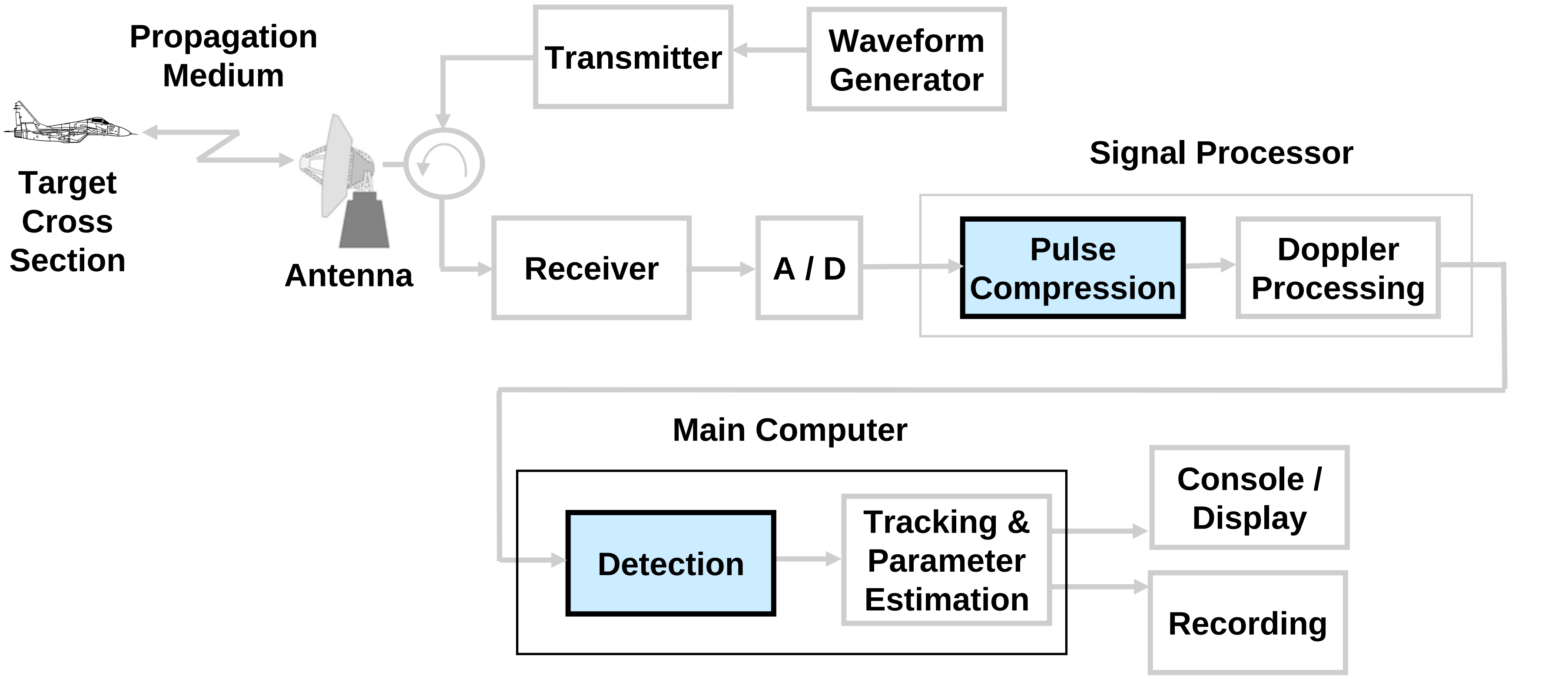
Introduction to Radar Systems

Detection of Targets in Noise
and
Pulse Compression Techniques

Disclaimer of Endorsement and Liability

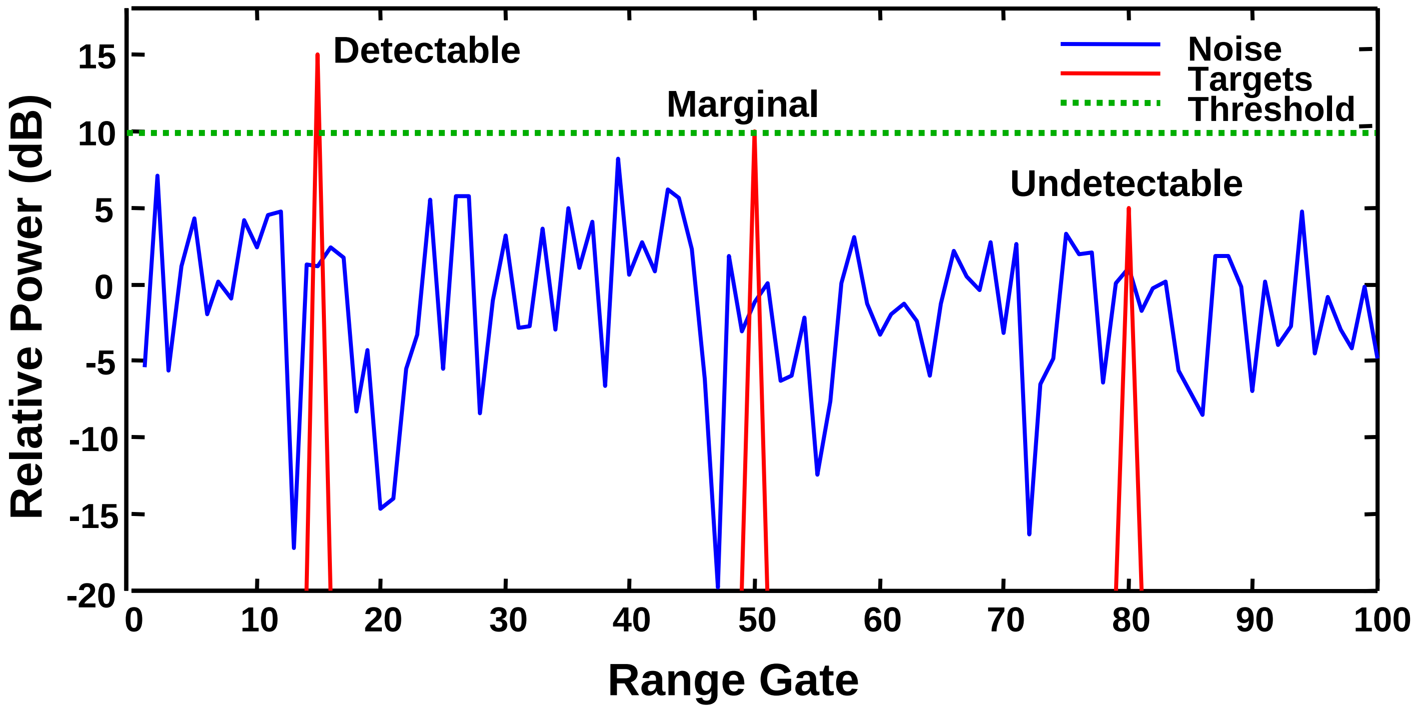
Detection and Pulse Compression



Outline

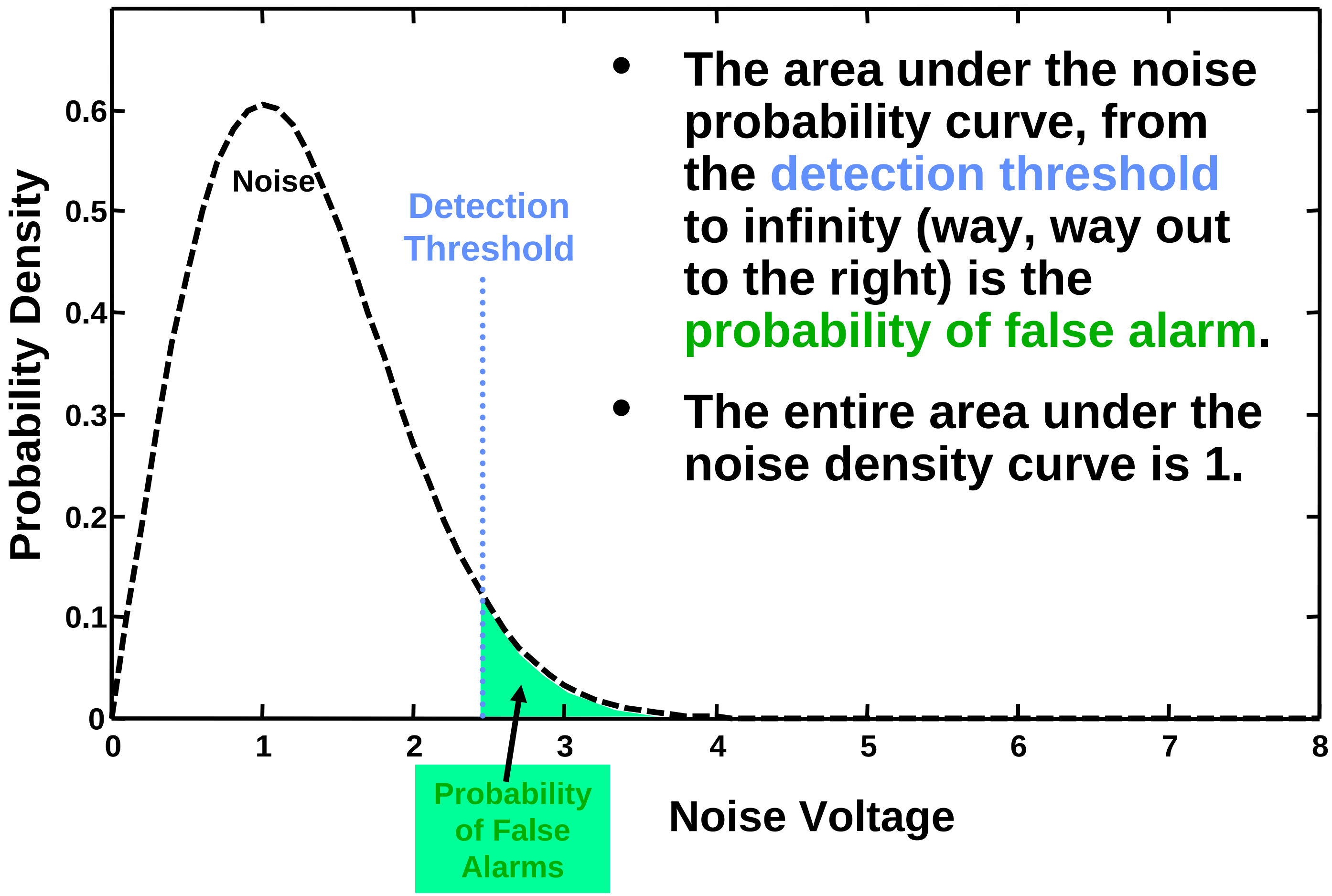
- **Detection of Target Echoes in Noise**
  - **Basic Concepts**
  - **Integration of Pulses**
  - **Fluctuating Targets Issues**
  - **Adaptive Thresholding Techniques**
- **Pulse Compression**

Target Detection in the Presence of Noise



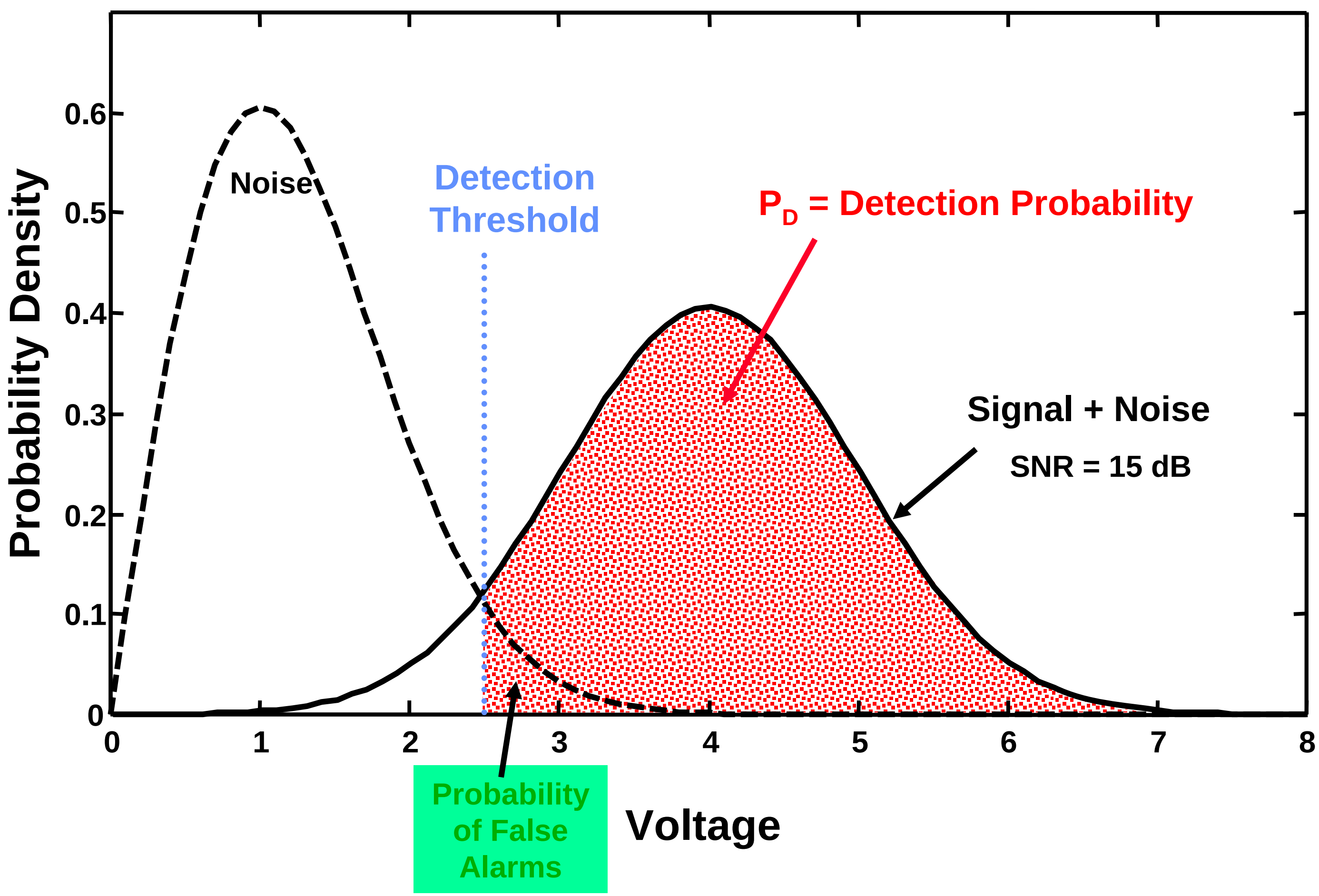
- **The radar return is sampled at regular intervals with A/D (Analog to Digital) converters**
- **The sampled returns may include the target of interest and noise**
- **A threshold is used to reject noise**

The Detection Problem

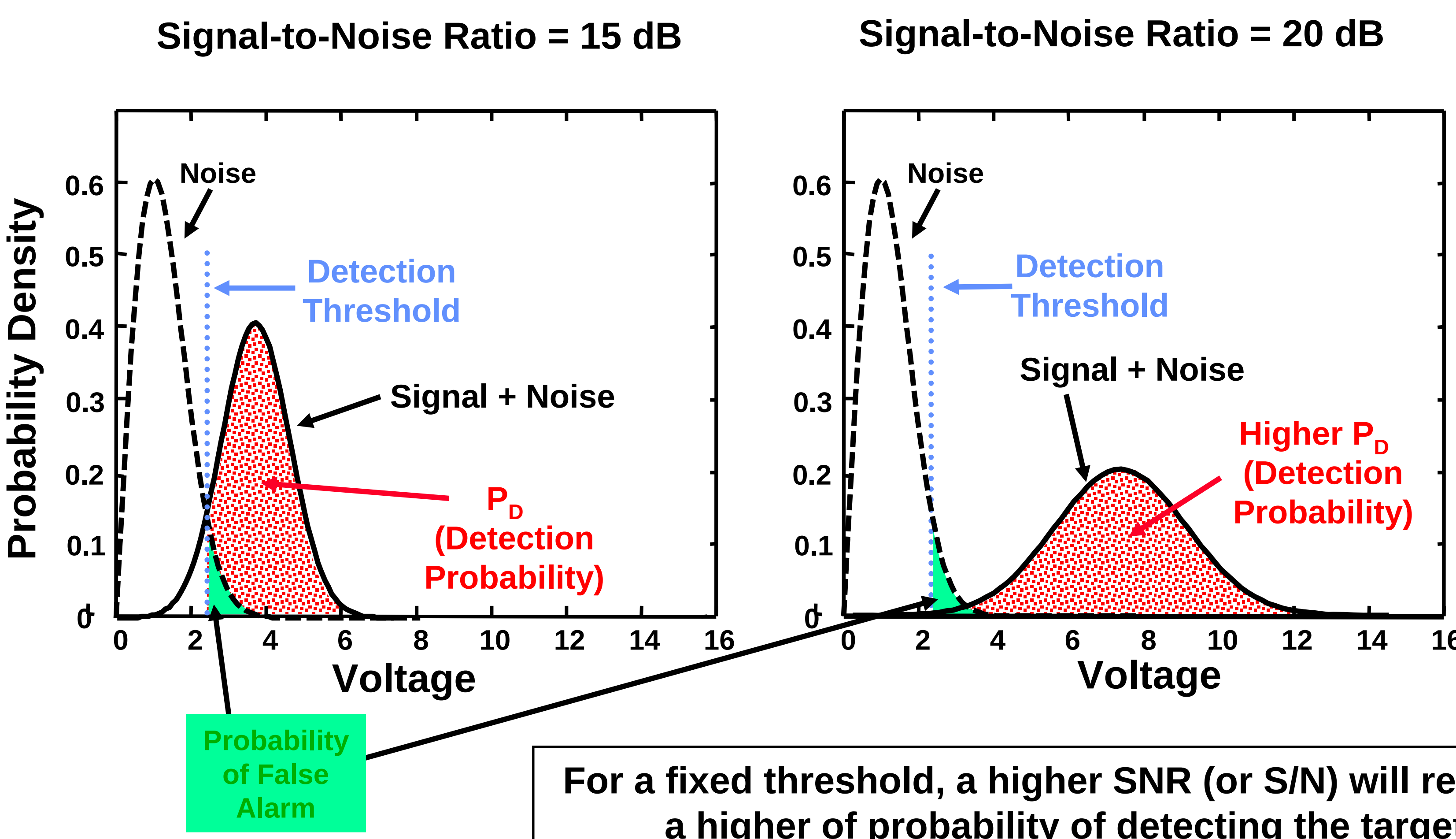


- The area under the noise probability curve, from the detection threshold to infinity (way, way out to the right) is the probability of false alarm.
- The entire area under the noise density curve is 1.

The Detection Problem

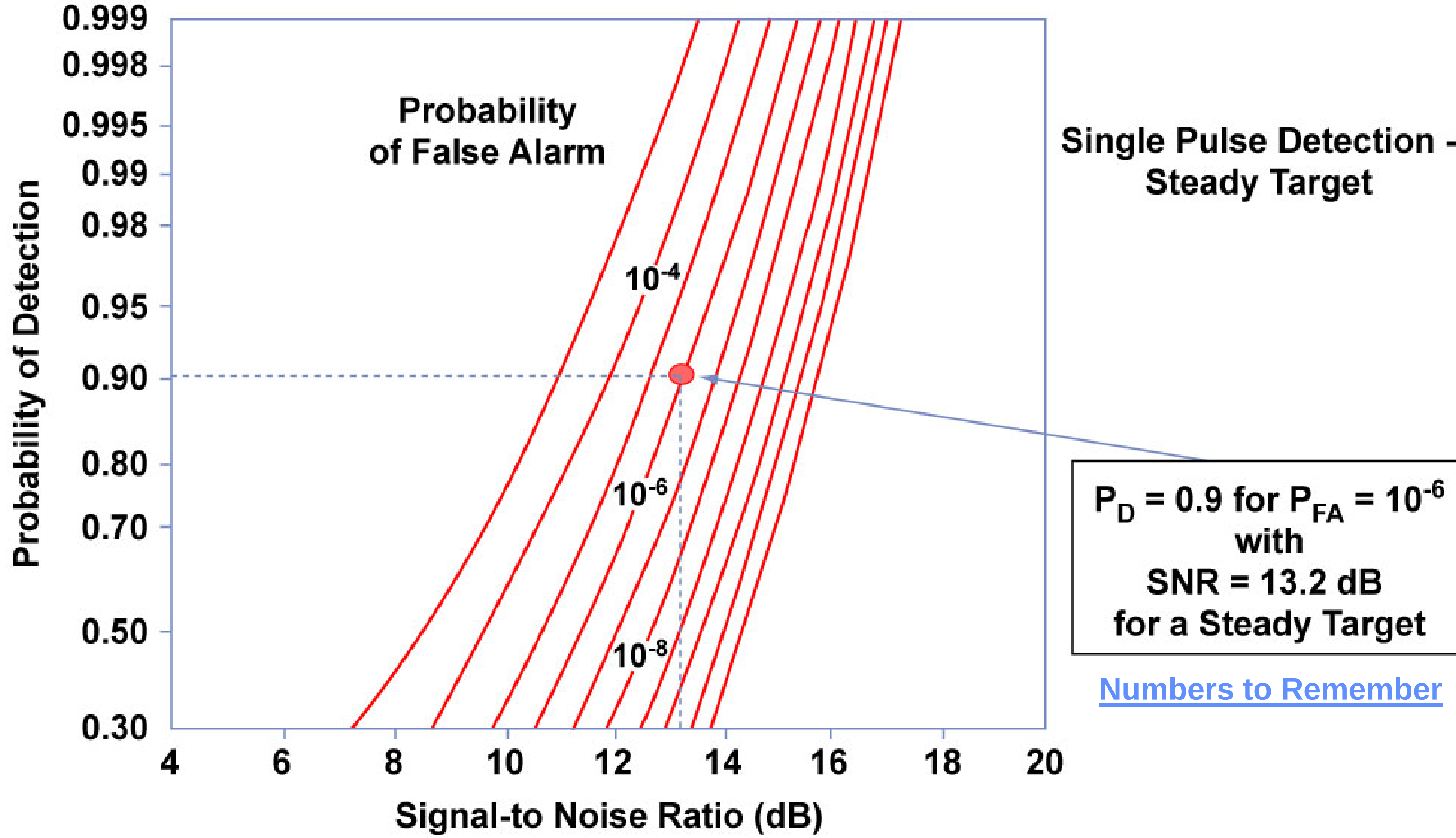


Detection Examples with Different SNR



For a fixed threshold, a higher SNR (or S/N) will result in a higher of probability of detecting the target

Probability of Detection vs. SNR



P_D = 0.9 for $P_{FA} = 10^{-6}$ with SNR = 13.2 dB for a Steady Target

Numbers to Remember

Figure by MIT OCW.

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Integration of Radar Pulses

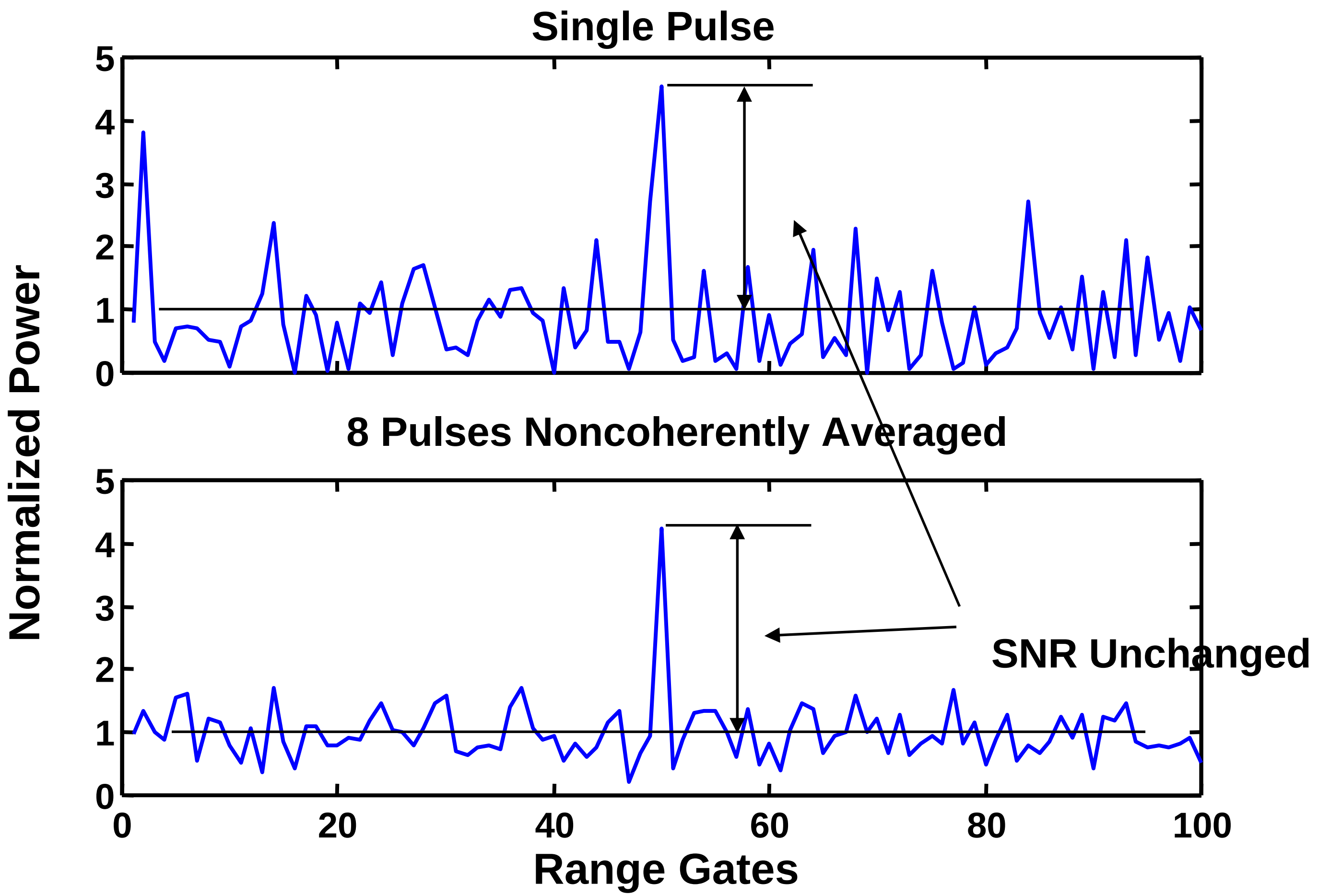
- **Improve ability of radar to detect targets by combining the returns from multiple pulses**
- **Coherent Integration**
  - **No information lost (amplitude or phase)**
- **Non-coherent integration techniques**
  - **Some information lost (phase)**
  - **Non-coherent (video) Integration**
  - **Binary Integration**
  - **Cumulative detection**
  - **For most cases, coherent integration is more efficient than non-coherent integration**

Coherent Integration

- Real and Imaginary (In-phase and Quadrature) parts of the complex radar return are added, and the magnitude of the voltage is calculated
  - $V=(I^2 + Q^2)^{1/2}$
- This quantity is then thresholded
- The coherent integration gain is equal to the number of pulses coherently integrated
  - 2 pulses 3 dB
  - 10 pulses 10 dB
  - 20 pulses 13 dB
- For this gain to be realized, the noise samples, from pulse to pulse must be independent
  - The background noise is white Gaussian noise

Noncoherent Integration

Steady Target



Noise Variance Reduced after Integration (Allows Lower Threshold)

Different Types of Non-Coherent Integration

- **Non Coherent Integration – General (aka video integration)**
  - Generate magnitude for each of N pulses
  - Add magnitudes and then threshold

- **Binary Integration**
  - Generate magnitude for each of N pulses and then threshold
  - Require at least M detections in N scans

- **Cumulative Detection**
  - Generate magnitude for each of N pulses and then threshold
  - Require at least 1 detection in N scans

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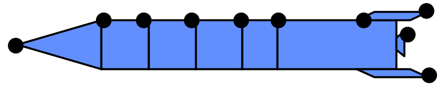
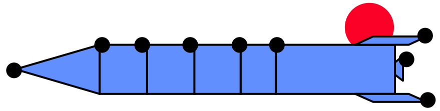
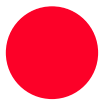
Target Fluctuations
Swerling Models

Fluctuation Interval

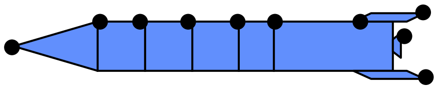
Nature of Scatterers		scan-to-scan (multiple pulses/scan)	pulse-to-pulse
	similar amplitudes  $p(\sigma) = \frac{1}{\sigma_{av}} e^{-\sigma/\sigma_{av}}$	Swerling I	Swerling II
	one amplitude much larger than others  $p(\sigma) = \frac{4\sigma}{\sigma_{av}^2} e^{-2\sigma/\sigma_{av}}$	Swerling III	Swerling IV

RCS Variability for Different Target Models

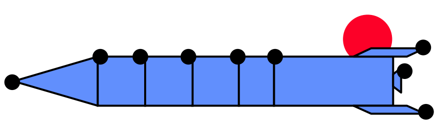
Non-fluctuating Target

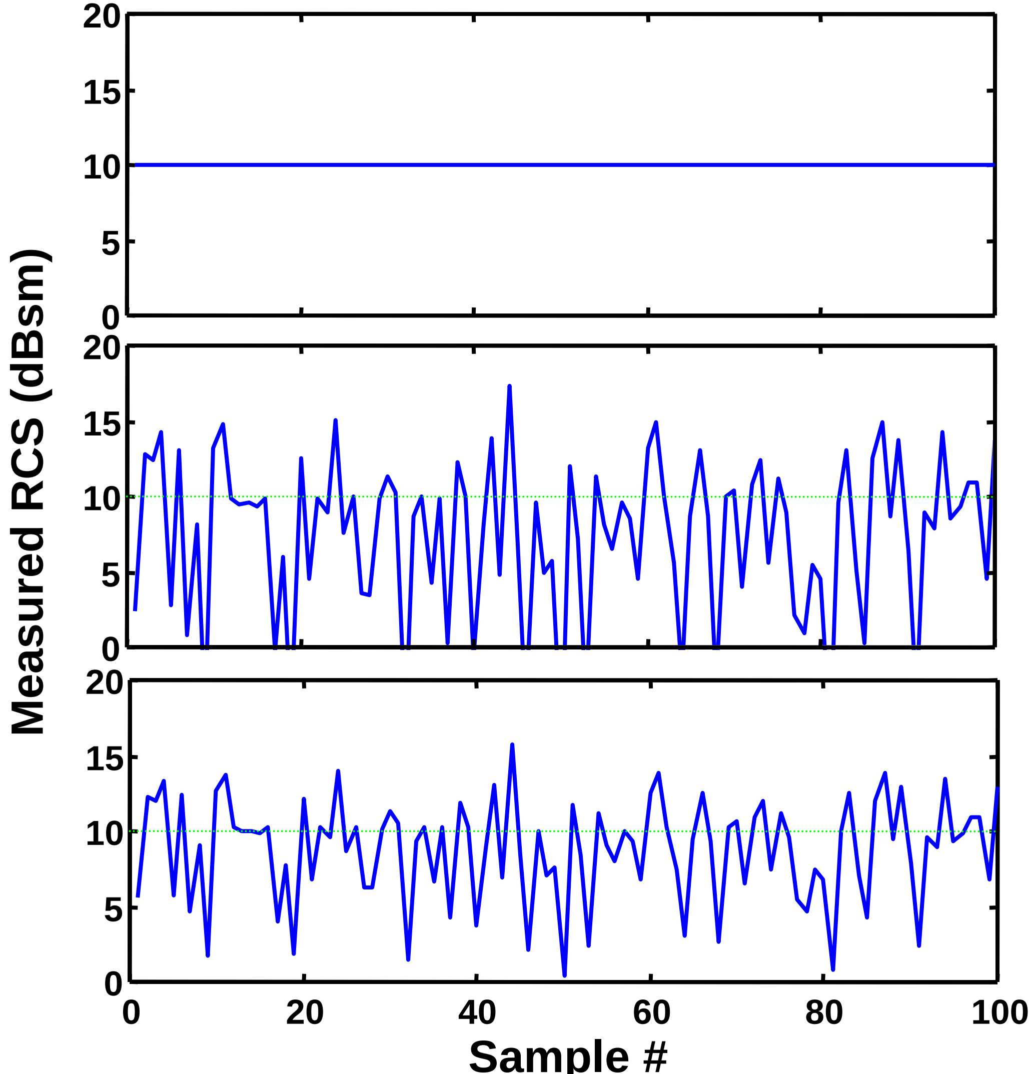


Swerling I/II



Swerling III/IV





Detection Statistics for Fluctuating Targets

Single Pulse Detection

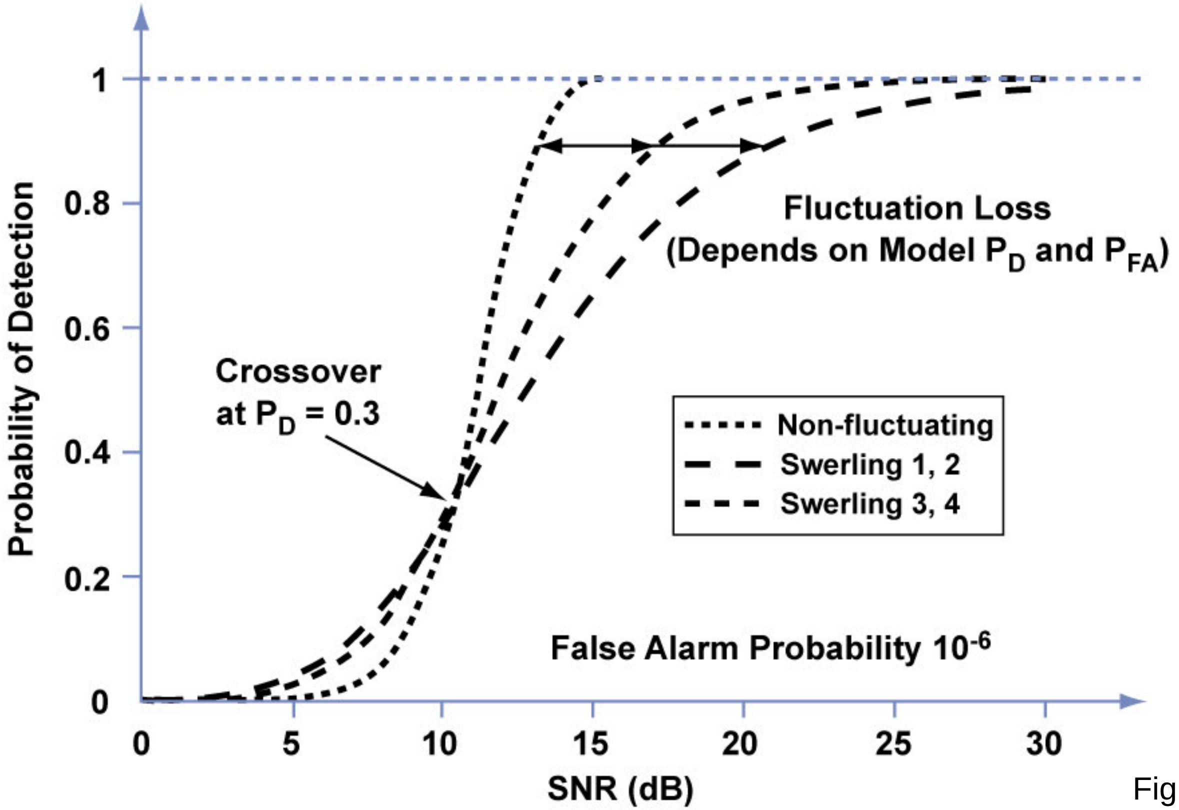


Figure by MIT OCW.

Fluctuating Targets Require More SNR than Non-fluctuating Targets to Maintain a High Probability of Detection

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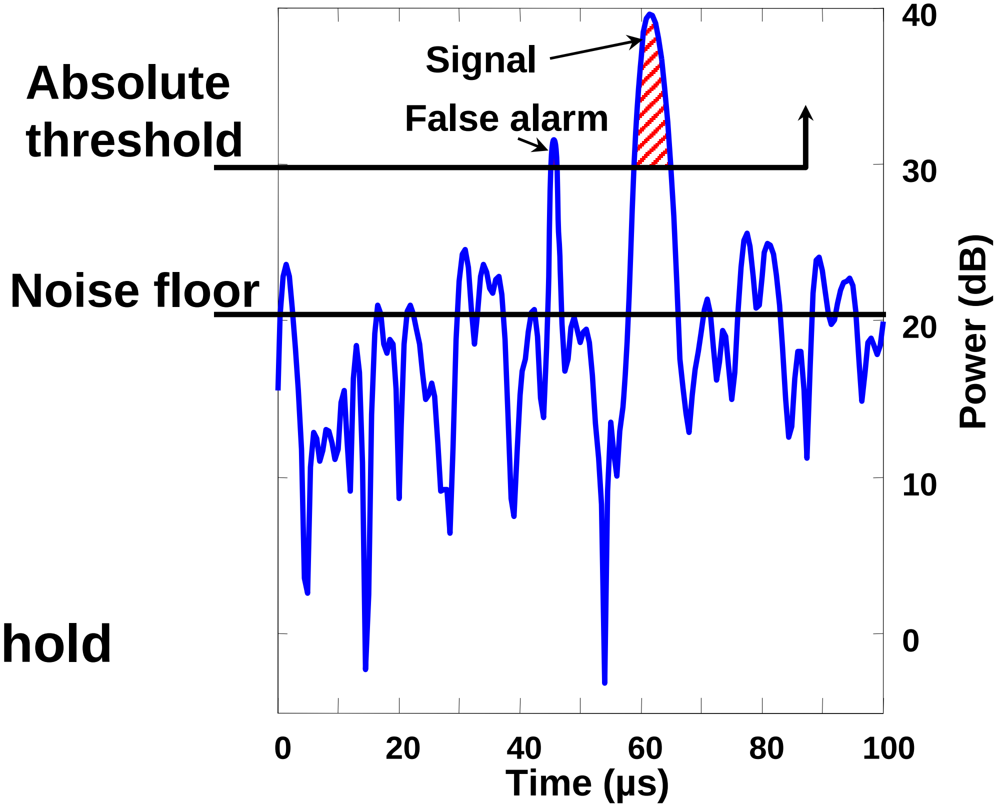
Constant False Alarm Rate (CFAR) Thresholding

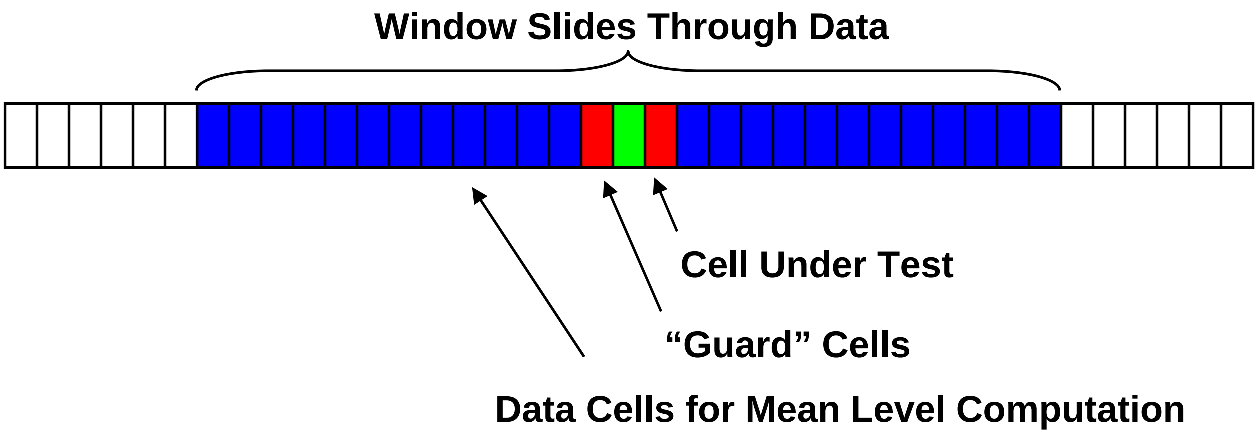
- **Problem: Must know (or estimate) noise floor to set threshold**
- **Solution: Estimate noise floor using noise-only samples**
  - **Adaptive thresholding**
- **CFAR thresholding:**

$$\frac{\text{test cell}}{\text{noise floor estimate}} > \text{threshold}$$



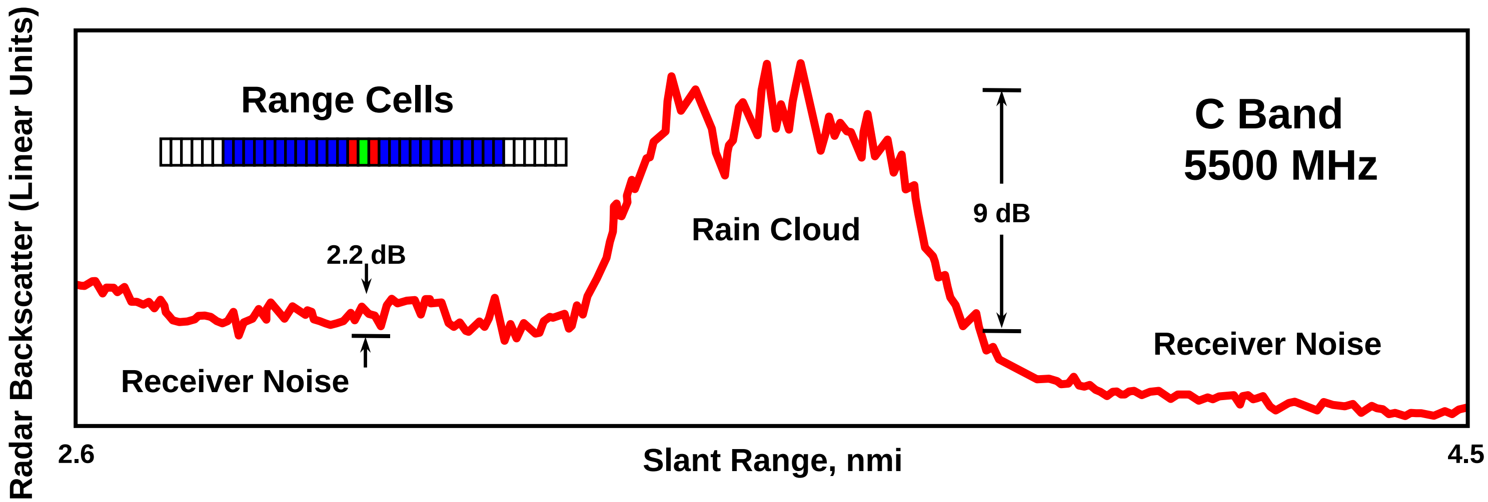
The Mean Level CFAR

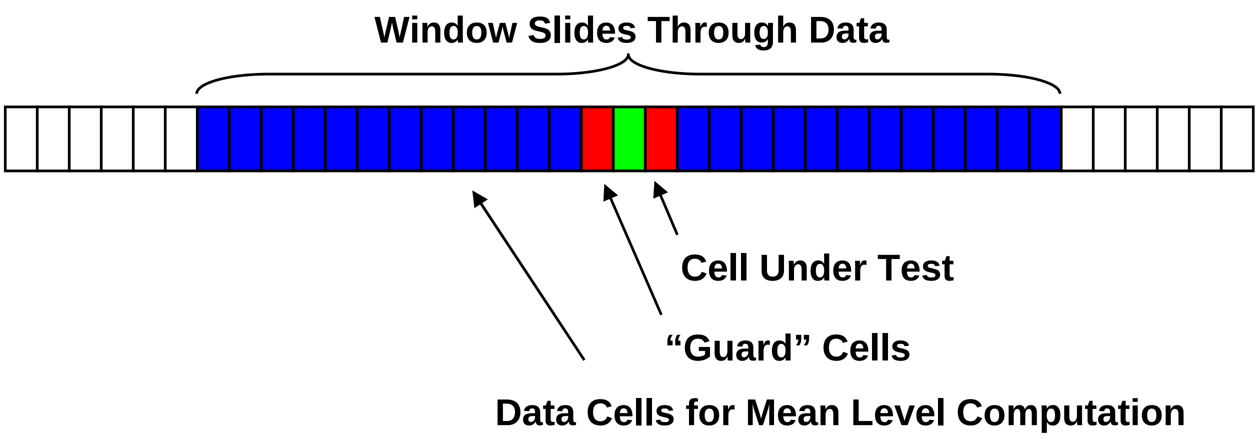
- Use mean value of surrounding range cells to determine threshold for cell under test



- Nearby targets can raise threshold and suppress detection

Effect of Rain on CFAR Thresholding





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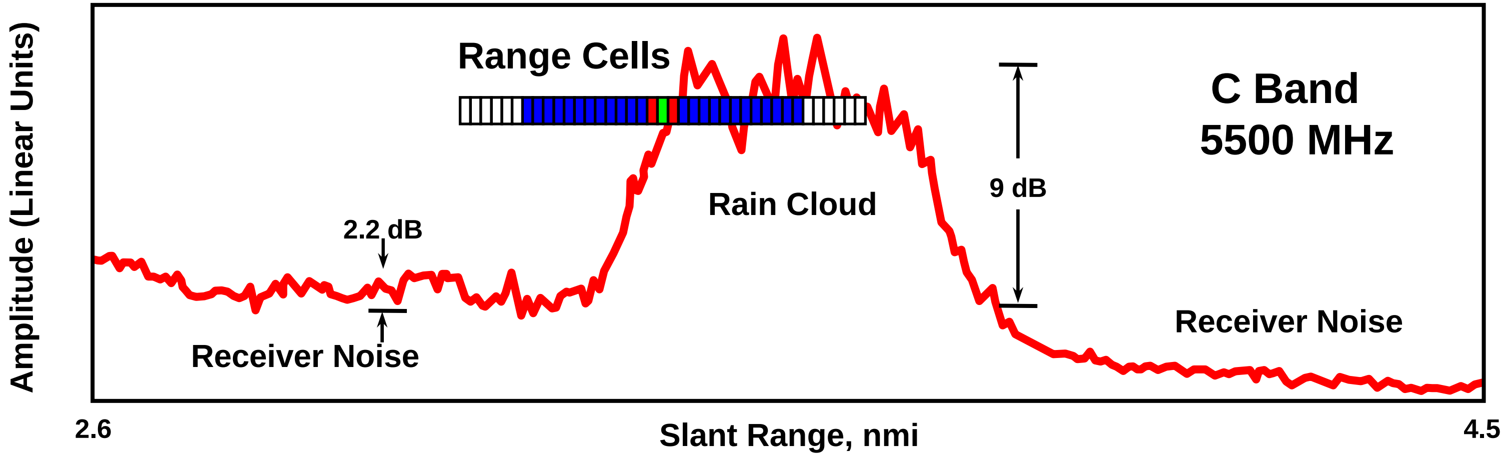
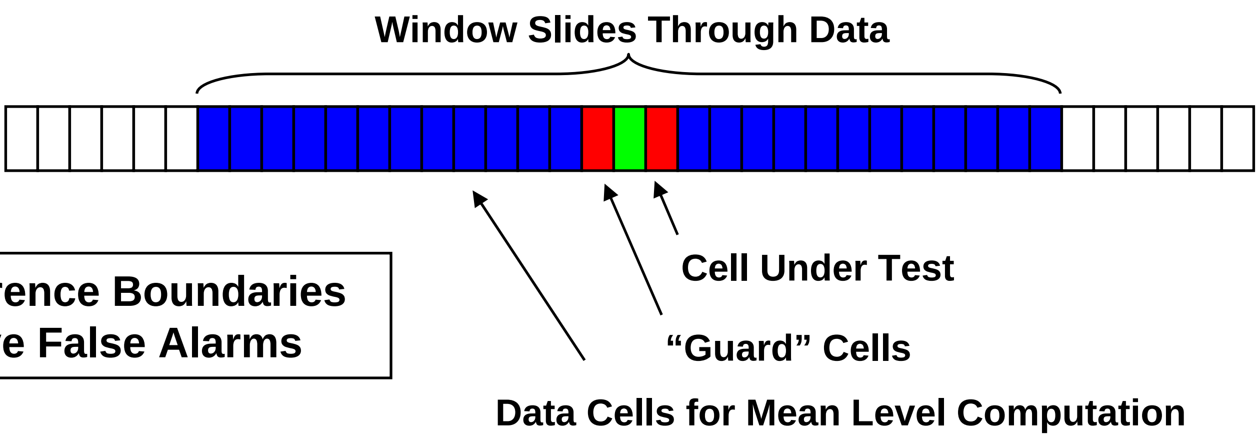
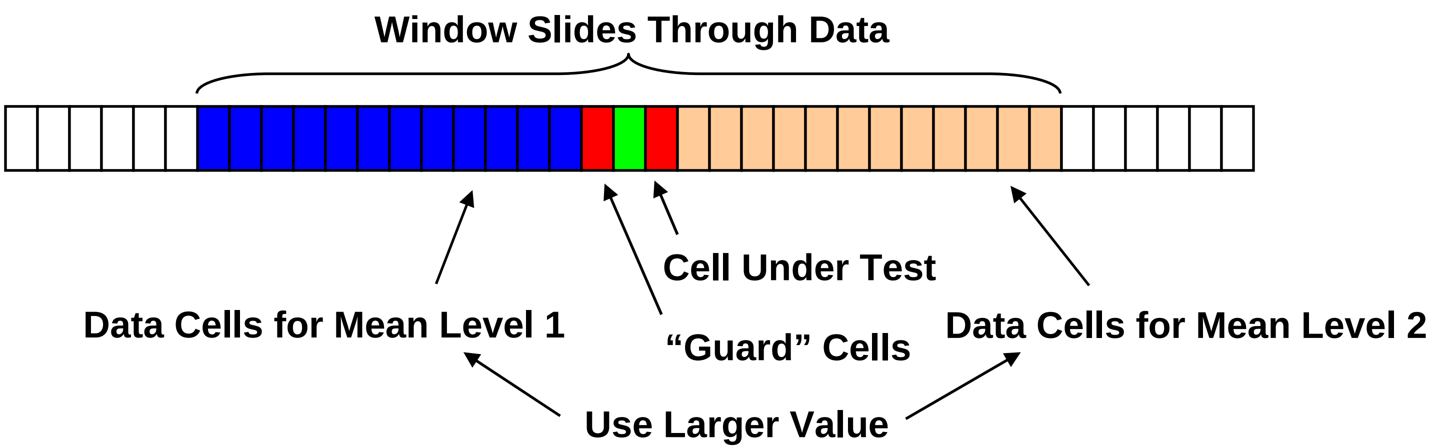




Sharp Clutter or Interference Boundaries Can Lead to Excessive False Alarms

Greatest-of Mean Level CFAR

- **Find mean value of N/2 cells before and after test cell separately**
- **Use larger noise estimate to determine threshold**



- **Helps reduce false alarms near sharp clutter or interference boundaries**
- **Nearby targets still raise threshold and suppress detection**

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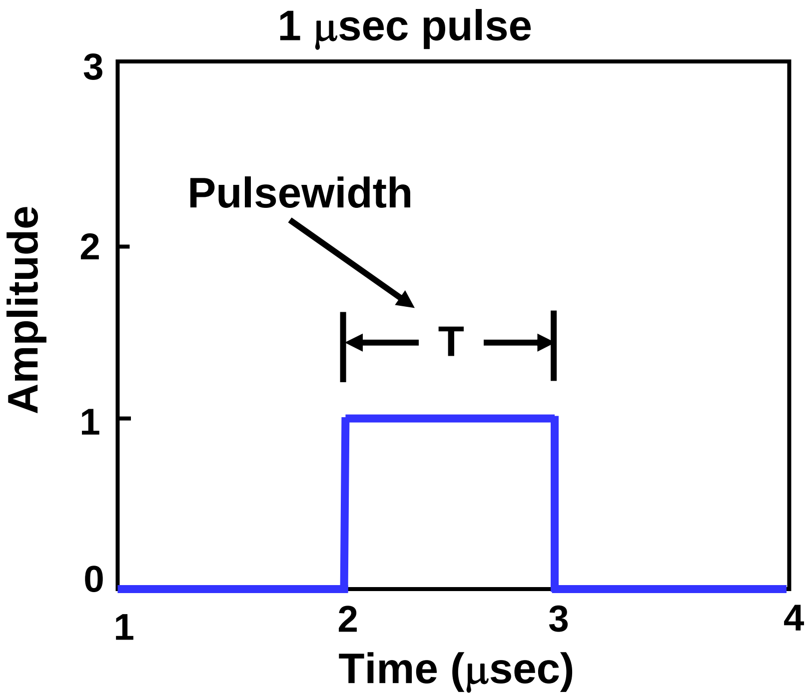
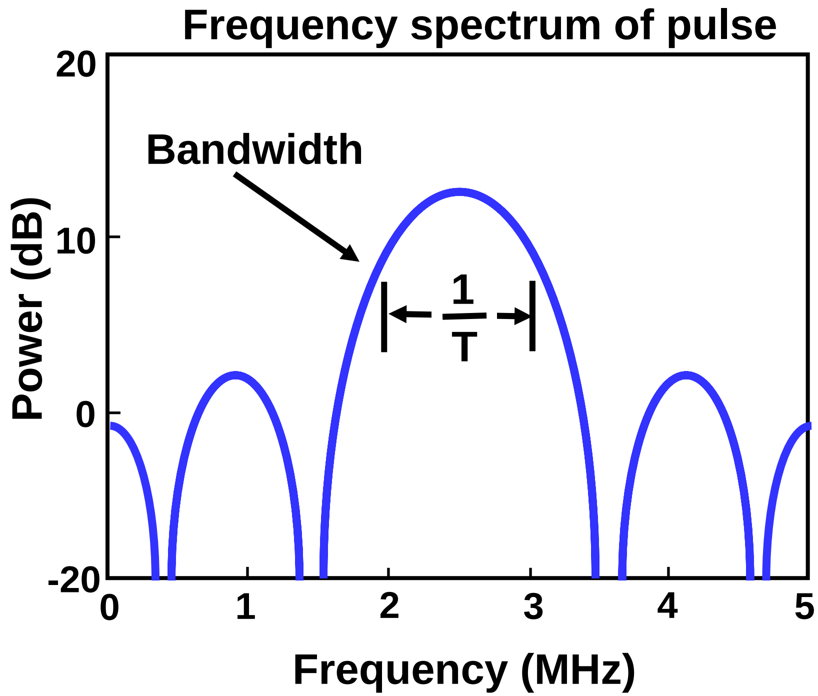
- **Detection of Target Echoes in Noise**
- **Pulse Compression**
  - **Introduction**
  - **Phase Coded Waveforms**
  - **Linear Frequency Modulation Waveforms**

Pulsed CW Radar Fundamentals

Range Resolution





- **Range Resolution (Δ r)**
  - **Proportional to pulse width (T)**
  - **Inversely proportional to bandwidth (B = 1/T)**

    1 MHz Bandwidth => 150 m of range resolution

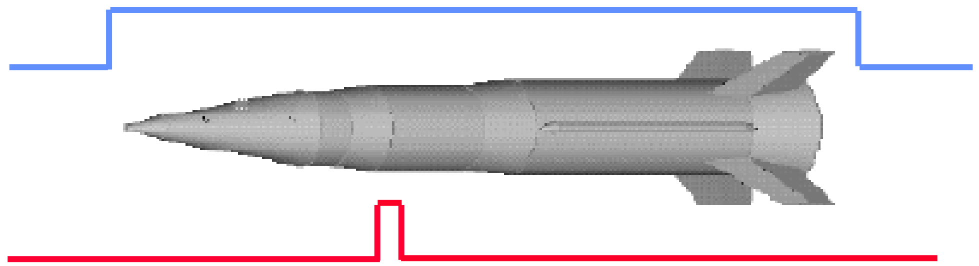
$$\Delta r = \frac{c\,T}{2}$$

$$\Delta r = \frac{c}{2B}$$

Pulse Width, Bandwidth and Resolution for a Square Pulse

Resolution: **Pulse Length is Larger than Target Length**

Cannot Resolve Features Along the Target



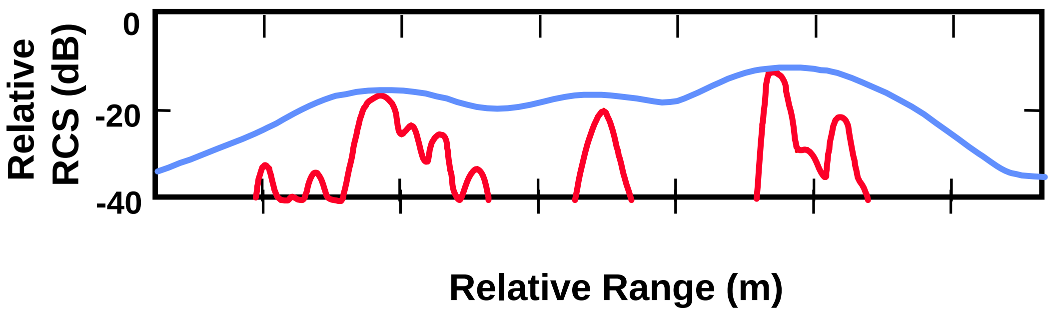
$$\Delta r = \frac{cT}{2}$$

$$\Delta r = \frac{c}{2B}$$

Pulse Length is Smaller than Target Length

Can Resolve Features Along the Target

Example :



High Bandwidth

$\Delta r = .1 \times \Delta r$

$BW = 10 \times BW$

Low Bandwidth

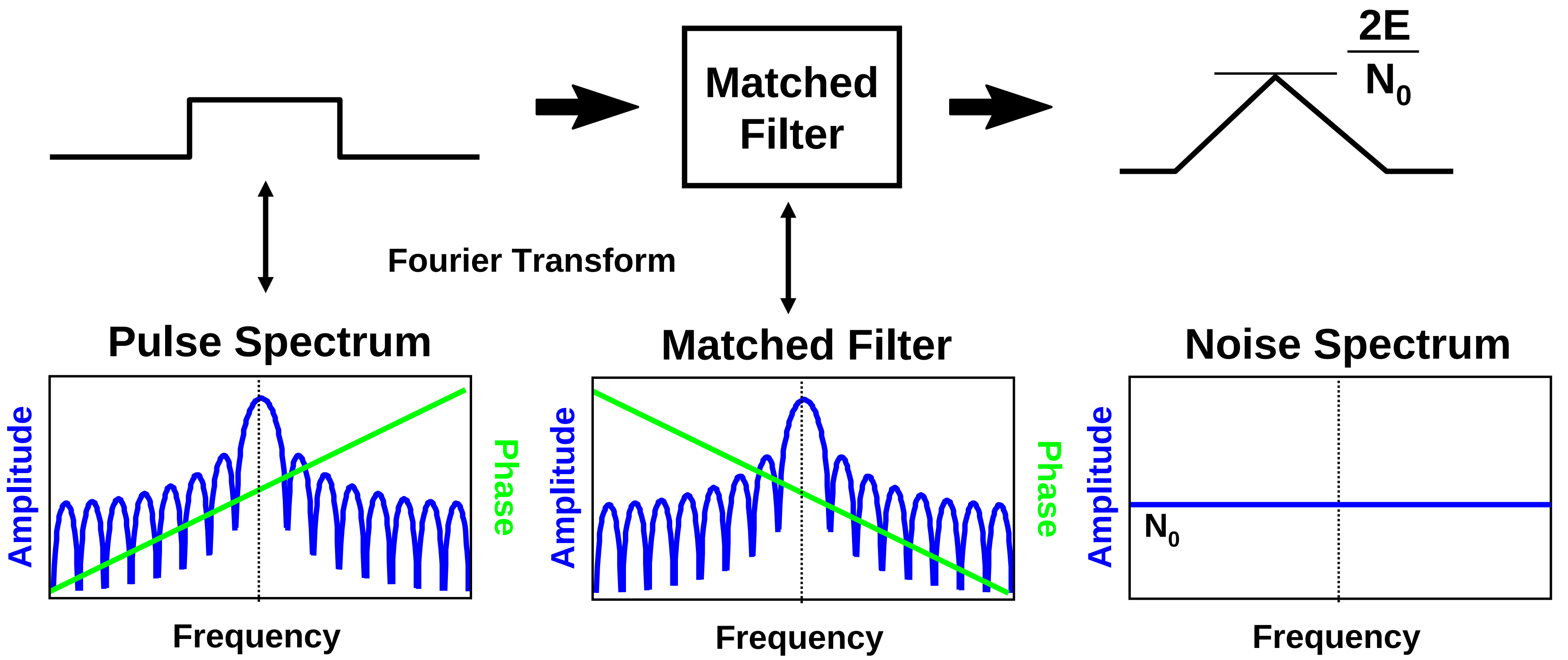
Shorter Pulses have Higher Bandwidth and Better Resolution

Motivation for Pulse Compression

- **Hard to get "good" average power and resolution at the same time using a pulsed CW system**
  - **Higher average power is proportional to pulse width**
  - **Better resolution is inversely proportional to pulse width**
- **A long pulse can have the same bandwidth (resolution) as a short pulse if the long pulse is modulated in frequency or phase**
- **These pulse compression techniques allow a radar to simultaneously achieve the energy of a long pulse and the resolution of a short pulse**

Matched Filter Concept

E = Pulse Energy (Power × Time)

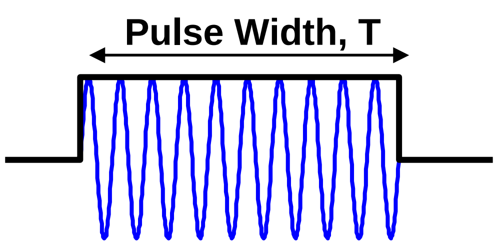


- Matched Filter maximizes the peak-signal to mean noise ratio
  – For rectangular pulse, matched filter is a simple pass band filter

Frequency and Phase Modulation of Pulses

- **Resolution of a short pulse can be achieved by modulating a long pulse, increasing the time-bandwidth product**
- **Signal must be processed on return to “pulse compress”**

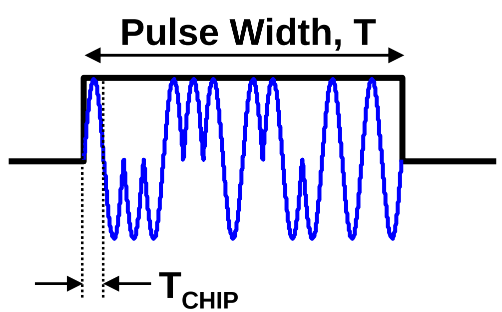
Square Pulse



Bandwidth = 1/T

Time × Bandwidth = 1

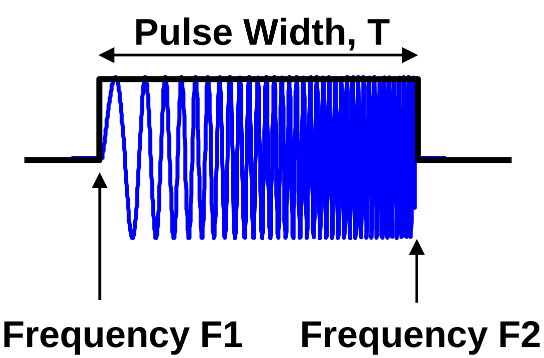
Binary Phase Coded Waveform



Bandwidth = $1/T_{CHIP}$

Time × Bandwidth = T/T_{CHIP}

Linear Frequency Modulated Waveform

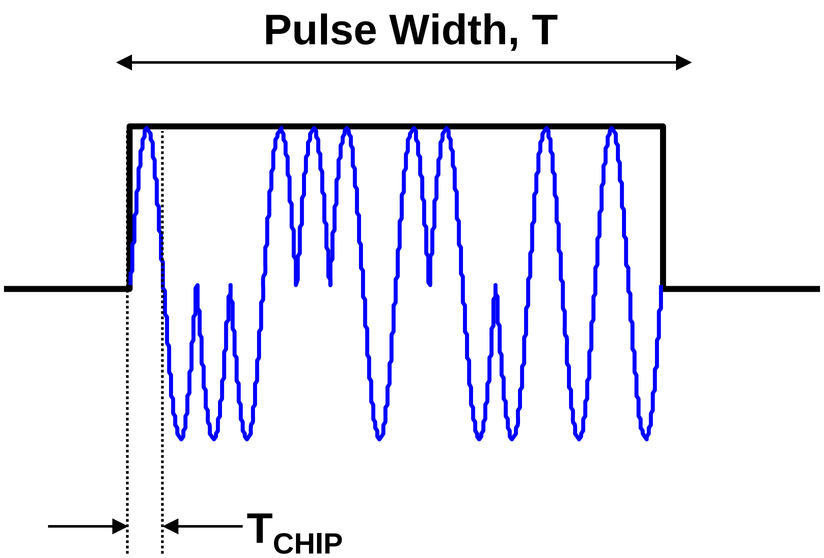


Bandwidth = ΔF = F2-F1

Time × Bandwidth = $T\Delta F$

Binary Phase Coded Waveforms

Binary Phase Coded Waveform



Bandwidth = 1/ T_{CHIP}

Pulse Compression Ratio = T/ T_{CHIP}

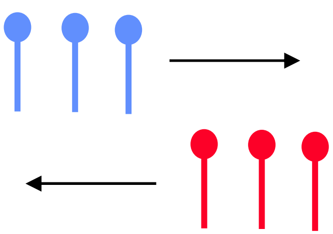
- Changes in phase can be used to increase the signal bandwidth of a long pulse
- A pulse of duration T is divided into N sub-pulses of duration T_{CHIP}
- The phase of each sub-pulse is changed or not changed, according to a binary phase code
- Phase changes 0 or π radians (+ or -)
- Pulse compression filter output will be a compressed pulse of width T_{CHIP} and a peak N times that of the uncompressed pulse

Implementation of Matched Filter

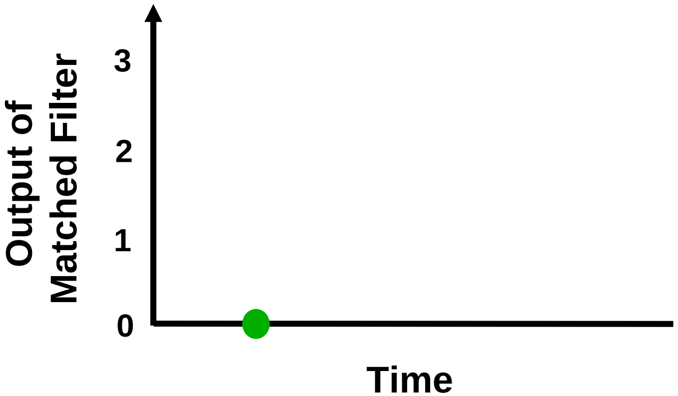
- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

Reflected echo **Time reversed pulse**

- **Convolution process:**
  - **Move digitized pulses by each other, in steps**
  - **When data overlaps, multiply samples and sum them up**



No overlap – Output 0



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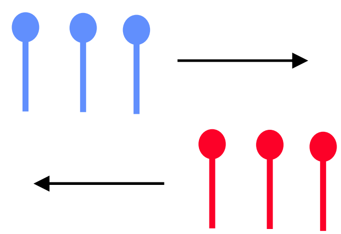

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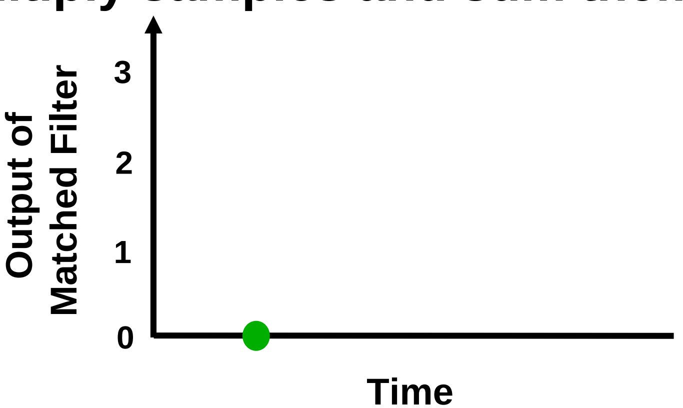

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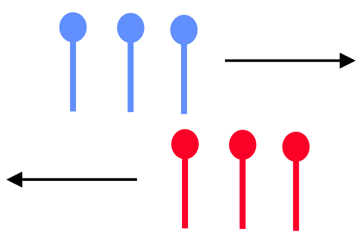
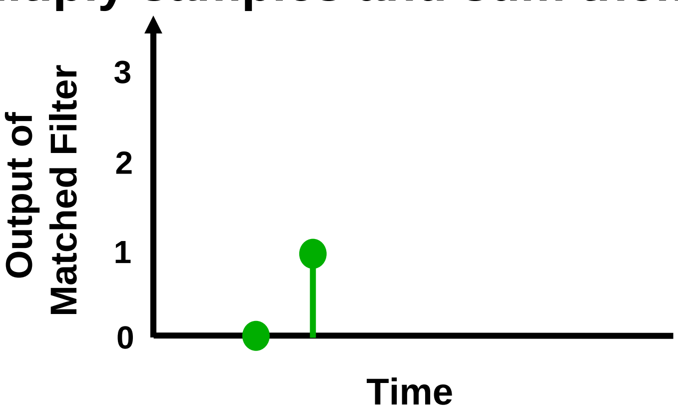


One sample overlaps 1x1 =1



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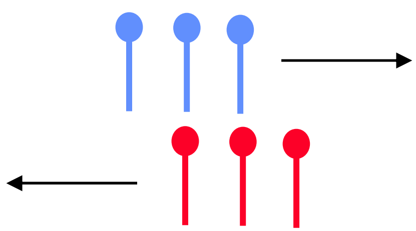

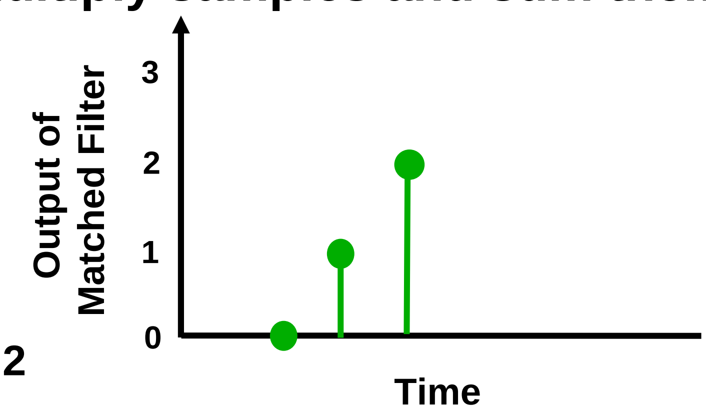

Two samples overlap (1x1) + (1x1) = 2

Implementation of Matched Filter

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Reflected echo Time reversed pulse

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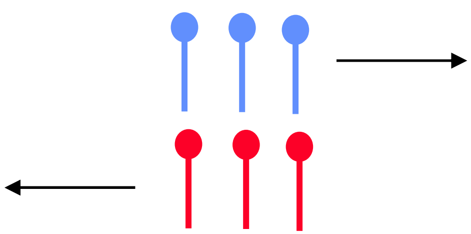
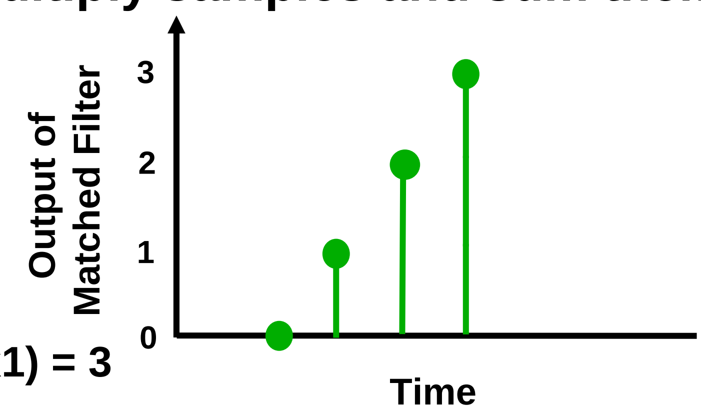


Three samples overlap (1x1) + (1x1) + (1x1) = 3



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Reflected echo **Time reversed pulse**

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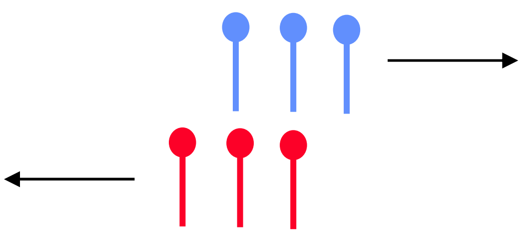

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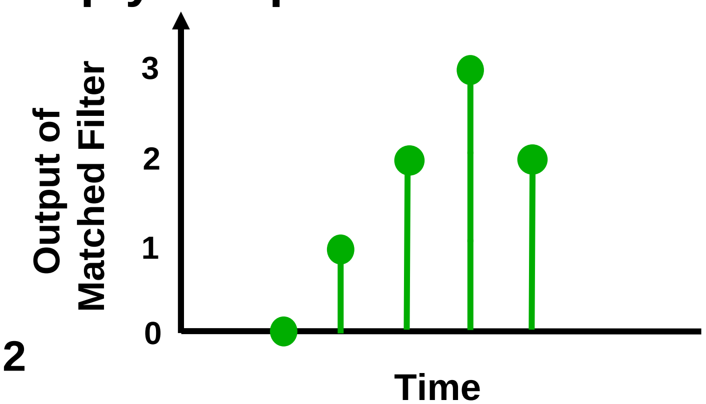

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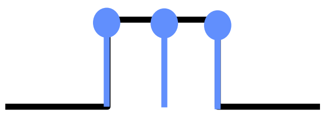
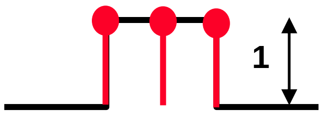


Reflected echo



Time reversed pulse

- Convolution process:
  - Move digitized pulses by each other, in steps
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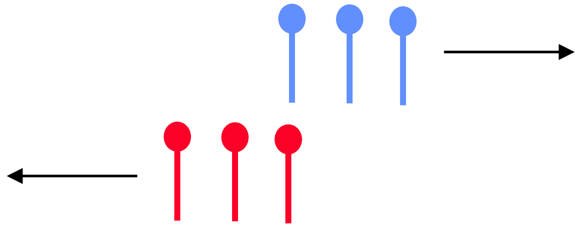

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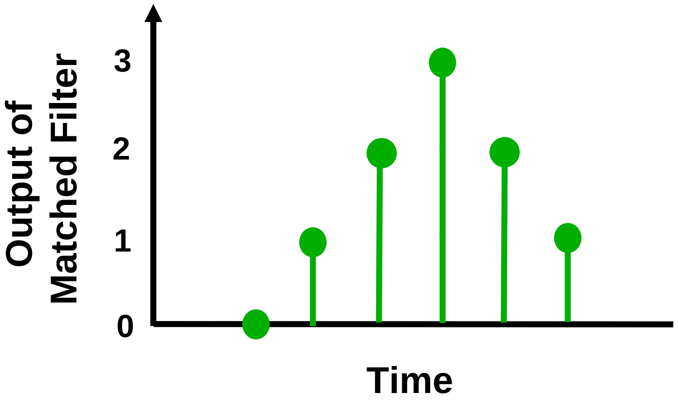

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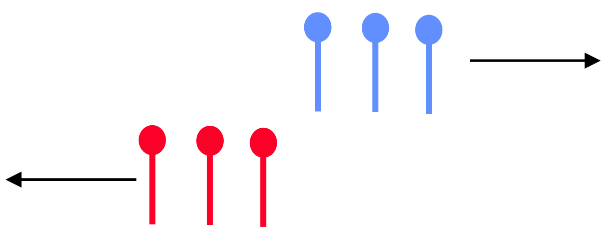
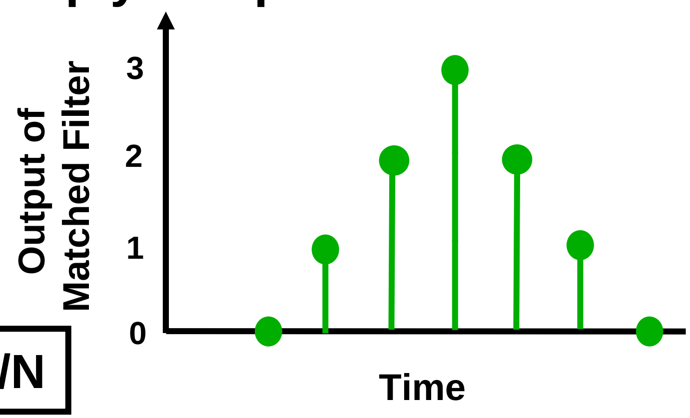




Use of Matched Filter Maximizes S/N

Pulse Compression

Binary Phase Modulation Example

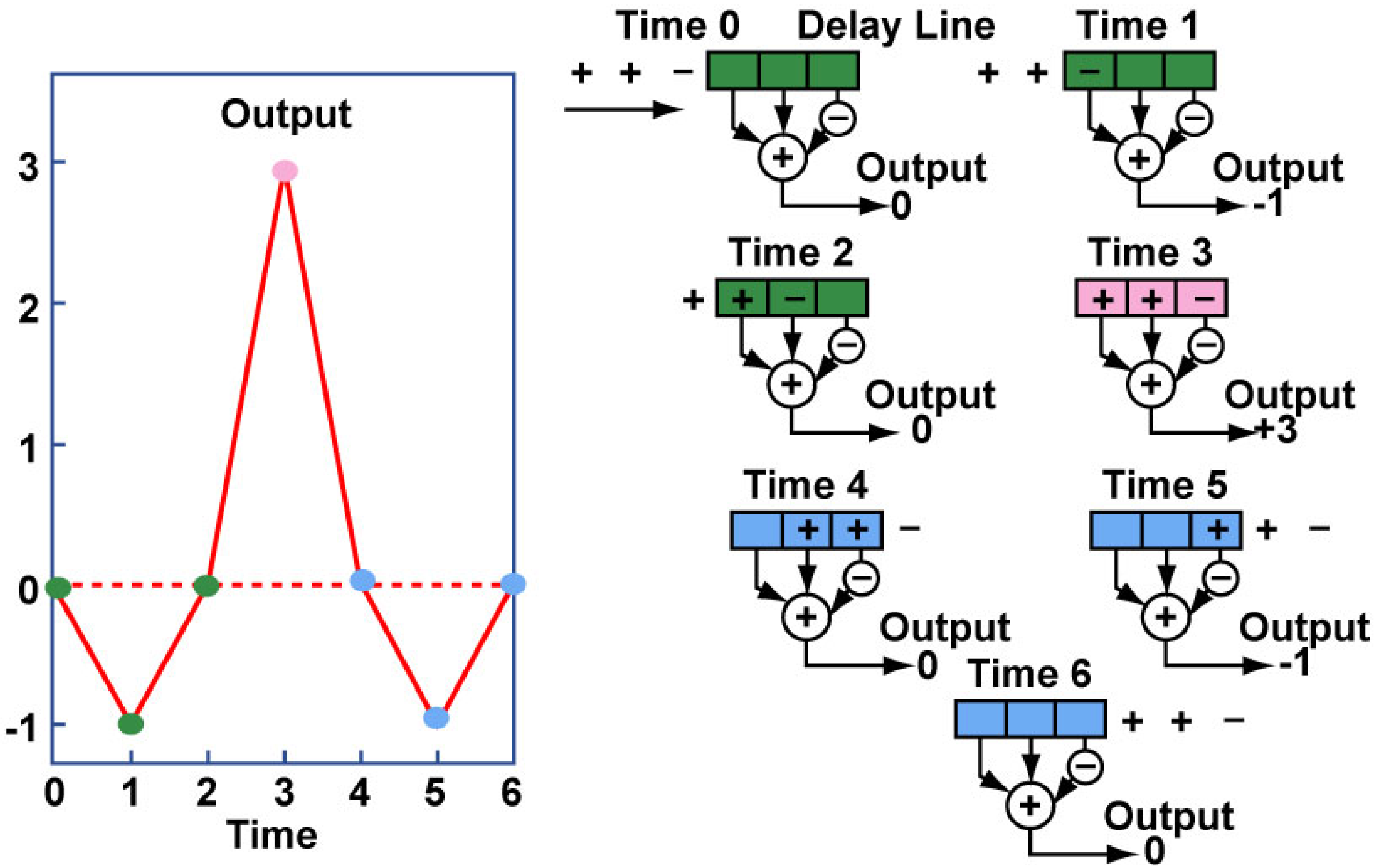
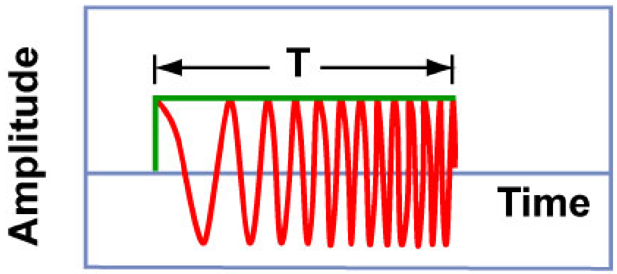


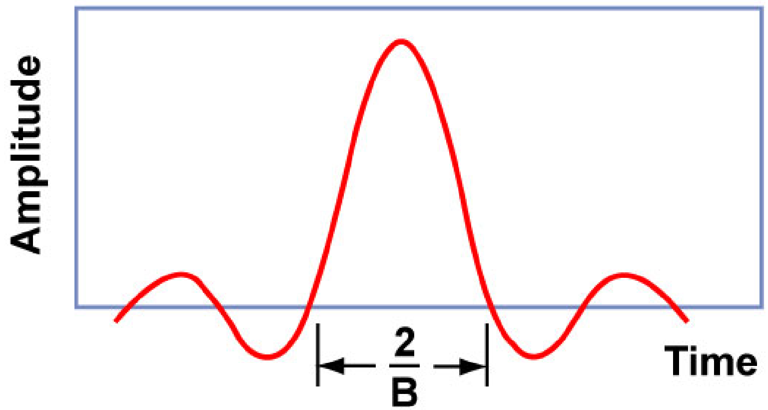
Figure by MIT OCW.

Linear FM Pulse Compression

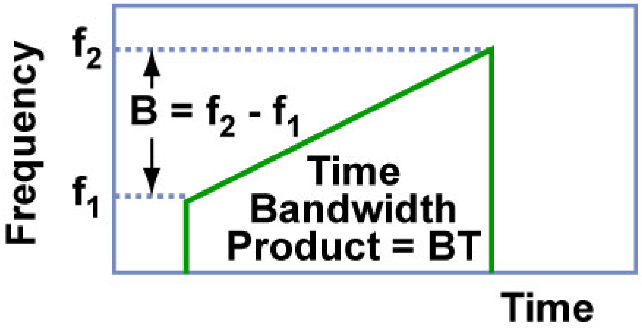
Linear FM waveform



Output of Pulse Compression Filter



Frequency of transmitted pulse as a function of time



Because range is measured by a shift in Doppler frequency, there is a coupling of the range and Doppler velocity measurement

Figure by MIT OCW.

Summary

- **Detection of Targets in Noise**
  - Both target properties and radar design features affect the ability to detect signals in noise
  - Coherent and non-coherent integration pulse integration can improve target detection
  - Adaptive thresholding (CFAR) techniques are needed in realistic environments
- **Pulse compression offers a means to simultaneous have high average power and good resolution**
  - A long pulse can have the same bandwidth (resolution) as a short pulse, if it is modulated in frequency or phase
  - Phase-encoded pulse compression divides long pulses into binary encoded sub-pulses
  - With frequency-encoded pulse compression, the radar frequency is increased linearly as the pulse is transmitted

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Toomay, J. C., Radar Principles for the Non-Specialist, New York, Van Nostrand Reinhold, 1989