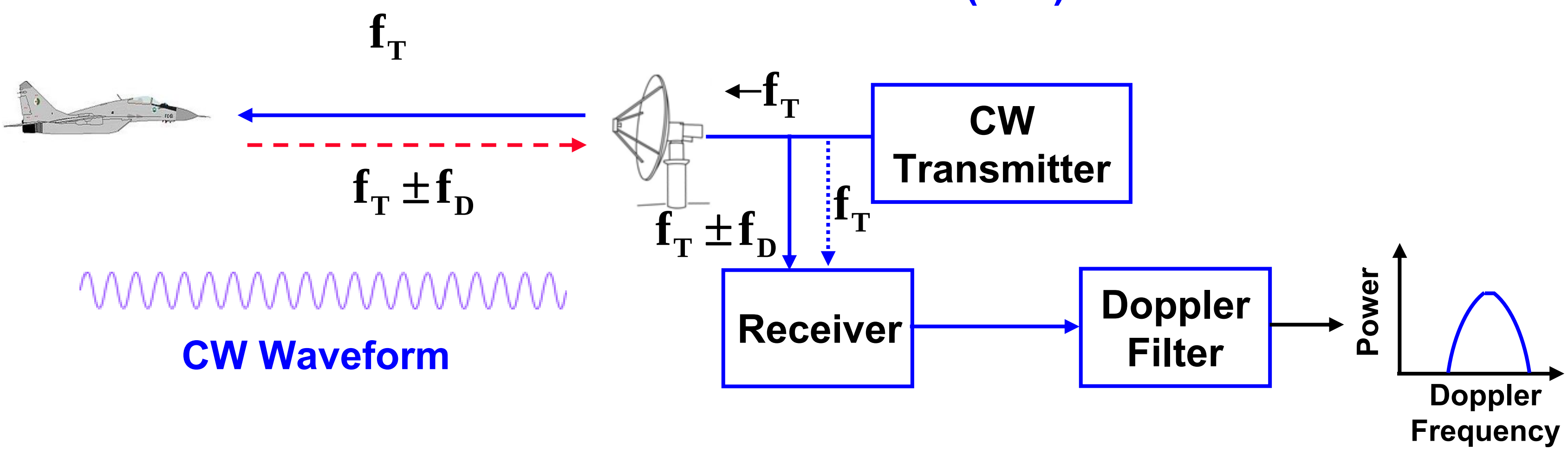
Map-like Display
Radial distance to center — Range
Angle of radius vector — Azimuth
Threshold crossings — Detections

- **The earliest clutter (ground backscatter) rejection technique consisted of storing an entire pulse of radar echoes and subtracting it from the next pulse of echoes**
  - **The storage devices were very crude by today's standards**

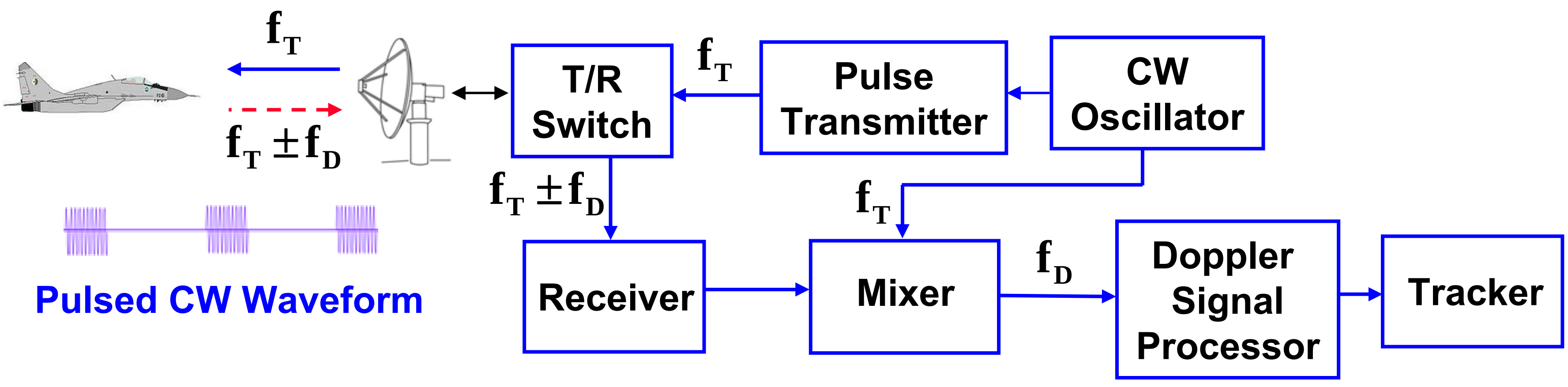
PPI movie Courtesy of Flyingidiot

Block Diagrams of CW and Pulse Radars

Basic Continuous Wave (CW) Radar

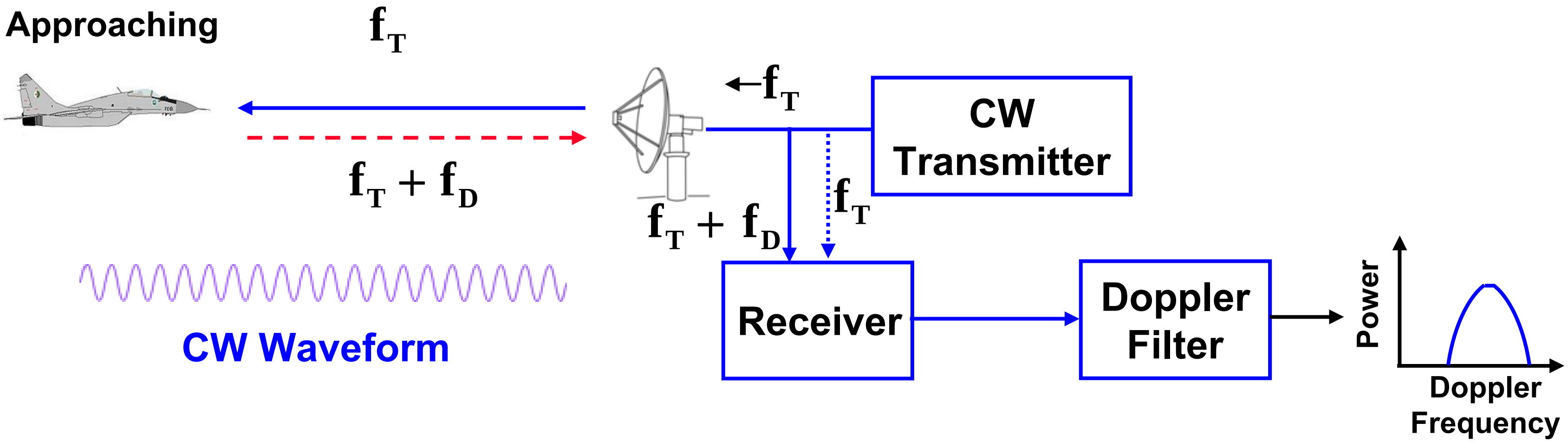


Basic Pulse Radar

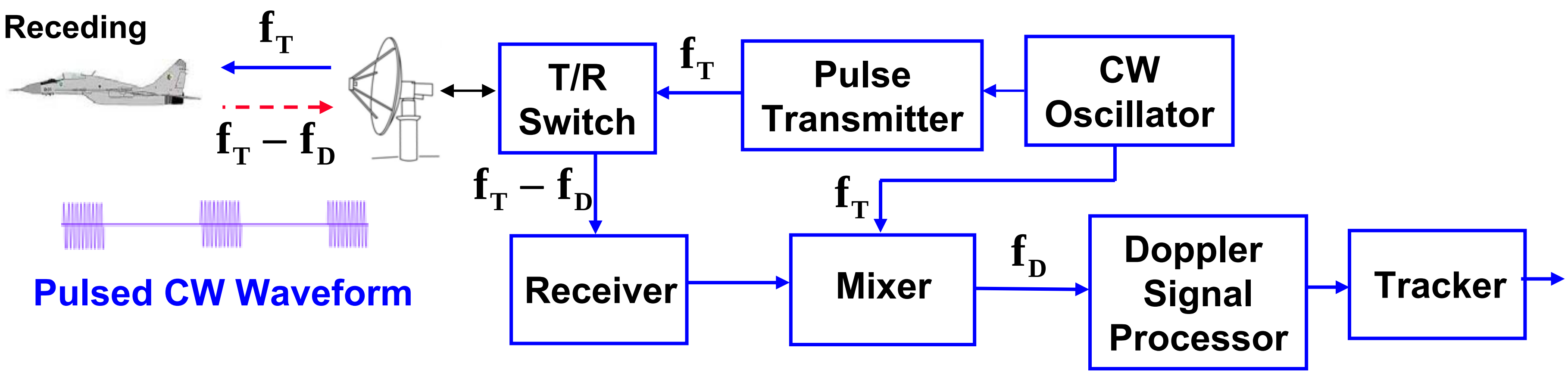


Block Diagrams of CW and Pulse Radars

Basic Continuous Wave (CW) Radar



Basic Pulse Radar



Clutter Rejection History

- 1960s to mid 1970s
  - Stability was a real problem
  - Delay line cancellers
    - Several milliseconds delay
    - Quartz and mercury
    - Velocity of acoustic waves is 1/10,000 that of electromagnetic waves
    - Disadvantages
      - Secondary waves
      - Large insertion waves
    - Dynamic range limitations of analog displays caused signals to be limited
- Mid 1970s to present
  - Revolution in digital technology
    - Memory capacity and processor speed continually increase, while cost spirals downward
    - Affordable complex signal processing more and more easy and less expensive to implement

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A Technology Perspective

- Three technologies have evolved and revolutionized radar processing over the past 40 to 50 years
  - Coherent transmitters
  - A/D converter developments
    - High sample rate, linear, wide dynamic range
  - The digital processing revolution - Moore's law
    - - Low cost and compact digital memory and processors
  - The development of the algorithmic formalism to practically use this new digital hardware
    - "Digital Signal Processing"
- These developments have been the 'technology enablers' that have been key to the development the modern clutter rejection techniques in today's radar systems

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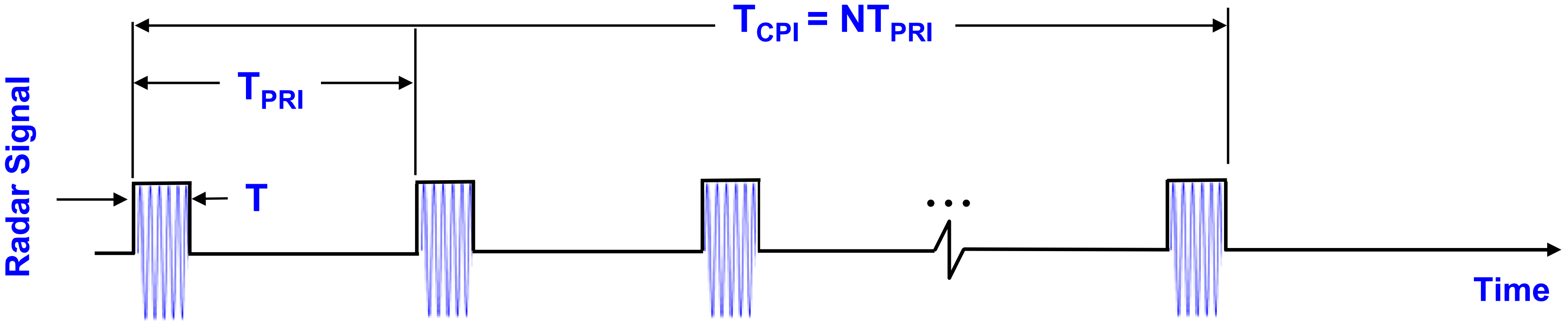
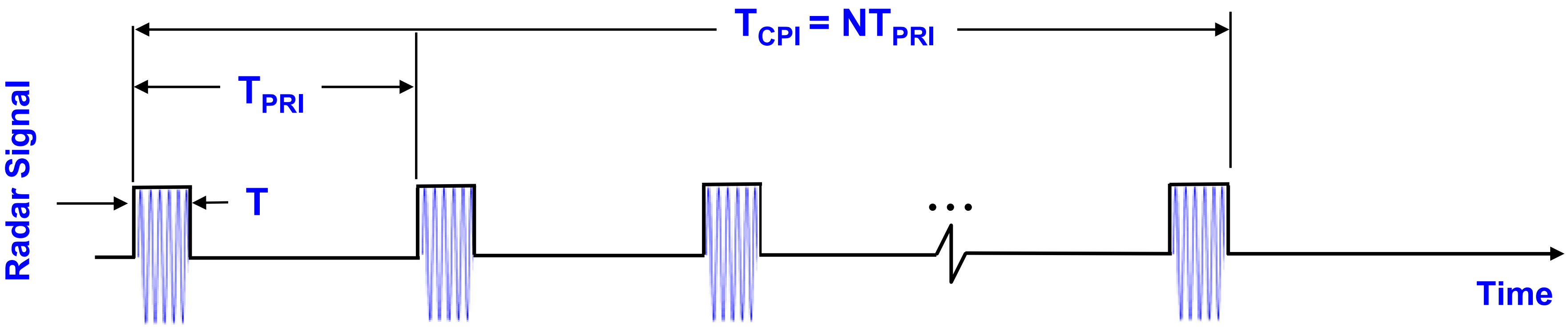
Waveforms for MTI and Pulse Doppler Processing



T	=	Pulse Length
B	$= 1/T$	Bandwidth
T_{PRI}	=	Pulse Repetition Interval (PRI)
f_P	$= 1/T_{PRI}$	Pulse Repetition Frequency (PRF)
δ	$= T/T_{PRI}$	Duty Cycle (%)
T_{CPI}	$= NT_{PRI}$	Coherent Processing Interval (CPI)
N	=	Number of pulses in the CPI N = 2, 3, or 4 for MTI N usually much greater (8 to ~1000) for Pulse Doppler

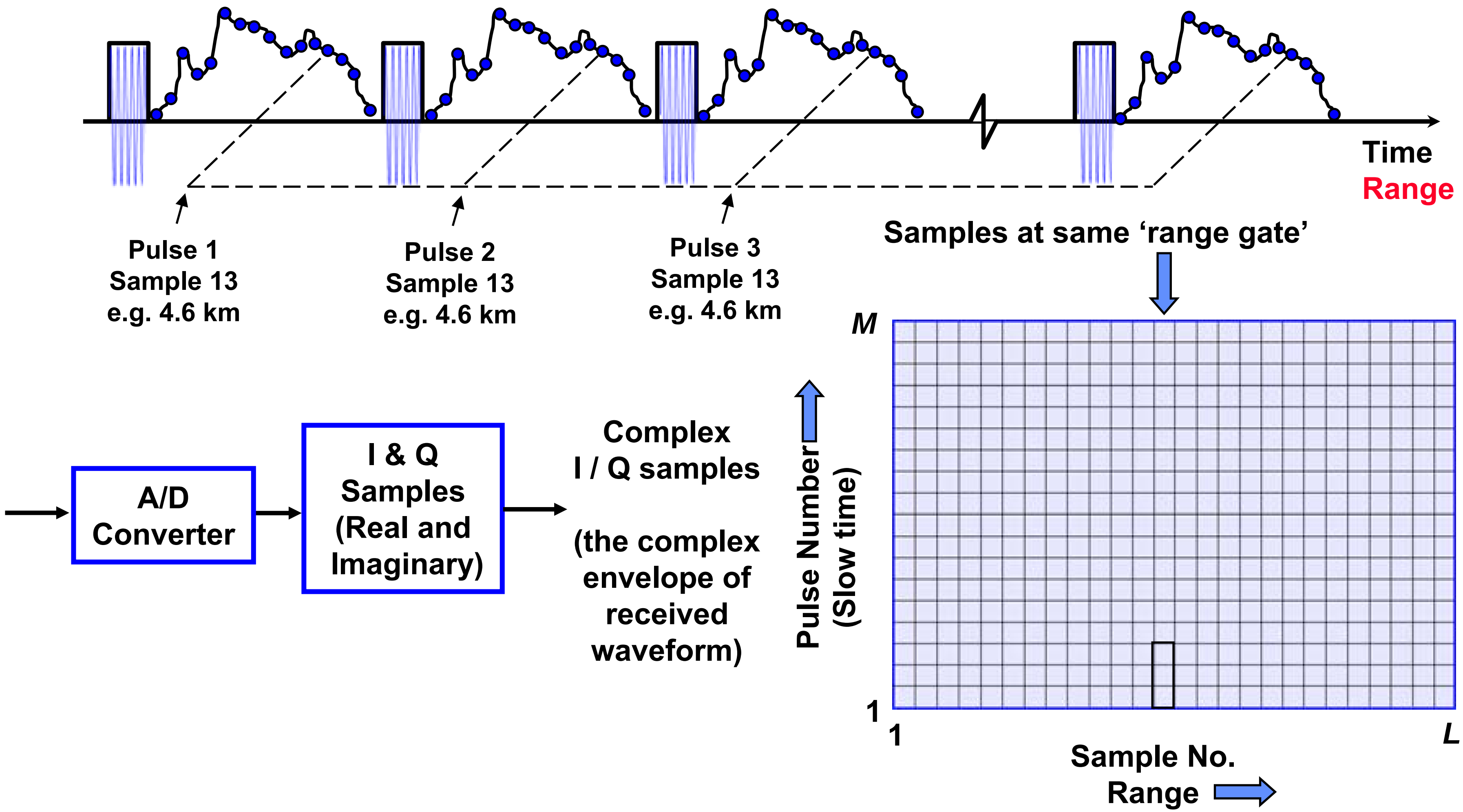
Waveforms for MTI and Pulse Doppler Processing



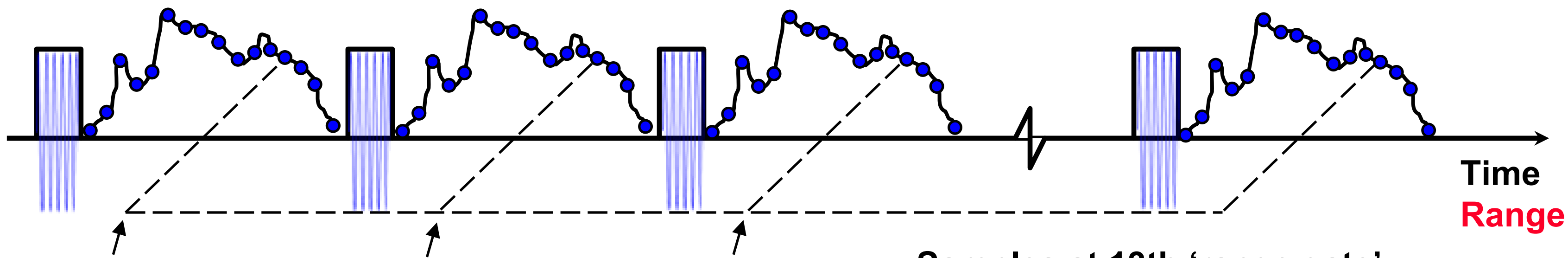
For Airport Surveillance Radar

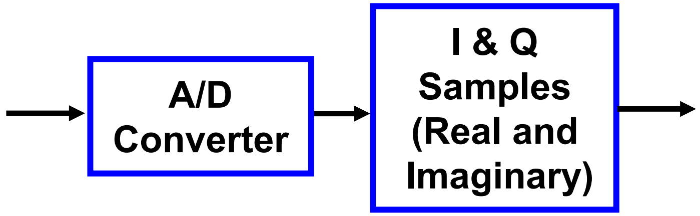
T	$=$	Pulse Length	1 μsec
B	$= 1/T$	Bandwidth	1 MHz
T_{PRI}	$=$	Pulse Repetition Interval (PRI)	1 msec
f_P	$= 1/T_{PRI}$	Pulse Repetition Frequency (PRF)	1 KHz
δ	$= T/T_{PRI}$	Duty Cycle (%)	.1 %
T_{CPI}	$= NT_{PRI}$	Coherent Processing Interval (CPI)	10 pulses
N	$=$	Number of pulses in the CPI N = 2, 3, or 4 for MTI N usually much greater (8 to ~1000) for Pulse Doppler	

Data Collection for MTI Processing



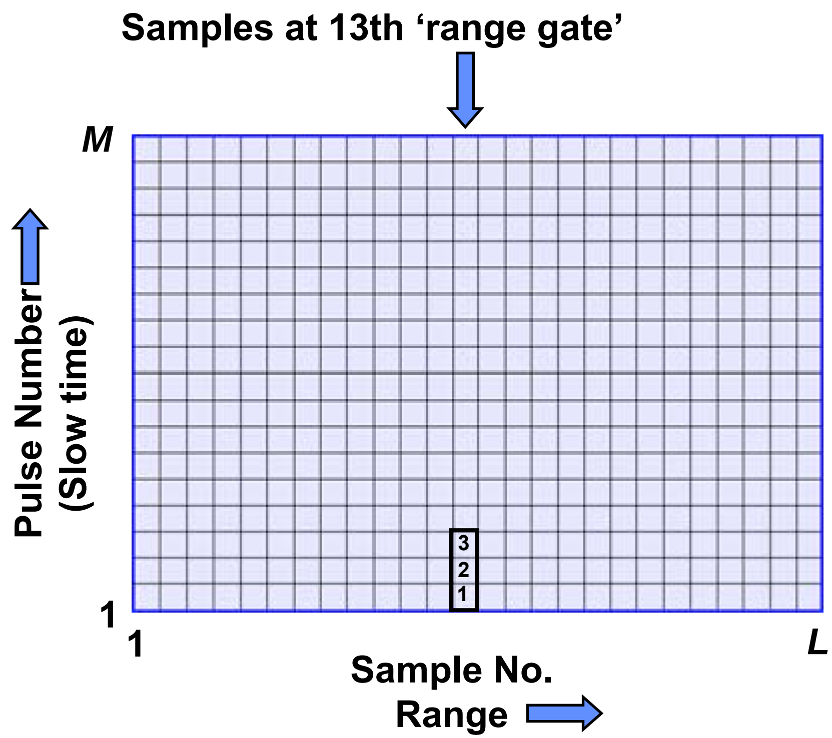
Data Collection for MTI Processing



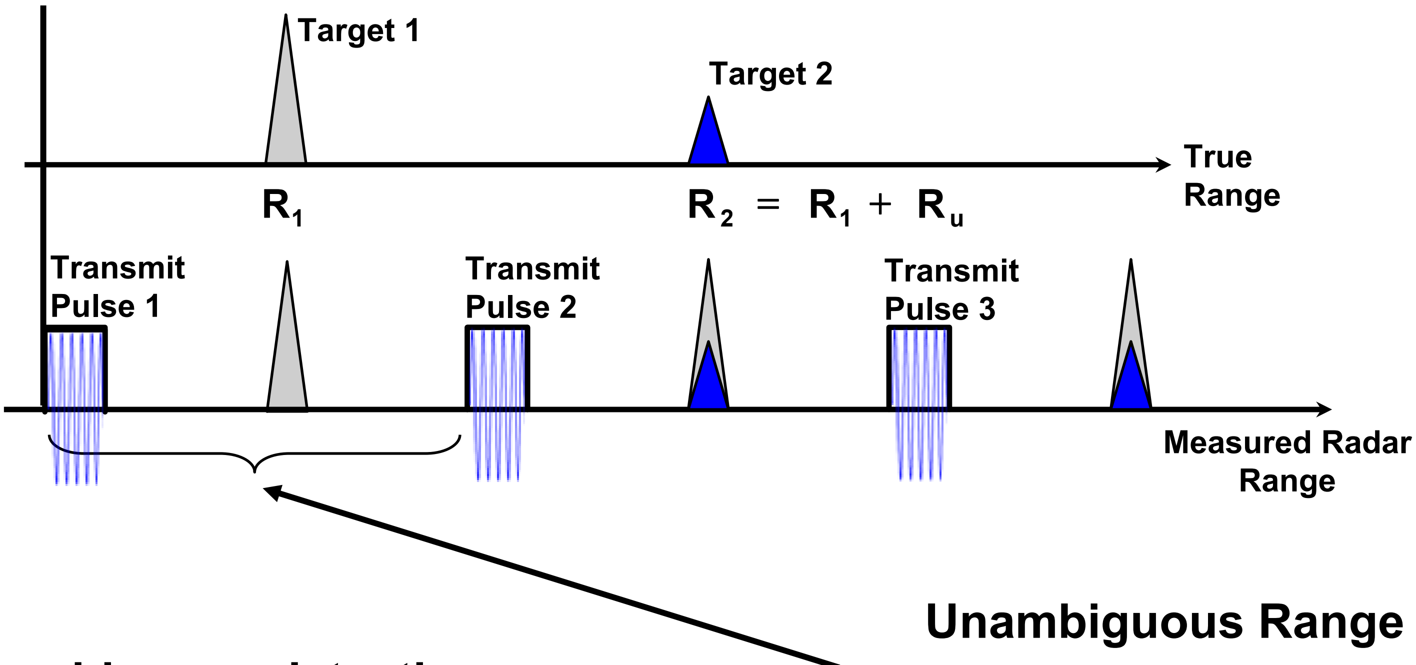


Complex
I / Q samples

(the complex
envelope of
received
waveform)



Range Ambiguities



- **Range ambiguous detections occur when echoes from one pulse are not all received before the next pulse**
- **Strong close targets (clutter) can mask far weak targets**

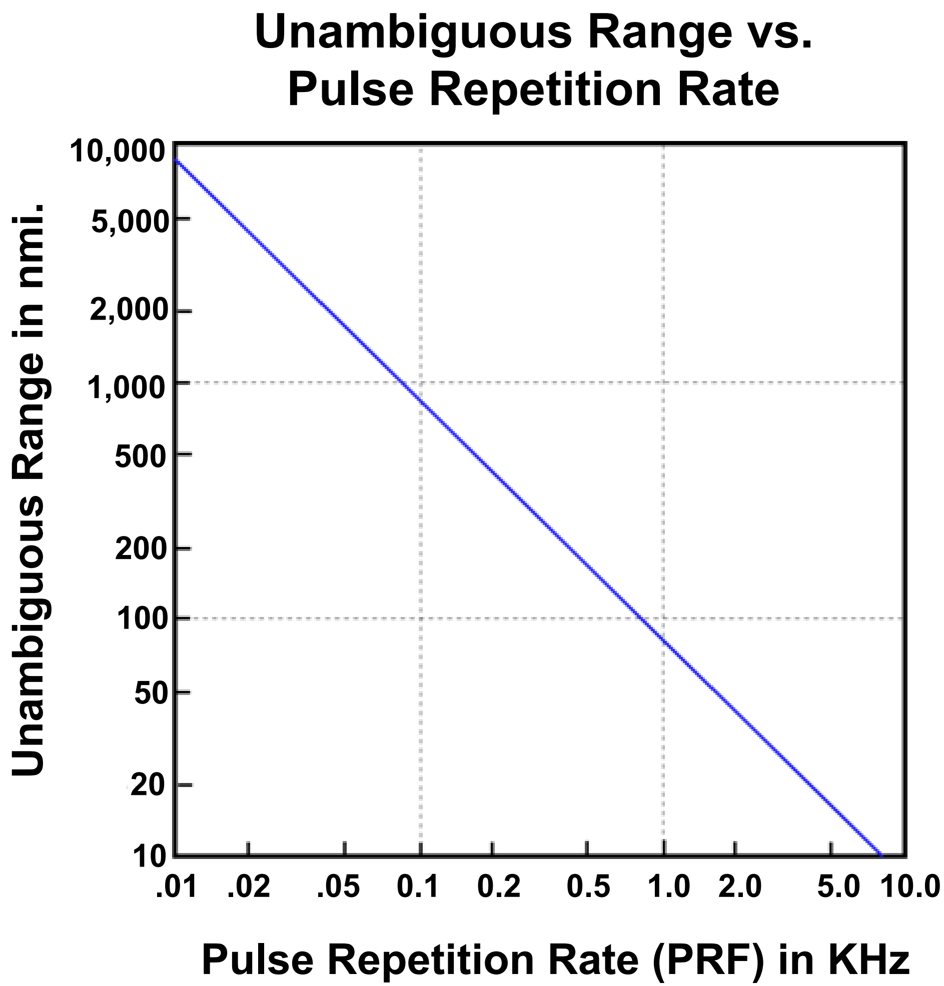
Unambiguous Range

$$R_U = \frac{c\,T_{PRI}}{2} = \frac{c}{2\,f_{PRF}}$$

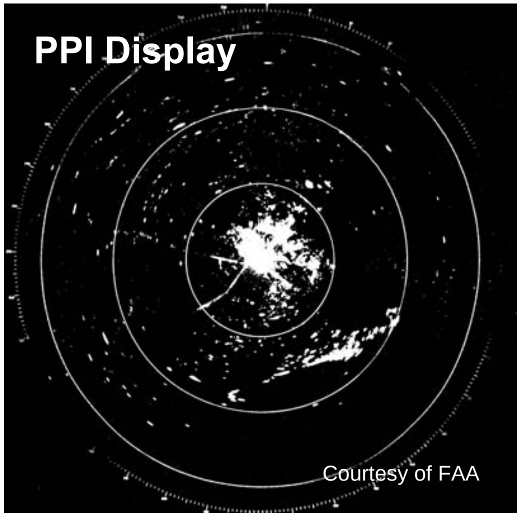
Radar Range and Choice of PRF

- Unambiguous range is inversely proportional to the PRF.
- If the PRF is to high "2nd time around" clutter can be an issue
- ASR-9
  - Range = 60 nmi
  - PRF ≈ 1250 Hz

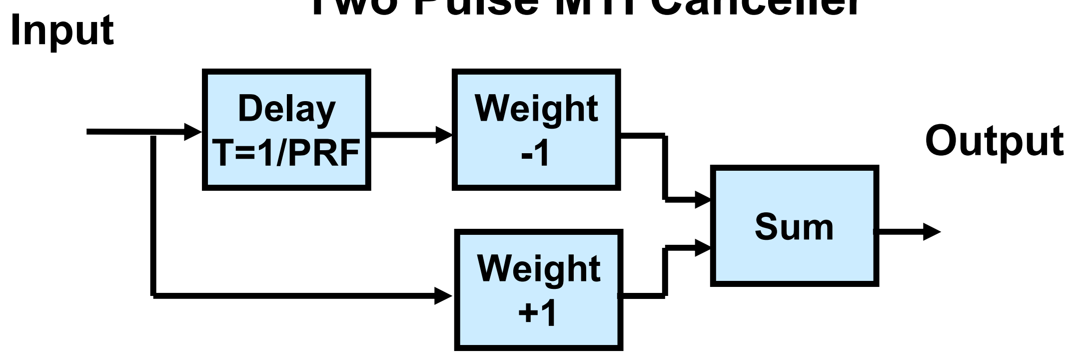
$$R_U = \frac{c\,T_{PRI}}{2} = \frac{c}{2\,f_{PRF}}$$



Unprocessed Radar Backscatter



Two Pulse MTI Canceller



$$V_{output} = V_i - V_{i-1}$$

Use low pass Doppler filter to suppress clutter backscatter

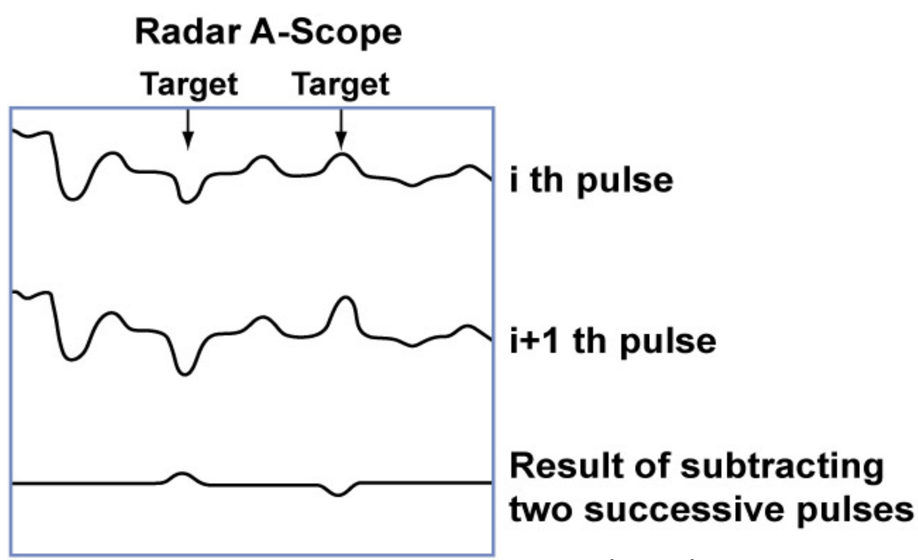
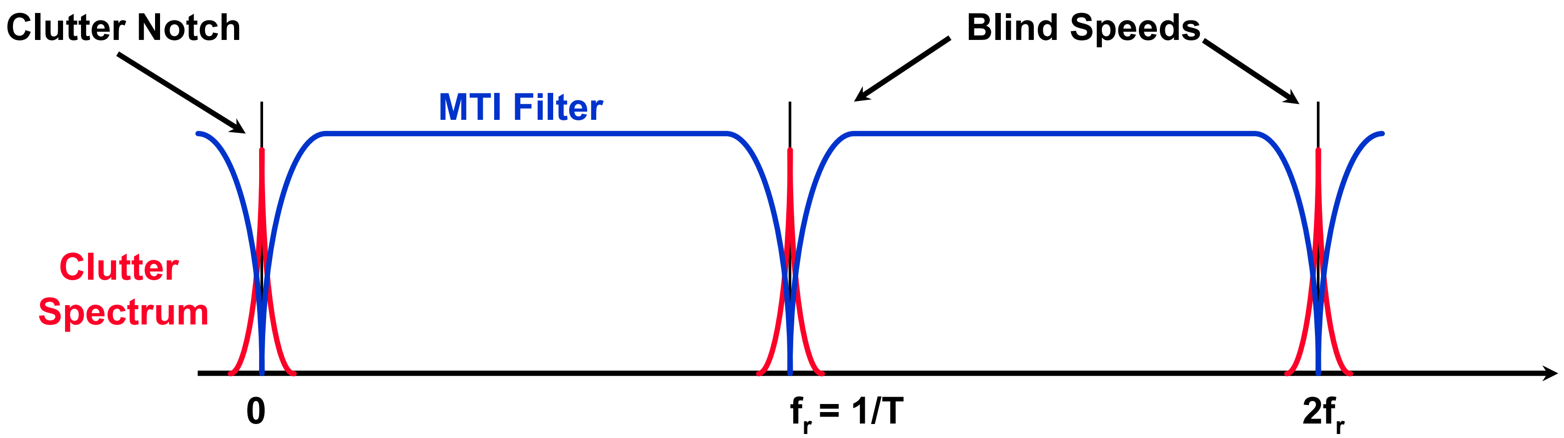


Figure by MIT OCW.

Moving Target Indicator (MTI) Processing

- **Notch out Doppler spectrum occupied by stationary clutter**
- **Provide broad Doppler passband everywhere else**
- **Blind speeds occur at multiples of the pulse repetition frequency**
  - **When sample frequency (PRF) equals a multiple of the Doppler frequency (aliasing)**

The Ideal Case



Viewgraph Courtesy of MIT Lincoln Laboratory
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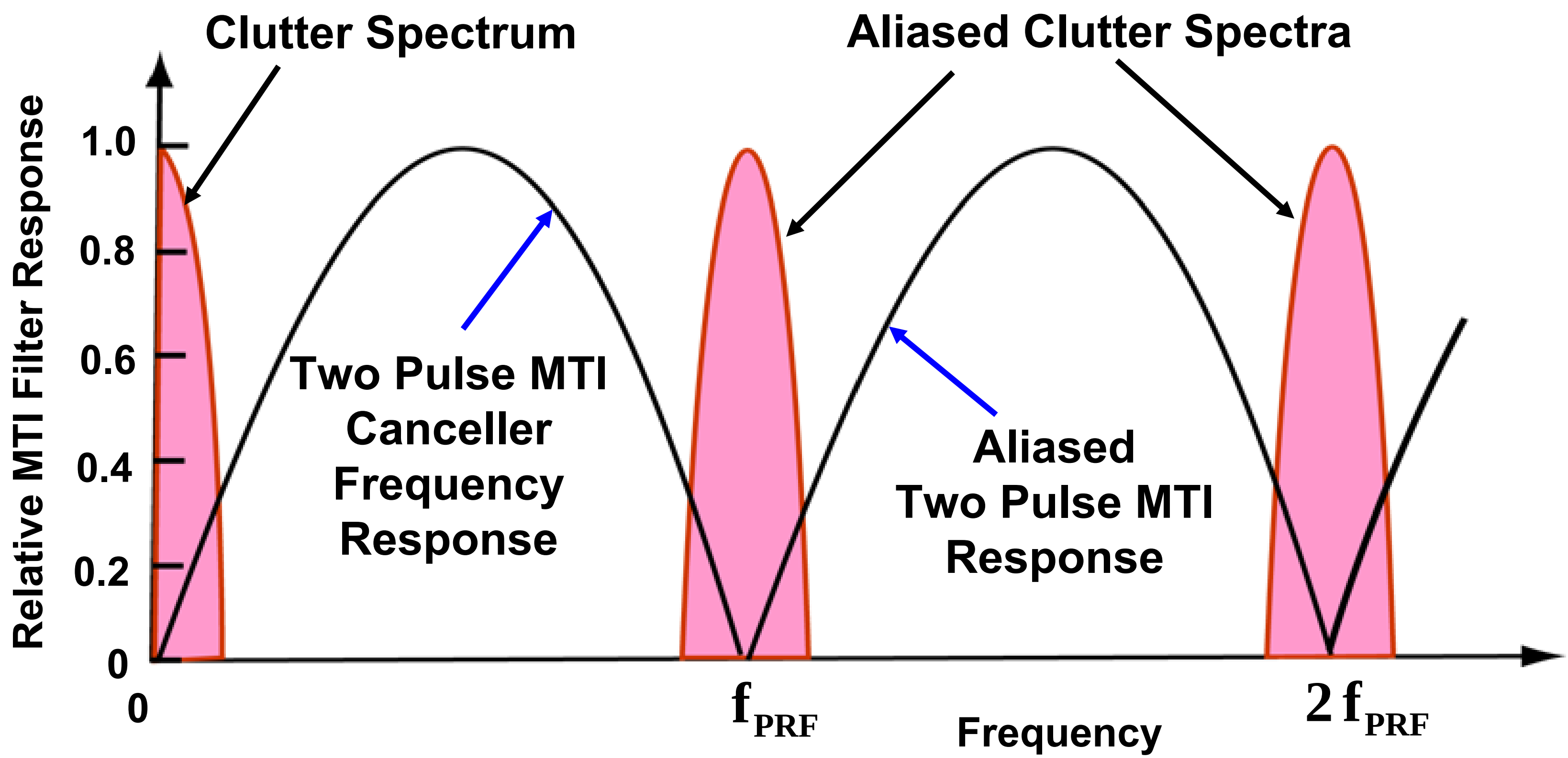
Frequency Response of Two Pulse MTI Canceller



Frequency Response : $H(f_D) = 2\sin(\pi\, f_d\, T_{PRI})$

$V_{output} = V_i - V_{i-1}$

Adapted from Skolnik, reference 1

MTI Processing – The Reality

- Clutter spectrum has finite width which depends on
  - Antenna motion, if antenna is rotating mechanically
  - Motion of ground backscatter (forest, vegetation, etc.)
  - Instabilities of transmitter
- All MTI processors see some of this spectrally spread ground clutter
  - Two pulse, three pulse, four pulse etc, MTI cancellers
  - Use of feedback in the MTI canceller design
- All of these have their strengths and weaknesses
  - The main issue is how much clutter backscatter leaks through the MTI Canceller

    Called "Clutter Residue"
-

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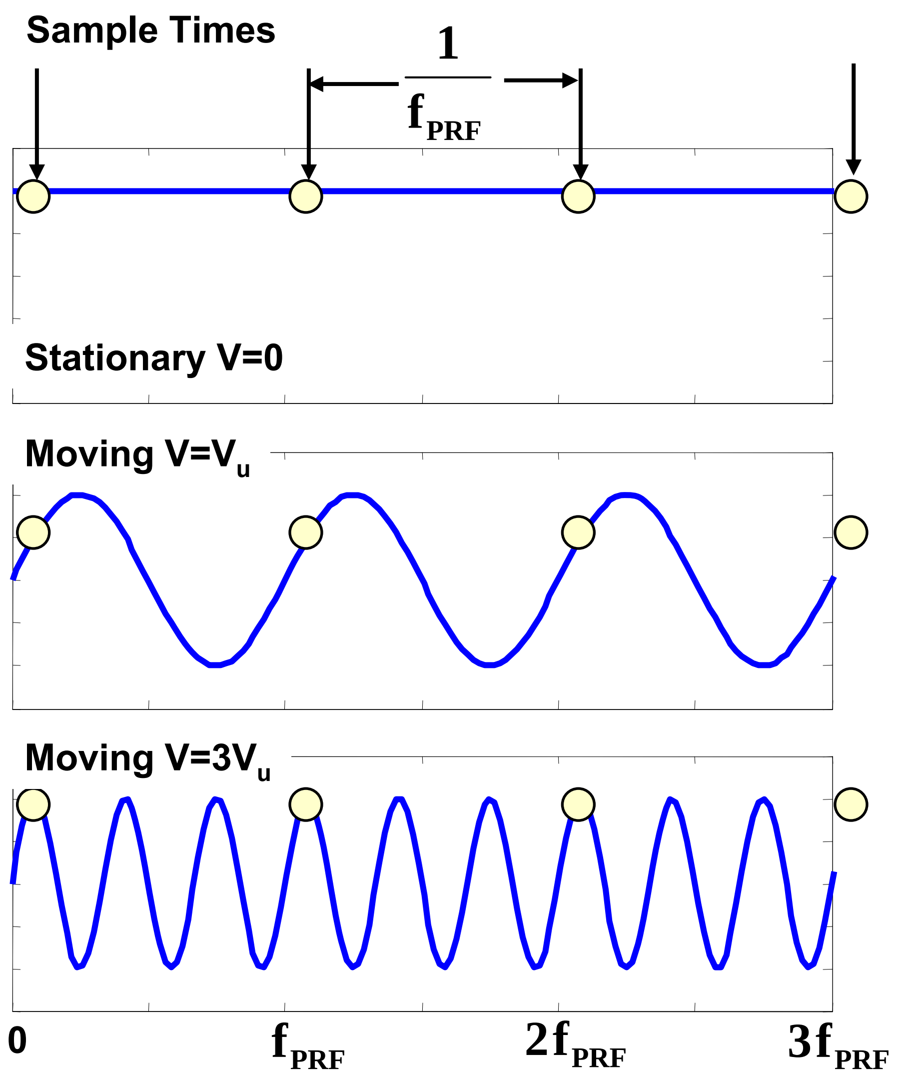
Doppler Ambiguities

- Pulse Doppler waveform samples target with sampling rate = PRF
- Sampling causes aliasing at multiples of PRF
- Two targets with Doppler frequencies separated by an integer multiple of the PRF are indistinguishable
- Unambiguous velocity is given by:

$$V_U = \frac{\lambda f_{PRF}}{2}$$



Viewgraph Courtesy of MIT Lincoln Laboratory
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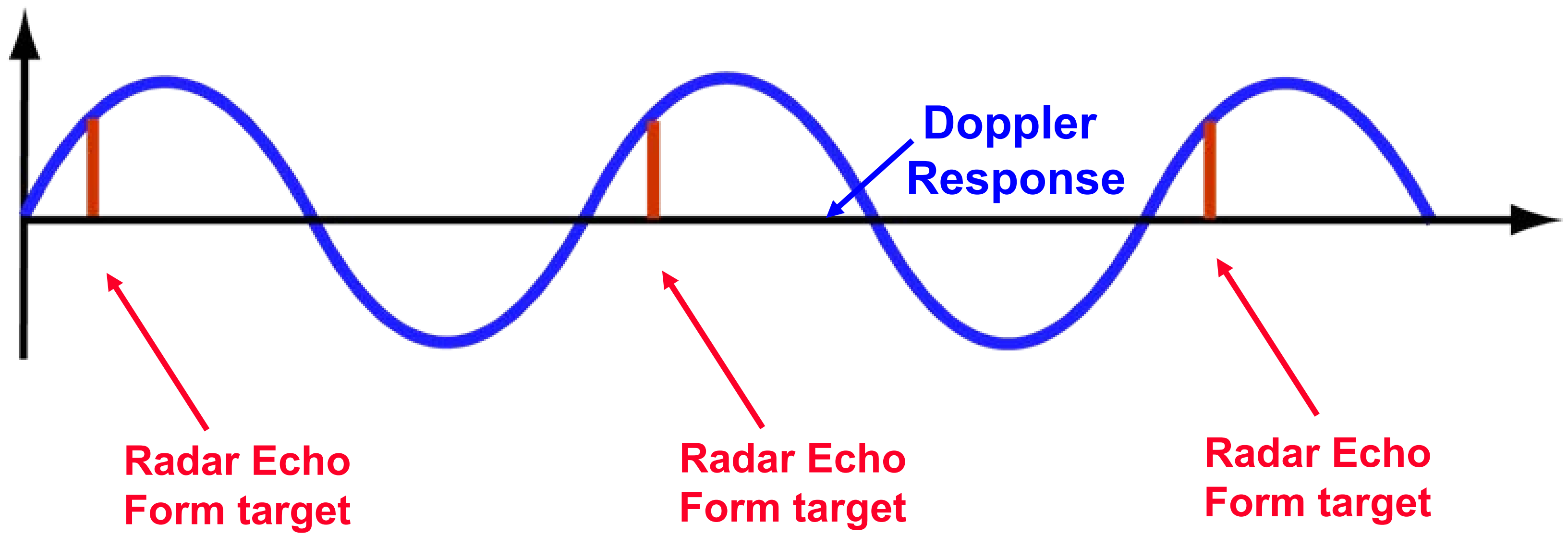
Blind Speed - Example

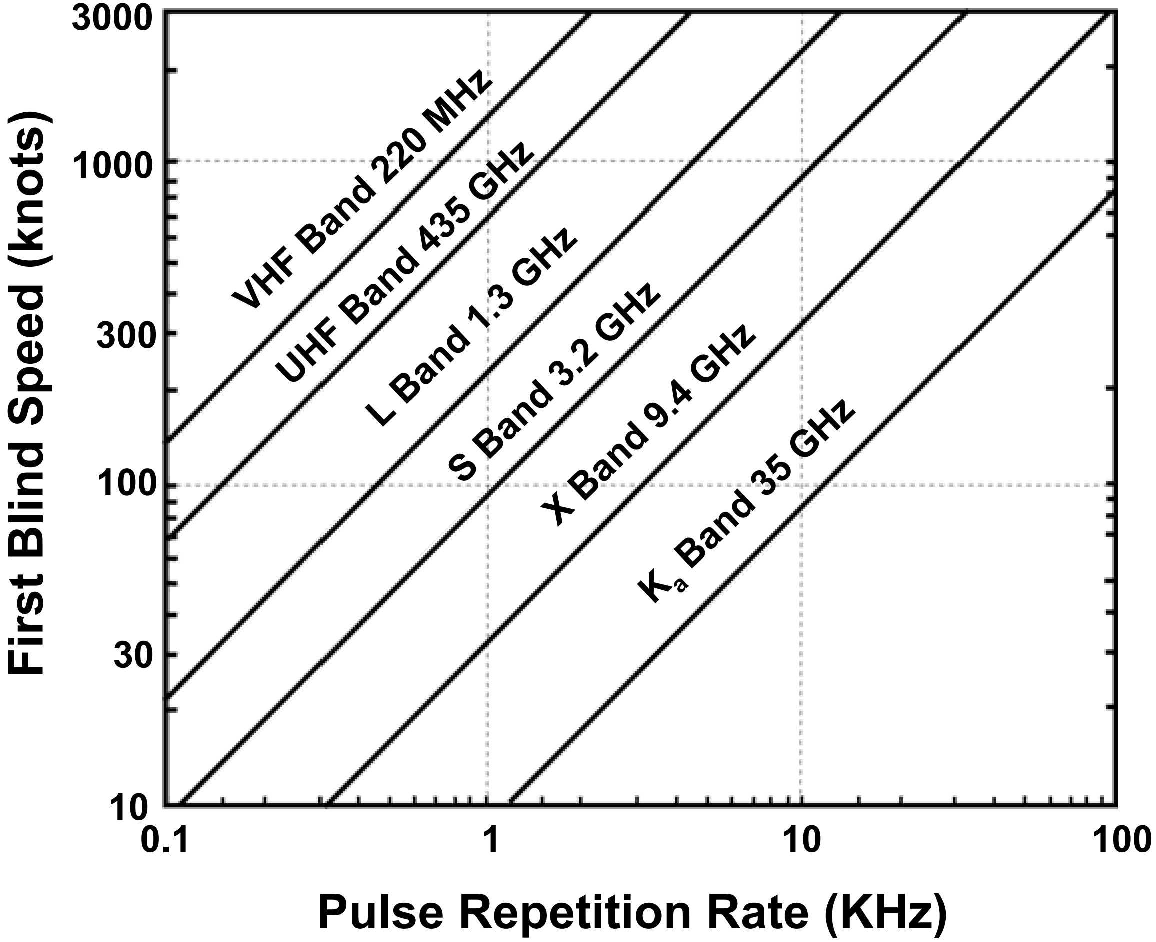


- Blind Speeds, V_B , result when the PRF (f_{PRF}) is equal to the target's Doppler velocity (or a multiple of it)

- Doppler Velocity related to the Doppler Frequency by:

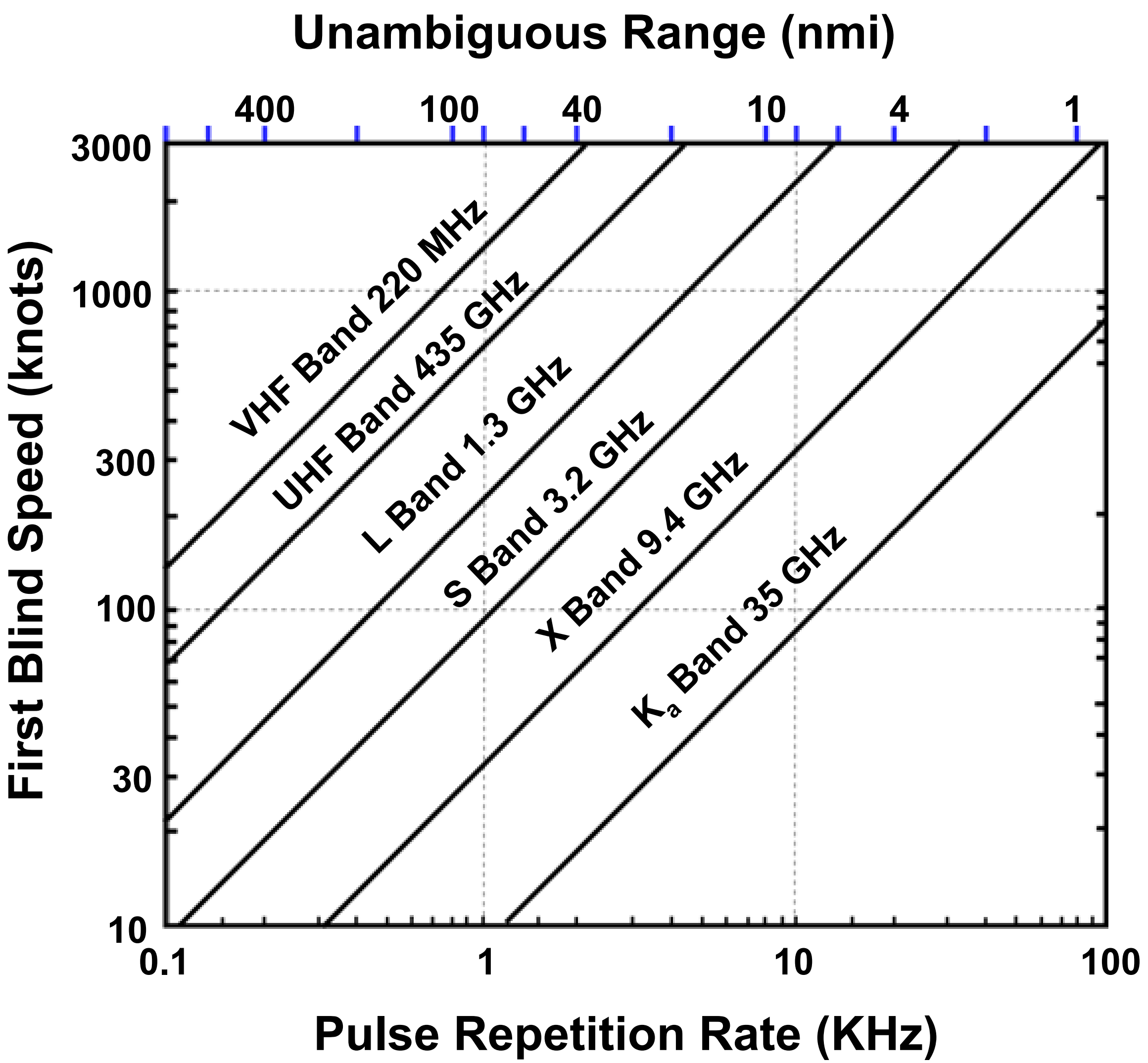
$$V_D = \frac{\lambda f_D}{2} \qquad V_U = \frac{\lambda f_{PRF}}{2} = n V_B \qquad n = \pm \text{integers}$$

Unambiguous Doppler Velocity and Range



$$V_B = \frac{\lambda \, f_{PRF}}{2}$$

Unambiguous Doppler Velocity and Range

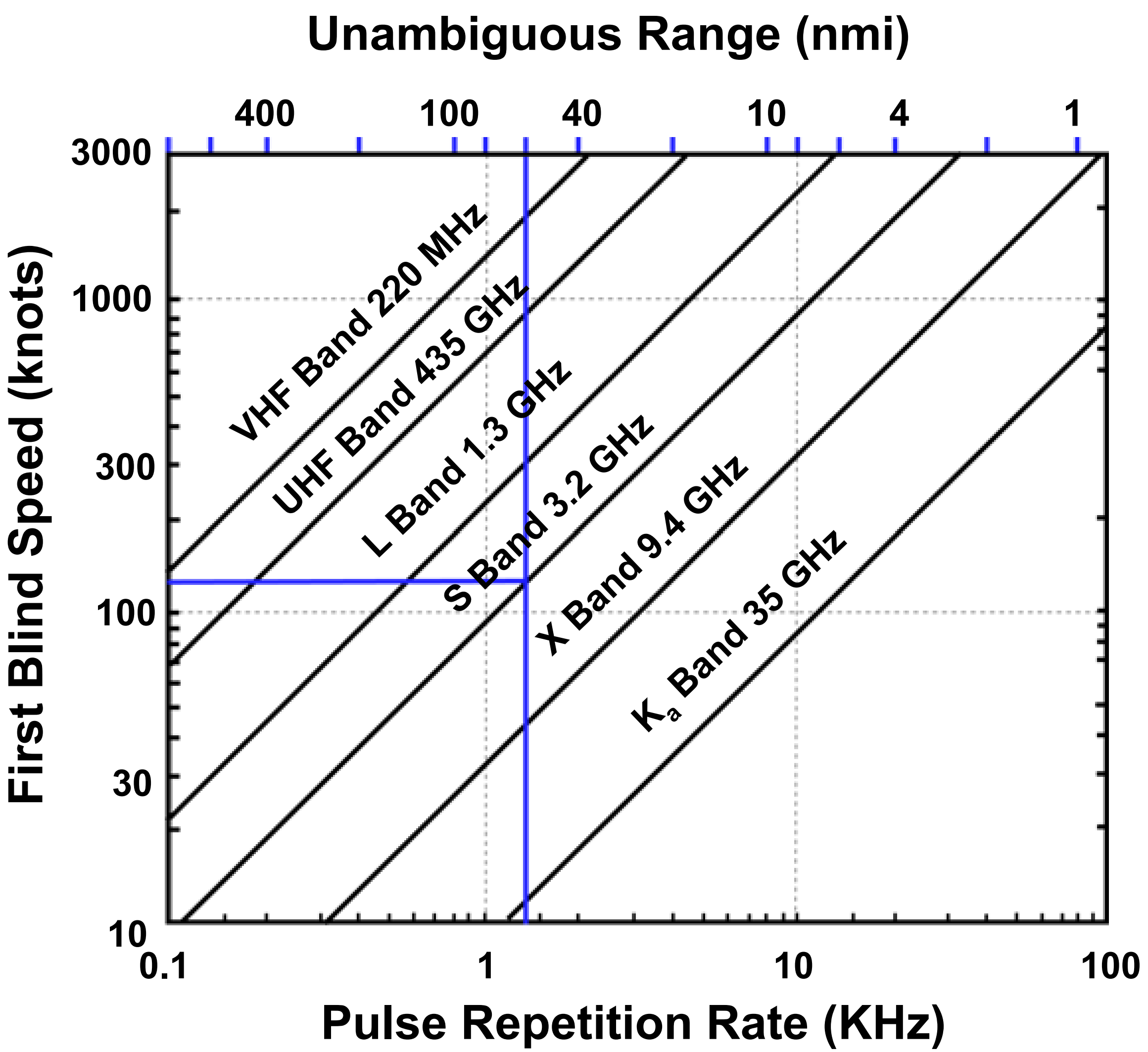


$$V_B = \frac{\lambda\, f_{PRF}}{2}$$

and

$$R_U = \frac{c}{2\, f_{PRF}}$$

Unambiguous Doppler Velocity and Range



Combining

$$V_B = \frac{\lambda f_{PRF}}{2}$$

and

$$R_U = \frac{c}{2 f_{PRF}}$$

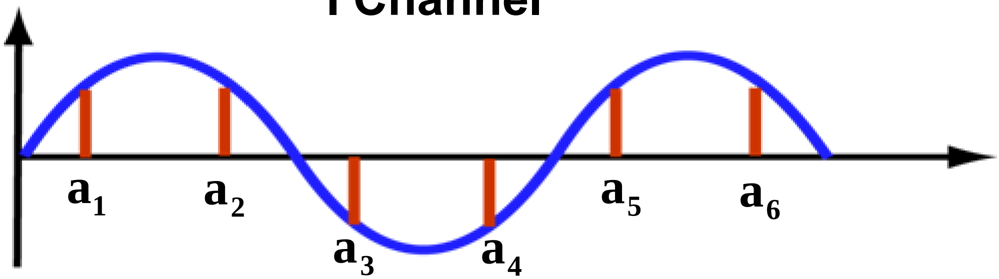
Yields

$$V_B = \frac{\lambda c}{4 R_U}$$

Example – ASR-9 $R_U = 60\,\text{nmi} \;-\; f_{PRF} \sim 1250\text{Hz} - V_B \sim 120\,\text{knots}$

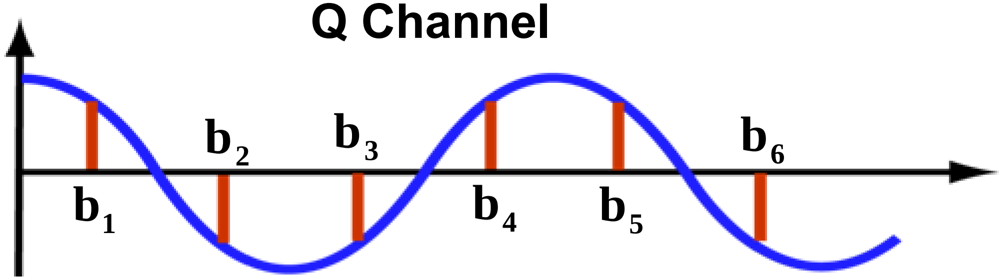
MTI Blind Phase Loss – Example 1

I Channel



$$a_1 - a_2 = 0$$
$$a_2 - a_3 \neq 0$$
$$a_3 - a_4 = 0$$
$$a_4 - a_5 \neq 0$$

Q Channel

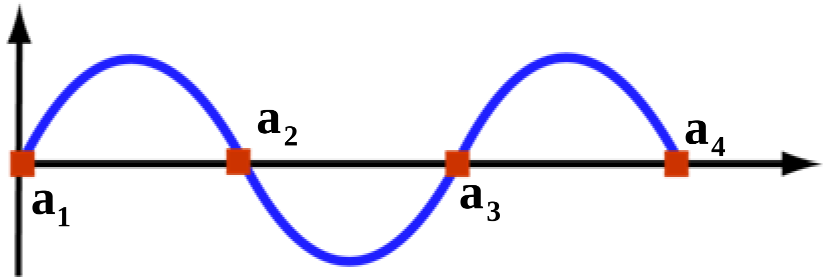


$$b_1 - b_2 \neq 0$$
$$b_2 - b_3 = 0$$
$$b_3 - b_4 \neq 0$$
$$b_4 - b_5 = 0$$

- In this case, after processing through a two pulse MTI, half of the signal energy is lost if only the I channel is used
- Use of both I and Q channels will solve this problem

MTI Blind Phase Loss – Example 2

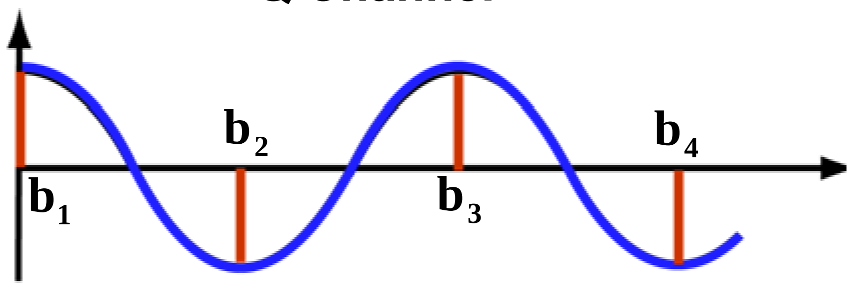
I Channel



$$a_1 - a_2 = 0$$
$$a_2 - a_3 = 0$$
$$a_3 - a_4 = 0$$

Because all samples =0

Q Channel



$$b_1 - b_2 \neq 0$$
$$b_2 - b_3 \neq 0$$
$$b_3 - b_4 \neq 0$$

- The PRF is twice the Doppler frequency of the target signal.
- The phase of the PRF is such that, for the I channel, sampling occurs at zero crossings
- However, in the Q channel sampling, the signal is completely recovered, again showing the need for implementation of both the I and Q channels

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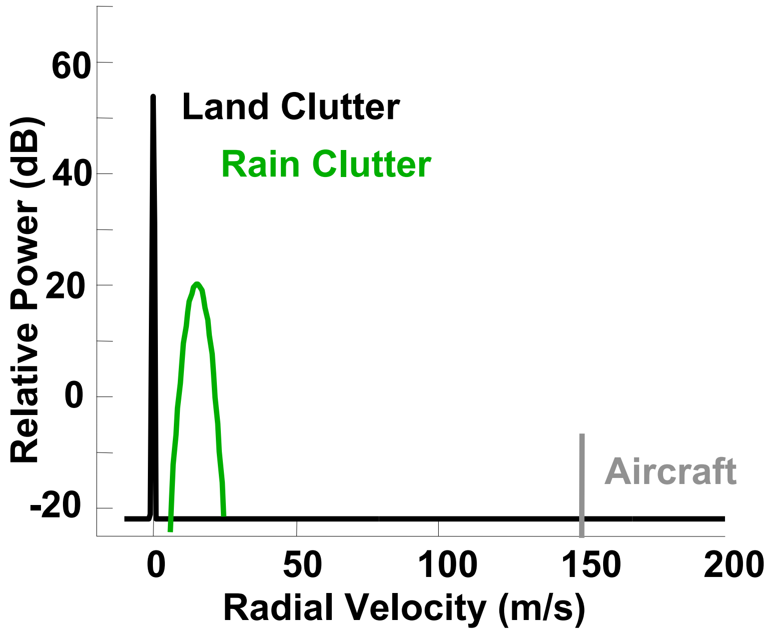
MTI Improvement Factor Redo

- S_{in} and C_{in} - Input target and clutter power per pulse
- $S_{out}(f_d)$ and $C_{out}(f_d)$ – Output target and clutter power from processor at Doppler frequency, f_d
- MTI Improvement Factor = $I(f_d)$ =

$$\left. \frac{(\text{Signal / Clutter})_{out}}{(\text{Signal / Clutter})_{in}} \right|_{f_d}$$



MTI Improvement Factor

$$I(f_d) = \left. \frac{C_{in}}{C_{out}} \times \frac{S_{out}}{S_{in}} \right|_{f_d}$$

Clutter Attenuation

Signal Gain

Viewgraph Courtesy of MIT Lincoln Laboratory
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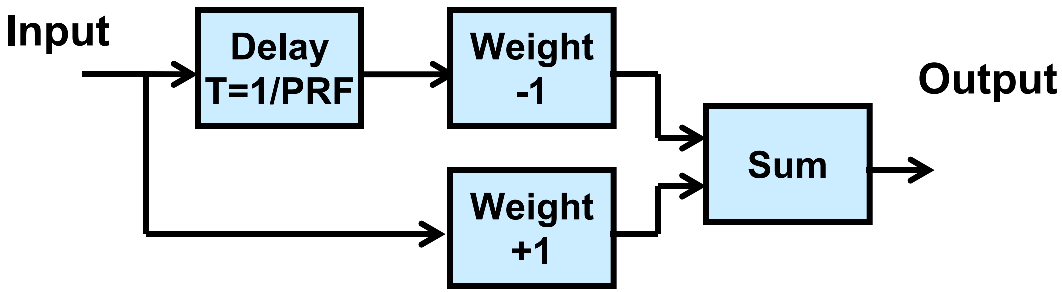
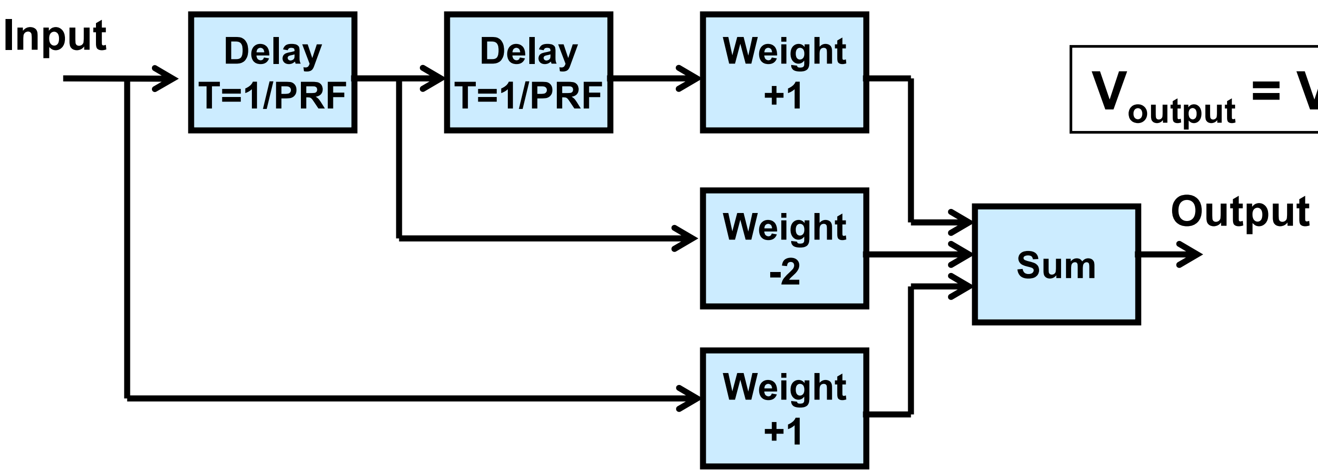
Two and Three Pulse MTI Canceller

Two Pulse Canceller



$$V_{output} = V_i - V_{i-1}$$

Three Pulse Canceller



$$V_{output} = V_i - 2V_{i-1} + V_{i-2}$$

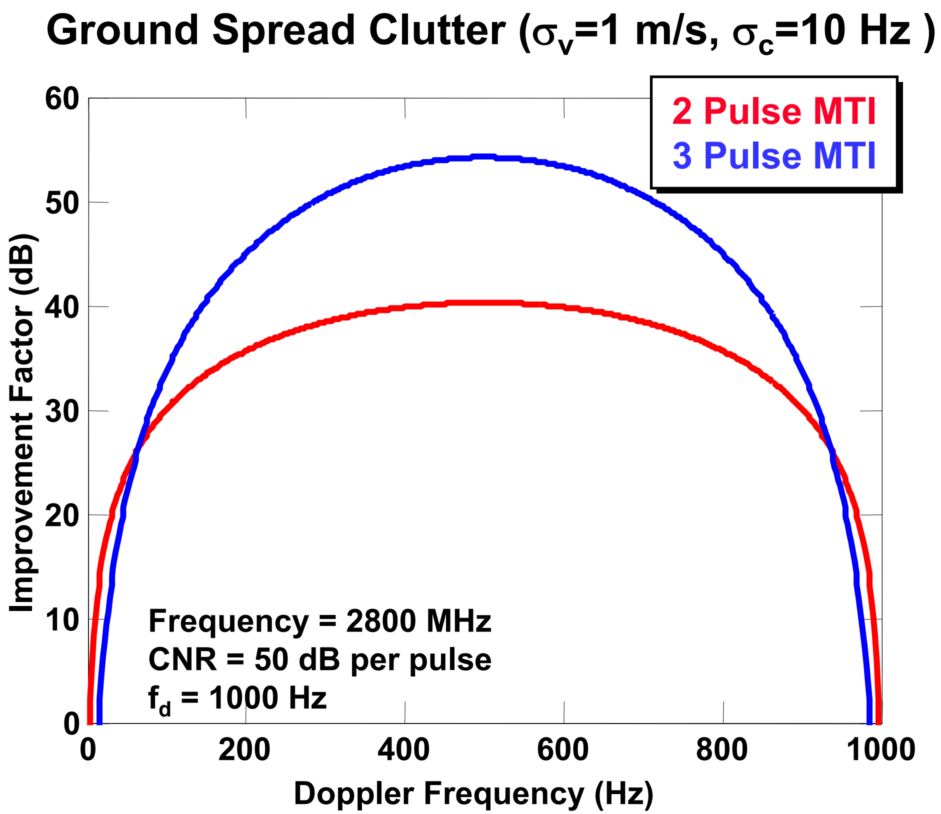
MTI Improvement Factor Examples

2-Pulse MTI

$$V_{output} = V_i - V_{i-1}$$

3-Pulse MTI

$$V_{output} = V_i - 2V_{i-1} + V_{i-2}$$



Three-pulse canceller provides wider clutter notch and greater clutter attenuation for this model , which includes only the effect of ground clutter

Viewgraph Courtesy of MIT Lincoln Laboratory
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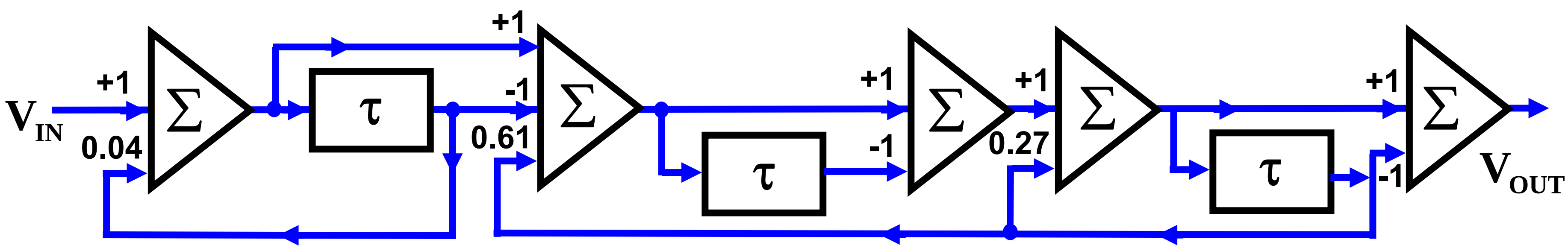
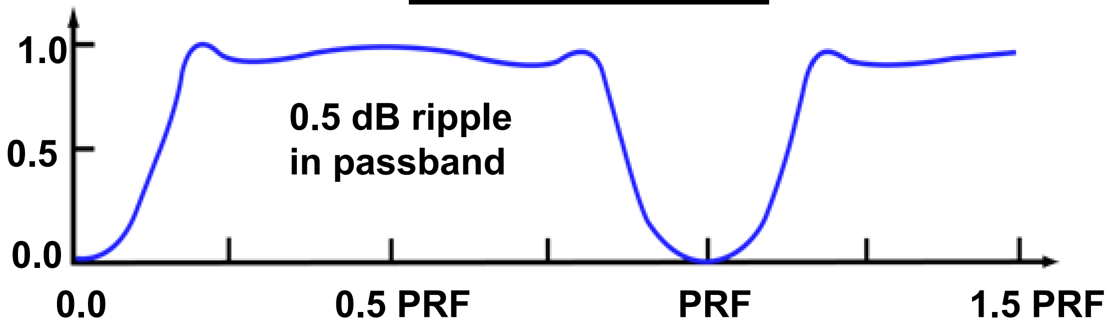
MTI Cancellers Employing Feedback

- With few pulses it is very difficult to develop a filter, which has a rectangular shape without employing feedback in the MTI canceller

Recursive MTI Filter Based on a Three Pole Chebyshev Design



Filter Response



Recursive Techniques For MTI Cancellation

- **Advantages**
  - Good rectangular response across Doppler spectrum
  - Well suited for weather sensing radars, which want to reject ground clutter and detect moving precipitation
    - NEXRAD (WSR-88)
    - Terminal Doppler Weather radar (TDWR)
- **Disadvantages**
  - Poor rejection of moving clutter, such as rain or chaff
  - Large discrete clutter echoes and interference from other nearby radars can produce transient ringing in these recursive filters
    - Avoided in military radars

Outline

- Introduction
- History of Clutter Rejection
  - Non-coherent MTI
- Impact of the Digital Revolution – Moore's law
- MTI Clutter Cancellation
  - General description
    - Doppler ambiguities and blind speed effects
    - MTI Improvement factor
  - MTI cancellers
    - Two pulse, three pulse, etc.
    - Feedback
  - Effect of signal limiting on performance
  - Multiple and staggered PRFs
- Summary

Use of Limiters in MTI Radars

- **Before the days of modern A/D converters, with wide dynamic range and high sample rate, radars needed to apply a limiter to the radar signal in the receiver of saturation would occur.**
  - Analog displays would "bloom" because they had only 20 db or so dynamic range.
  - Limiting of the amplitude of large clutter discrete echoes, causes significant spread of their spectra
- **Its has been shown that use of limiters with MTI cancellers significantly reduces their performance**
  - MTI Improvement factor of a 3 pulse canceller is reduced from 42 db (without limiting) to 29 dB (with limiting)
- **The modern and simple solution is to use A/D converters, with enough bits, so that they can adequately accommodate all of the expected signal and clutter echoes within their dynamic range**

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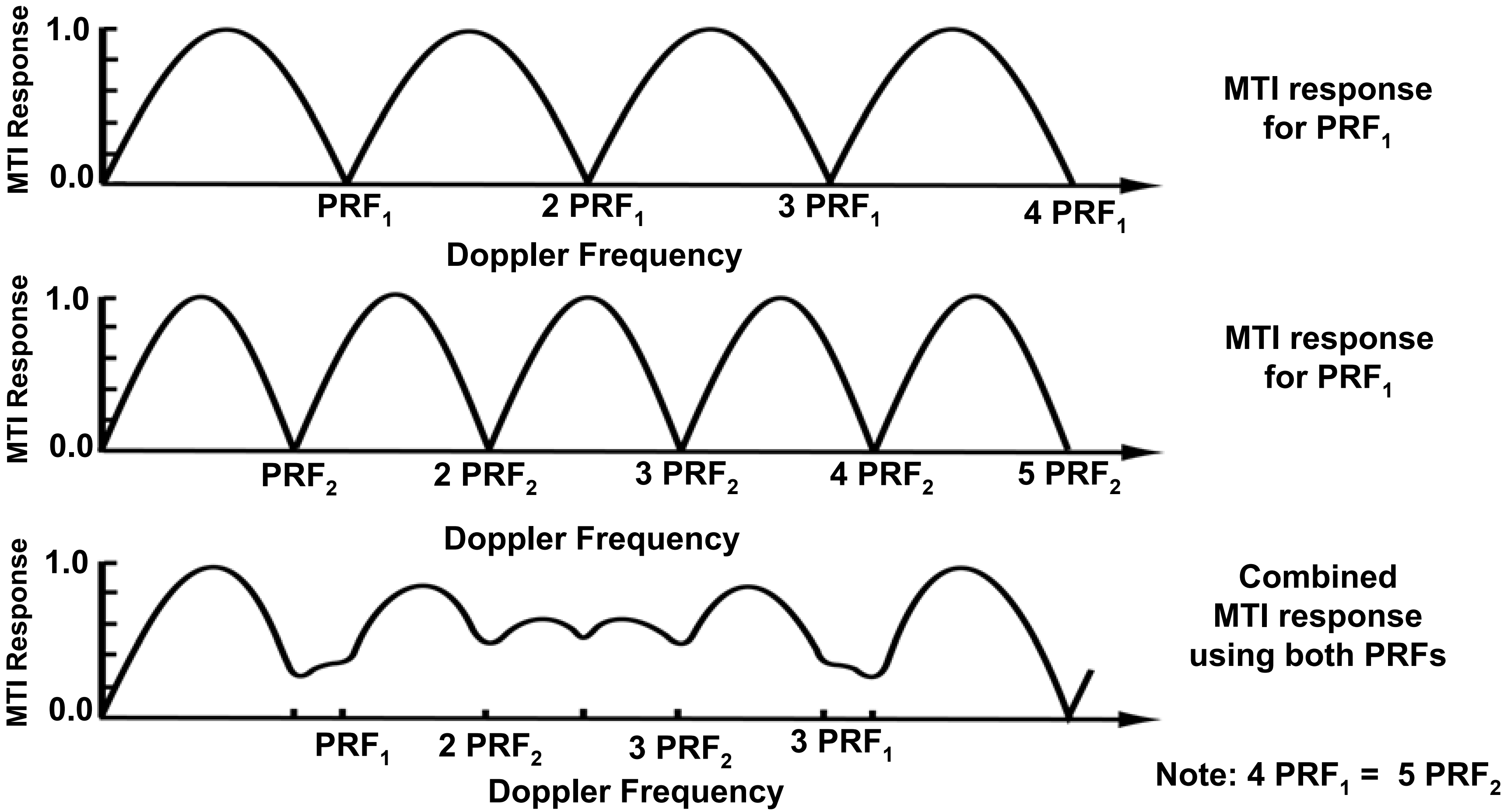
- Summary

Use of Multiple PRFs to Mitigate Blind Speed Issues



- Using multiple PRFs allows targets, whose radial velocity corresponds to the blind speed at 1 PRF, to be detected at another PRF.
- PRFs may be changed from scan to scan, dwell to dwell, or from pulse to pulse (Staggered PRFs)

Staggered PRFs to Increase Blind Speed

- Staggering or changing the time between pulses (Pulse Repetition Rate - PRF) will raise the blind speed

- Although the staggered PRFs remove the blind speeds that would have been obtained with a constant PRF, there will eventually be a new blind speed

- This occurs when the $\mathbf{n}$ PRFs have the following relationship:

$$\eta_1 \mathbf{f}_1 = \eta_2 \mathbf{f}_2 = \eta_3 \mathbf{f}_3 = \cdots = \eta_n \mathbf{f}_n$$

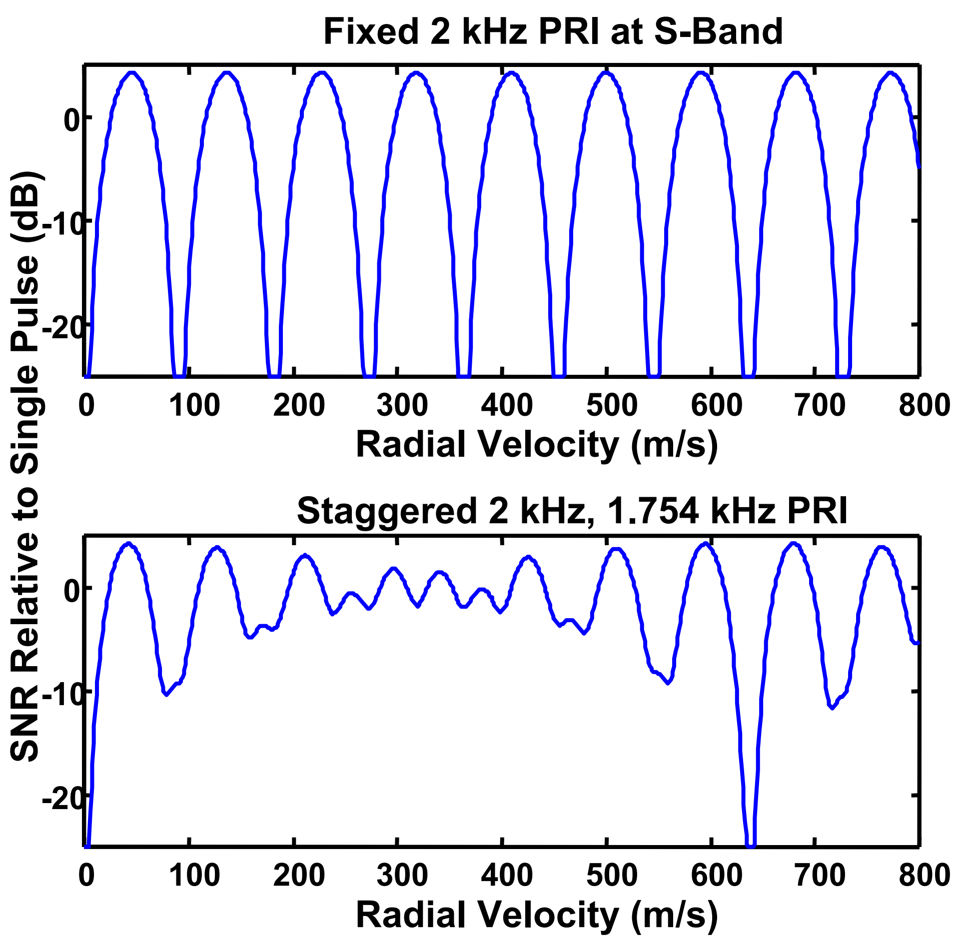
- Where $\eta_1, \eta_2, \eta_3, \cdots \eta_n$ are relatively prime integers

- The ratio of the first blind speed, $\mathbf{v}_1$, with the staggered PRF waveform to the first blind speed, $\mathbf{v}_B$, of a waveform with a constant PRF is:

$$\frac{\mathbf{v}_1}{\mathbf{v}_B} = \frac{(\eta_1 + \eta_2 + \eta_3 + \cdots + \eta_n)}{\mathbf{n}}$$

Staggered PRFs to Increase Blind Speed

MTI Frequency Response



- **Staggering or changing the time between pulses will raise the blind speed**
- **Although the staggered PRF's remove the blind speeds that would have been obtained with a constant PRF, there will be a new much higher blind speed**
- **Use of staggered PRFs does not allow he MTI cancellation of "2nd time around clutter"**

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Summary

- **Moving Target Indicator (MTI) techniques are Doppler filtering techniques that reject stationary clutter**
  - **Radial velocity is not measured**
- **Blind speeds are regions of Doppler space where targets with those Doppler velocities cannot be detected**
- **Two and three pulse MTI cancellers are examples of MTI filters**
- **Methods of increasing the blind speed**
  - **Changing the time between groups of pulses (multiple PRFs)**
  - **Changing the time between individual pulses (staggered PRFs)**
  - **There are pros and cons to each of these techniques**
- **There is significant difficulty suppressing moving clutter (rain) with MTI techniques**

Homework Problems

- **From Skolnik (Reference 1)**
  - **Problems 3-1, 3-2, 3-3, 3-4, 3-5, 3-6 and 3-8**

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
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