AuE 8200: Machine Perception and Intelligence

Lecture: Automotive radar principles and analysis

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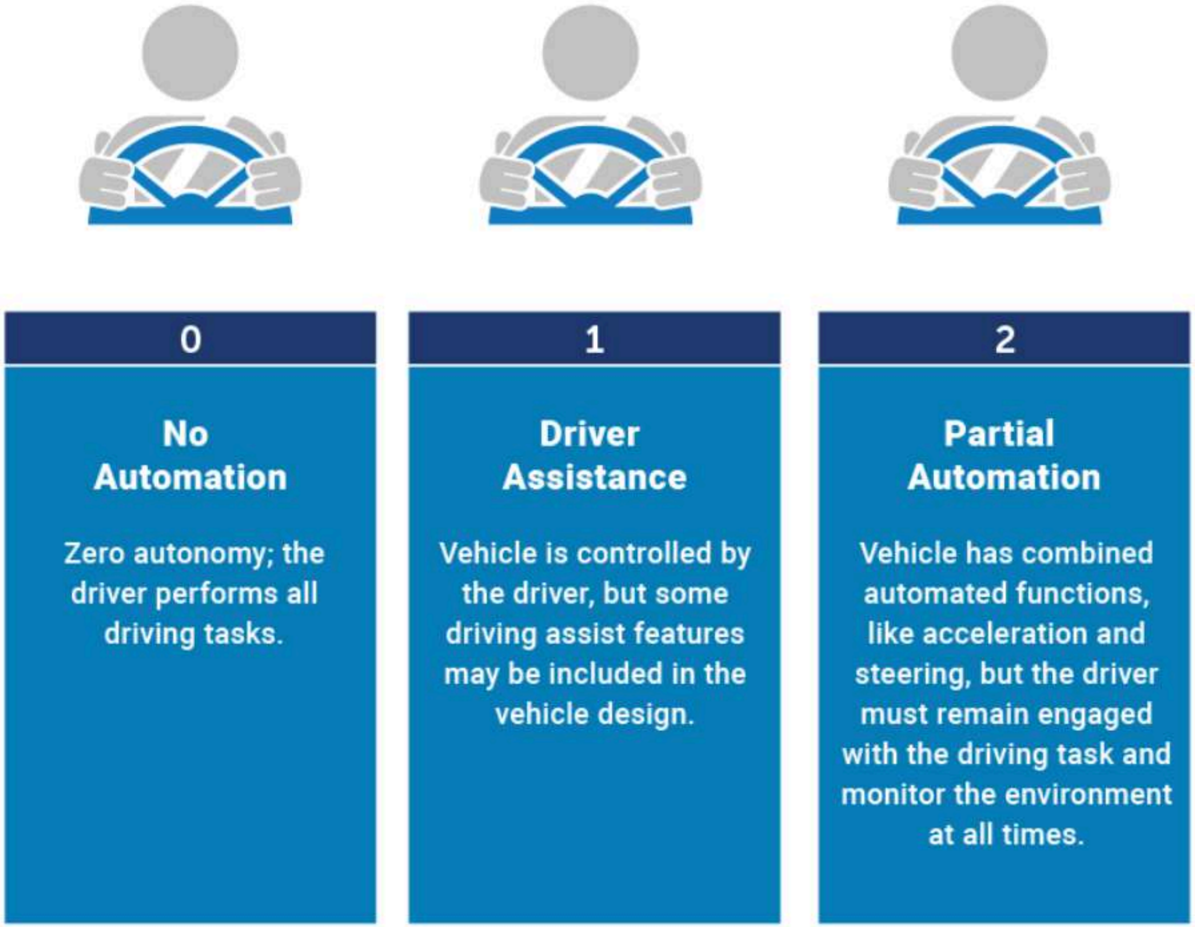
Outline

- Automotive Radar Motivation
- Automotive Radar History
- Automotive Radar Basics
  - Ranges
  - Frequency Bands
- Automotive Radar Principle
  - Pulsed Radar
  - FMCW Radar
  - DOA
- Automotive Radar Object Detection
  - Object Clustering
  - Object Classification
  - Object Tracking

Automotive Radar Motivation

Society of Automotive Engineers (SAE) automation levels

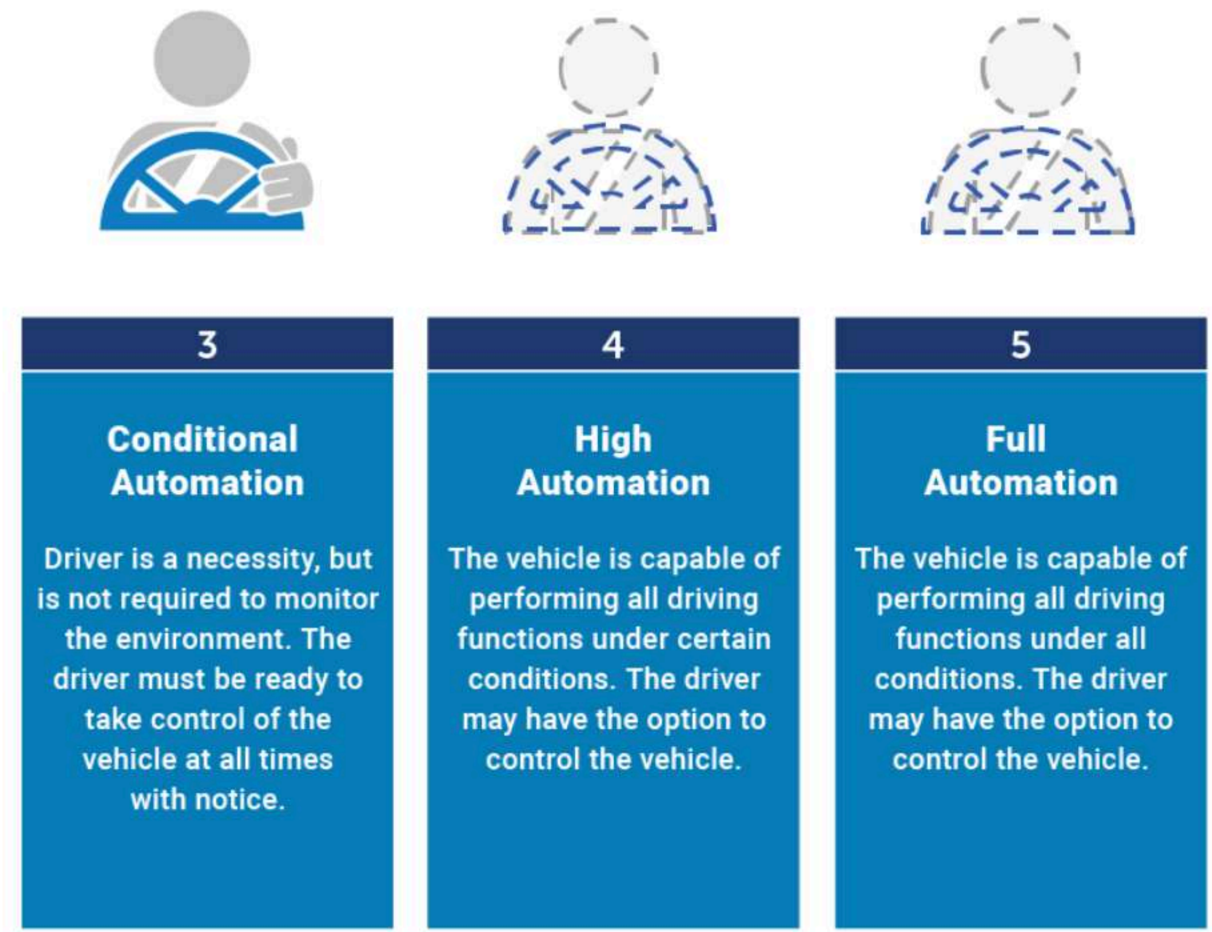


NHTSA

Advanced driver assistance system (ADAS)

Automotive Radar Motivation

Society of Automotive Engineers (SAE) automation levels



NHTSA

Automated driving system (ADS)

Automotive Radar Motivation

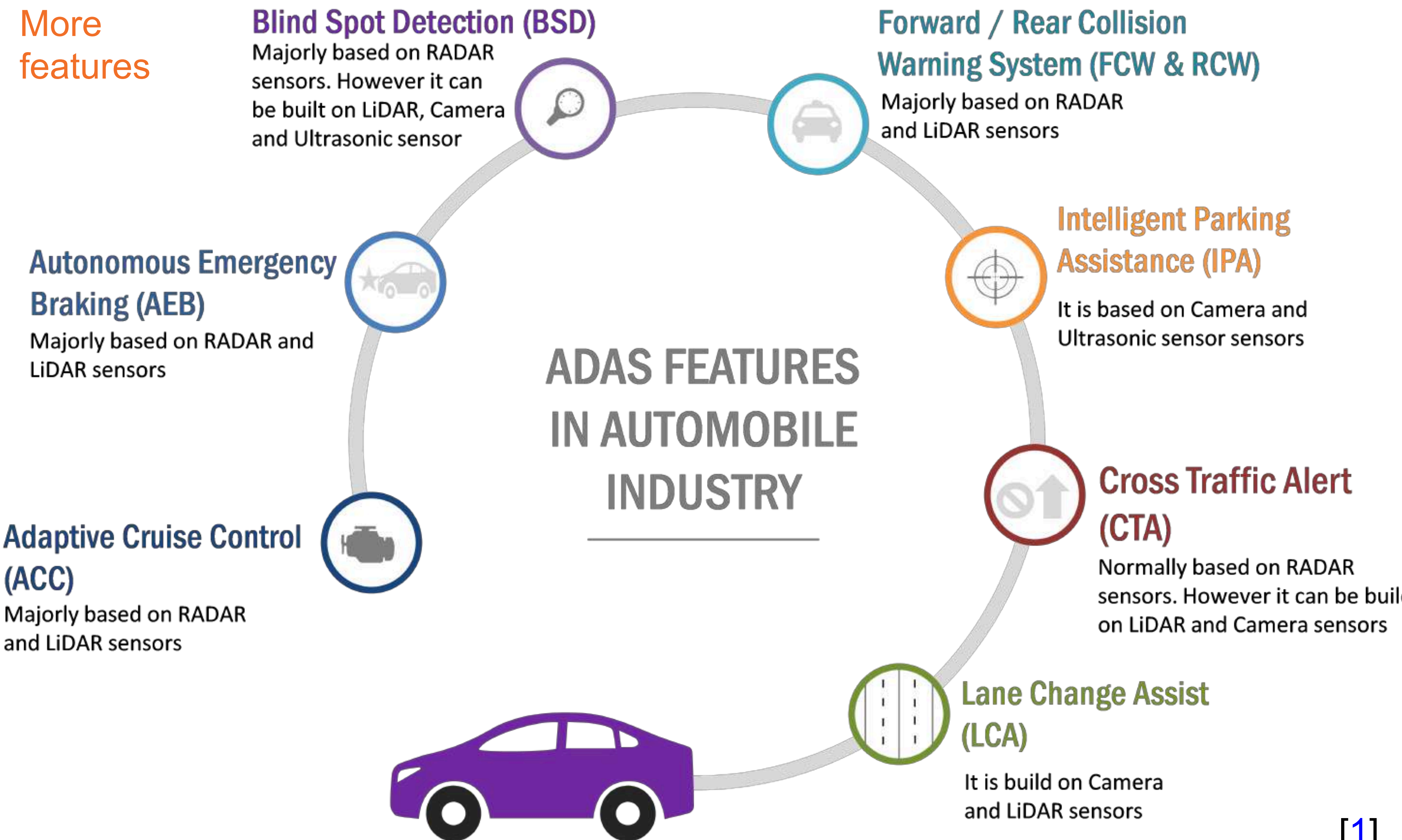
Consumer Electronics Show (CES) 2019

CES 2019: NVIDIA launches Level 2+ automated driving solution

[1]

Automotive Radar Motivation

More features



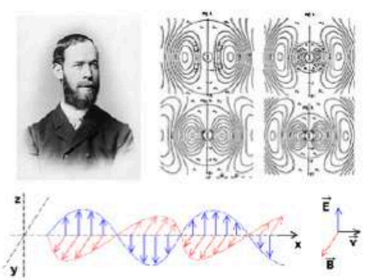
[1]

Automotive Radar History

1864
James Clerk Maxwell
Postulation of electromagnetic waves

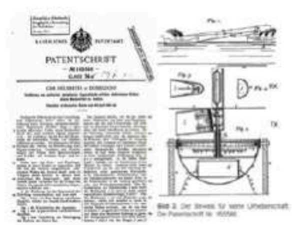
$$\oint E \cdot dA = \frac{q}{\epsilon_0}$$
$$\oint B \cdot dA = 0$$
$$\oint E \cdot ds = -\frac{d\Phi_B}{dt}$$
$$\oint B \cdot ds = \mu_0 i + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

1888
Heinrich Hertz
Prove of electromagnetic waves & speed of light

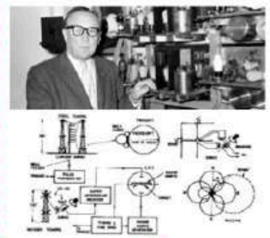


1895
Guglielmo Marconi
first wireless communication system

1904
Christian Hülsmeyer
First radar patent
"Telemobiloskop"



1935
Sir R.A. Watson-Watt
first airplane radio-location



1946
Air Traffic Control
First civil radars

1958
Radar Speed Meter
For traffic speed limit enforcement
"Gatsometer"

1970's
First automotive Radar

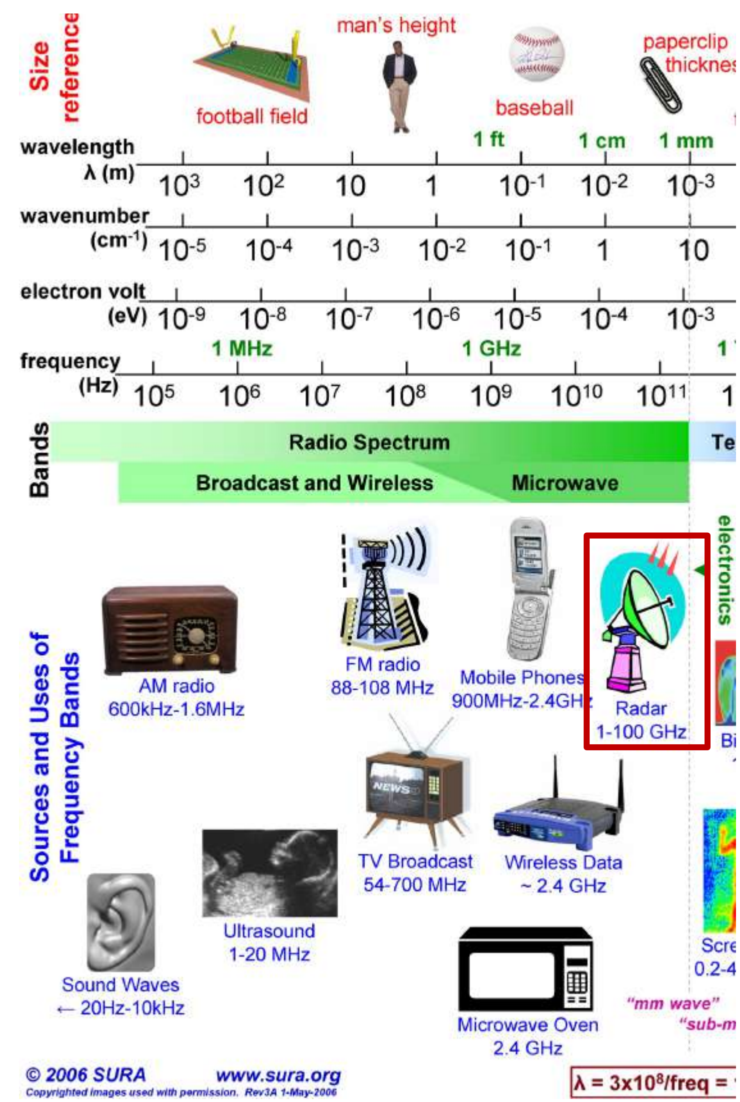
1992
Greyhound bus radar
First collision warning 24 GHz radar for 1500 busses (Eaton Vorad T-200)

1999
77 GHz ACC Radar
Distronic in Mercedes Benz S-class sedan

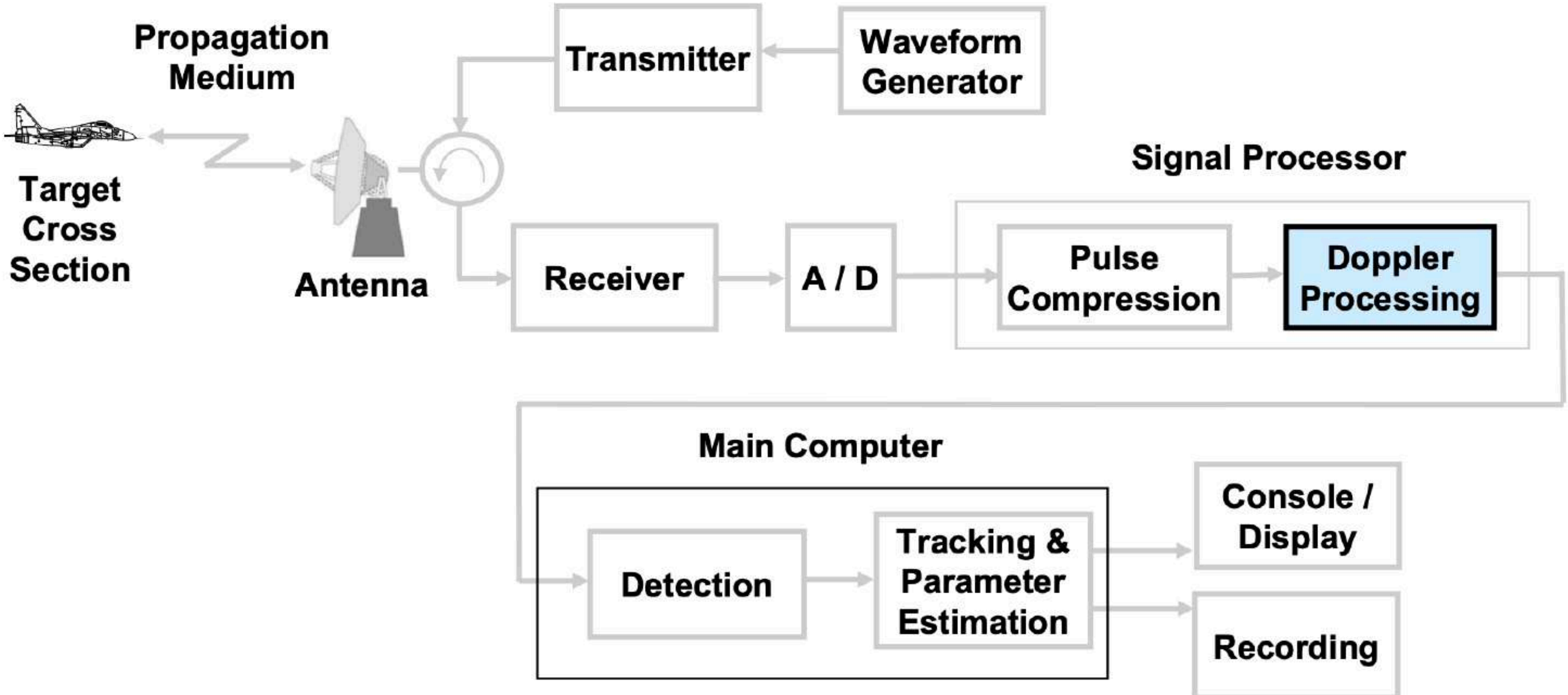
2003
Widely available

Automotive Radar Basics

- Radar (RAdio Detection And Ranging)
  - Relative position
  - Relative speed
  - Relative azimuth angle
- Electromagnetic wave
  - Radio wave
  - Signal echo
- Advantages over optical sensors
  - Robustness in harsh weather conditions (darkness/brightness, fog, rain, temperature, et al)
  - Long, middle and short ranges
  - High accuracy



Automotive Radar Basics



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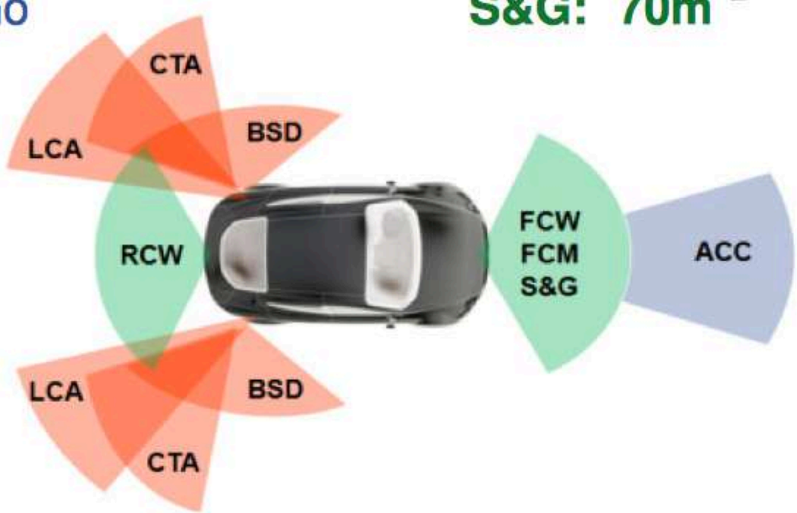
Automotive Radar Basics - Ranges

Long Range

Adaptive Cruise Control	ACC: 150 to 200m	FOV: +/-8°

Short/Medium Range

Blind Spot Detection	BSD: 10m	FOV: +/-75°
Lane Change Assist	LCA: 70m	
Cross Traffic Alert	CTA: 30m	
Forward Collision Warning	FCW: 70m	FOV: +/-65°
Forward Collision Mitigation	FCM: 70m	
Rear Collision Warning	RCW: 70m	
Stop & Go	S&G: 70m	



Field of View (FOV)

[1]

Automotive Radar Frequency Bands

24GHz NB	24GHz UWB	26GHz UWB	77GHz	79GHz UWB
Worldwide	US/Canada Japan EU until 2013/ will be extended to 2022 but with reduced bandwidth	US/Canada Japan	"Worldwide"	Singapore EU
different bandwidth EU: 200MHz (75cm) [450MHz] (33cm) US: 200MHz (75cm) JP: 200MHz (75cm)	US: 7GHz (2.2cm) JP+EU: 5GHz (3cm)	US: 1 GHz (15cm) JP: July 2010 5 GHz (3cm)	1 GHz (15cm) JP: 500MHz (30cm)	4 GHz (4cm)
20dBm	**-41dBm**	**-41dBm**	**23.5dBm**	**-9dBm**

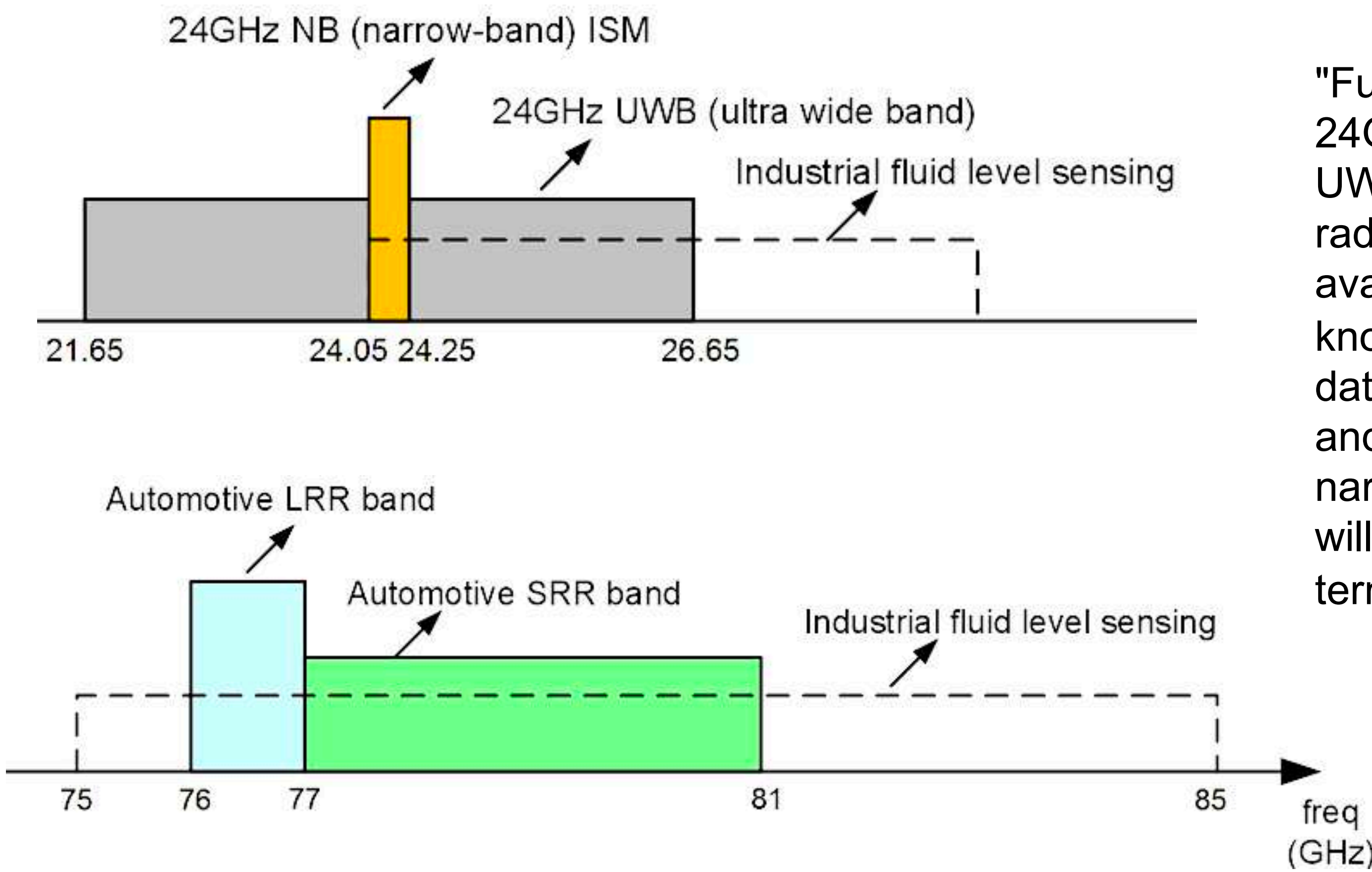
24/26 GHz → 76-81 GHz

K Band (24 GHz) E Band (77 GHz)

regulations

Automotive Radar Frequency Bands

Moving from 24GHZ to 77GHz radar



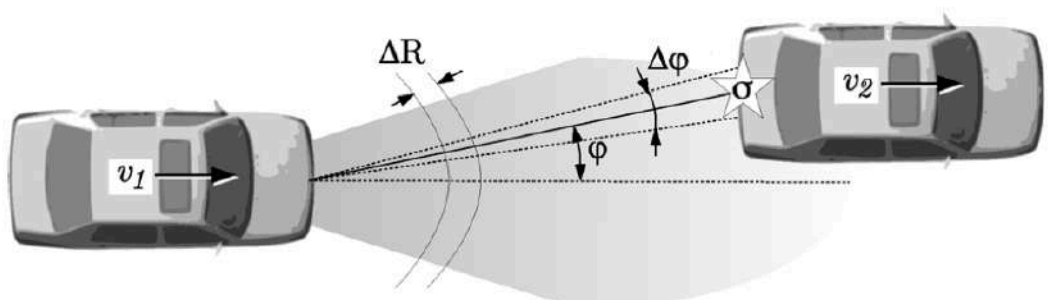
"Future use of the 24GHz wideband and UWB band vehicular radars will not be available after 2021, known as the “sunset date,” both in Europe and the U.S.; only the narrowband ISM band will be available long term." [1]

Range resolution, Velocity resolution and Smaller components

Automotive Radar Frequency Bands

Type	LRR	MRR	SRR
Maximum transmit power (EIRP)	55 dBm	-9 dBm/MHz	-9 dBm/MHz
Frequency band	76-77 GHz	77-81 GHz	77-81 GHz
Bandwidth	600 MHz	600 MHz	4 GHz
Distance range $R_{\min}...R_{\max}$	10-250 m	1-100 m	0.15-30 m
Distance resolution ΔR	0.5 m	0.5 m	0.1 m
Distance accuracy δR	0.1 m	0.1 m	0.02 m
Velocity resolution Δv	0.6 m/s	0.6 m/s	0.6 m/s
Velocity accuracy δv	0.1 m/s	0.1 m/s	0.1 m/s
Angular accuracy $\delta\varphi$	0.1°	0.5°	1°
3 dB beamwidth in azimuth $\pm\varphi_{\max}$	±15°	±40°	±80°
3 dB beamwidth in elevation $\pm\vartheta_{\max}$	±5°	±5°	±10°
Dimensions	74x77x58 mm	50x50x50 mm	50x50x20 mm

* SRR:
24 GHz is still being used in SRR.



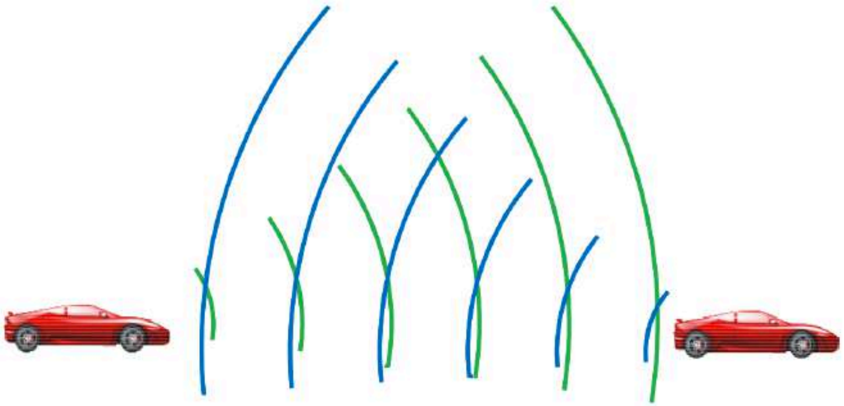
[1]

Automotive Radar Principle

- Radar signal and echo

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

- R: relative distance
- c: EM wave travel speed as a constant
- τ: time of flight (ToF)



- Radar P, R models

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L} \quad \rightarrow \quad R = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 L P_r}}$$

$$R \leftrightarrow \lambda \qquad\qquad R \leftrightarrow \sigma$$

P_t: Transmit signal power
G: Antenna gain (A_o/A_i)
λ: Radar wavelength
σ: Radar cross section (RCS)
R: relative distance
L: Other losses (propagation,)

Automotive Radar Principle

- Automotive radar measures what?
- Distance
- Speed

Race cars approach and then recede from us, what's the sound difference?

Automotive Radar Principle

- Radar echo back time

$$\tau = \frac{R}{c} \qquad \tau_{echo} = \frac{(R+v\Delta t)}{c}$$

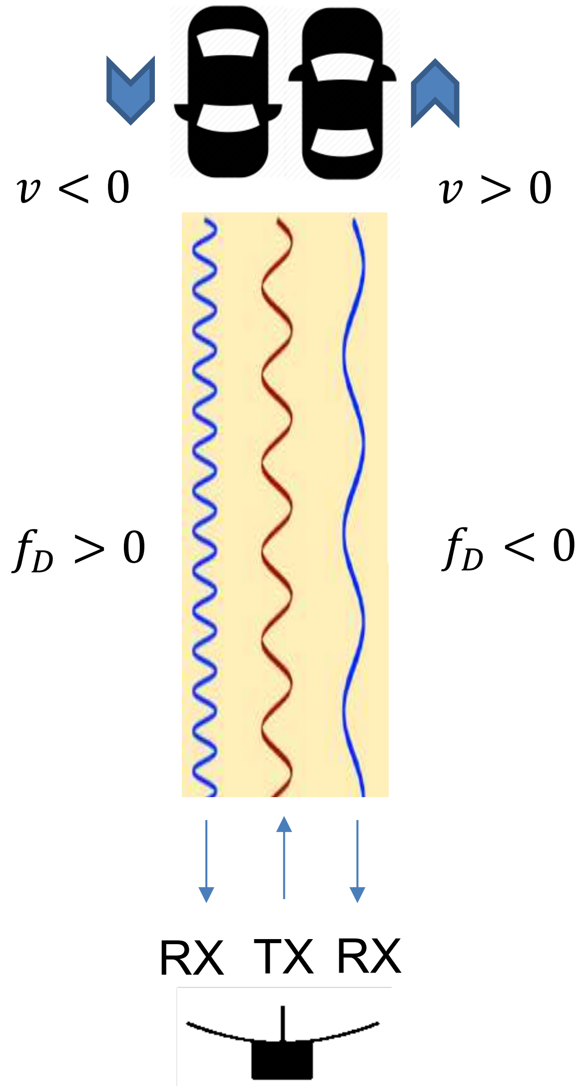
- The difference causes a frequency change f_D :

$$f_D \sim v, \lambda_c \,?$$

λ_c is the wavelength of carrier

Doppler effect

Named after physicist Christian Doppler 1842



Rader transmitter/receiver

Automotive Radar Principle

- Doppler shift effect:

Transmitted signal: $\cos(2\pi f_c t)$

Received signal: $\cos(2\pi f_c(t + \frac{2R}{c}))$

Range change w.r.t velocity in one cycle: $R = R_o + v_o t$

Substituting:

$$\cos\left(2\pi f_c\left(t + \frac{2(R_o + v_o t)}{c}\right)\right) =$$

$$\cos\left(2\pi(f_c + \underbrace{f_c\frac{2v_o}{c}}_{-f_D})t + \frac{2\pi f_c R_o}{c}\right)$$

$$f_D = -f_c\frac{2v_o}{c} = -\frac{2v_o}{\lambda_c}$$

Automotive Radar - Pulse Radar

- Pulse radar
  - T_r Pulse Repetition Interval (PRI)
  - Pulse Repetition Frequency (PRF)
    PRF = 1 / PRI
  - One antenna for both transition and reception

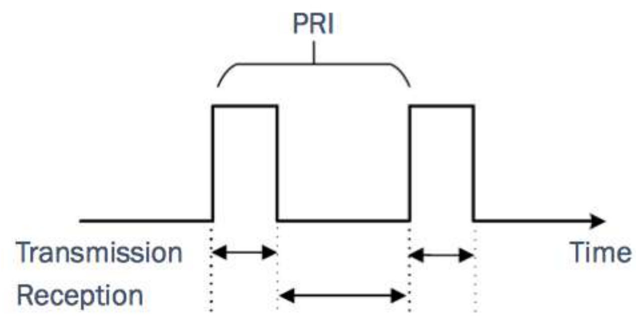
- Range measurement $R = \dfrac{c\tau}{2}$

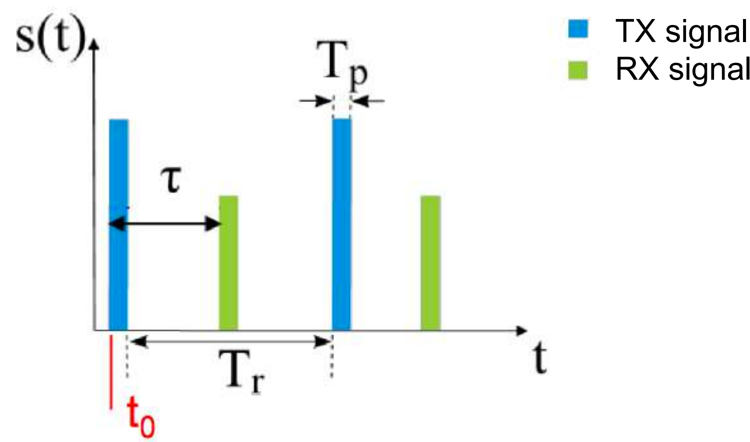
- Maximum unambiguous range

$$R_{max} = \frac{c}{2} T_r = \frac{c}{2\ PRF}$$

- Range ambiguity resolution

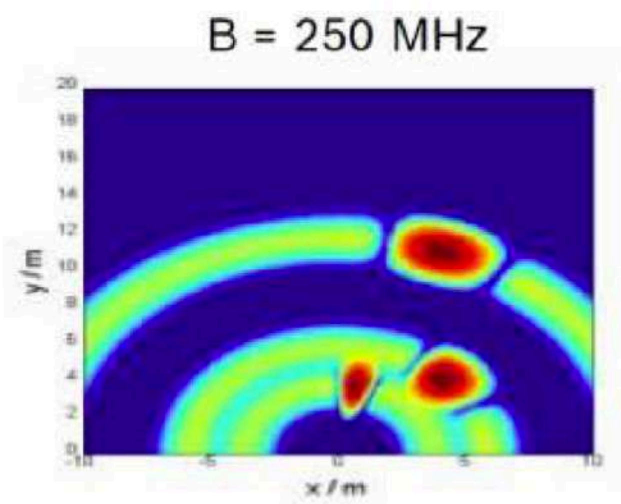
$$\Delta R = \frac{cT_p}{2} \approx \frac{c}{2B}, \text{where B is the Bandwidth}$$



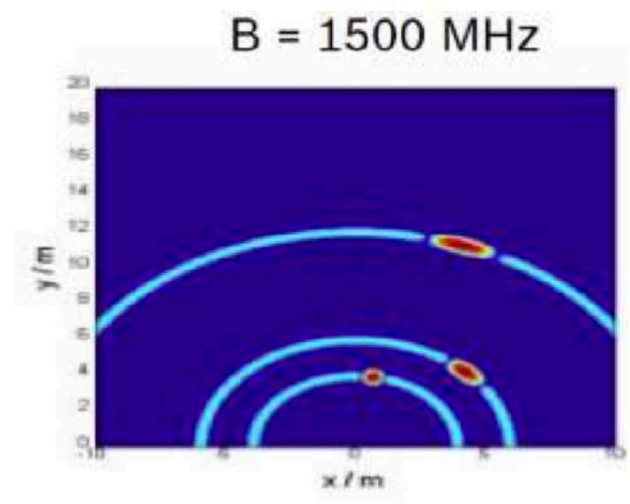


Automotive Radar - Pulse Radar

- Target separation capability



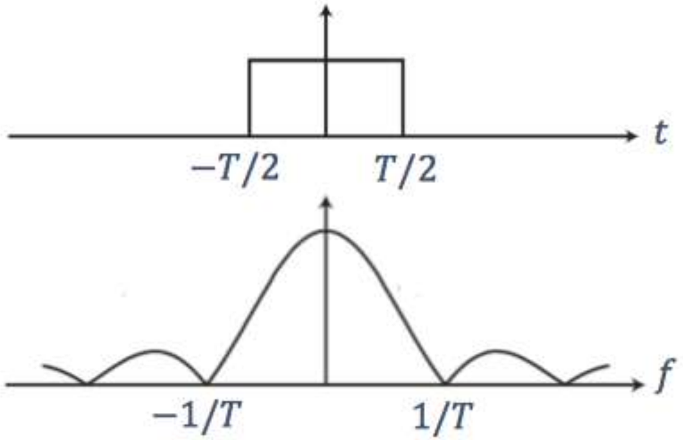
Long range radar bandwidth

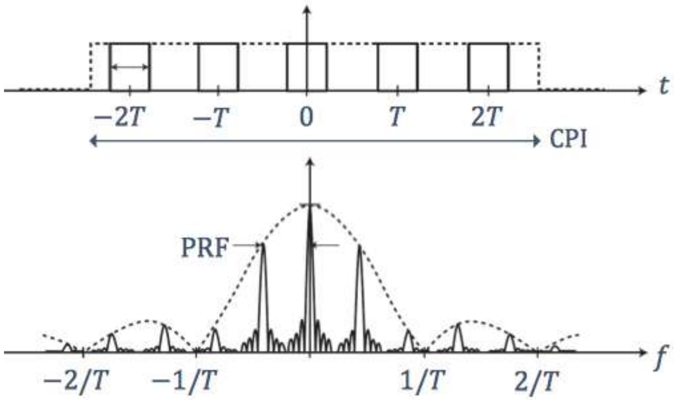


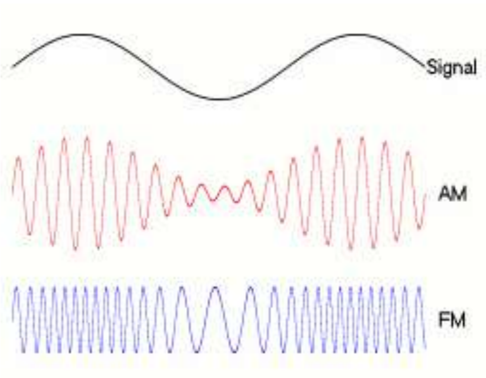
High-range resolution radar bandwidth

Automotive Radar - Pulse Radar

- How to measure velocity?
- Spectrum of pulsed radar signal
  - Fourier transform (FT)
- Coherent pulse interval (CPI)
  - Phase → Frequency modulation
  - What is Frequency modulation?







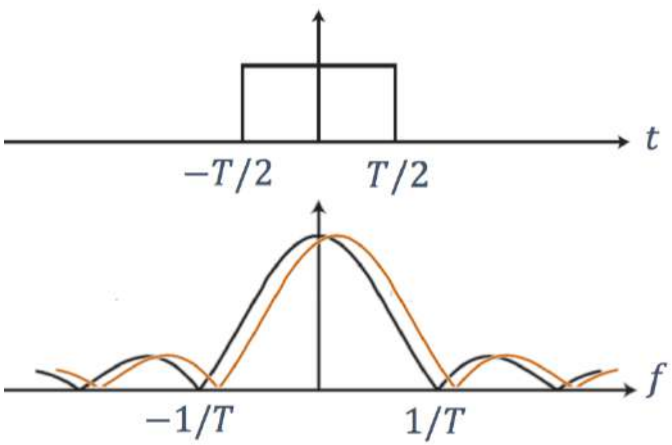
Amplitude modulation

Frequency Modulation

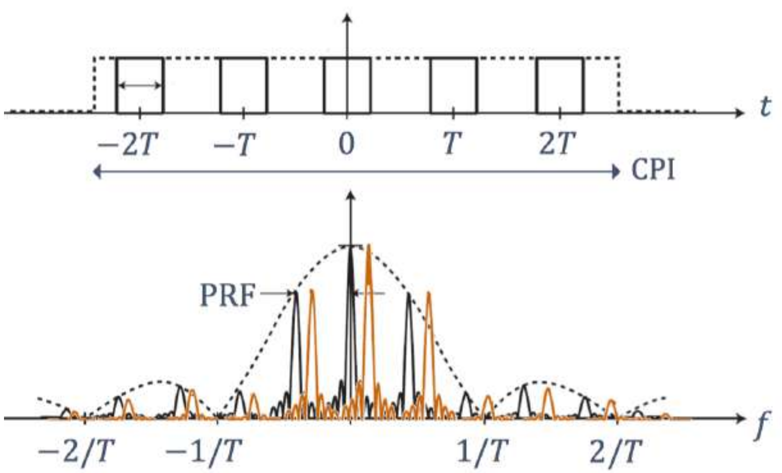
Automotive Radar - Pulse Radar

- Spectrum of coherent pulsed signals

- Reflection signal:
  - An object is detected

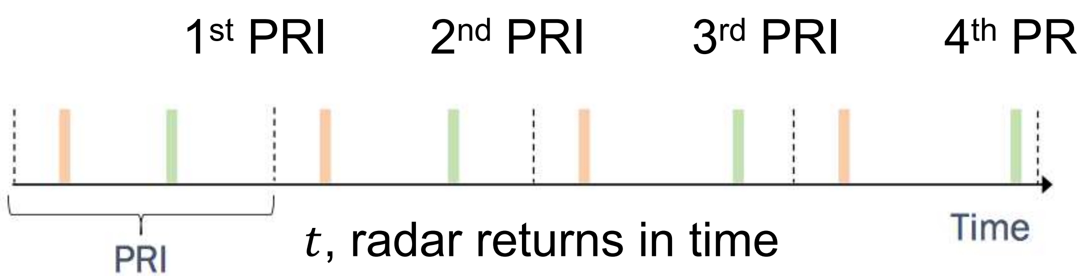


- Velocity estimation
  - Doppler shift



Automotive Radar - Pulse Radar

- Coherent pulsed signal data matrix
  - Fast Time: the different time slots composing a PRI, sampling rate dependent;
  - Slow Time: the time axis of PRI;



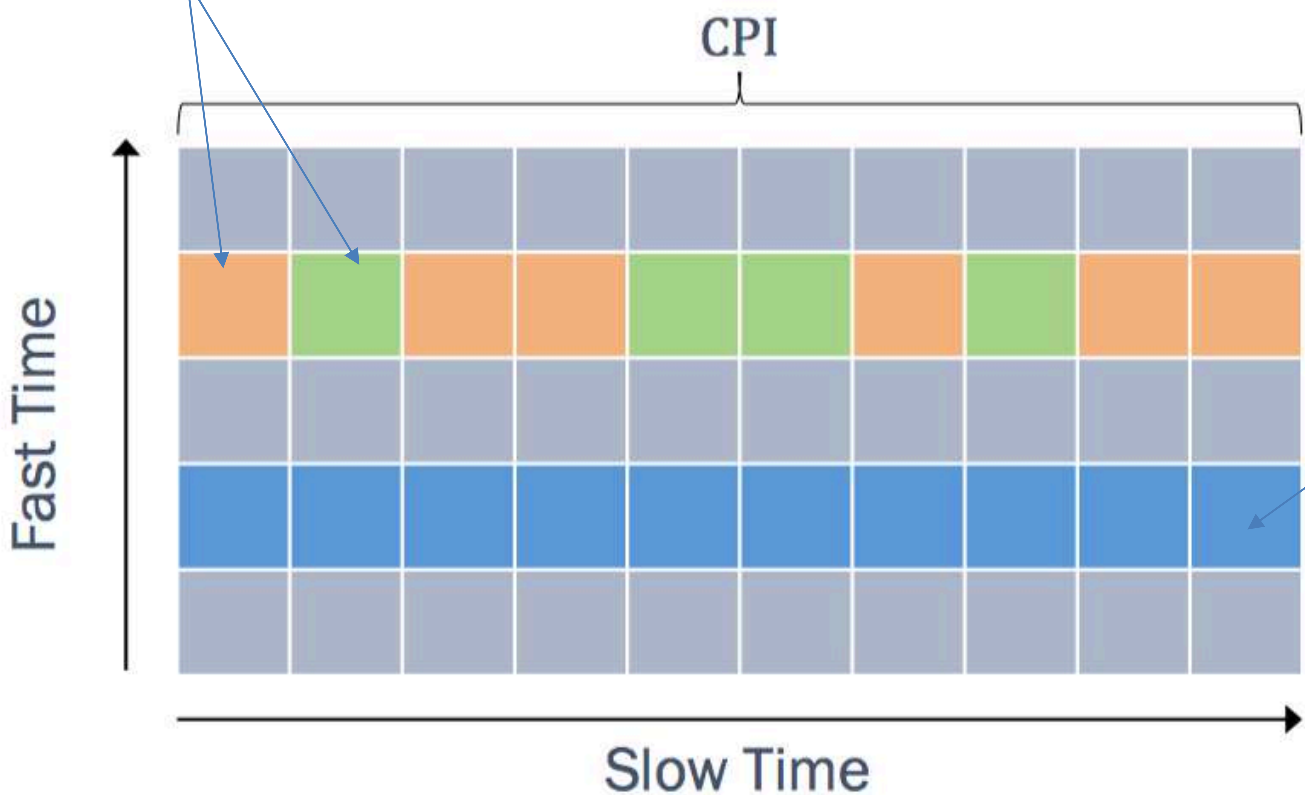
Sample: ranges and velocities of two objects

[1]

Automotive Radar - Pulse Radar

- Coherent pulsed signal data matrix

Two objects are in the same rang bin, but different velocity



One object
in another rang bin

Sample: ranges and velocities when there are three objects

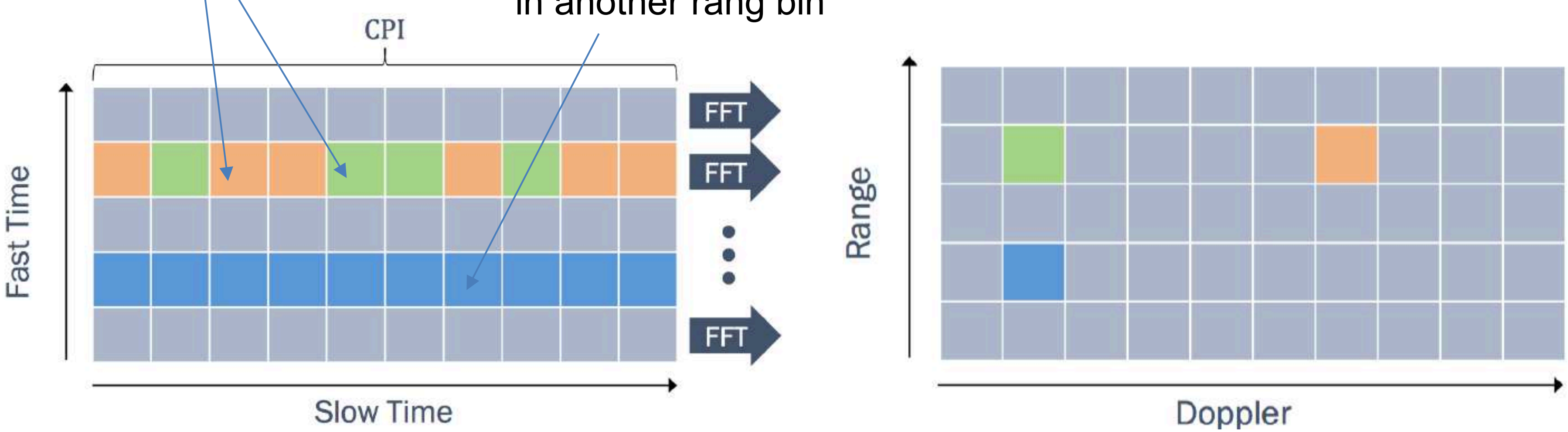
[1]

Automotive Radar - Pulse Radar

- Coherent and Doppler processing
  - Different returns show differently in the Doppler domain.
  - By applying Fourier Transform, range-Doppler map transfer Fast time -> Range and Slow time -> Doppler

Two objects are in the same rang bin, but different velocity

One object
in another rang bin



Sample of three objects

Range-Doppler Maps

[1]

Automotive Radar - Pulse Radar

- Pulse radar characteristics
  - Low cost circuitry
  - Higher power consumption
  - High accuracy for the detection
  - Environment distortions
- Applications
  - Short range radar, et al
- Pulse Radar

  (1) Pulse Doppler Radar
  - High pulse repetition frequency (PRF)
  - No Doppler ambiguities
  - Numerous range ambiguities

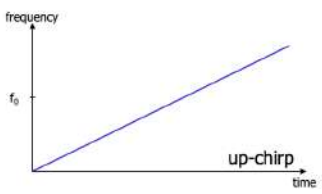
  (2) Moving Target Indicator Radar
  - Low pulse repetition frequency
  - No range ambiguities
  - Doppler ambiguities

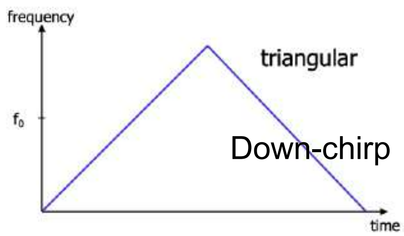
Automotive Radar - FMCW Radar

- Continuous wave (CW) radar
  - Constantly transmit and receive

- Frequency Modulated Continuous Wave (**FMCW**)

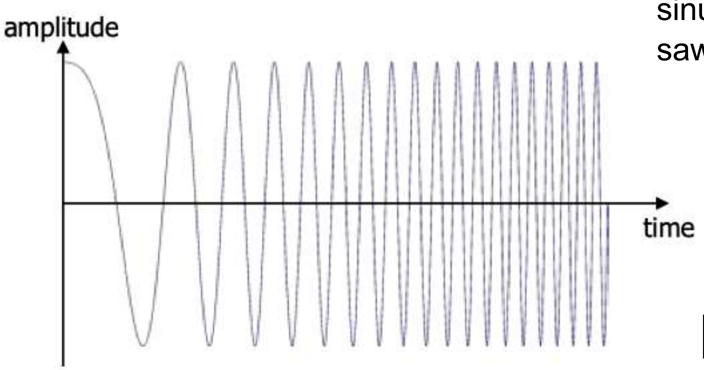
Frequency modulation





We concentrate on: linear FMCW Radar

continuous-wave

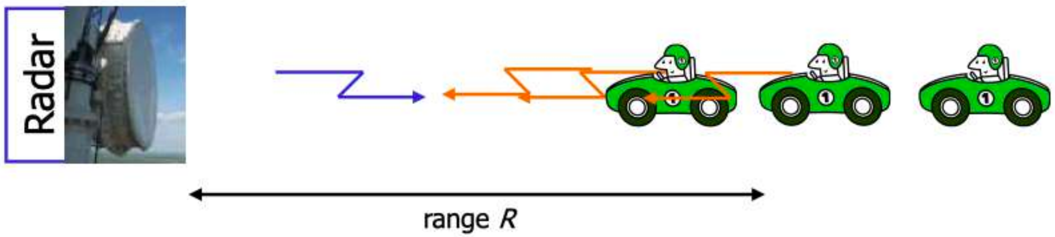


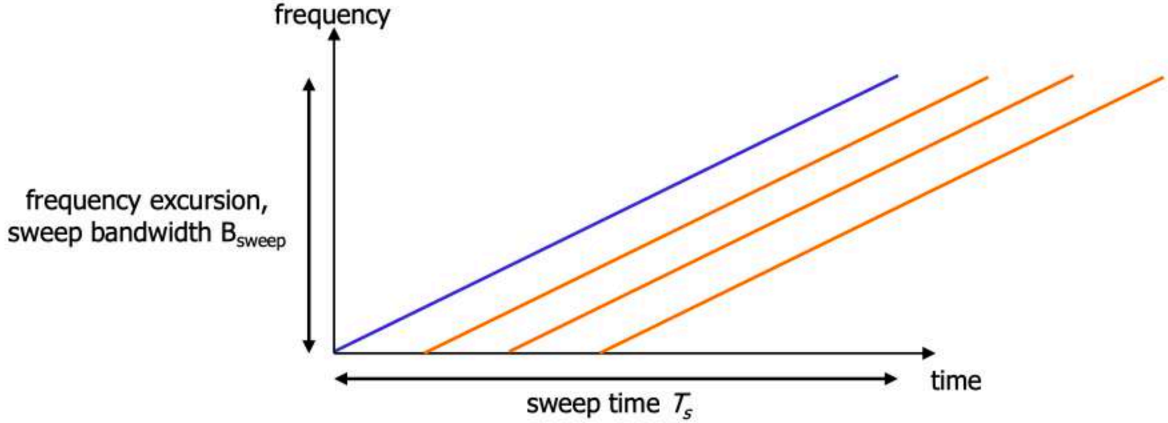
Such as:
sinusoid or
sawtooth

[1]

Automotive Radar - FMCW Radar

- FMCW – single target





[1]

Automotive Radar - FMCW Radar

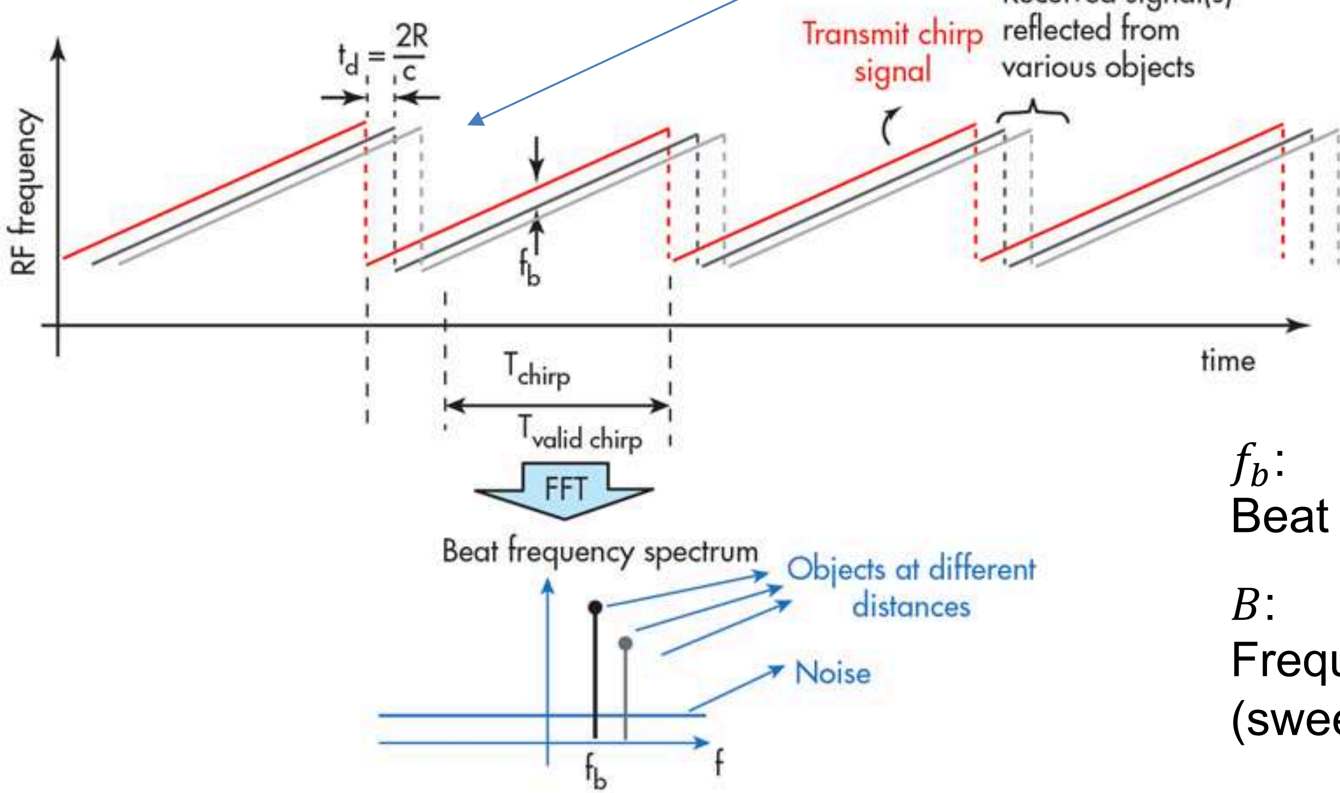
- For waveform with up chirp only - Range

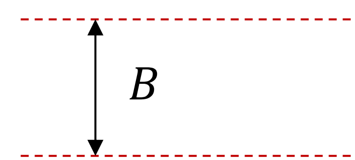
$$R = \frac{ct_d}{2} \quad \rightarrow \quad t_d = \frac{2R}{c}$$

Based on triangle similarity:

$$\frac{t_d}{f_b} = \frac{T}{B} \quad \rightarrow \quad R = f_b \frac{cT}{2B}$$

For waveform with up chirp only





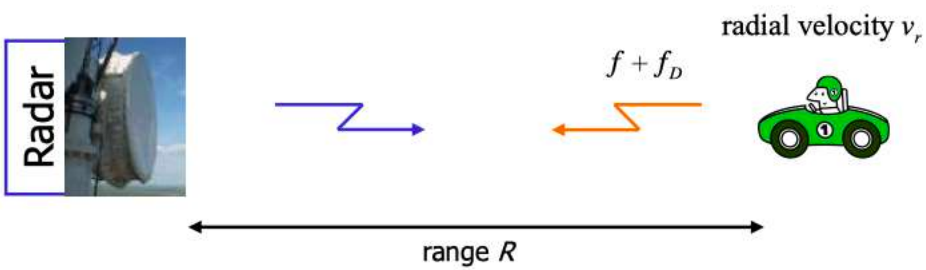
f_b:
Beat frequency

B:
Frequency band (sweep bandwidth)

[1]

Automotive Radar - FMCW Radar

- For waveform with up chirp only - Speed



Re-visit

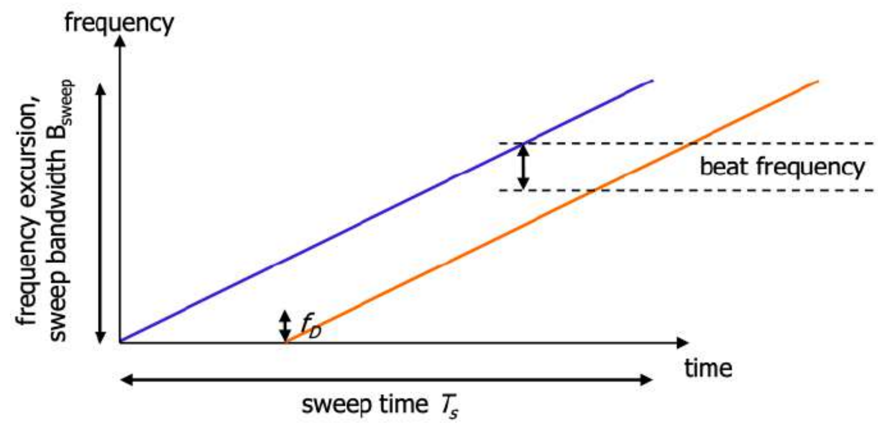
$$\cos\left(2\pi f_c\left(t + \frac{2(R_o + v_o t)}{c}\right)\right) =$$

$$\cos\left(2\pi(\underbrace{f_c + f_c\frac{2v_o}{c}}_{-f_D})t + \frac{2\pi f_c R_o}{c}\right)$$

$$f_D = -f_c\frac{2v_o}{c} = -\frac{2v_o}{\lambda_c}$$

- A moving target induces a Doppler frequency shift with the radar wavelength λ

$$f_d = \frac{2V}{\lambda_c}$$



The beat frequency is not only related to the range of the target, but also to its relative radial velocity with respect to the radar.

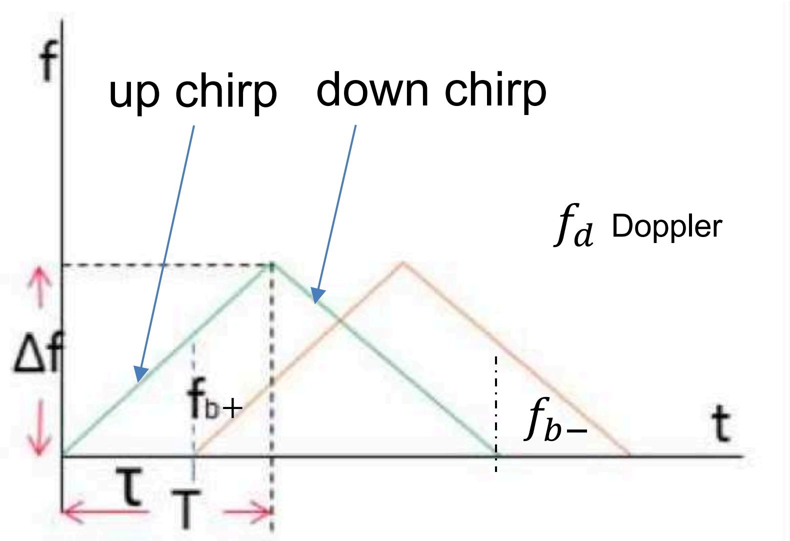
Both are mixed, how to resolve it?

[1]

Automotive Radar - FMCW Radar

- For waveform with both up and down chirps

$$f_b = \frac{2BR}{cT} \qquad f_d = \frac{2V}{\lambda_c}$$



Upsweep Beat Frequency

$$f_{b+} = f_b - f_d$$

Downsweep Beat Frequency

$$f_{b-} = f_b + f_d$$

Range $\quad R = \frac{cT}{4B} f_{b+} + f_{b-}$

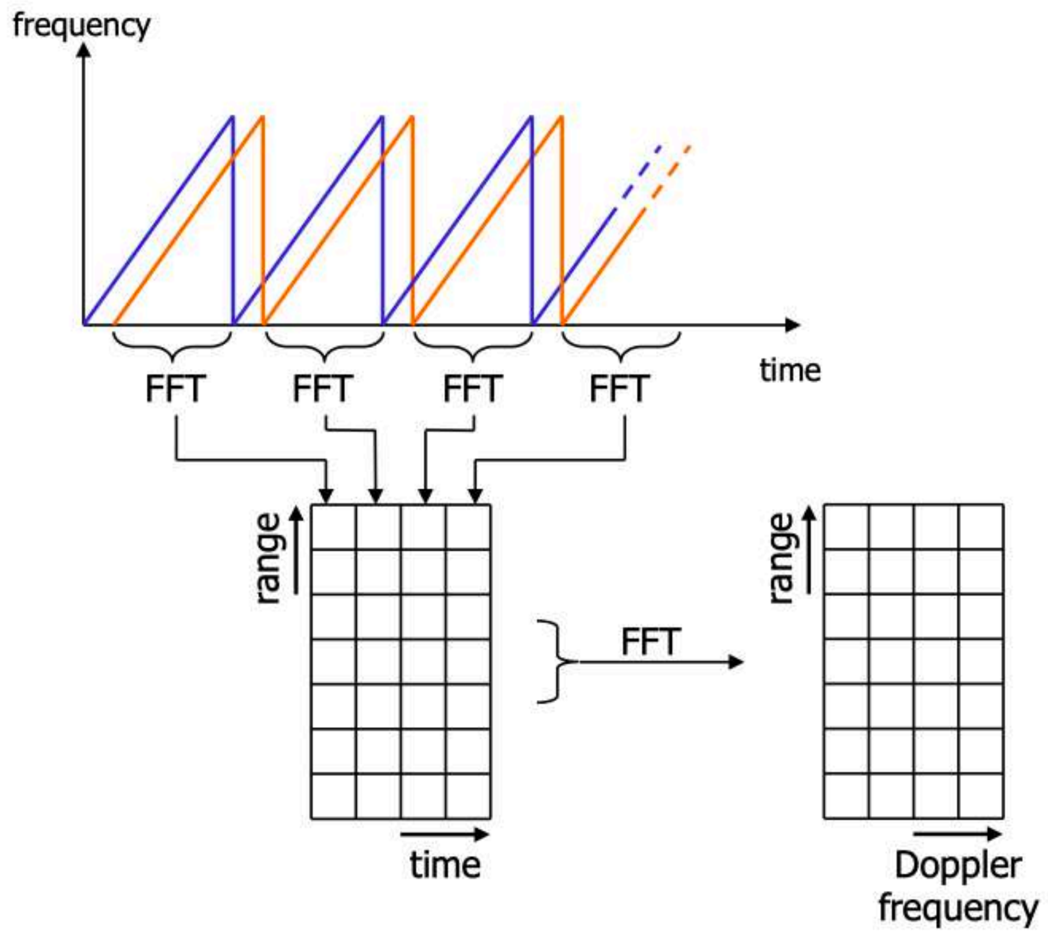
Speed $\quad V = \frac{\lambda}{4} f_{b+} - f_{b-}$

Advantage of both up and down chirps?
- Less bandwidth for same transmitted power

$$P = \frac{1}{\pi} \int_{B_{low}}^{B_{high}} F(\omega) d\omega$$

Automotive Radar - FMCW Radar

- FMCW Radar signal processing



[1]

Automotive Radar - FMCW Radar

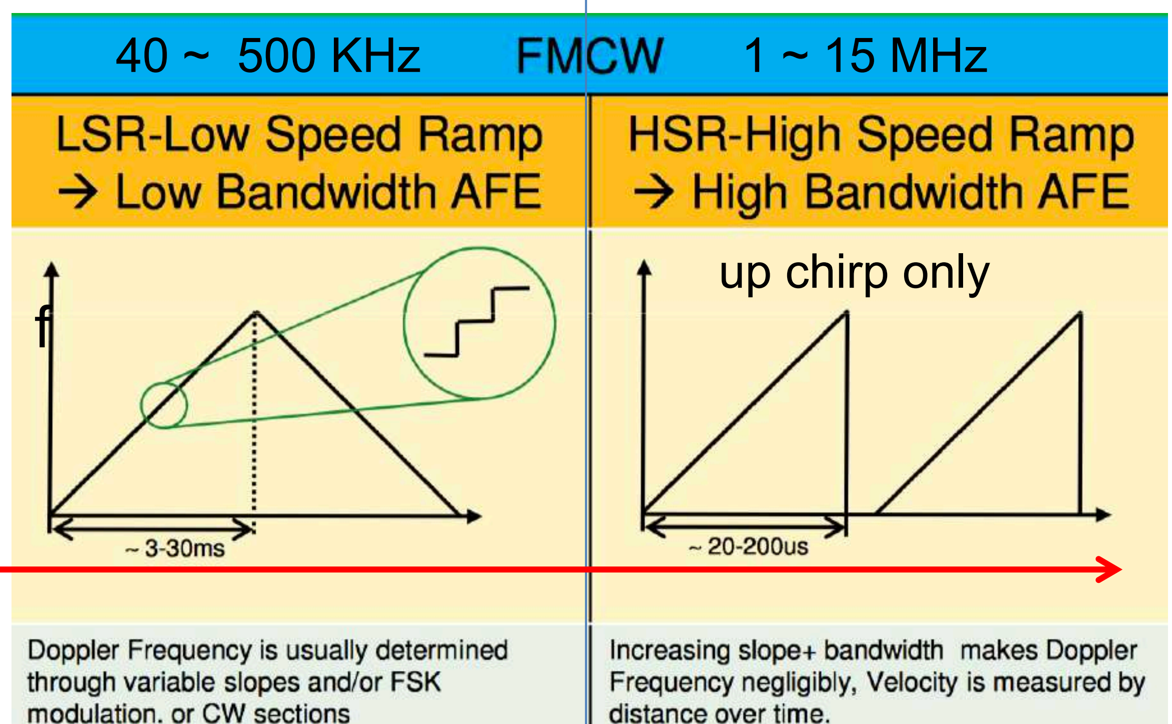
- Two categories of FMCW radar modulated frequency [1]

Slow ramp

Fast ramp

Higher multi-target detection capability

analog front-end (AFE)



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Preferred for automotive radar

Larger computation memory

Higher computational load

Two types for Fast ramp waveforms:
- Up or down chirp only
- Both up and down chirps

Automotive Radar - FMCW Radar

- FMCW radar characteristics
  - Higher cost circuitry
  - Lower power consumption
  - Lower accuracy for the detection
  - Simultaneous range and radial velocity
- Applications:
  - Long range radar, et al

Table: Comparison of UWB and FMCW Radar.
(Bold text represents the superior system in each category)

Category	UWB *(Pulsed radar)*	FMCW (tested at 5.8 GHz)
Precision indoor	1.3 cm to 2.8 cm	**1.1 cm to 2.3 cm**
→ relative	< **0.4 %**	< 0.8 %
Precision outdoor	1.4 cm to 2.2 cm	**1.2 cm to 2.2 cm**
→ relative	< 0.6 %	< **0.4 %**
Accuracy indoor	**always <2 % or 25 cm**	generally <3 % or 25 cm
Accuracy outdoor	generally <1 % or 20 cm	**generally <1 % or 10 cm**
Maximum range	32 m at high data rate	**At least 70 m**
→ theoretical	240 m with 10 % packet loss	**245 m**
Update rate	**Around 400 Hz**	Around 4 Hz
Track moving targets	**Very good**	Glitches, low update rate
Spectral efficiency	$1.36 \cdot 10^{-2}$ bit/s/Hz	no data transfer
Bandwidth	500 MHz	**100 MHz/150 MHz** at 2.4 GHz/5.8 GHz
Output power	-12 dBm	18 dBm
Transceiver power	520 mW peak	≈ 900 mW
Processing power	≈ 8 mW	≈ 700 mW
Computational effort	**Very low** (timestamp subtraction)	High (very large FFTs)

[1]

Automotive Radar - FMCW Radar

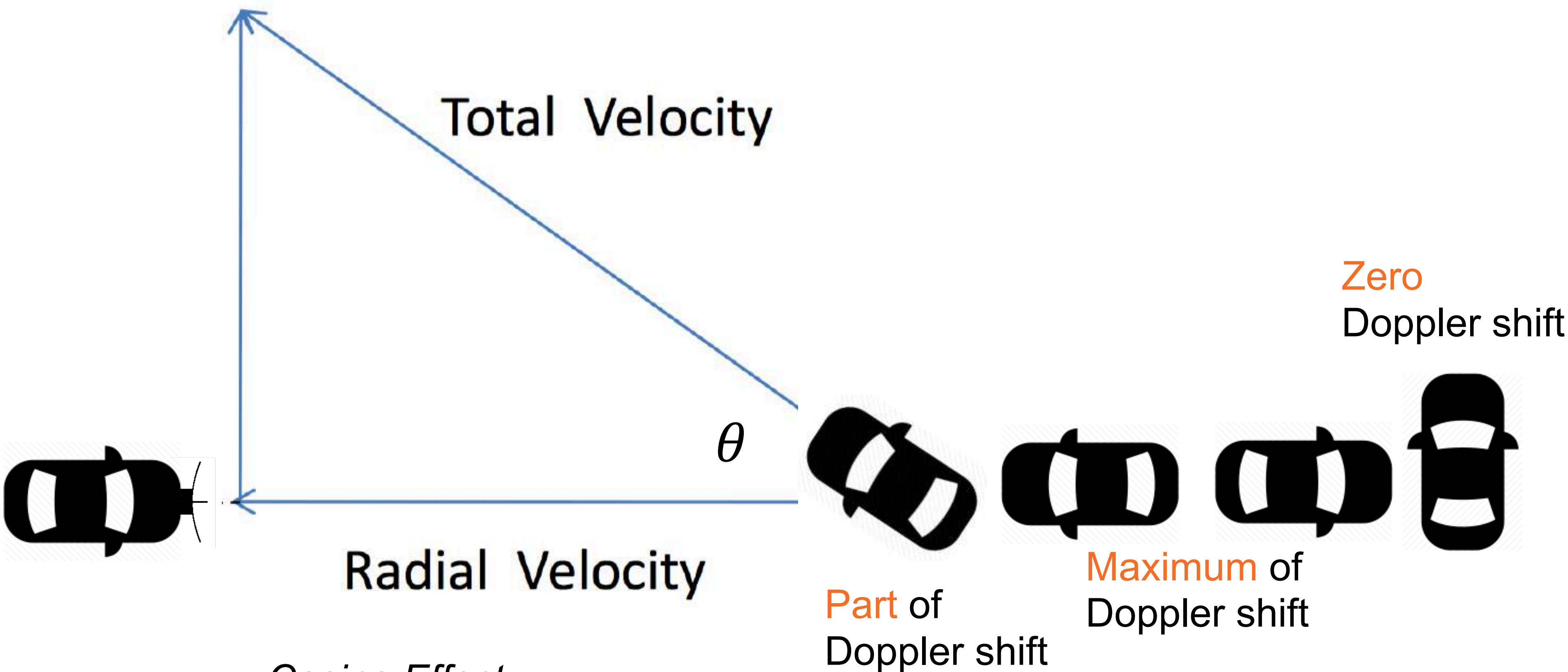
- FMCW radar V.S. Pulse Doppler radar

Architecture	FMCW	Pulse Doppler
Principle of operation	Imaging	Doppler
Transmission	Continuous, low power	Pulse, high power
Cause of detection	change in return look to look	Phase shift caused by motion
Resolution	High, approx 800,000 cells	Low, approx 100,000 cells
Zones of low Probability of Detection (PD)	No	Yes
Target radial motion threshold	zero	Approx 2.5 mph
Sensitivity to wind blown false alarms	Almost zero	High
Detection sensitive to direction of travel	No	Highly
Detect zero speed target	Yes	No

[1]

Automotive Radar DOA

- Direction of Arrival (DOA)
- Motivation (Relative) horizontal angle θ



Cosine Effect

Automotive Radar DOA

Application for ACC

Azimuth estimation

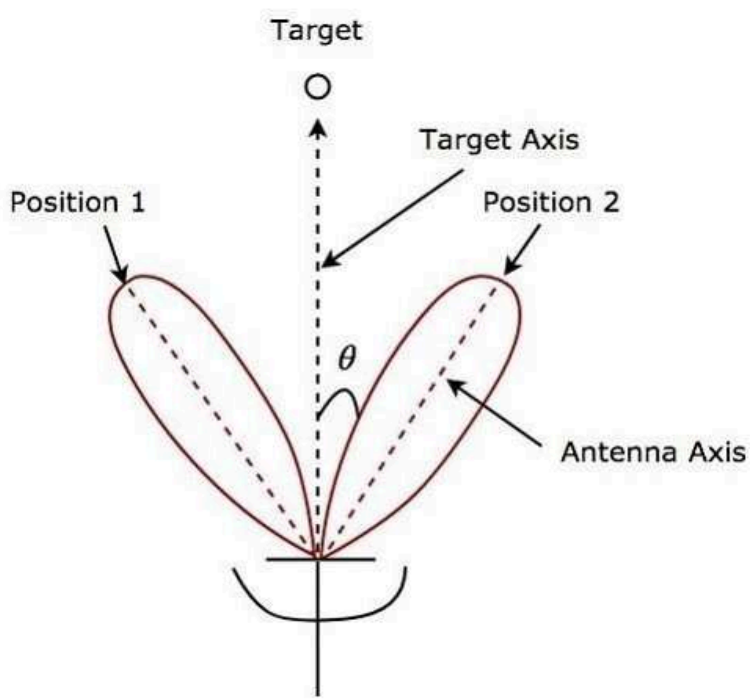
LRR typically ± 5~10° in 250 m

MRR typically ±45° in 60 m

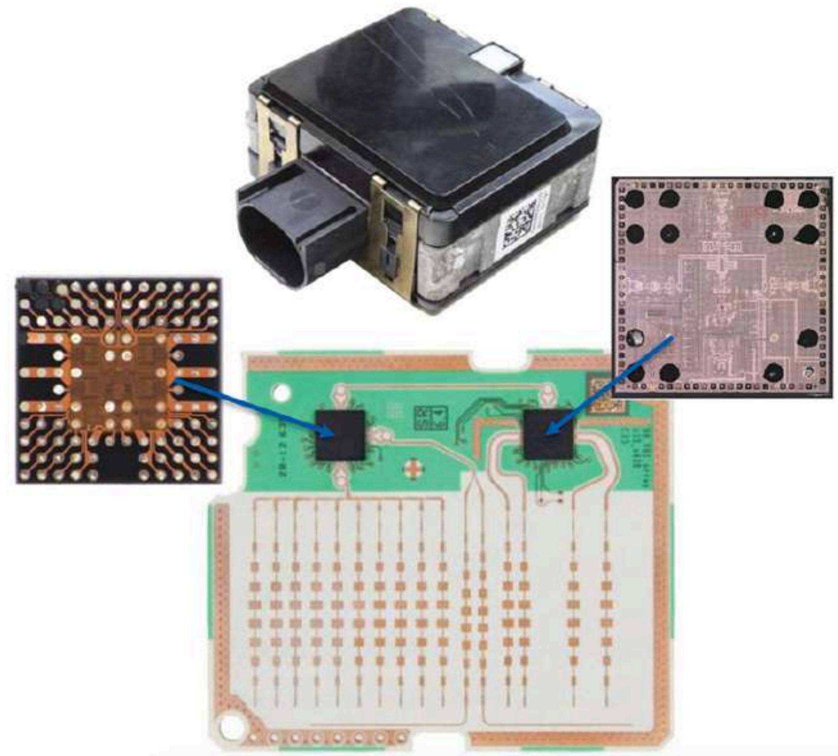
Adaptive cruise control

Automotive Radar DOA

- Digital beamforming with antenna-array
- Multiple radar beams



Sequential lobing

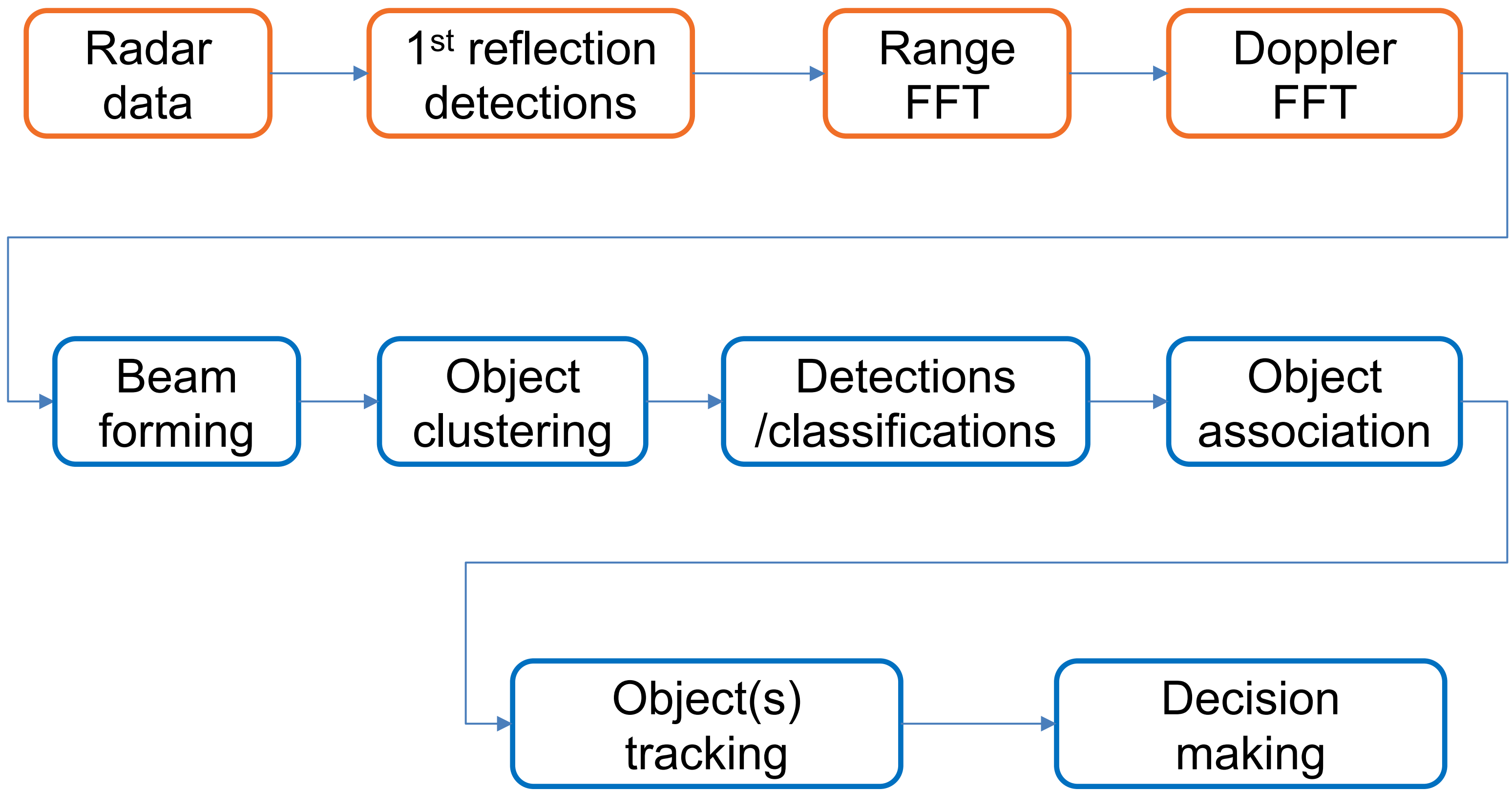


Bosch MRR sensor

Main antenna: ±10° in 60 m
Elevation antenna: ±25° in 36 m

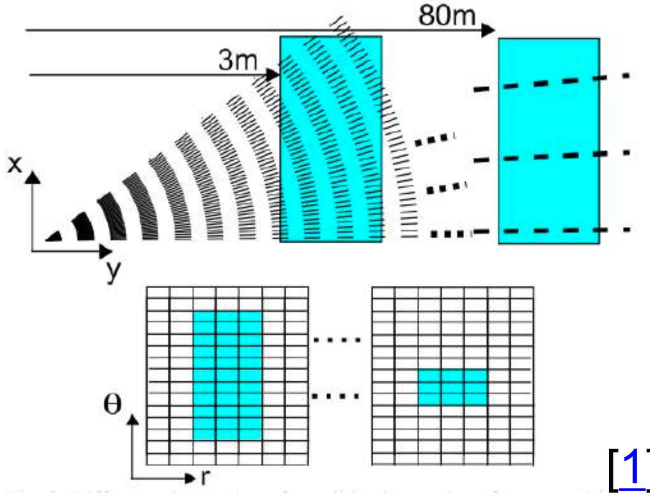
Automotive Radar Object Detection

- Object detection and tracking procedure



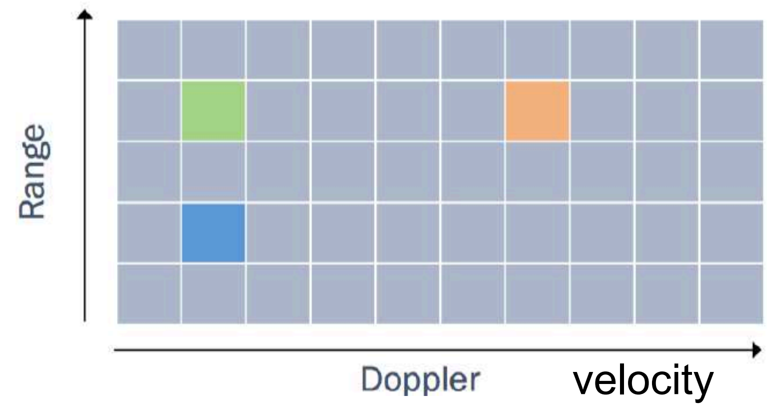
FFT (Fast Fourier Transform)

Automotive Radar Object Clustering

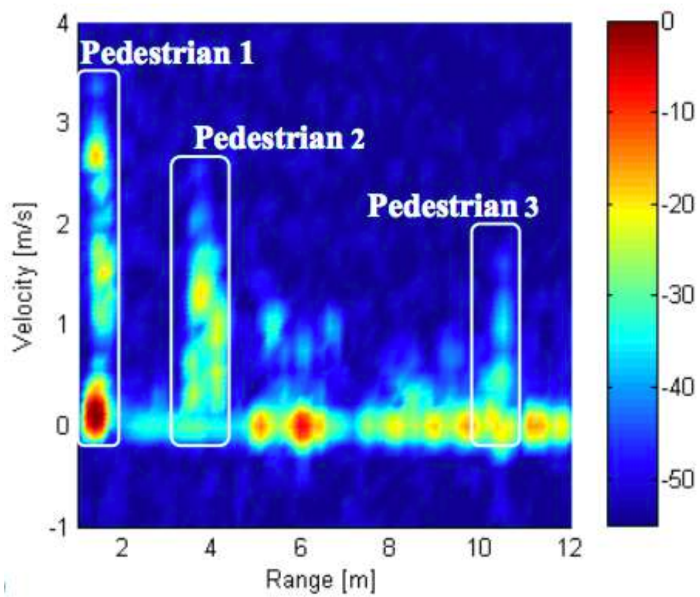


[1]

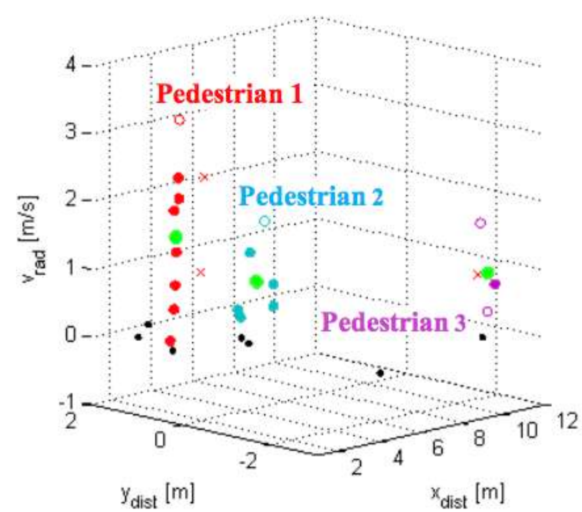
Ranges and velocities of three objects:



Detection data:



Based on Constant false alarm rate (CFAR) techniques:



[2]

Automotive Radar Object Clustering

- DBSCAN approach (parameter-based)
  - Density-Based Spatial Clustering of Applications with Noise (DBSCAN)

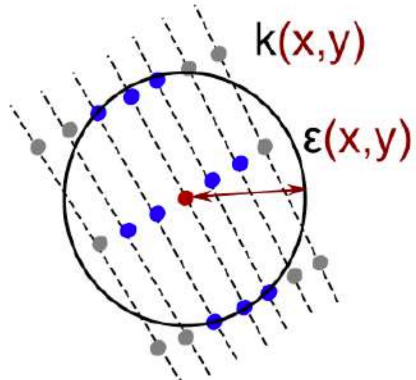
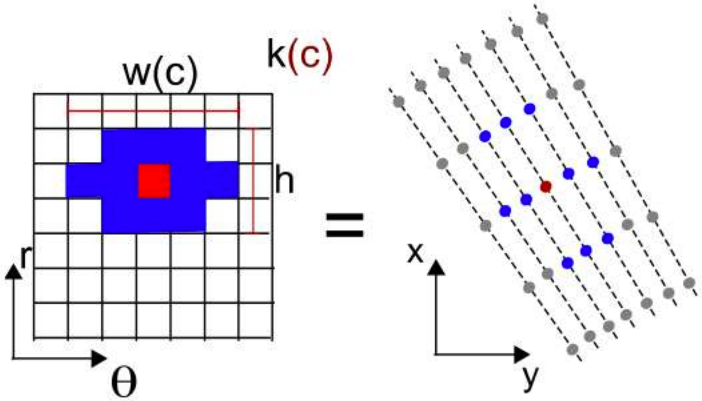


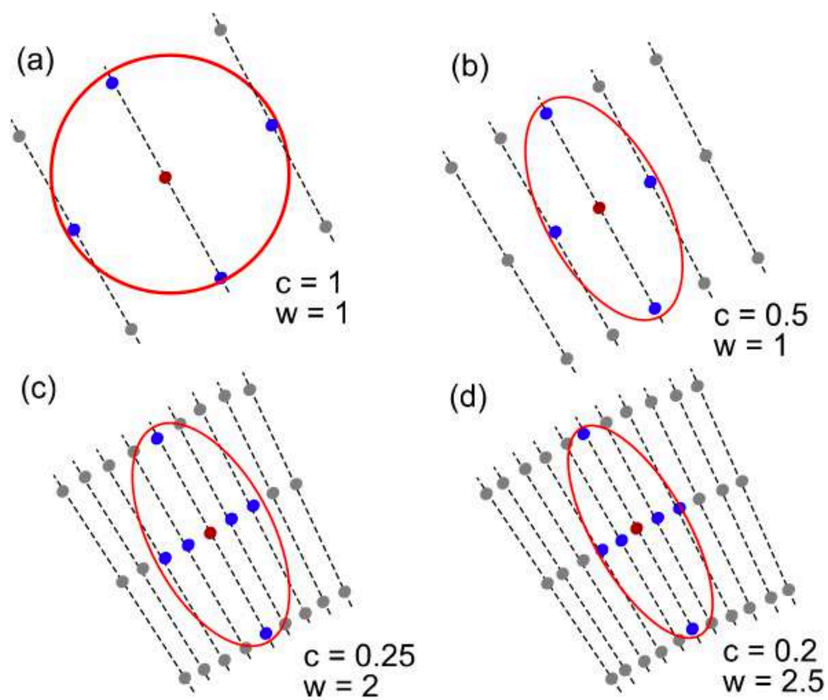
Fig. 4: Calculation of the density criterion using DBSCAN with an adaptive search radius ε and adaptive threshold k in Cartesian coordinates

$$w_{i,j}(c) = \frac{g}{f \cdot c_{i,j}}$$

$$c_{i,j} = \frac{r_{i,j}}{2\Delta r}\left(\sin(\theta_{i,j+1} - \theta_{i,j}) + \sin(\theta_{i,j} - \theta_{i,j-1})\right)$$

with: i,j index of grid in r / θ - direction
$r_{i,j}$ radial distance
Δr radial resolution (constant)
$\theta_{i,j}$ azimuth angle





[1]

Automotive Radar Object Clustering

- DBSCAN result
- Segmentation

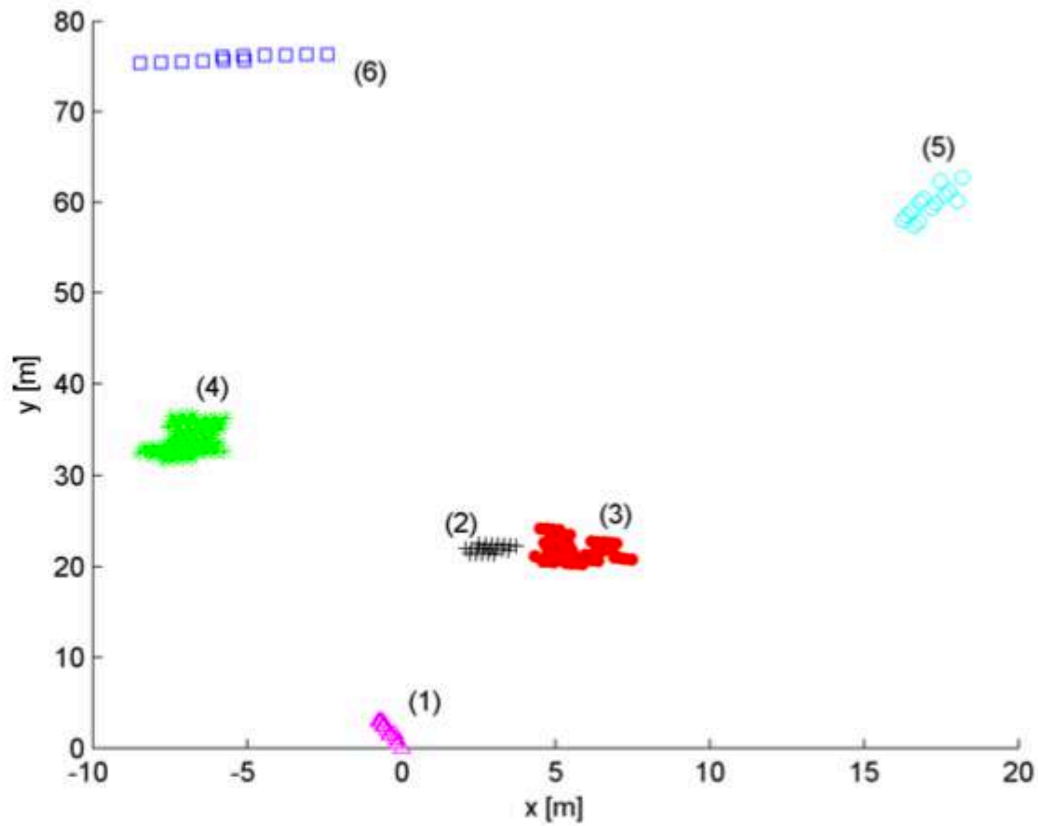


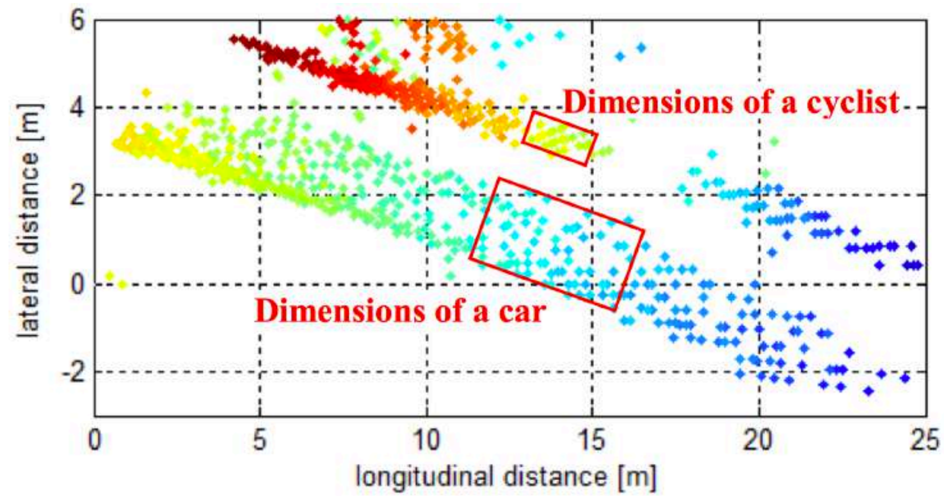
Fig. 9: Clustering results for grid-based DBSCAN (f = 2) showing outliers (pink triangle) and 5 clusters (red, green, black, blue, cyan) for clutter (1), a pedestrian (2) next to a car (3), two other vehicles (4-5) and a barrier (6)

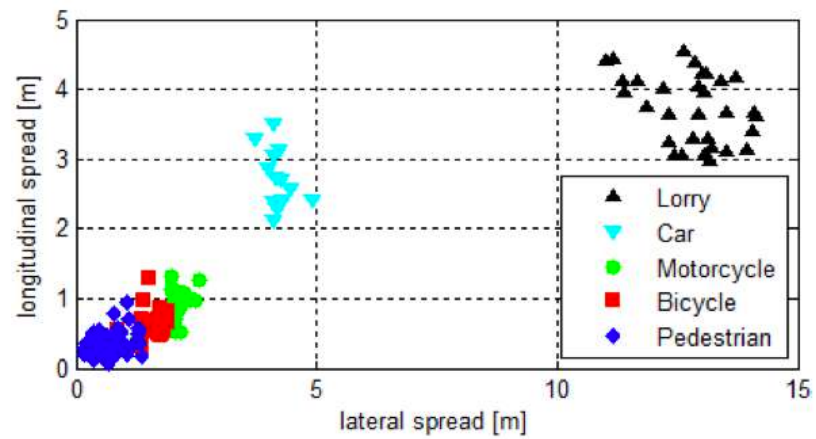
[1]

Automotive Radar Object Classification

- Classification approach

Segmented objects From Radar data
↓
Extract features of objects in Radar data
↓
Machine learning (classification) algorithm ← Training dataset
↓
Classification results





[1]

Features: Distance spread, Dimension, Velocity
σ: Radar cross section (RCS) …

Automotive Radar Object Tracking

- Tracking based on motion model

$$\mu_t = [x, y, v_x, v_y, \ldots]^T$$

- For linear model trajectory
  - zero acceleration model

$$\mu_t = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \mu_{t-1}$$

- For non-linear model trajectory
  - Linearization

$$H_t = \frac{\partial h(\bar{\mu}_t)}{\partial x_t} \qquad G_t = \frac{\partial g(u_t, \mu_{t-1})}{\partial x_{t-1}}$$

Kalman filter:

$$\bar{\mu}_t = A_t \mu_{t-1} + B_t u_t$$
$$\bar{\Sigma}_t = A_t \Sigma_{t-1} A_t^T + R_t$$

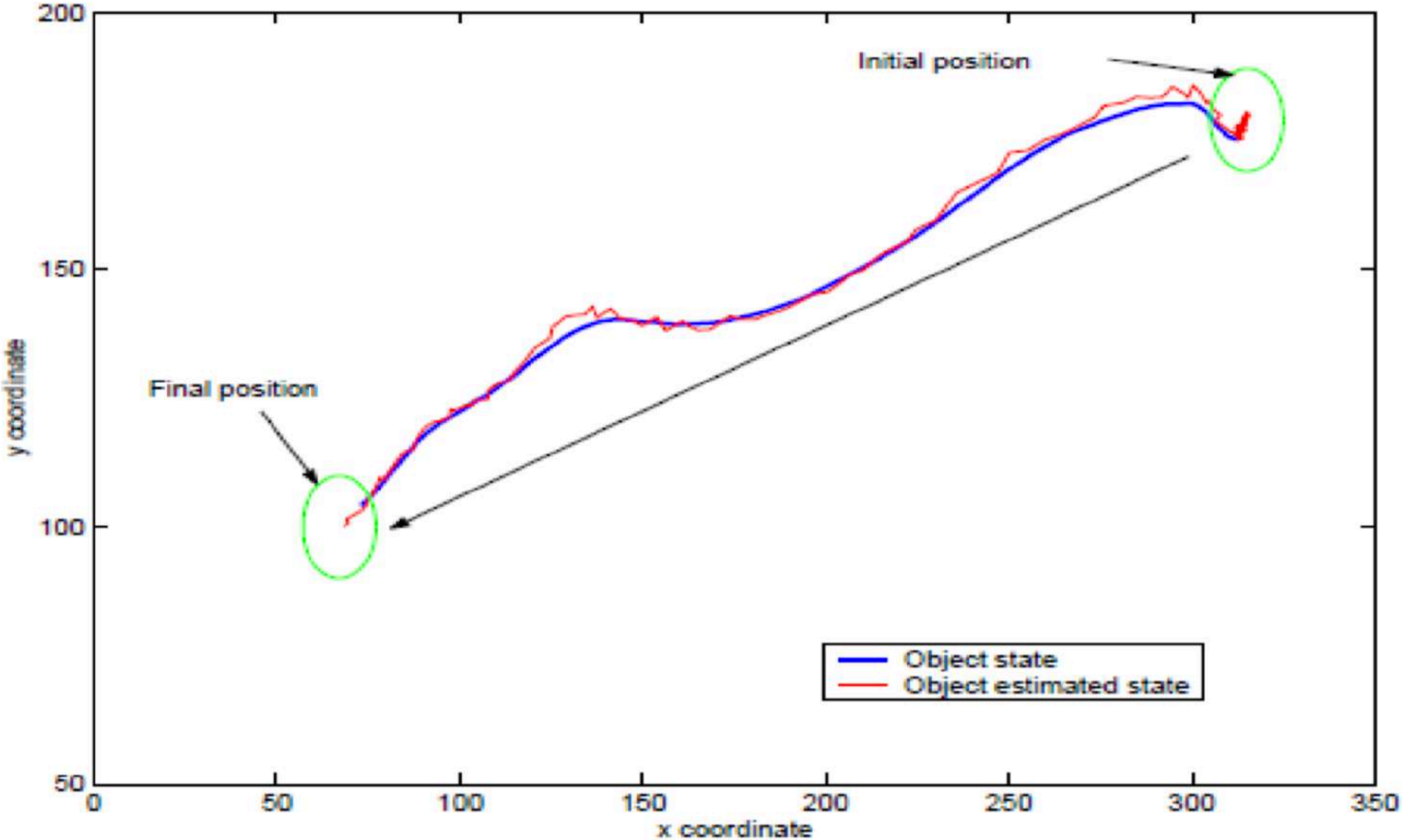
$$K_t = \bar{\Sigma}_t C_t^T (C_t \bar{\Sigma}_t C_t^T + Q_t)^{-1}$$
$$\mu_t = \bar{\mu}_t + K_t (z_t - C_t \bar{\mu}_t)$$
$$\Sigma_t = (I - K_t C_t) \bar{\Sigma}_t$$

Extended Kalman filter:

$$\bar{\mu}_t = g(u_t, \mu_{t-1})$$
$$\bar{\Sigma}_t = G_t \Sigma_{t-1} G_t^T + R_t$$

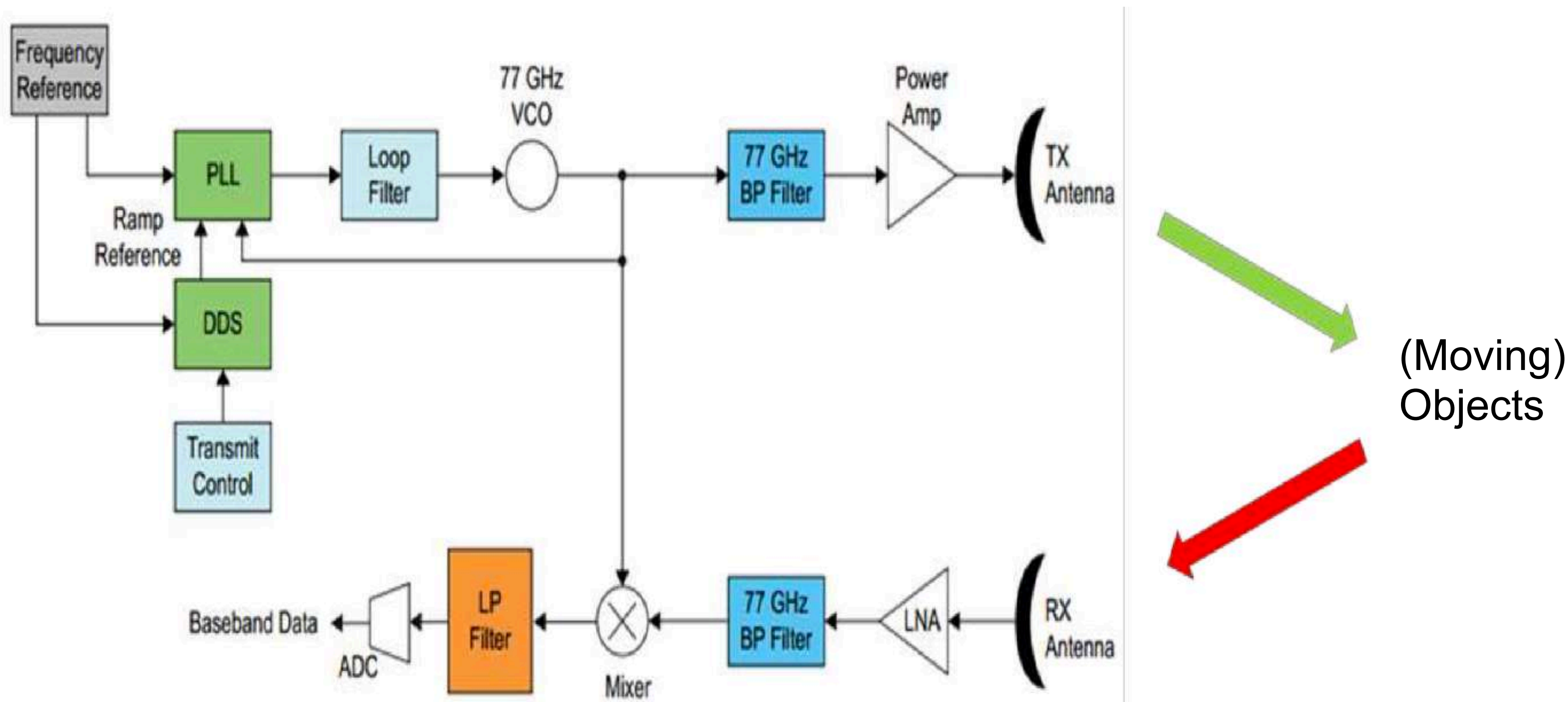
$$K_t = \bar{\Sigma}_t H_t^T (H_t \bar{\Sigma}_t H_t^T + Q_t)^{-1}$$
$$\mu_t = \bar{\mu}_t + K_t (z_t - h(\bar{\mu}_t))$$
$$\Sigma_t = (I - K_t H_t) \bar{\Sigma}_t$$

Automotive Radar Object Tracking

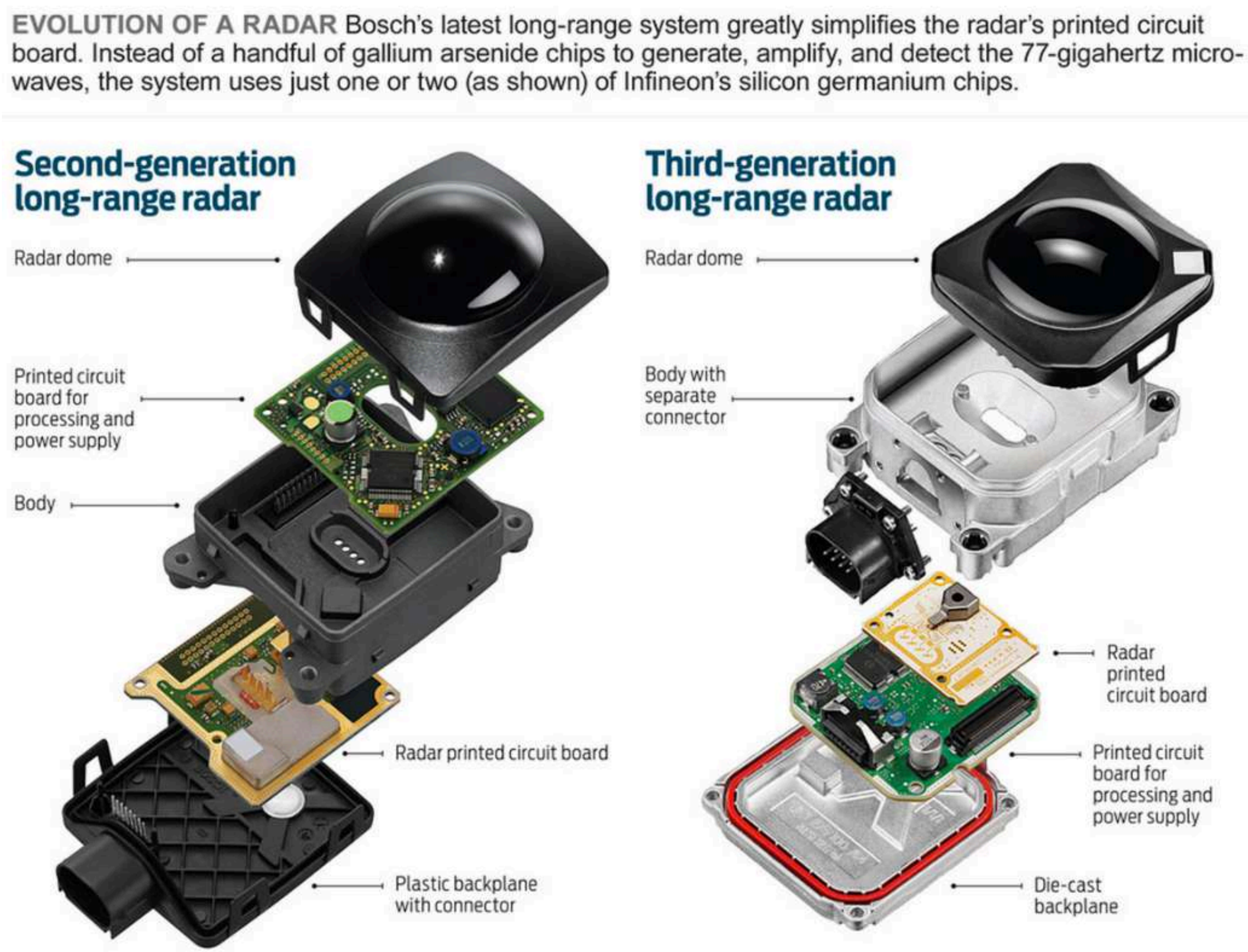


Automotive Radar Systems

- 77 GHz Automotive Radar system example



Automotive Radar Systems



Bosch radar generations
(Source: Bosch)

Bosch based on SiGe Infineon Chipset

FCMW modulation

LRR 7dBm Pout,
4 channels (2 TX/RX)

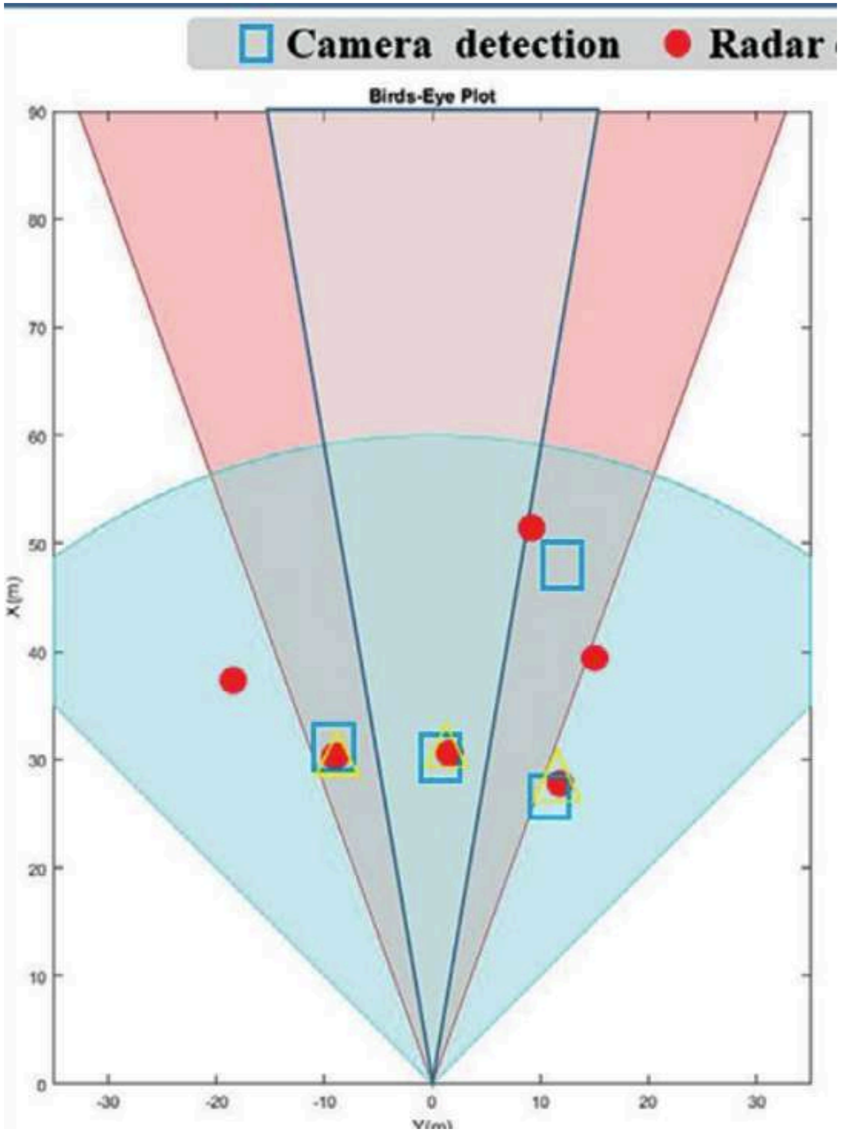
Two PCB boards

On-board Integrated antennas

7.4 x 7 x 5.8 cm

Automotive Radar Systems

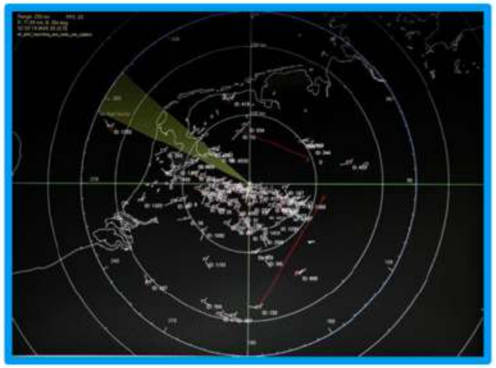
- Radar-camera fusion



Radar: Other Application Examples

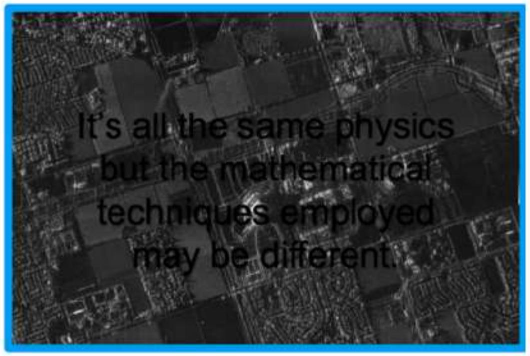
Automotive localization and mapping

Military



Weather

Imaging



Speed enforcement

Summary Highlights

- Automotive radar
  - SRR/MRR/LRR
  - Range, relative velocity
  - Bandwidth
  - Pulsed VS. FMCW
  - Doppler shift
  - Antenna-array and radar beams
  - Object detection and tracking

END, Thank you

Reference

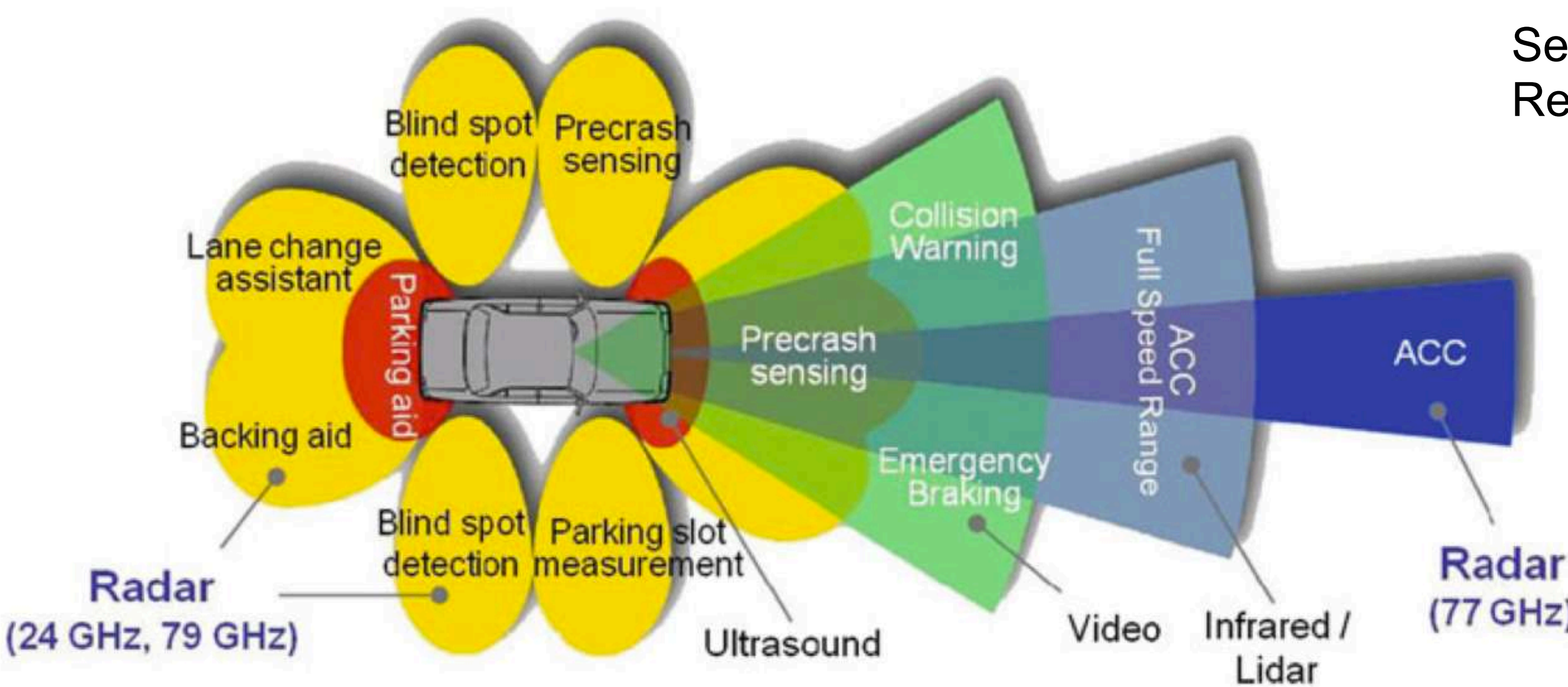
- Maria S. Greco. "Automotive Radar.", IEEE Radar Conference 2012.
- Hasch, Jürgen, Eray Topak, Raik Schnabel, Thomas Zwick, Robert Weigel, and Christian Waldschmidt. "Millimeter-wave technology for automotive radar sensors in the 77 GHz frequency band." IEEE Transactions on Microwave Theory and Techniques 60, no. 3 (2012): 845-860.
- Greg Kregoski. "FMCW Radar in Automotive Applications.", ROHDE & SCHWARZ
- Prasad Malai. "Automotive Radar System.",
- Larry Hawkins, et al. "Radar Defense VS. Automotive.", Analog Devices.
- Brian Su. "Automotive Radar Signal Generation、Analysis And Test Challenges", Keysight Technologies.
- Helena Perslow, and eremy Carlson. "ADAS – Current & Future Perspectives". IHS Automotive 2015.

Appendix Related Resource

- Why are automotive radar systems moving from 24GHz to 77GHz?
- Automotive Dataset: nuScenes (Data and Python Code), which includes Automotive Radar data
- Distance Sensors - RADAR, Clemson CVEL
- Automotive Radar Signals: Analysis and Limitations (Video)
- Radar System Modeling and Simulation for Automotive Advanced Driver Assistance Systems (Video)

Appendix

- Advanced Driver-Assistance Systems (ADAS)
- Society of Automotive Engineers (SAE): autonomous vehicle levels 0 ~ 5
  - Level 3: Environment detection
- Level 2+ Automated Driving System on CES 2019



Sensor Redundancy

Appendix

Consumer Electronics Show (CES) 2019 --- Level 2+

- Self-driving autopilot capabilities:
  - highway merge
  - lane change
  - lane splits
  - personal mapping

- Inside the vehicle:
  - driver monitoring
  - AI co-pilot capabilities
  - advanced in-cabin visualization

[1]