AJOU UNIVERSITY
1973

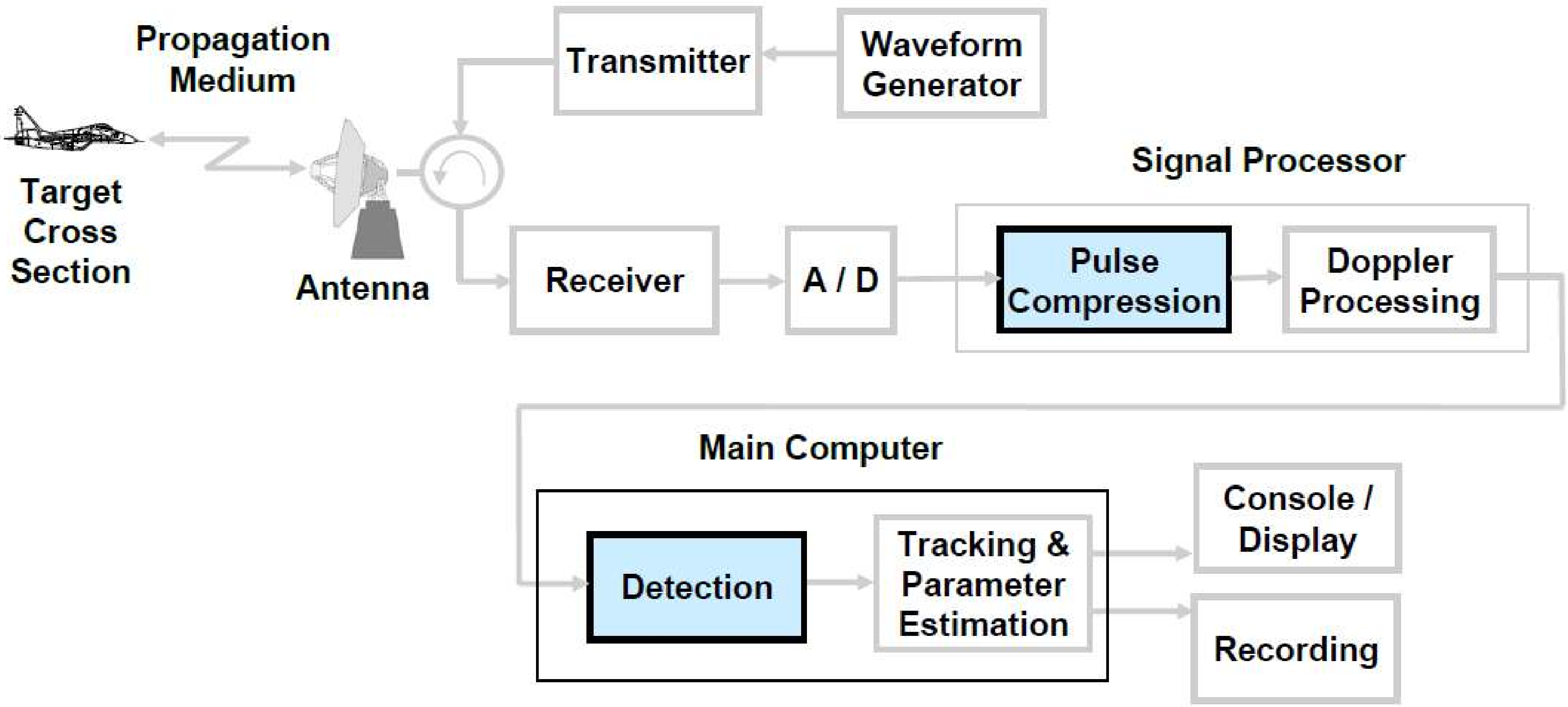
Radar Systems

Lecture 5.

Detection of Targets in Noise and Pulse Compression Techniques

구 자 열

Detection and Pulse Compression

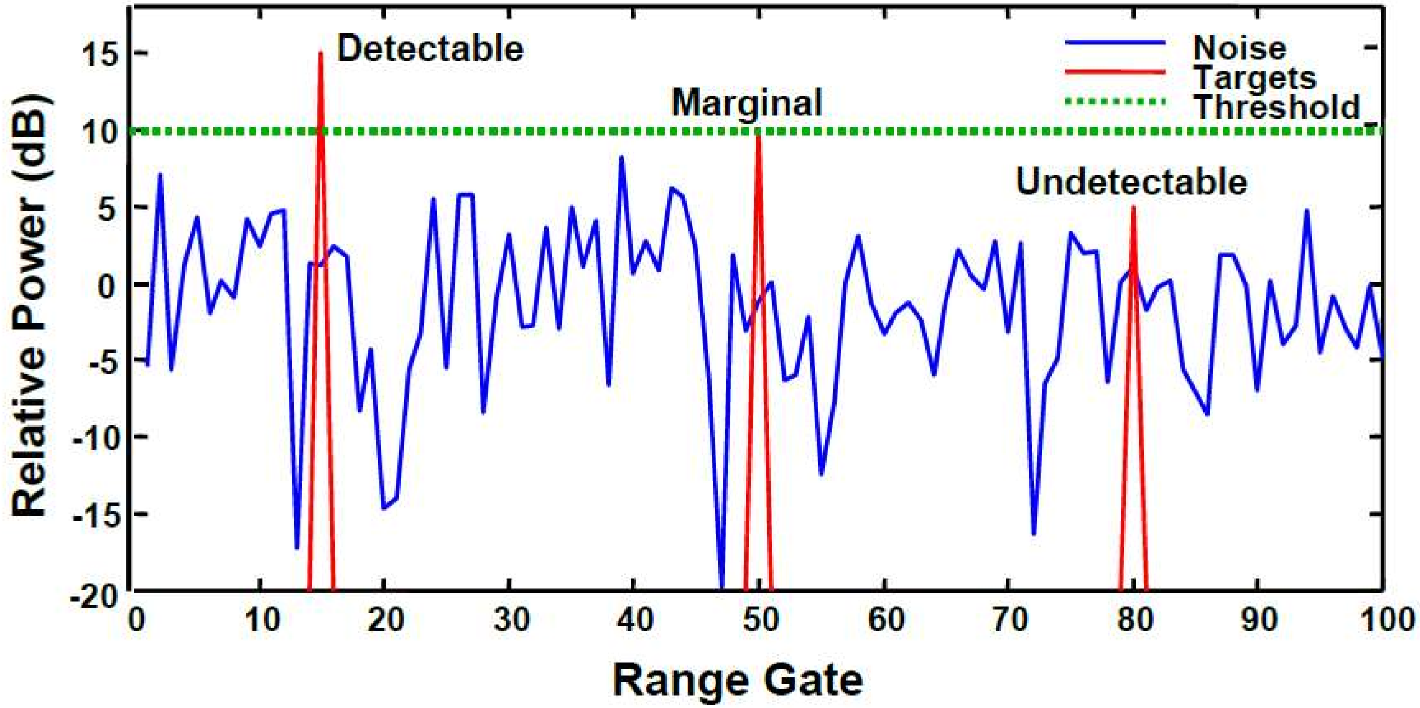


차　　례

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

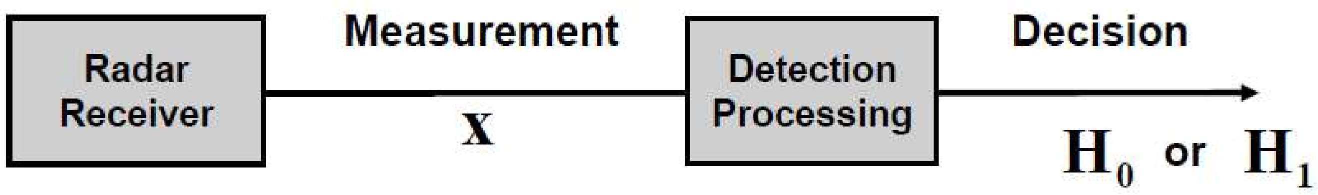
• **Pulse Compression**

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 Radar Detection Problem



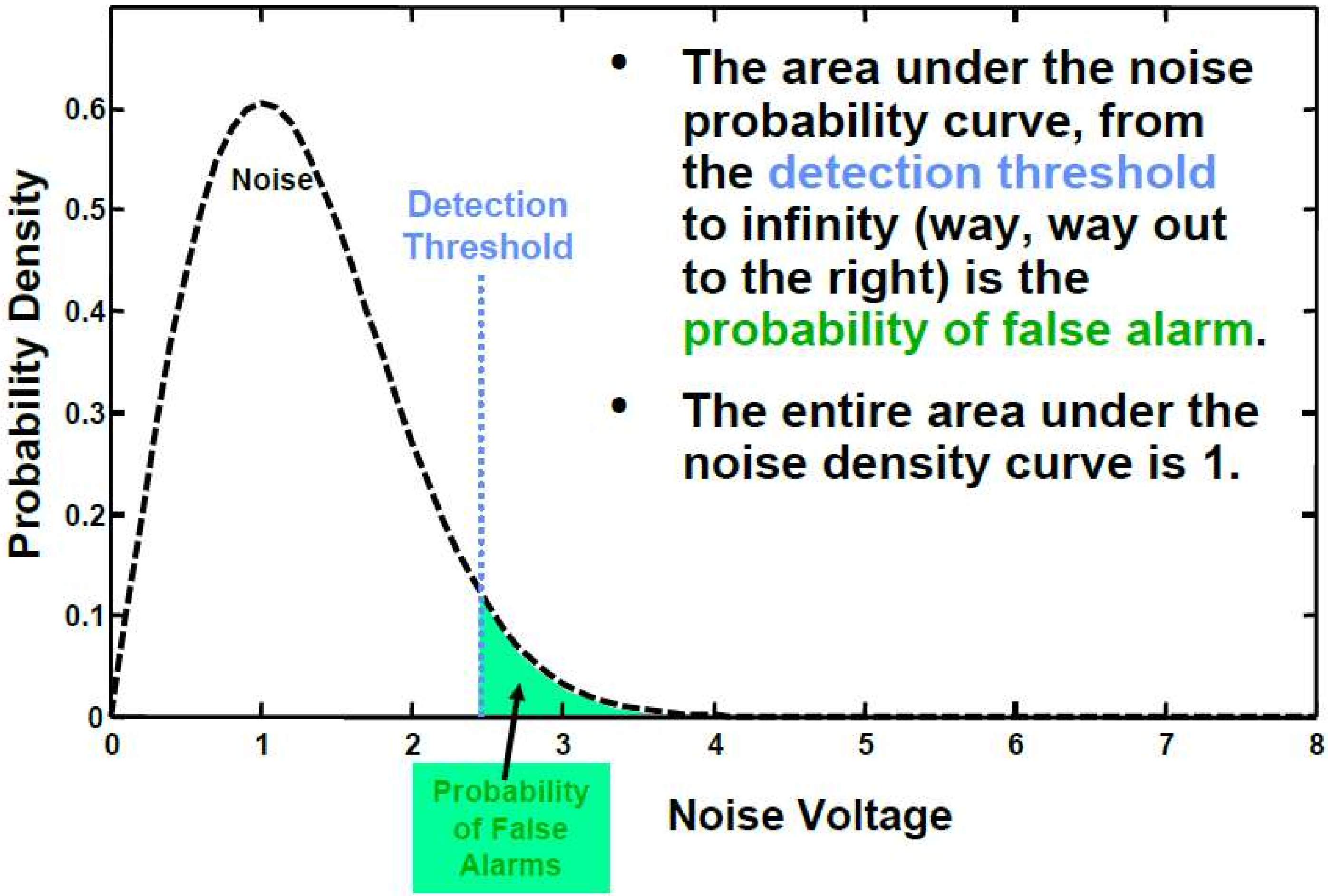
For each measurement
There are two possibilities:

	Measurement	Probability Density
Target absent hypothesis, H_0 Noise only	$x = n$	$p(x \mid H_0)$
Target present hypothesis, H_1 Signal plus noise	$x = a + n$	$p(x \mid H_1)$

For each measurement
There are four decisions:

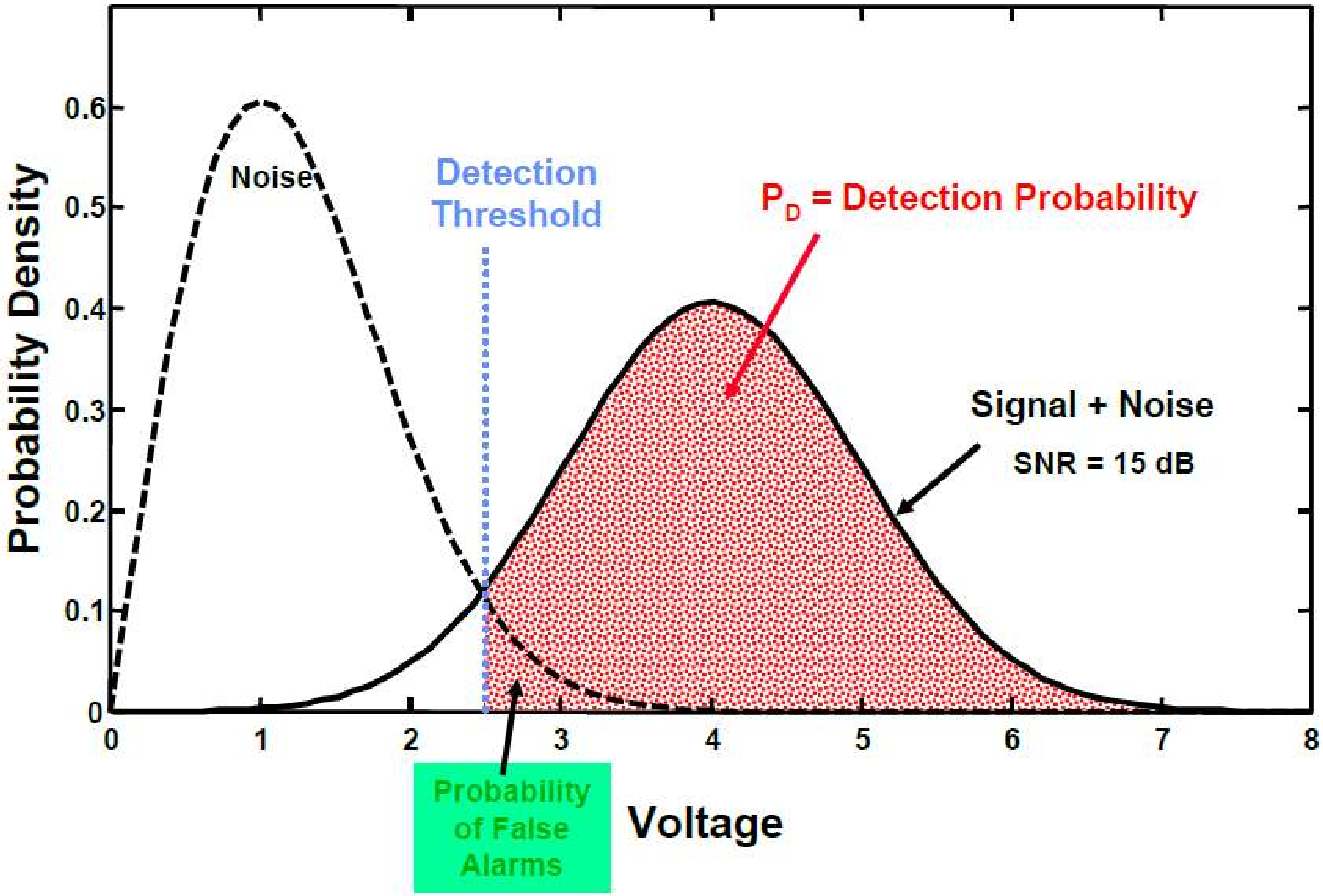
Truth \ Decision	H_0	H_1
H_0	Don't Report	False Alarm
H_1	Missed Detection	Detection

The Detection Problem

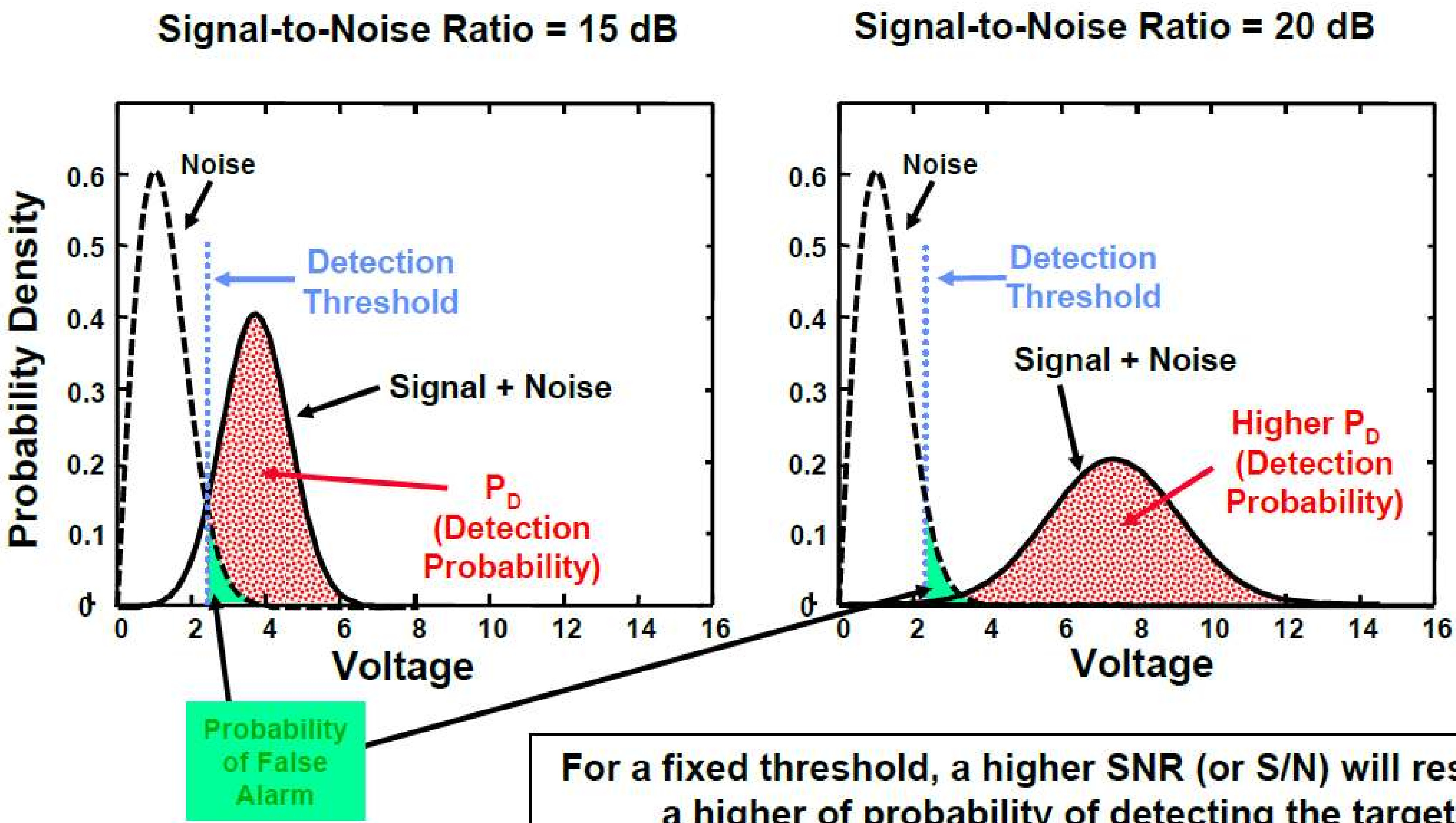


- The area under the noise probability curve, from the detection threshold to infinity (way, way out to the right) is the probability of false alarm.
- The entire area under the noise density curve is 1.

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

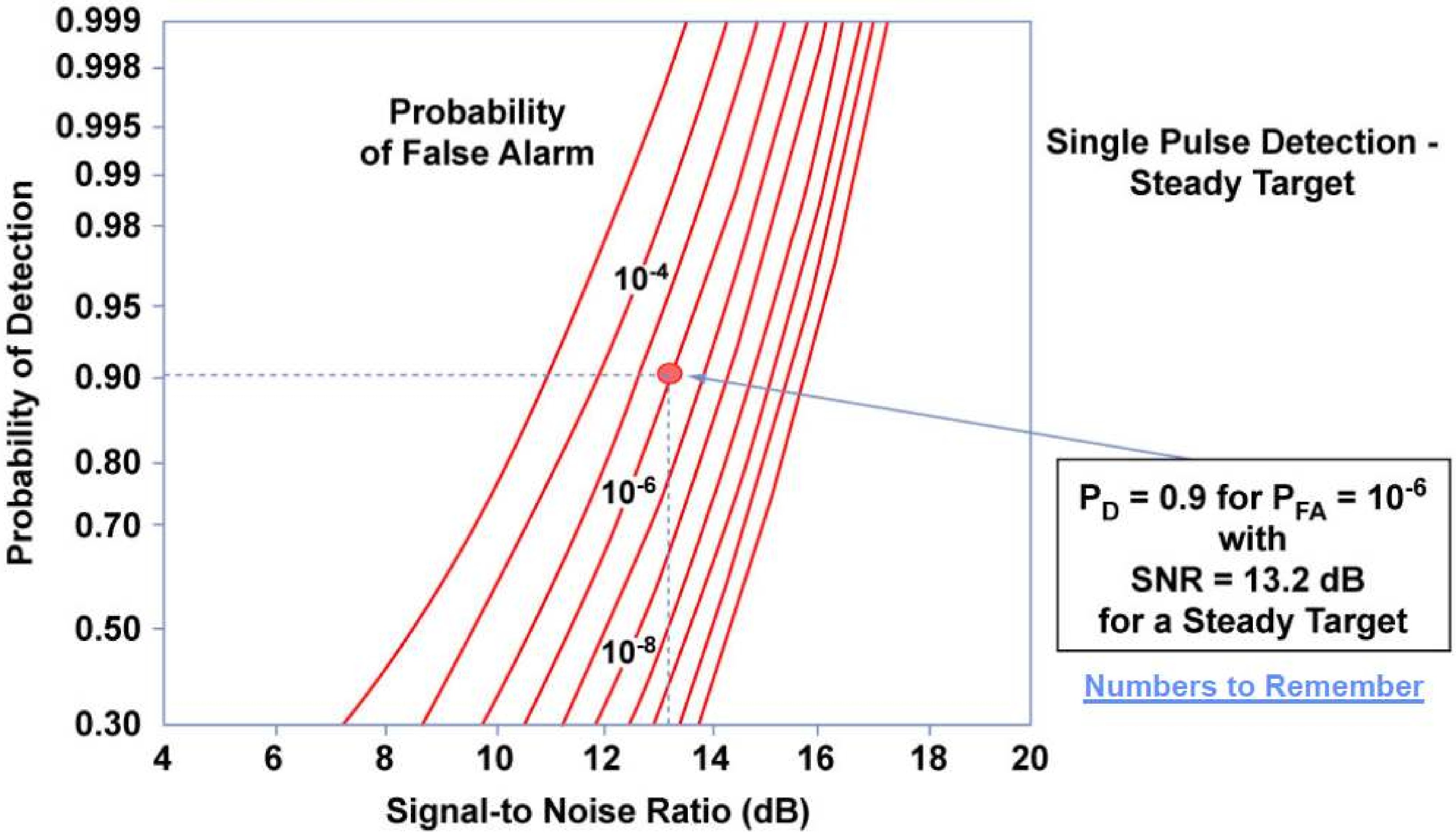


Figure by MIT OCW.

차 례

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

- Pulse Compression

Integration of Pulse

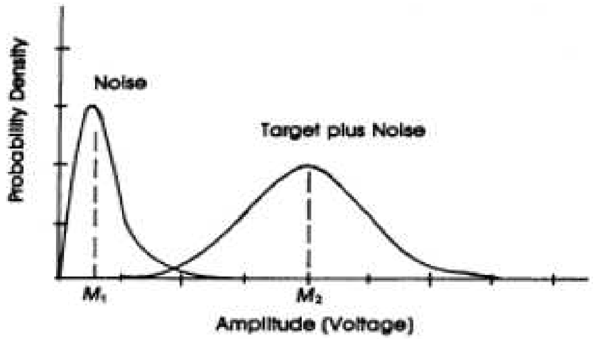
- The process of summing all the radar pulses to improve detection is known as "Pulse integration"
- A search-radar beam scans, the target will remain in the beam sufficiently long for more than one pulse to hit it. This number is known as hits per scan.

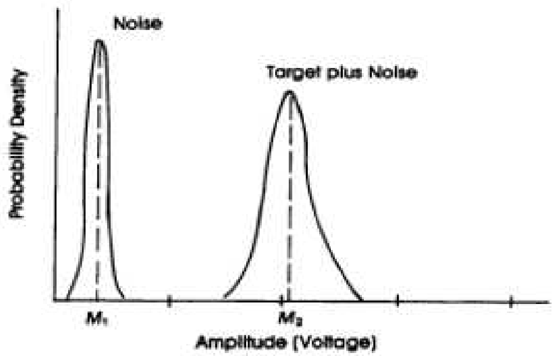
$$n_b = \frac{\theta_b f_p}{\dot{\theta}_s} = \frac{\theta_b f_p}{6\omega_m},$$

- For a ground based search radar with antenna scan rate 5 rpm, beam width 1.5° and PRF 300Hz, the number of hits would be 15/scan.

Integration of Pulse

- A pulse integrator is a improvement technique to address gains in probability of detection by using multiple transmit pulses.





- Depending on location of the pulse integrator in the signal processing chain this process is referred to as
  - coherent integration.
  - non-coherent integration.

Integration of Pulse

- Coherent Integration:
  - Insertion of a Pulse integrator between the matched filter and amplitude detector.
  - The signal processor samples the return from each transmit pulse at a spacing equal to the range resolution of the radar set and adds the returns from N pulses. After it accumulates the N pulses, performs the amplitude detection and threshold check.
- Non-Coherent Integration :
  - Integrator is placed after the amplitude or square law detector.
  - The name non-coherent integration derives from the fact that, since the signal has undergone amplitude or square law detection, the phase information is lost.
  - The non-coherent integrator operates in the same fashion as the coherent integrator in that it sums the returns from N pulses before performing the threshold check.

Integration of Pulse

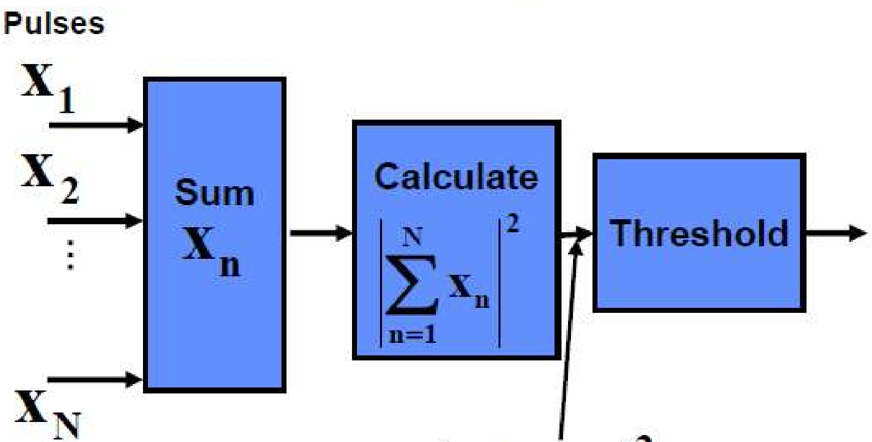
Coherent Integration	Non-Coherent Integration
Predetection Integration	Postdetection Integration
Phase information of the echo signal is preserved	Detector destroys phase information. Less efficient than predetection.
If n pulse are integrated, the SNR of integrated signal is nSNR.	If n pulse are integrated, the SNR of integrated signal is lesser than nSNR.
Difficult to implement	Easy to implement

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

Integration of Radar Pulses

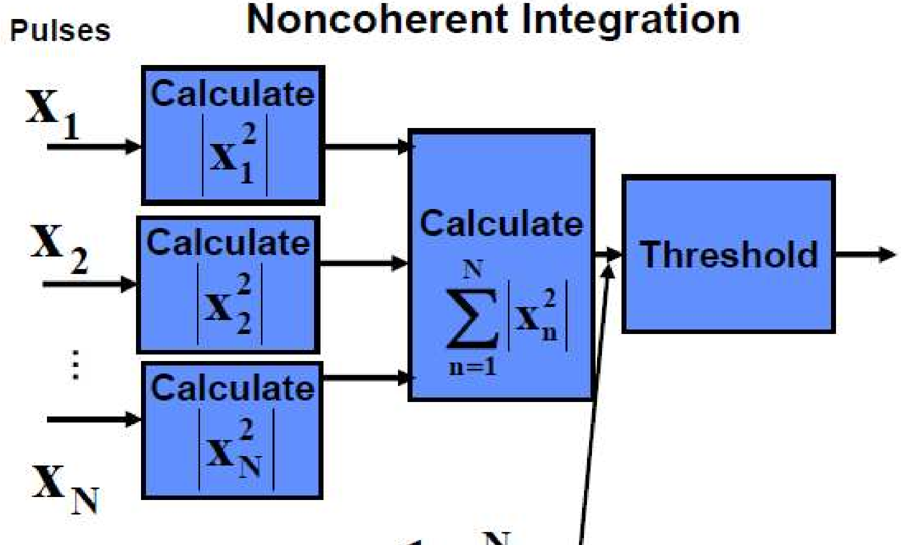
Coherent Integration



Target Detection Declared if $\frac{1}{N}\left|\sum_{n=1}^{N} X_n\right|^2 > T$

- Adds ‘voltages’ , then square
- Phase is preserved
- pulse-to-pulse phase coherence required
- SNR Improvement = 10 $\log_{10} N$

Noncoherent Integration



Target Detection Declared if $\frac{1}{N}\sum_{n=1}^{N} |X_n^2| > T$

- Adds ‘powers’ not voltages
- Phase neither preserved nor required
- Easier to implement, not as efficient

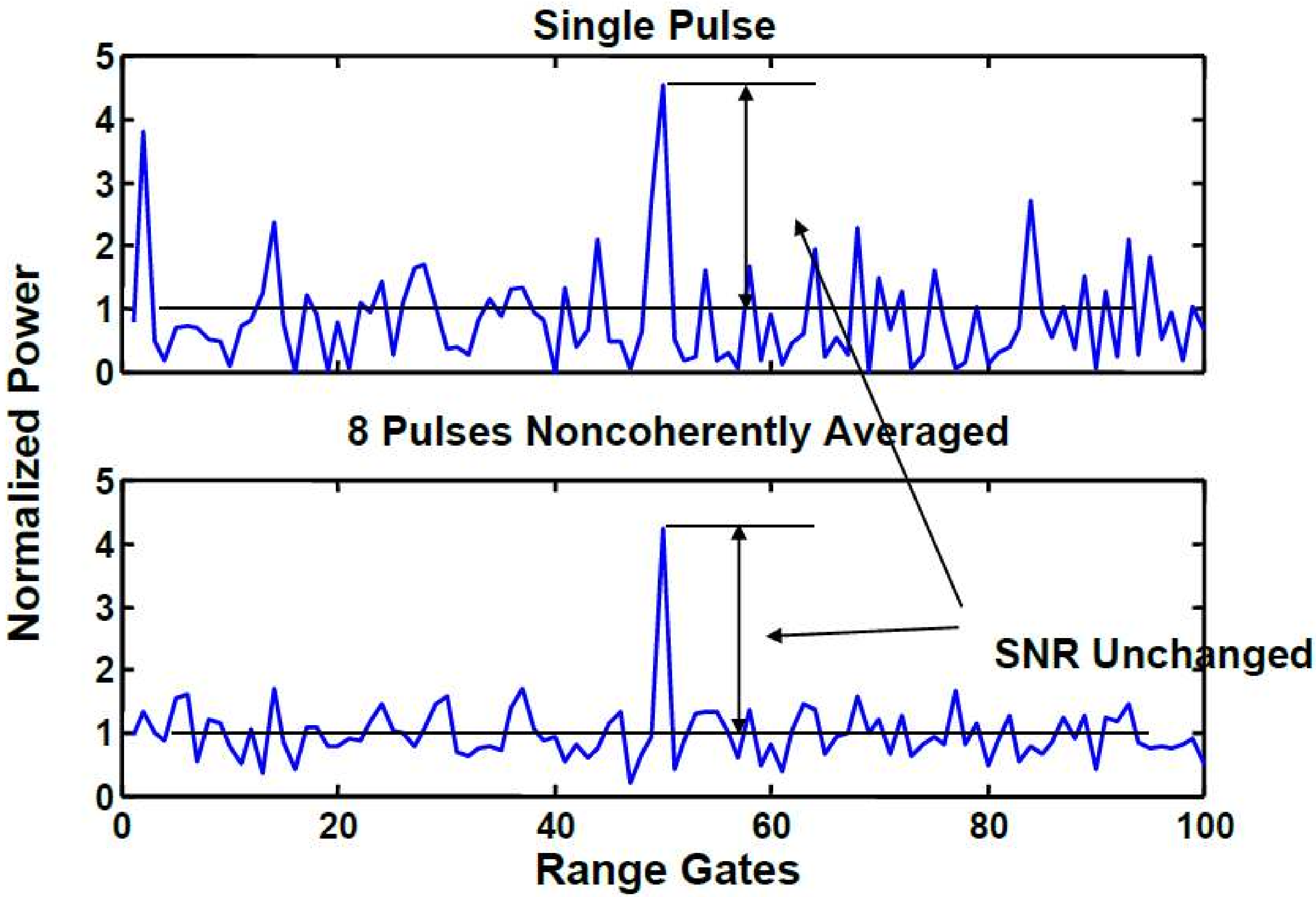
Detection performance can be improved by integrating multiple pulses

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

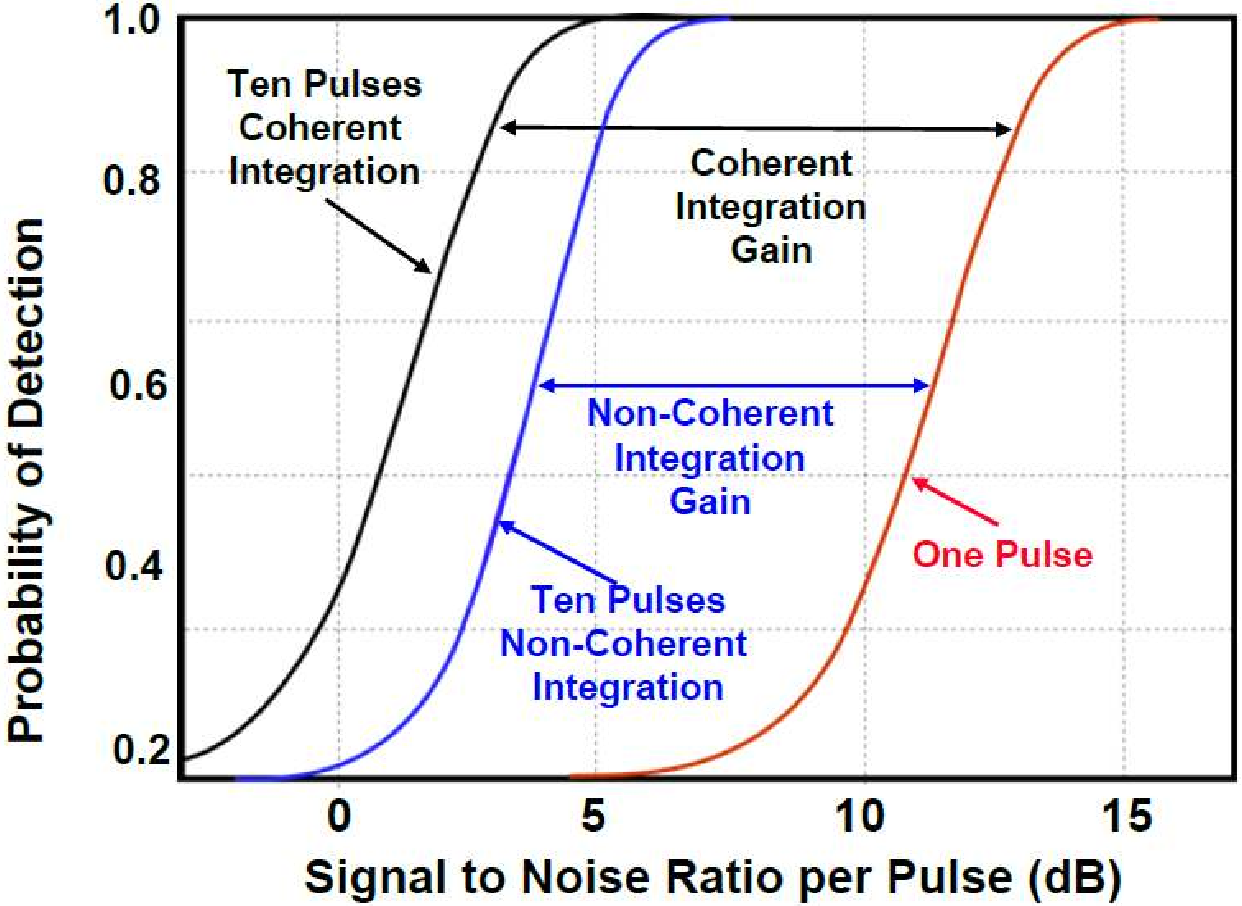
Noncoherent Integration

Steady Target



Noise Variance Reduced after Integration (Allows Lower Threshold)

Integration of Pulses



Steady Target

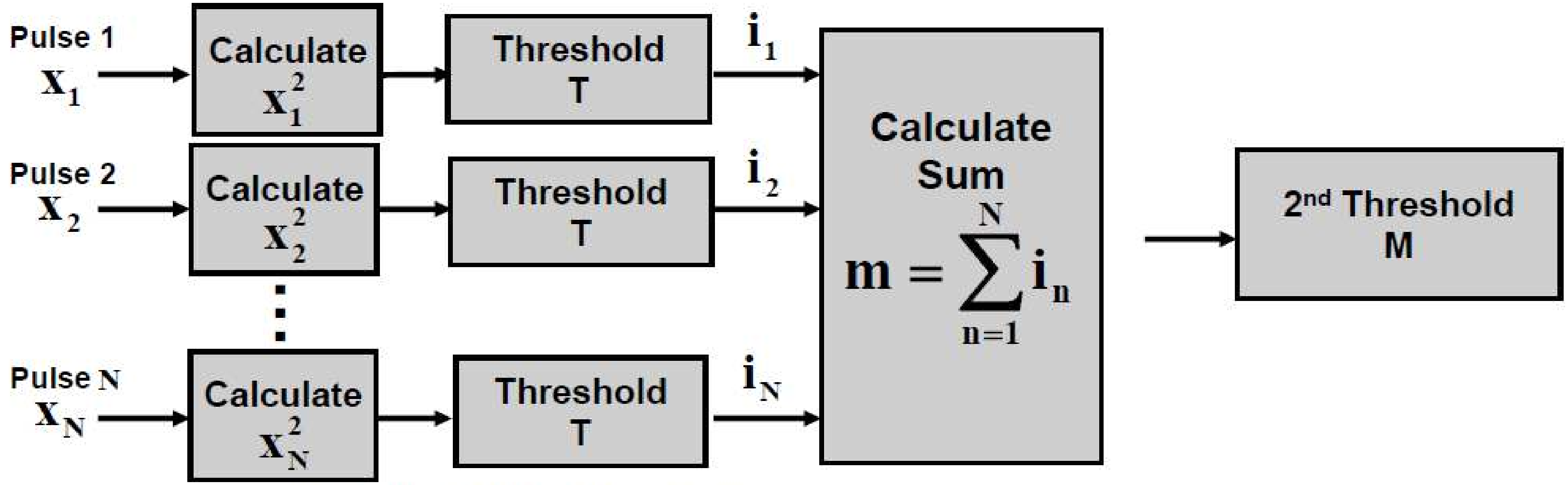
$P_{FA}=10^{-6}$

For Most Cases, Coherent Integration is More Efficient than Non-Coherent Integration

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

Binary (*M*-of-*N*) Integration



Individual pulse detectors:

$$
\begin{aligned}
|x_n|^2 &\geq T, \quad i_n = 1 \\
|x_n|^2 &< T, \quad i_n = 0
\end{aligned}
$$

2nd thresholding:

$m \geq M$, target present

$m < M$, target absent

Target present if at least *M* detections in *N* pulses

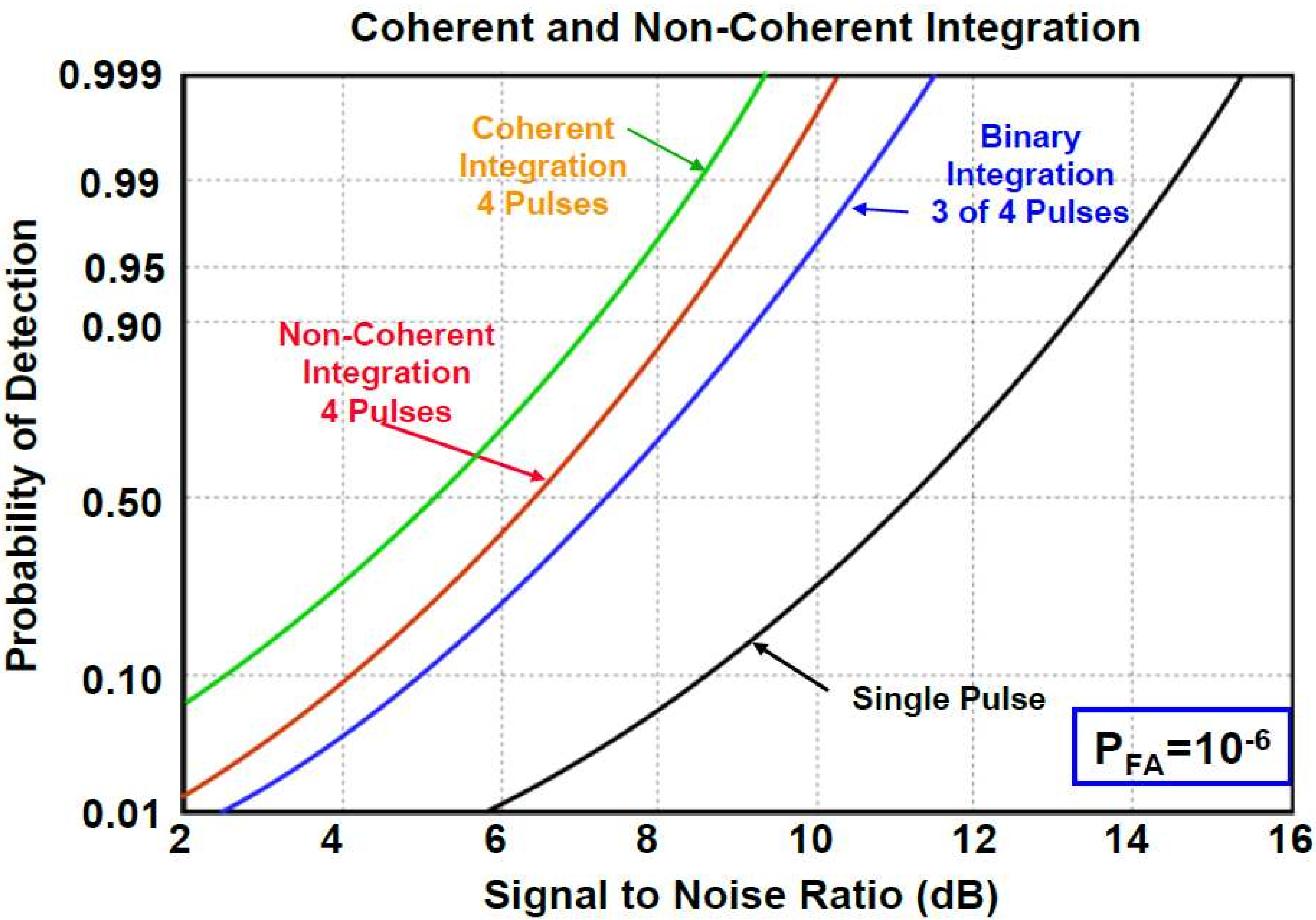
Binary Integration

At Least M of N Detections $\quad P_{M/N} = \sum_{k=M}^{N} \frac{N!}{k!(N-k)!} p^k (1-p)^{N-k}$

Cumulative Detection

At Least 1 of N $\quad P_C = 1 - (1-p)^N$

Detection Statistics for Different Types of Integration



차 례

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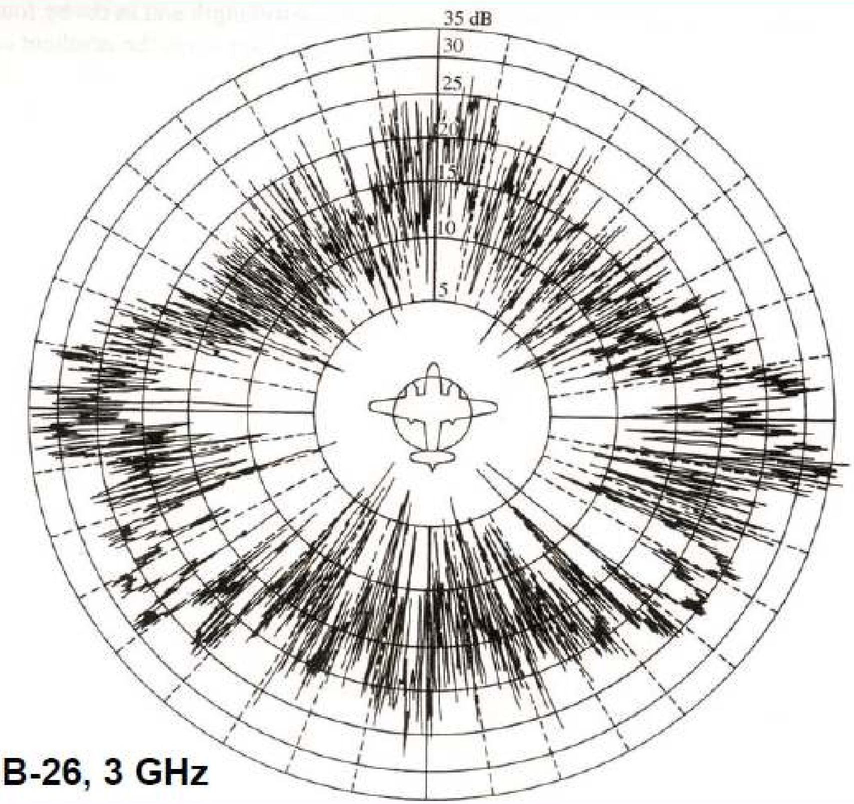
Fluctuating Target Models

RCS vs. Azimuth for a Typical Complex Target

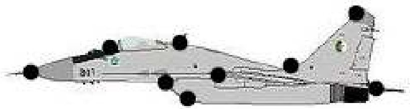
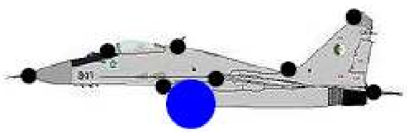


B-26, 3 GHz

RCS versus Azimuth

- For many types of targets, the received radar backscatter amplitude of the target will vary a lot from pulse-to-pulse:
  - Different scattering centers on complex targets can interfere constructively and destructively
  - Small aspect angle changes or frequency diversity of the radar's waveform can cause this effect
- Fluctuating target models are used to more accurately predict detection statistics (P_D vs., $P_{FA,}$ and S/N) in the presence of target amplitude fluctuations

Swerling Target Models

Nature of Scattering	RCS Model	Fluctuation Rate	
		Slow Fluctuation "Scan-to-Scan"	Fast Fluctuation "Pulse-to-Pulse"
Similar amplitudes 	Exponential (Chi-Squared DOF=2) $p(\sigma)=\frac{1}{\bar{\sigma}}\exp\left(-\frac{\sigma}{\bar{\sigma}}\right)$	Swerling I	Swerling II
One scatterer much Larger than others 	(Chi-Squared DOF=4) $p(\sigma)=\frac{4\sigma}{\bar{\sigma}^2}\exp\left(-\frac{2\sigma}{\bar{\sigma}}\right)$	Swerling III	Swerling IV

$\bar{\sigma} =$ Average RCS (m^2)

Courtesy of MIT Lincoln Laboratory
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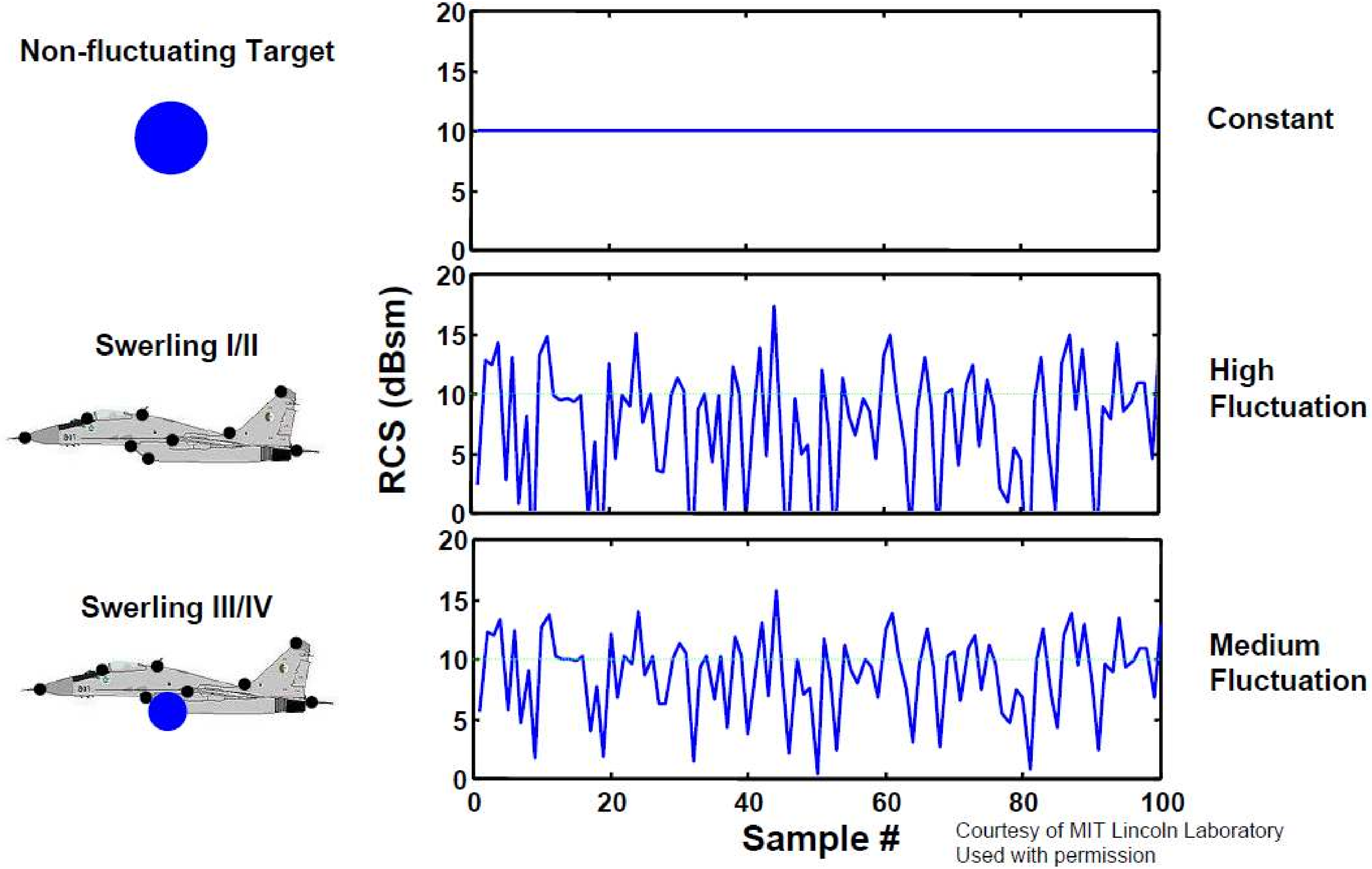
RCS Variability for Different Target Models



Courtesy of MIT Lincoln Laboratory
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Detection Statistics for Fluctuating Targets

Single Pulse Detection

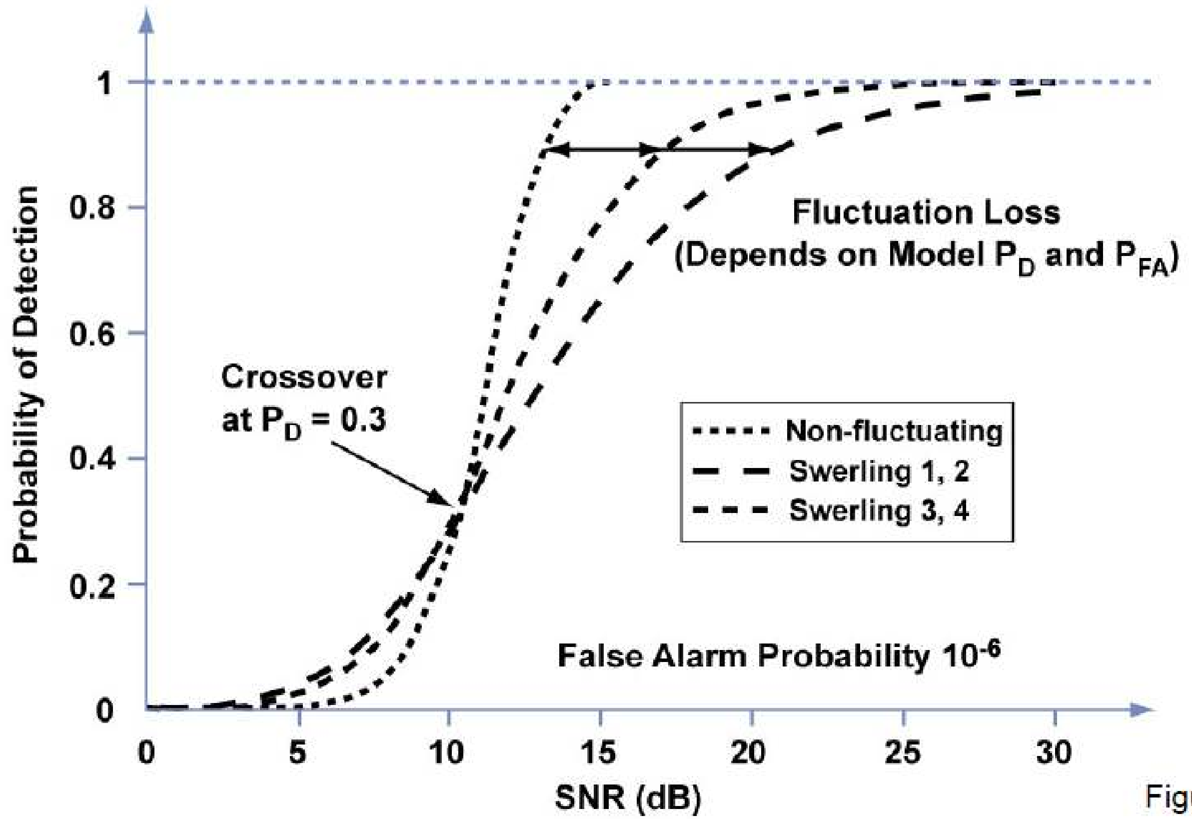

Figure by MIT OCW.

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

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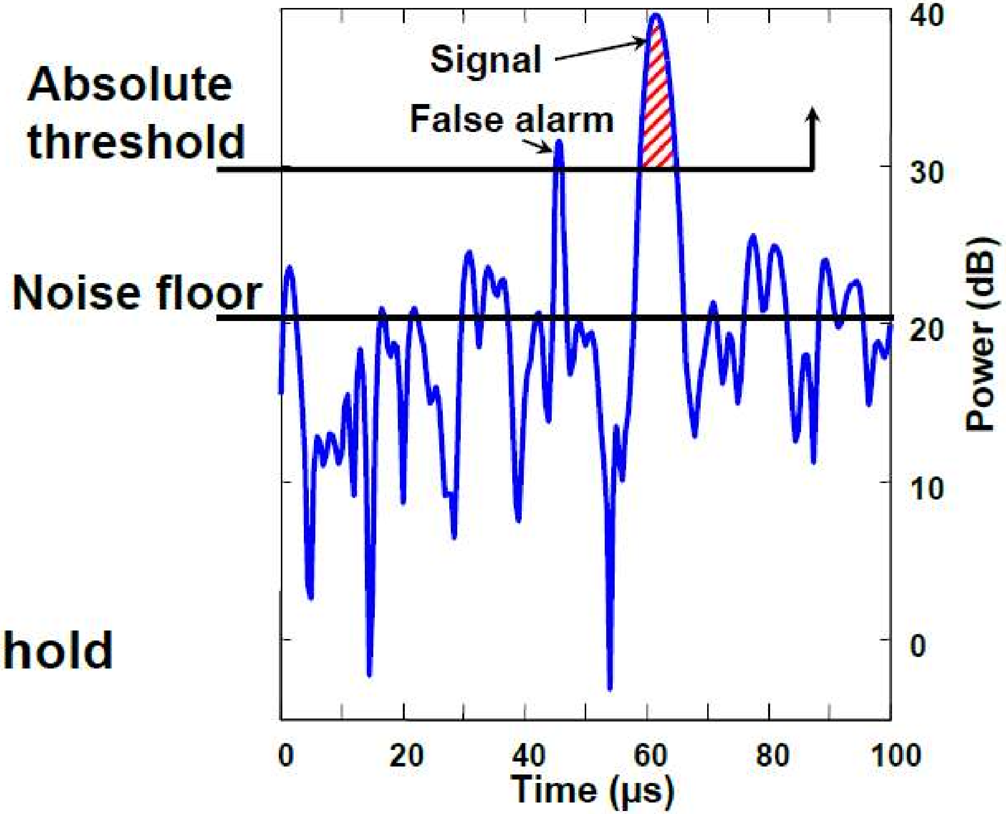
Constant False Alarm Rate (CFAR) Thresholding

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

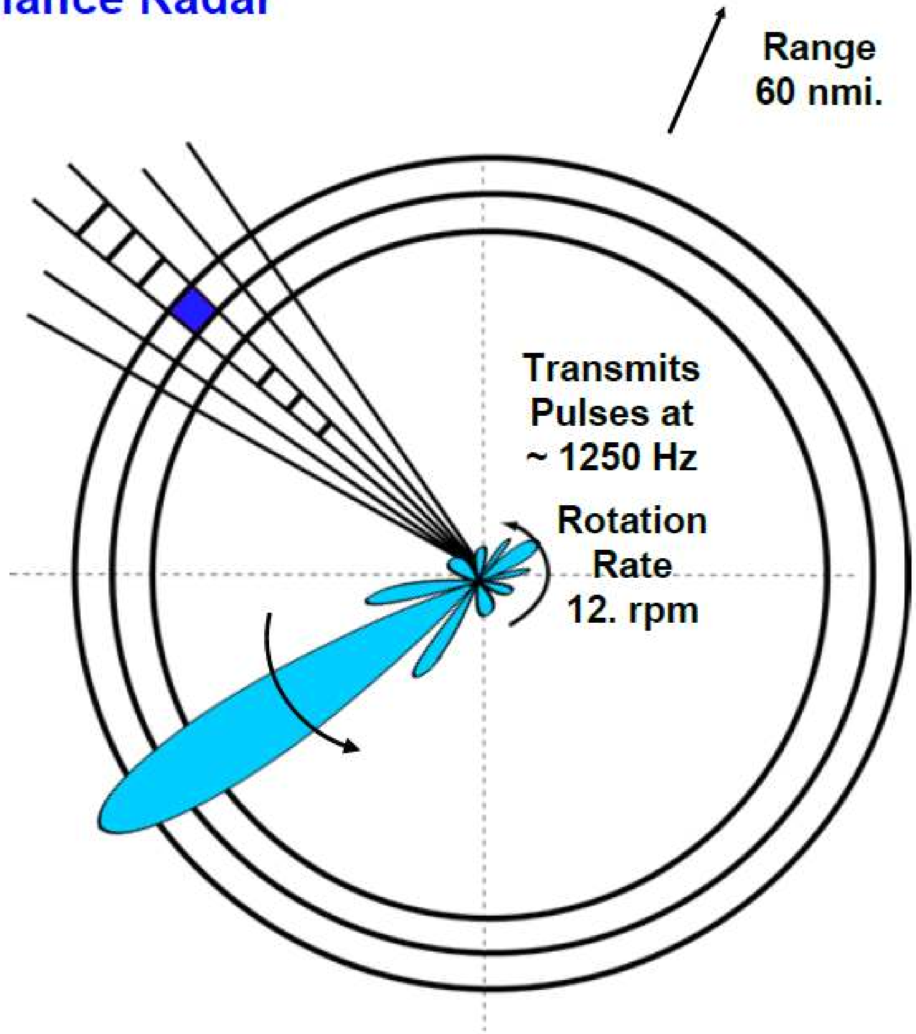
$$\frac{\text{test cell}}{\text{noise floor estimate}} > \text{threshold}$$



Radar Detection – "The Big Picture"

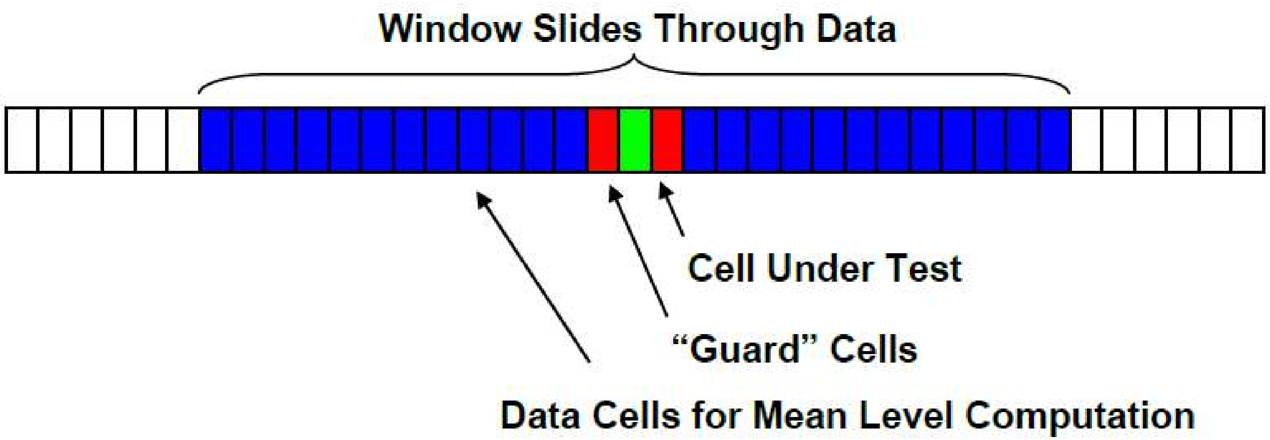
Example – Typical Aircraft Surveillance Radar
ASR-9

- **Mission – Detect and track all aircraft within 60 nmi of radar**
- **S-band $\lambda \sim 10$ cm**



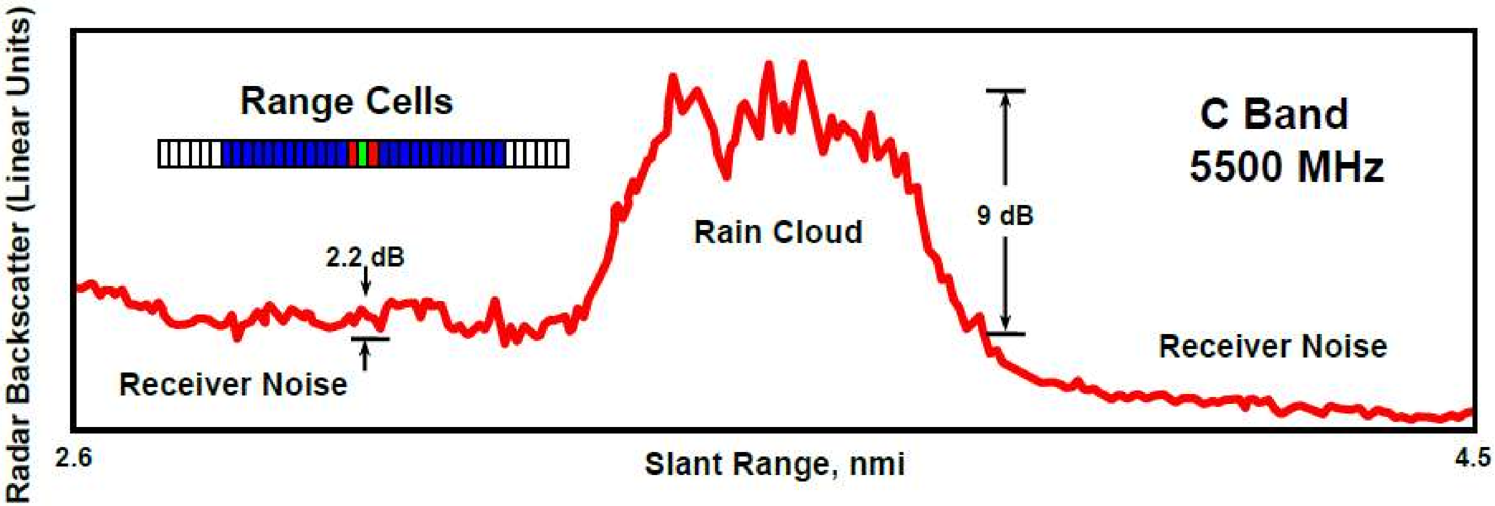
The Mean Level CFAR

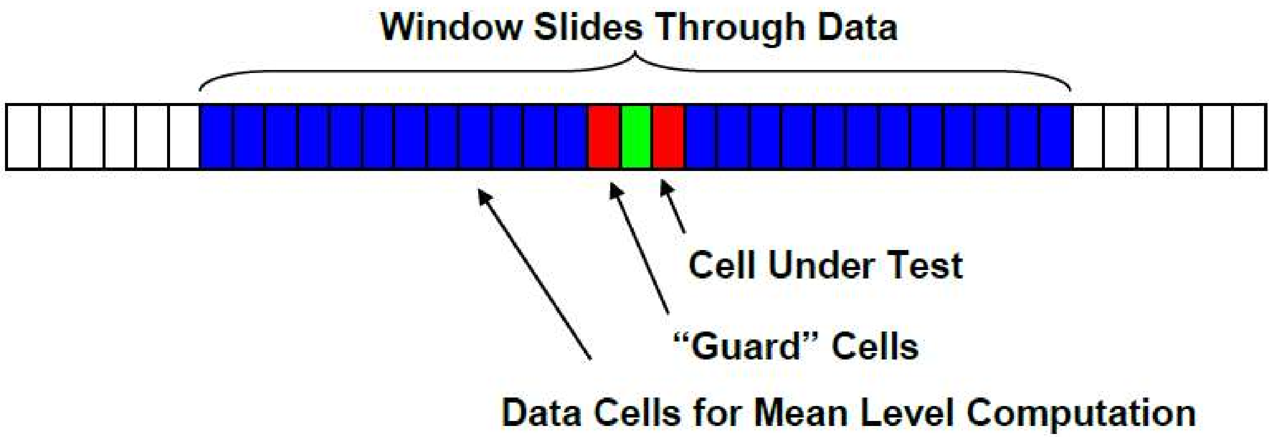
- Use mean value of surrounding range cells to determine threshold for cell under test



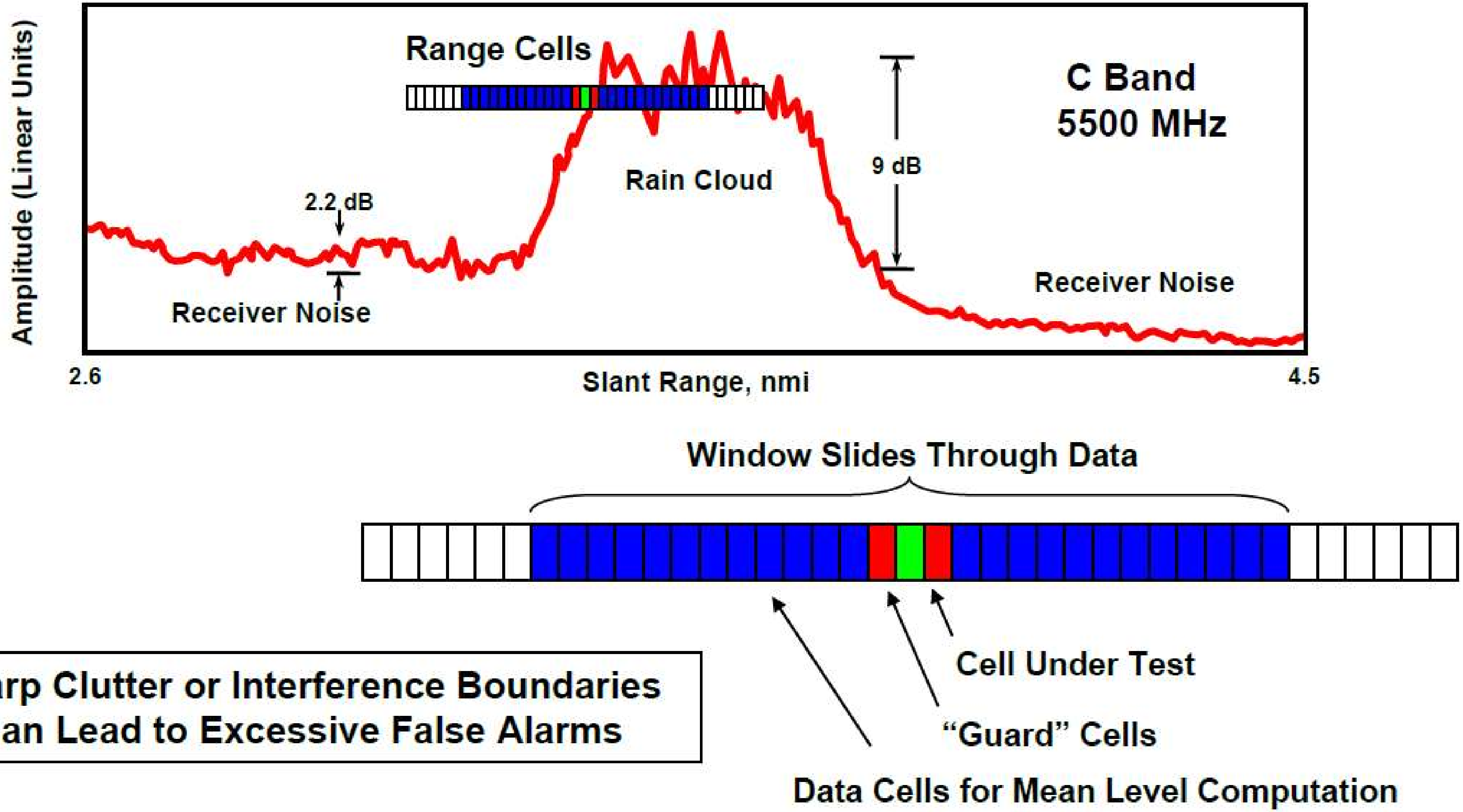
- Nearby targets can raise threshold and suppress detection

Effect of Rain on CFAR Thresholding





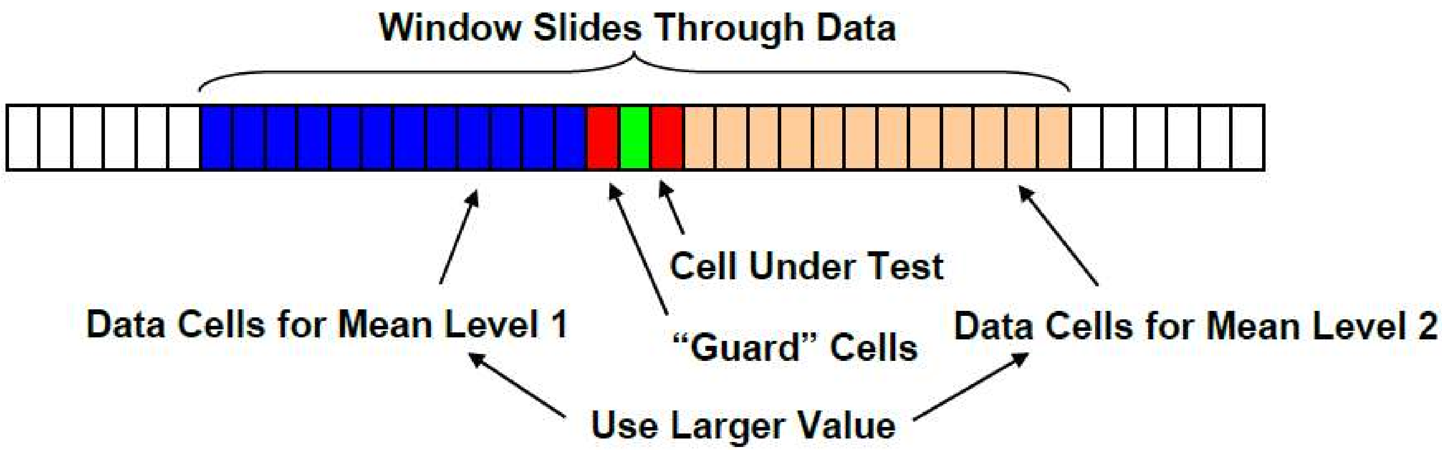
Effect of Rain on CFAR Thresholding



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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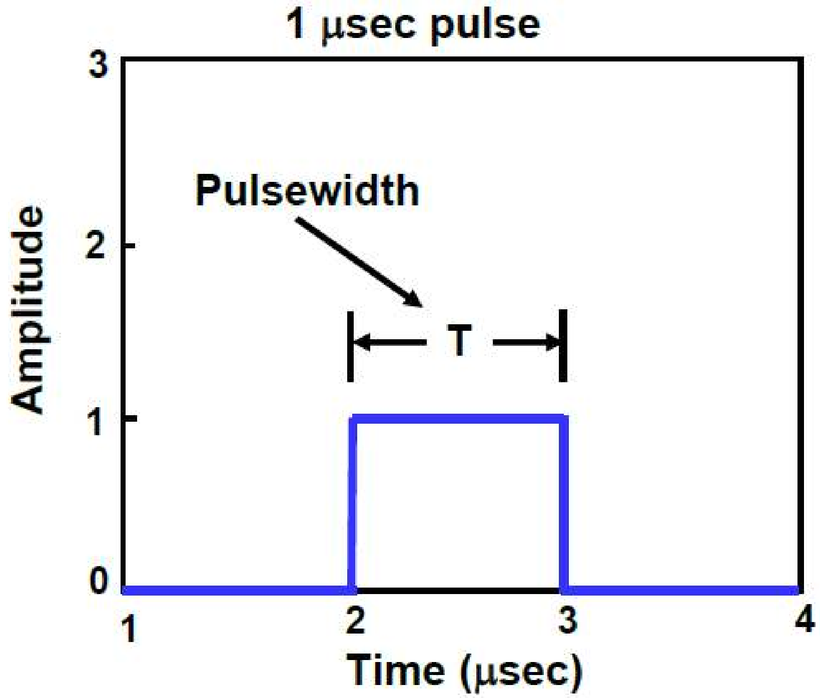
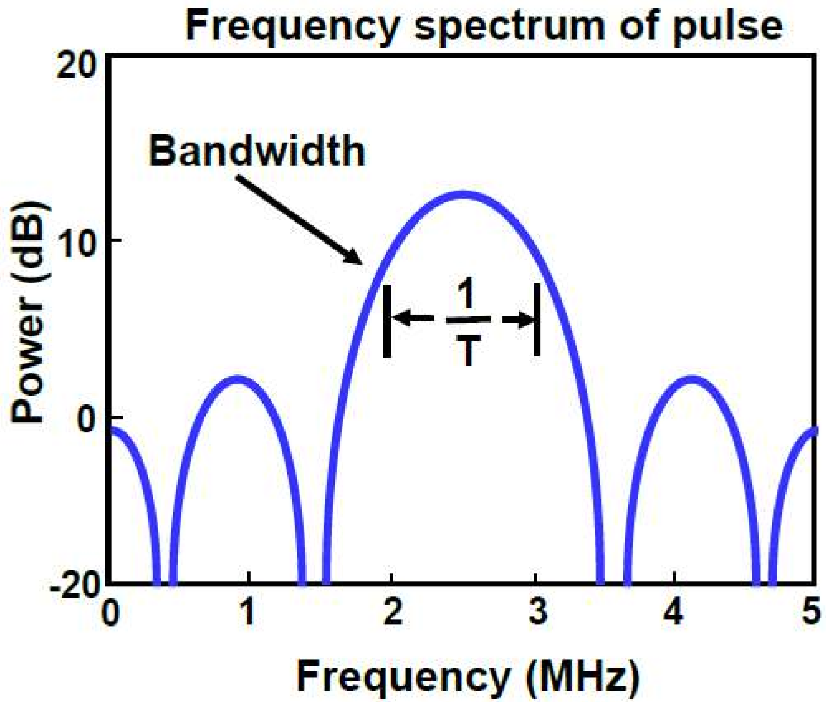
Pulsed CW Radar Fundamentals

Range Resolution





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

    1 MHz Bandwidth => 150 m of range resolution

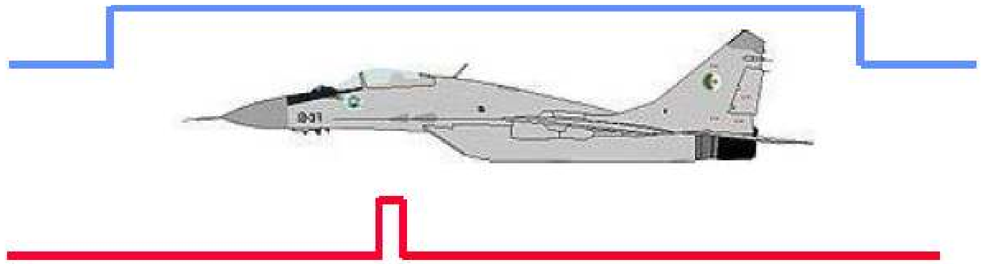
$$\Delta r = \frac{c\,T}{2}$$

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

Pulse Width, Bandwidth and Resolution for a Square Pulse

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

Cannot Resolve Features Along the Target



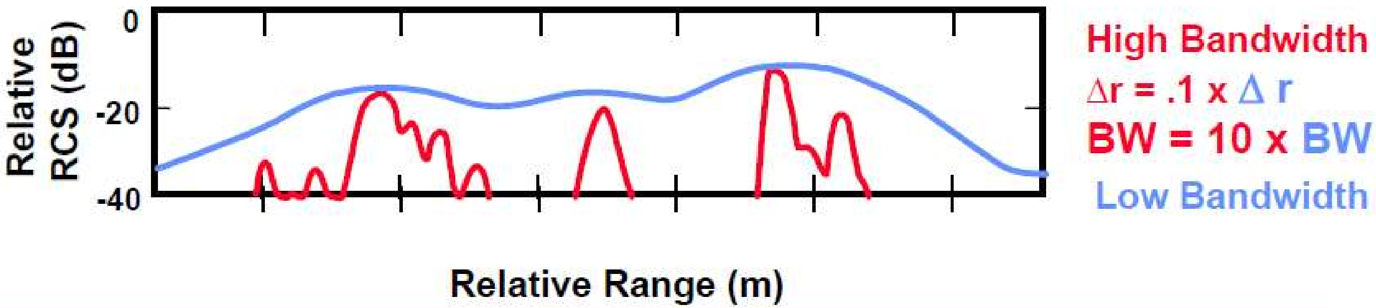
$$\Delta r = \frac{c\,T}{2}$$

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

Pulse Length is Smaller than Target Length

Can Resolve Features Along the Target

Metaphorical Example :



Shorter Pulses have Higher Bandwidth and Better Resolution

Viewgraph courtesy of MIT Lincoln Laboratory
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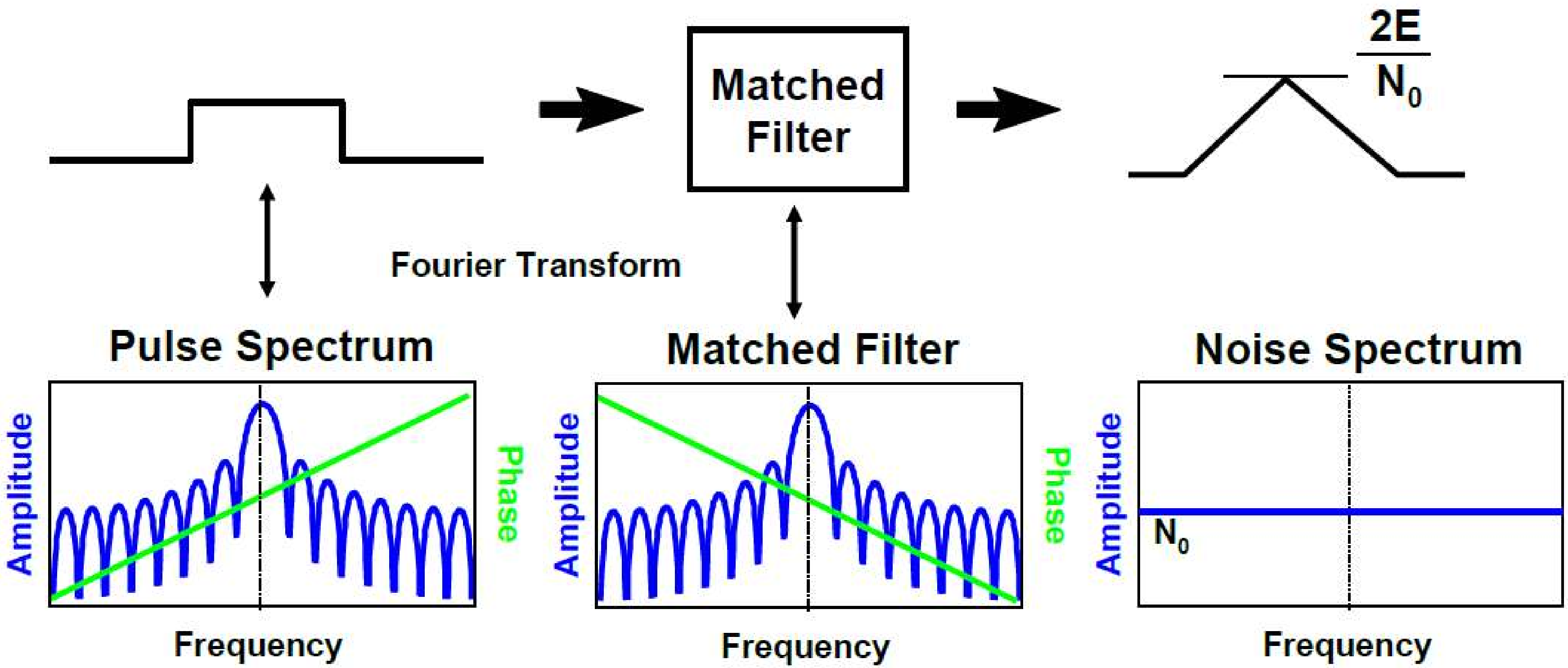
Motivation for Pulse Compression

- 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)

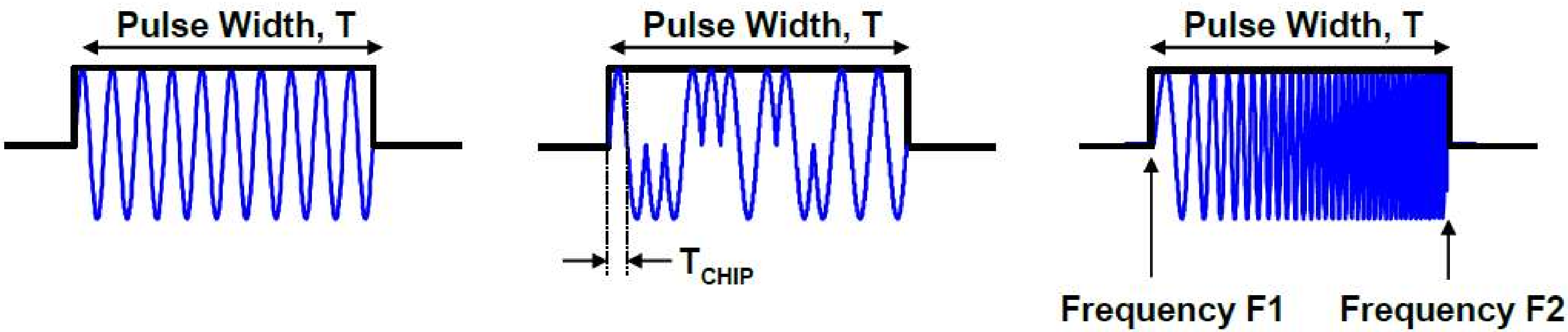


- Matched Filter maximizes the peak-signal to mean noise ratio
  - For rectangular pulse, matched filter is a simple pass band filter

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 | **Binary Phase Coded Waveform** | **Linear Frequency Modulated Waveform**



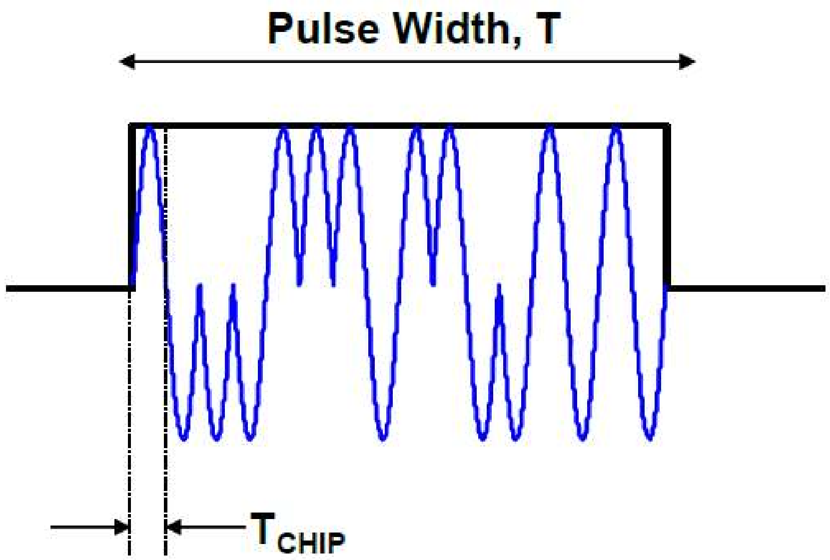
Square Pulse: Bandwidth = $1/T$; Time × Bandwidth = 1

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 = $1/T_{CHIP}$

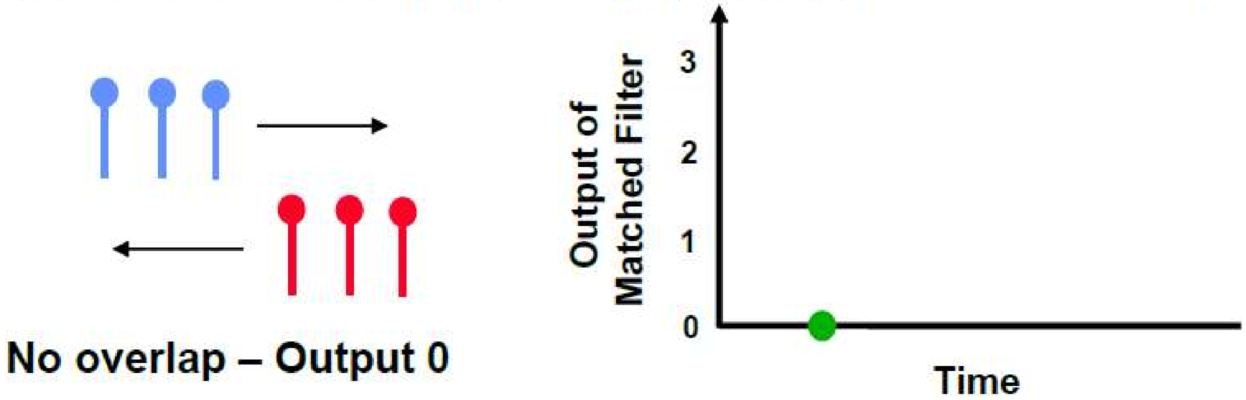
Pulse Compression Ratio = T/T_{CHIP}

- 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

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



Implementation of Matched Filter

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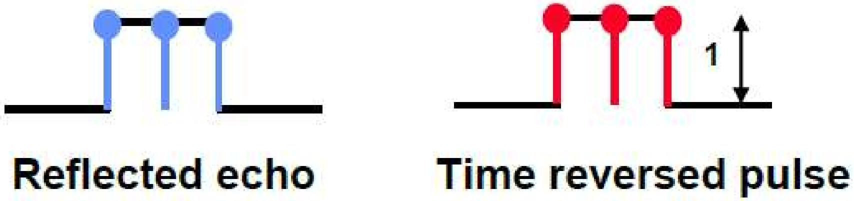

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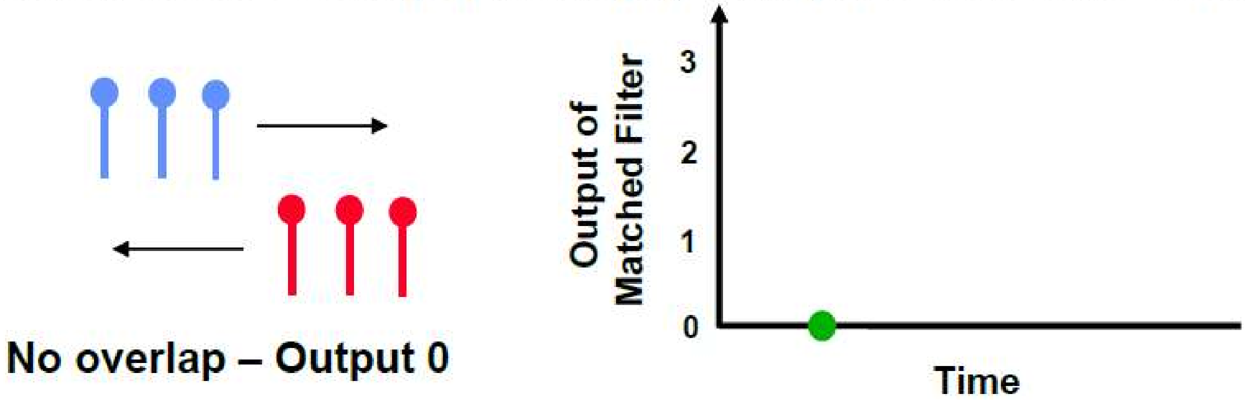
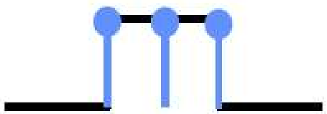
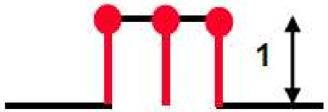


Implementation of Matched Filter

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

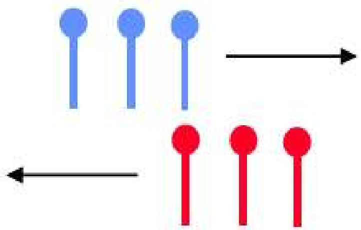


Reflected echo

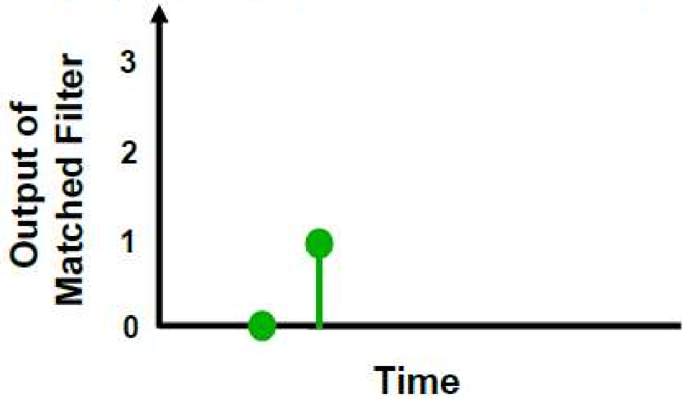


Time reversed pulse

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



One sample overlaps 1x1 =1

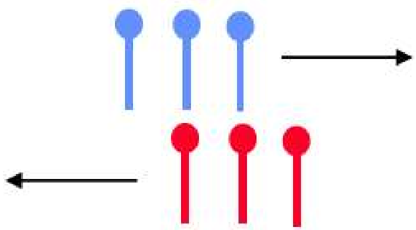


Implementation of Matched Filter

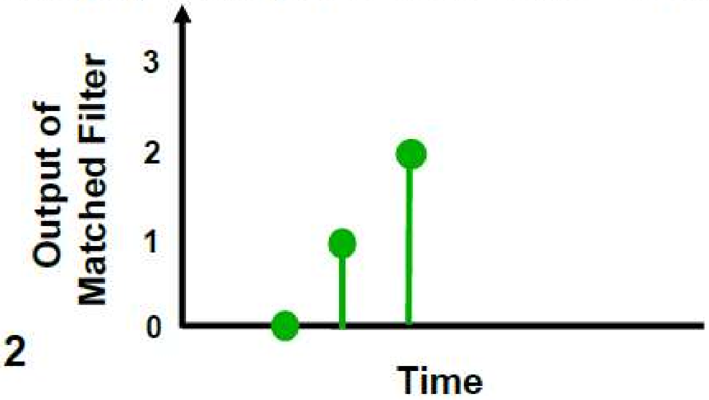
- Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse

Reflected echo   Time reversed pulse

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



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

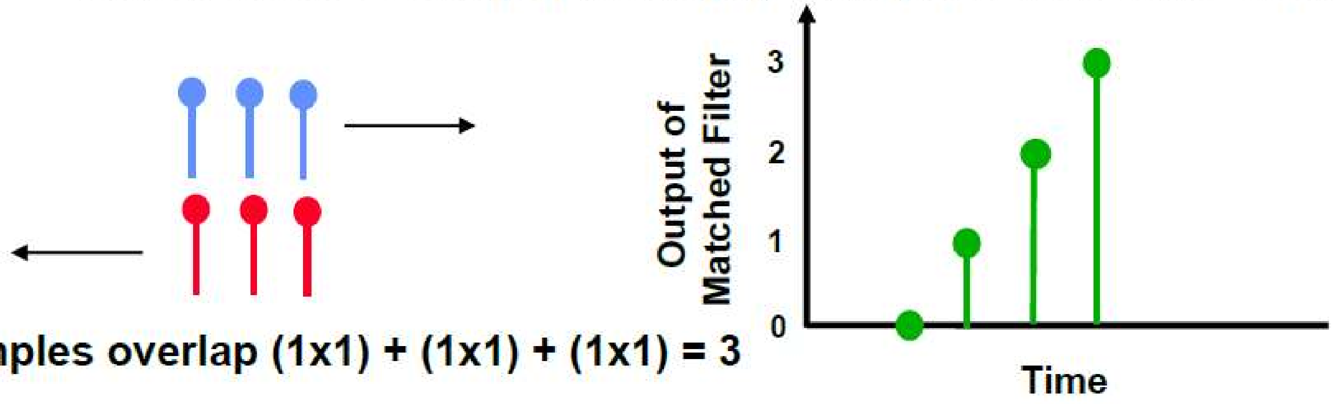


Implementation of Matched Filter

- 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



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

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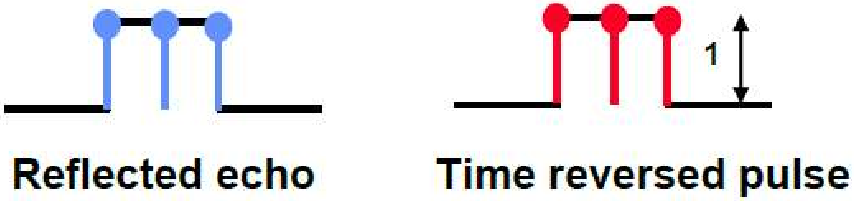
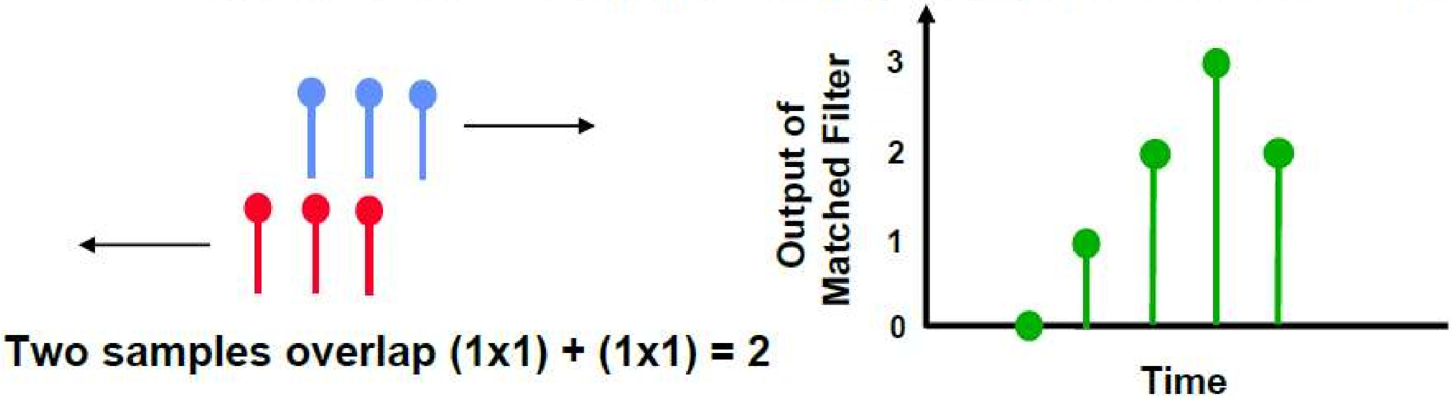
Implementation of Matched Filter

- Matched filter is implemented by “convolving” the reflected echo with the “time reversed” transmit pulse

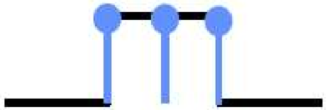


- Convolution process:
  - Move digitized pulses by each other, in steps
  - When data overlaps, multiply samples and sum them up

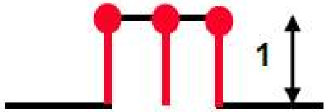


Implementation of Matched Filter

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

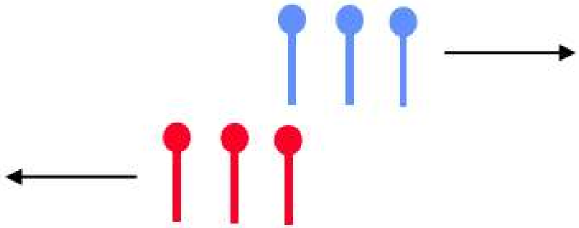


Reflected echo

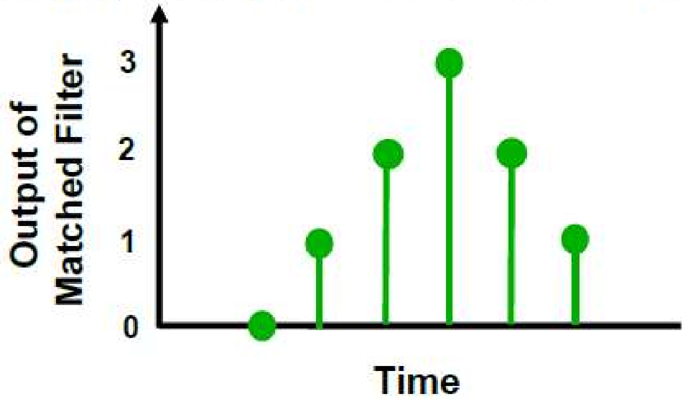


Time reversed pulse

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

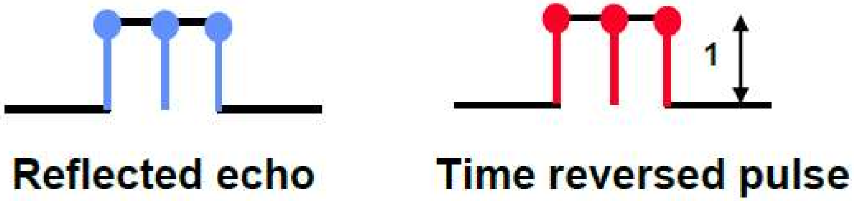


One sample overlaps 1x1 =1



Implementation of Matched Filter

- Matched filter is implemented by “convolving” the reflected echo with the “time reversed” transmit pulse



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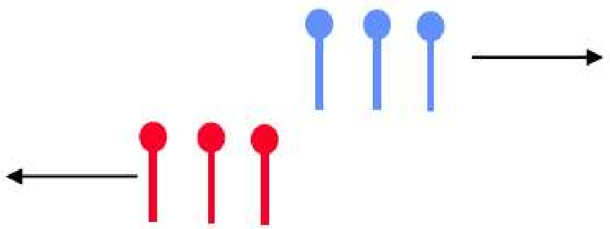

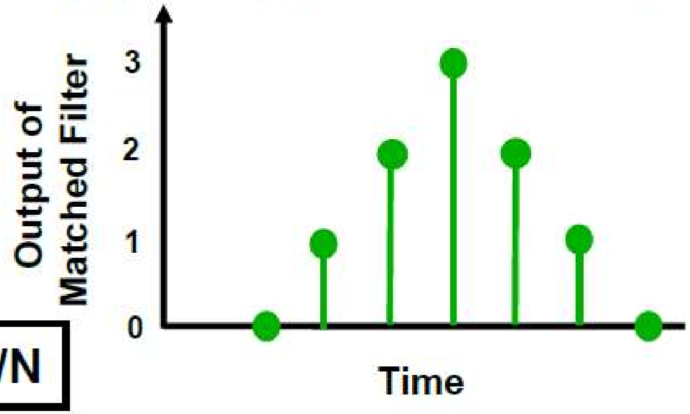

Use of Matched Filter Maximizes S/N

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Pulse Compression

Binary Phase Modulation Example

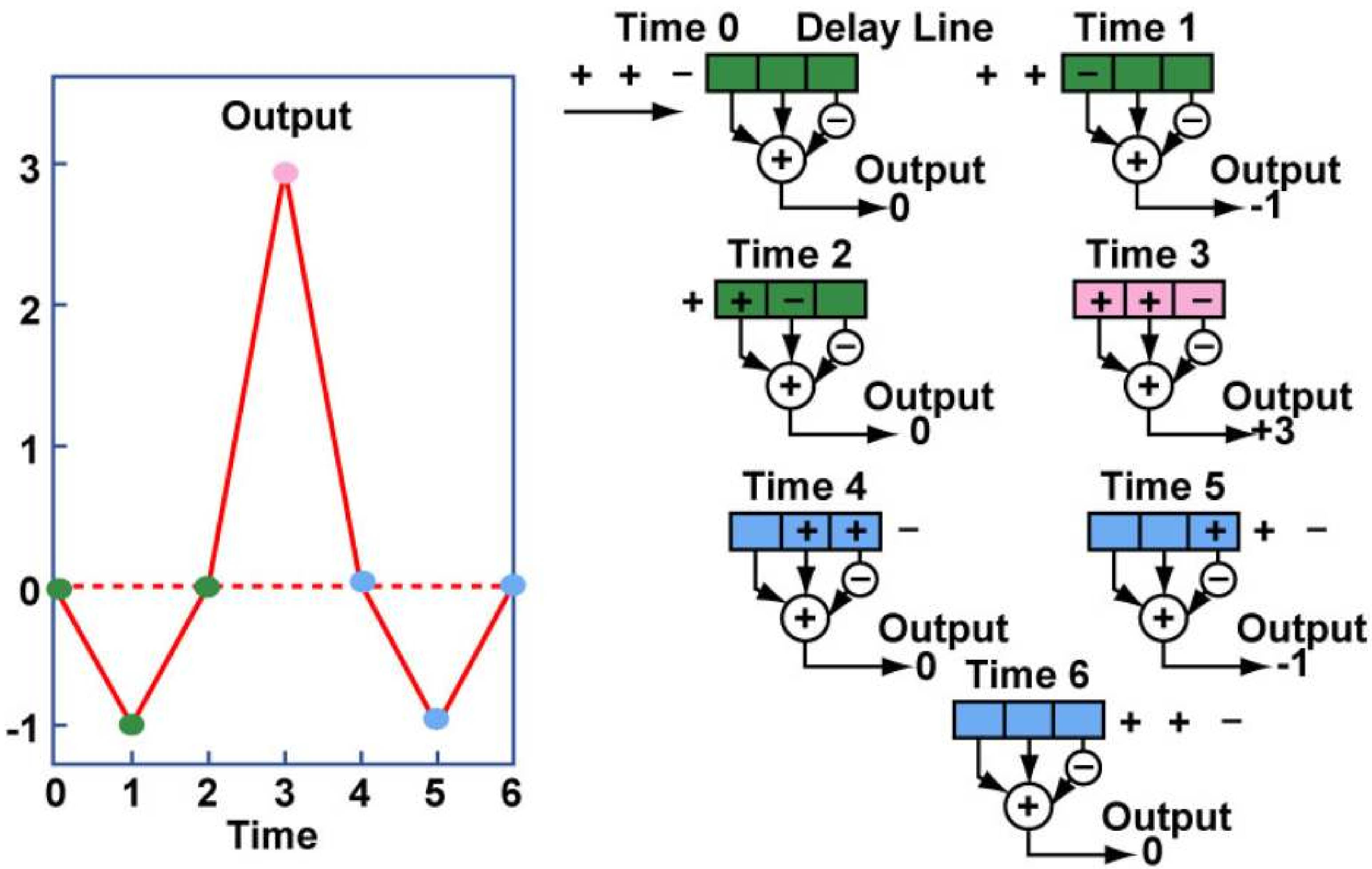
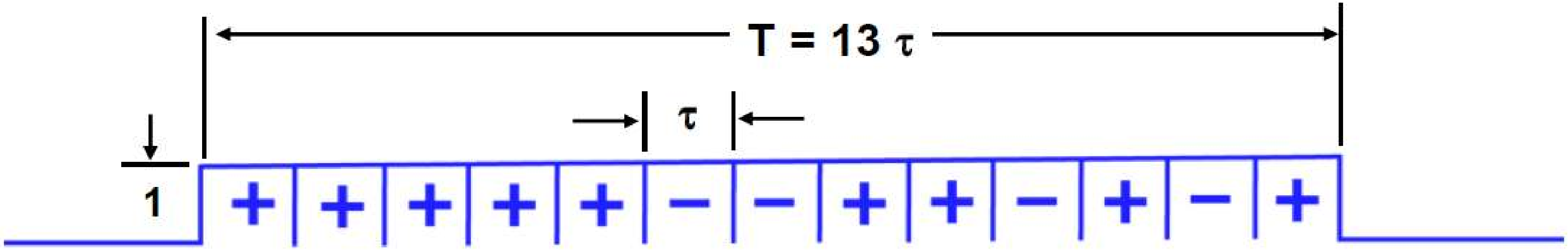
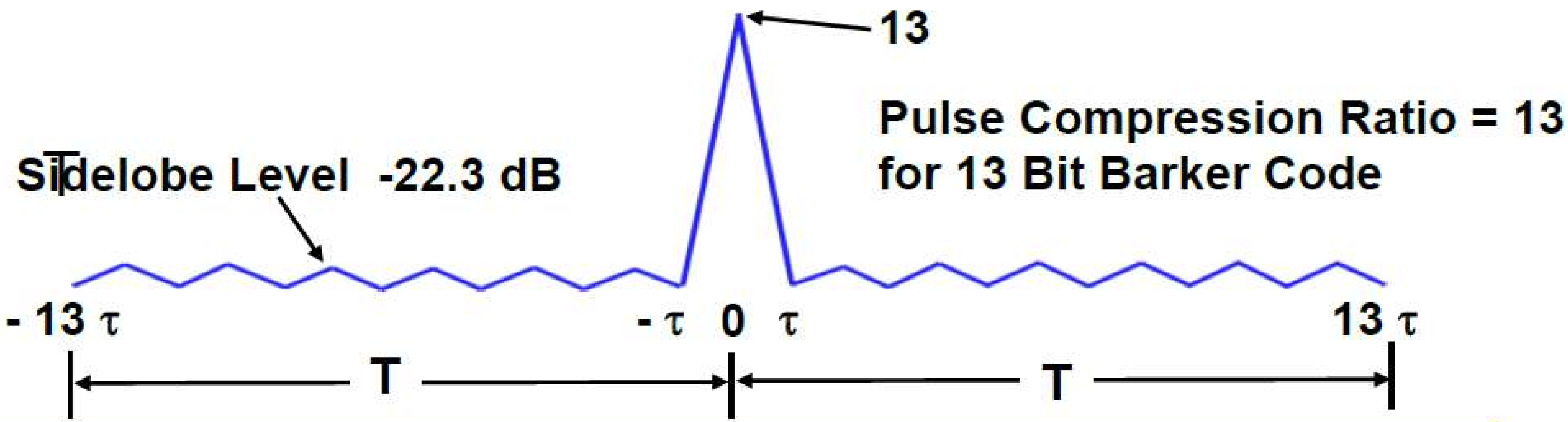


Figure by MIT OCW.

Example - 13 Bit Barker Code



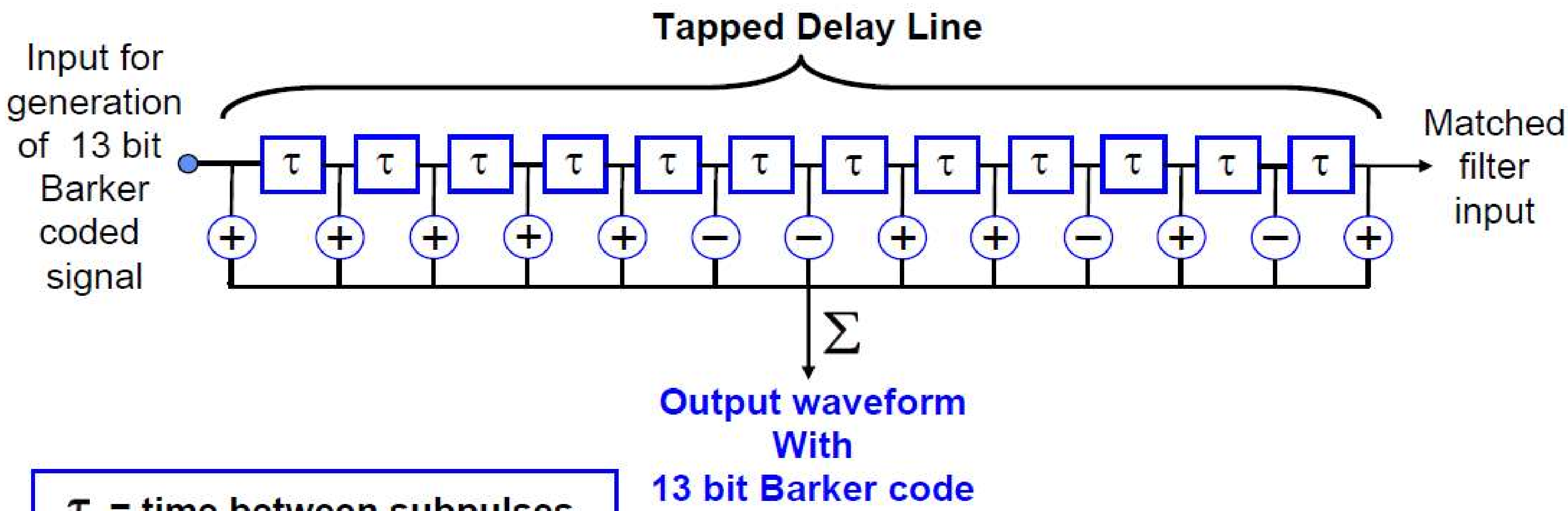
A long pulse with 13 equal sub-pulses, whose individual phases are either 0 (+) or π (-) relative to the un-coded pulse



Auto-correlation function of above pulse, which represents the output of the matched filter

Tapped Delay Line

Generating the Barker Code of Length 13



τ = time between subpulses

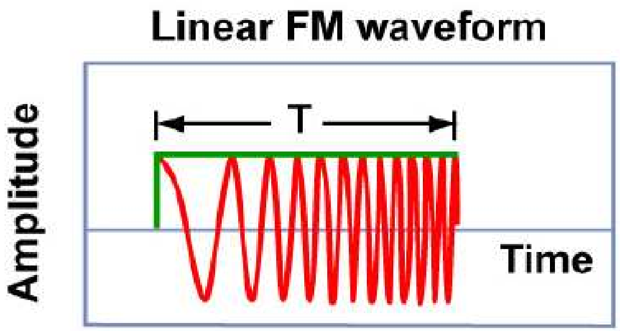
T = 13 τ = total pulse length

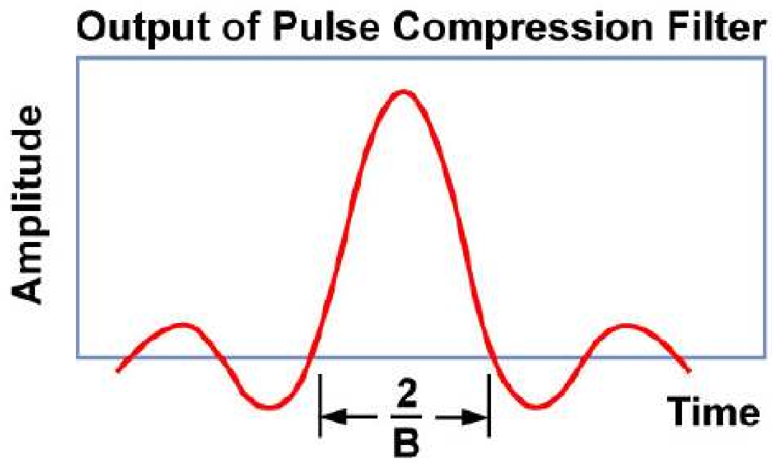
Barker Codes

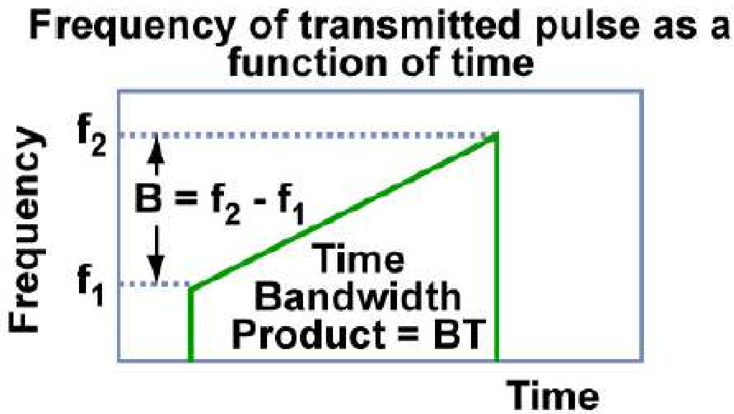
Code Length	Code Elements	Sidelobe Level (dB)
2	+ - , + +	- 6.0
3	+ + -	- 9.5
4	+ + - + , + + + -	- 12.0
5	+ + + - +	- 14.0
7	+ + + - - + -	- 16.9
11	+ + + - - - + - - + -	- 20.8
13	+ + + + + - - + + - + - +	- 22.3

- The 0, and π binary phase codes that result in equal time sidelobes are called Barker Codes
- Sidelobe level of Barker Code is $1 / N^2$ that of the peak power (N = code length)
- None greater than length 13

Linear FM Pulse Compression







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.

Q & A