INDRAPRASTHA INSTITUTE of INFORMATION TECHNOLOGY DELHI

M.Tech thesis

Doppler-Resilient 802.11ad-Based Ultra-Short Range Automotive Radar

By

Gaurav Duggal (MT17091)

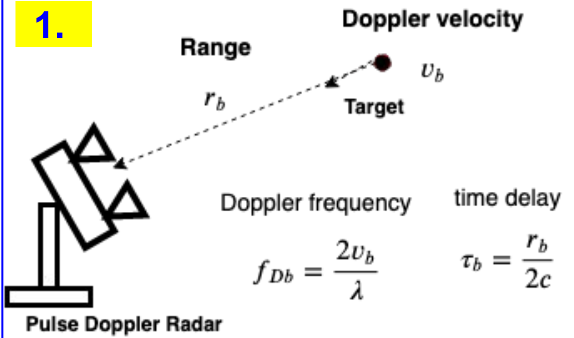
Supervisor: Shobha Sundar Ram

Organisation

1. Pulse Doppler Radar working
2. Literature Survey and introduction to 802.11ad
3. Methodology
4. Radar Signal Model
5. Target Models and Radar Signatures
6. Radar Operating Curves
7. Conclusion

1.1 Pulse-Doppler Radar

1.



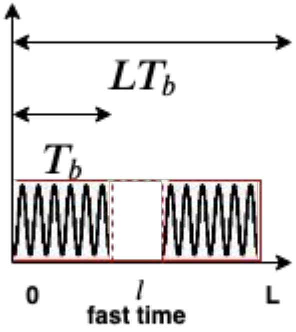
T_{CPI} – *Coherent Processing Interval*

T_{PRI} – *Pulse Repetition Interval*

T_b – *Bit duration*

2.

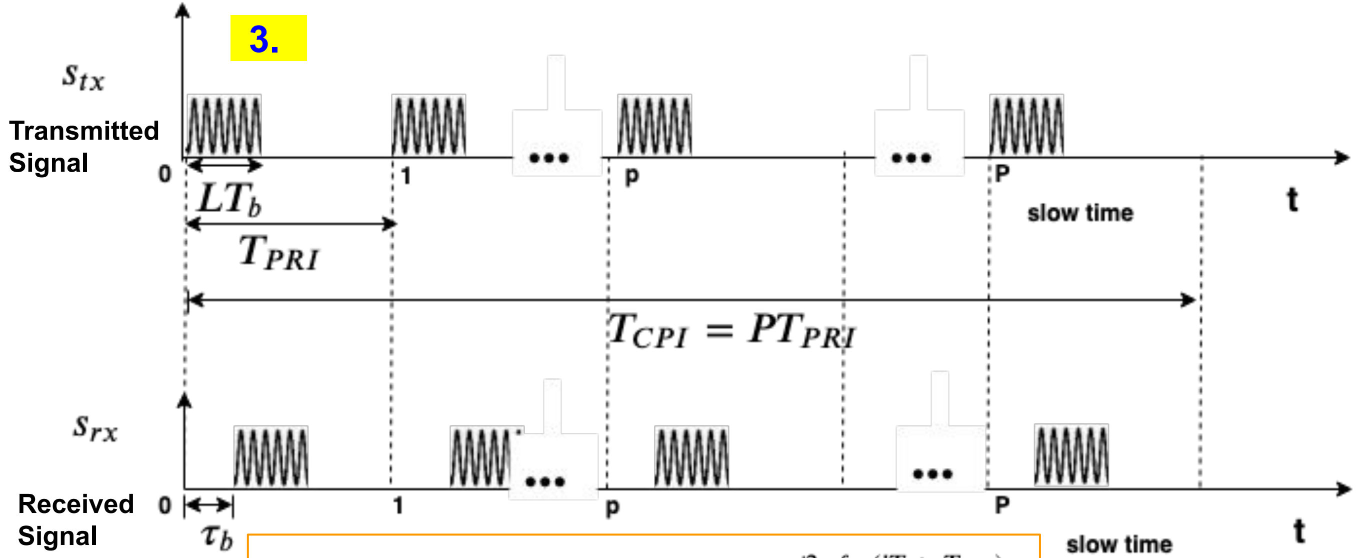
L bits in 1 Sequence



Bit duration

$$T_b = \frac{1}{B}$$

3.



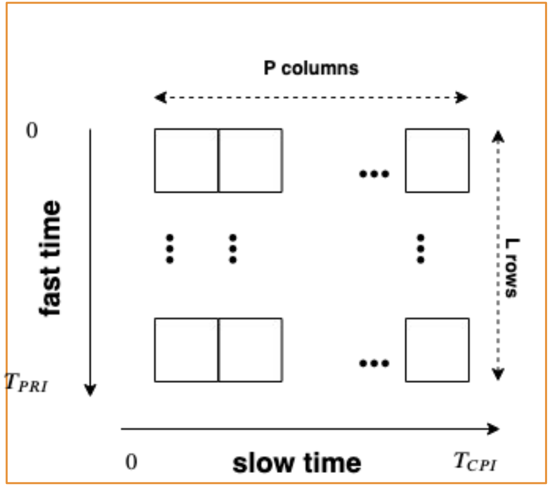
$$s_{rx}(l, p) = s_{tx}(lT_b + pT_{PRI} - \tau_b)e^{-j2\pi f_{Db}(lT_b + pT_{PRI})}$$

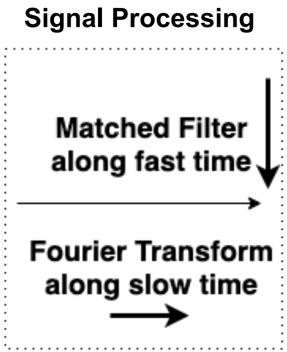
1.2 Pulse - Doppler Radar Signal Processing

1.

Received baseband signal

$$S_{rx}(l,p) = S_{tx}(lT_b + pT_{PRI} - \tau_b)e^{-j2\pi f_{Db}(lT_b + pT_{PRI})}$$





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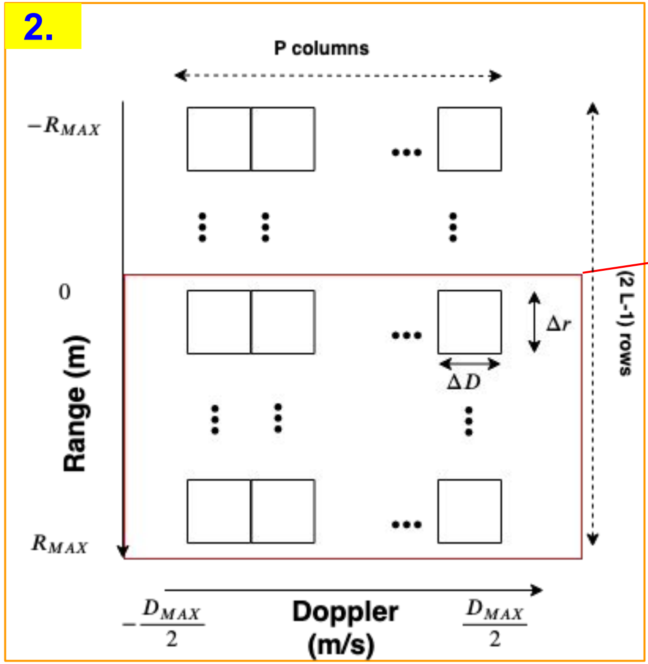
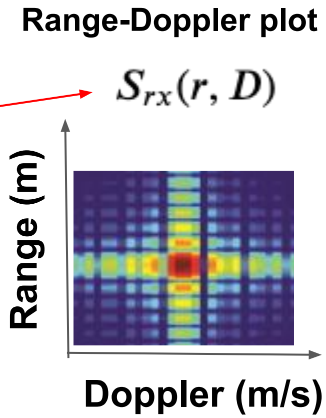




Range Resolution	Max. Range	Doppler velocity resolution	Max. Doppler velocity
$\Delta r = \frac{cT_b}{2}$	$R_{max} = \frac{cLT_b}{2}$	$\Delta D = \frac{\lambda}{2T_{CPI}}$	$D_{max} = \frac{\lambda}{4T_{PRI}}$

2.1 Introduction to the IEEE 802.11ad

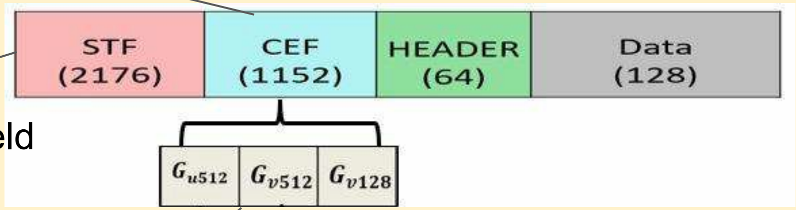
1. 60 GHz wireless link for 5G communications between autonomous vehicles
2. Signal bandwidth: 1.76 GHz - significantly more than 802.11ac (20/40MHz)
3. Joint radar and communication framework

Range Resolution

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

Channel Estimation Field

Short Training Field

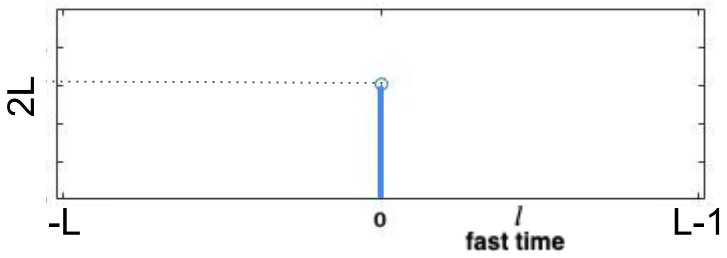


2 Golay Sequences of length 512 bits, 1 Golay Sequence of length 128

Total number of bits in a packet = (2176+1152+64+128)

Procotol	Range Resolution
802.11ad	0.085 m
802.11ac	0.9 m
802.11n	3.75 m
802.11g	7.5 m

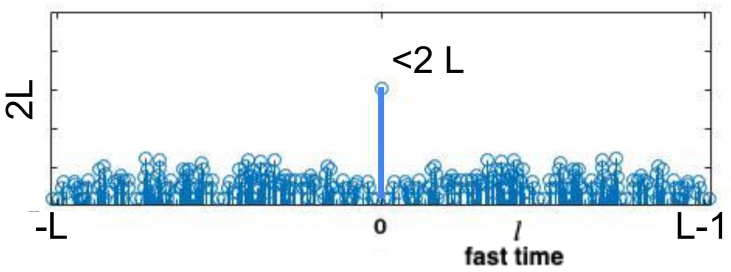
2.2 Golay Perfect Autocorrelation Property



1. This is the received signal for a static target at zero delay and we see there are zero sidelobes

$$(G_{a,L}[l] * G_{a,L}[l]) + (G_{b,L}[l] * G_{b,L}[l]) = 6L\delta[l], l = -L, \ldots .0, \ldots L-1$$

2. This is the received signal for a moving target at zero delay and we see there are sidelobes present



$$(G_{a,L}[l] * G_{a,L}[l]) + (G_{b,L}[l] * G_{b,L}[l])e^{j\theta} \neq 6L\delta[l], l = -L, \ldots .0, \ldots L-1$$

2.3 Literature Survey

Parameters	**Current Literature**	**Shortcomings**
Range	Long Range (~200m)	Attenuation is high (20 dB/km at sea level) for 60 GHz
Target Model	Simple point targets	For short range radar, targets are closer, we hypothesize simple point target model isn't accurate
Type of target	Static	Automotive scenario has moving targets

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3.1 Methodology

1.	Test extended target model hypothesis
2.	Implement Standard Golay (SG) Processing and Modified Golay (MG) Processing to test range-sidelobe level reduction for simple point scatterer
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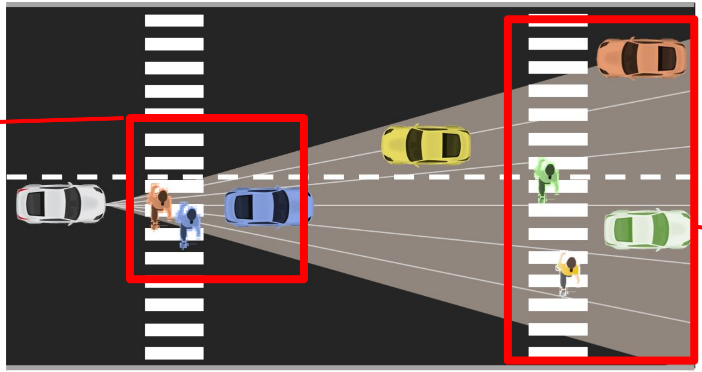
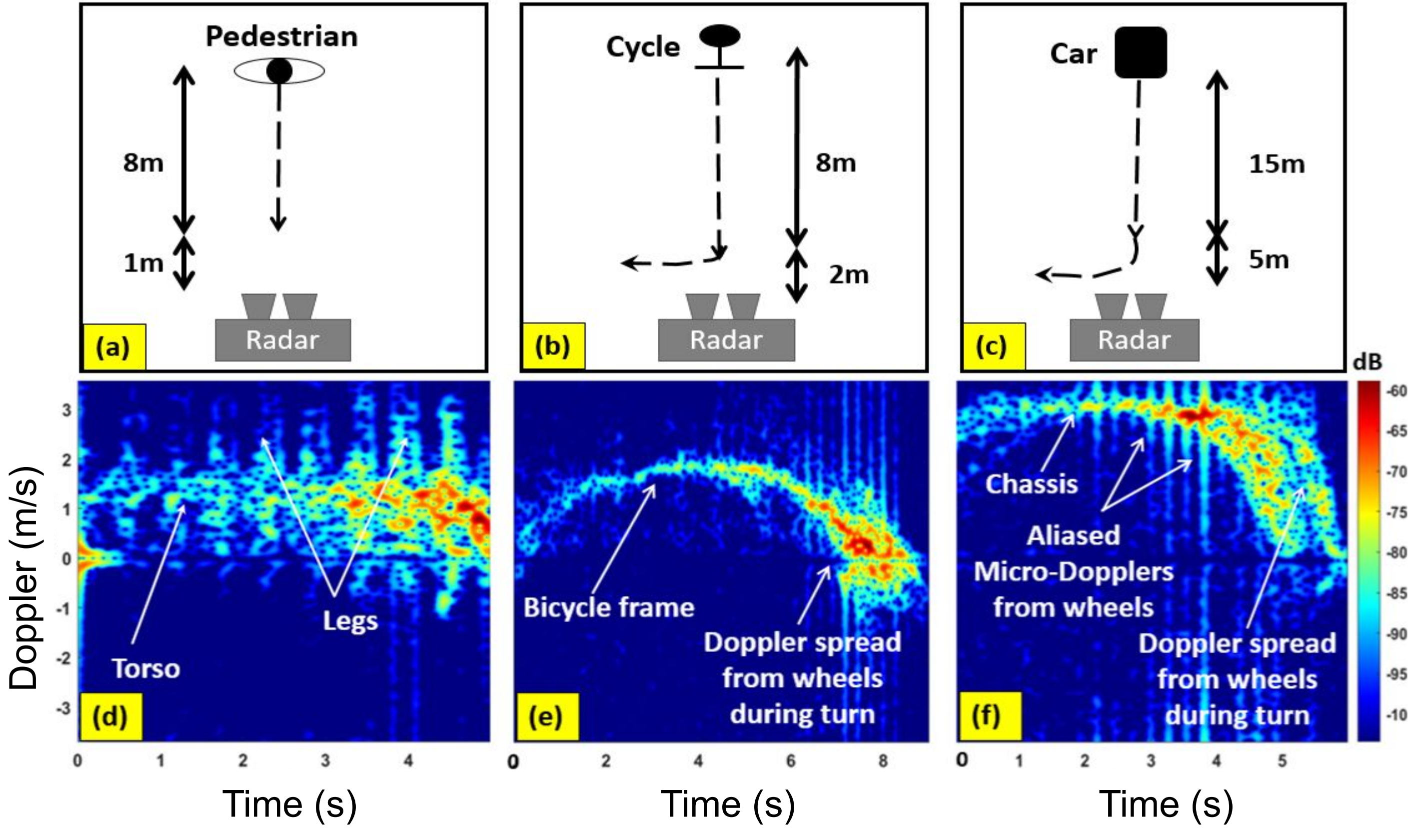
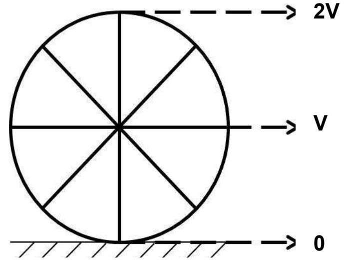
Short range targets fit in multiple bins and need to be modelled as extended targets



Long range targets fit in 1 bin and should appear as point targets

3.2 Short Range Automotive Scenario Experiment





Wheel

Test Setup

4.1 Standard Golay (SG) waveform Example, L=512

Example for 4 packets

1. Consider a Golay Pair $\{G_{a,L}[n], G_{b,L}[n]\}$ of length 512 bits each.

Transmit Waveform

$G_{1,L}[l] = G_{a,L}[l]$	$G_{2,L}[l] = G_{b,L}[l]$	$G_{3,L}[l] = G_{a,L}[l]$	$G_{4,L}[l] = G_{b,L}[l]$
Packet p=0	Packet p=1	Packet p=2	Packet p=3

Receiver matched filter processing

$$\sum_{p=0}^{3} e^{jp\theta}(G_{p,L}[l] * G_{p,L}[l]) \neq 6L\delta[l], \quad l = -L, ..l, ...(L-1)$$

4.2 Modified Golay (MG) waveform, L=512

Example for 4 packets

1. Generate Prou-Thue-Morse (PTM) sequence of length 2 bits - **{0,1}**
2. In PTM sequence replace all **0**'s with Golay Pair **{$G_{a,L}$[l],$G_{b,L}$[l]}** and **1's** with Golay Pair **{-$G_{b,L}$[-l],$G_{a,L}$[-l]}**

0 (Packets p=0 and p=1) — **1** (Packets p=2 and p=3)

Transmit Waveform →

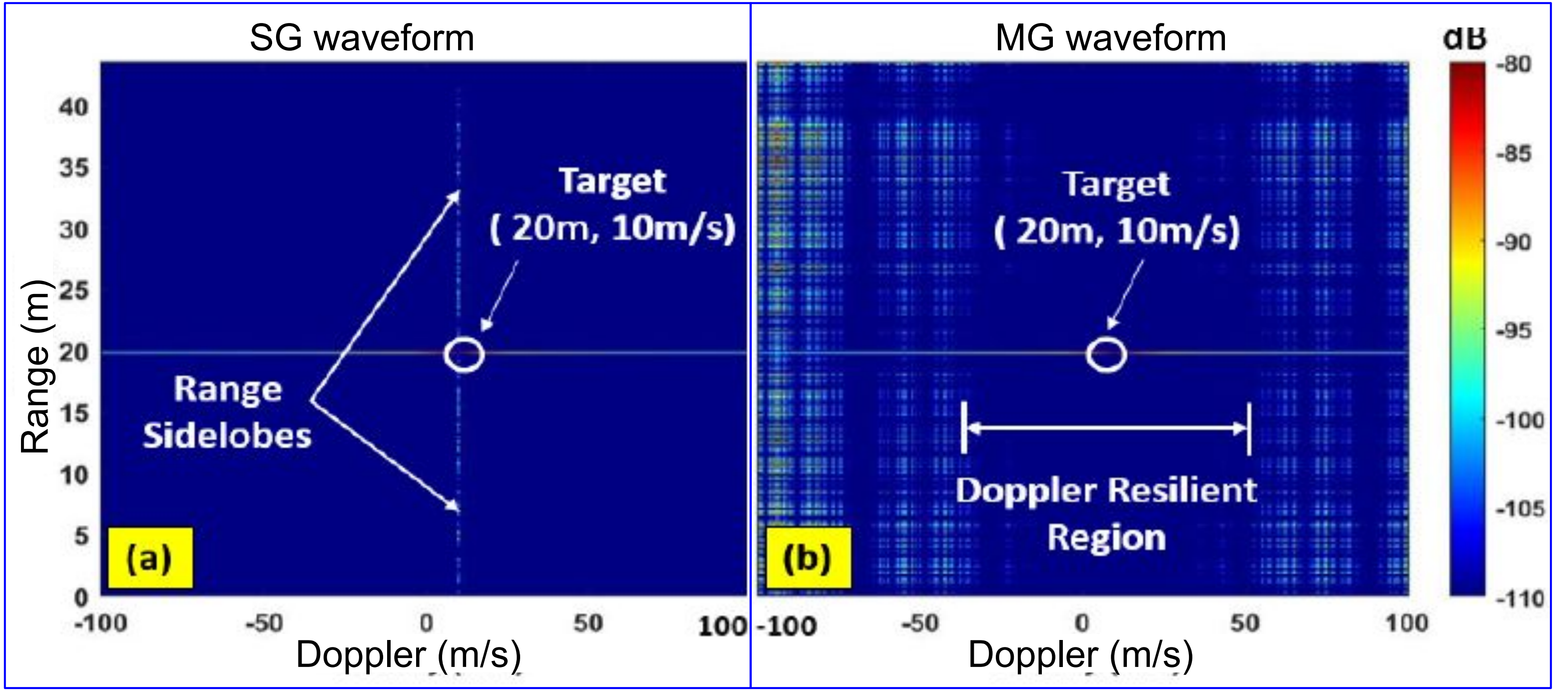
$G_{1,512}[l] = G_{a,L}[l]$	$G_{2,512}[l] = G_{b,L}[l]$	$G_{3,512}[l] = -G_{b,L}[-l]$	$G_{4,512}[l] = G_{a,L}[-l]$
Packet p=0	Packet p=1	Packet p=2	Packet p=3

Receiver matched filter processing

$$\sum_{p=0}^{3} e^{jp\theta}(G_{p,L}[l] * G_{p,L}[l]) \approx 1(G_{1,L}[l] * G_{1,L}[l]) + 2(G_{2,L}[l] * G_{2,L}[l]) + 3(G_{3,L}[l] * G_{3,L}[l])$$
$$= 1((G_{b,L}[l] * G_{b,L}[l]) + (G_{a,L}[-l] * G_{a,L}[-l])) + 2((-G_{b,L}[-l] * -G_{b,L}[-l]) + (G_{a,L}[-l] * G_{a,L}[-l]))$$
$$= (2L + 2(2L))\delta[l]$$
$$= 6L\delta[l]$$

Pezeshki et.al, Doppler resilient Golay complementary waveforms Trans. Information Theory 2008

4.3 MG vs SG for a moving point target, P=2048 packets



Range sidelobes have been suppressed by 20 dB

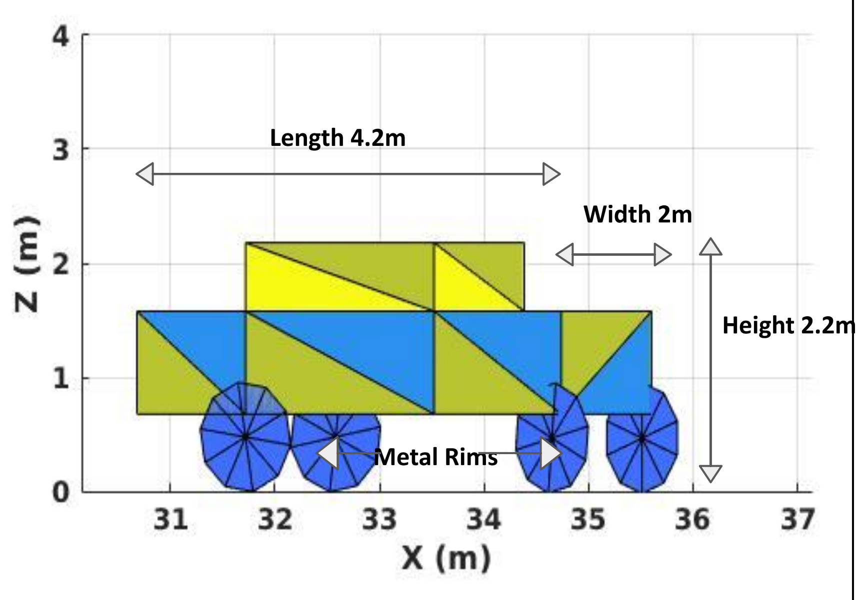
4.4 Ultra Short Range Radar

Parameter	Proposed Radar	Commercial SRR
Carrier Frequency	60 GHz	77 GHz
Bandwidth	1.76 GHz	2 GHz
Range resolution	0.085 m	0.075 m
Maximum unambiguous range	44 m	40 m
Pulse repetition interval	2 us	1.67 us
Velocity resolution	0.6 m/s	0.27 m/s
Maximum unambiguous velocity	625 m/s	111 m/s
Coherent Processing interval	0.0041 s (P=2048)	0.007 s

Ultra short range automotive radars have the following usage scenarios:

1. Parking assistance
2. Lane change assistance
3. Object detection and tracking

5.1 Extended target model of a car



Primitive chosen for a car is a triangular plate and can be represented in 3D space by its centroid

Radar cross section of a triangular plate

$$\sigma_b[n] = \frac{4\pi A_b^2 \cos^2\theta_b[n]}{\lambda^2}\left(\frac{\sin\left(kd_b \sin\frac{\theta_b[n]}{2}\right)}{kd_b \sin\frac{\theta_b[n]}{2}}\right)^4$$

$A_b = area\ of\ the\ plate$

$\theta_b = aspect\ angle$

$d_b = dimension\ along\ aspect\ angle$

$k = propagationconstant$

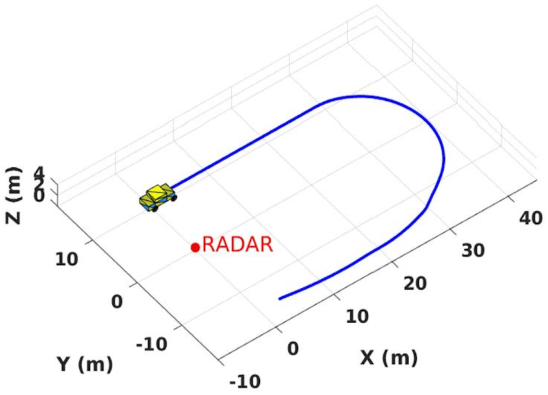
$\lambda = wavelength$

Received signal

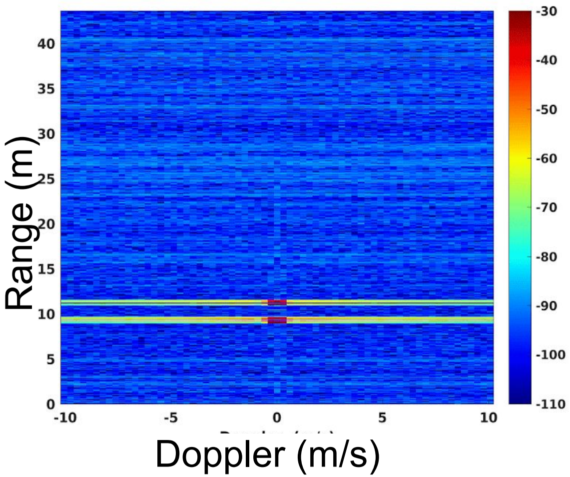
$$x_R(t) = \sum_{b=0}^{B} A\frac{\sqrt{\sigma_b(\theta)}}{r_b(t)^2} x_T\left(t - \frac{2r_b(t)}{c}\right) + \eta$$

5.2 Car range-Doppler MG waveform vs SG waveform

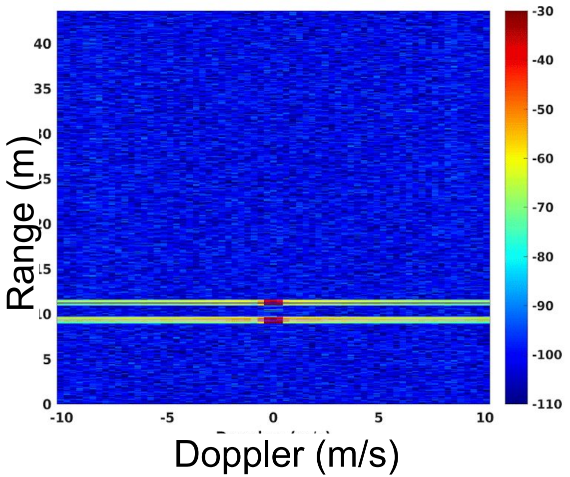
Scene View



SG waveform



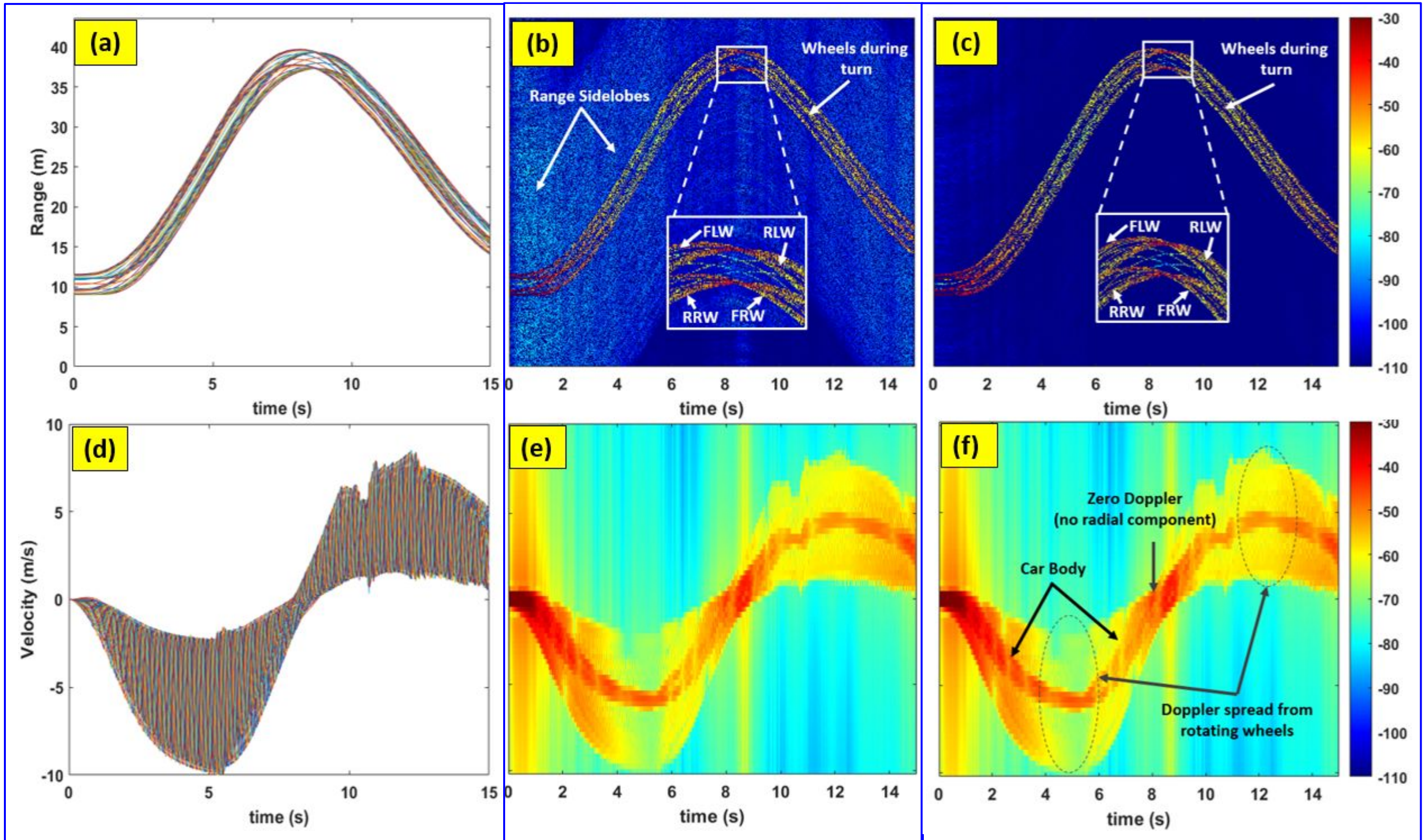
MG waveform



Key Observations:

1. The extended target model of the car manifests itself over multiple range-Doppler bins.
2. The power of the reflected signal from the car causes the fluctuations in colour in the range-Doppler plot.
3. Range sidelobes are suppressed in the MG waveform making it Doppler resilient.

5.3 Car Radar Signatures



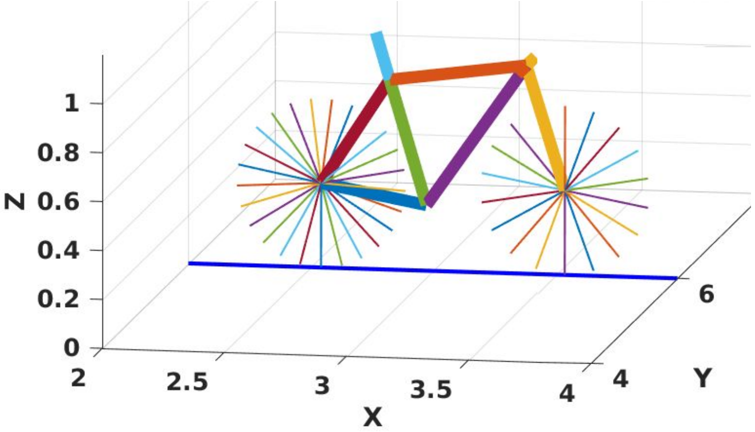
Ground Truth

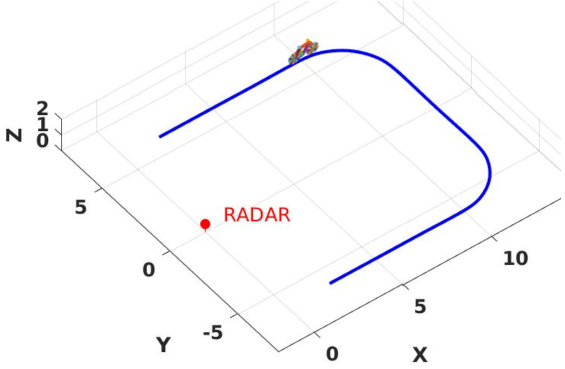
SG waveform

MG waveform

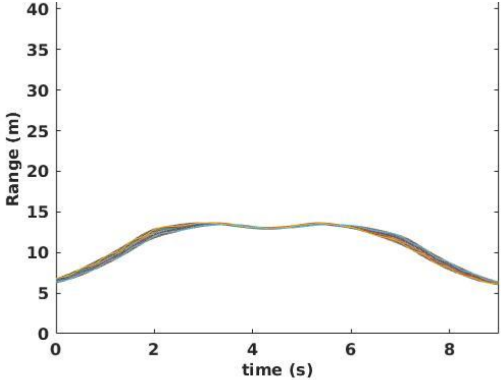
5.4 Extended target model of a bicycle

Primitives are rods



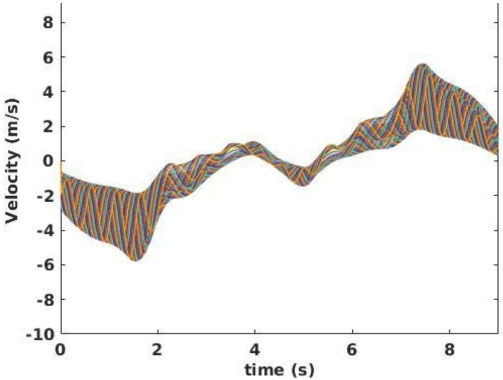


Range-time ground truth



$$\sigma_b[n] = \frac{2\pi a_b L_b^2}{\lambda} \cos^2(\theta_b[n]) \left(\frac{\sin\left(k L_b \sin\theta_b[n]\right)}{k L_b \sin\theta_b[n]} \right)^2$$

Doppler-time ground truth

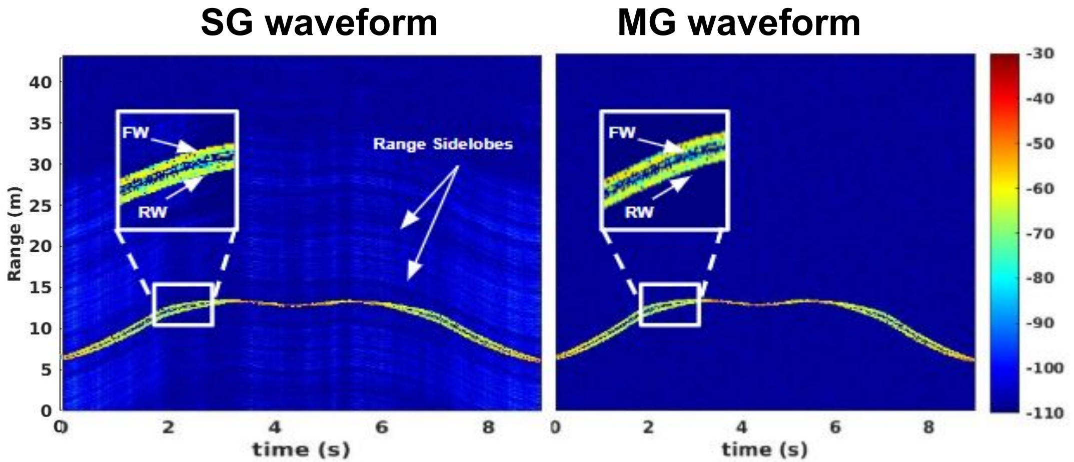


The metal rods of the frame and the metal rods of the spokes are modelled in this electromagnetic model

5.5 Extended Target Model: Bicycle radar signatures

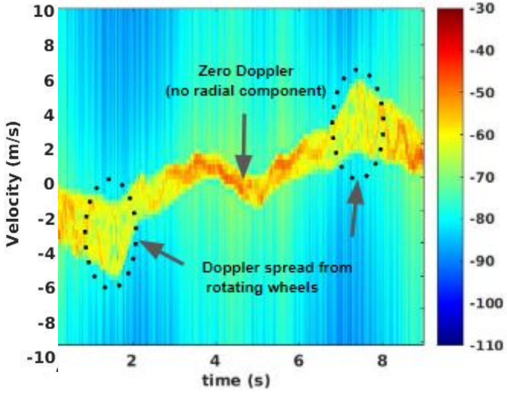
Range-time plot

1. Range-sidelobes are supressed in the MG waveform
2. Micro-range information from the wheels is visible

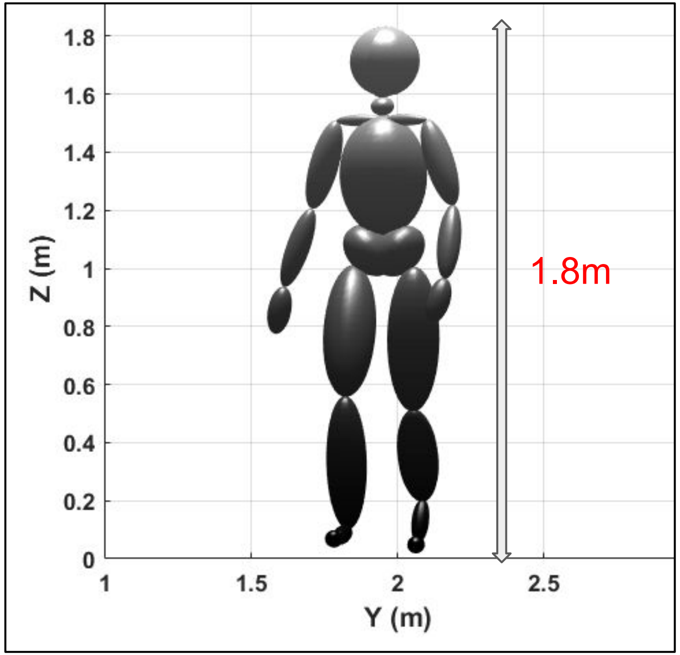


Doppler-time plot

1. The aspect angle variation manifests itself in the variation of the received power and we can see it on the colour bar
2. When the bicycle is directly in front of the radar, it is moving in the transverse direction hence there is zero Doppler in the received signal



5.6 Extended target model of a pedestrian



Radar cross section of an ellipsoid

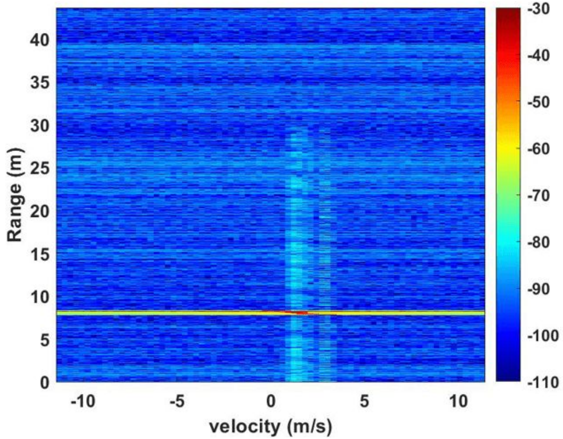
$$\sigma_b[n] = \frac{\frac{1}{4} R_b^4 H_b^2}{R_b^2 \sin^2 \theta_b[n] + \frac{1}{4} H_b^2 \cos^2 \theta_b[n]}$$

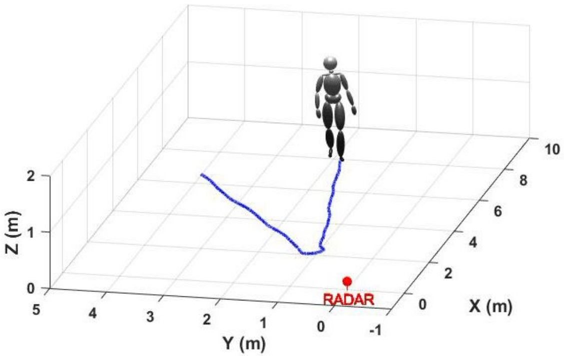
H_b = length of the ellipsoid
R_b = radius of the ellipsoid

SS Ram, H Ling , Simulation of human microDopplers using computer animation data

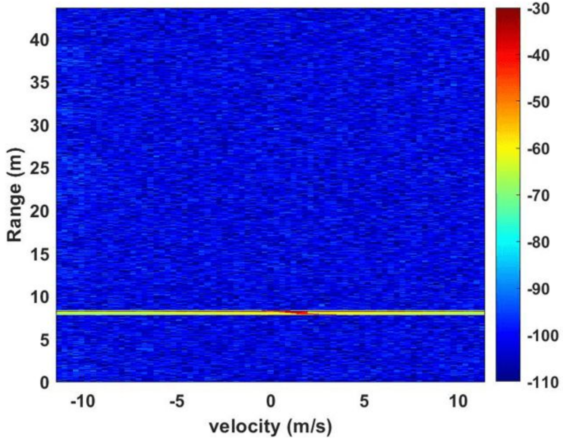
5.7 Pedestrian MG waveform vs SG waveform

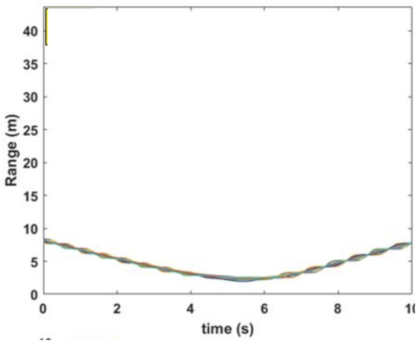
SG Waveform





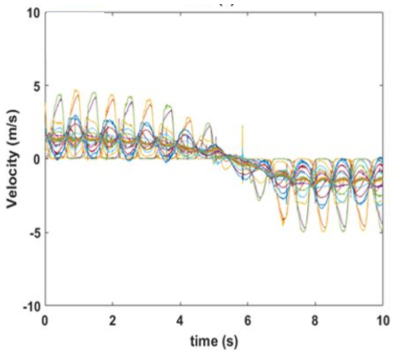
MG Waveform





Range-time
Ground truth

Doppler-time
Ground truth



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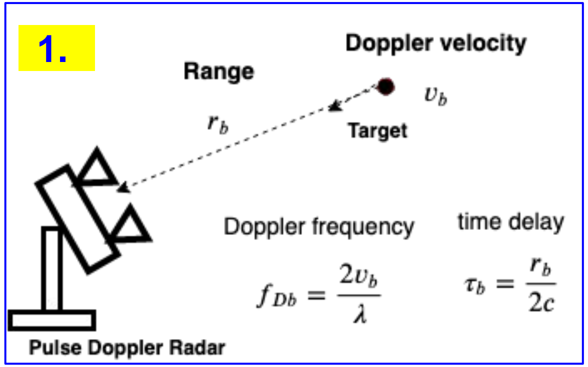

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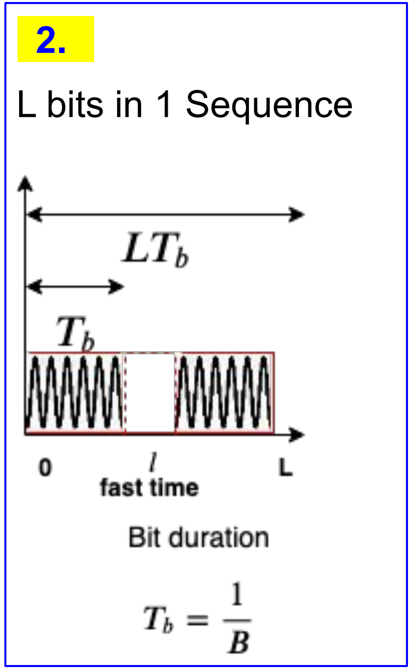

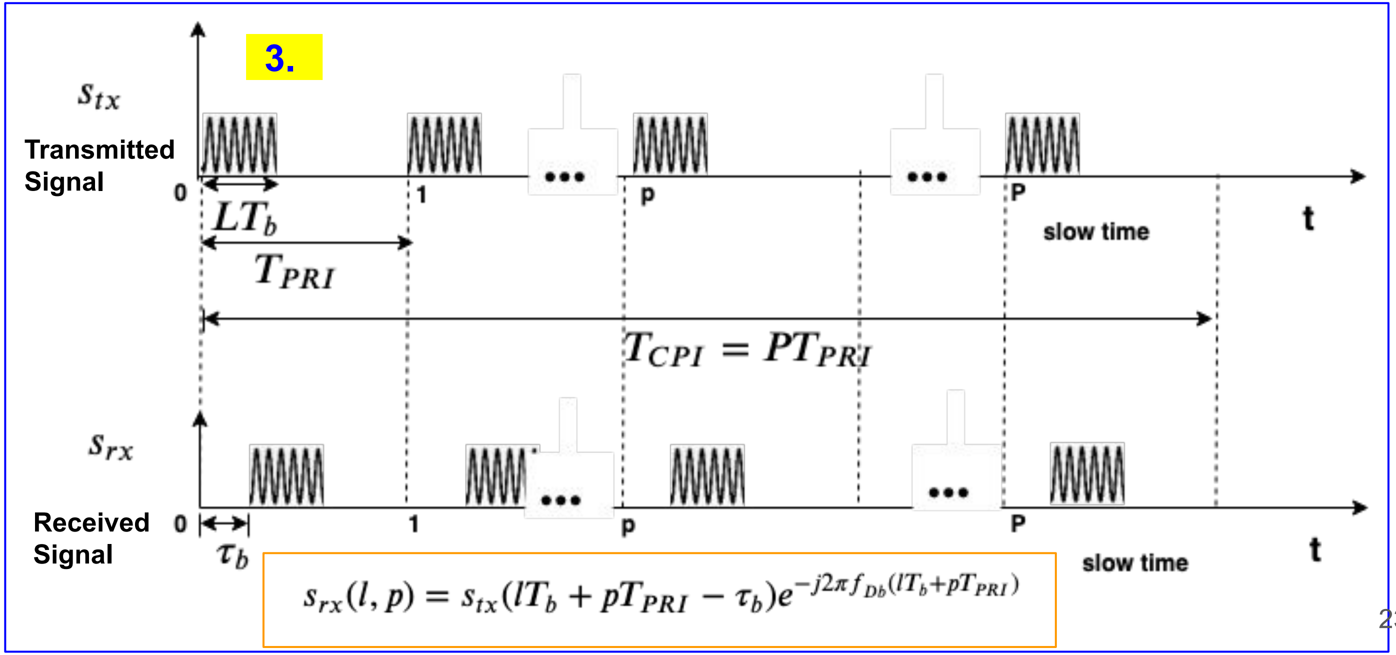

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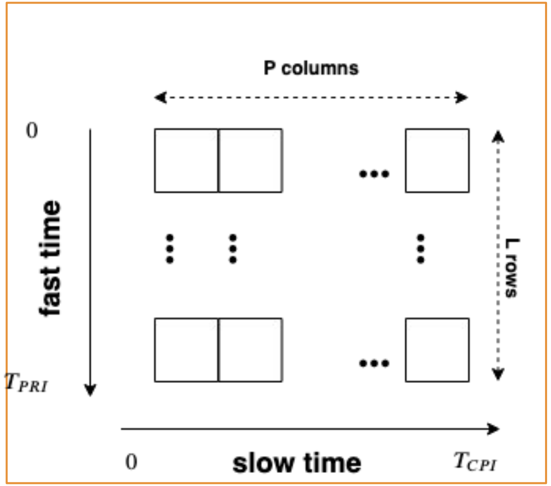

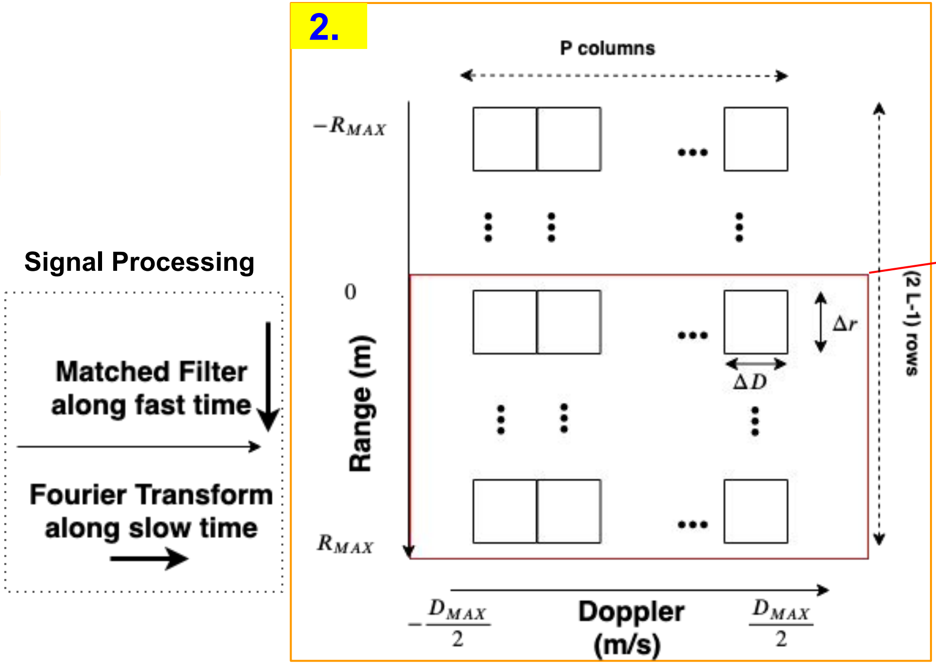

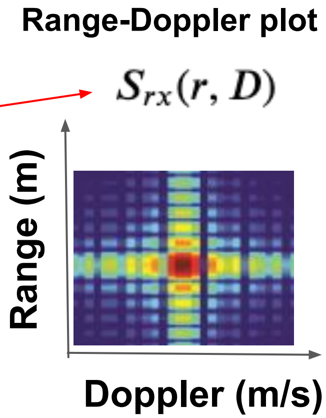

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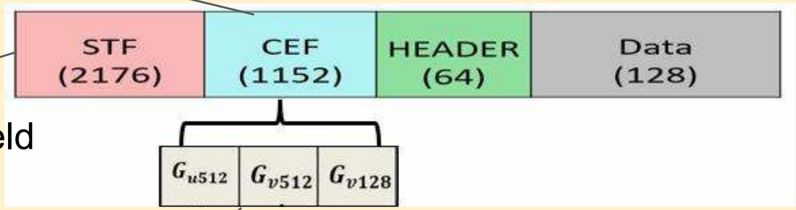

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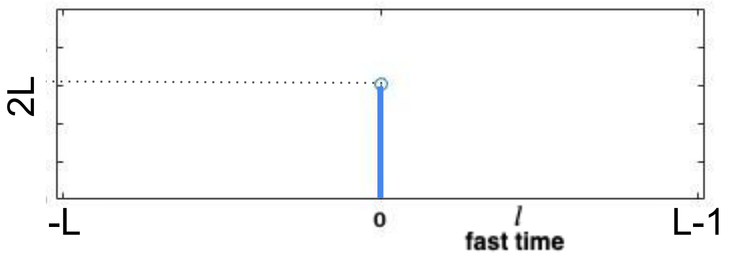

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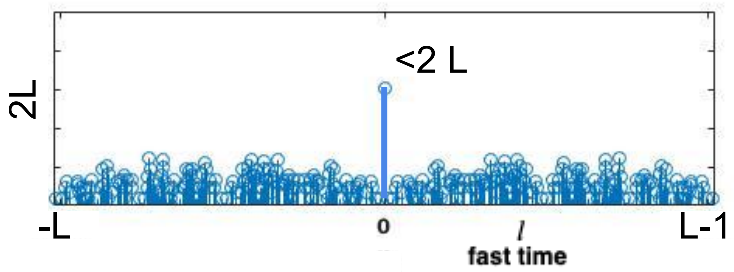

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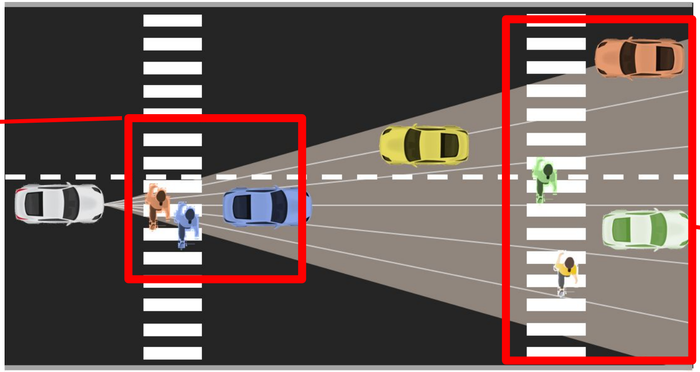
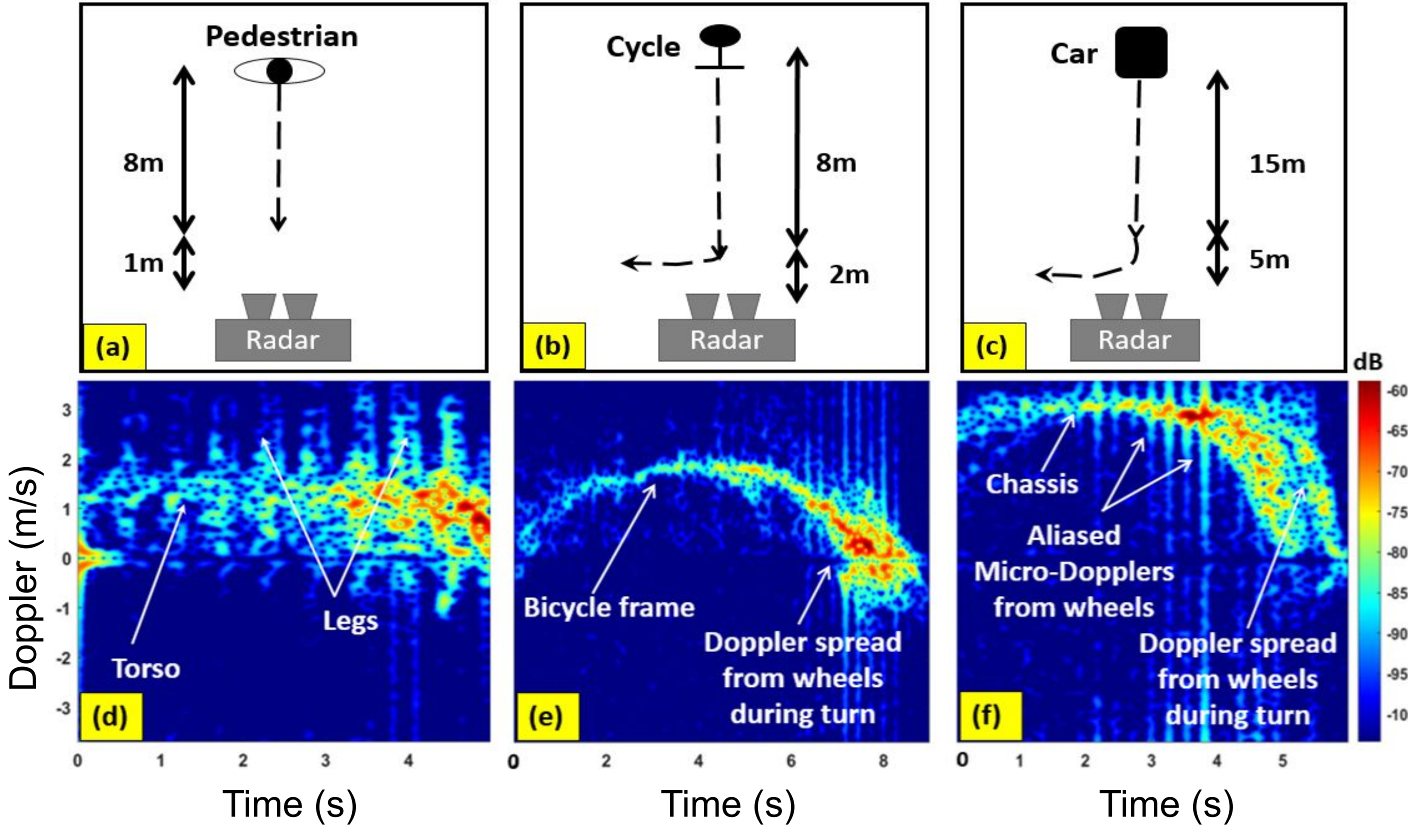
4.	Generate radar receiver operating curves to quantify the improvement in an objective manner

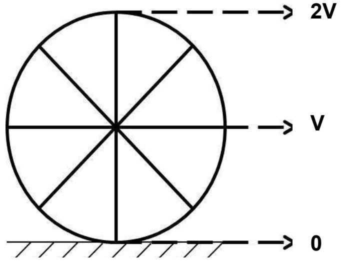
Short range targets fit in multiple bins and need to be modelled as extended targets



Long range targets fit in 1 bin and should appear as point targets

3.2 Short Range Automotive Scenario Experiment





Wheel

Test Setup

4.1 Standard Golay (SG) waveform Example, L=512

Example for 4 packets

1. Consider a Golay Pair $\{G_{a,L}[n], G_{b,L}[n]\}$ of length 512 bits each.

Transmit Waveform

Packet p=0	Packet p=1	Packet p=2	Packet p=3
$G_{1,L}[l] = G_{a,L}[l]$	$G_{2,L}[l] = G_{b,L}[l]$	$G_{3,L}[l] = G_{a,L}[l]$	$G_{4,L}[l] = G_{b,L}[l]$

Receiver matched filter processing

$$\sum_{p=0}^{3} e^{jp\theta}(G_{p,L}[l] * G_{p,L}[l]) \neq 6L\delta[l], \quad l = -L, ..l, ...(L-1)$$

4.2 Modified Golay (MG) waveform, L=512

Example for 4 packets

1. Generate Prou-Thue-Morse (PTM) sequence of length 2 bits - **{0,1}**
2. In PTM sequence replace all **0**'s with Golay Pair **{$G_{a,L}[l]$,$G_{b,L}[l]$}** and **1's** with Golay Pair **{$-G_{b,L}[-l]$,$G_{a,L}[-l]$}**

0 — 1

Transmit Waveform

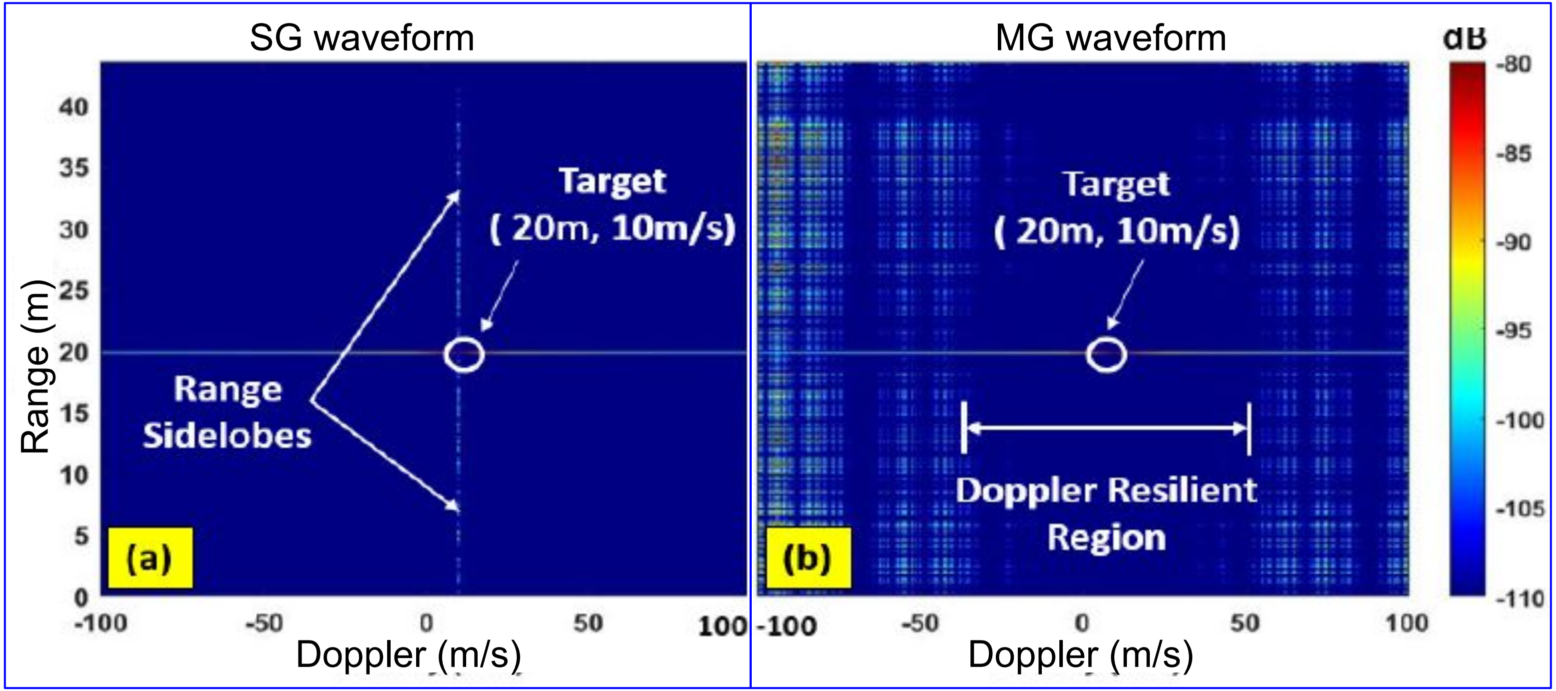
Packet p=0	Packet p=1	Packet p=2	Packet p=3
$G_{1,512}[l] = G_{a,L}[l]$	$G_{2,512}[l] = G_{b,L}[l]$	$G_{3,512}[l] = -G_{b,L}[-l]$	$G_{4,512}[l] = G_{a,L}[-l]$

Receiver matched filter processing

$$\sum_{p=0}^{3} e^{jp\theta}(G_{p,L}[l] * G_{p,L}[l]) \approx 1(G_{1,L}[l] * G_{1,L}[l]) + 2(G_{2,L}[l] * G_{2,L}[l]) + 3(G_{3,L}[l] * G_{3,L}[l])$$
$$= 1((G_{b,L}[l] * G_{b,L}[l]) + (G_{a,L}[-l] * G_{a,L}[-l])) + 2((-G_{b,L}[-l] * -G_{b,L}[-l]) + (G_{a,L}[-l] * G_{a,L}[-l]))$$
$$= (2L + 2(2L))\delta[l]$$
$$= 6L\delta[l]$$

Pezeshki et.al, Doppler resilient Golay complementary waveforms Trans. Information Theory 2008

4.3 MG vs SG for a moving point target, P=2048 packets



Range sidelobes have been suppressed by 20 dB

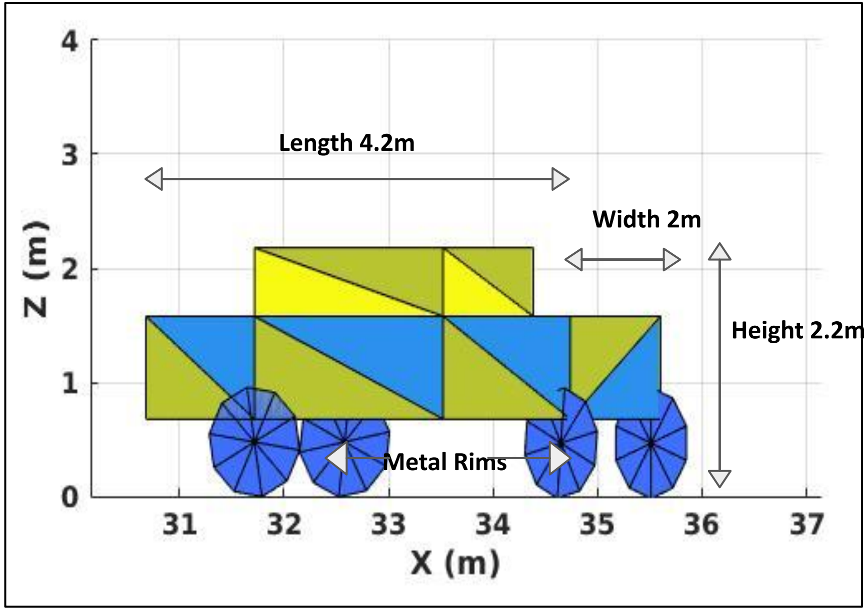
4.4 Ultra Short Range Radar

Parameter	Proposed Radar	Commercial SRR
Carrier Frequency	60 GHz	77 GHz
Bandwidth	1.76 GHz	2 GHz
Range resolution	0.085 m	0.075 m
Maximum unambiguous range	44 m	40 m
Pulse repetition interval	2 us	1.67 us
Velocity resolution	0.6 m/s	0.27 m/s
Maximum unambiguous velocity	625 m/s	111 m/s
Coherent Processing interval	0.0041 s (P=2048)	0.007 s

Ultra short range automotive radars have the following usage scenarios:

1. Parking assistance
2. Lane change assistance
3. Object detection and tracking

5.1 Extended target model of a car



Primitive chosen for a car is a triangular plate and can be represented in 3D space by its centroid

Radar cross section of a triangular plate

$$\sigma_b[n] = \frac{4\pi A_b^2 \cos^2 \theta_b[n]}{\lambda^2} \left(\frac{\sin\left(k d_b \sin \frac{\theta_b[n]}{2}\right)}{k d_b \sin \frac{\theta_b[n]}{2}} \right)^4$$

$A_b = area\ of\ the\ plate$

$\theta_b = aspect\ angle$

$d_b = dimension\ along\ aspect\ angle$

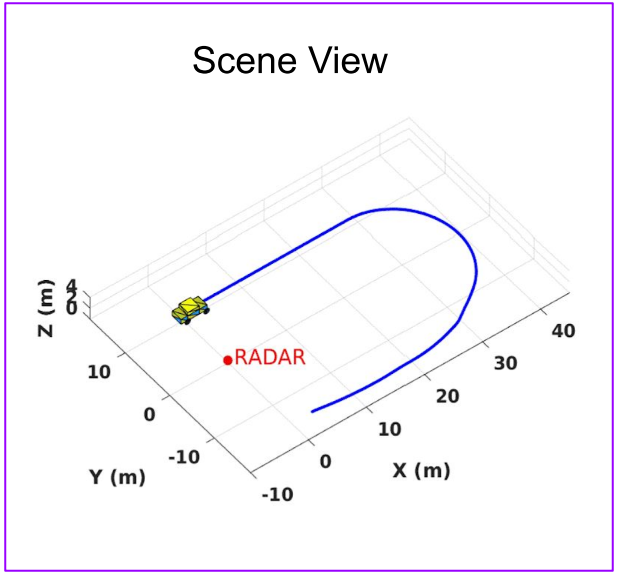
$k = propagationconstant$

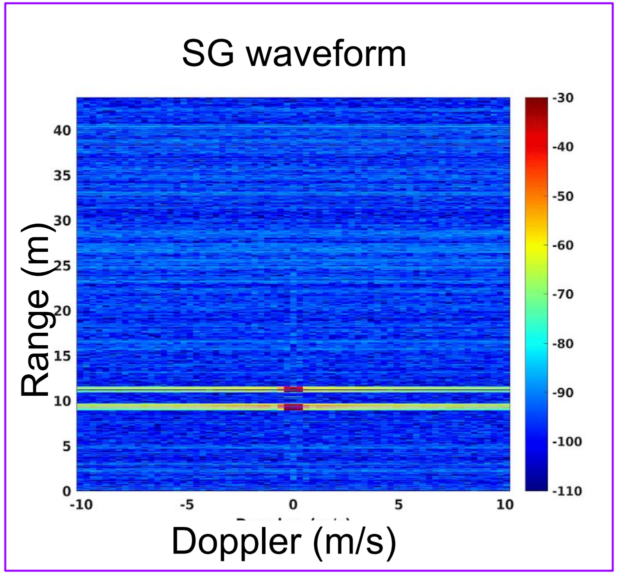
$\lambda = wavelength$

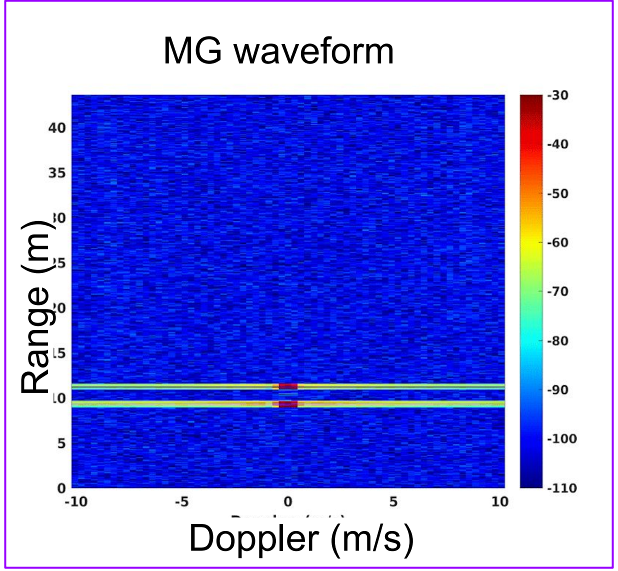
Received signal

$$x_R(t) = \sum_{b=0}^{B} A \frac{\sqrt{\sigma_b(\theta)}}{r_b(t)^2} x_T\left(t - \frac{2r_b(t)}{c}\right) + \eta$$

5.2 Car range-Doppler MG waveform vs SG waveform



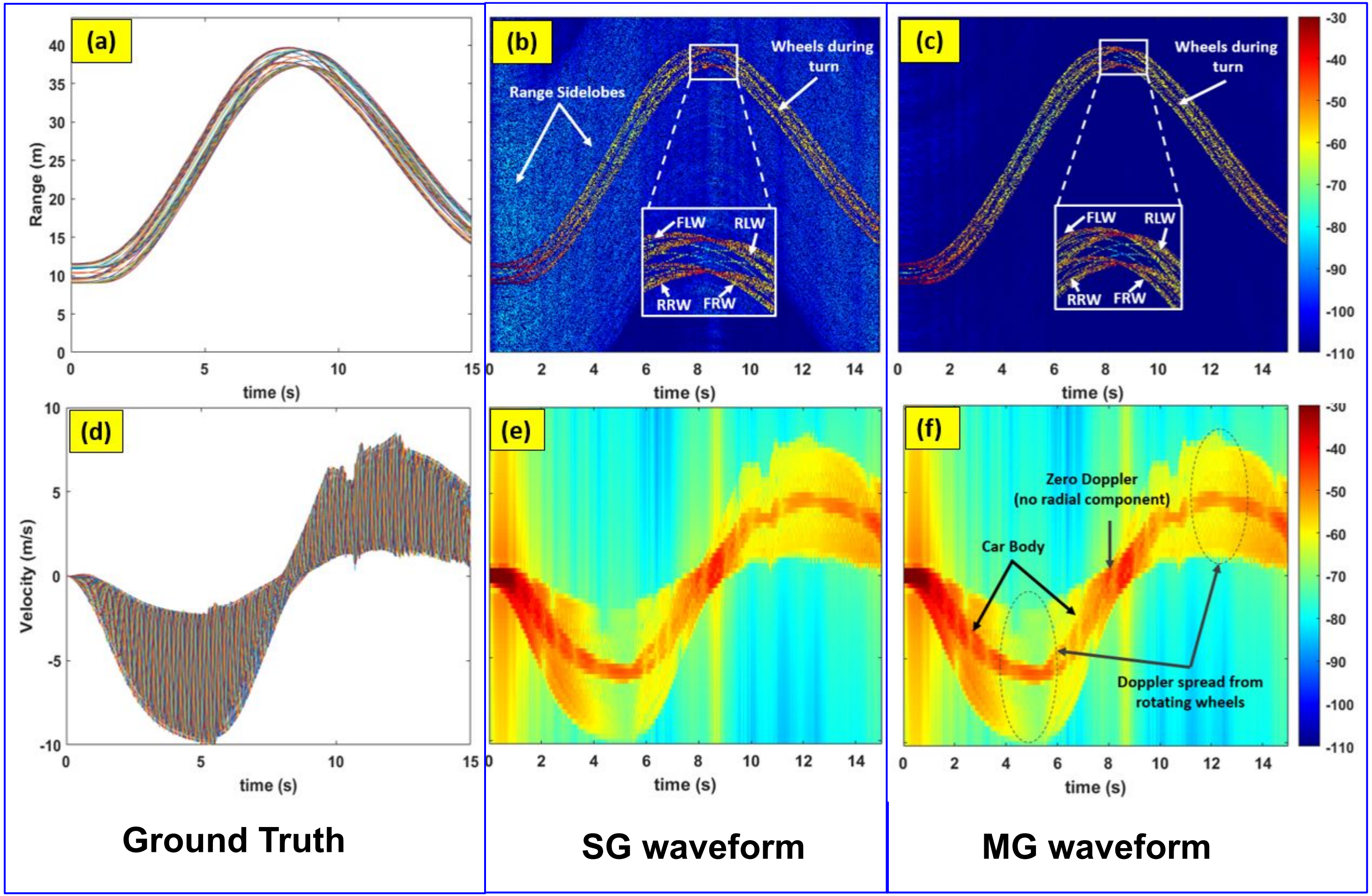




Key Observations:

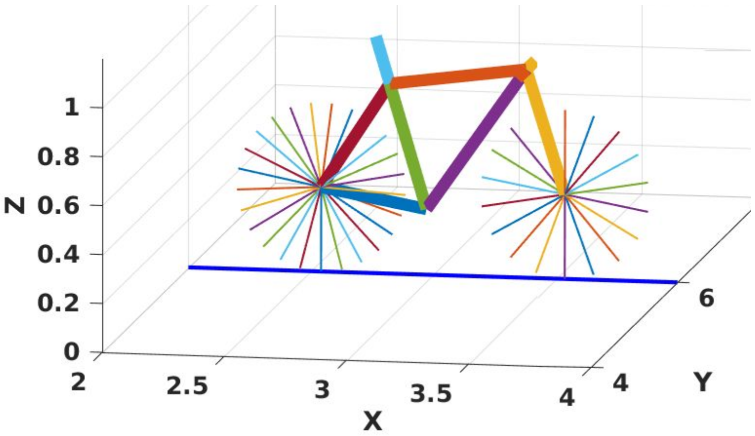
1. The extended target model of the car manifests itself over multiple range-Doppler bins.
2. The power of the reflected signal from the car causes the fluctuations in colour in the range-Doppler plot.
3. Range sidelobes are suppressed in the MG waveform making it Doppler resilient.

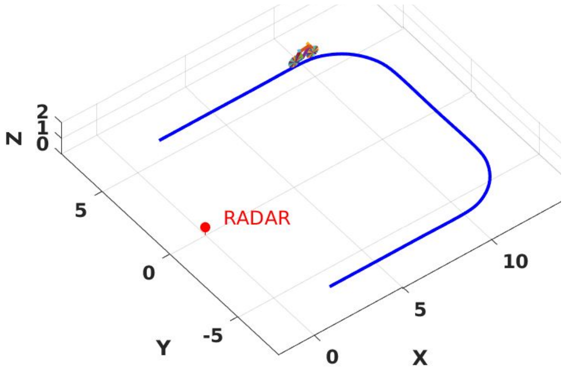
5.3 Car Radar Signatures



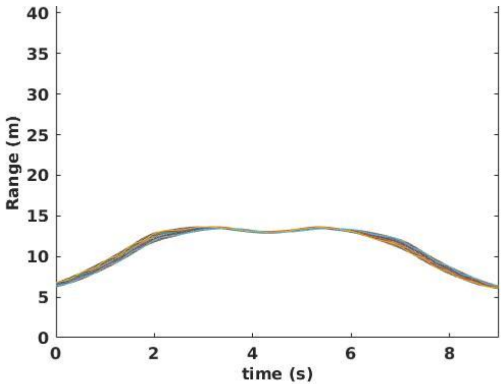
5.4 Extended target model of a bicycle

Primitives are rods

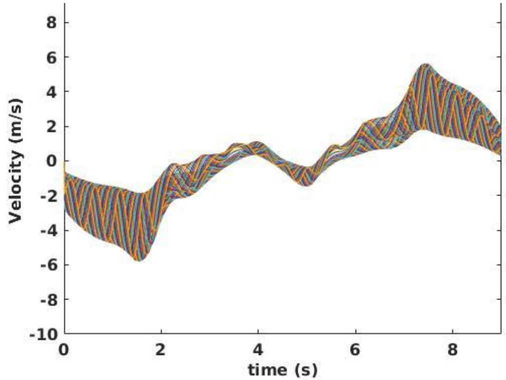




Range-time ground truth



Doppler-time ground truth



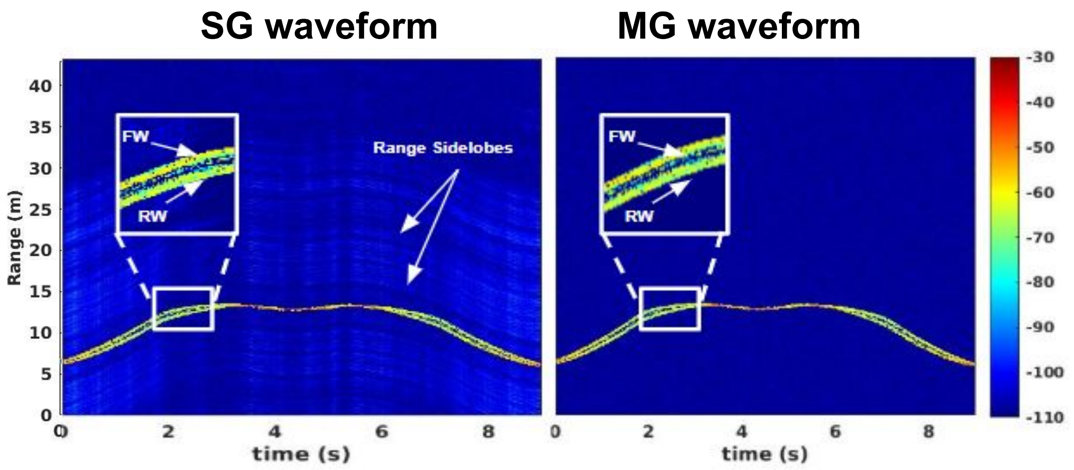
$$\sigma_b[n] = \frac{2\pi a_b L_b^2}{\lambda} \cos^2(\theta_b[n]) \left(\frac{\sin\left(k L_b \sin\theta_b[n]\right)}{k L_b \sin\theta_b[n]} \right)^2$$

The metal rods of the frame and the metal rods of the spokes are modelled in this electromagnetic model

5.5 Extended Target Model: Bicycle radar signatures

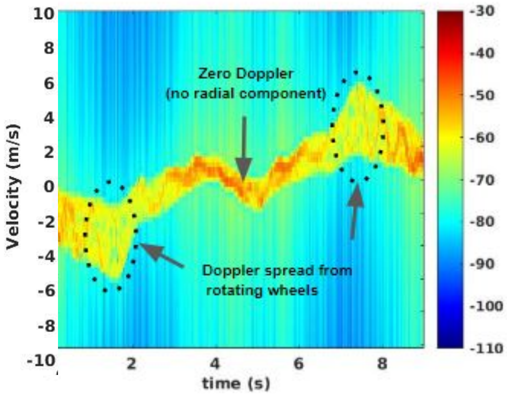
<u>Range-time plot</u>

1. Range-sidelobes are supressed in the MG waveform
2. Micro-range information from the wheels is visible

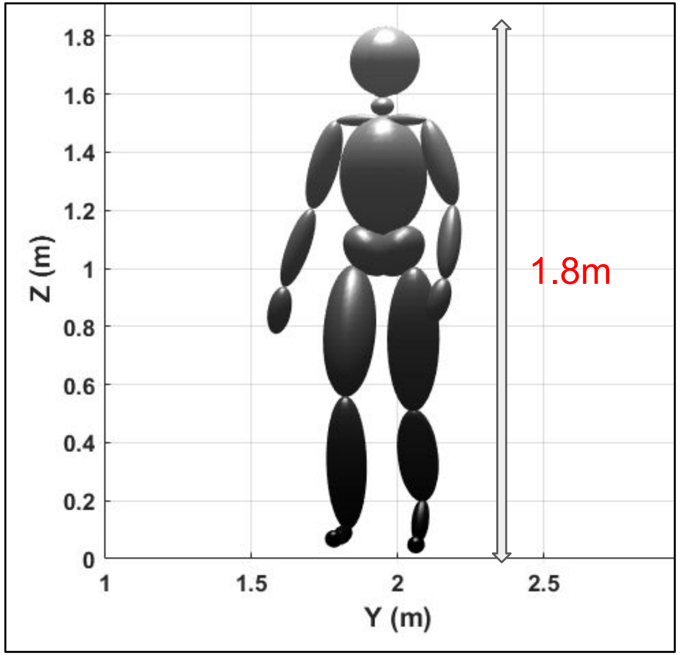


<u>Doppler-time plot</u>

1. The aspect angle variation manifests itself in the variation of the received power and we can see it on the colour bar
2. When the bicycle is directly in front of the radar, it is moving in the transverse direction hence there is zero Doppler in the received signal



5.6 Extended target model of a pedestrian



Radar cross section of an ellipsoid

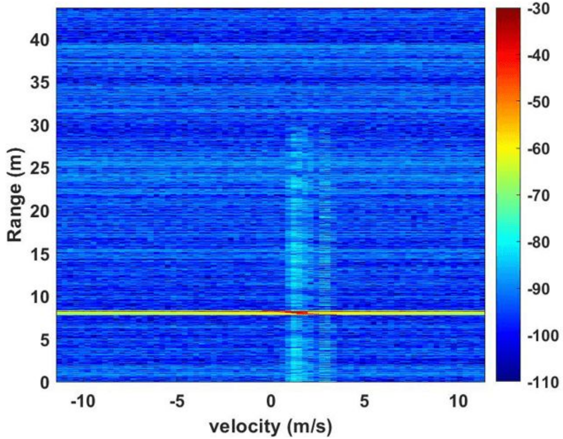
$$\sigma_b[n] = \frac{\frac{1}{4} R_b^4 H_b^2}{R_b^2 \sin^2 \theta_b[n] + \frac{1}{4} H_b^2 \cos^2 \theta_b[n]}$$

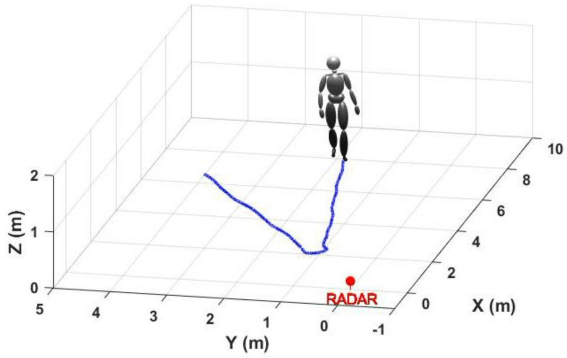
H_b = length of the ellipsoid
R_b = radius of the ellipsoid

SS Ram, H Ling , Simulation of human microDopplers using computer animation data

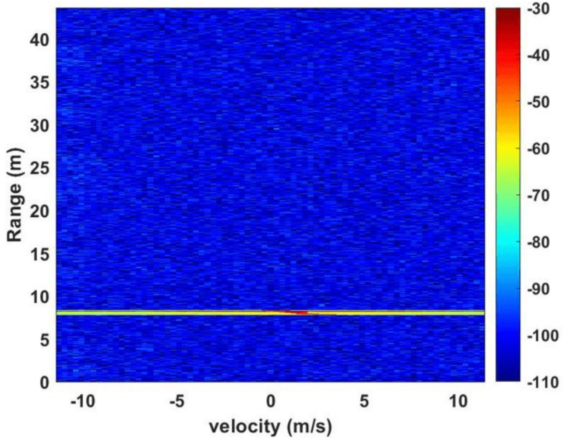
5.7 Pedestrian MG waveform vs SG waveform

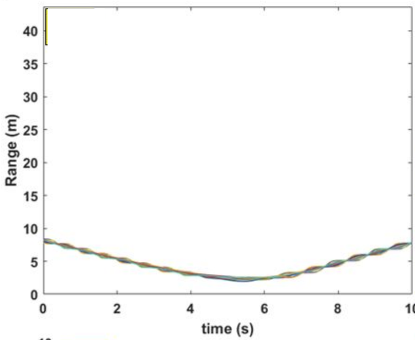
SG Waveform





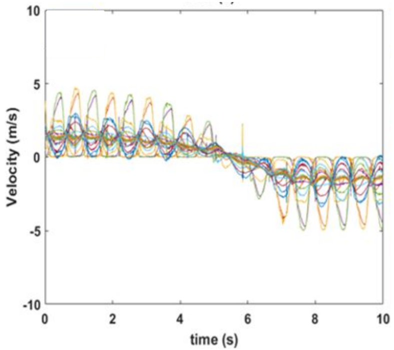
MG Waveform



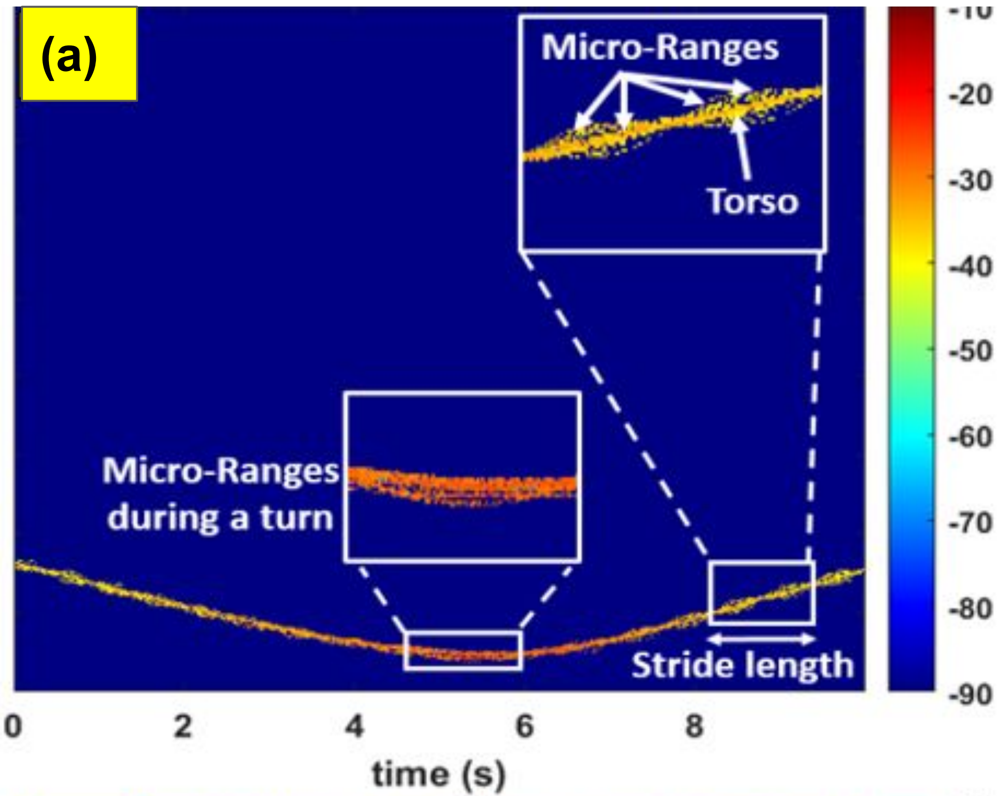


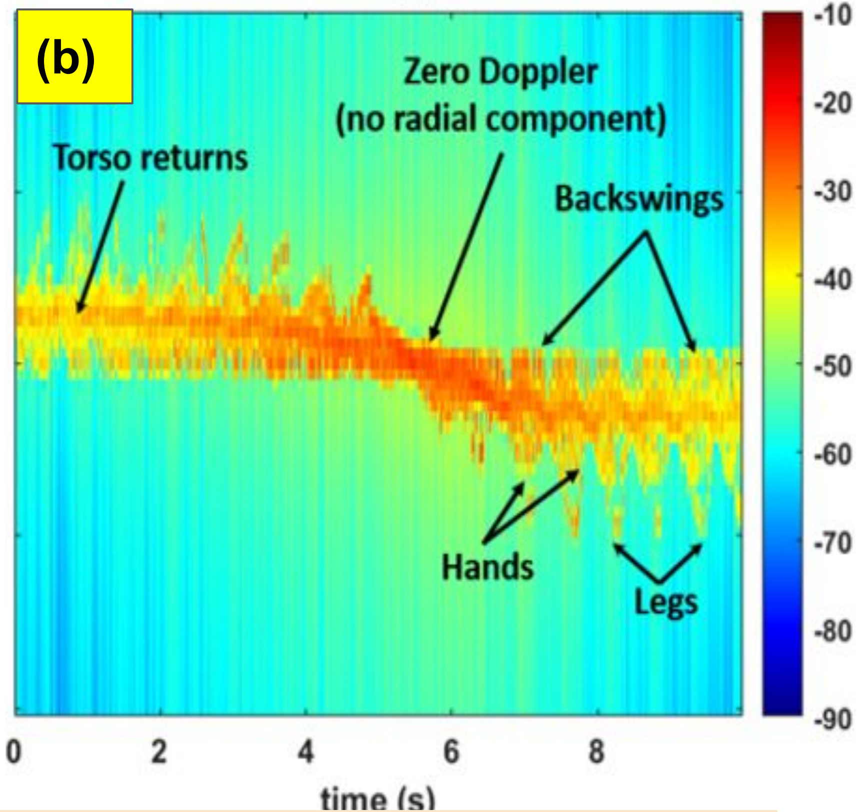
Range-time
Ground truth

Doppler-time
Ground truth



5.8 Pedestrian Radar Signatures





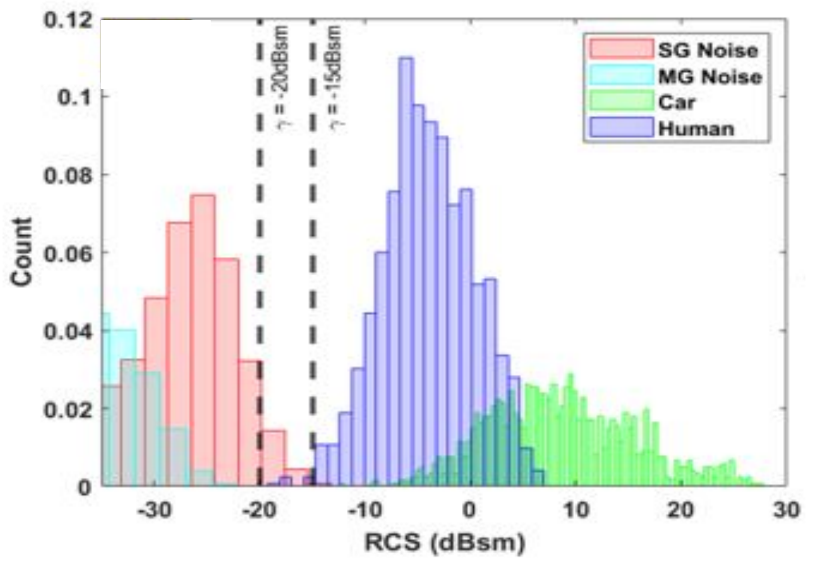
In the range-time plot We can see the stride length of the pedestrian.

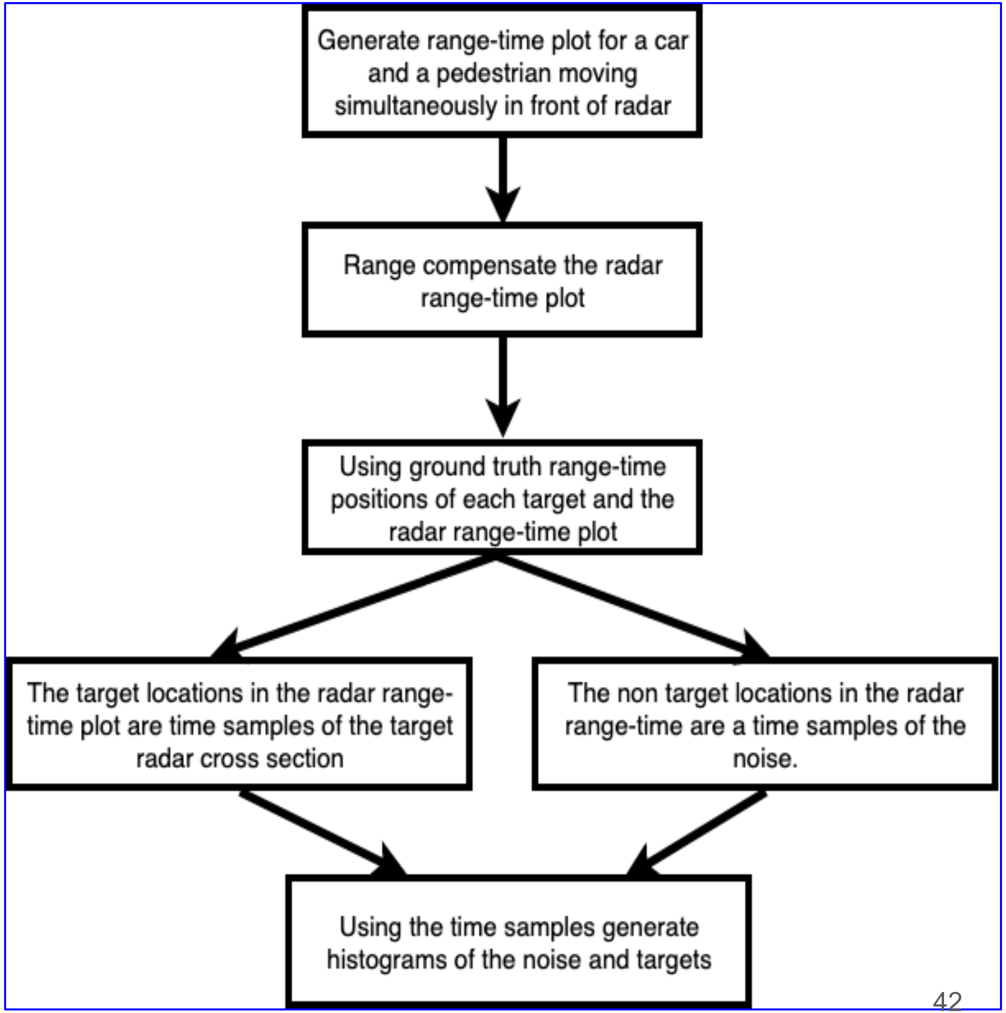
In the Doppler time plot, we can see the swing of the arms and legs of the pedestrian

6.1 Detection Methodology

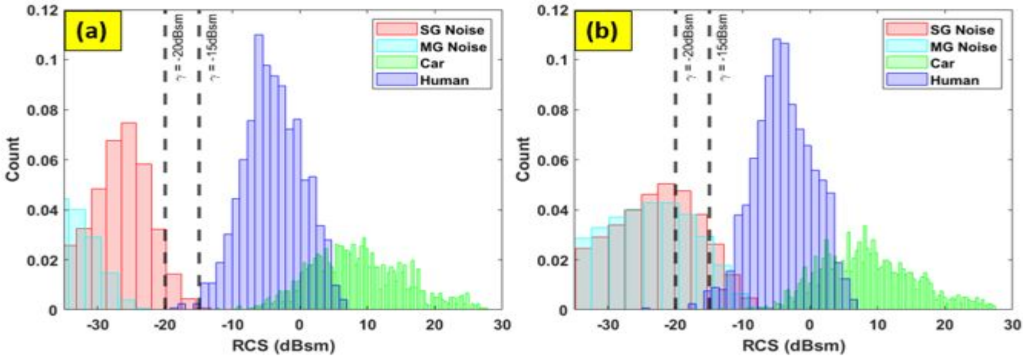
RCS calculation after range compensation

$$\sigma_{\text{target}}(m) = \left\| \sum_{b=1}^{B} \chi_{RT}[m, r_b] r_b^2 e^{+j2\frac{2\pi}{\lambda} r_b} \right\|^2$$





6.2 Radar Operating Curves

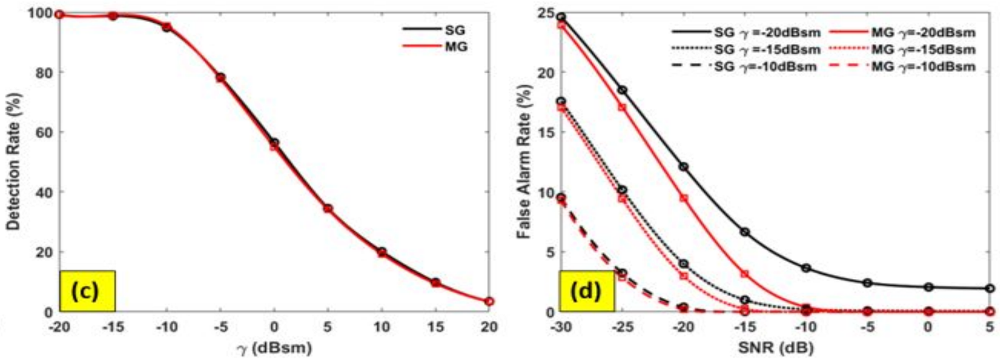


(a) Radar cross section histogram at an SNR of -20 dB

(b) Radar cross section histogram at an SNR of +5 dB

(c) Detection threshold vs probability of detection

(d) False alarm probability vs SNR for three different detection thresholds.



7.1 Conclusion

What we did:

1. Designed an ultra short range Automotive Radar based on the 802.11ad protocol
2. Changed the transmit waveform to improve the detection on radar signatures for dynamic targets
3. Constructed an extended target model and processed high resolution radar signatures for typical automotive targets

What we found:

4. The MG radar, on comparing with the SG radar, was observed to be performing better on the following metrics:
   a. Suppressed range-sidelobes by 20 dB for point targets
   b. Reduced probability of false alarms by 2.5% at low SNR (-20dB to 0dB)

5. Interesting micro-Doppler and micro-range features for different automotive targets

Questions?

Acknowledgements

I would like to thank my supervisor Dr. Shobha Sunder Ram for guiding me during this thesis. I would also like to thank Dr. Kumar Vijay Mishra without whose technical inputs this thesis would not have been possible. Mrs. Shelly Vishwakarma for helping with the data collection and detection section for performance metrics. Lastly I'd like to thank Dr. Aditya Jaganathan and Dr. Vivek Bohara for being part of the thesis committee.

Conclusion

1. We designed an ultra short range Radar based on the 802.11ad protocol
2. The transmit waveform was changed slightly to improve the detection on radar signatures for dynamic targets
3. An extended target model was constructed and high resolution radar signatures for typical automotive targets were processed
4. The MG radar was tested with the SG radar and shown to be better using performance metrics

Detection Methodology

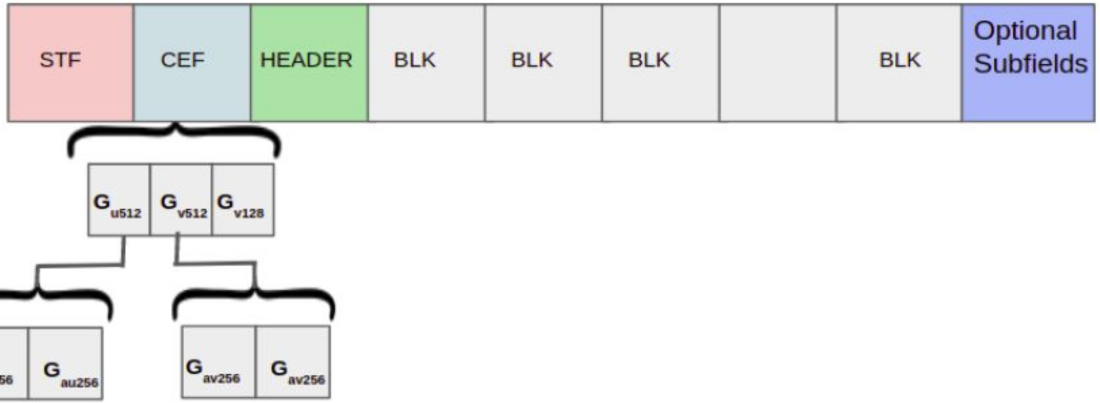
1. For two targets - a car and a pedestrian moving in front of the Radar, we generate a range-time signature
2. Range compensate the range-time signature.
3. From the ground truth range values of each target calculate the radar cross section by doing a coherent sum of all the point scatterers of each individual target

$$\sigma_{\text{target}}(m) = \left\| \sum_{b=1}^{B} \chi_{RT}[m, r_b] r_b^2 e^{+j2\frac{2\pi}{\lambda} r_b} \right\|^2$$

4. The range compensated range-time signature also gives us the virtual noise radar cross section values at all points in time.
5. Plot a histogram of the radar cross section and the virtual noise cross section
6. Use thresholding for detection

IEEE802.11AD

1. 60GHz wireless link for 5G communications between autonomous vehicles
2. Modes: Control (CPHY), Single Carrier (SCPHY), Orthogonal Frequency Division Multiplexing (OFDM)
3. Chip rates: 1.76 GHz / 2.64GHz
4. Joint radar and communication framework

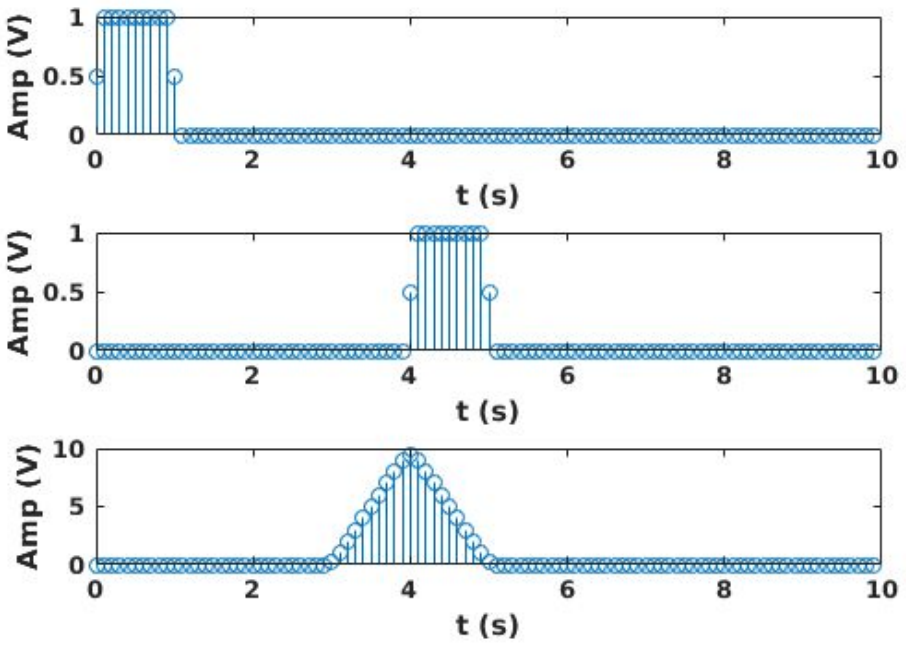


Pulse - Doppler Radar Operation

TX Pulse

RX Pulse

Matched Filter



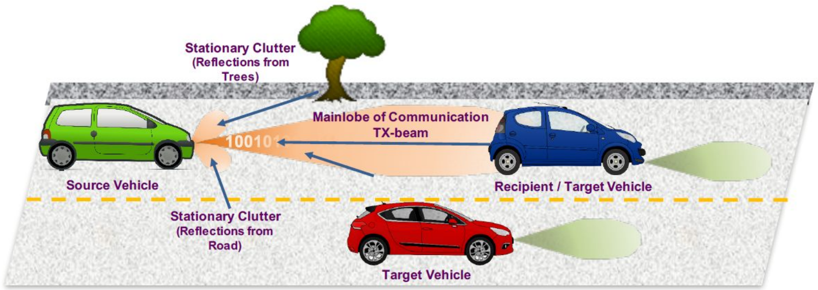
The last plot gives us the delay at which the target is located

-IEEE 802.11.ad based radar transmits a Golay Coded waveform and the received signal is delayed in time and Doppler shifted

- The received signal after signal processing results in a range-Doppler plot

Previous work

- Preeti Kumari used the CEF in the SC mode in IEEE 802.11.AD to create a Long Range Radar (~200m) and assumed targets as point targets



*Taken from: P. Kumari et.al IEEE 802.11ad-based radar: An approach to joint vehicular
communication-radar system, IEEE Transactions on Vehicular Technology, 2018.

802.11.ad based radar

Perfect Autocorrelation Property

$$G_{a,N}[n] * G_{a,N}[-n] + G_{b,N}[n] * G_{b,N}[-n] = 2N\delta[n].$$

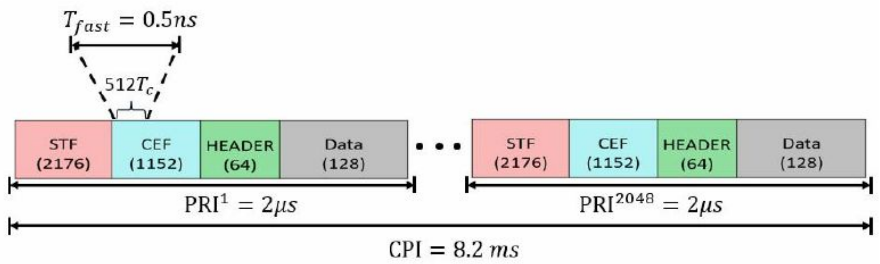
$$(G_{a,N}[n] * G_{a,N}[-n]) + (G_{b,N}[n] * G_{b,N}[-n])\, e^{-j\theta} \neq 2N\delta[n],$$

- In case of Non Stationary targets, the perfect autocorrelation property is not valid and creates range sidelobes due to Doppler in received signal
- Put main plots of above equations here

Our objectives

1. Create a Short range radar as attenuation is high for 60 GHz radio waves and we are looking for 2 way propagation
2. Solve the range side-lobes due to Doppler problem
3. Since we have a high radar resolution and close range to targets, our targets are modelled as extended targets

Radar Signal Model and Parameters



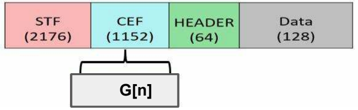
Parameter	Proposed Radar	Commercial SRR
Carrier frequency	60 GHz	77 GHz
Bandwidth	1.76 GHz	2 GHz
Range resolution	0.085 m	0.075 m
Maximum unambiguous range	44m	40m
Pulse repetition interval	2μs	1.67μs
Velocity resolution	0.05 m/s	0.3 m/s
Maximum unambiguous velocity	111 m/s	625 m/s

2. Modified Golay (MG) signal model

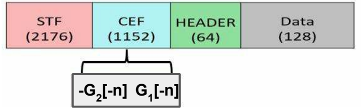
<u>Example for 4 packets</u>

1. Generate PTM sequence of length 2 bits - **{0,1}**
2. In PTM sequence replace all **0**'s with Golay Pair **{G_1[n],G_2[n]}** and **1's** with Golay Pair **{-G_2[-n],G_1[-n]}**

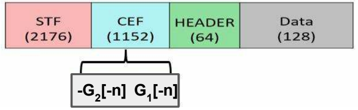
0



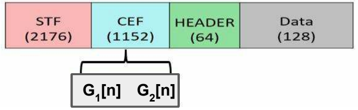
Packet 1



Packet 2



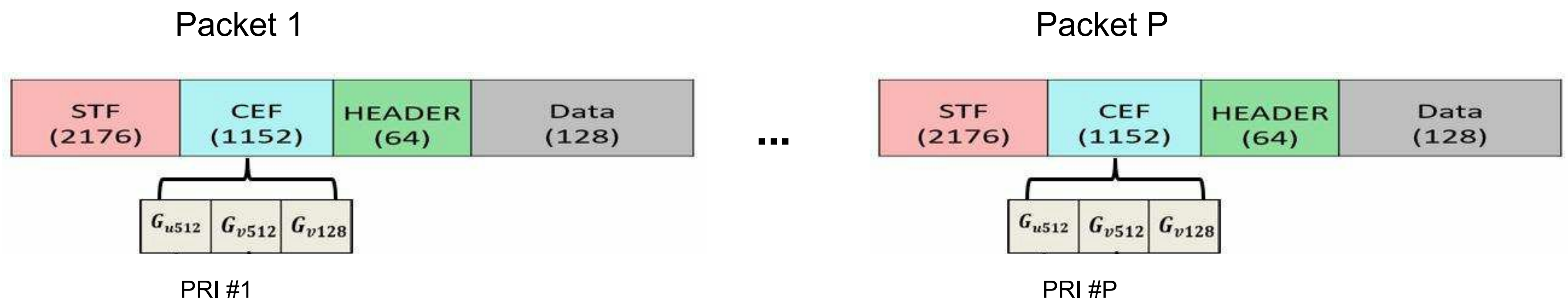
Packet 3



Packet 4

*Pezeshki reference

2. Standard Golay (SG) signal model



<u>The received signal for P packets after reflection from a point target</u>

$$S_{rx}[n] = \sum_{p=0}^{P-1} \sum_{b=1}^{B} a_b[n] S_{tx}(nt_s - \tau_b - pT_{PRI}) e^{-j2\pi f_{D_b} p T_{PRI}} + z[n]$$

$\tau_b = delay\ for\ b^{th}\ point\ scatterer$

$a_b = reflectivity\ for\ b^{th}\ point\ scatterer$

$f_{D_b} = Doppler\ for\ b^{th}\ point\ scatterer$

Modified Golay: Doppler Resilience

Theta = 2*pi*fd*PRI

For P packets at the receiver the matched filter looks like this

$$\sum_{p=0}^{P-1} e^{jn\theta}(G_{p,N}[n] * G_{p,N}[n]) \approx$$
$$0(G_{0,N}[n] * G_{0,N}[n]) + 1(G_{1,N}[n] * G_{1,N}[n]) + 2(G_{2,N}[n] * G_{2,N}[n]) + \cdots + (P-1)(G_{P-1,N}[n] * G_{P-1,N}[n]).$$

- Using the first order Taylor Expansion about 0 for small theta i.e. small Doppler, we make RHS as close to the original perfect autocorrelation property as possible.

Modified Golay: PTM sequence

Pezeshki et.al, *Doppler resilient Golay complementary waveforms* Trans. Information Theory 2008

Prouhet-Thue-Morse (PTM) Sequence

$$q_p = \begin{cases} 0, & \text{if } p = 0 \\ q_{\frac{p}{2}}, & \text{if } (p \text{ modulo } 2) = 0 \\ \overline{q_{\frac{p-1}{2}}}, & \text{if } (p \text{ modulo } 2) = 1, \end{cases}$$

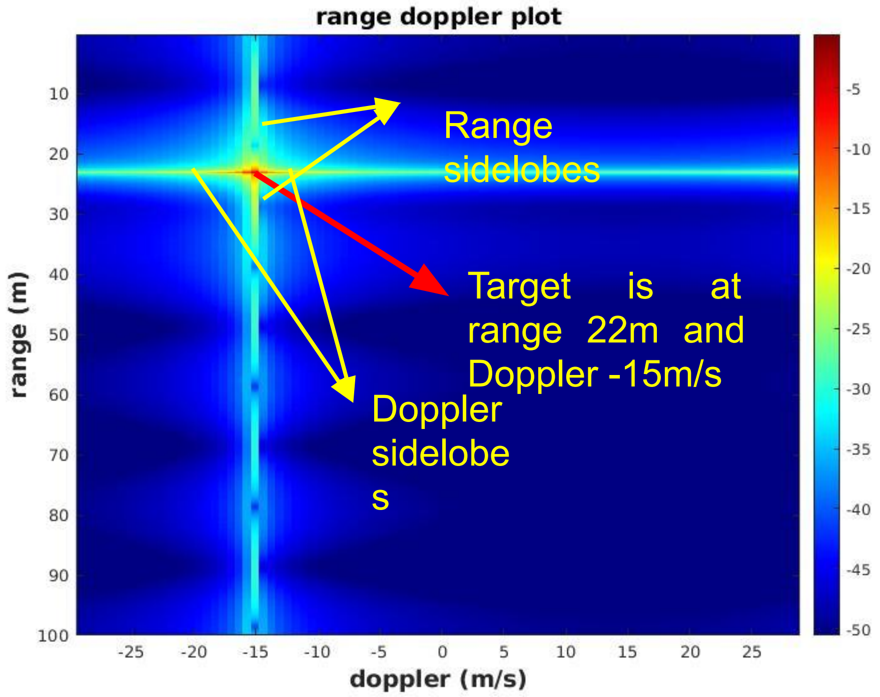
Modified Golay sequence

$$\text{if } q_p = 0, \{G_{a,N}[n], G_{b,N}[n]\}$$
$$\text{if } q_p = 1, \{-G_{b,N}[-n], G_{a,N}[-n]\}$$

Example

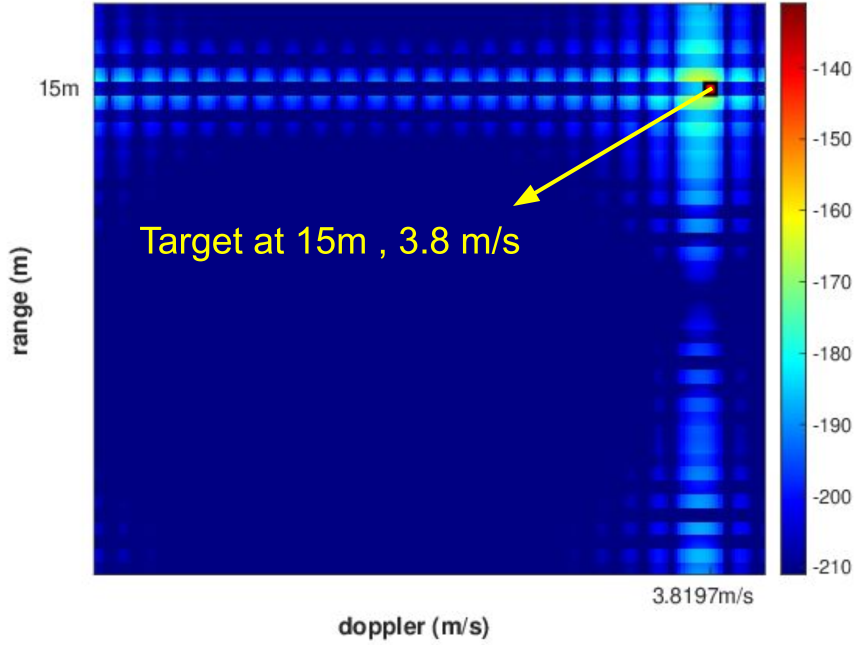
PTM Sequence: [01] : $G_{a,N}[n], G_{b,N}[n], -G_{b,N}[-n], G_{a,N}[-n]$:

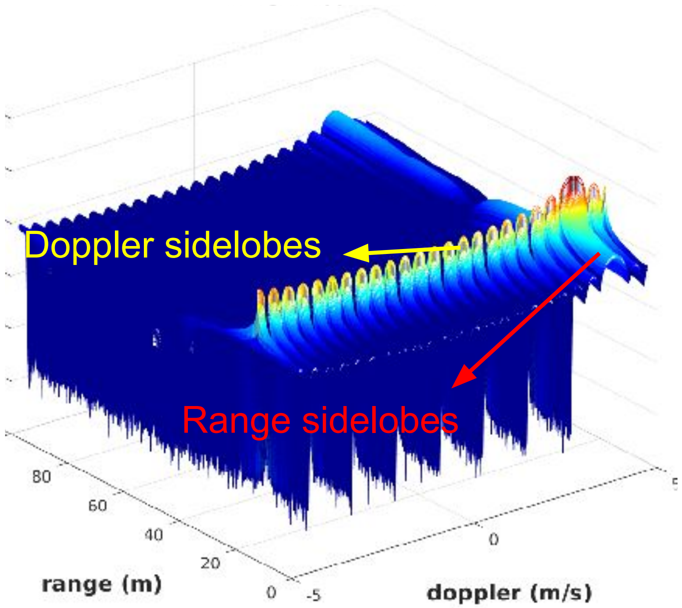
$$\sum_{p=0}^{3} e^{-jp\theta}(G_{p,N}[n] * G_{p,N}[-n]) \approx 1((G_{1,N}[n] * G_{1,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$+2((G_{2,N}[n] * G_{2,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$= (2N + 2(2N))\delta[n] = 6N\delta[n].$$



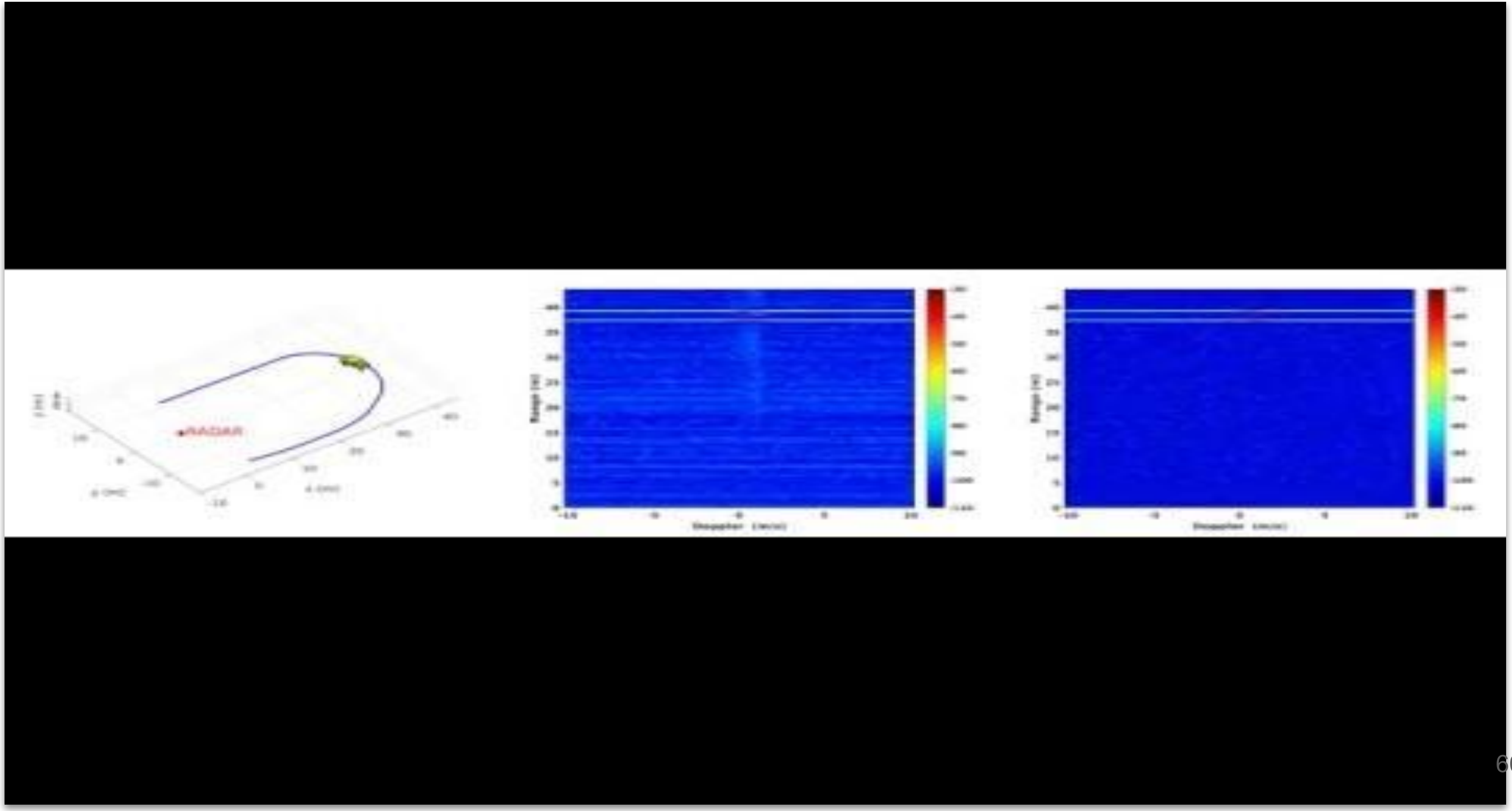
range doppler plot
range (m)
doppler (m/s)
10
20
30
40
50
60
70
80
90
100
-25
-20
-15
-10
-5
0
5
10
15
20
25
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Range sidelobes
Target is at range 22m and Doppler -15m/s
Doppler sidelobes

An example of a range-Doppler plot





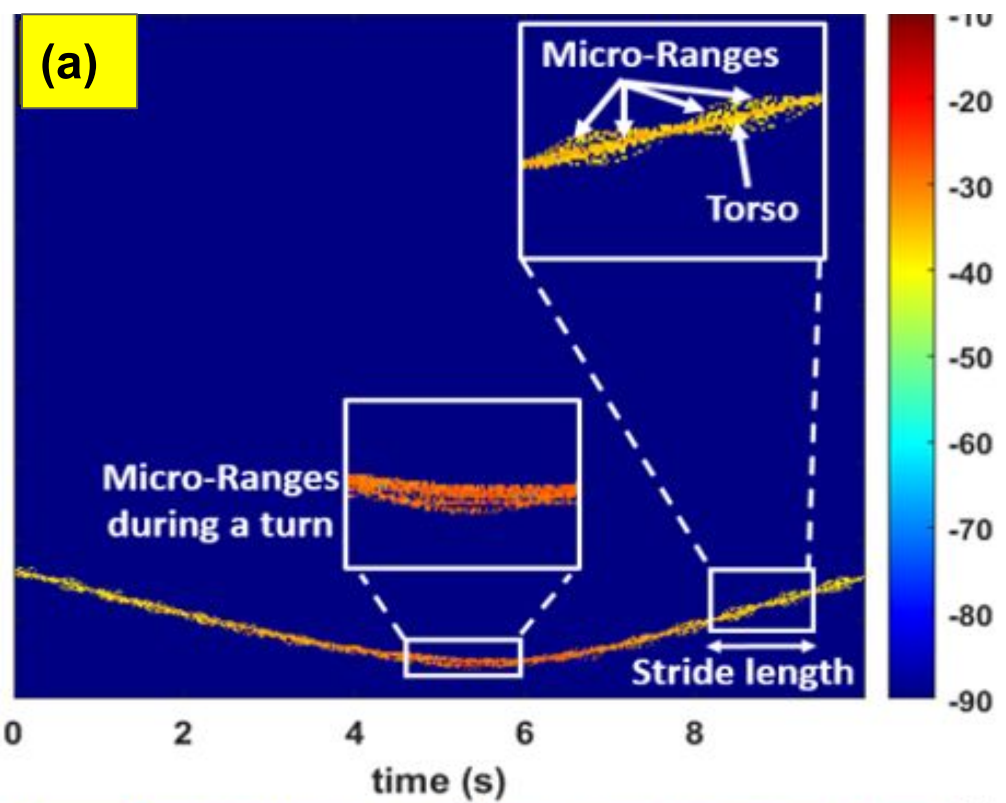
3. Car MG vs SG radar

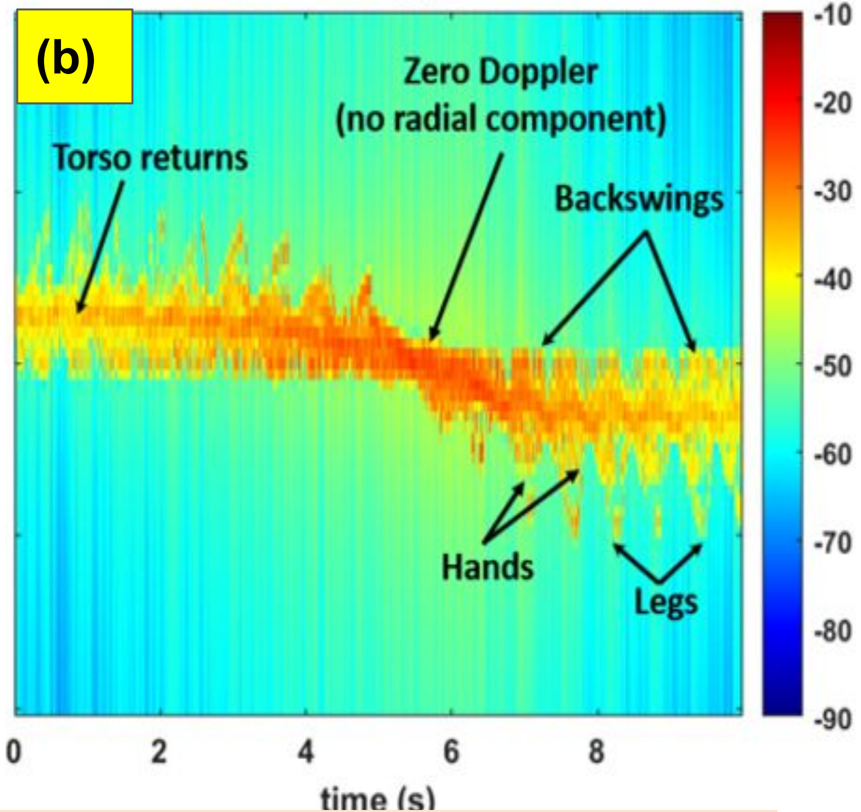


Acknowledgement

I would like to thank my supervisor Dr. Shobha Sunder Ram for guiding me during this thesis. I would also like to thank Dr. Vijay mishra without whose technical inputs these thesis would not have been possible. Mrs. Shelly Vishwakarma for helping with the data collection and performance metrics. Lastly I'd like to thank Dr. Aditya Jaganathan and Dr. Vivek Bohara for being part of the thesis committee.

5.8 Pedestrian Radar Signatures





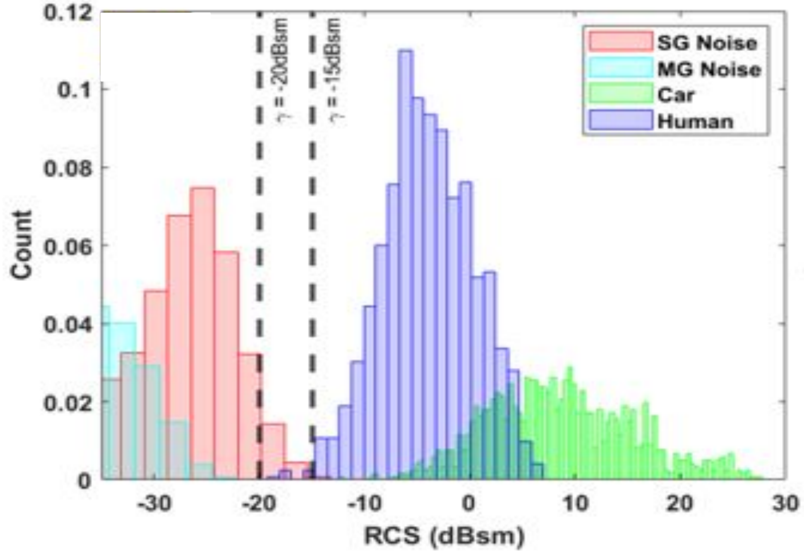
In the range-time plot We can see the stride length of the pedestrian.

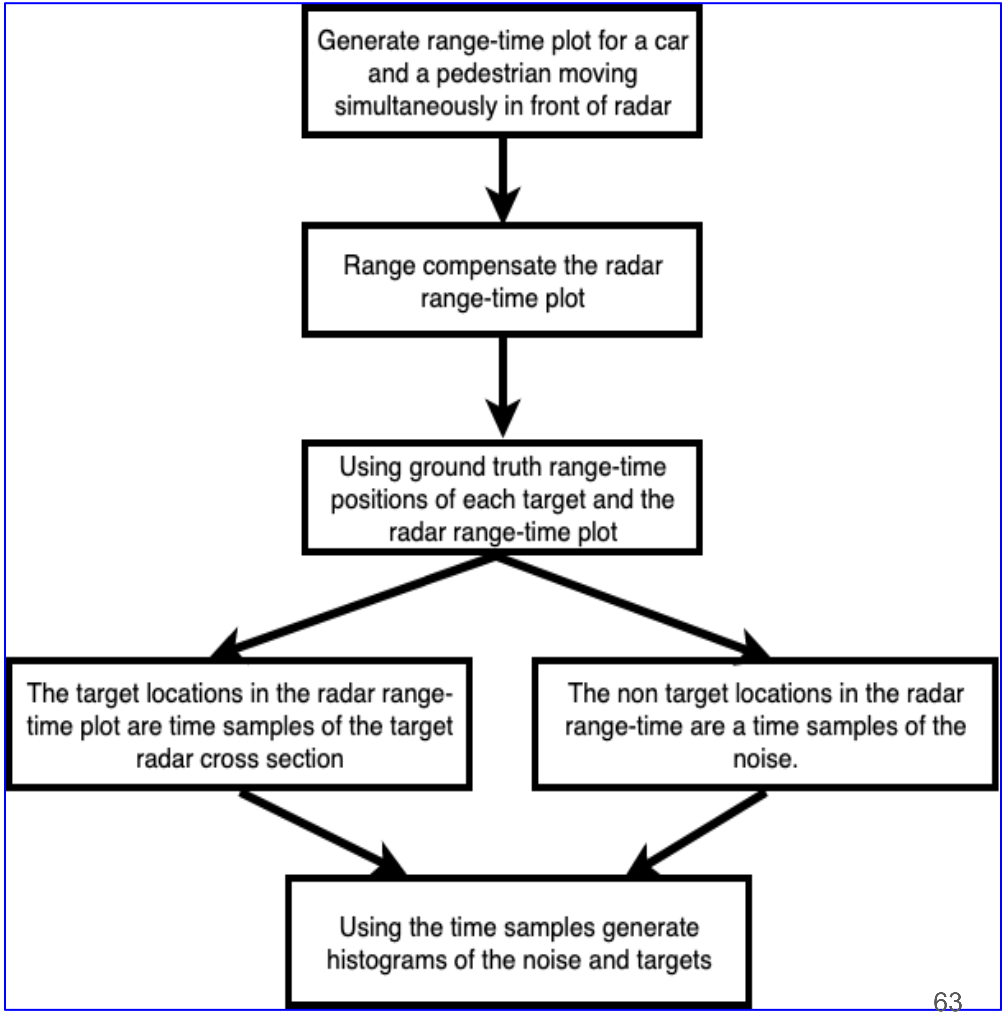
In the Doppler time plot, we can see the swing of the arms and legs of the pedestrian

6.1 Detection Methodology

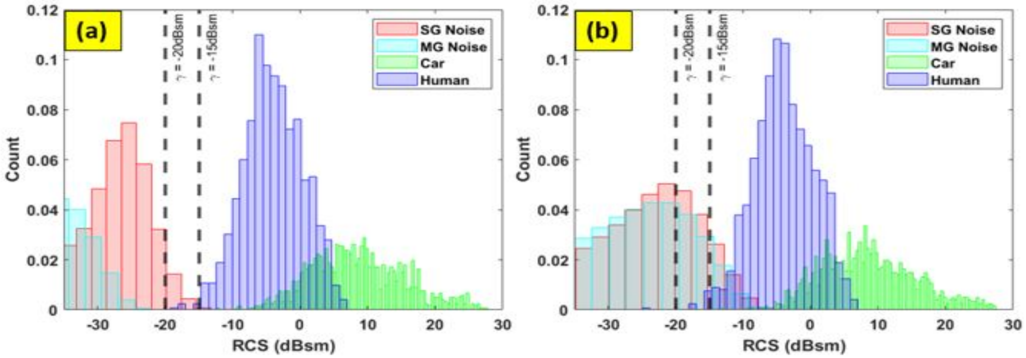
RCS calculation after range compensation

$$\sigma_{\text{target}}(m) = \left\| \sum_{b=1}^{B} \chi_{RT}[m, r_b] r_b^2 e^{+j2\frac{2\pi}{\lambda}r_b} \right\|^2$$





6.2 Radar Operating Curves

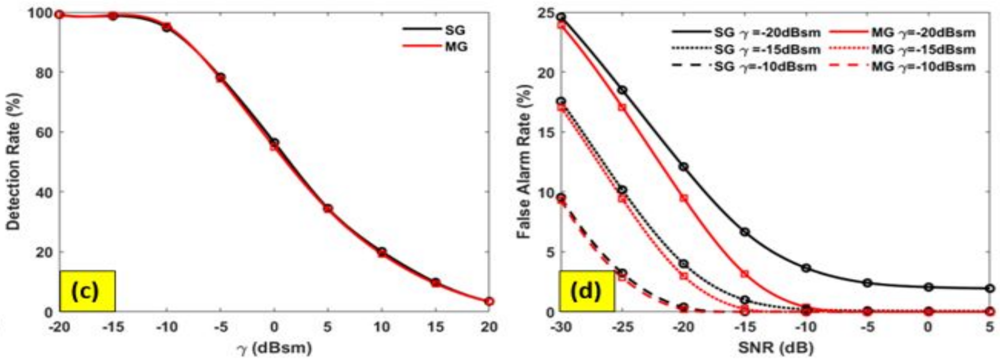


(a) Radar cross section histogram at an SNR of -20 dB

(b) Radar cross section histogram at an SNR of +5 dB

(c) Detection threshold vs probability of detection

(d) False alarm probability vs SNR for three different detection thresholds.



7.1 Conclusion

What we did:

1. Designed an ultra short range Automotive Radar based on the 802.11ad protocol
2. Changed the transmit waveform to improve the detection on radar signatures for dynamic targets
3. Constructed an extended target model and processed high resolution radar signatures for typical automotive targets

What we found:

4. The MG radar, on comparing with the SG radar, was observed to be performing better on the following metrics:
   a. Suppressed range-sidelobes by 20 dB for point targets
   b. Reduced probability of false alarms by 2.5% at low SNR (-20dB to 0dB)

5. Interesting micro-Doppler and micro-range features for different automotive targets

Questions?

Acknowledgements

I would like to thank my supervisor Dr. Shobha Sunder Ram for guiding me during this thesis. I would also like to thank Dr. Kumar Vijay Mishra without whose technical inputs this thesis would not have been possible. Mrs. Shelly Vishwakarma for helping with the data collection and detection section for performance metrics. Lastly I'd like to thank Dr. Aditya Jaganathan and Dr. Vivek Bohara for being part of the thesis committee.

Conclusion

1. We designed an ultra short range Radar based on the 802.11ad protocol
2. The transmit waveform was changed slightly to improve the detection on radar signatures for dynamic targets
3. An extended target model was constructed and high resolution radar signatures for typical automotive targets were processed
4. The MG radar was tested with the SG radar and shown to be better using performance metrics

Detection Methodology

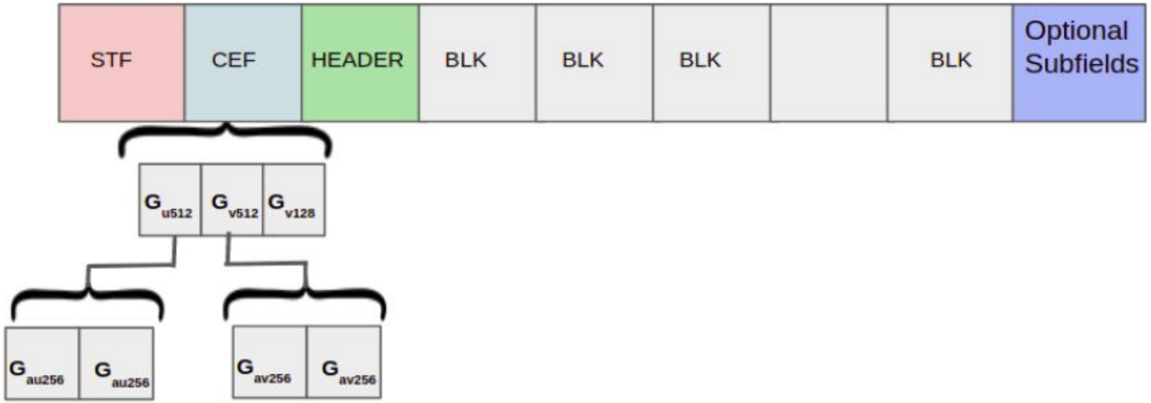
1. For two targets - a car and a pedestrian moving in front of the Radar, we generate a range-time signature
2. Range compensate the range-time signature.
3. From the ground truth range values of each target calculate the radar cross section by doing a coherent sum of all the point scatterers of each individual target

$$\sigma_{\text{target}}(m) = \left\| \sum_{b=1}^{B} \chi_{RT}[m, r_b] r_b^2 e^{+j2\frac{2\pi}{\lambda} r_b} \right\|^2$$

4. The range compensated range-time signature also gives us the virtual noise radar cross section values at all points in time.
5. Plot a histogram of the radar cross section and the virtual noise cross section
6. Use thresholding for detection

IEEE802.11AD

1. 60GHz wireless link for 5G communications between autonomous vehicles
2. Modes: Control (CPHY), Single Carrier (SCPHY), Orthogonal Frequency Division Multiplexing (OFDM)
3. Chip rates: 1.76 GHz / 2.64GHz
4. Joint radar and communication framework

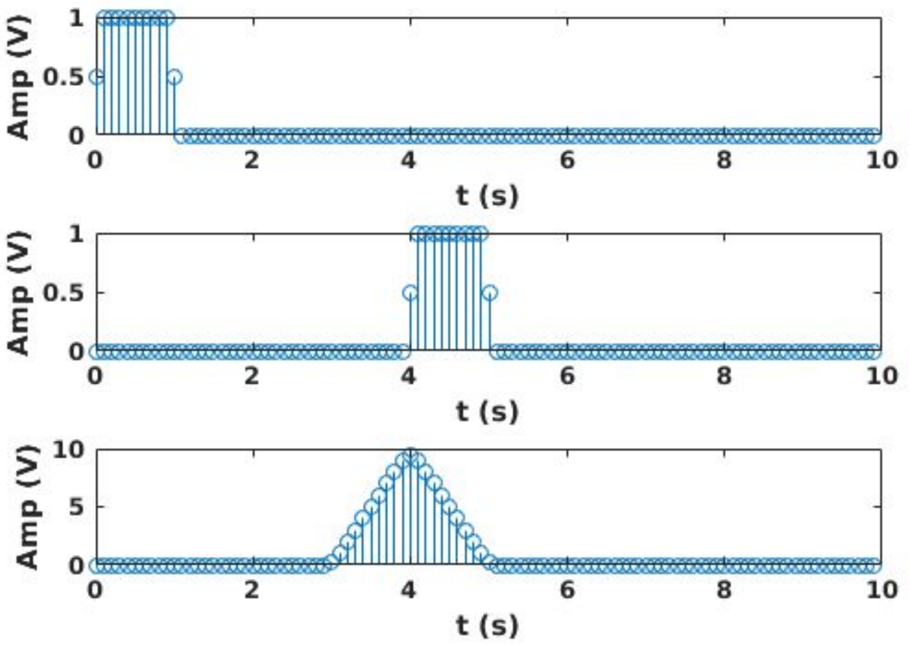


Pulse - Doppler Radar Operation

TX Pulse

RX Pulse

Matched Filter



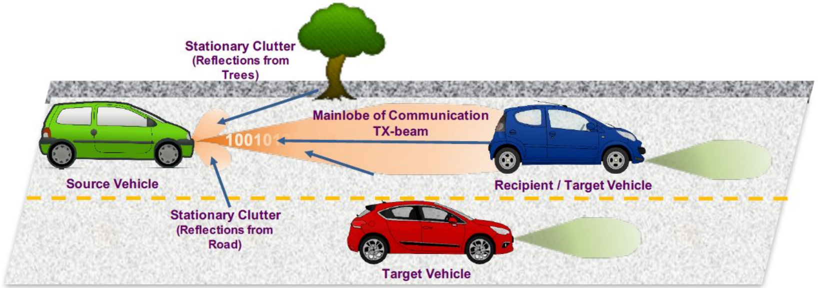
The last plot gives us the delay at which the target is located

-IEEE 802.11.ad based radar transmits a Golay Coded waveform and the received signal is delayed in time and Doppler shifted

- The received signal after signal processing results in a range-Doppler plot

Previous work

- Preeti Kumari used the CEF in the SC mode in IEEE 802.11.AD to create a Long Range Radar (~200m) and assumed targets as point targets



*Taken from: P. Kumari et.al IEEE 802.11ad-based radar: An approach to joint vehicular
communication-radar system, IEEE Transactions on Vehicular Technology, 2018.

802.11.ad based radar

Perfect Autocorrelation Property

$$G_{a,N}[n] * G_{a,N}[-n] + G_{b,N}[n] * G_{b,N}[-n] = 2N\delta[n].$$

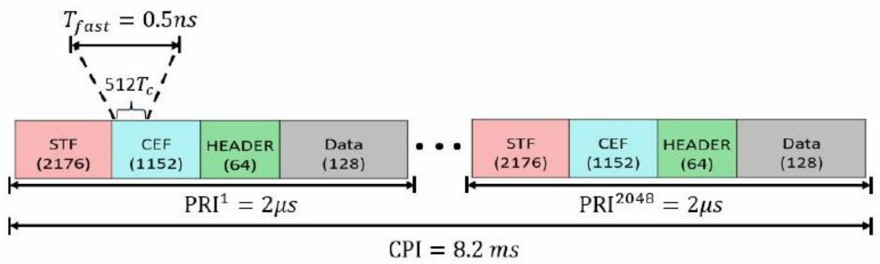
$$(G_{a,N}[n] * G_{a,N}[-n]) + (G_{b,N}[n] * G_{b,N}[-n])\, e^{-j\theta} \neq 2N\delta[n],$$

- In case of Non Stationary targets, the perfect autocorrelation property is not valid and creates range sidelobes due to Doppler in received signal
- Put main plots of above equations here

Our objectives

1. Create a Short range radar as attenuation is high for 60 GHz radio waves and we are looking for 2 way propagation
2. Solve the range side-lobes due to Doppler problem
3. Since we have a high radar resolution and close range to targets, our targets are modelled as extended targets

Radar Signal Model and Parameters



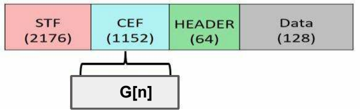
Parameter	Proposed Radar	Commercial SRR
Carrier frequency	60 GHz	77 GHz
Bandwidth	1.76 GHz	2 GHz
Range resolution	0.085 m	0.075 m
Maximum unambiguous range	44m	40m
Pulse repetition interval	2μs	1.67μs
Velocity resolution	0.05 m/s	0.3 m/s
Maximum unambiguous velocity	111 m/s	625 m/s

2. Modified Golay (MG) signal model

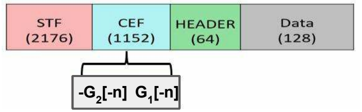
Example for 4 packets

1. Generate PTM sequence of length 2 bits - **{0,1}**
2. In PTM sequence replace all **0**'s with Golay Pair **{G_1[n],G_2[n]}** and **1's** with Golay Pair **{-G_2[-n],G_1[-n]}**

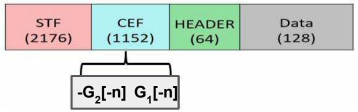
0



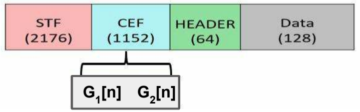
Packet 1



Packet 2



Packet 3

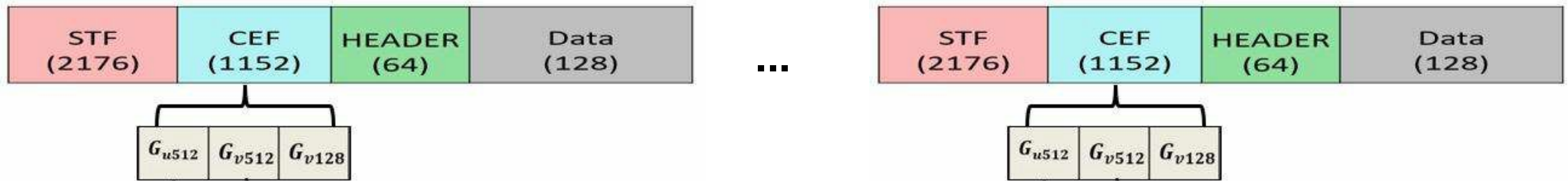


Packet 4

*Pezeshki reference

2. Standard Golay (SG) signal model

Packet 1 Packet P



PRI #1 PRI #P

The received signal for P packets after reflection from a point target

$$S_{rx}[n] = \sum_{p=0}^{P-1} \sum_{b=1}^{B} a_b[n] S_{tx}(nt_s - \tau_b - pT_{PRI}) e^{-j2\pi f_{D_b} p T_{PRI}} + z[n]$$

$\tau_b = delay\ for\ b^{th}\ point\ scatterer$

$a_b = reflectivity\ for\ b^{th}\ point\ scatterer$

$f_{D_b} = Doppler\ for\ b^{th}\ point\ scatterer$

Modified Golay: Doppler Resilience

Theta = 2*pi*fd*PRI

For P packets at the receiver the matched filter looks like this

$$\sum_{p=0}^{P-1} e^{jn\theta}(G_{p,N}[n] * G_{p,N}[n]) \approx$$
$$0(G_{0,N}[n] * G_{0,N}[n]) + 1(G_{1,N}[n] * G_{1,N}[n]) + 2(G_{2,N}[n] * G_{2,N}[n]) + \cdots + (P-1)(G_{P-1,N}[n] * G_{P-1,N}[n]).$$

- Using the first order Taylor Expansion about 0 for small theta i.e. small Doppler, we make RHS as close to the original perfect autocorrelation property as possible.

Modified Golay: PTM sequence

Pezeshki et.al, *Doppler resilient Golay complementary waveforms* Trans. Information Theory 2008

Prouhet-Thue-Morse (PTM) Sequence

$$q_p = \begin{cases} 0, & \text{if } p = 0 \\ q_{\frac{p}{2}}, & \text{if } (p \text{ modulo } 2) = 0 \\ \overline{q_{\frac{p-1}{2}}}, & \text{if } (p \text{ modulo } 2) = 1, \end{cases}$$

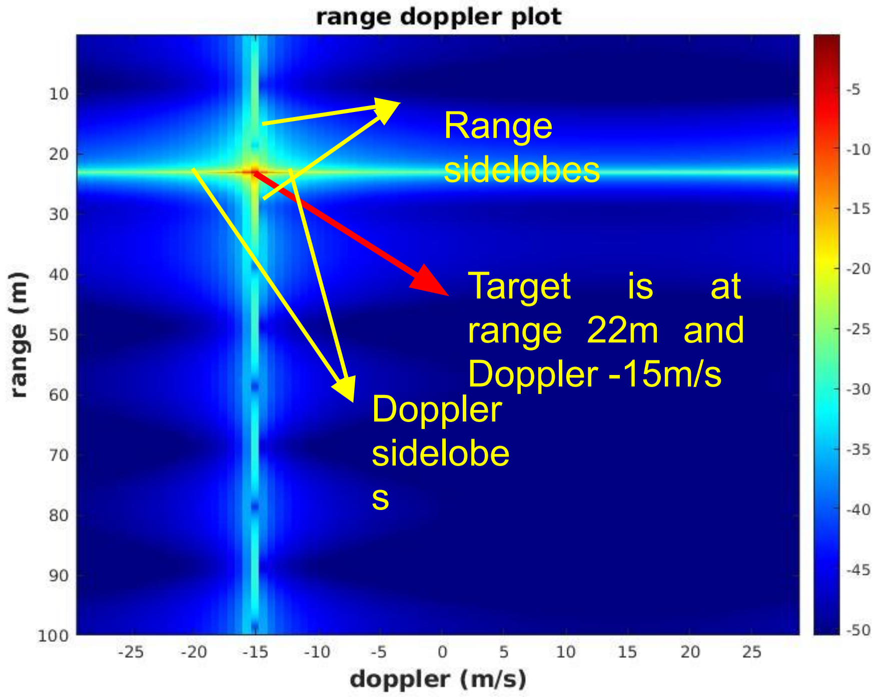
Modified Golay sequence

$$\text{if } q_p = 0, \{G_{a,N}[n], G_{b,N}[n]\}$$
$$\text{if } q_p = 1, \{-G_{b,N}[-n], G_{a,N}[-n]\}$$

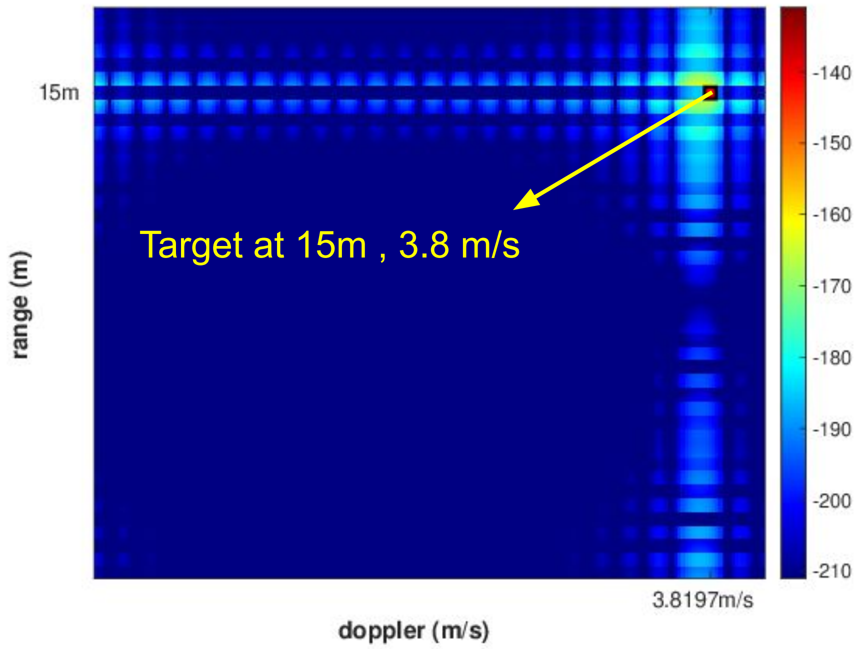
Example

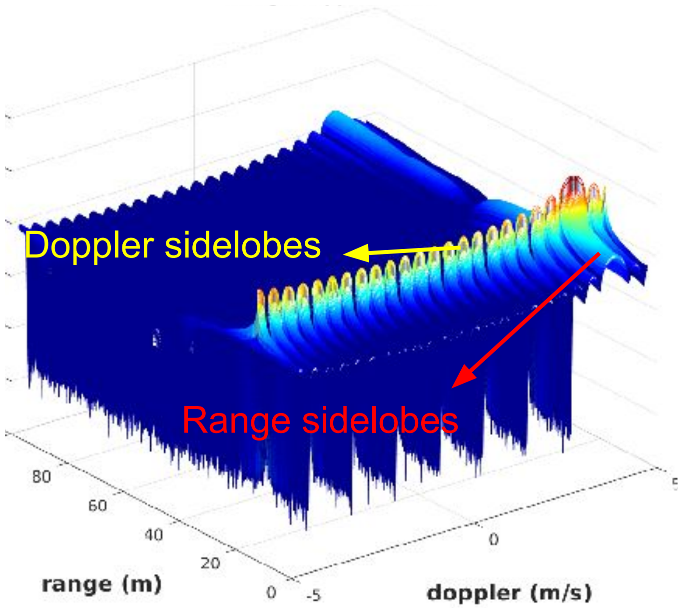
PTM Sequence: [01] : $G_{a,N}[n], G_{b,N}[n], -G_{b,N}[-n], G_{a,N}[-n]$:

$$\sum_{p=0}^{3} e^{-jp\theta}(G_{p,N}[n] * G_{p,N}[-n]) \approx 1((G_{1,N}[n] * G_{1,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$+2((G_{2,N}[n] * G_{2,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$= (2N + 2(2N))\delta[n] = 6N\delta[n].$$

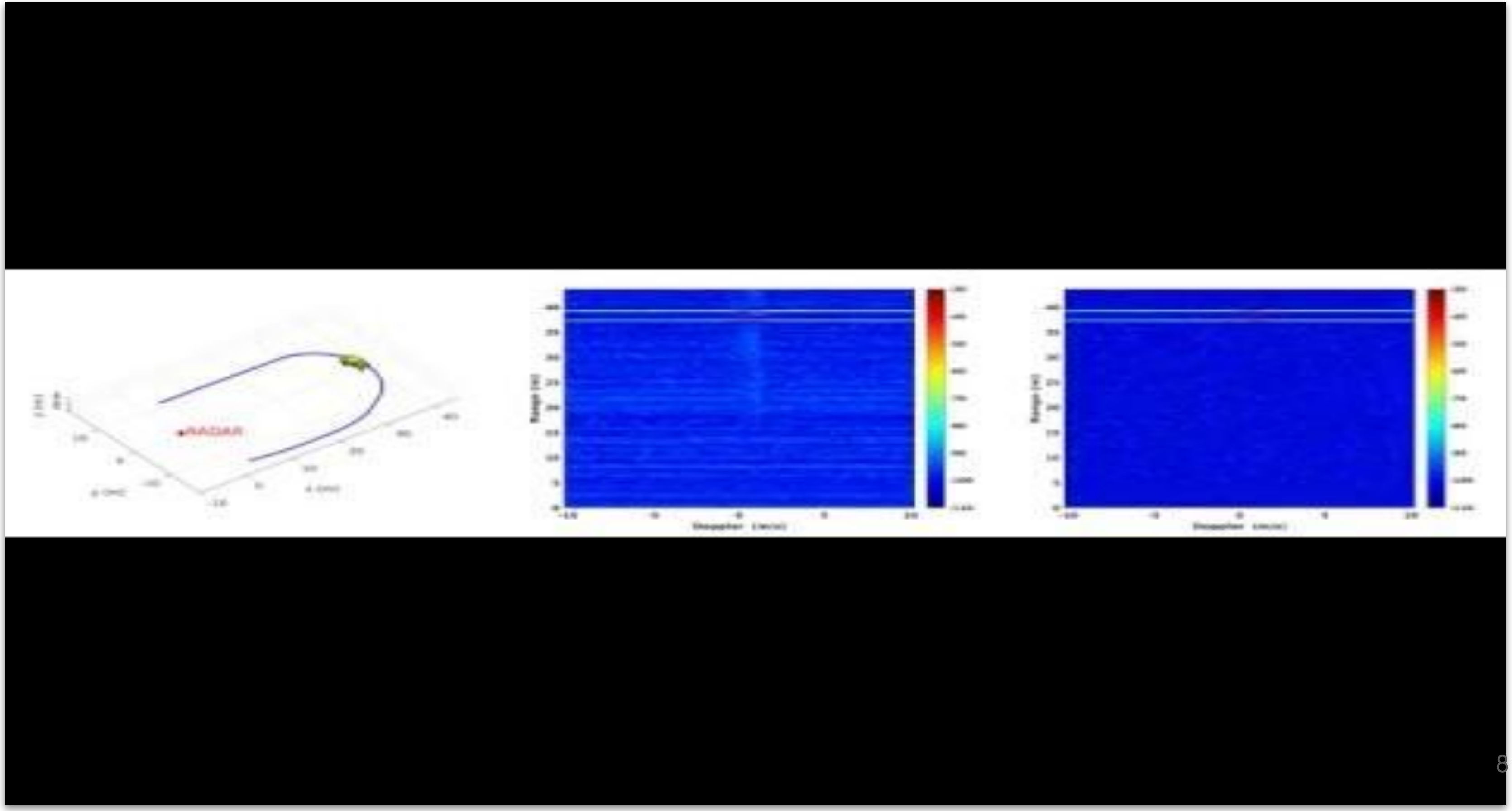

range doppler plot
Range sidelobes
Target is at range 22m and Doppler -15m/s
Doppler sidelobes
range (m)
doppler (m/s)
10
20
30
40
50
60
70
80
90
100
-25
-20
-15
-10
-5
0
5
10
15
20
25
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50

An example of a range-Doppler plot





3. Car MG vs SG radar



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