IEEE Signal Processing Society

IEEE

Radar Signal Processing Mastery

Theory and Hands-On Applications with mmWave MIMO Radar Sensors

Date: 7-11 October 2024
Time: 9:00AM-11:00AM ET (New York Time)

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Outline

Time: 9:00AM-11:00AM ET (New York Time)

Lecture	Duration	Date
Lecture 1: Radar Systems Fundamental	**2 Hours**	October 7th , 2024
Lecture 2: Advanced Radar Systems	**2 Hours**	October 8th , 2024
Lecture 3: Practical Radar Signal Processing - Motion Detection	**2 Hours**	October 9th , 2024
Lecture 4: Practical Radar Signal Processing - Breathing and Heart Rate Estimation	**2 Hours**	October 10th , 2024
Lecture 5: Practical Radar Signal Processing – Angle estimation with MIMO radar	**2 Hours**	October 11th , 2024

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Lecture 1

Radar Fundamentals

Lecture 1: Radar Systems Fundamental

What we learn in Lecture 1

- **Pulsed Radar**
- **Pulse Doppler Radar**
- **Pulse Compression Radar**
- **Continuous Wave Radar**
- **Frequence Modulated Continuous Wave Radar**

Scan the QR code for access to the codes

- ❑ Pulse Repletion Interval (PRI), Pulse Repletion Frequency (PRF)
- ❑ Range resolution and Unambiguous Range
- ❑ Doppler resolution and Unambiguous Doppler
- ❑ Simple pulse, LFM, Binary Codes, Poly phase codes
- ❑ Fast-time, Slow-time, and ambiguity function
- ❑ Matched Filter, Range-Doppler Processing
- ❑ De-chirp/Stretch Processing

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Introduction to Radar Systems

Overview of radar applications

RADAR: RAdio Detection And Ranging

the acronym created in 1940 by the United States Navy

Radar is a system that uses radio waves to determine the distance (ranging), direction (azimuth and elevation angles), and radial velocity of objects relative to the site.

Applications

- ❑ Aerospace and Aviation
- ❑ Military and Defense
- ❑ Maritime
- ❑ Meteorology
- ❑ Space Exploration
- ❑ Geological and Environmental
- ❑ Healthcare and Biomedical
- ❑ Law Enforcement and Security
- ❑ Automotive
- ❑ Industrial

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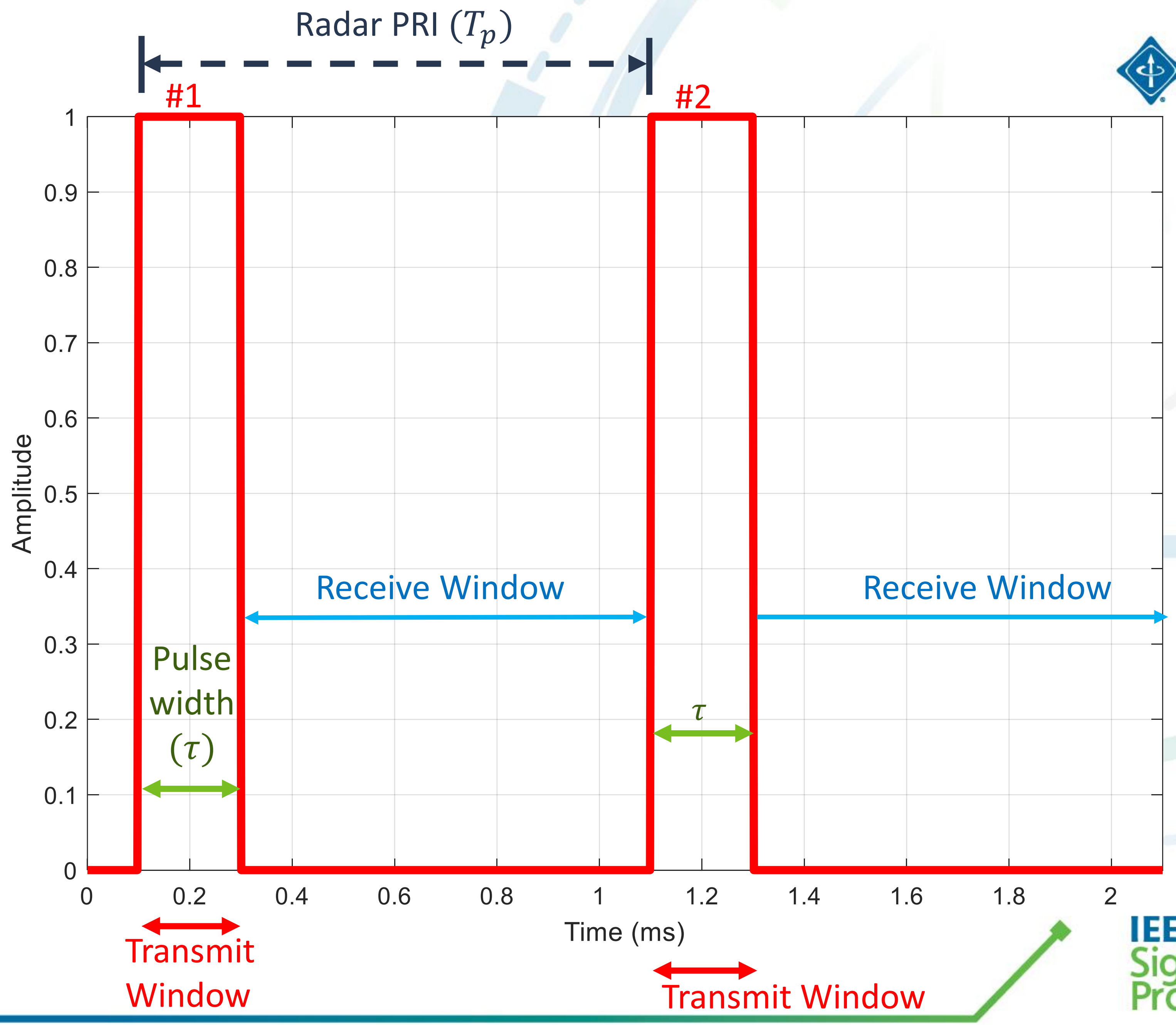
Pulsed Radar

Transmit signal

- transmits energy in short bursts, or pulses
- measures distances and detect the presence of objects



Lect1_example1.m

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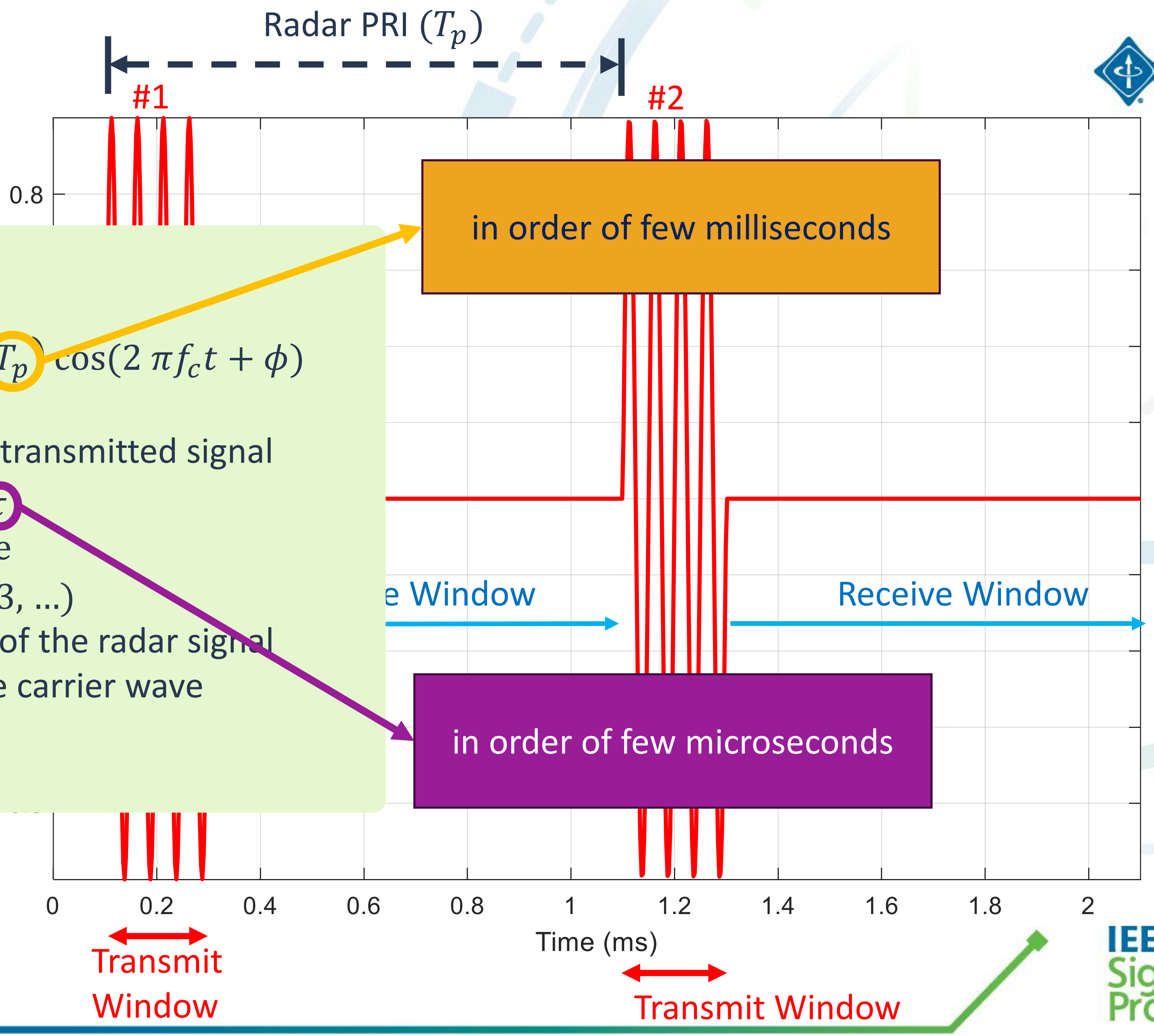
Pulsed Radar

Transmit signal

$$s_{tx}(t) = A_t \, \mathrm{rect}\left(t - (i-1)T_p\right) \cos(2\pi f_c t + \phi)$$

- A_t is the amplitude of the transmitted signal
- $\mathrm{rect}\,(t) = \begin{cases} 1 & 0 < t < \tau \\ 0 & \text{otherwise} \end{cases}$
- i is the pulse index $(1, 2, 3, \ldots)$
- f_c is the carrier frequency of the radar signal
- ϕ is the initial phase of the carrier wave



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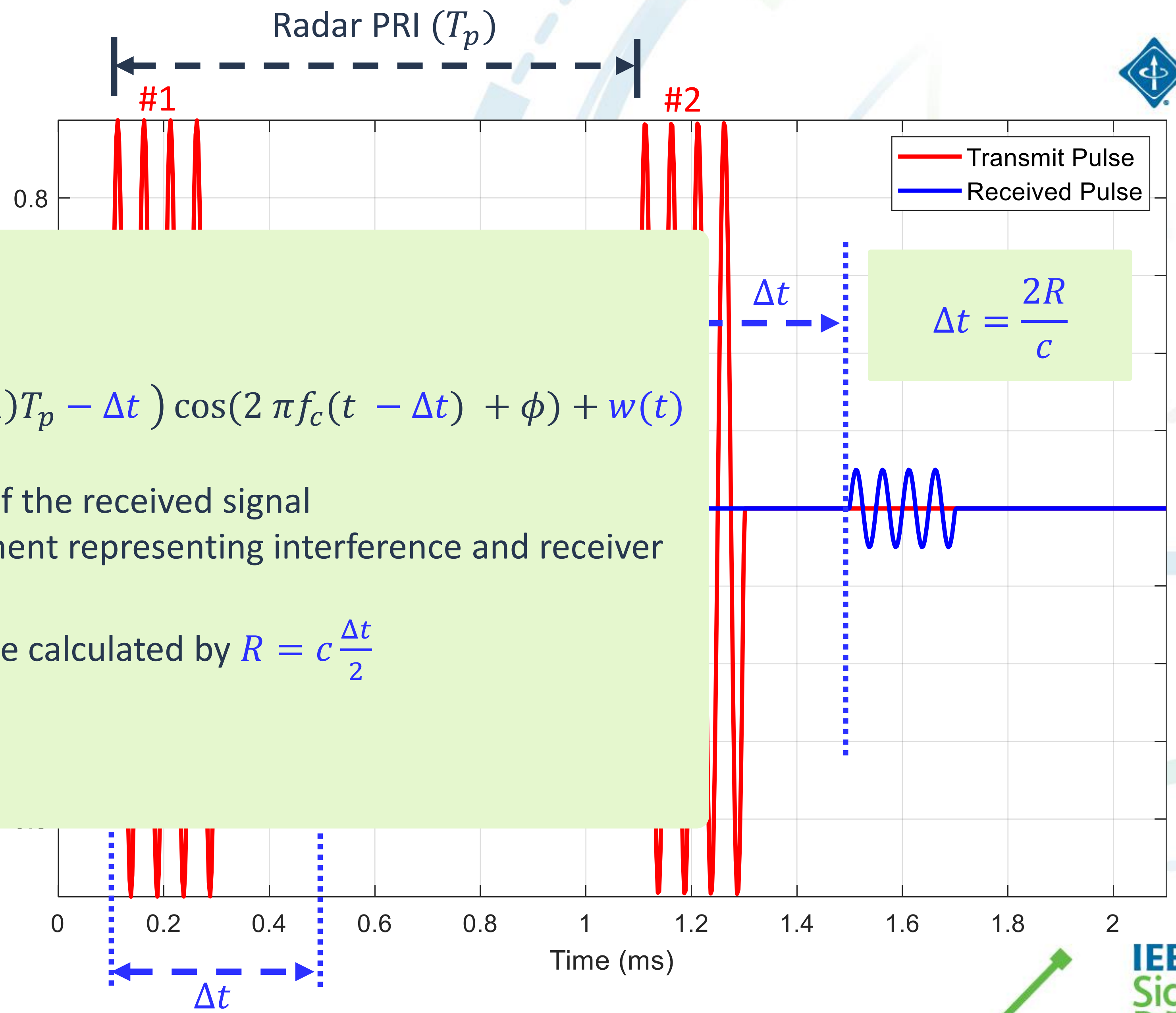
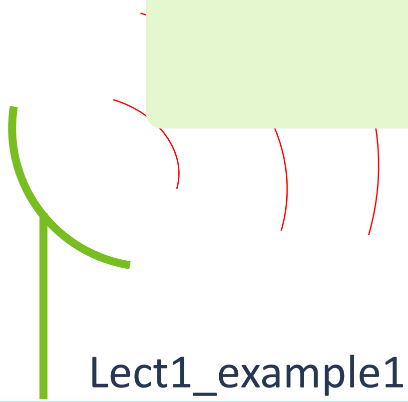
Pulsed Radar

Received signal



$$s_{rx}(t) = A_r \operatorname{rect}\left(t - (i-1)T_p - \Delta t\right) \cos(2\pi f_c (t - \Delta t) + \phi) + w(t)$$

- A_r is the amplitude of the received signal
- $w(t)$ is noise component representing interference and receiver noise
- Range of target can be calculated by $R = c\frac{\Delta t}{2}$



Lect1_example1.m

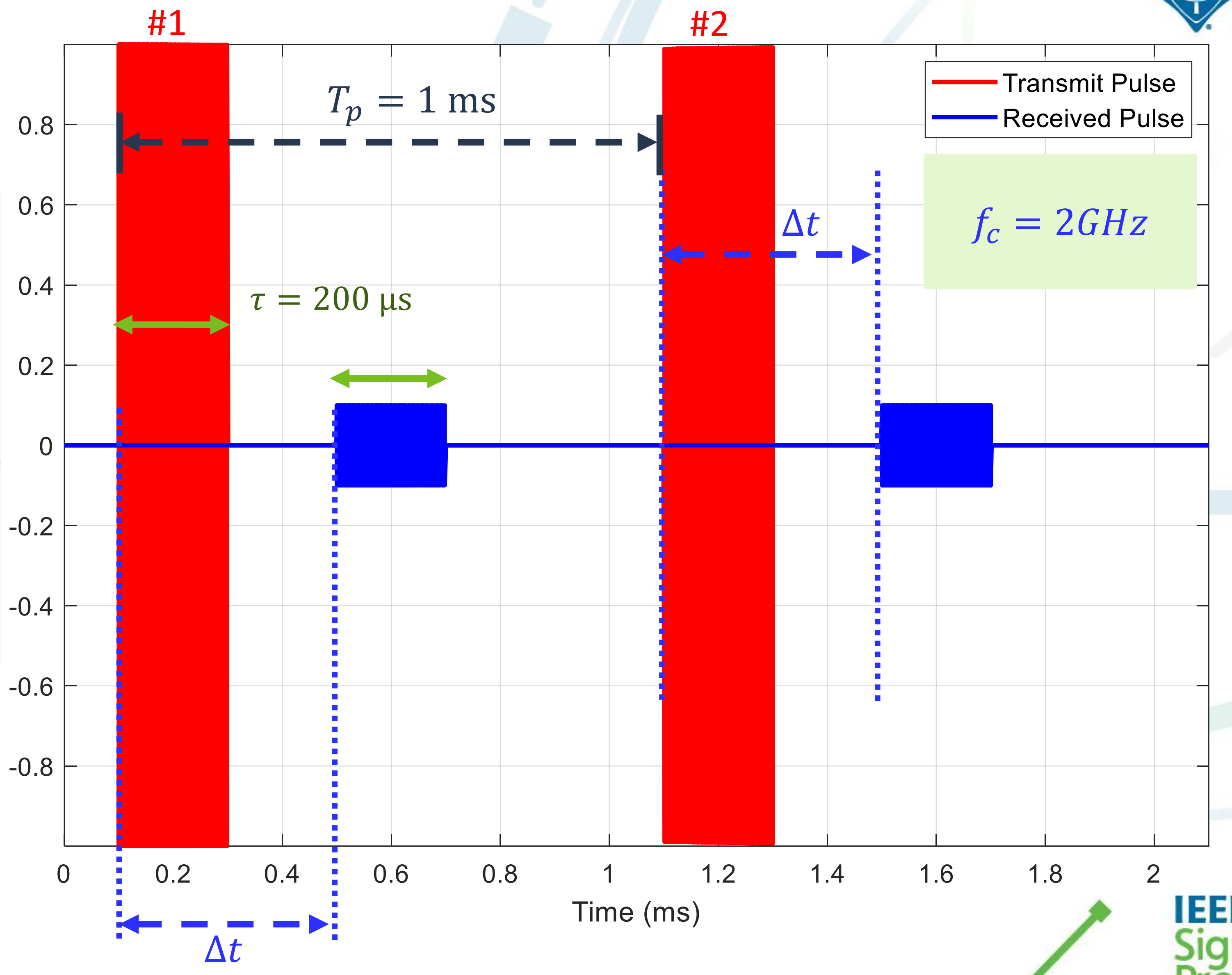
Pulsed Radar

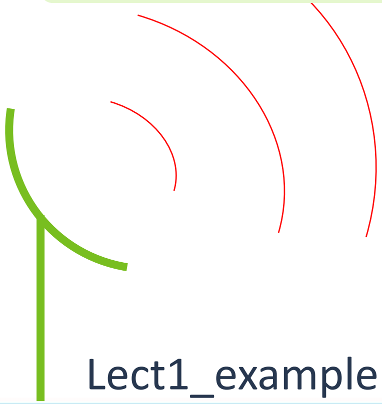
Received signal

$$T_p = 1\ \text{ms} \Rightarrow \frac{cT_p}{2} = 150\ \text{Km}$$

$$\tau = 200\ \mu\text{s} \Rightarrow \frac{c\tau}{2} = 30\ \text{Km}$$

$$\Delta t = 400\ \mu\text{s} \Rightarrow \frac{c\Delta t}{2} = 60\ \text{Km}$$





Lect1_example1.m

Pulsed Radar

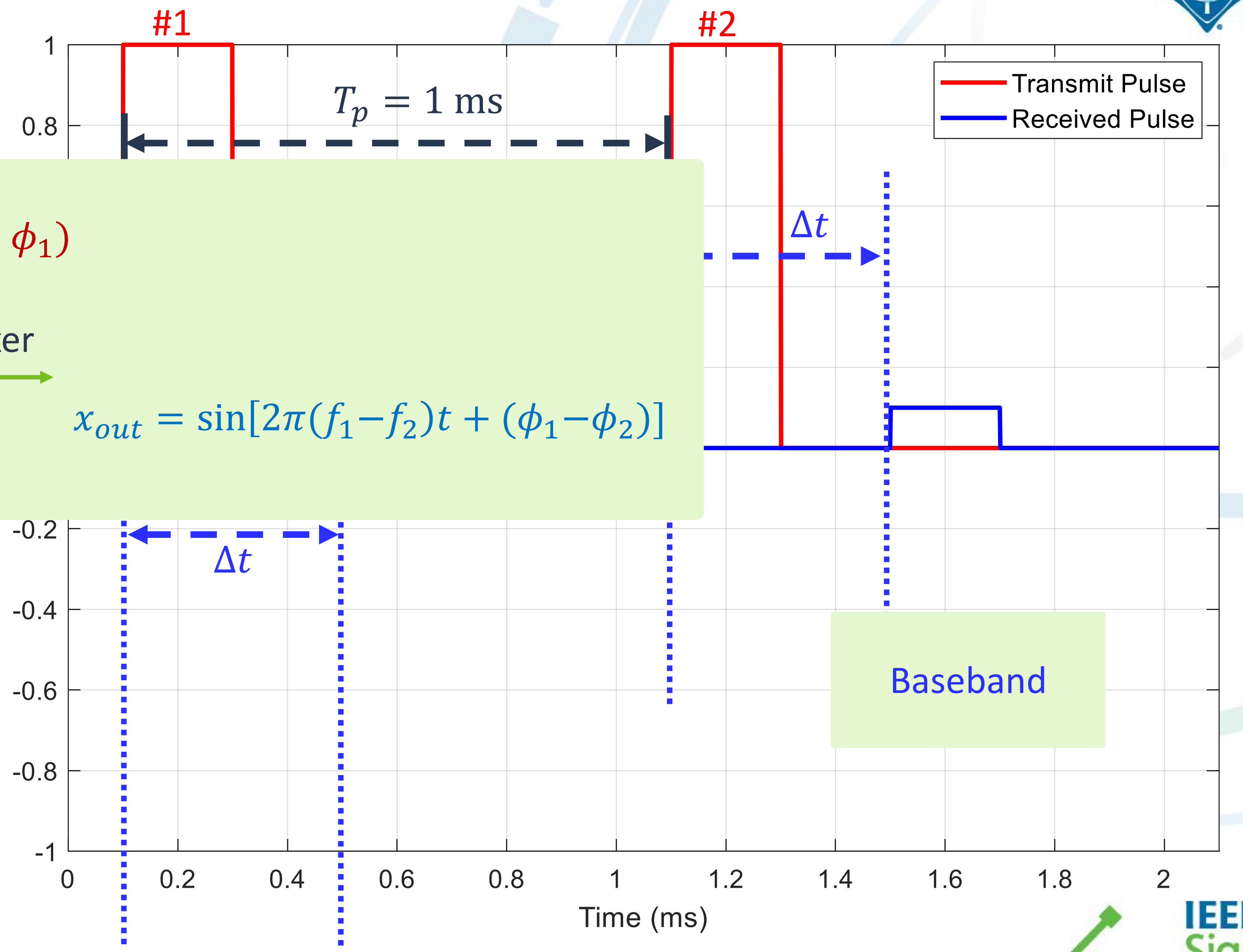
Received pulse

$$x_1 = \sin(2\pi f_1 t + \phi_1)$$

Mixer

$$x_2 = \sin(2\pi f_2 t + \phi_2)$$

$$x_{out} = \sin[2\pi(f_1 - f_2)t + (\phi_1 - \phi_2)]$$



Lect1_example2.m

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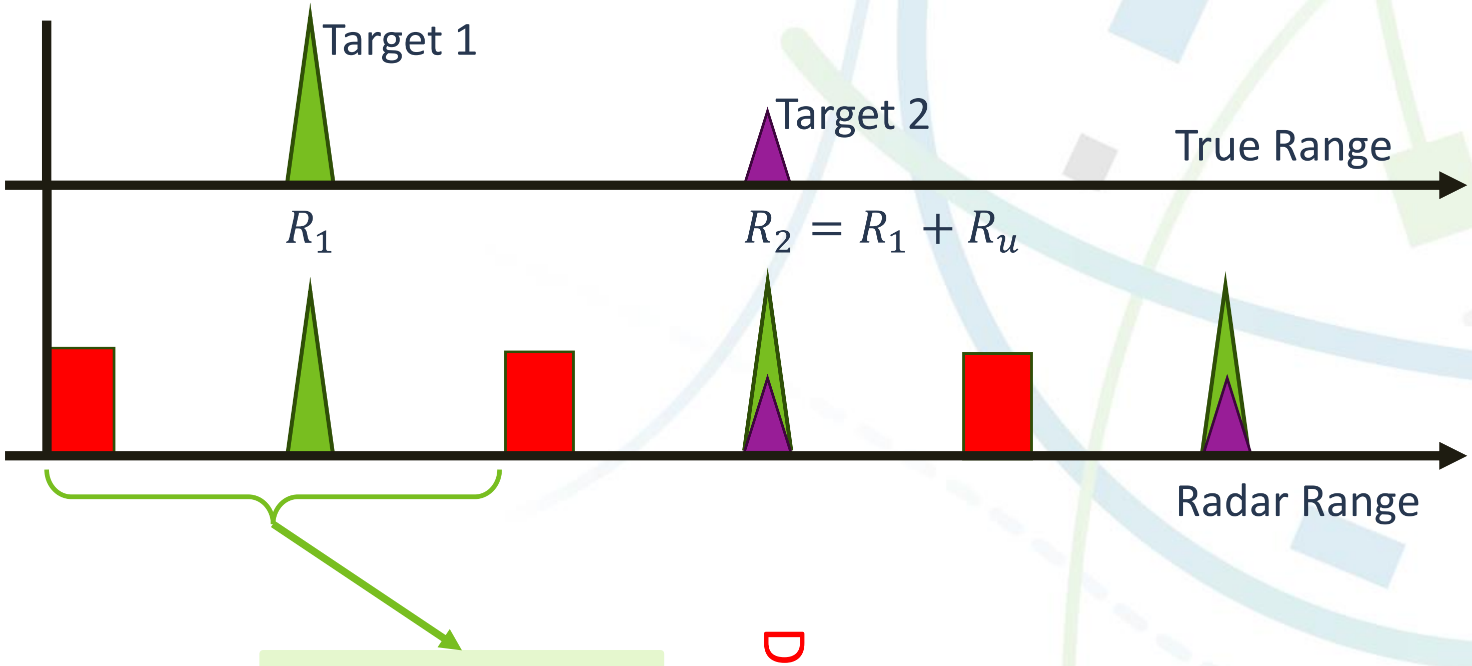
Pulsed Radar

Unambiguous Range

Range ambiguities occur when echoes from one pulse are not all received before the next pulse



$$R_{un} = \frac{cT_p}{2} = \frac{c}{2f_p}$$

Decrease f_p

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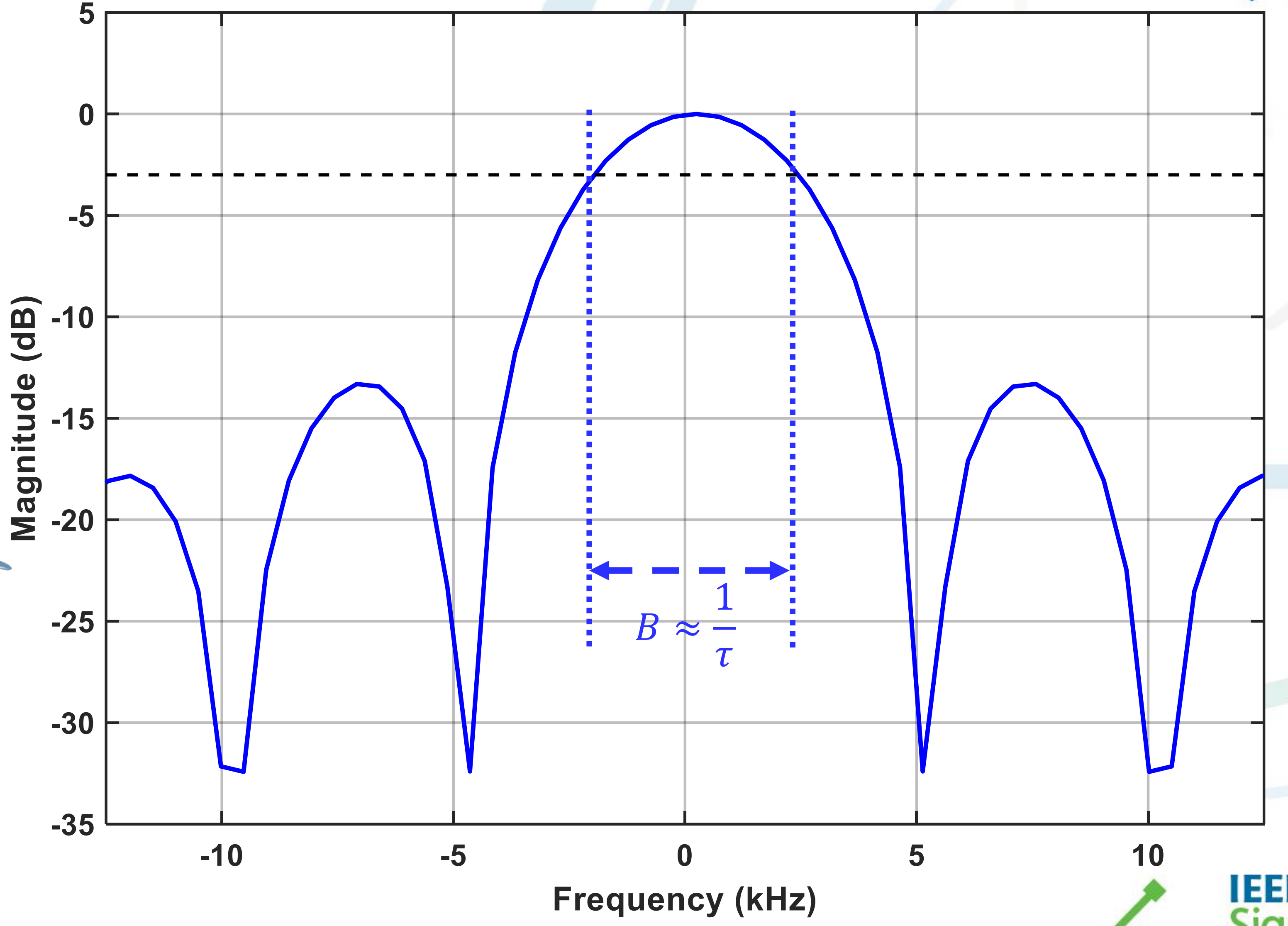
Pulsed Radar

Received pulse



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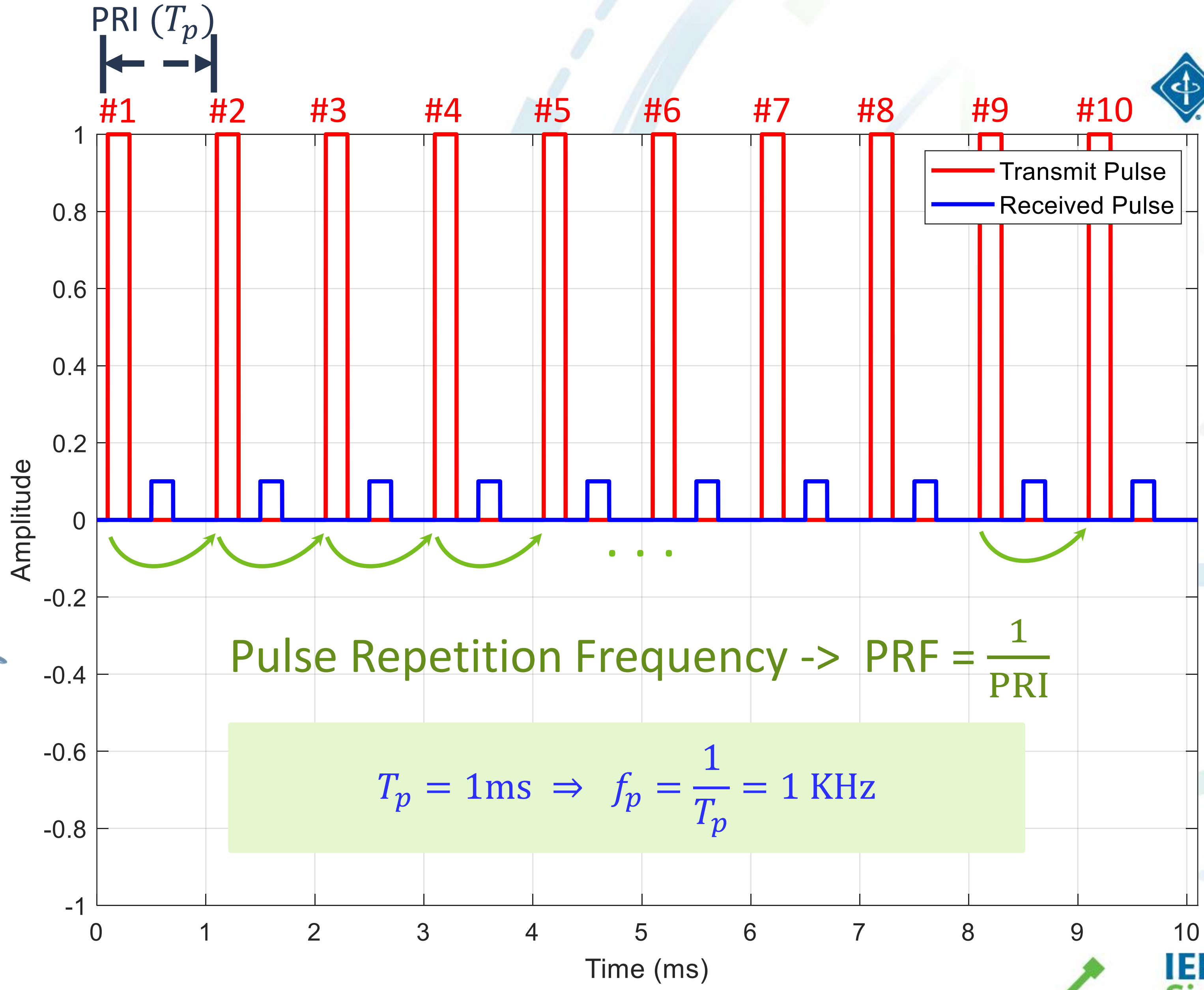
Pulsed Radar

Received pulses



Pulse Repetition Frequency -> $\text{PRF} = \dfrac{1}{\text{PRI}}$

$$T_p = 1\text{ms} \;\Rightarrow\; f_p = \frac{1}{T_p} = 1\text{ KHz}$$

Lect1_example2.m

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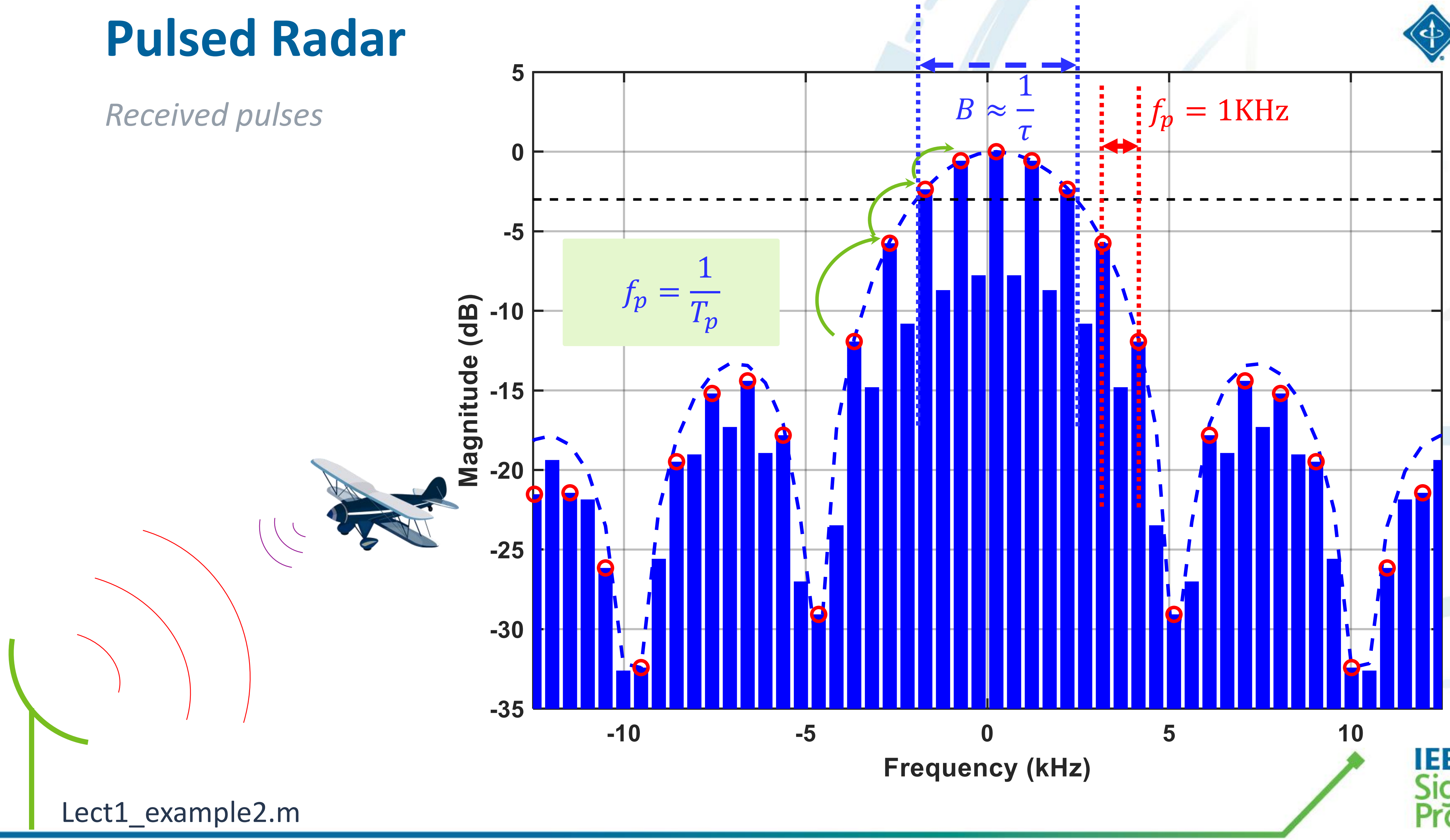
Pulsed Radar

Received pulses



Lect1_example2.m

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Doppler effect

Received pulses

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

Christian Andreas Doppler

(/ˈdɒplər/; 29 November 1803 – 17 March 1853)[1] was an Austrian mathematician and physicist. He formulated the principle – now known as the Doppler effect – that the observed frequency of a wave depends on the relative speed of the source and the observer.

https://en.wikipedia.org/wiki/Christian_Doppler

Christian Doppler

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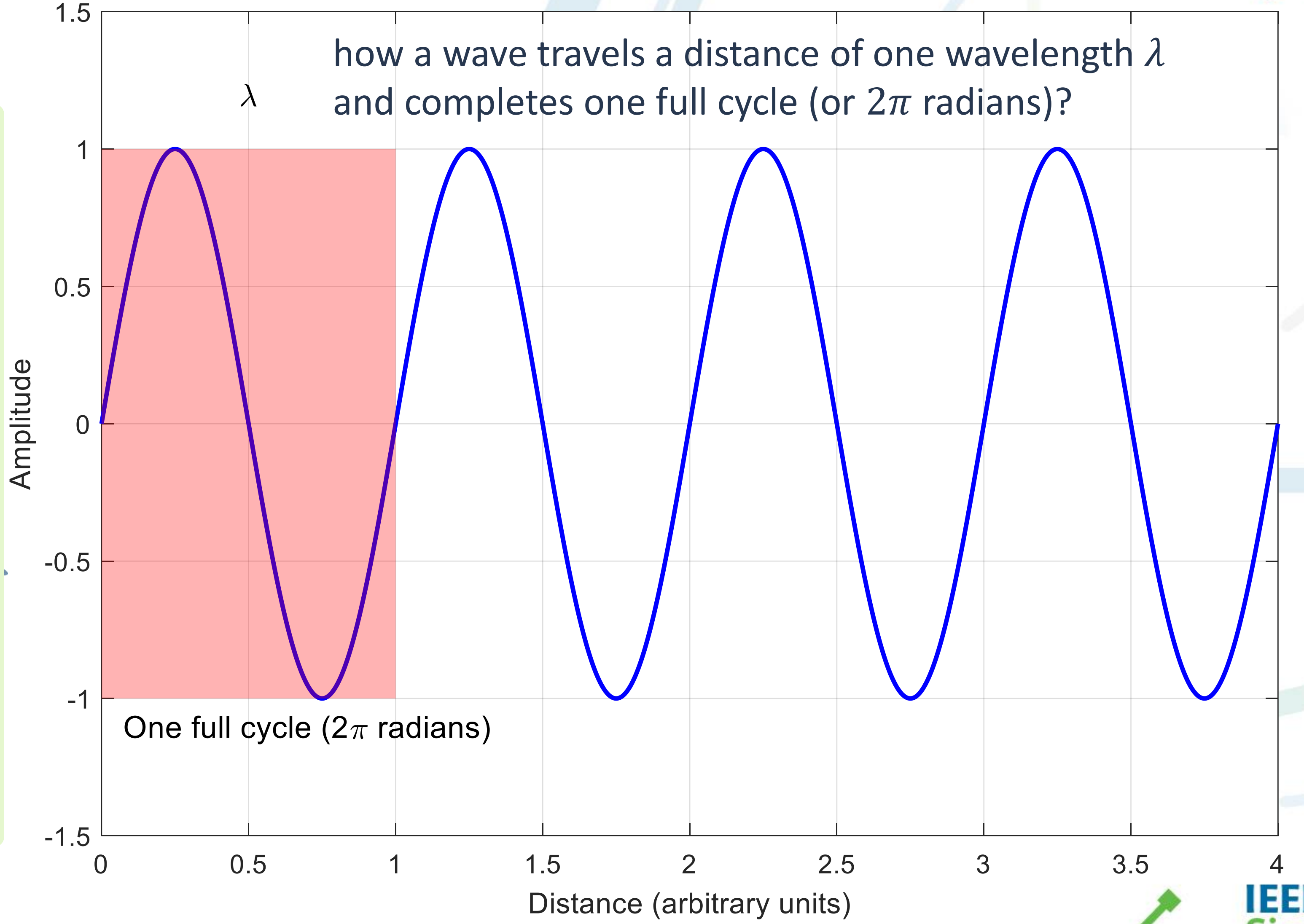
Doppler effect

phase difference between the transmitted signal and received signal

$$\phi = 2R \times \frac{2\pi}{\lambda}$$

$$\frac{d\phi}{dt} = 2\frac{dR}{dt}\frac{2\pi}{\lambda}$$

$$f_d = \frac{1}{2\pi}\frac{d\phi}{dt} = 2\frac{v_r}{\lambda}$$



Lect1_example3.m

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Pulsed Doppler Radar

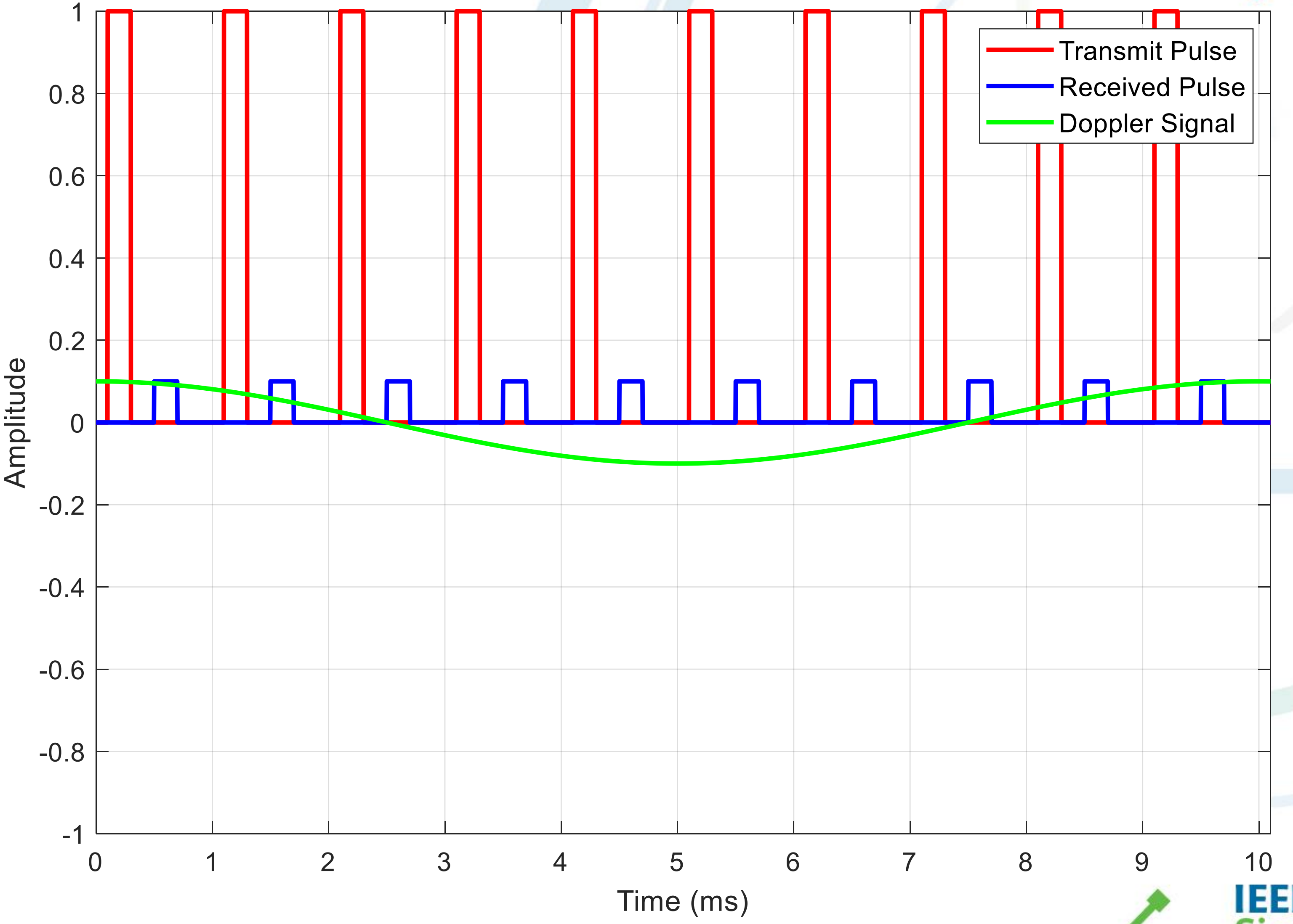
Received signal

$$f_c = 150\text{ MHz}$$

$$\lambda = \frac{c}{f_c} = 2\text{ m}$$

$$v_r = 100\text{ m/s}$$

$$f_d = 2\frac{v_r}{\lambda} = 100\text{ Hz}$$



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Pulsed Doppler Radar

Received signal

$$f_c = 150 \text{ MHz}$$

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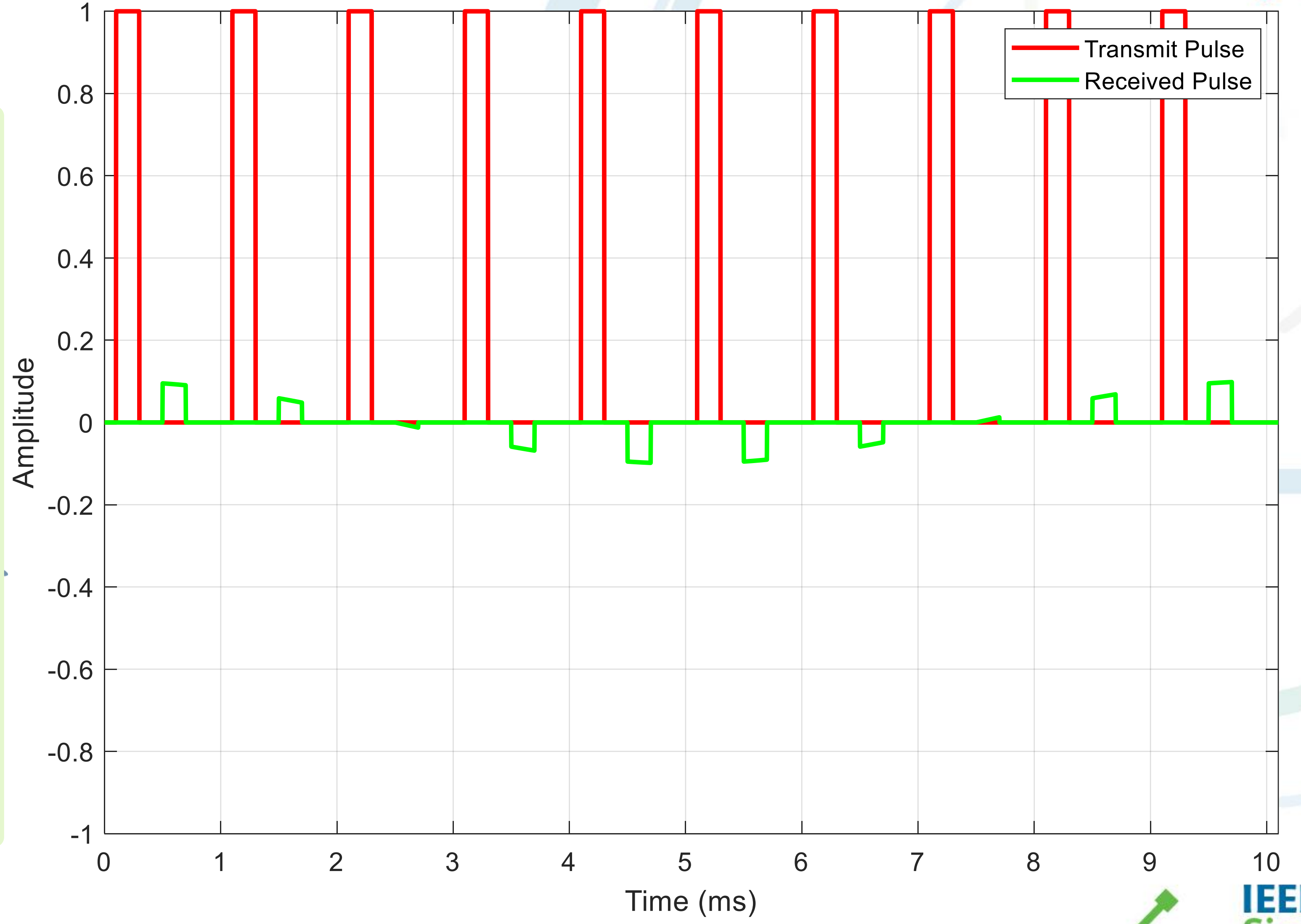

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Pulsed Doppler Radar

Received signal

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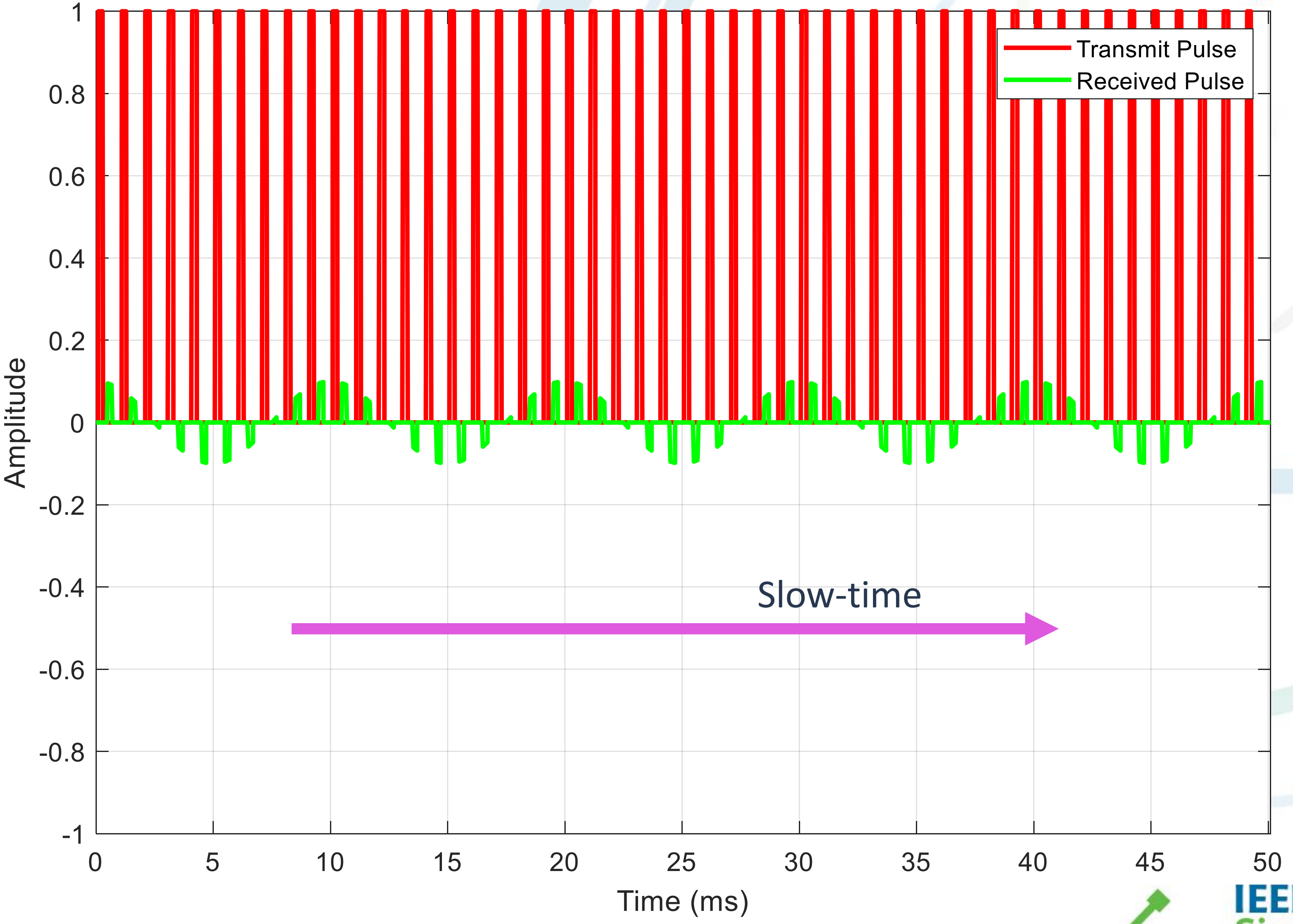

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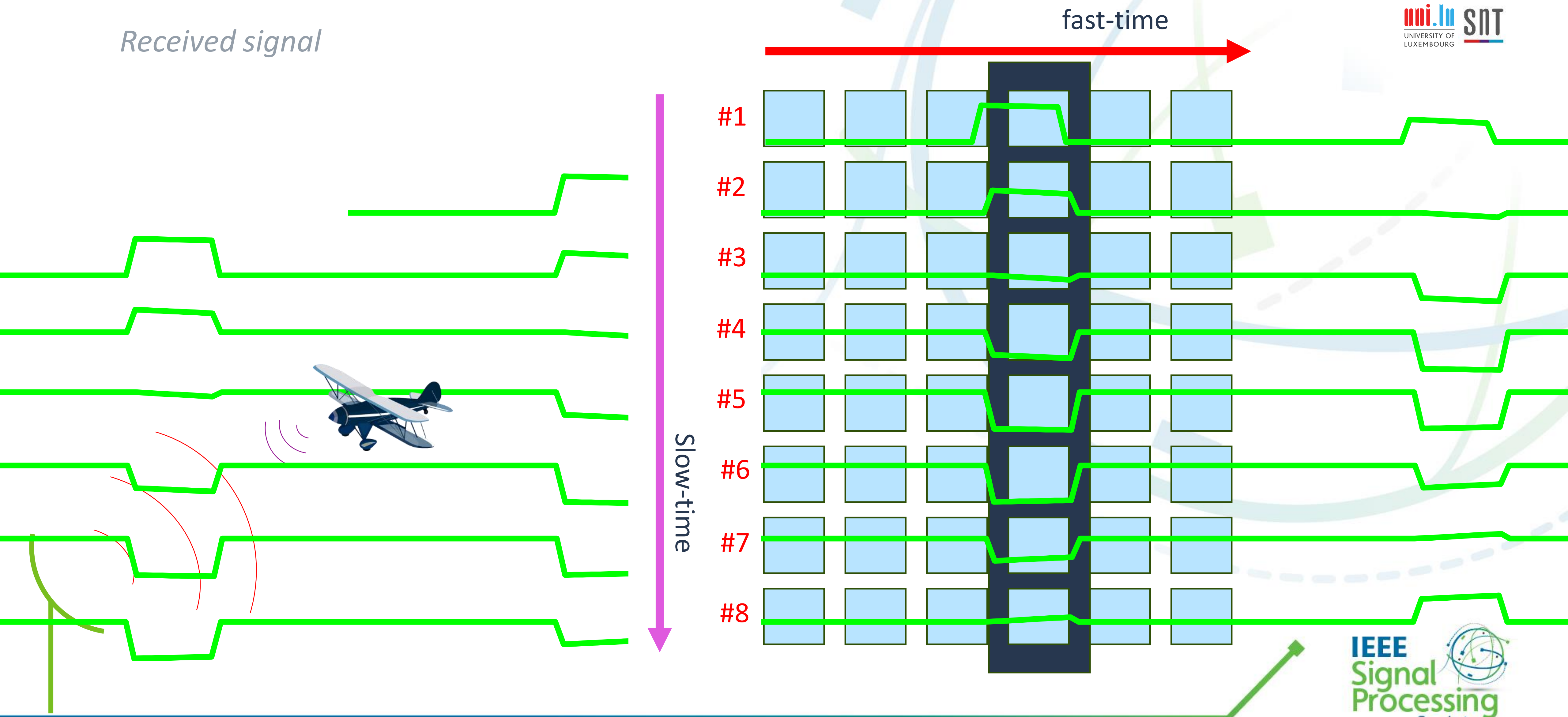
Pulsed Doppler Radar

Received signal



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Pulsed Doppler Radar

Received signal

$$f_c = 150\ \text{MHz}$$

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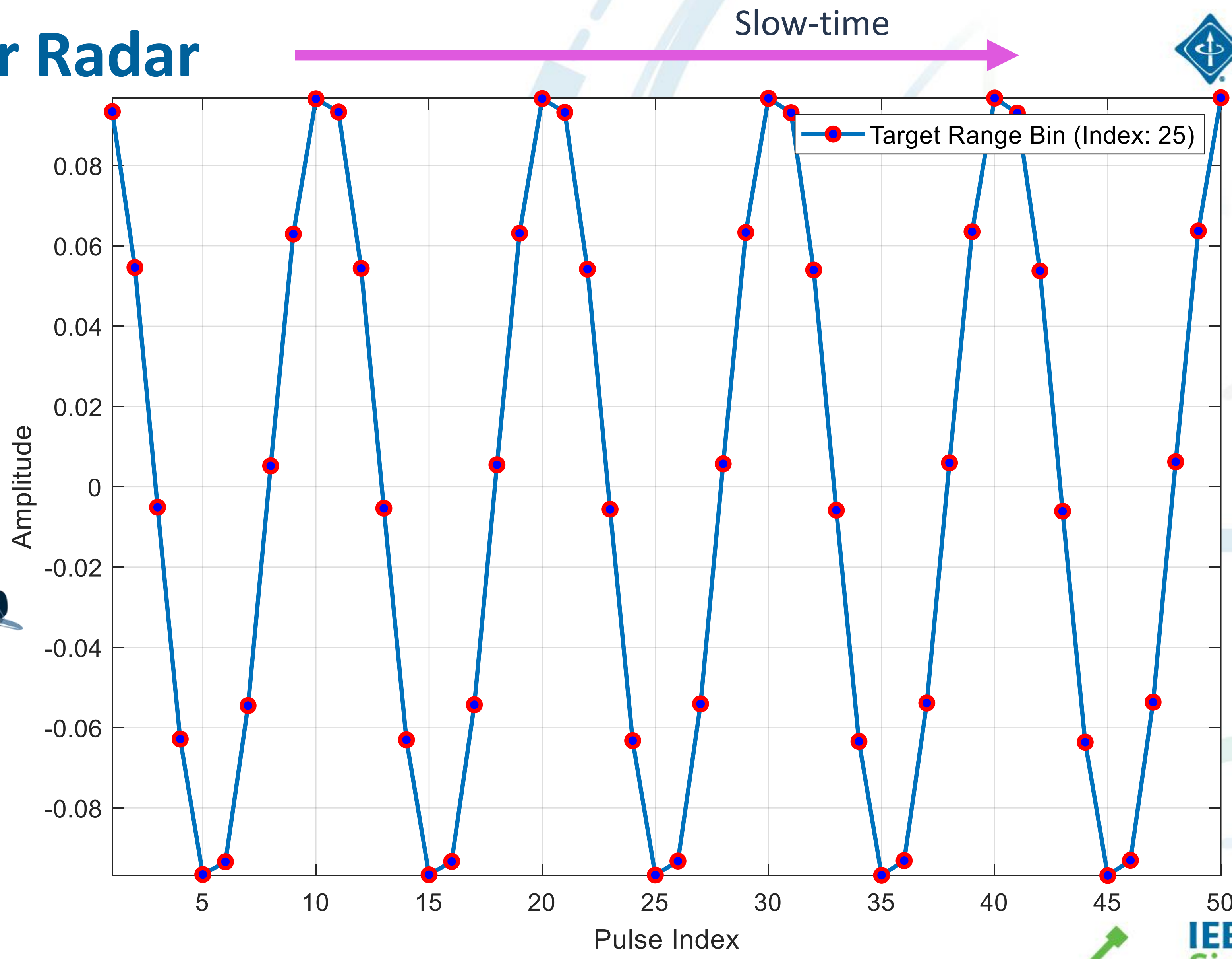

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Pulsed Doppler Radar

Received signal

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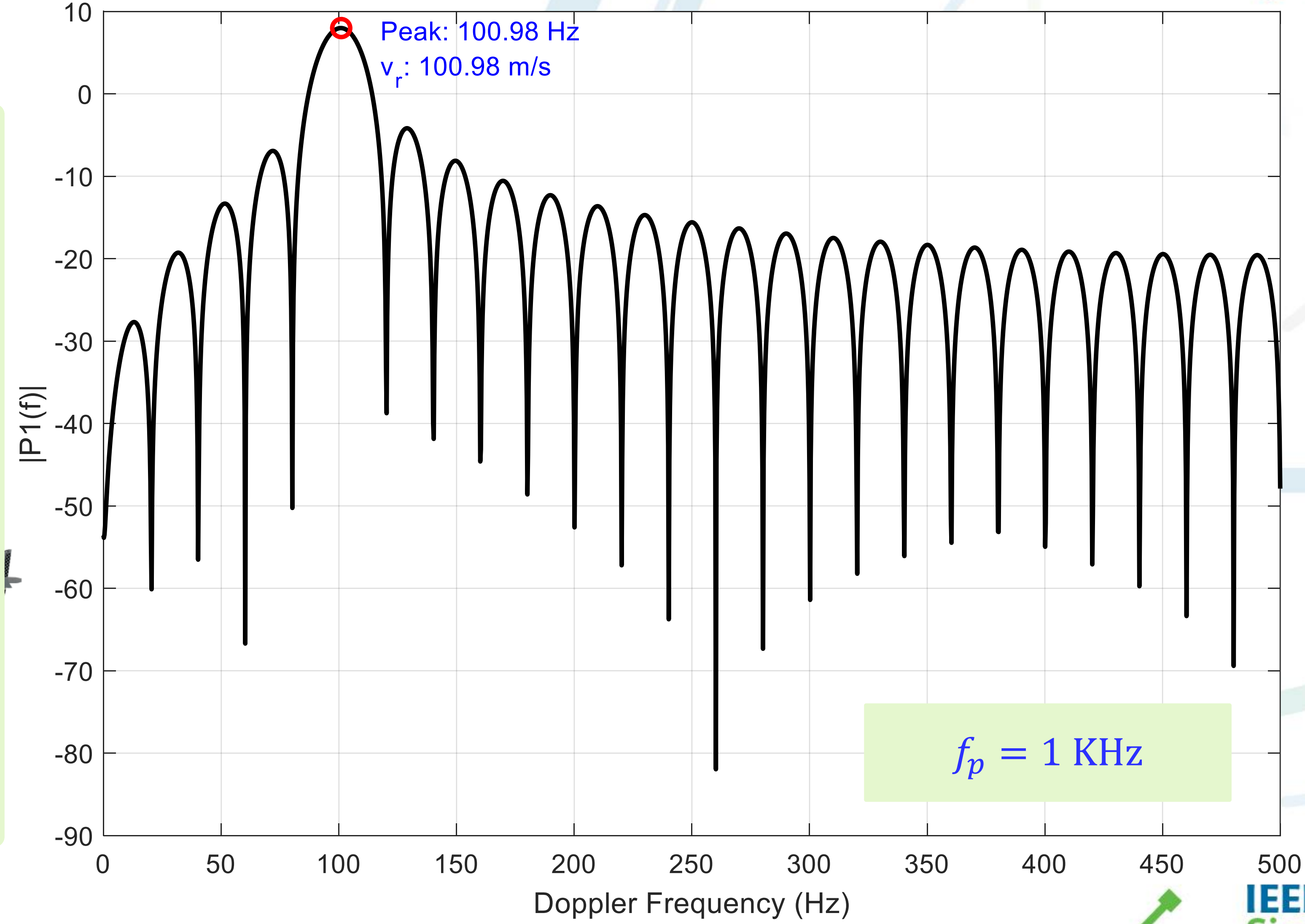

$$f_p = 1 \text{ KHz}$$

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Pulsed Doppler Radar

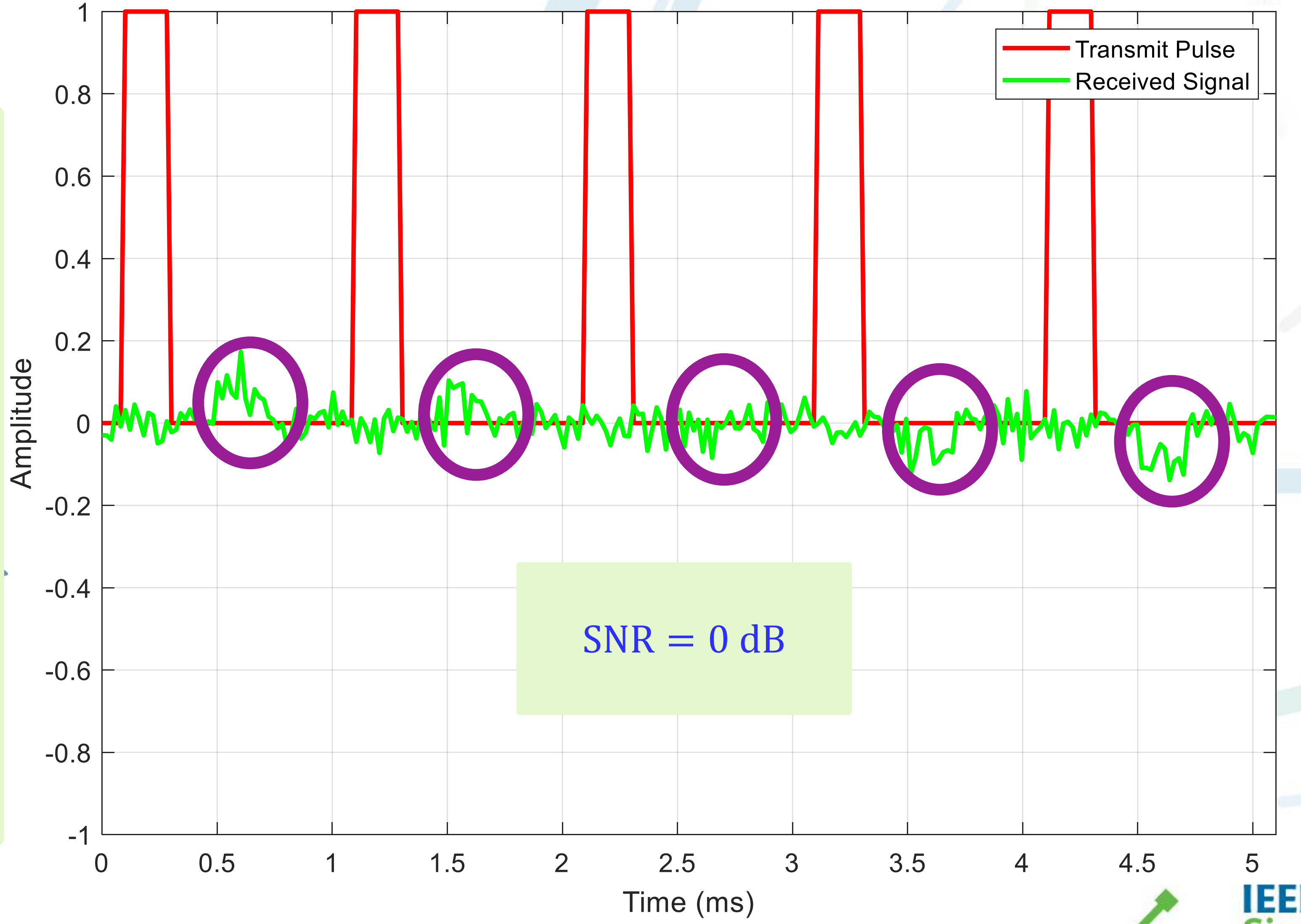
Received signal

$$f_c = 150 \text{ MHz}$$

$$\lambda = \frac{c}{f_c} = 2 \text{ m}$$

$$v_r = 100 \text{ m/s}$$

$$f_d = 2\frac{v_r}{\lambda} = 100 \text{ Hz}$$



$\text{SNR} = 0 \text{ dB}$

Lect1_example4.m

Pulsed Doppler Radar

Received signal

$$f_c = 150 \text{ MHz}$$

$$\lambda = \frac{c}{f_c} = 2 \text{ m}$$

$$v_r = 100 \text{ m/s}$$

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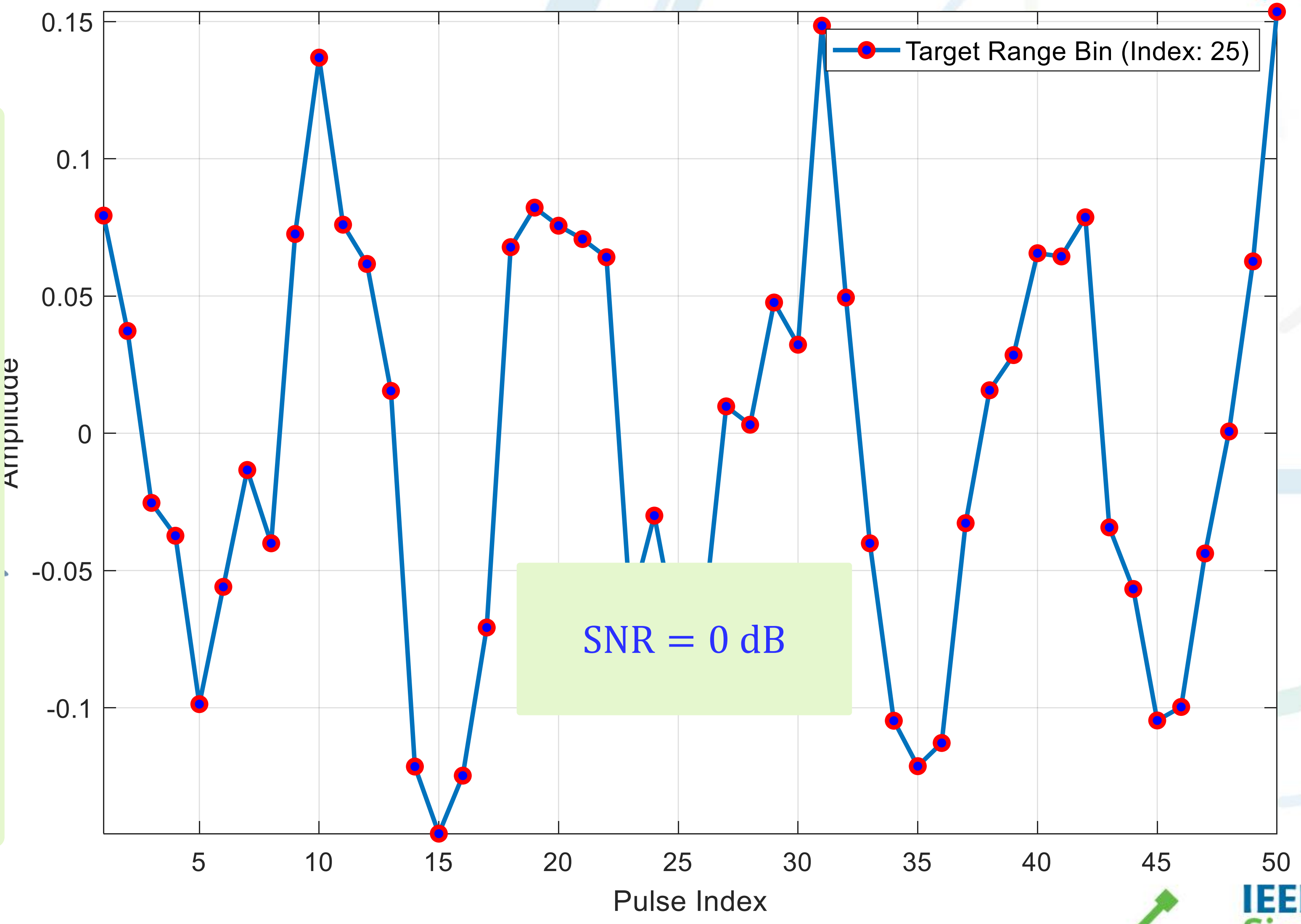

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Pulsed Doppler Radar

Received signal

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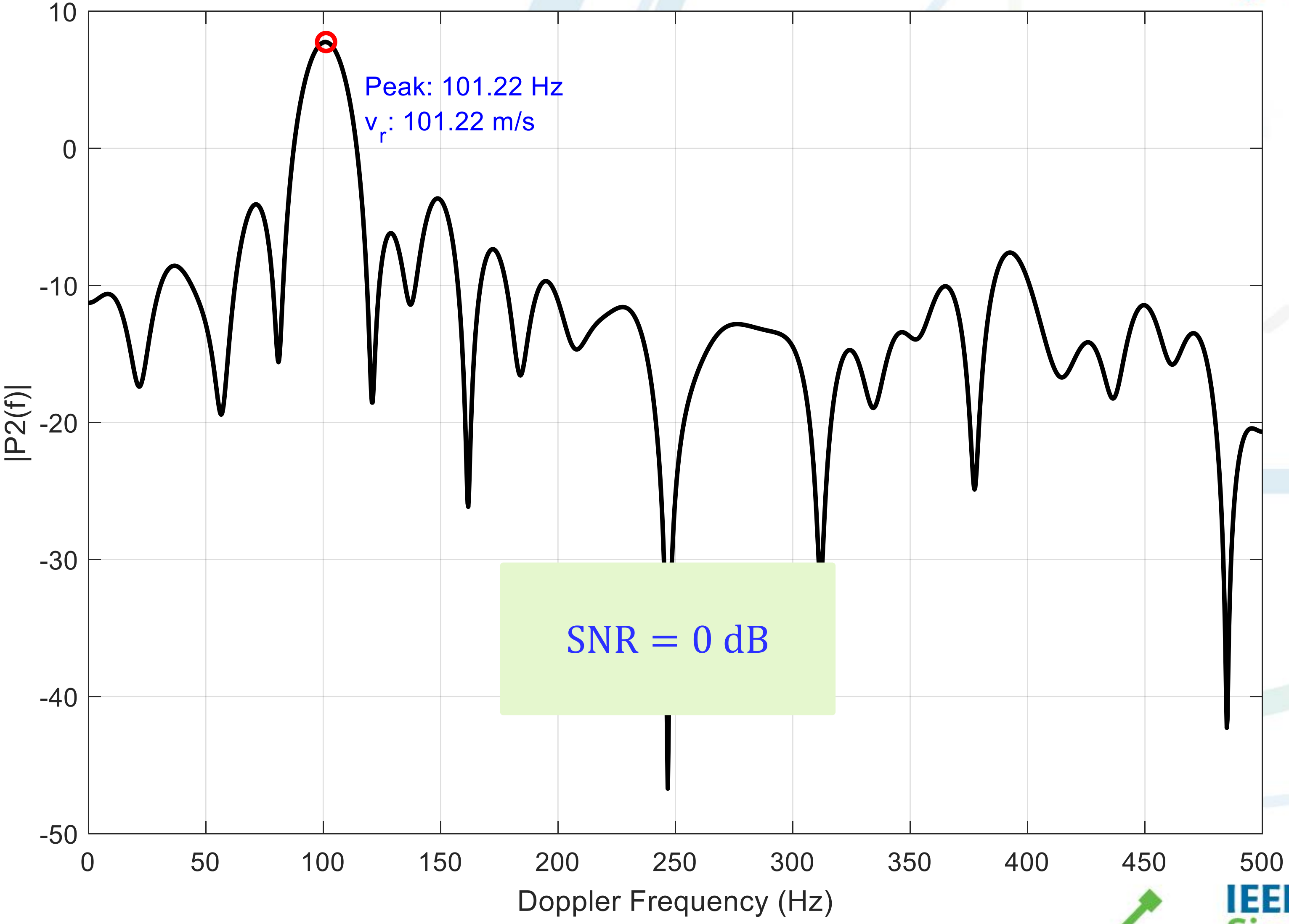

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Pulsed Doppler Radar

Doppler Sampling frequency

$$Doppler\ Sampling\ frequency = PRF$$

$$f_p = \frac{1}{T_p}$$

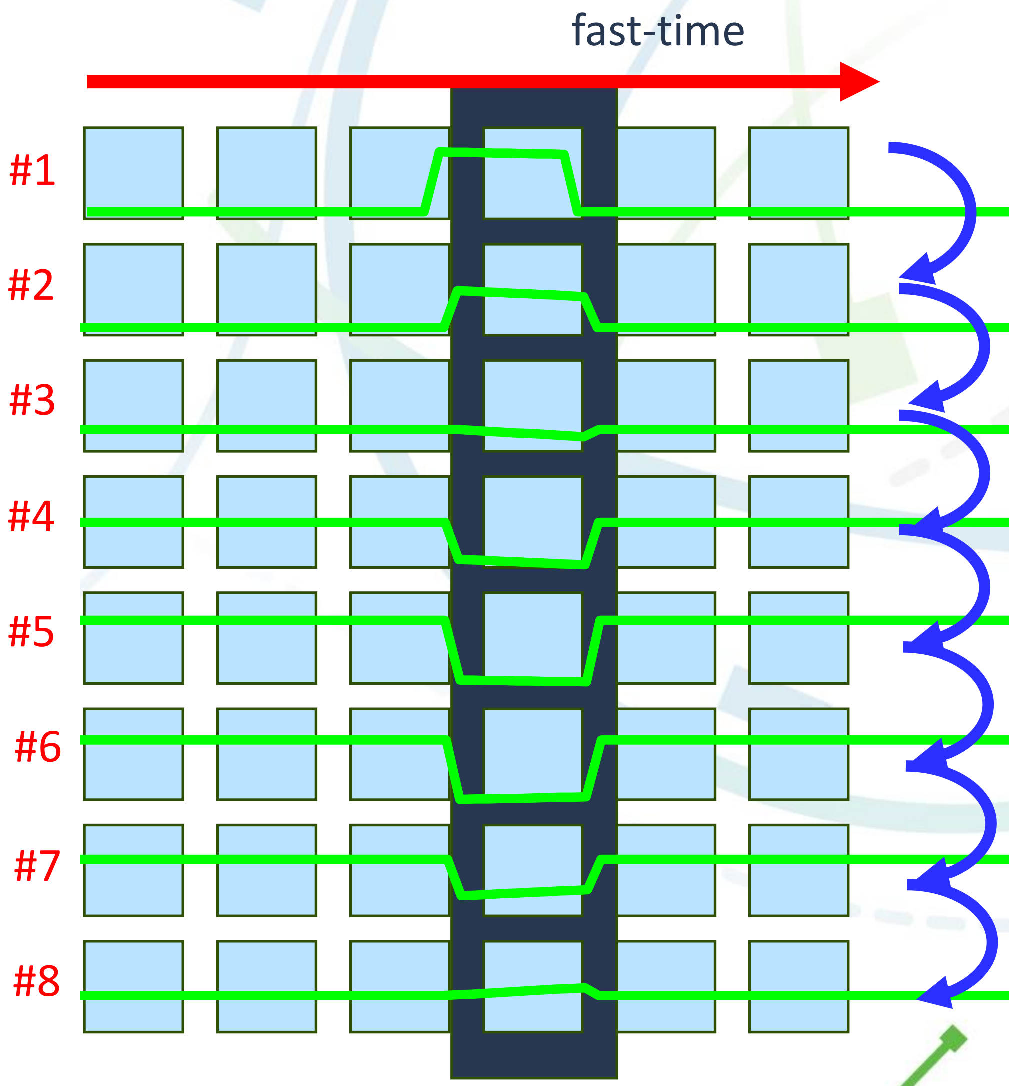
$$f_{d_{max}} \leq \frac{f_p}{2}$$

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

$$v_{r_{max}} = \lambda\frac{f_{d_{max}}}{2} \leq \frac{\lambda f_p}{4}$$

Increase f_p

Slow-time



$$PRI = T_p$$

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Pulsed Doppler Radar

Unambiguous Range and Doppler

Depends to both λ and f_p

Decrease f_p

Unambiguous Range

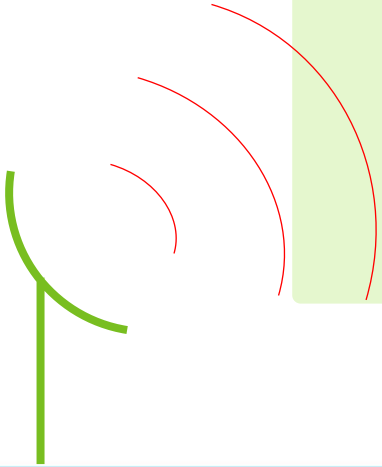
$$R_{un} \leq \frac{cT_p}{2} = \frac{c}{2f_p}$$

Unambiguous Doppler

$$v_{r_{max}} = \lambda \frac{f_{d_{max}}}{2} \leq \frac{\lambda f_p}{4}$$

Increase f_p

is independent to λ



$\lambda = 2\ \mathrm{m}$

$f_p = 1\ \mathrm{KHz}$

$R_{un} \leq 150\ \mathrm{Km}$

$v_{r_{max}} \leq 500\ \mathrm{m/s}$

f_p is a design parameter depending to the application should be carefully chosen

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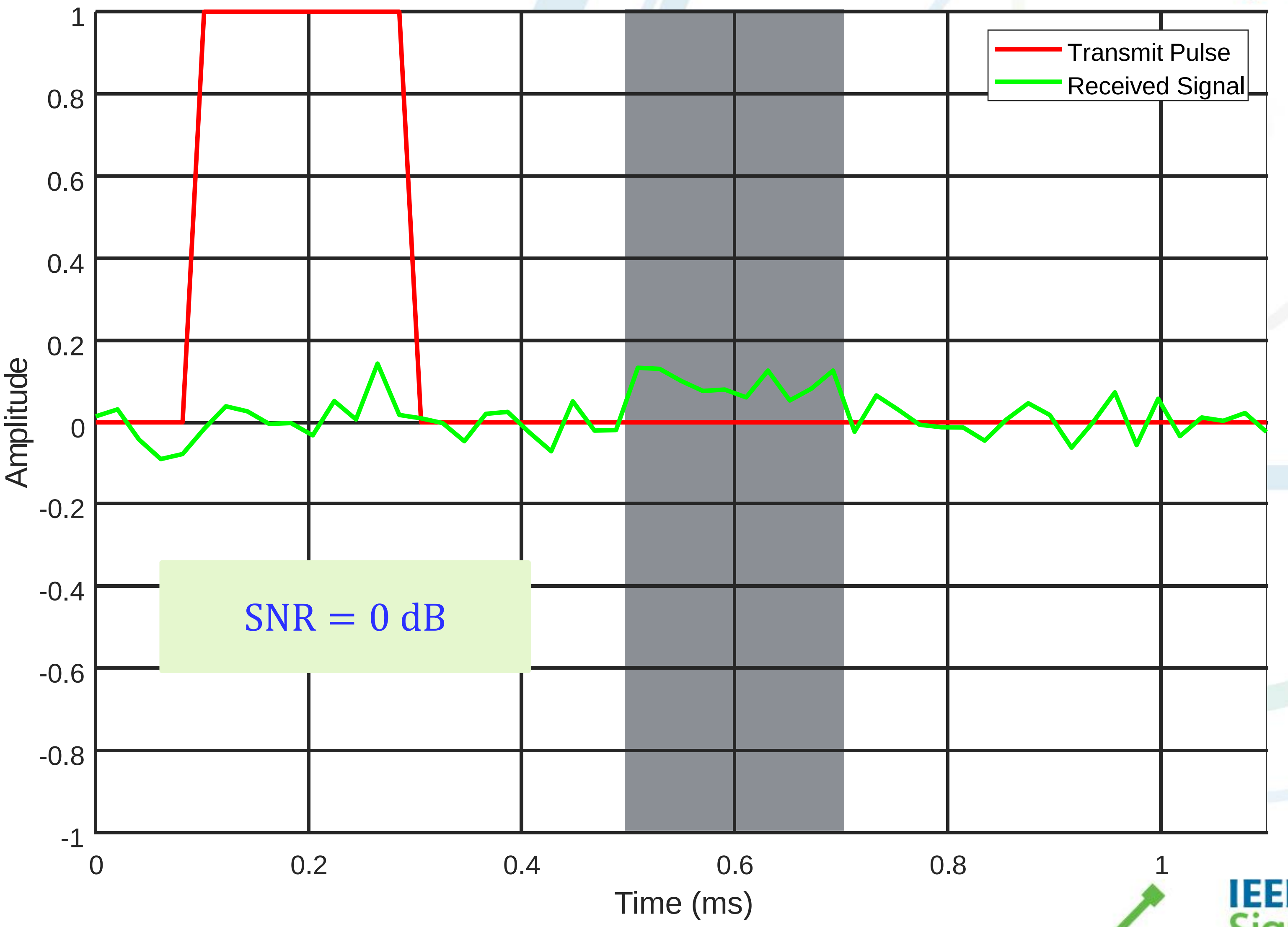
Pulsed Doppler Radar

Range Resolution

$$\tau = 200\ \mu s$$

$$T_p = 1\ ms$$



$$\text{SNR} = 0\ \text{dB}$$

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Pulsed Doppler Radar

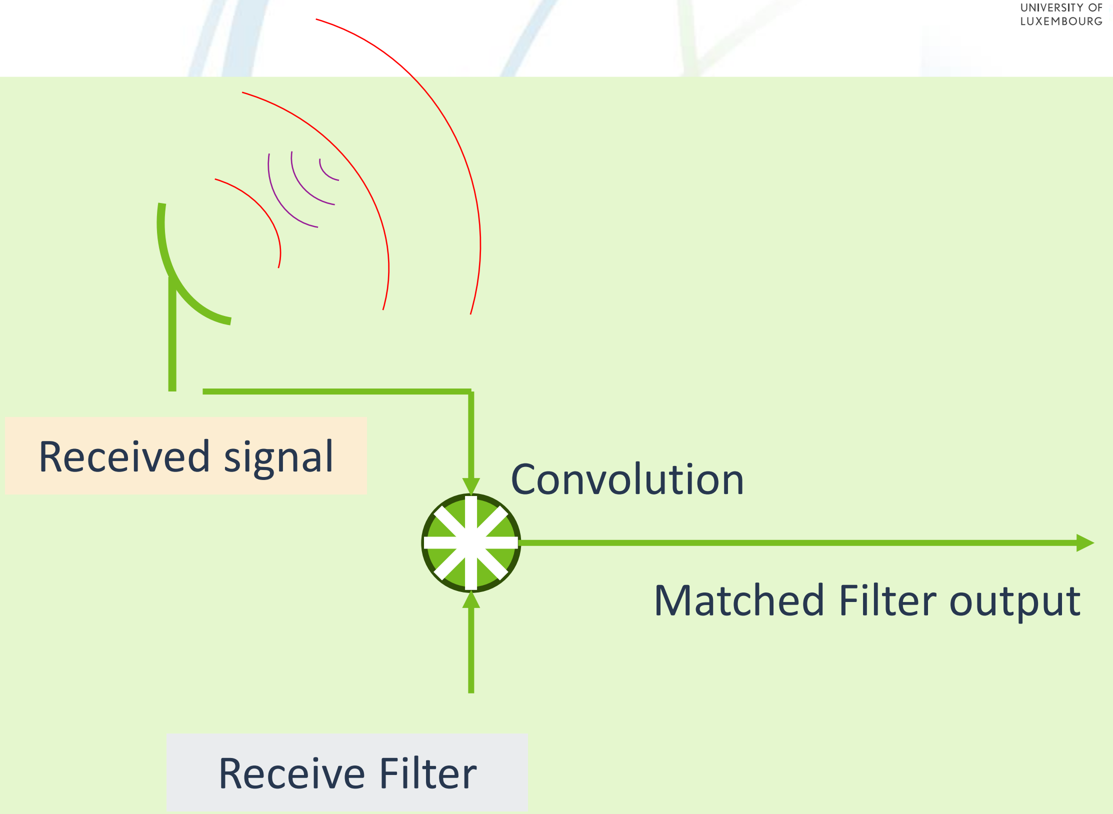
Matched Filter

$$s_{tx}[n] = A_t \mathrm{rect}\left[n - (i-1)T_p\right]$$

$$s_{rx}[n] = A_r \ \mathrm{rect}\left[n - (i-1)T_p - \Delta n\right] + w(n)$$

$$h[n] = s_{tx}^*[N-1-n]$$

- $h[n]$ is the impulse response of the matched filter
- $s_{tx}^*[n]$ is the complex conjugate of the transmitted signal $s_{tx}[n]$
- N is the total number of samples of the transmitted signal



$$y[n] = \sum_{k=0}^{N-1} s_{rx}[k]\, h[n-k] = \sum_{k=0}^{N-1} s_{rx}[k]\, s_{tx}^*[N-1-(n-k)]$$

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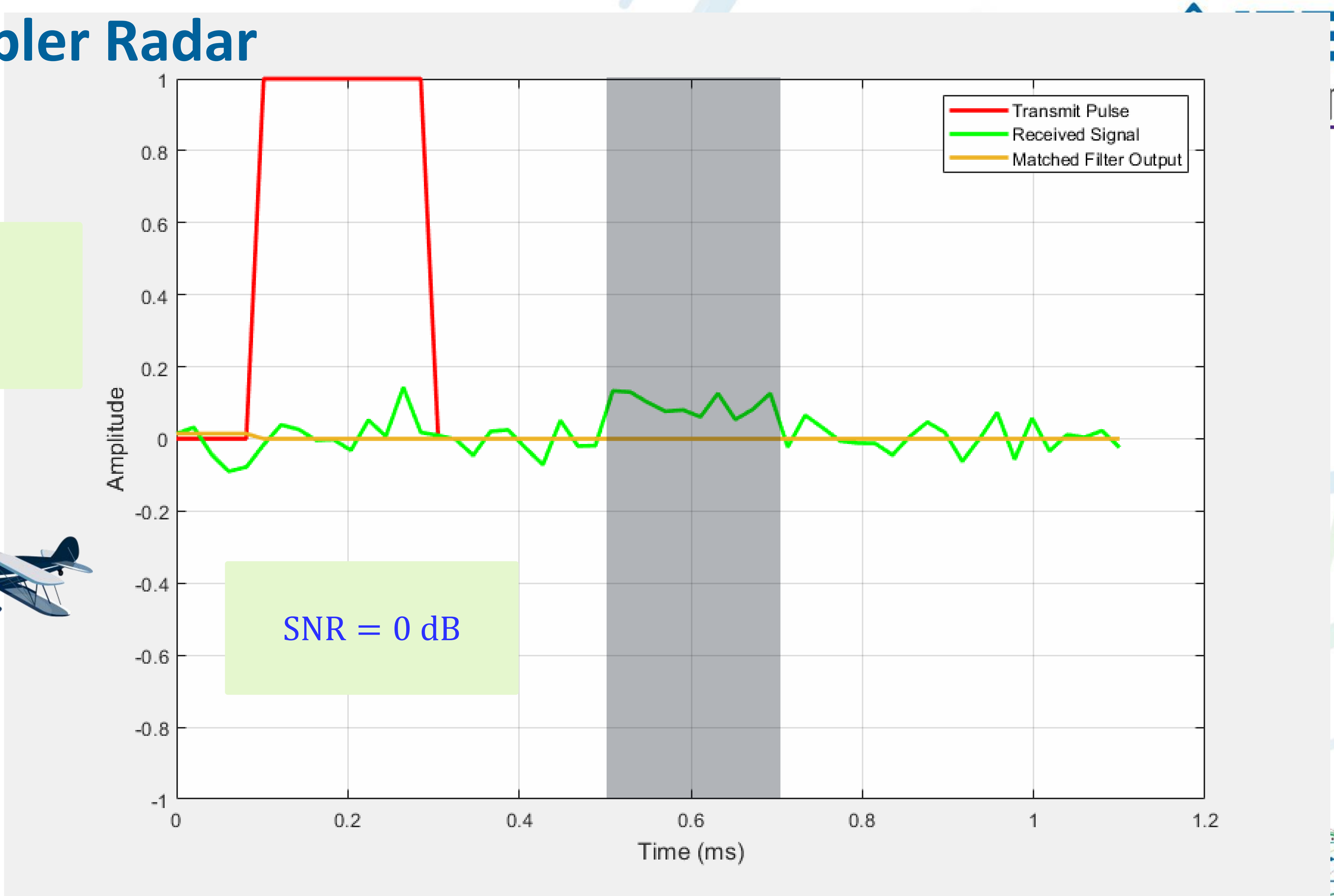
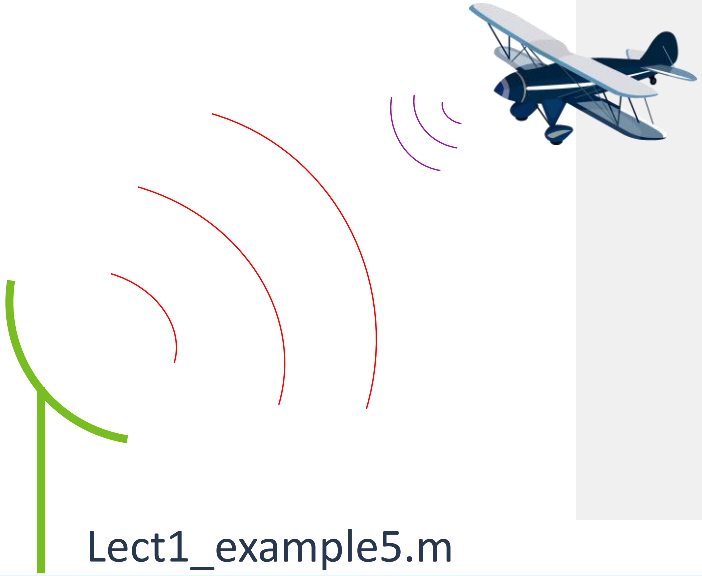
Pulsed Doppler Radar

Matched Filter

How close the second target could be?





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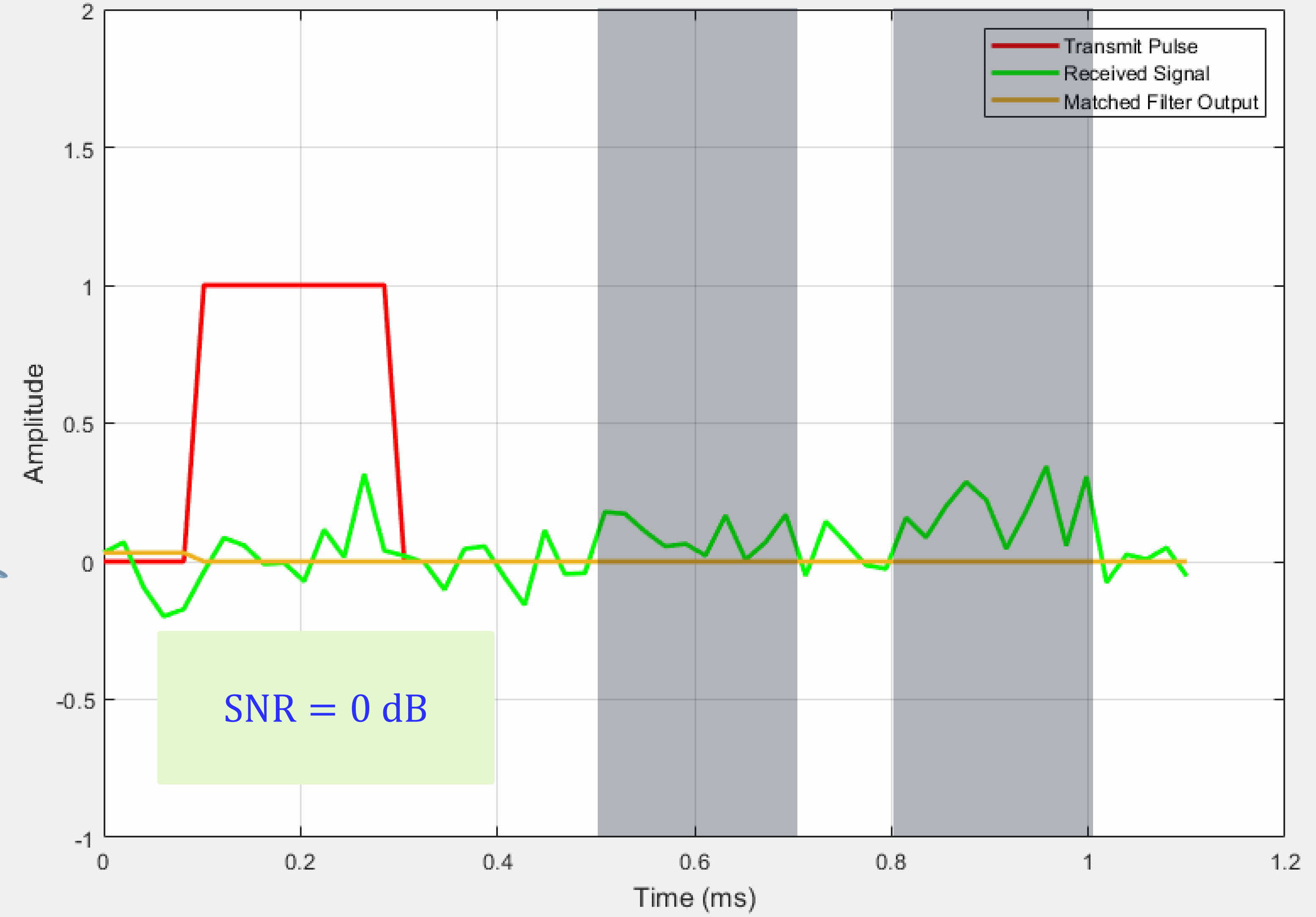
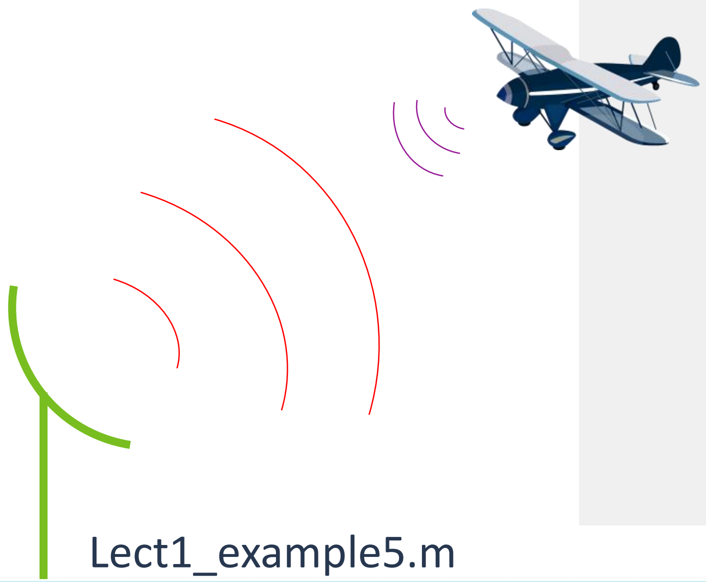
Pulsed Doppler Radar

Matched Filter

How close the second target could be?





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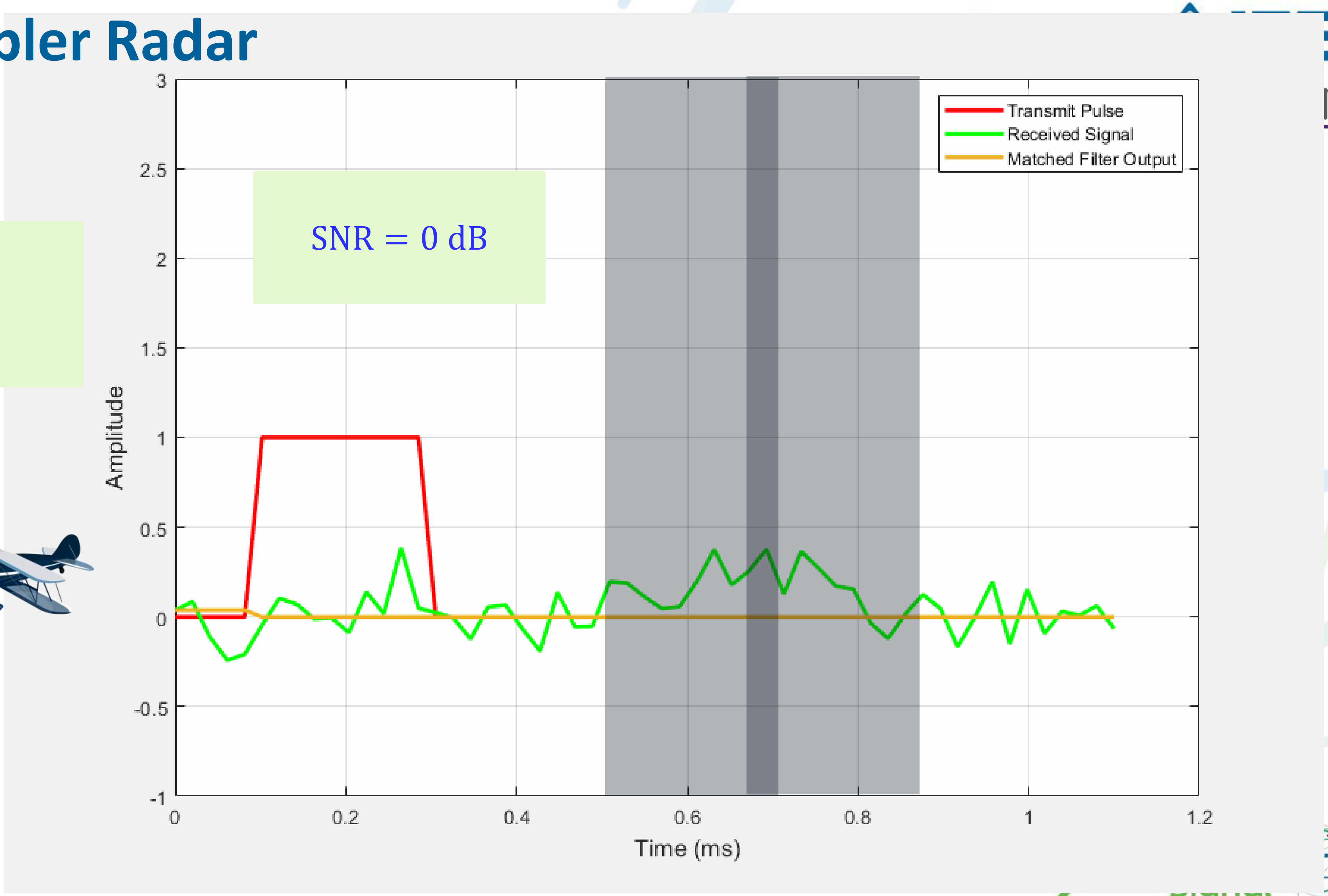
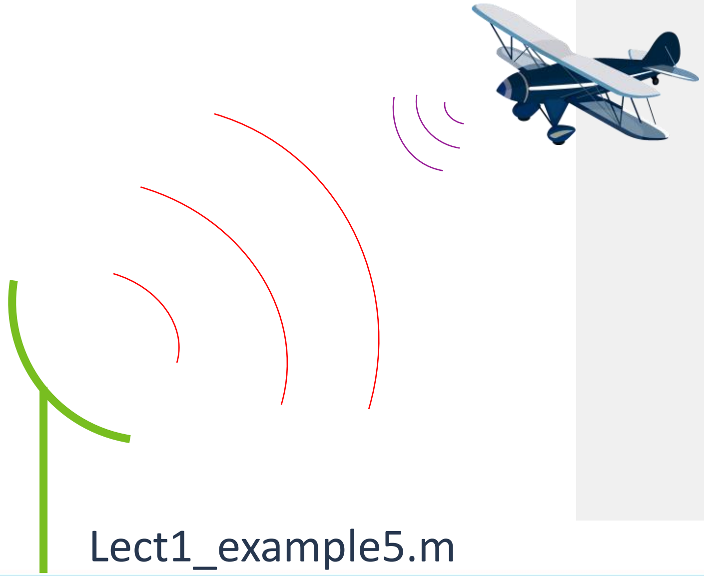
Pulsed Doppler Radar

Matched Filter

How close the second target could be?





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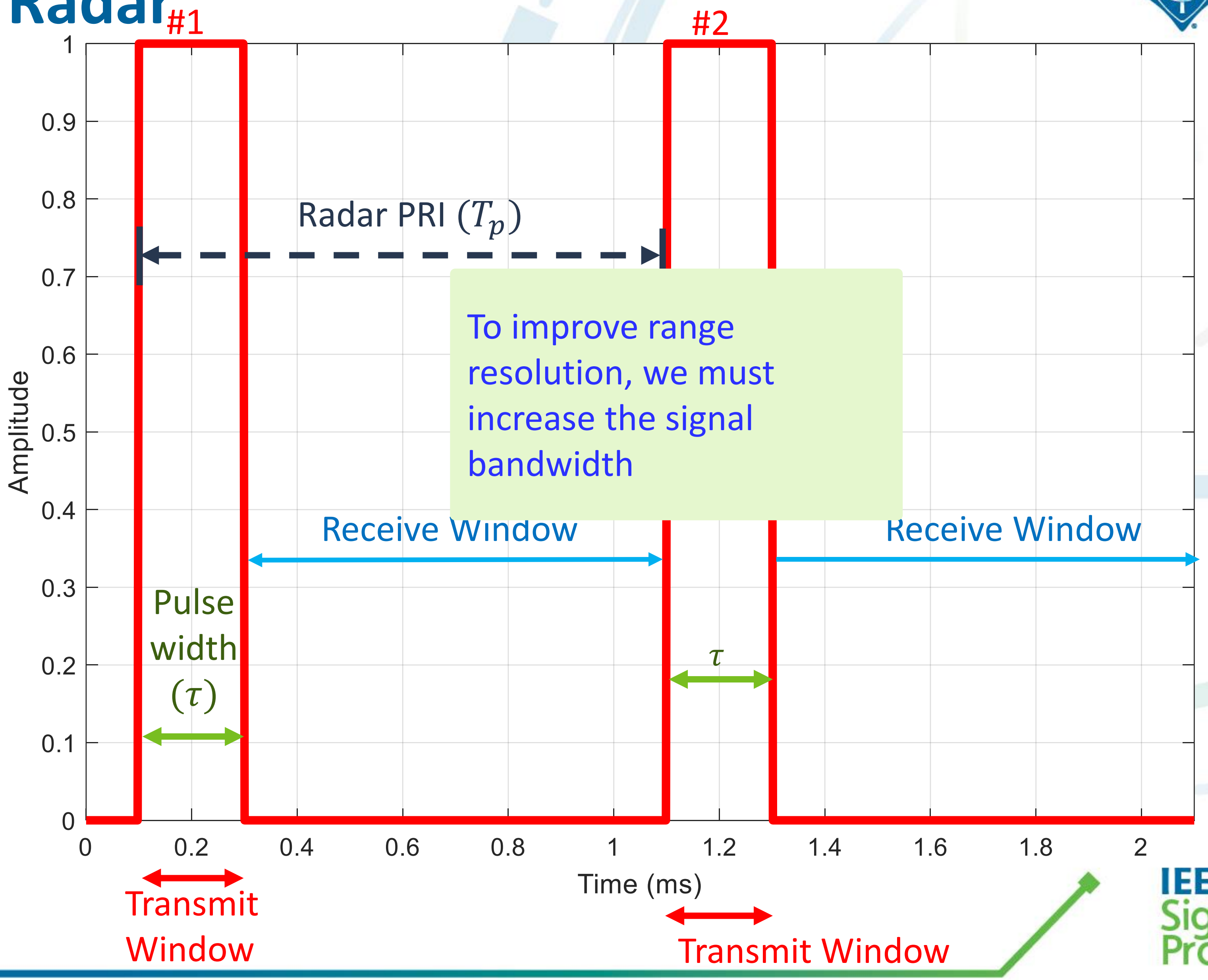
Pulsed Doppler Radar

Matched Filter

Range resolution $\Delta R = \frac{c\tau}{2}$

$$B \approx \frac{1}{\tau}$$

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

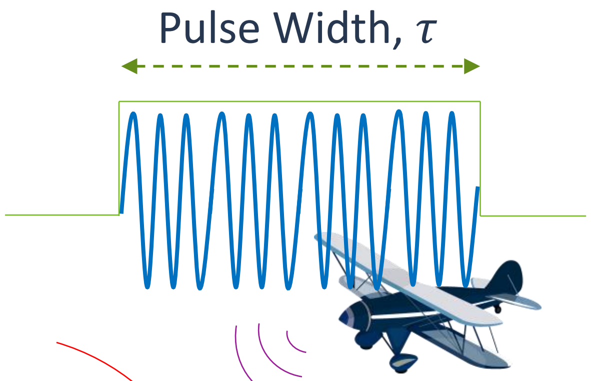


Lect1_example5.m

Pulse Compression Radar

intra-pulse modulation

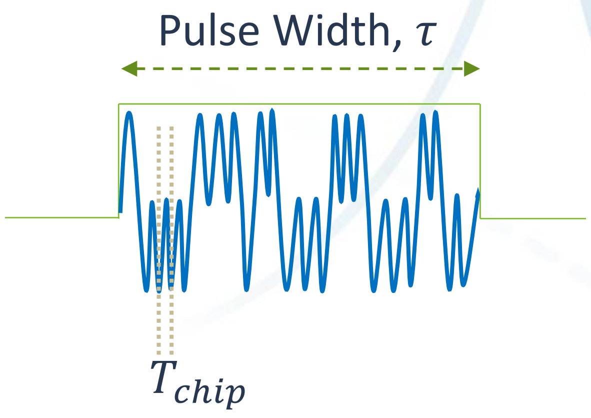
Square Pulse



Bandwidth $\approx \frac{1}{\tau}$

Time × Bandwidth = 1

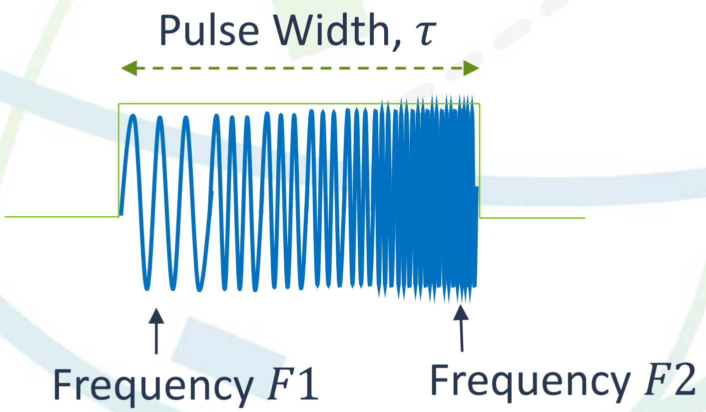
Phase Coded Waveform



Bandwidth $\approx \frac{1}{T_{chip}}$

Time × Bandwidth = $\frac{T}{T_{chip}}$

Linear Frequency Modulated (LFM) Waveform



Bandwidth = $\Delta F = F2 - F1$

Time × Bandwidth = $\tau \times \Delta F$

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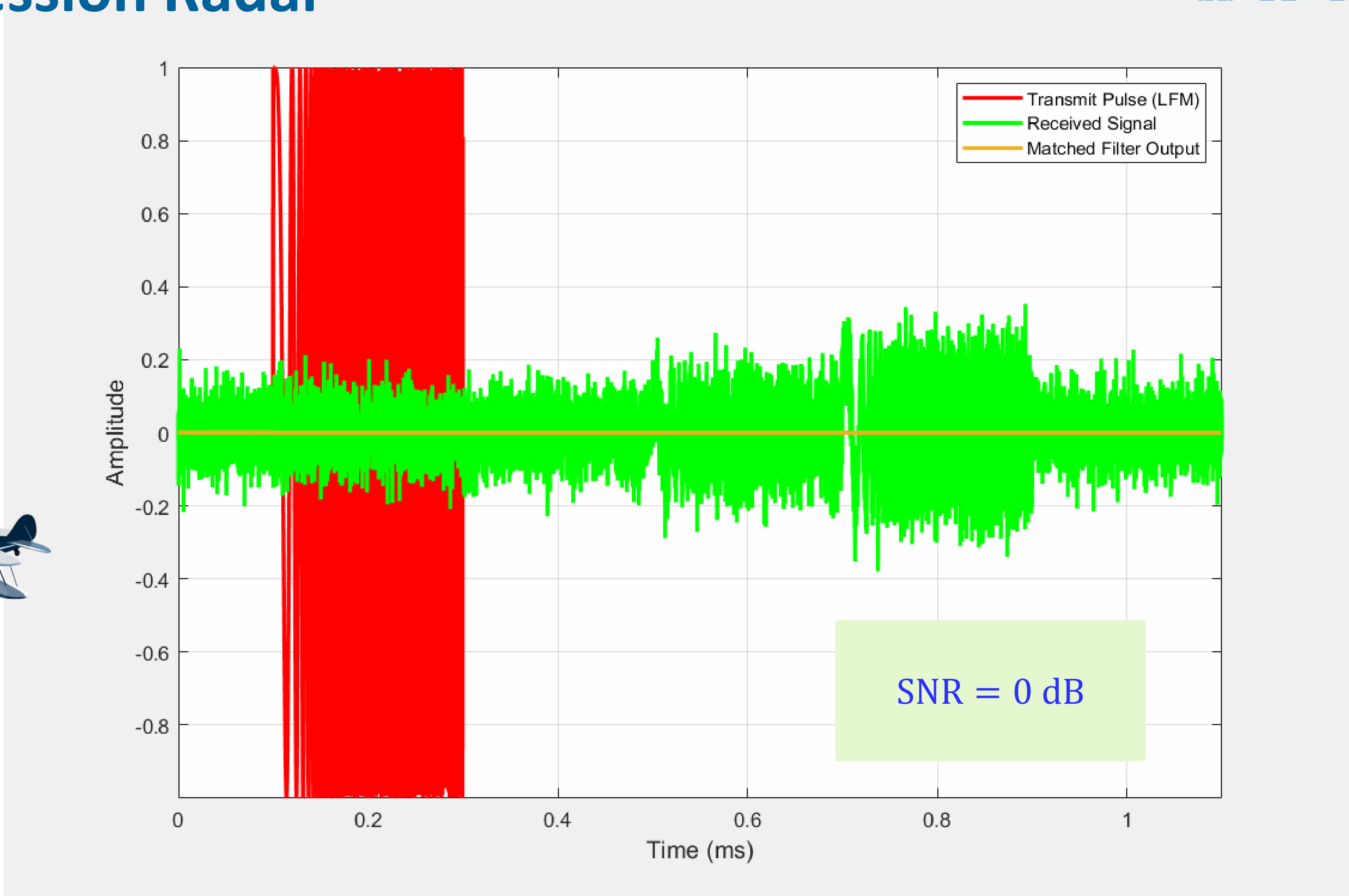
Pulse Compression Radar

LFM Waveform

$$B = 1 \text{ MHz}$$

$$\Delta R = \frac{c}{2B} = 150 \text{ m}$$



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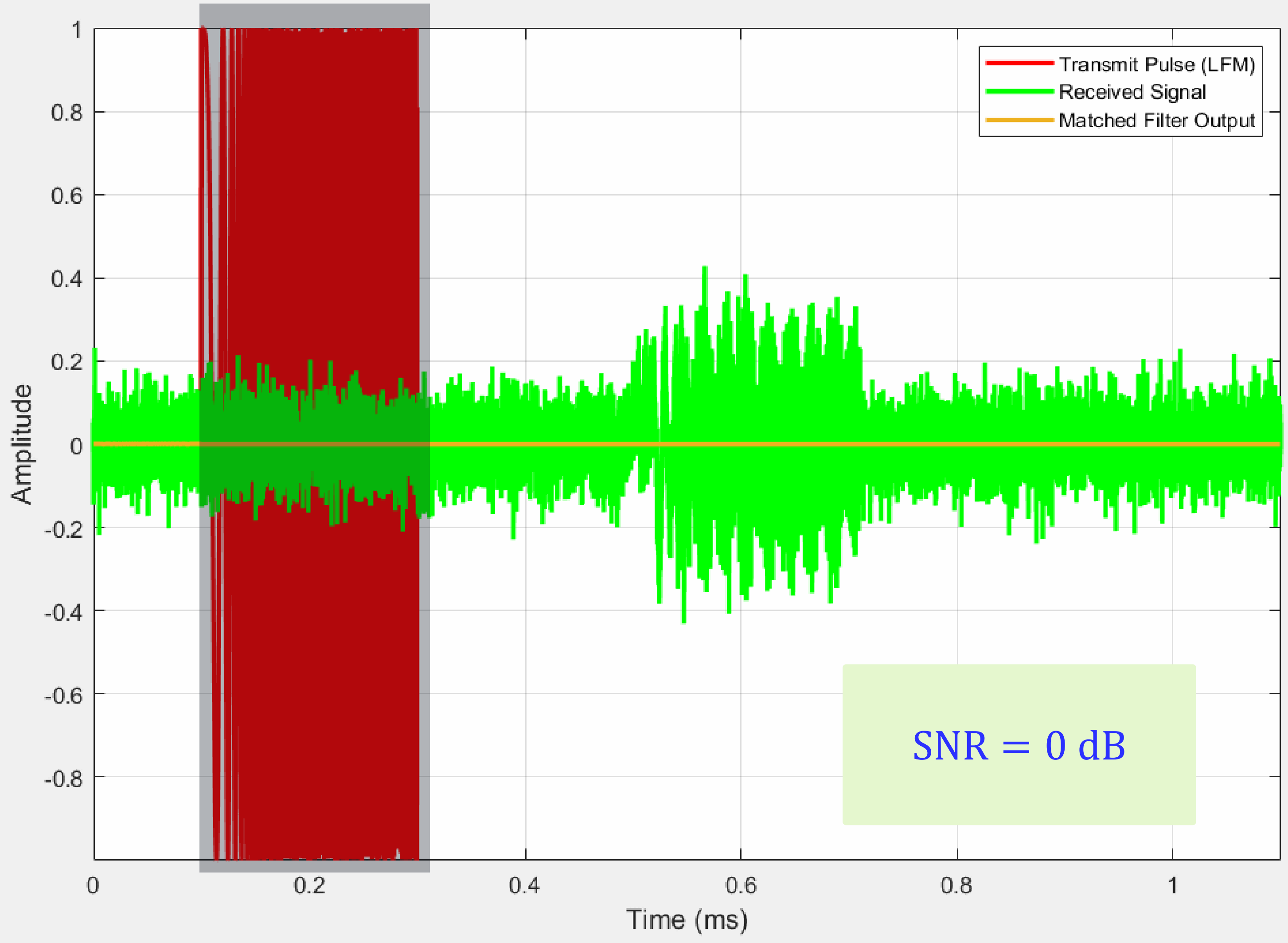
Pulse Compression Radar

LFM Waveform

$$B = 1 \text{ MHz}$$

$$\Delta R = \frac{c}{2B} = 150 \text{ m}$$



$\text{SNR} = 0 \text{ dB}$

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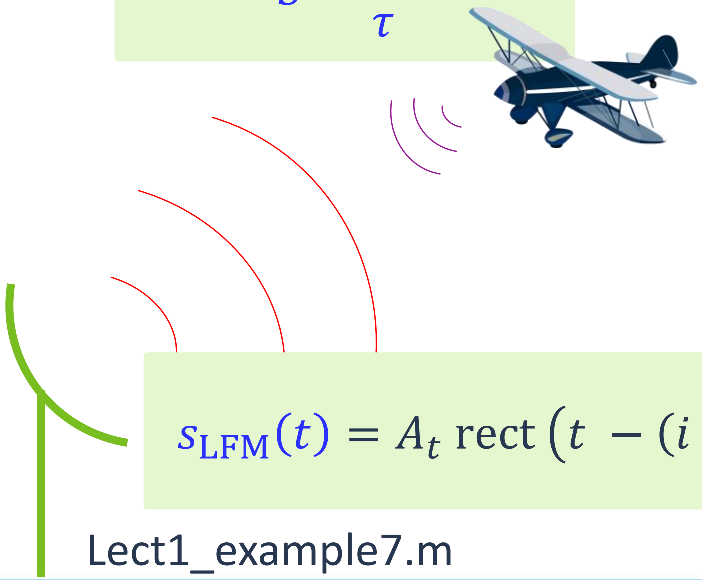
LFM Waveform

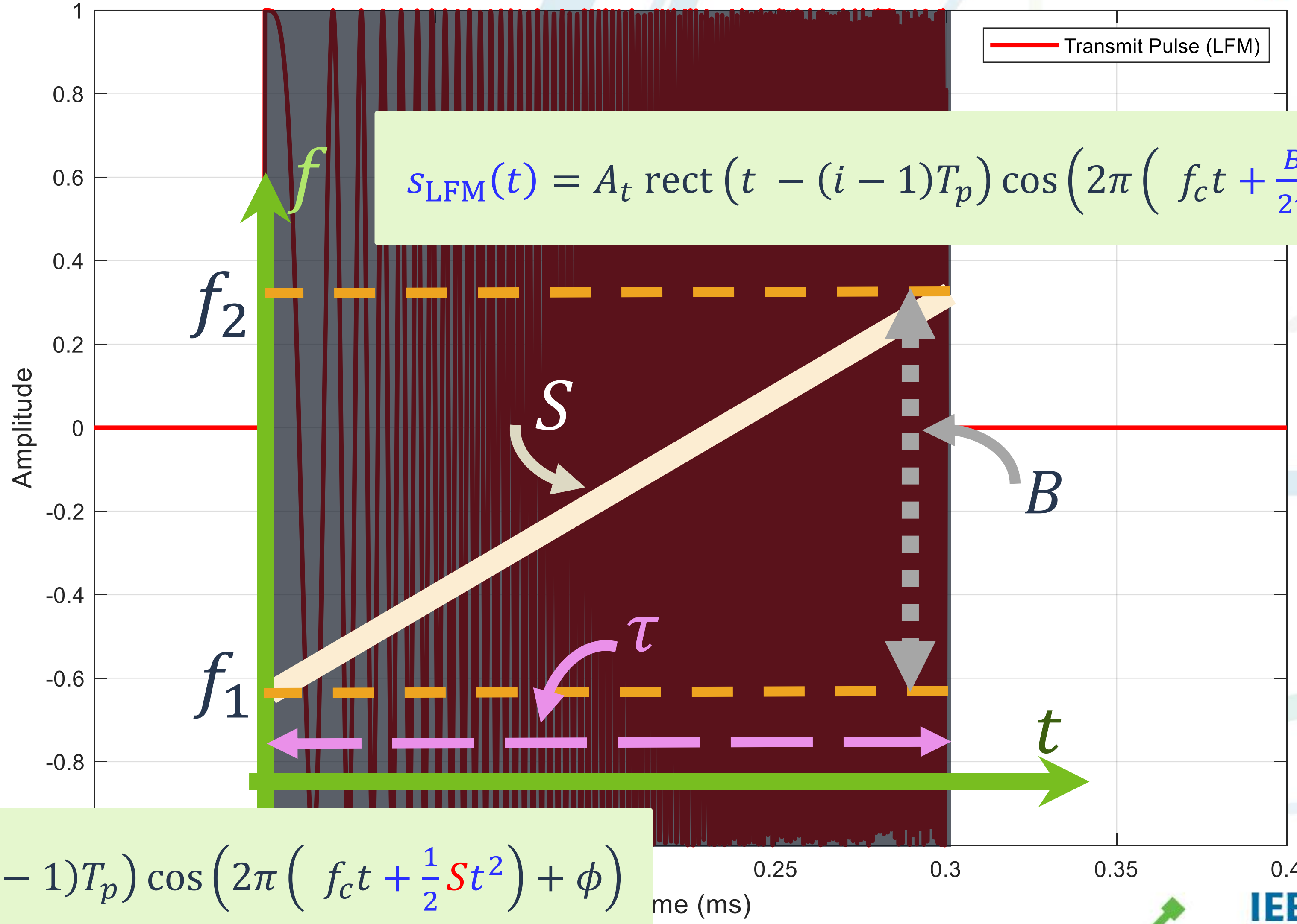
Slope

$$B = 1\ \text{MHz}$$

$$\Delta R = \frac{c}{2B} = 150\ \text{m}$$

$$S = \frac{B}{\tau}$$





$$s_{\text{LFM}}(t) = A_t \operatorname{rect}\left(t - (i-1)T_p\right) \cos\left(2\pi\left(f_c t + \frac{B}{2\tau} t^2\right) + \phi\right)$$

$$s_{\text{LFM}}(t) = A_t \operatorname{rect}\left(t - (i-1)T_p\right) \cos\left(2\pi\left(f_c t + \frac{1}{2} S t^2\right) + \phi\right)$$

Lect1_example7.m

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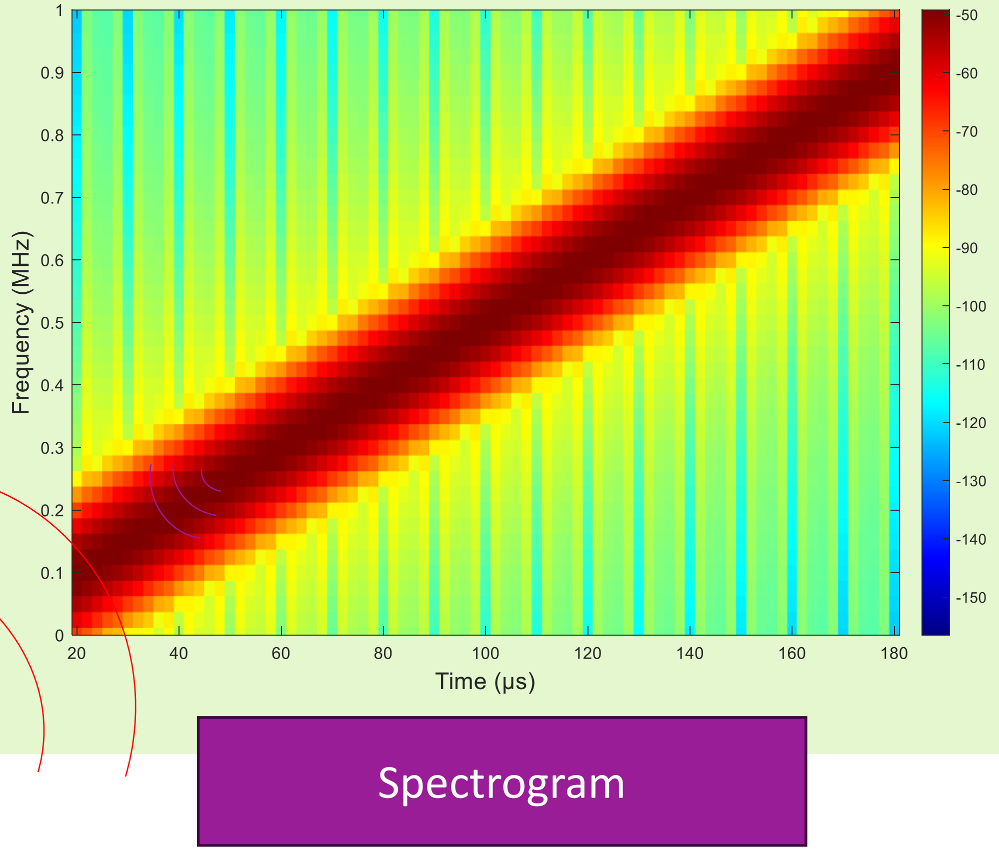
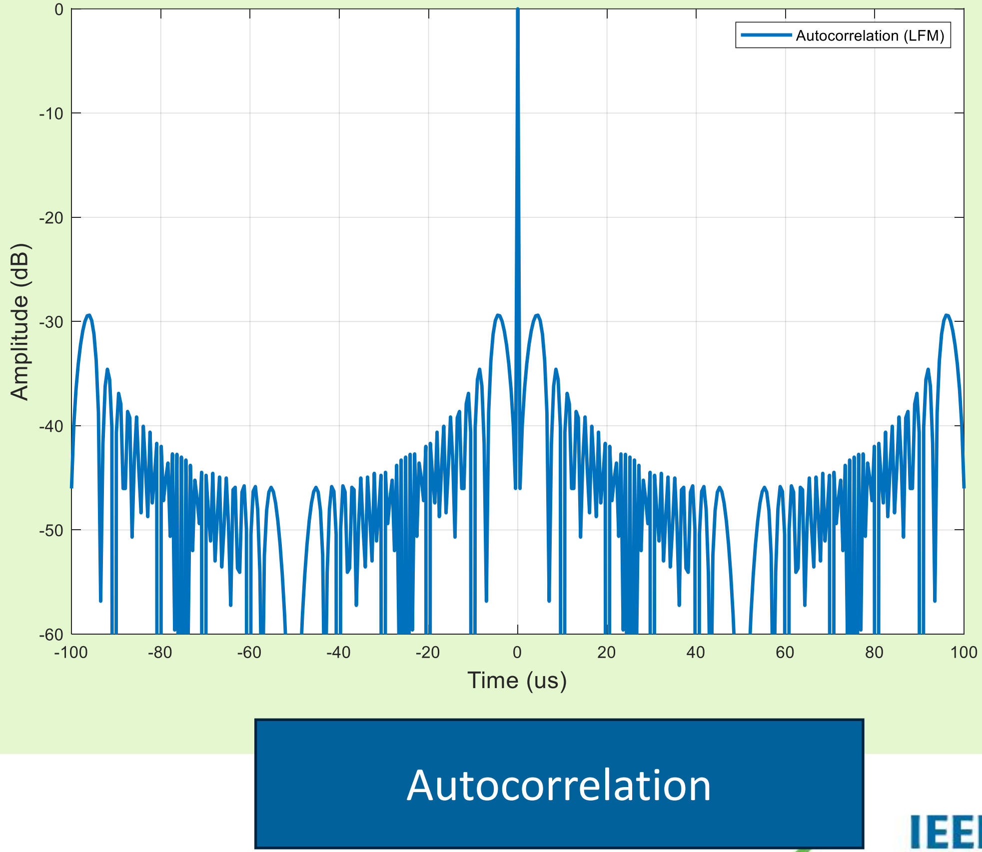
LFM Waveform

Spectrogram and Autocorrelation





Lect1_example7.m

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LFM Waveform

Ambiguity function

$$\chi(\tau, f_d) = \int_{-\infty}^{+\infty} s_{tx}(t)s^*(t - \tau)e^{j2\pi f_d t}dt$$

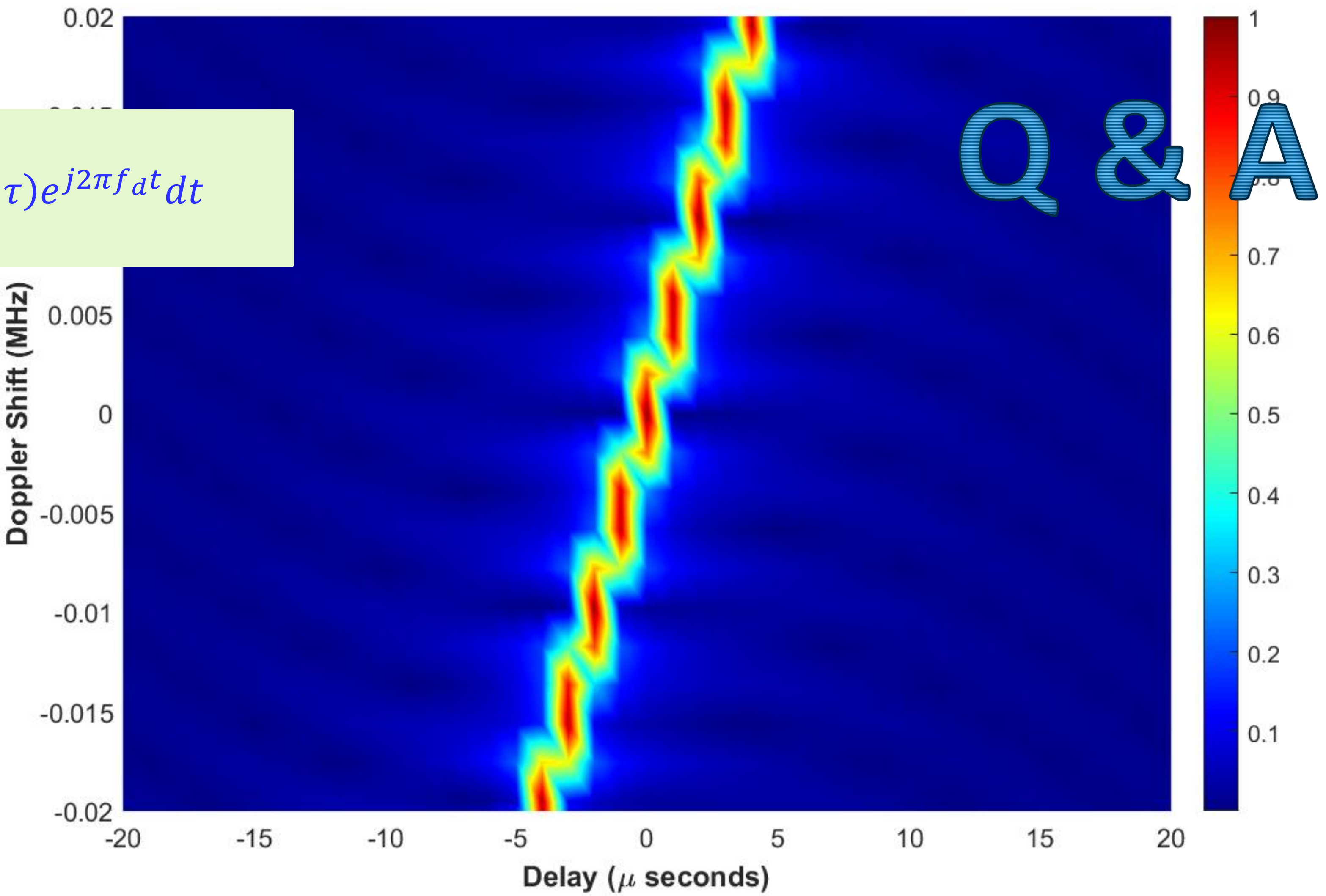
$$f_c = 10\text{ GHz}$$

$$\lambda = 0.03\text{ m}$$

$$v_r = 300\text{ m/s}$$

$$f_d = 2\frac{v_r}{\lambda} = 20\text{ KHz}$$

prominent ridge = “Doppler tolerant”



Lect1_example7.m

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Binary Phase Codes

Some well-known binary sequences	
	Barker codes
	M-sequences (Maximum length sequences)
	Gold codes
	Kasami codes
	Minimum Peak Sidelobe (MPS) sequences

Limited in length

No constraint on aperiodic auto-correlation function

Hard to find

Random binary codes

Heuristic Approaches

Mathematical Approaches

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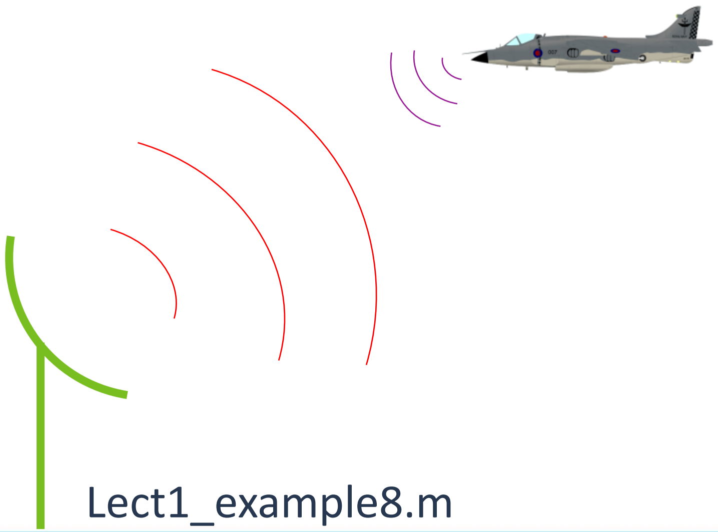
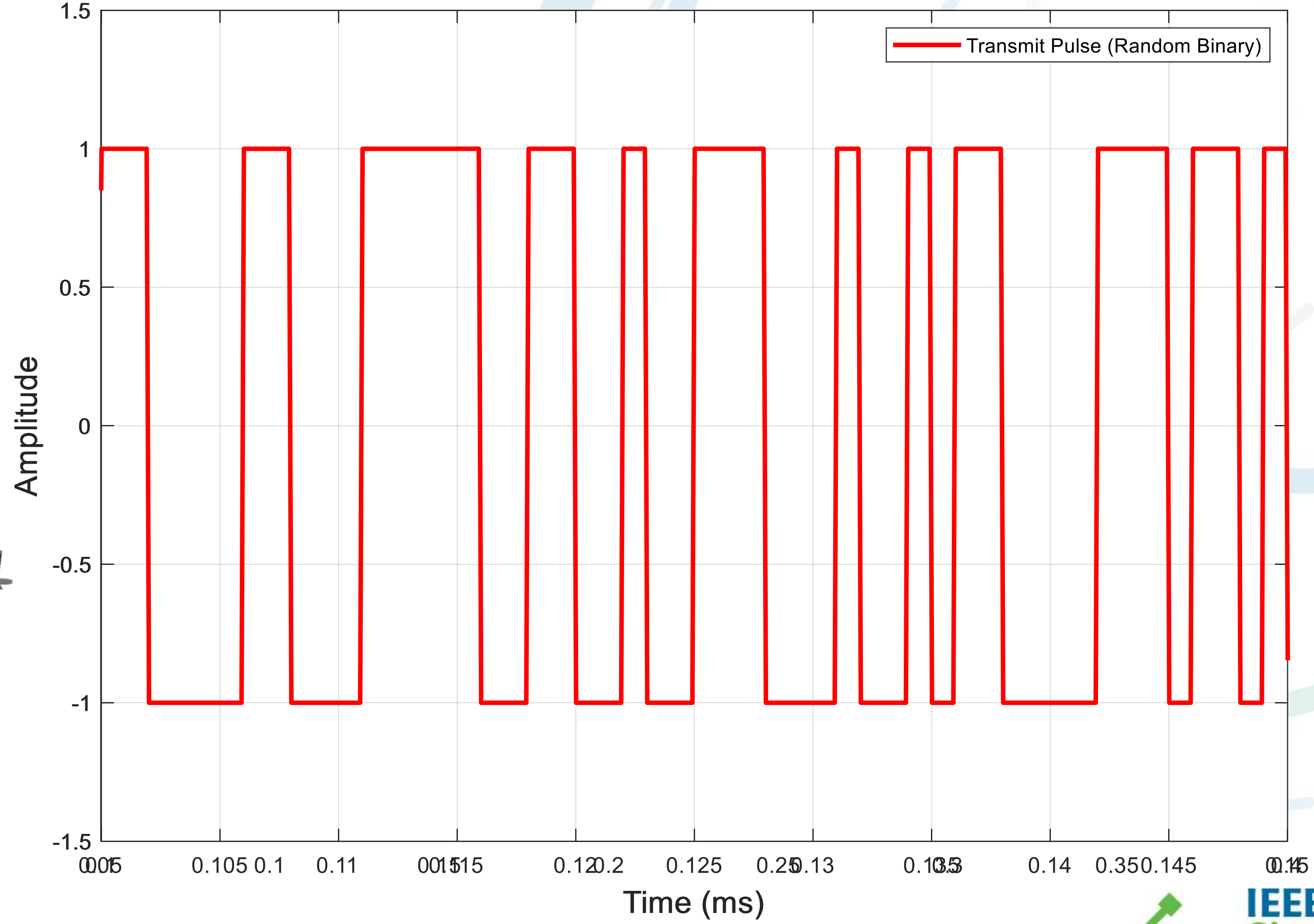
Random Binary Phase Code





Lect1_example8.m

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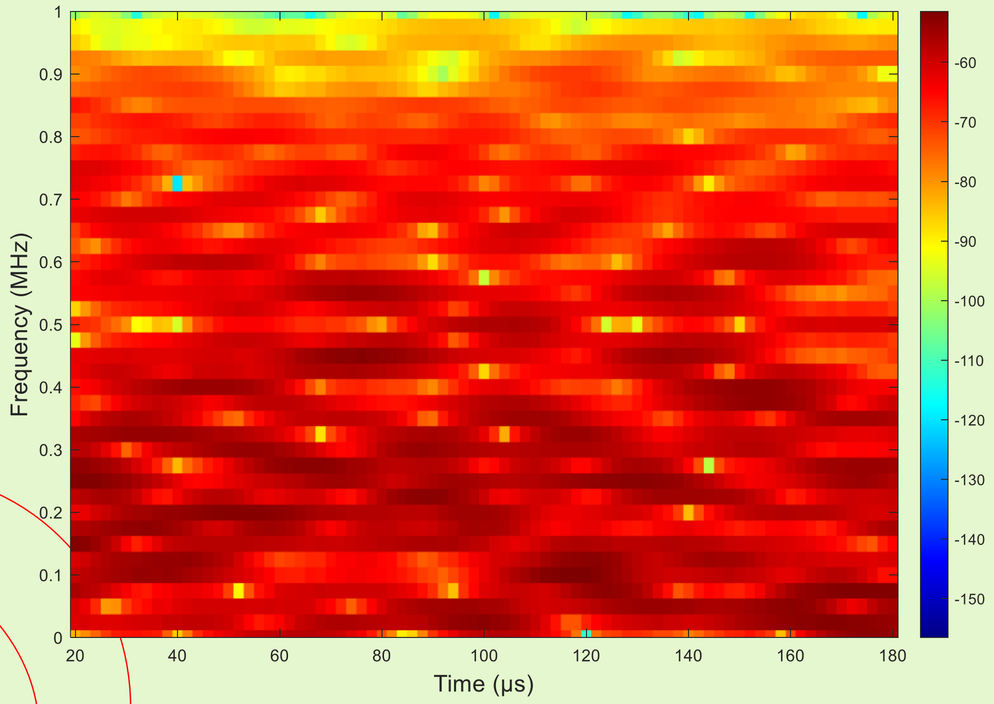
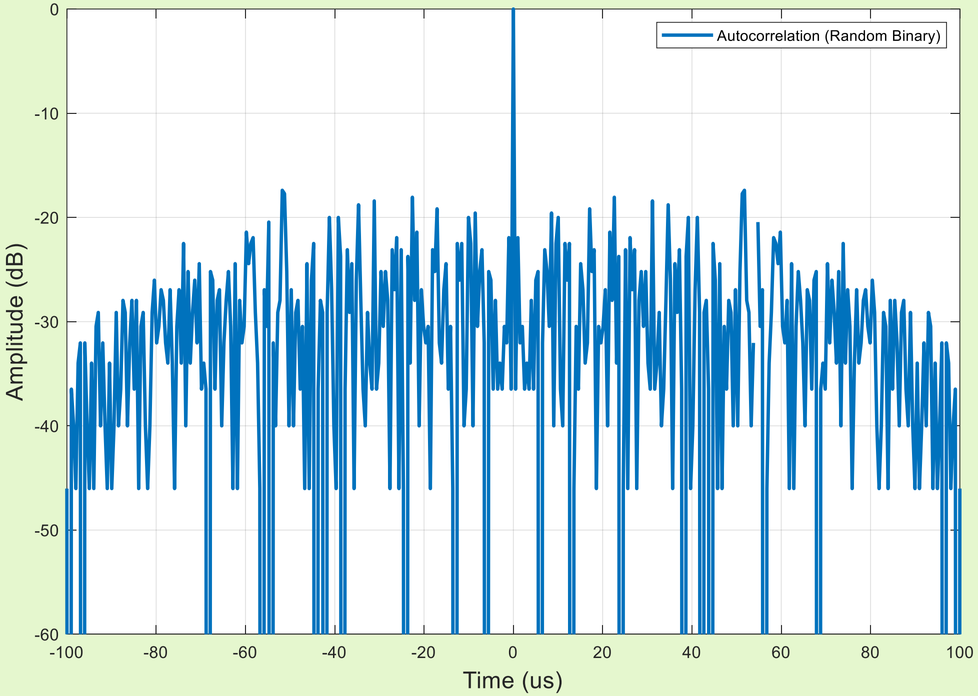
Random Binary Phase Code

Spectrogram and Autocorrelation





Spectrogram

Autocorrelation

Lect1_example8.m

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Random Binary Phase Code

Ambiguity function

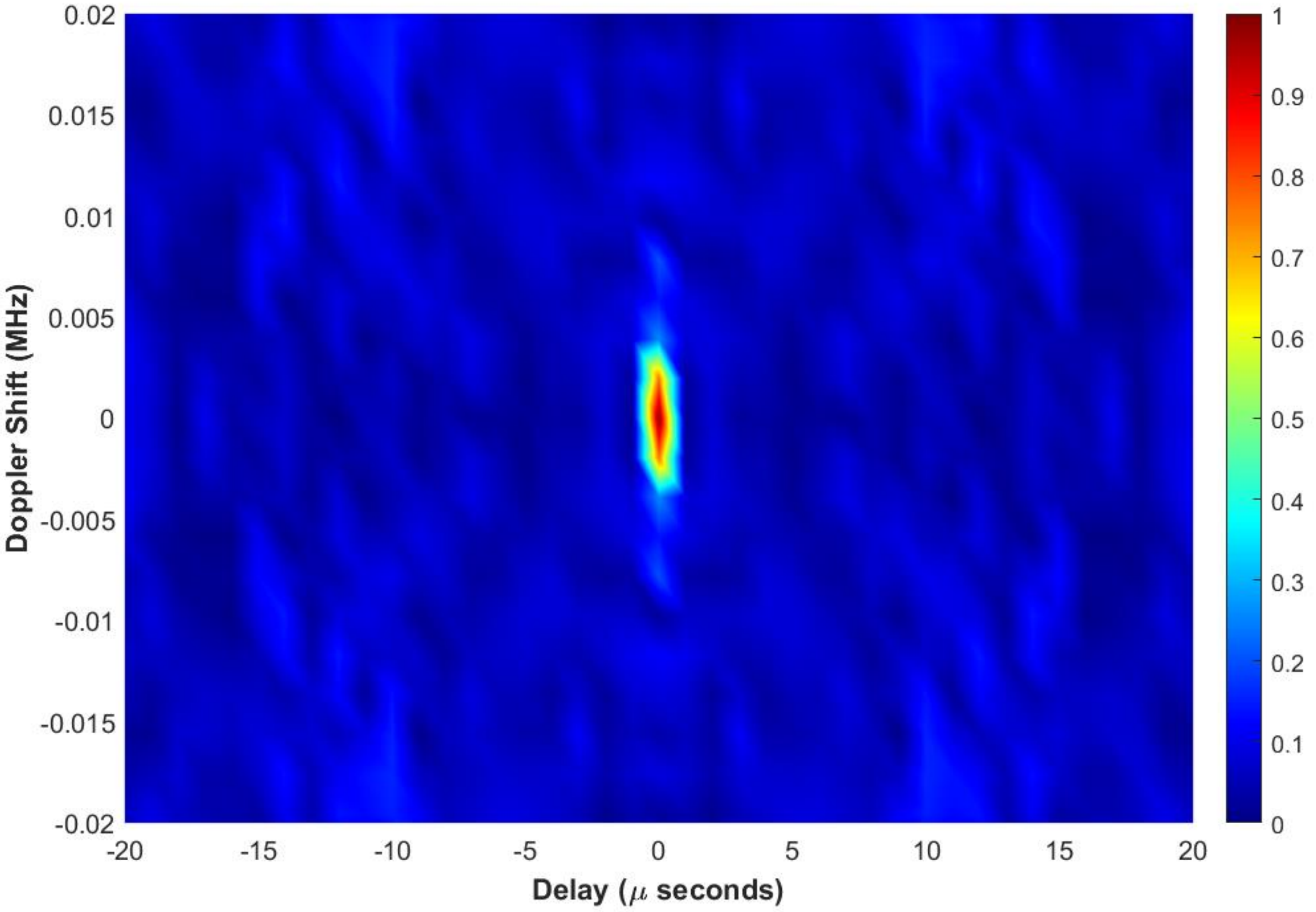
$$f_c = 10 \text{ GHz}$$

$$\lambda = 0.03 \text{ m}$$

$$v_r = 300 \text{ m/s}$$

$$f_d = 2\frac{v_r}{\lambda} = 20 \text{ KHz}$$

a “thumbtack” response



Lect1_example8.m

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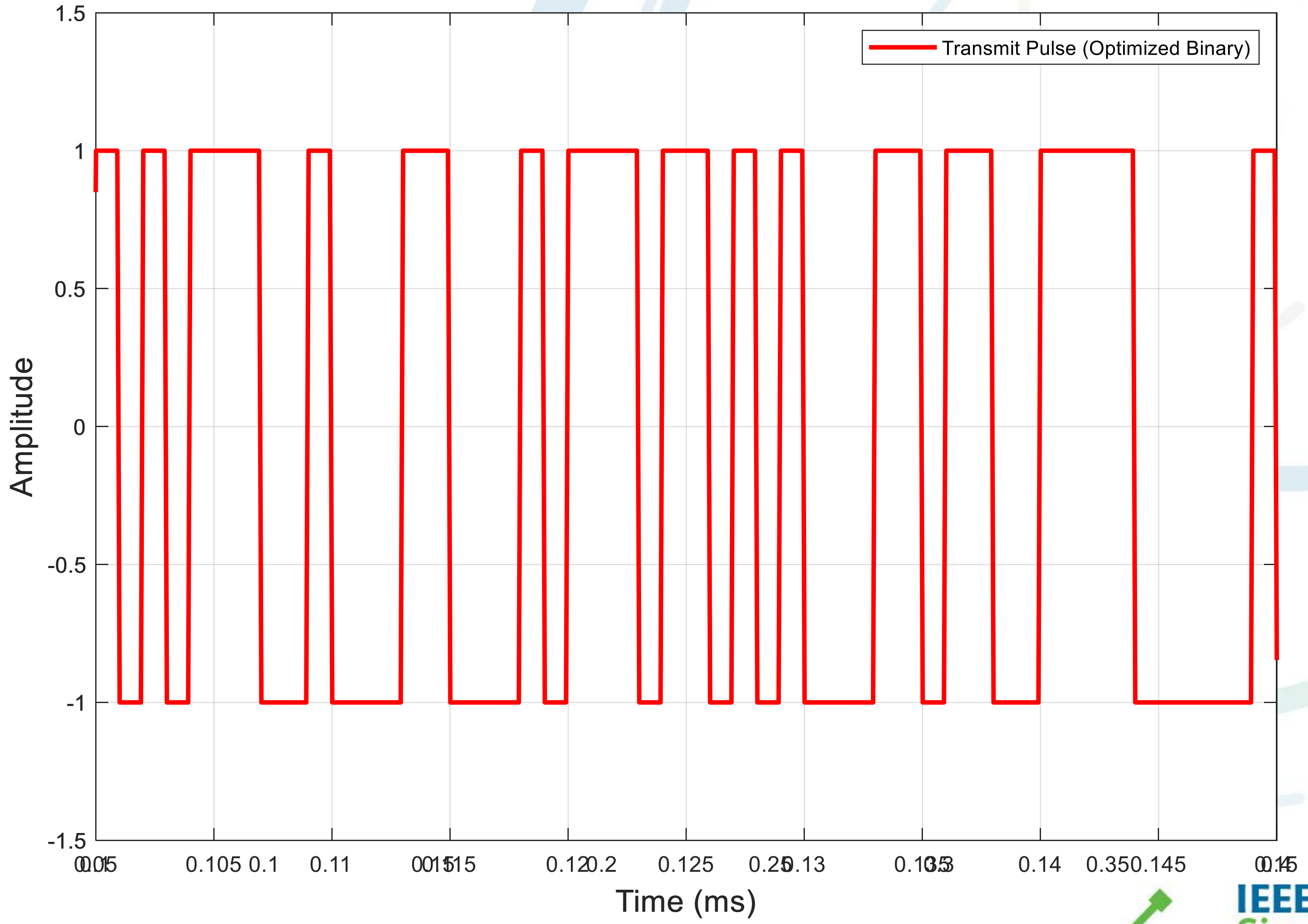
Optimized Binary Code – Mathematical Approaches



Lect1_example9.m

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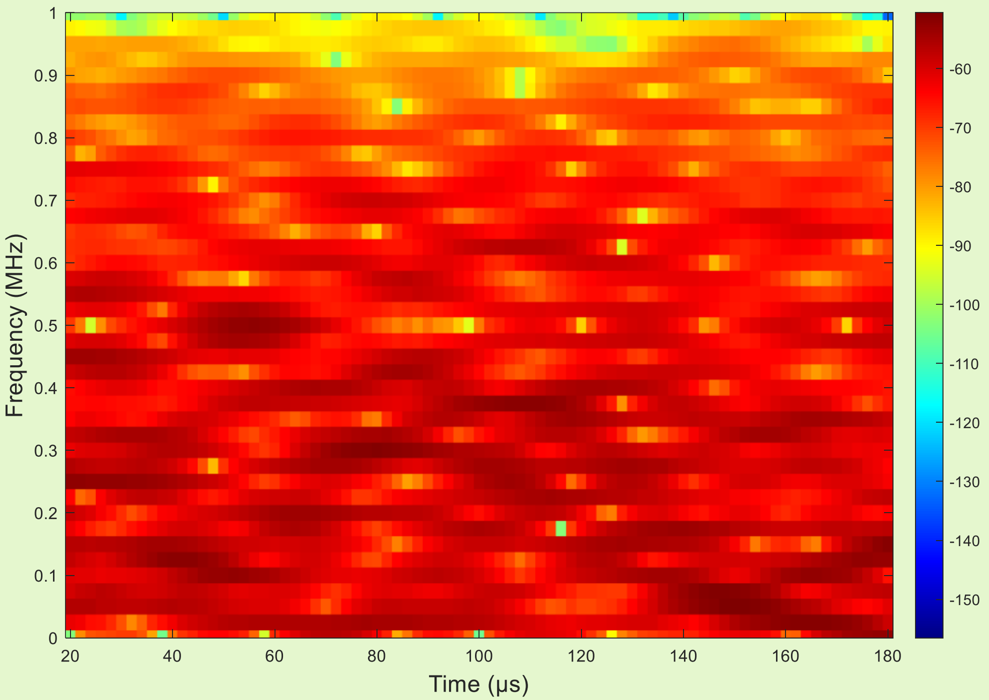
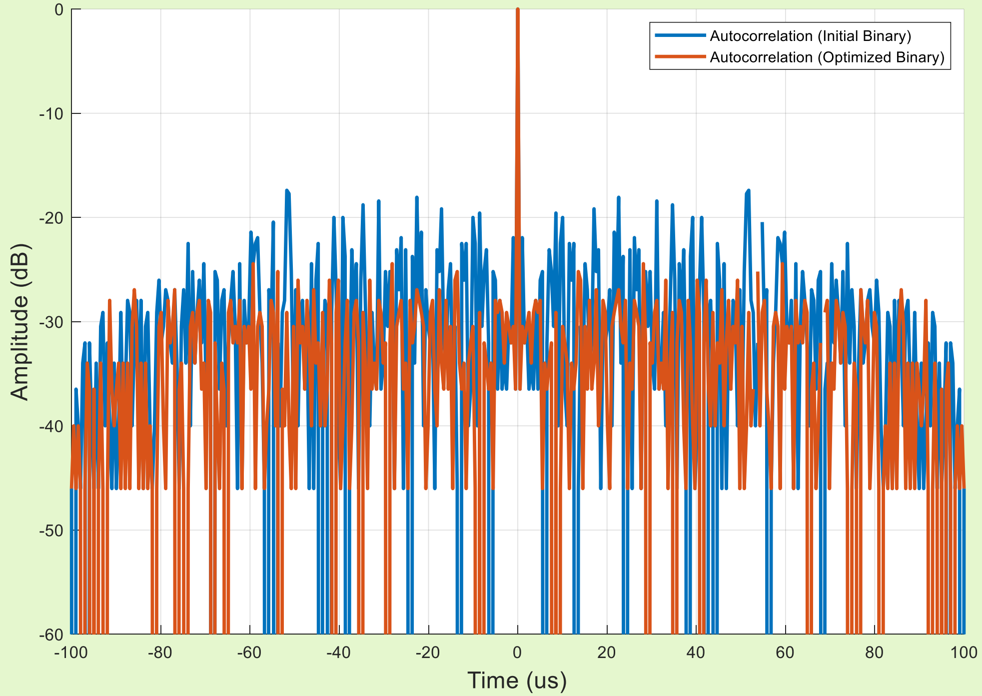
Optimized Binary Code – Mathematical Approaches

Spectrogram and Autocorrelation





Spectrogram

Autocorrelation

Lect1_example9.m

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Optimized Binary Code – Mathematical Approaches

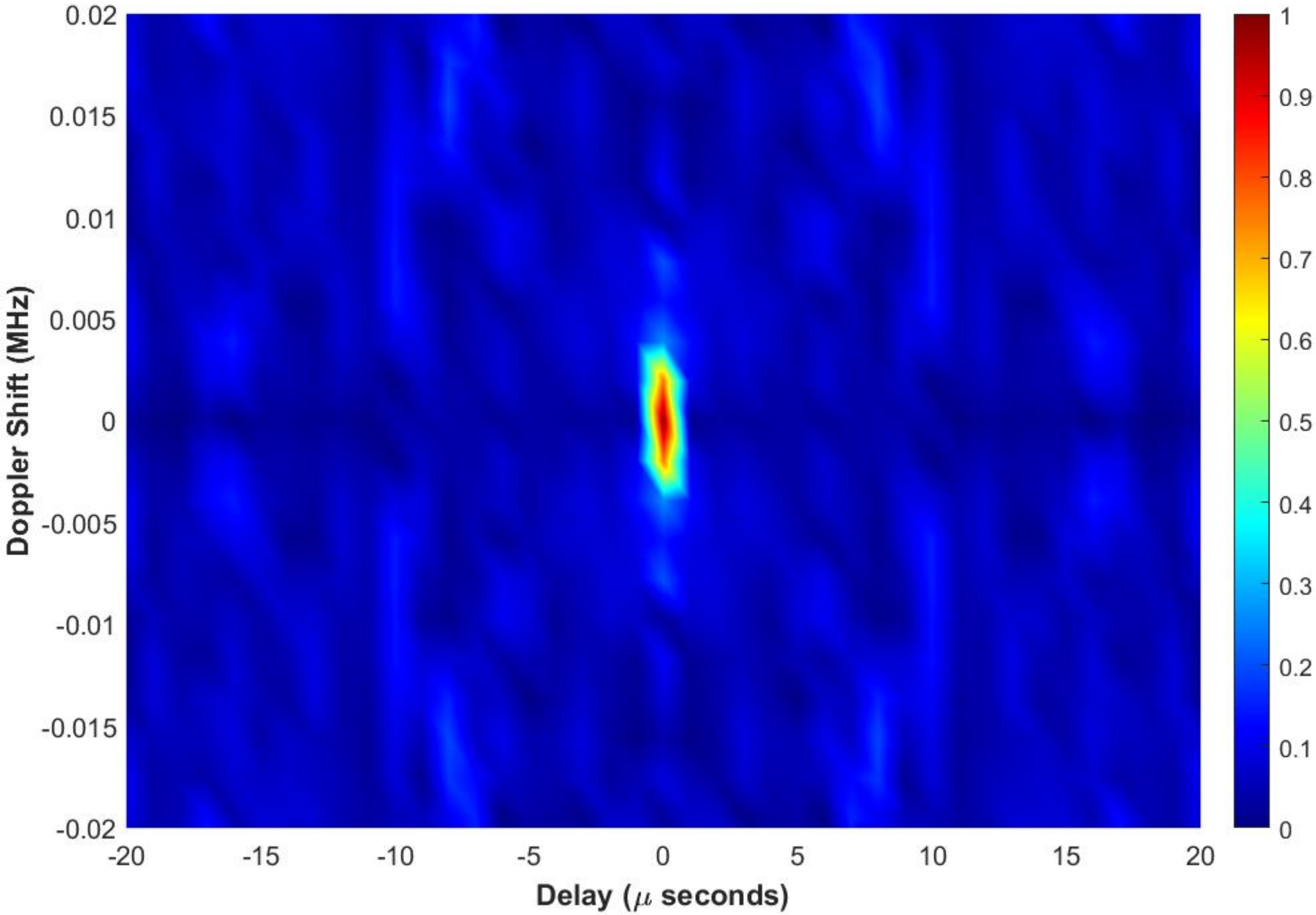
Ambiguity function

$$f_c = 10\ \text{GHz}$$

$$\lambda = 0.03\ \text{m}$$

$$v_r = 300\ \text{m/s}$$

$$f_d = 2\frac{v_r}{\lambda} = 20\ \text{KHz}$$



Lect1_example9.m

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Polyphase Codes

Some well-known Polyphase codes	
	Generalized Barker Codes
	Frank
	Golomb
	P1/P2/P3/P4/Px
	APAS and Several Others

Not easy to find them

Available for perfect square lengths

Random Polyphase codes

Heuristic Approaches

Mathematical Approaches

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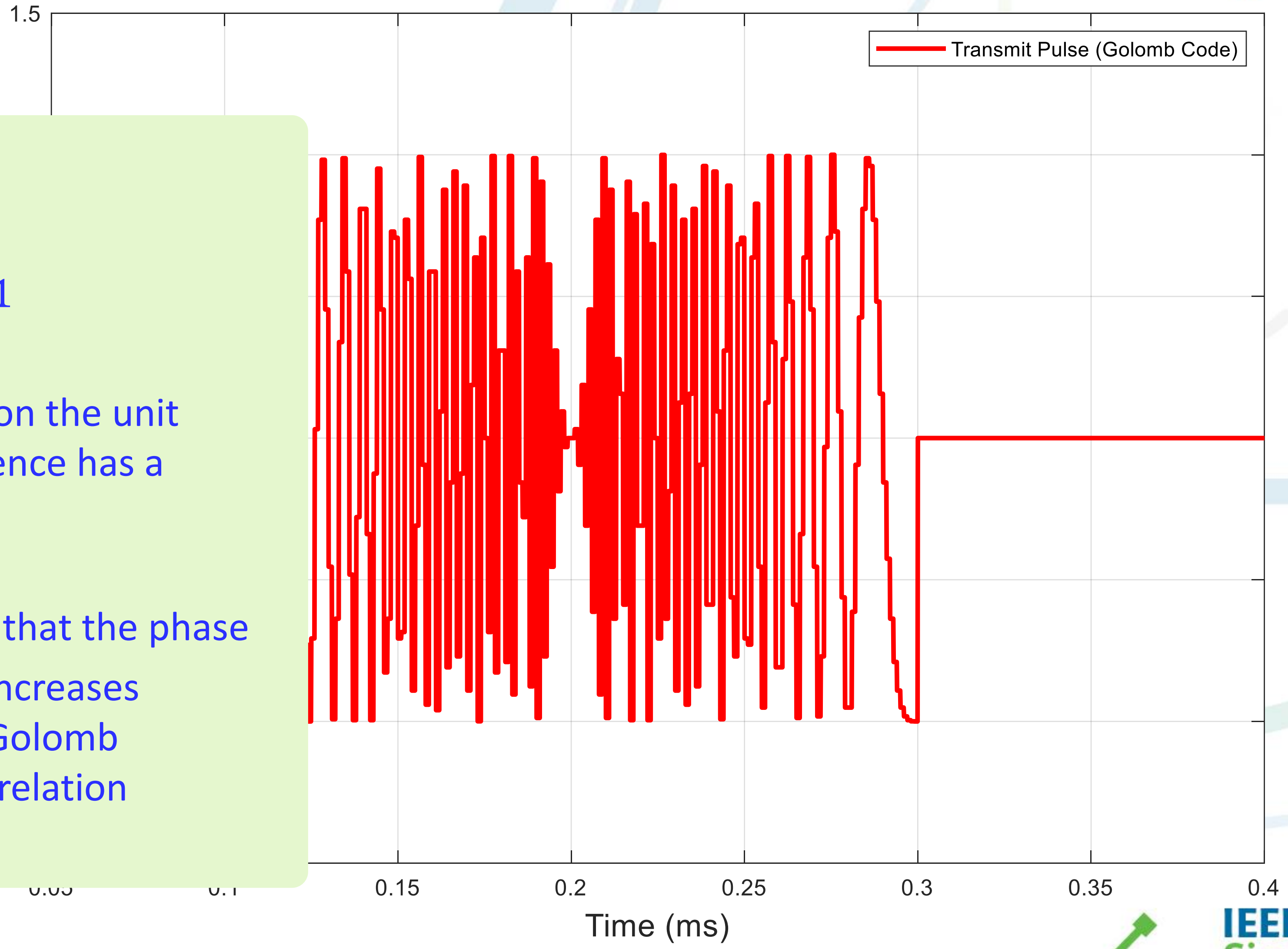
Polyphase Codes – Golomb Sequence



$$s[n] = \alpha^{\frac{n(n-1)}{2}},$$

$$n = 0, 1, \dots, N-1$$

- $\alpha = e^{j\frac{2\pi}{N}}$ is a complex number on the unit circle, which ensures the sequence has a uniform phase progression
- The exponent $\frac{n(n-1)}{2}$ ensures that the phase of each term in the sequence increases quadratically, which gives the Golomb sequence its favorable autocorrelation properties

Lect1_example10.m

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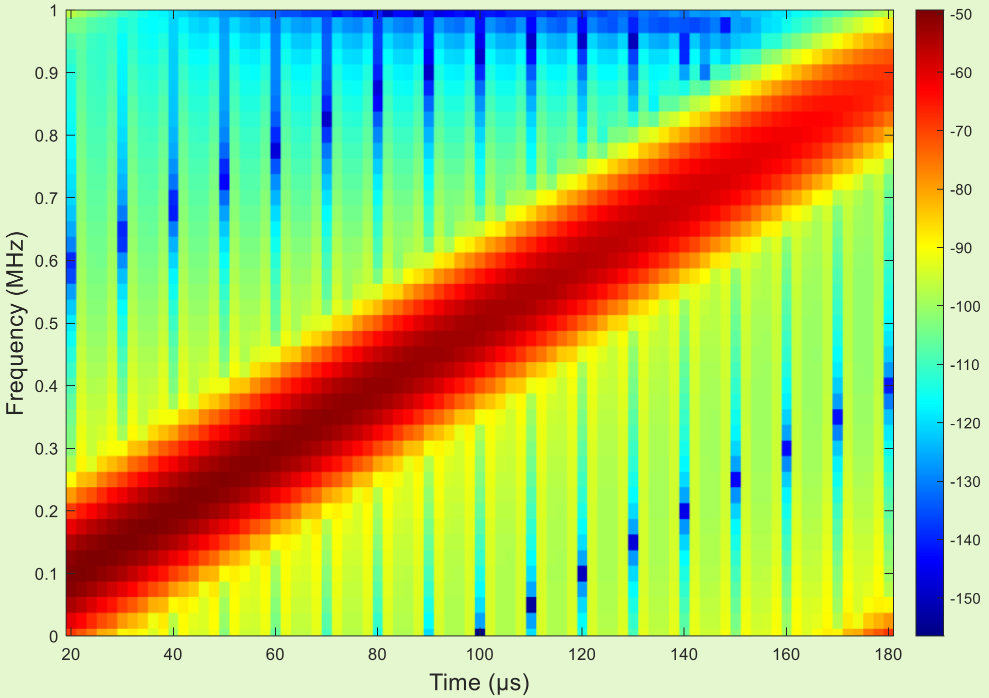
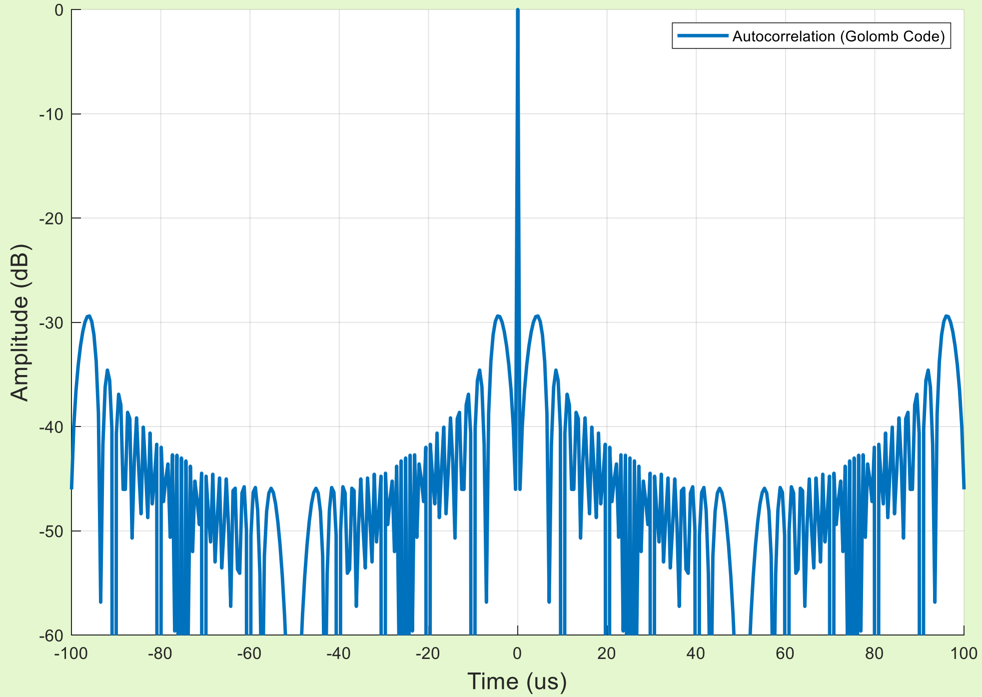
Polyphase Codes – Golomb Sequence

Spectrogram and Autocorrelation



Spectrogram



Autocorrelation

Lect1_example10.m

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Polyphase Codes – Golomb Sequence

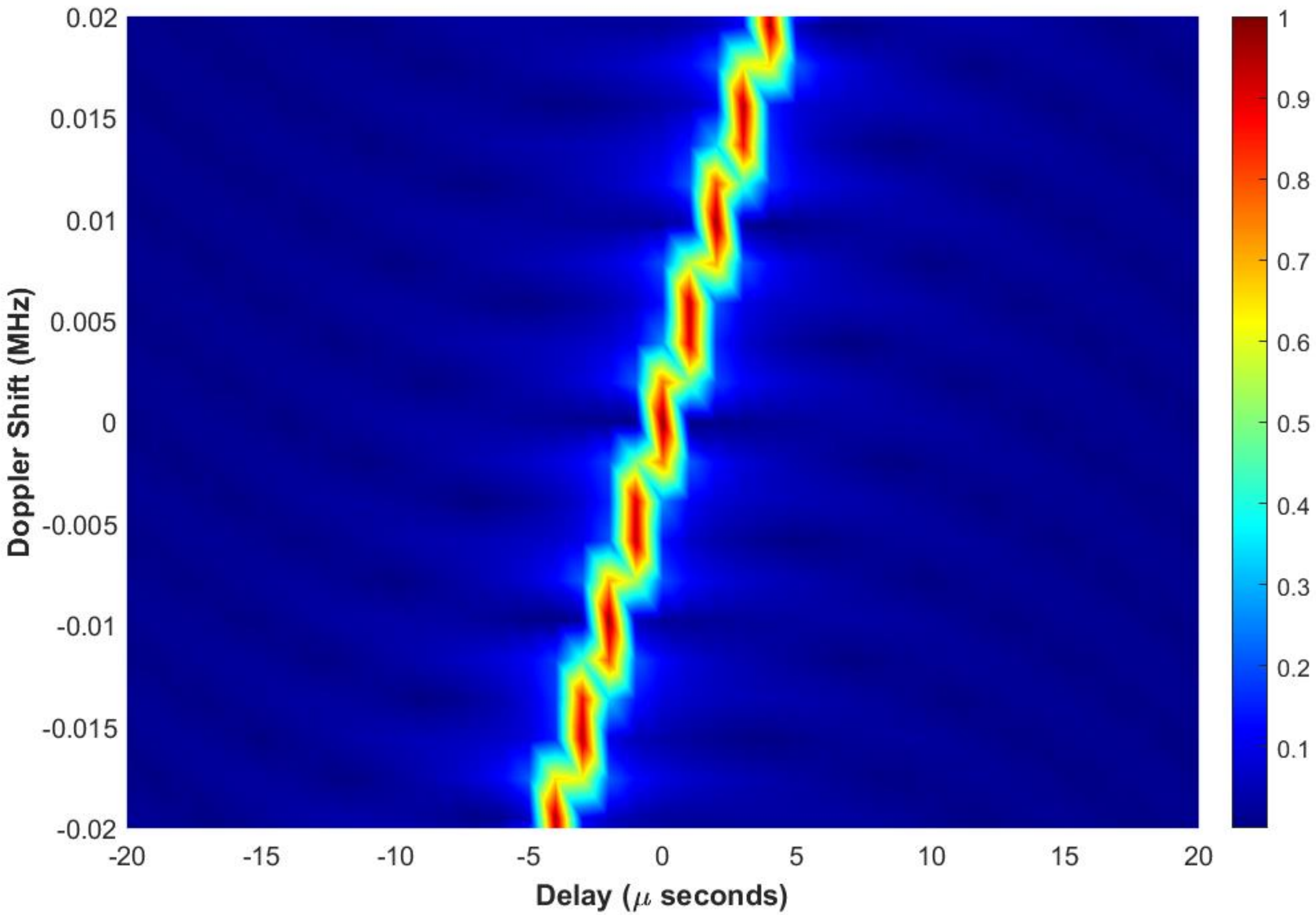
Ambiguity function

$f_c = 10$ GHz

$\lambda = 0.03$ m

$v_r = 300$ m/s

$f_d = 2\frac{v_r}{\lambda}$ = 20 KHz



Lect1_example10.m

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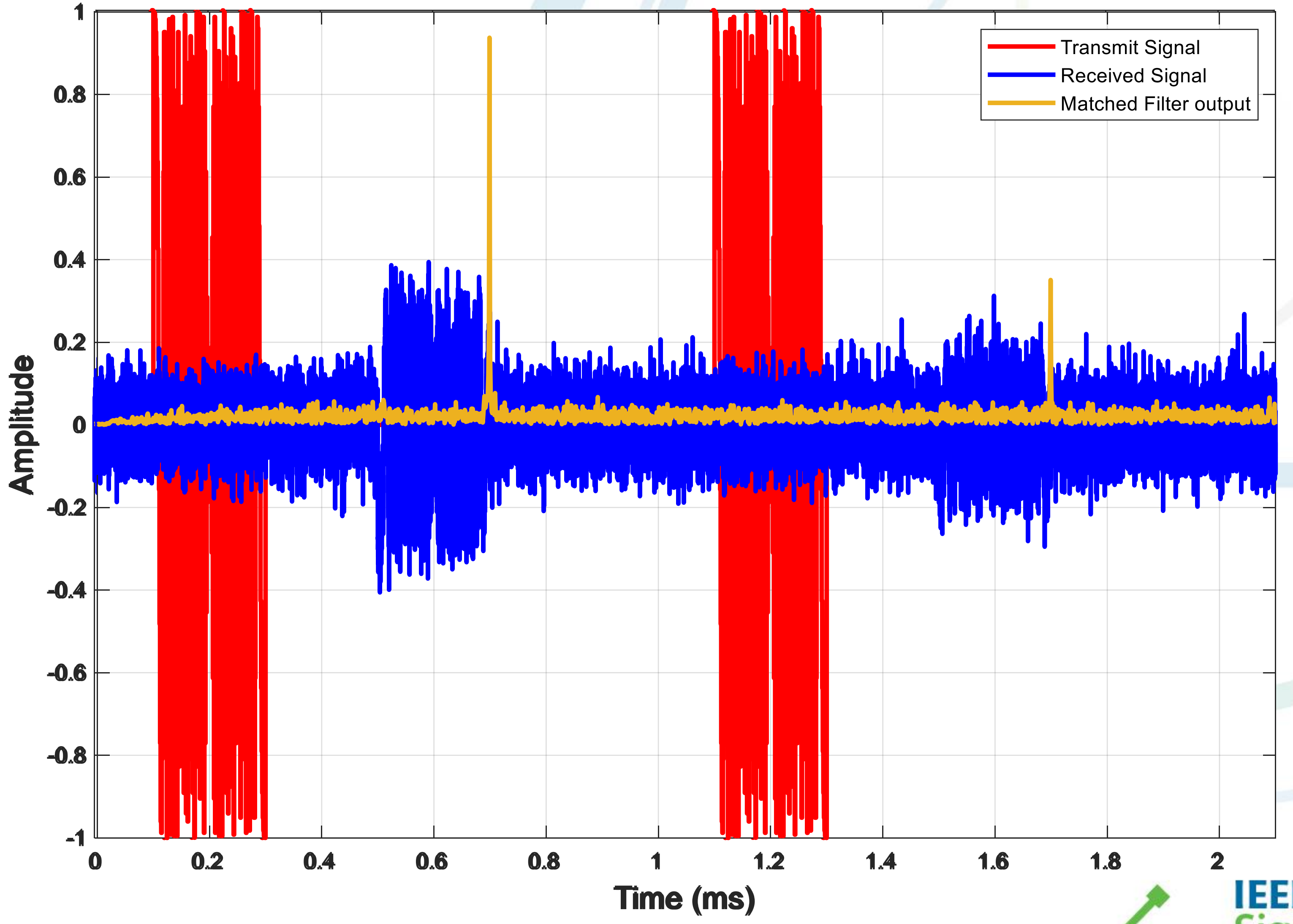
Doppler Resolution

Can we still separate two targets if they are in a similar distance from radar?



Lect1_example11.m

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Doppler Resolution in Pulse Doppler Radar

Range-Doppler Processing

Coherent Pulse Interval (CPI) = number of samples in the fast time × number of pulses in the slow-time

Assume M pulses are available in CPI

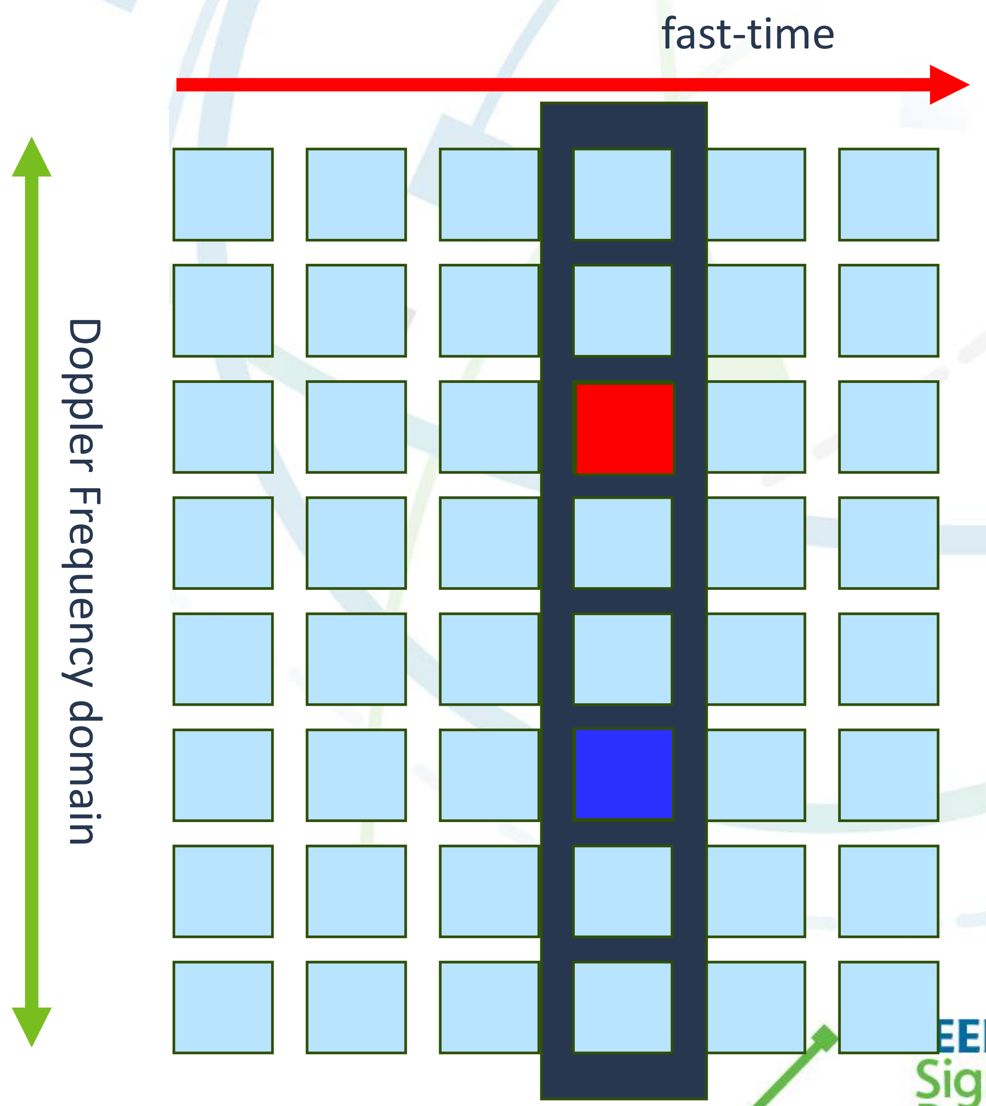
$$\mathrm{T_{CPI}} = M \times \mathrm{PRI}$$

$$\Delta f_d = \frac{1}{T_{\mathrm{CPI}}}$$

$$\mathrm{PRI} = 1\ \mathrm{ms}, \qquad \mathrm{M} = 128$$

$$\Delta f_d = \frac{1}{T_{\mathrm{CPI}}} = \frac{1}{128\ \mathrm{ms}} = 7.8\ \mathrm{Hz}$$

$$\mathrm{f_c} = 10\mathrm{GHz}, \qquad \Delta v_r = \frac{\lambda \Delta f_d}{2} = 0.03 \times \frac{7.8}{2} = 0.117\ \mathrm{m/s}$$



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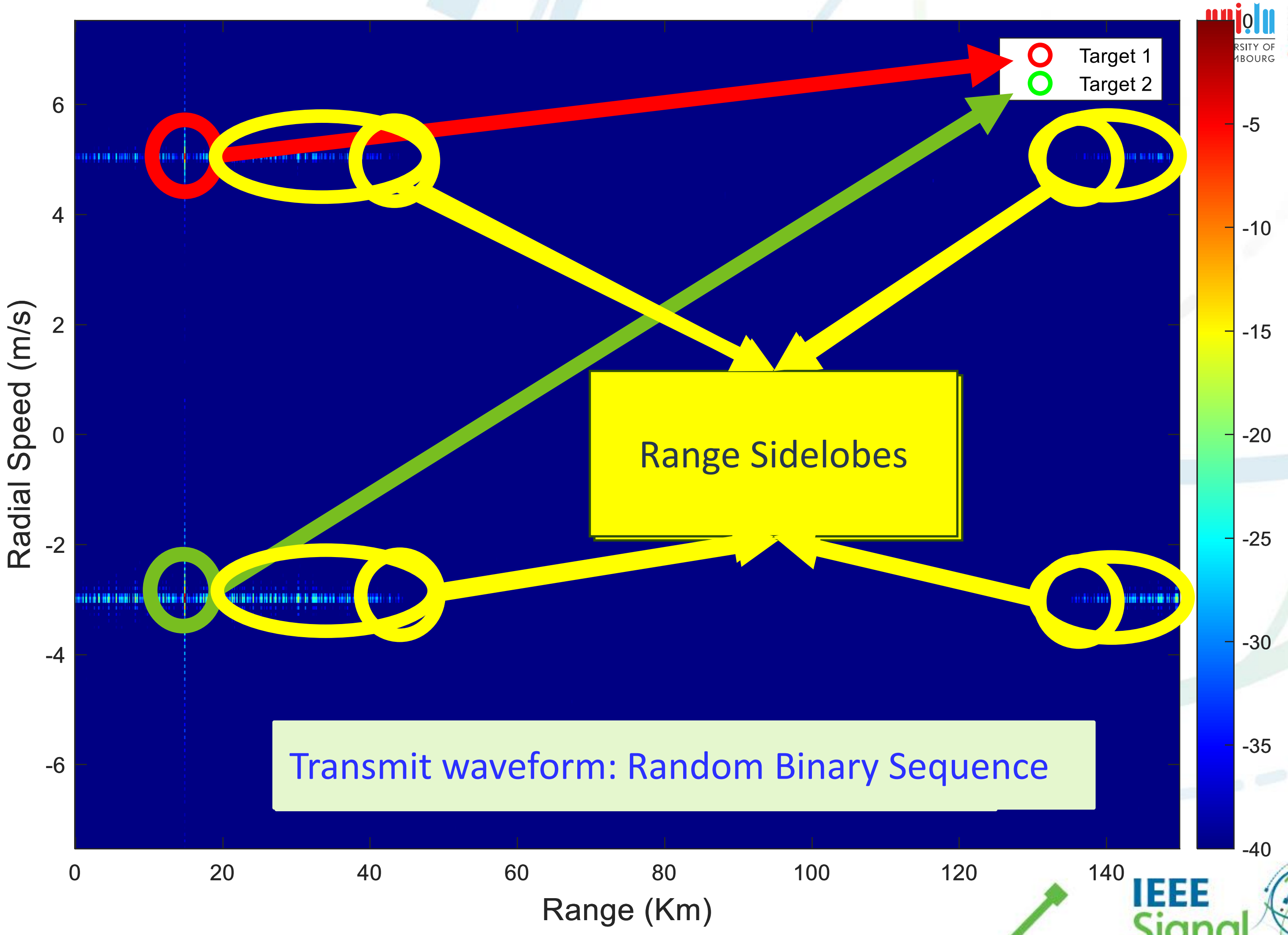
Doppler Resolution in Pulse Doppler Radar

$$\mathrm{PRI} = 1\ \mathrm{ms},$$
$$\mathrm{f_c} = 10\mathrm{GHz},$$
$$\mathrm{M} = 128$$

$$\Delta f_d = \frac{1}{T_{\mathrm{CPI}}} = \frac{1}{128\ \mathrm{ms}} = 7.8\ \mathrm{Hz}$$

$$\Delta v_r = \frac{\lambda \Delta f_d}{2} = 0.117\,\frac{\mathrm{m}}{\mathrm{s}}$$

$$v_{r\,max} = \frac{\lambda f_p}{4} = 7.5\,\frac{\mathrm{m}}{\mathrm{s}}$$



Lect1_example11.m

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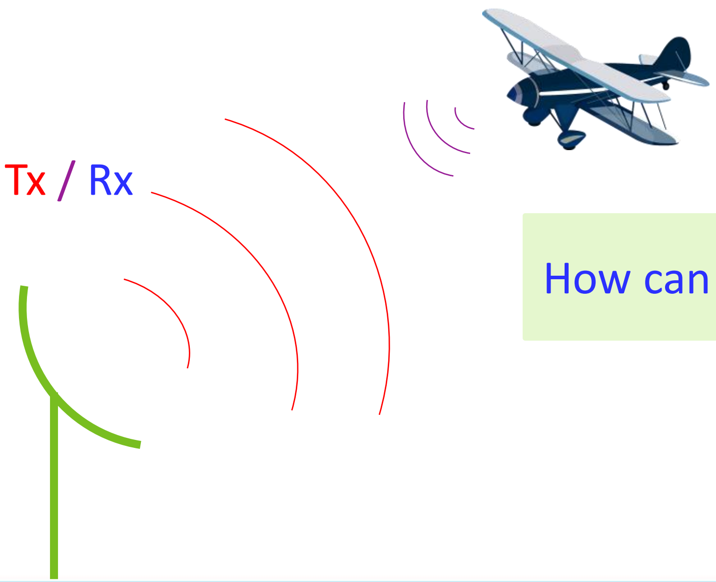
Pulse Compression Doppler Radar

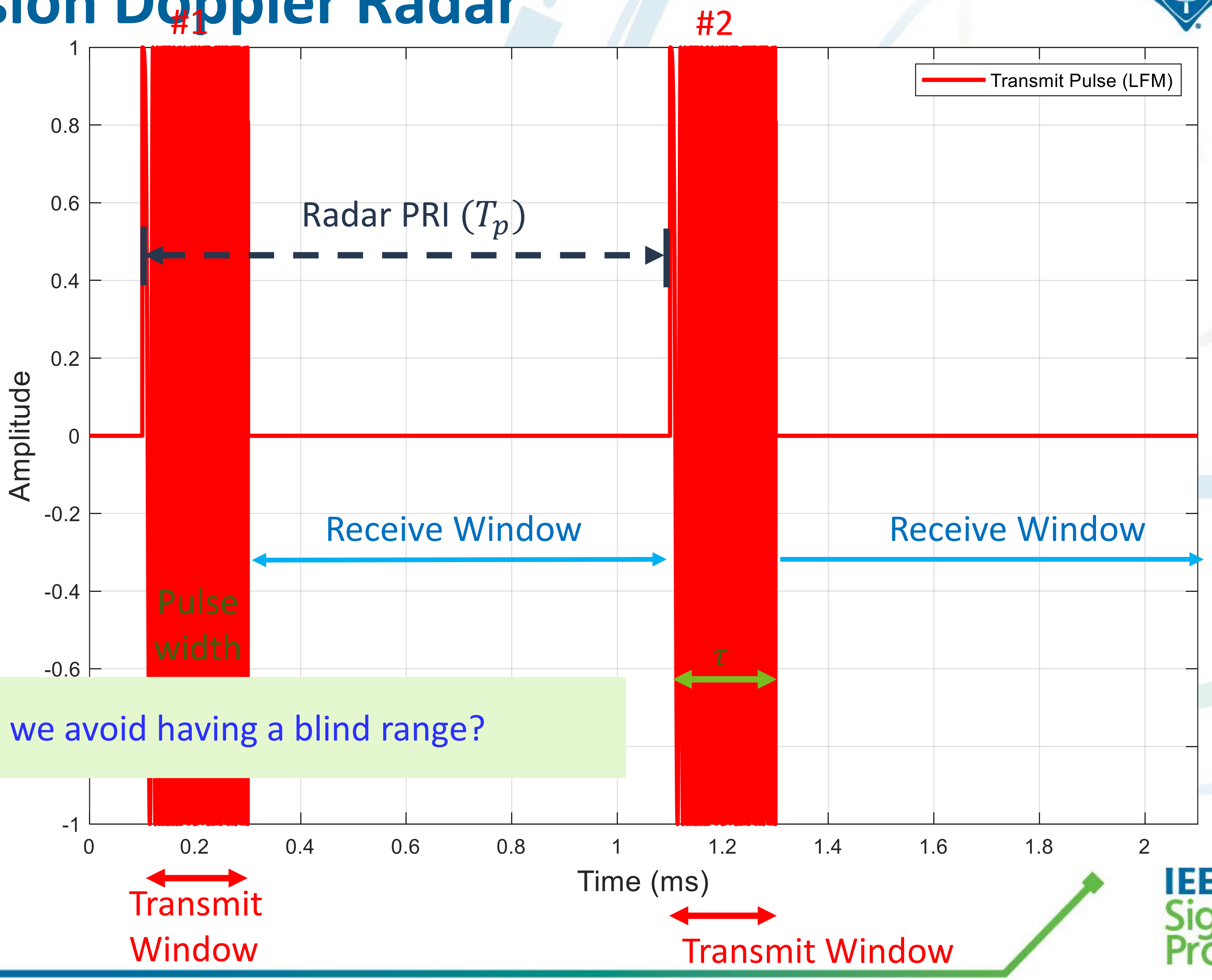
Blind Range

$$\text{Blind Range} = \frac{c\tau}{2}$$

$$\tau = 200\ \mu s$$

$$\text{Blind Range} = 30\ \text{Km}$$





How can we avoid having a blind range?

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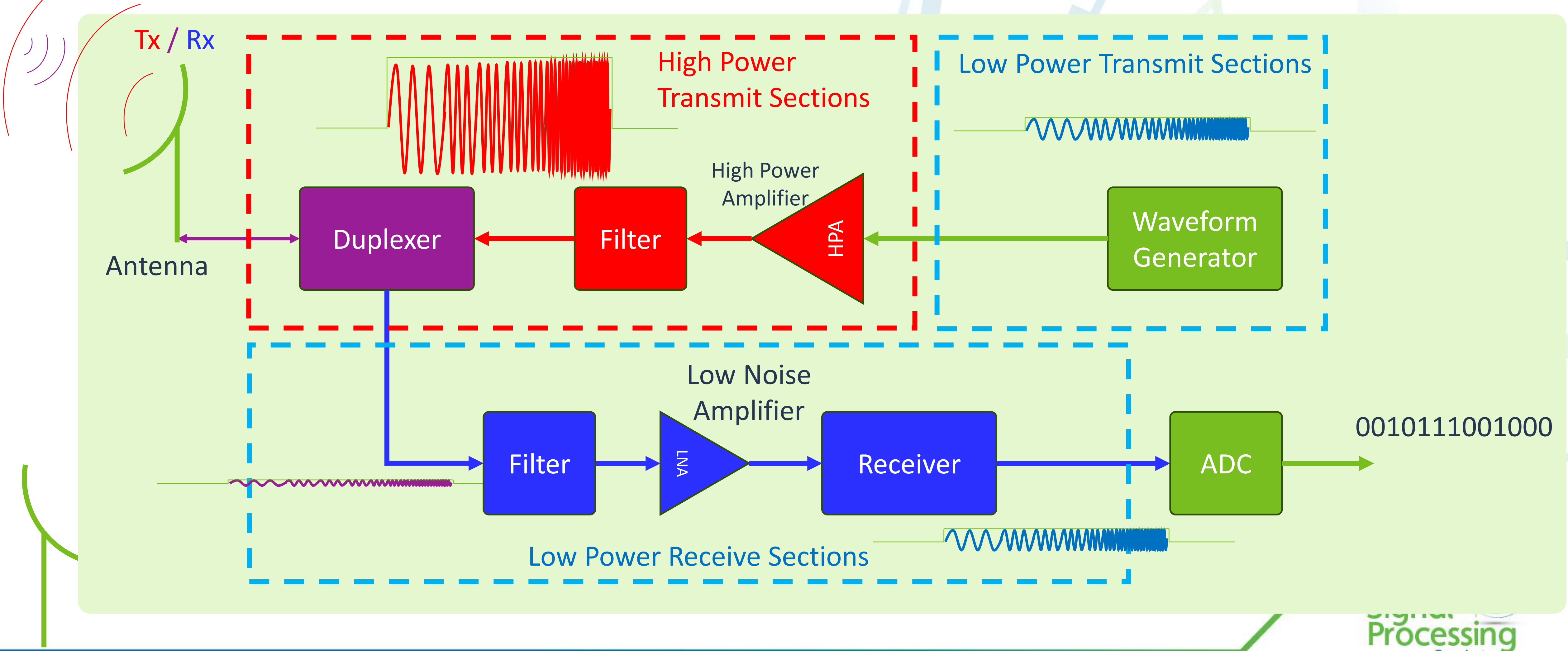
Pulse Compression Doppler Radar

Block Diagram

How can we avoid having a blind range?



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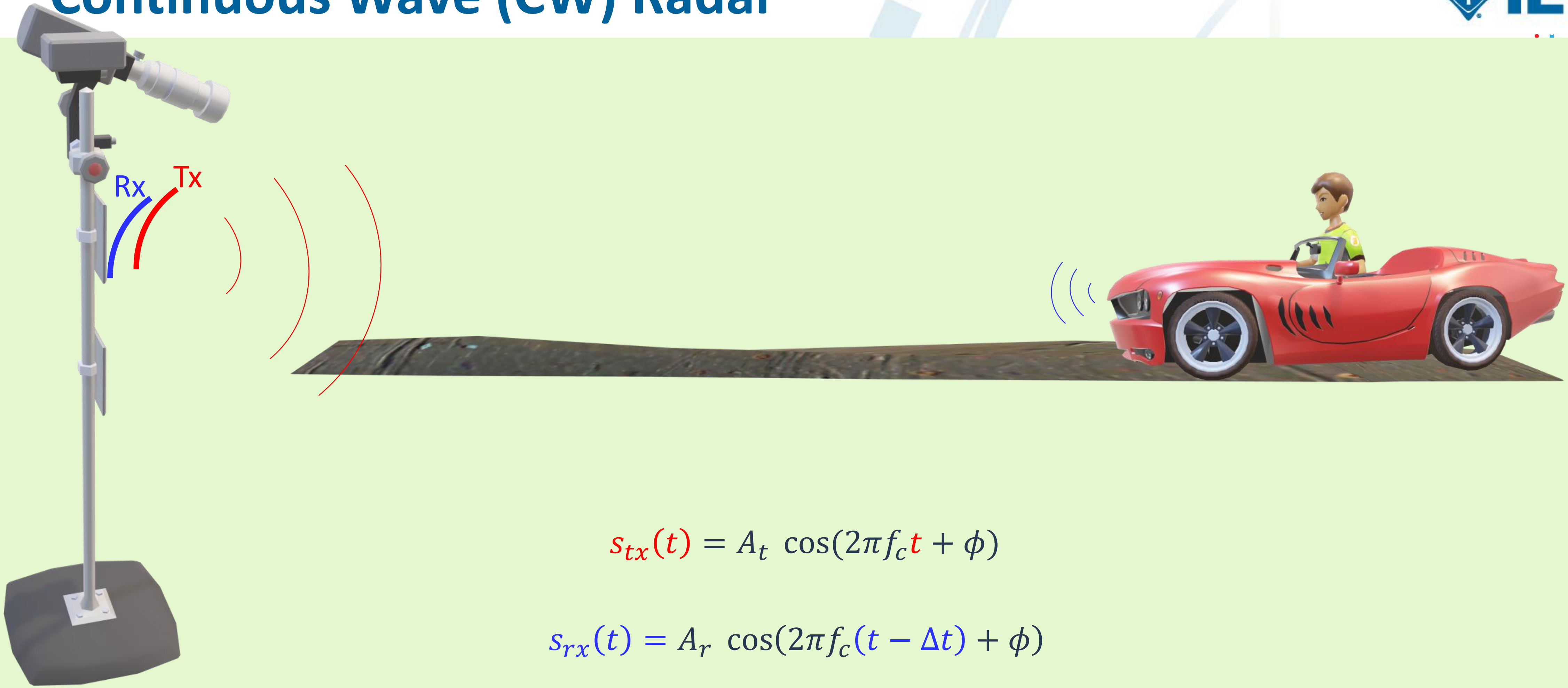
Continuous Wave (CW) Radar



$$s_{tx}(t) = A_t \cos(2\pi f_c t + \phi)$$

$$s_{rx}(t) = A_r \cos(2\pi f_c (t - \Delta t) + \phi)$$

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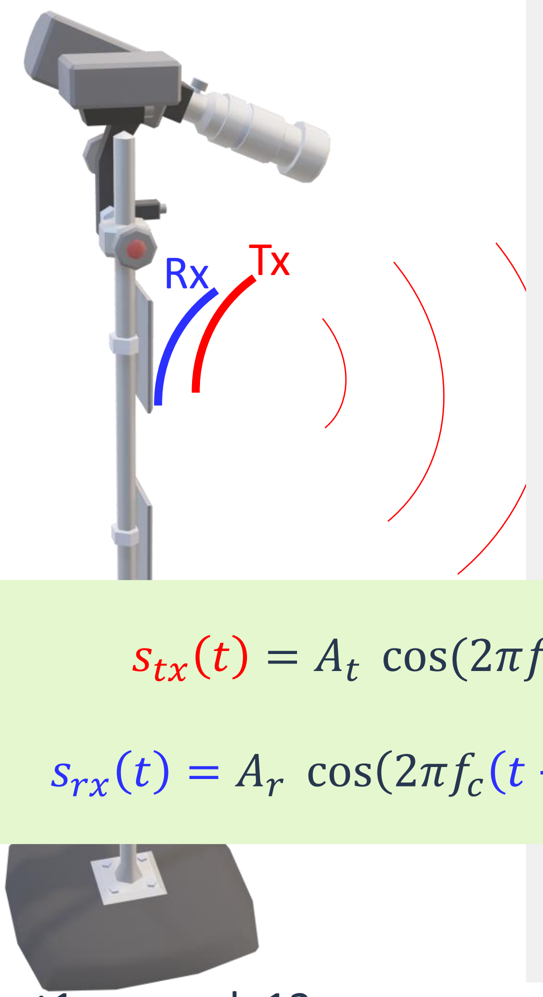
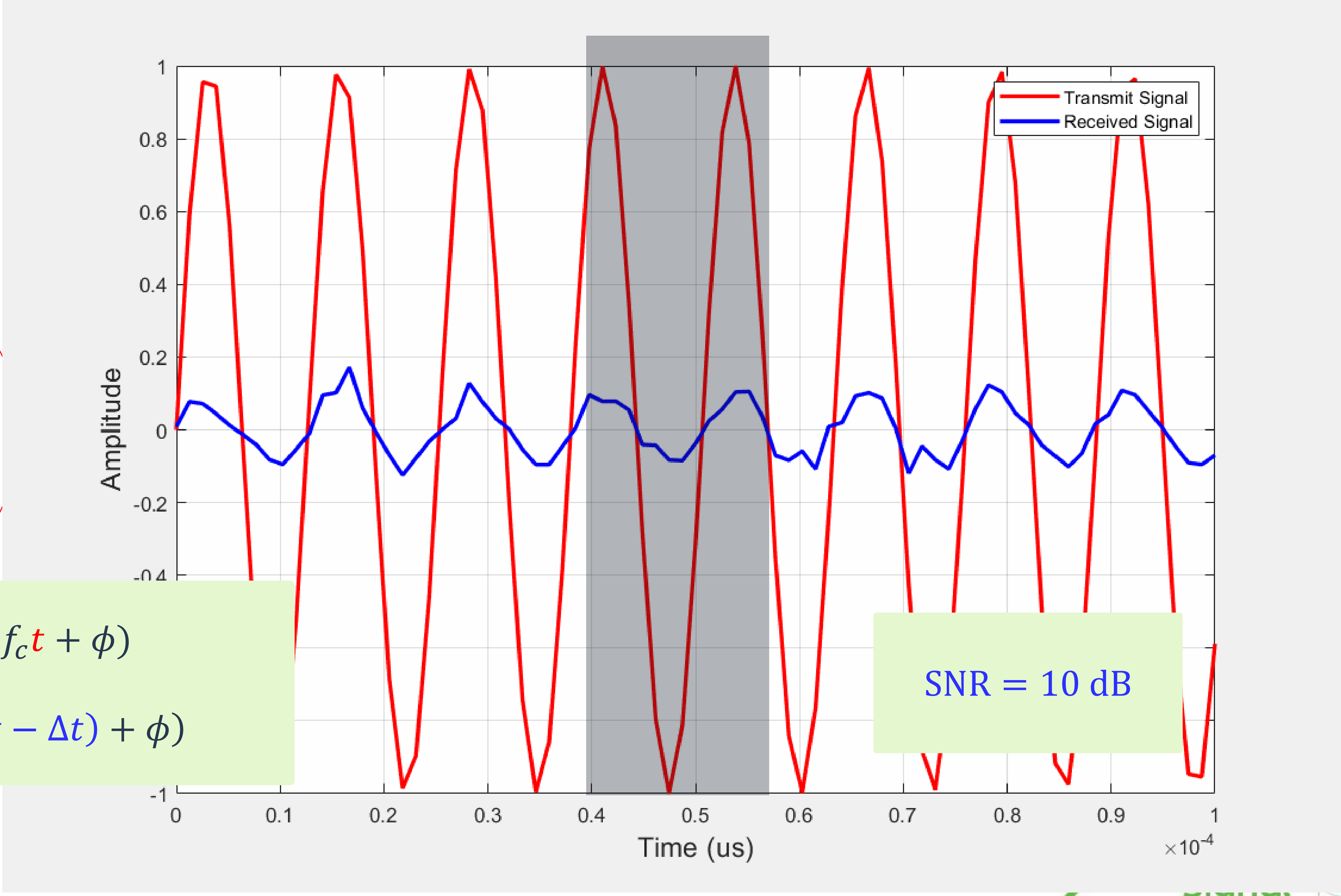
CW Radar





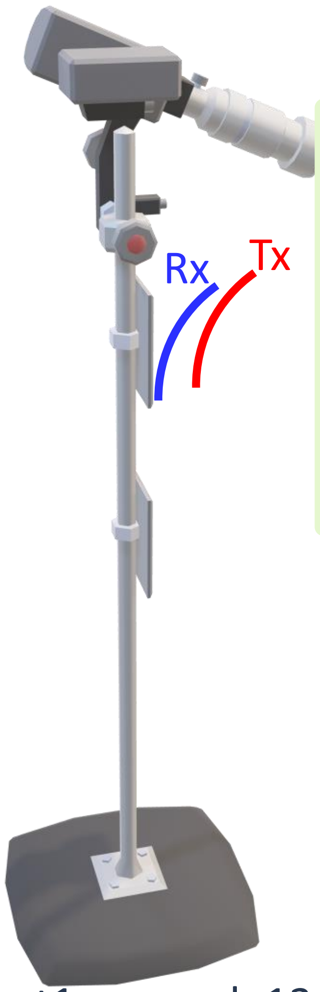
$$s_{tx}(t) = A_t \ \cos(2\pi f_c t + \phi)$$

$$s_{rx}(t) = A_r \ \cos(2\pi f_c(t - \Delta t) + \phi)$$

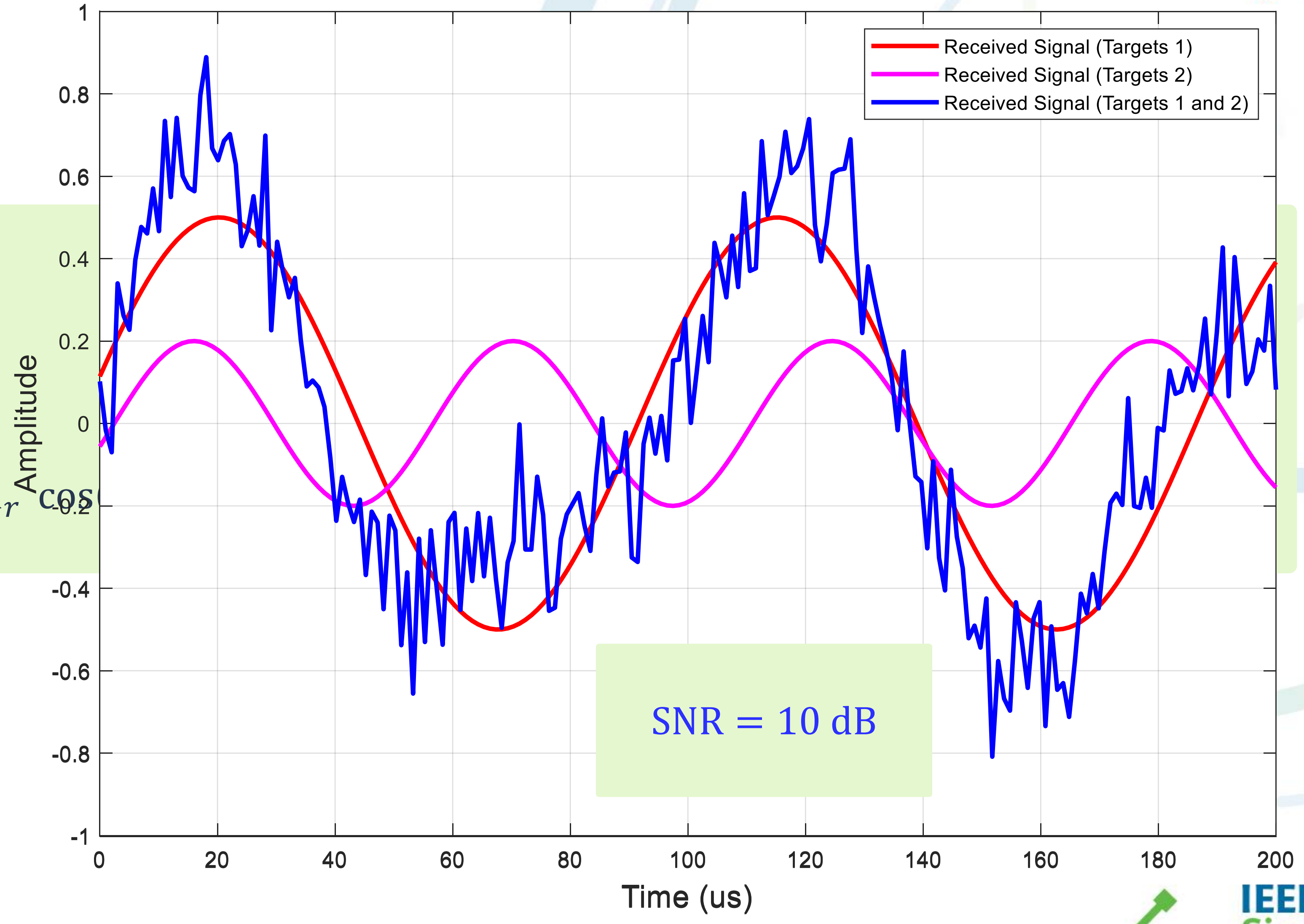
Lect1_example12.m

CW Radar

Doppler Effect



$s_{rx}(t) = A_r \cos($



SNR = 10 dB

Lect1_example13.m

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CW Radar

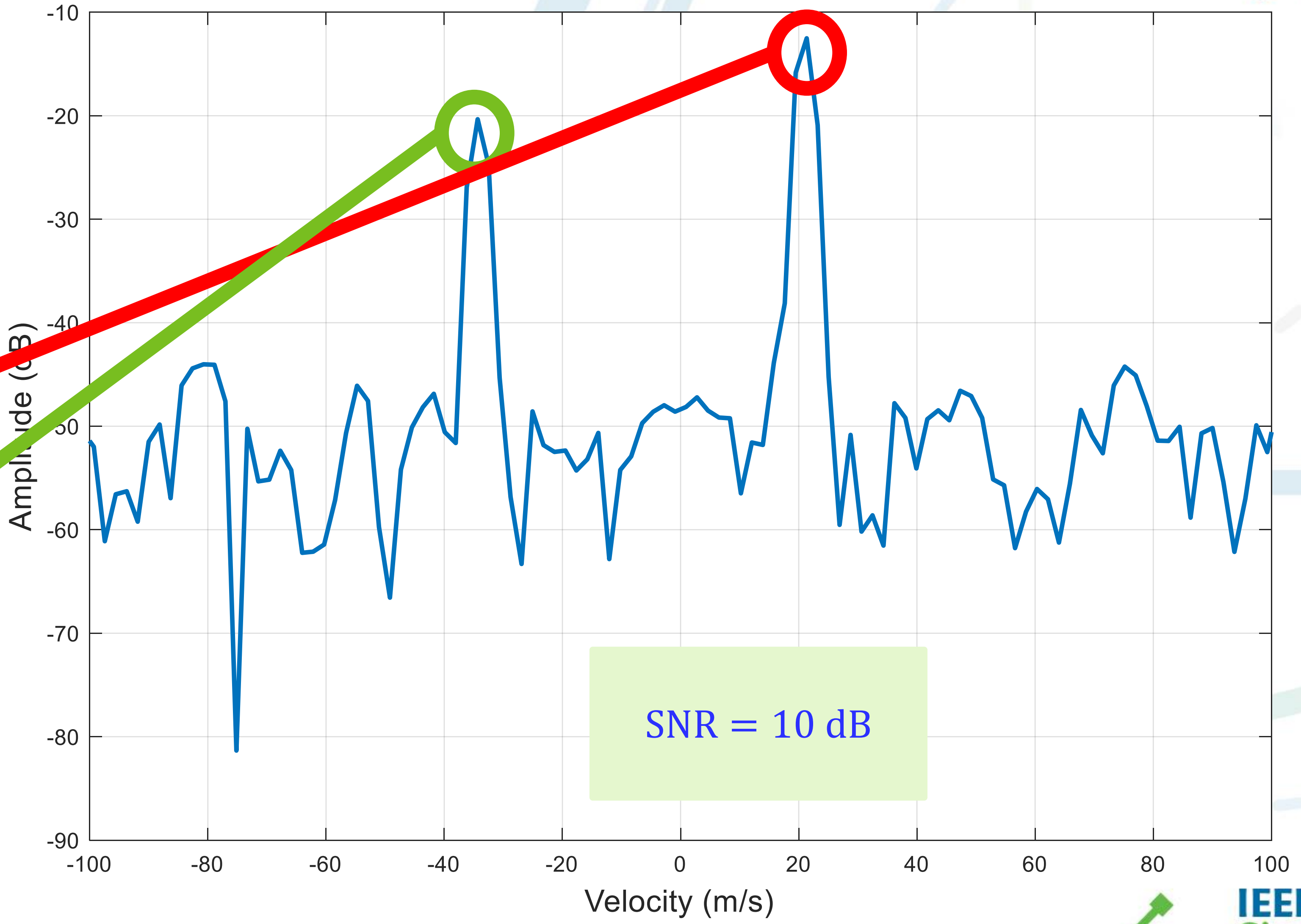
Doppler Effect

$$f_c = 79 \text{ GHz}$$

$$\lambda = 0.0038 \text{ m}$$

$$v_{r_1} = 20 \frac{\text{m}}{\text{s}}$$

$$v_{r_2} = -35 \frac{\text{m}}{\text{s}}$$



$$\text{SNR} = 10 \text{ dB}$$

Lect1_example13.m

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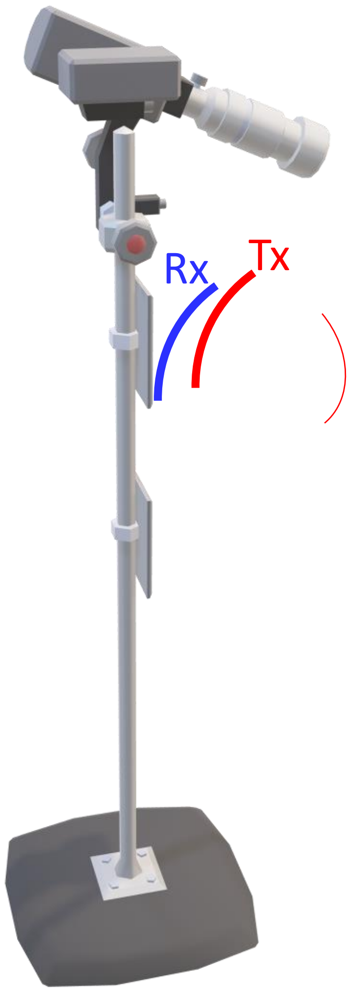
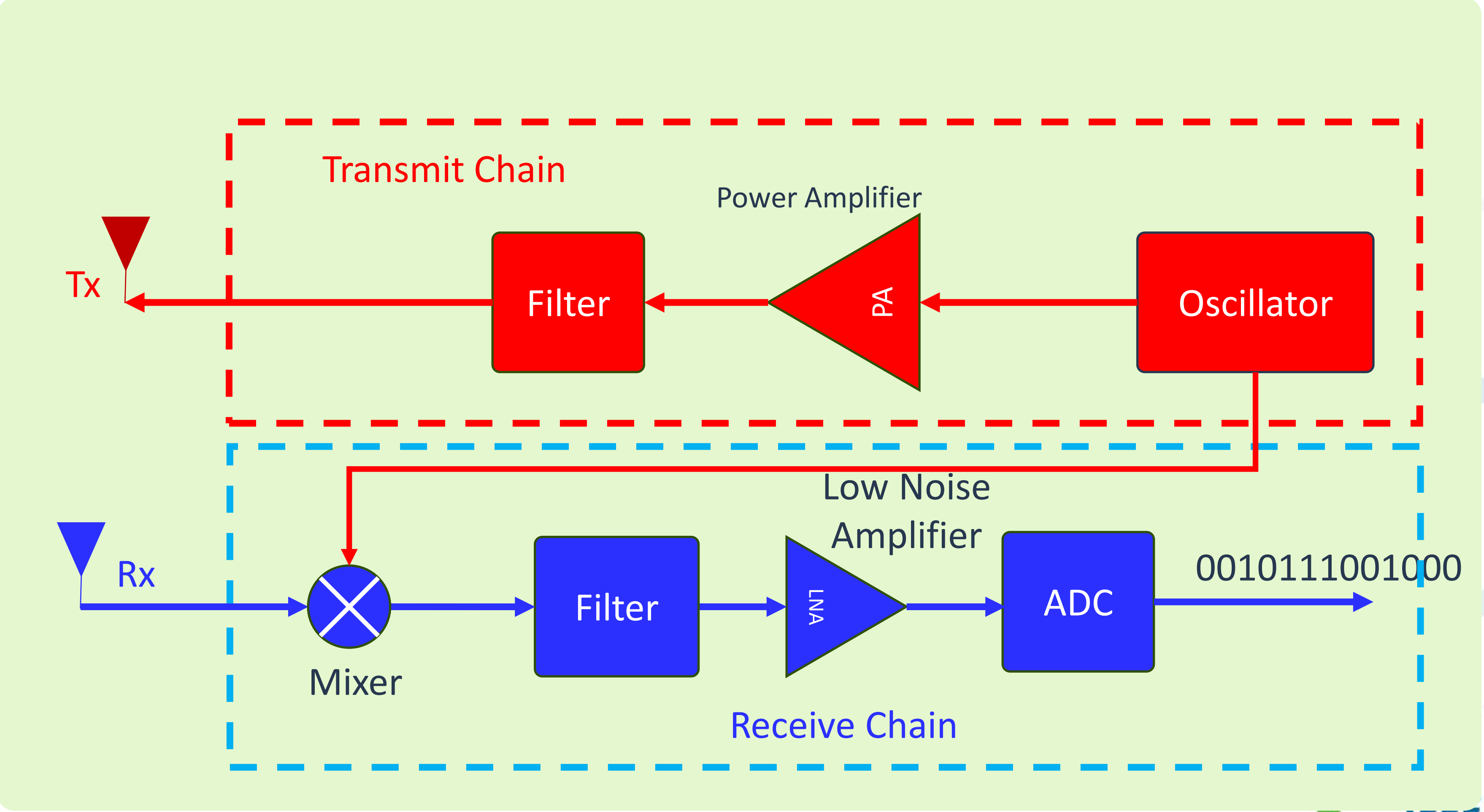
CW Radar

Block Diagram





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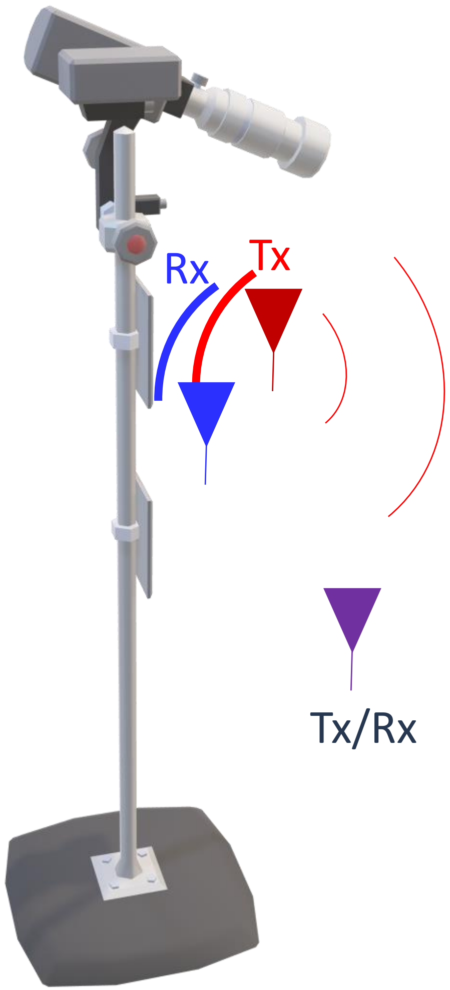
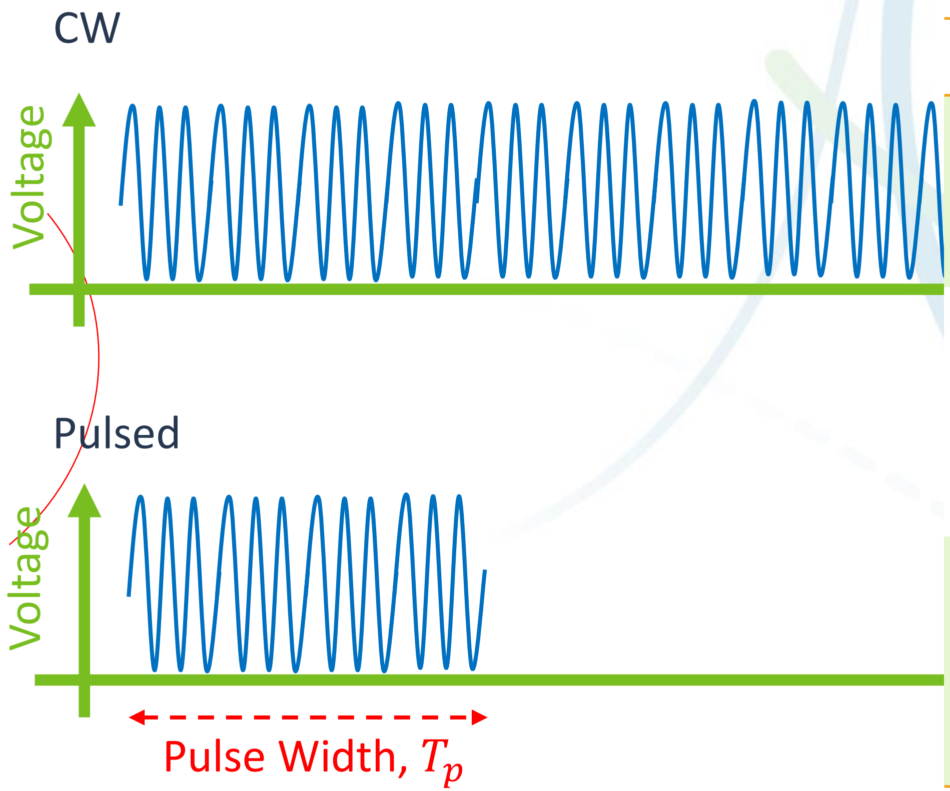
Pulsed or CW?





CW	Pulsed
Requires separate transmit and receive antennas.	Same antenna is used for transmit and receive.
Isolation requirements limit transmit power.	Time-multiplexing relaxes isolation requirements to allow high power.
Radar has no blind ranges.	Radar has blind ranges due to "eclipsing" during transmit events.

$$\text{Bandwidth} \approx \frac{1}{T_p} \quad \Rightarrow \quad \text{Time} \times \text{Bandwidth} \approx 1$$

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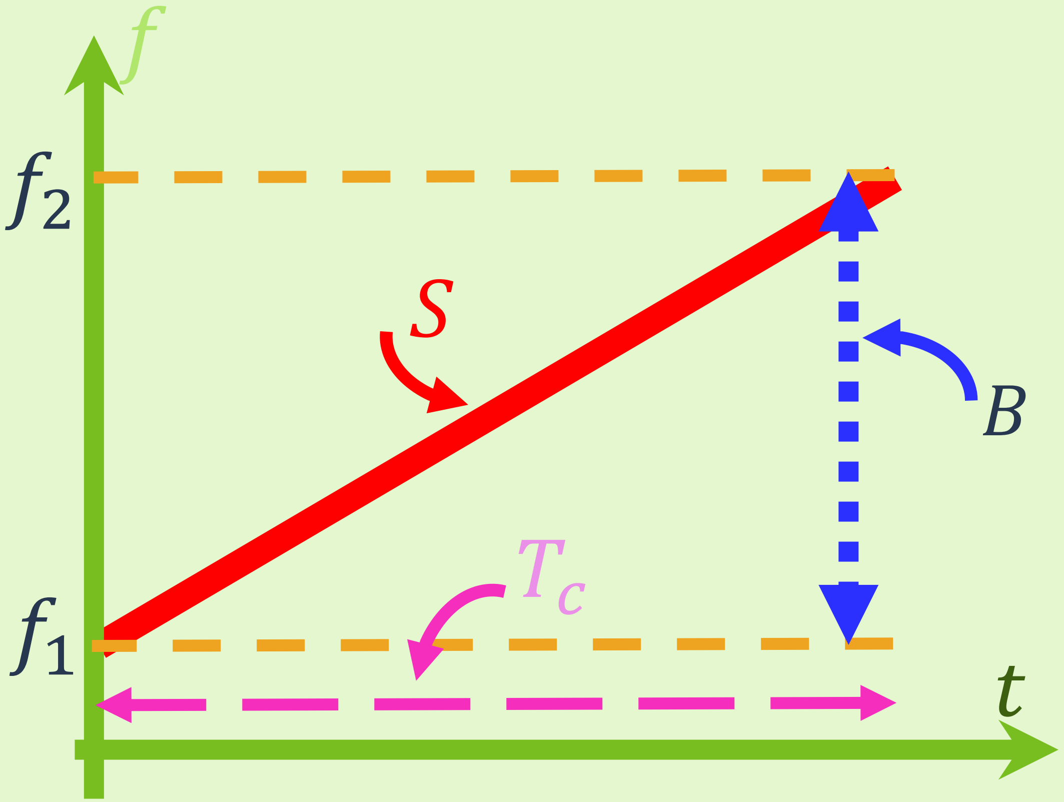
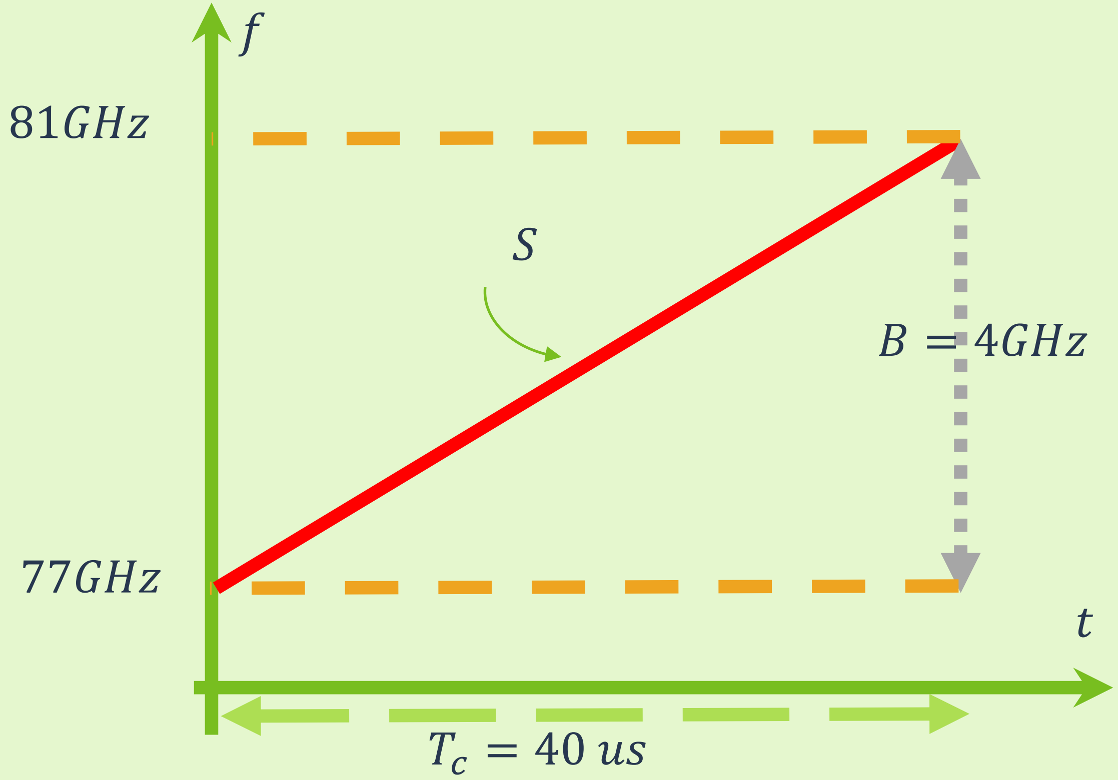
Frequency Modulated Continuous Wave (FMCW)

$$s_{\mathrm{FMCW}}(t) = A_t \cos\left(2\pi\left(f_c t + \frac{B}{2\tau} t^2\right) + \phi\right)$$





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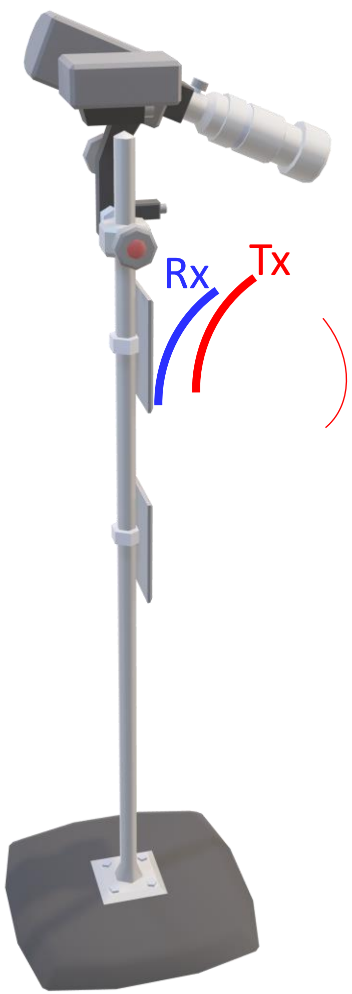
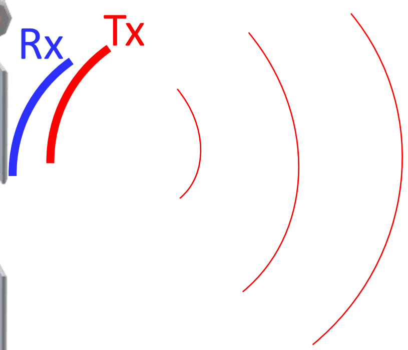
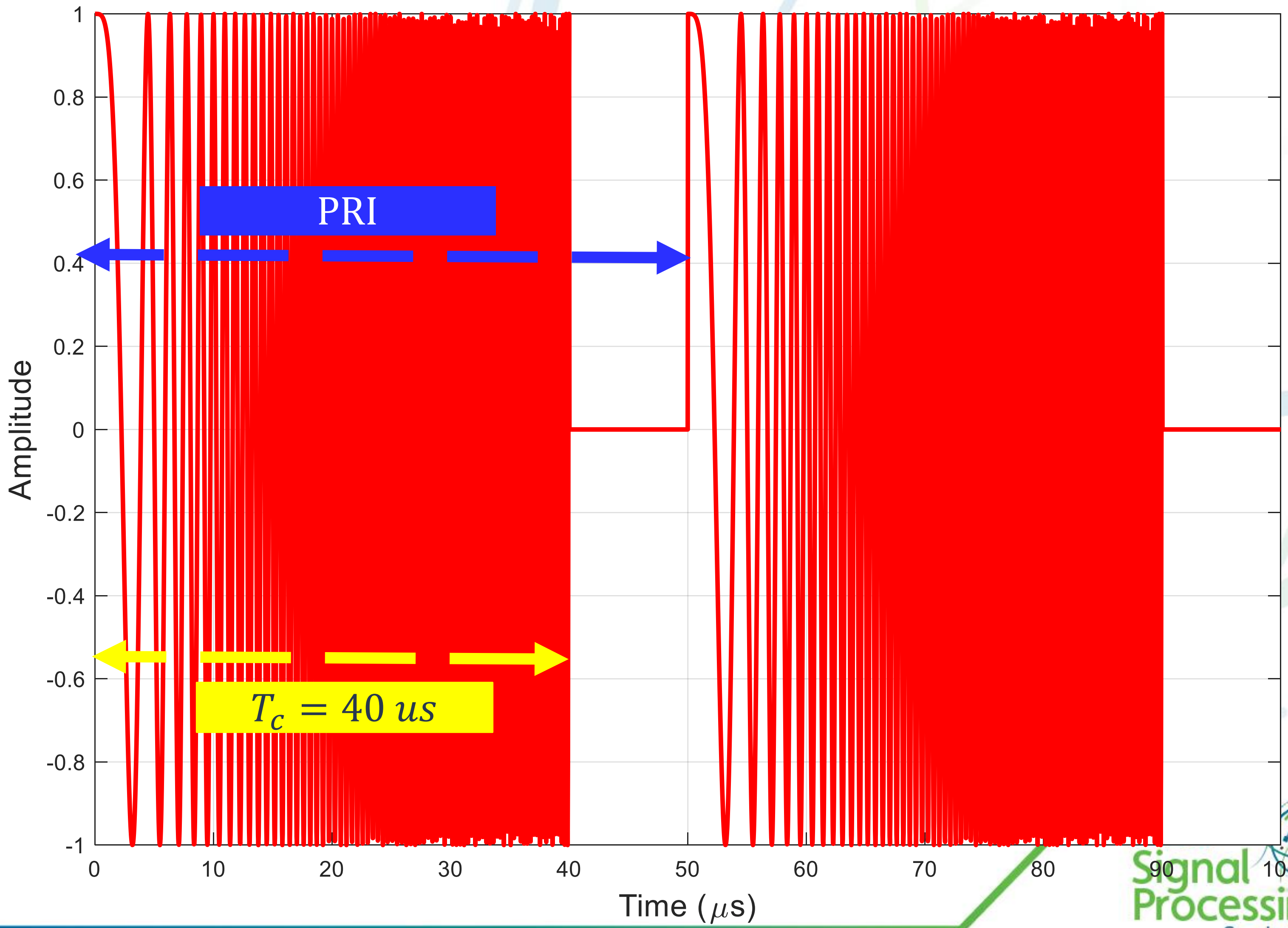
Frequency Modulated Continuous Wave (FMCW)







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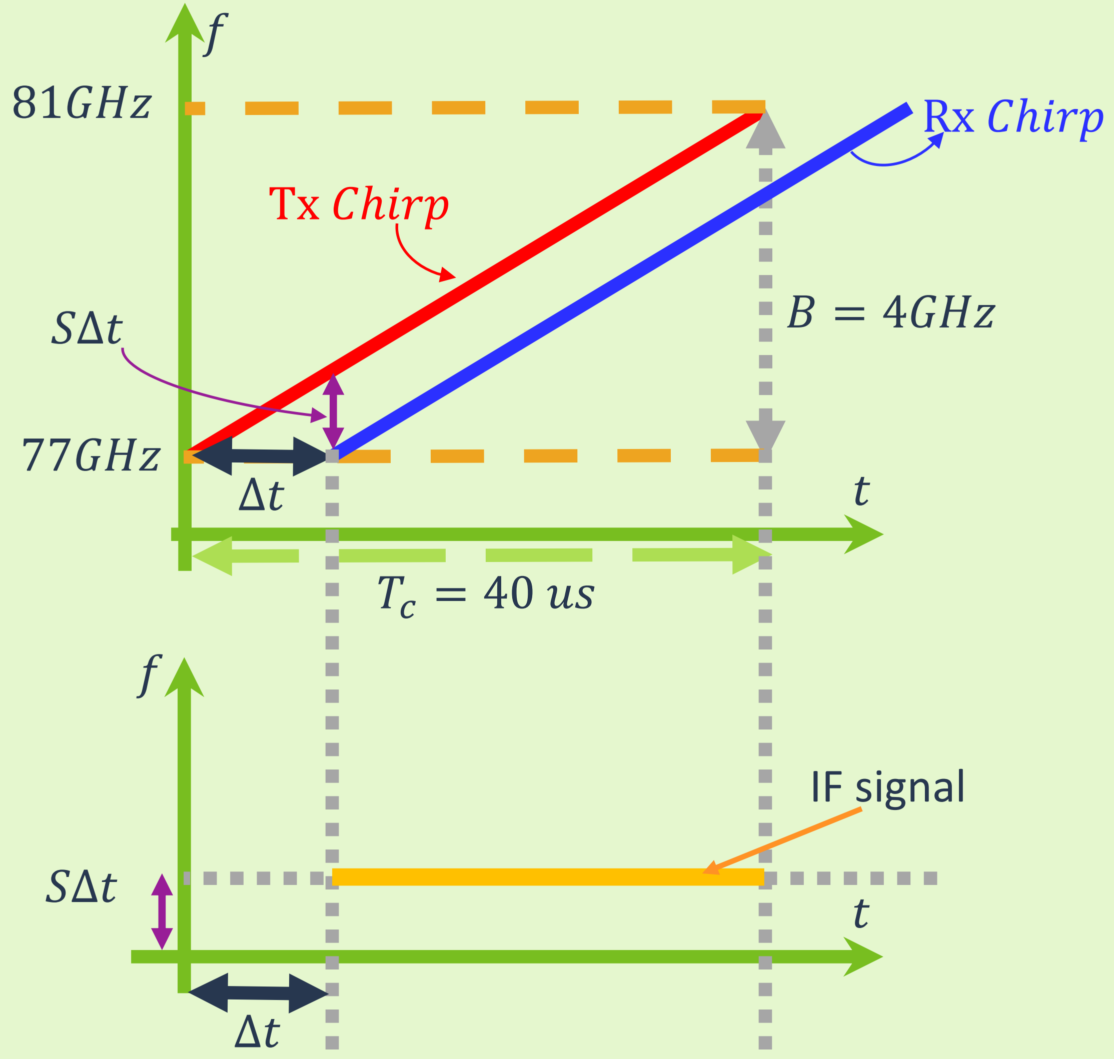
Frequency Modulated Continuous Wave (FMCW)



Example

$$S = \frac{B}{T_c} = \frac{4\ \text{GHz}}{40\ \mu\text{s}} = 100\,\frac{\text{MHz}}{\mu\text{s}}$$

$\Delta t = 0.1\ \mu$s (object at range of 15 m)

$$f_{\text{IF}} = S\Delta t = 100\,\frac{\text{MHz}}{\mu\text{s}} \times 0.1\ \mu\text{s} = 10\ \text{MHz}$$

$f_s = 10$ MHz (complex sampling ADCs) instead of 4 GHz (complex sampling ADCs)

This is called “de-chirp”

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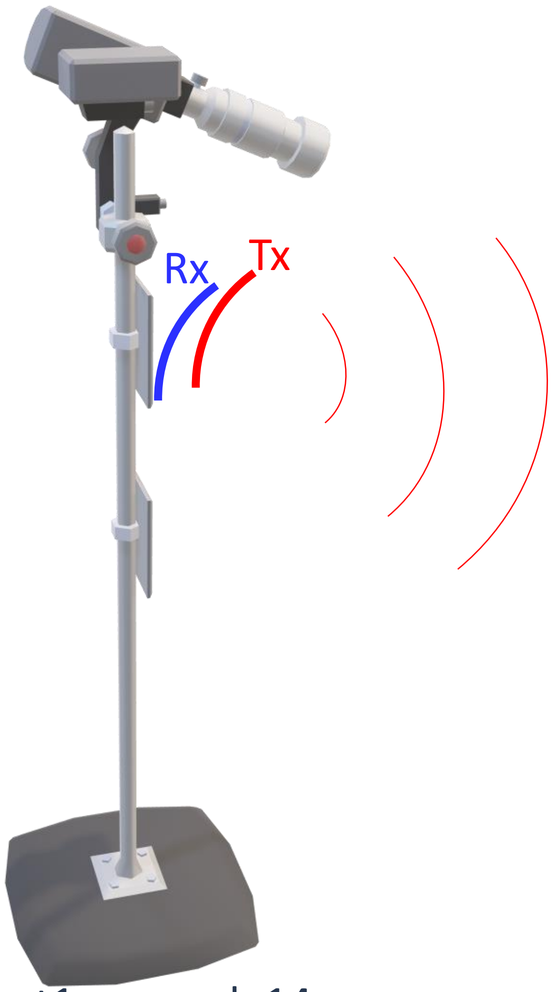
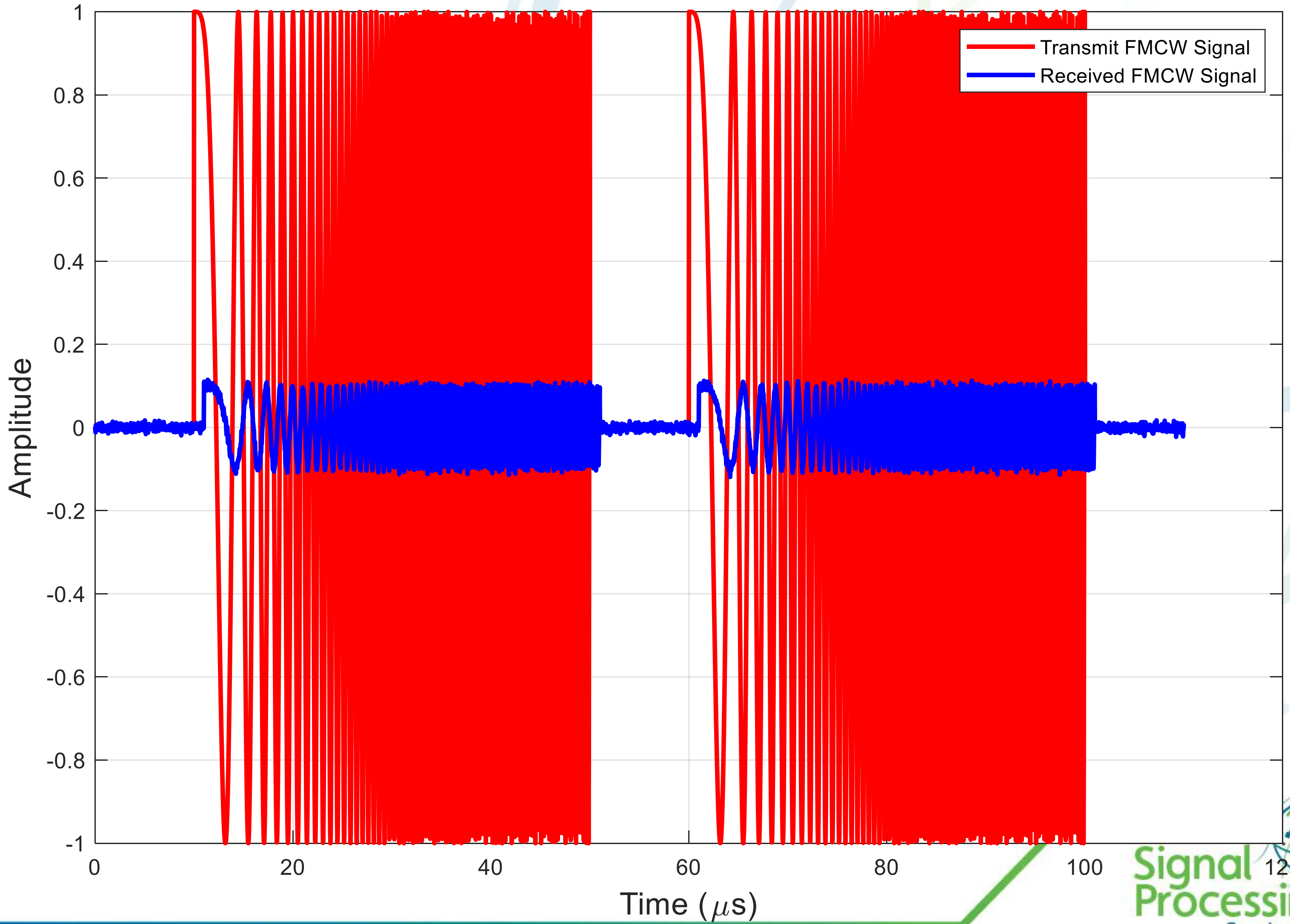
Frequency Modulated Continuous Wave (FMCW)





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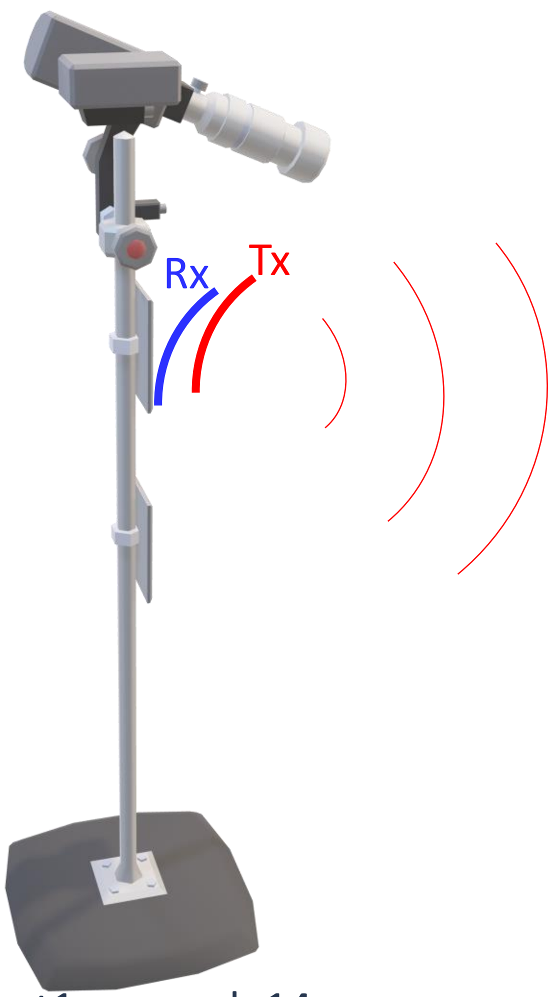
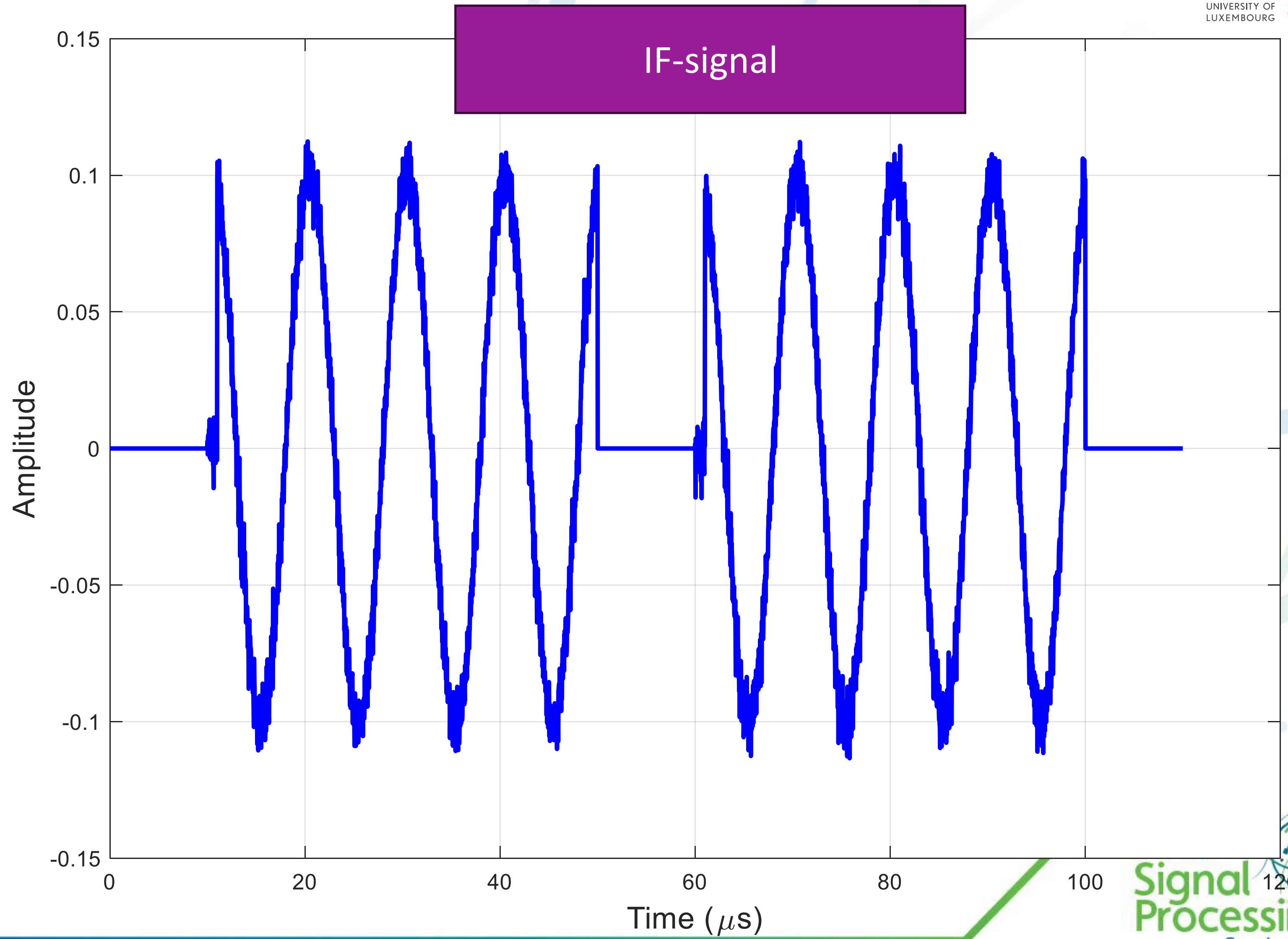
Frequency Modulated Continuous Wave (FMCW)





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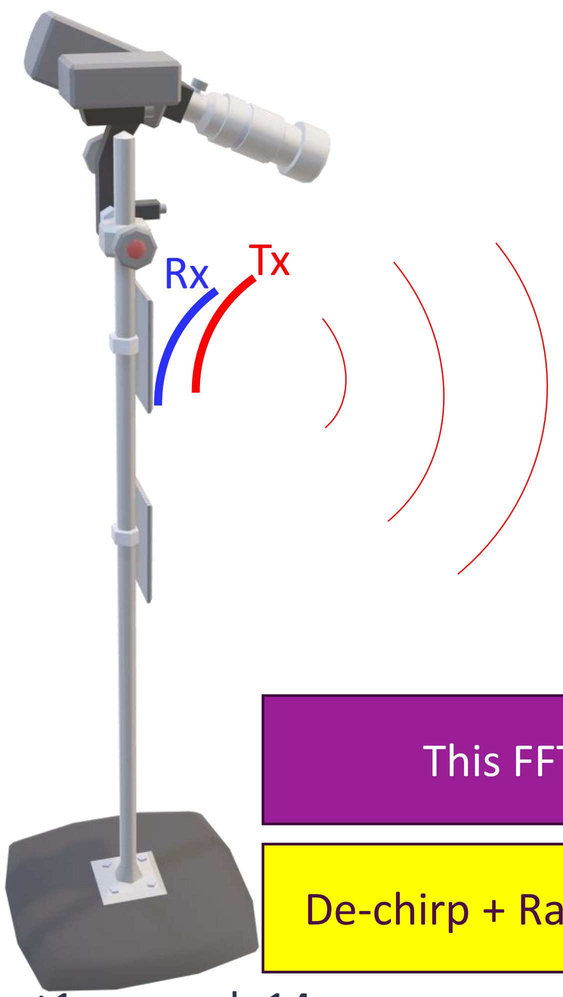
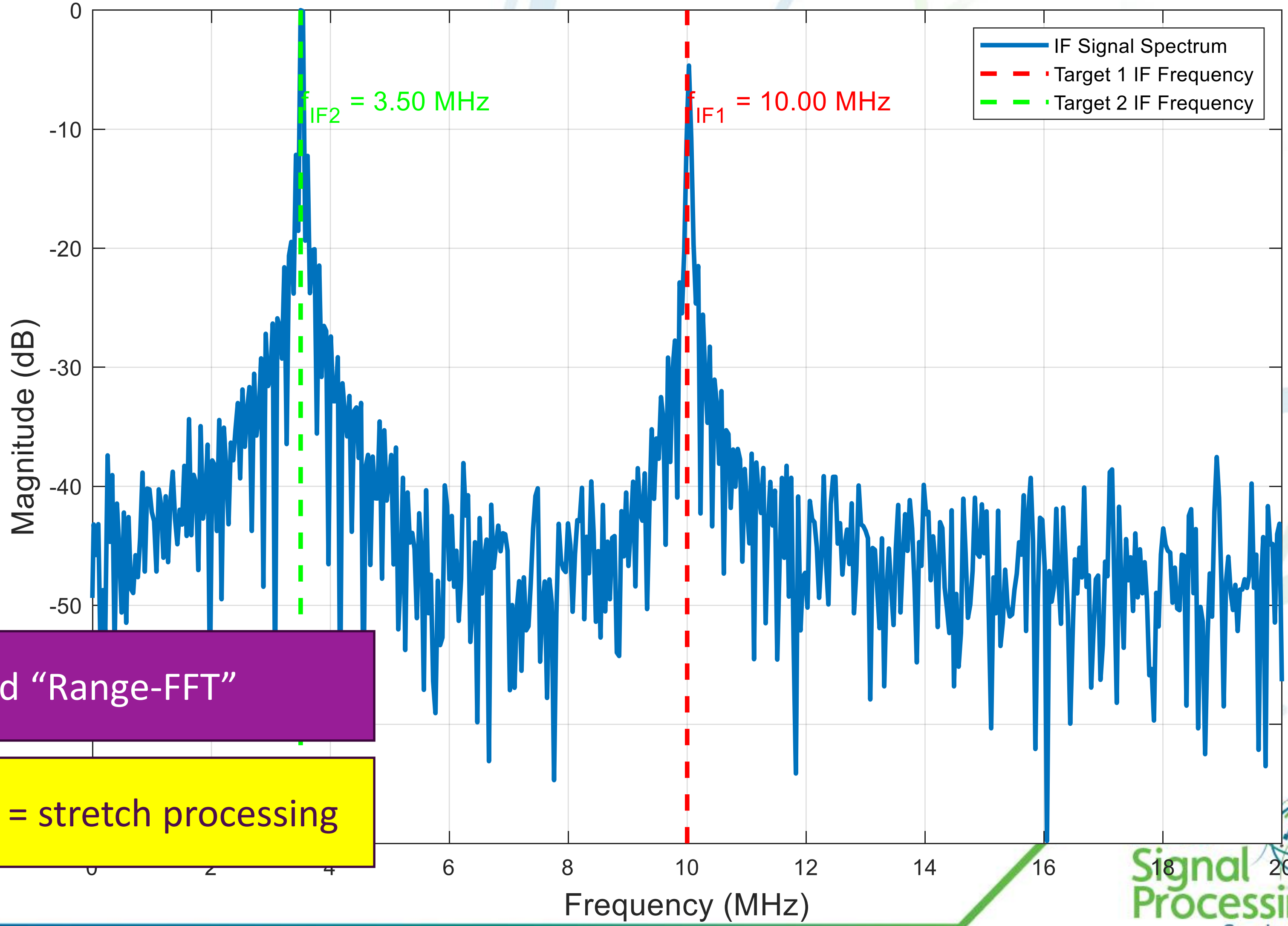
Frequency Modulated Continuous Wave (FMCW)





This FFT is called “Range-FFT”

De-chirp + Range-FFT = stretch processing

Lect1_example14.m

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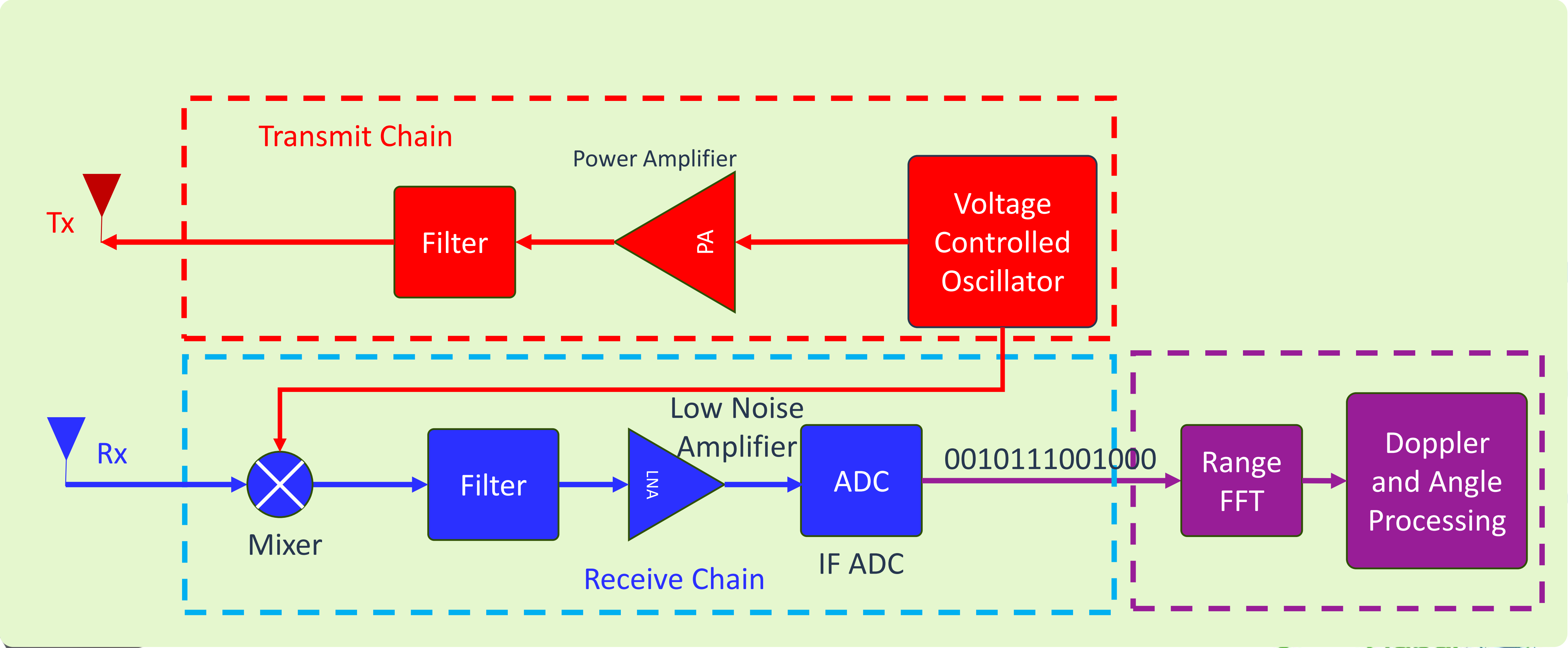
FMCW Radar

Block Diagram



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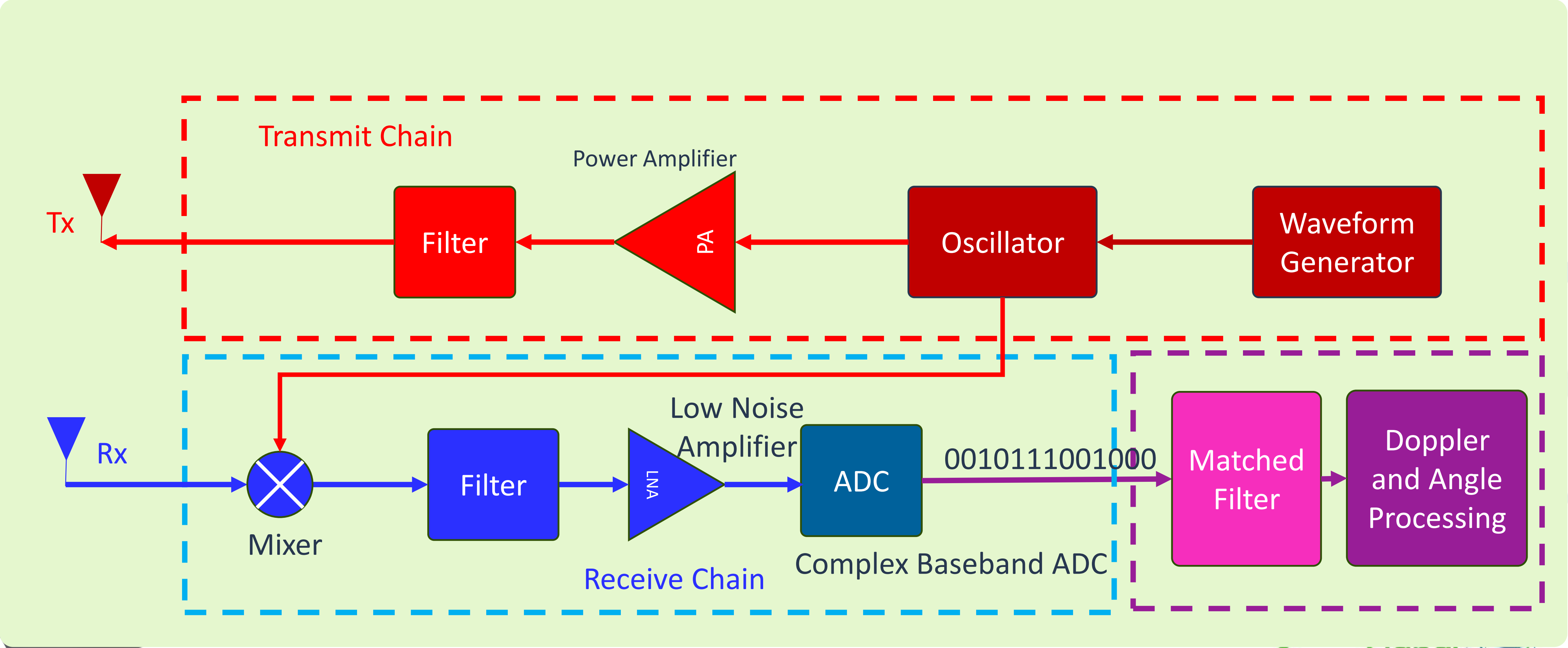
PMCW Radar

Block Diagram



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What we learned from Lecture 1

- Lecture 1 laid the groundwork for understanding radar signal processing by covering fundamental concepts such as radar types, key parameters, pulse compression techniques, different waveforms, and range-Doppler processing.

Scan the QR code for access to the codes

Q & A

Can we still discriminate two targets if they have the same range and Doppler information?

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