Self-Driving Cars with ROS and Autoware
Object Perception: Radar

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Outline

Outline of this lecture:

> Radar Basics
> Radar Based Object Detection
> Available Sensors and Integration

Radar Basics

FH AACHEN
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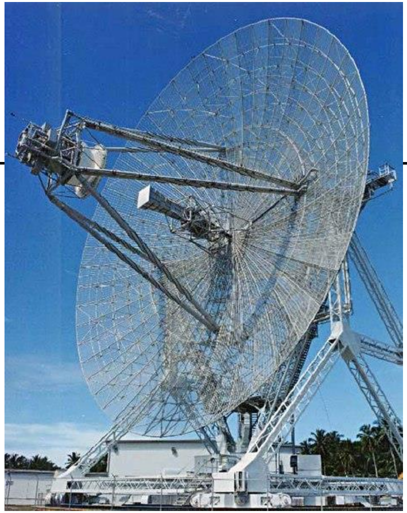
A very short history of radar:

1900-1930 First radar ideas and patents

Since 1940 Use of radar mainly in military and civil aviation

Since 1999 Use of radar in automotive applications like Adaptive Cruise Control (ACC)



M 93 / Attribution

Radar Basics

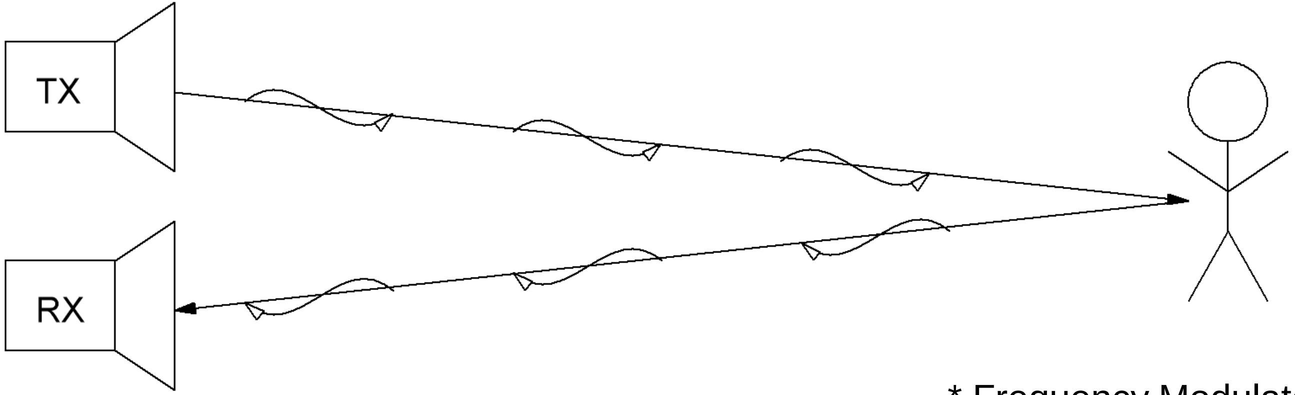
Advantages of Radar:

- Radar can measure the distance to objects
- Radar can measure the angle of objects
- Radar can measure the velocity of objects
- Radar can measure the cross section of objects

to detect and classify different objects!

Radar Basics

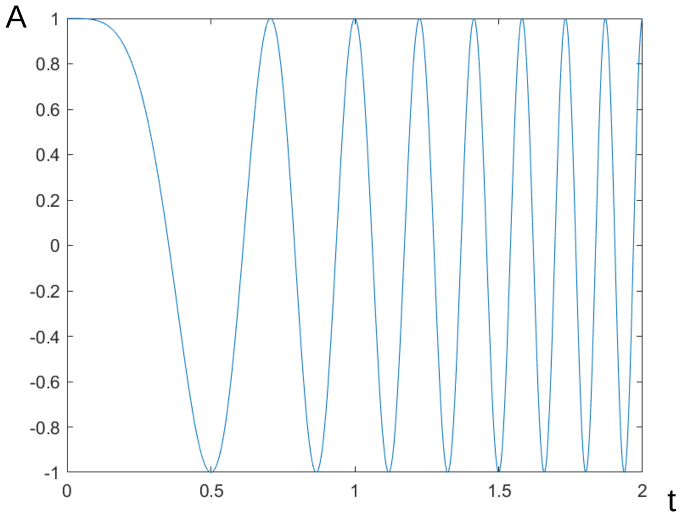
A Radar sensor consists at least of an EM wave transmitter (TX) and a receiver (RX). The EM waves are reflected by any objects and the frequency is modulated (FMCW*).

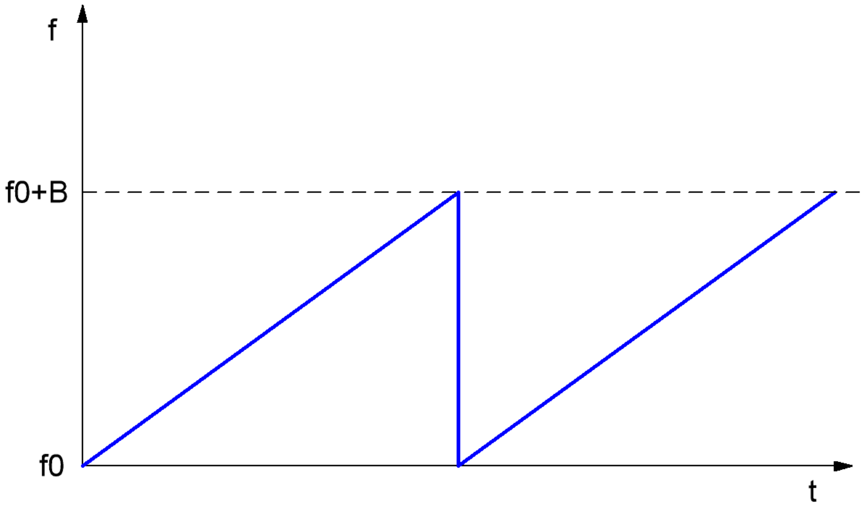


* Frequency Modulated Coninuous Wave

Radar Basics

The frequency of sent (and hence the received) wave is modulated (e.g. by a sawtooth signal).

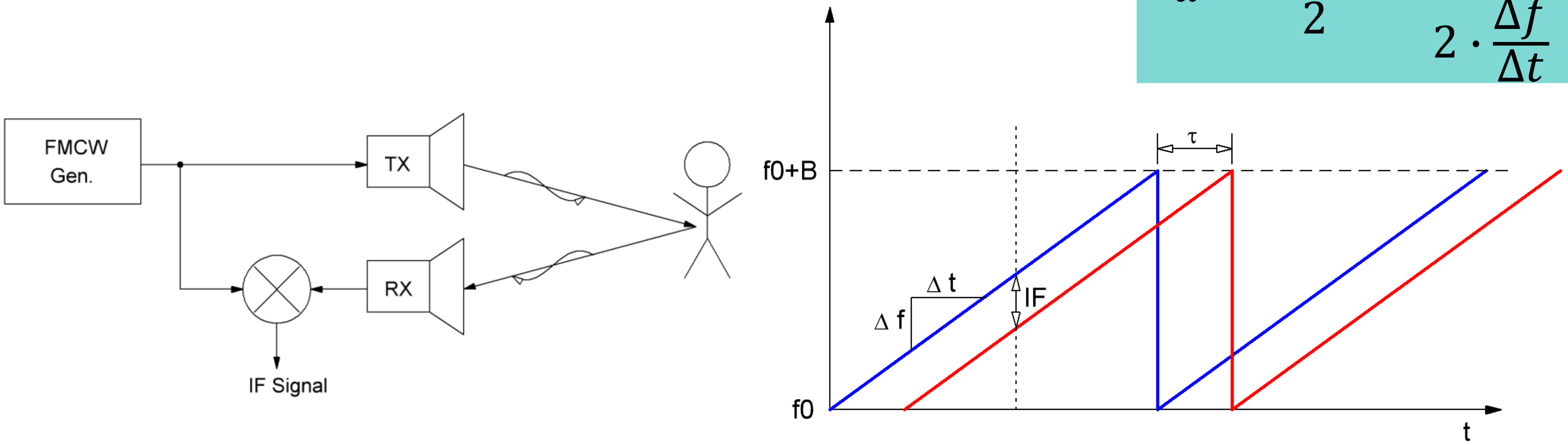




Radar Basics

The received signal is mixed with the sent signal. The resulting **intermediate frequency** (IF) is a **measure for the distance** (d).

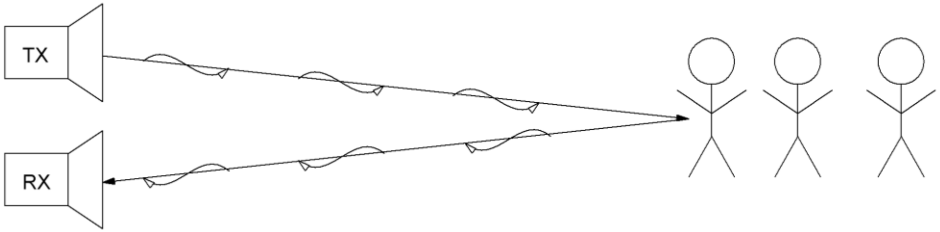
$$d = \frac{c_0 \cdot \tau}{2} = \frac{c_0 \cdot IF}{2 \cdot \frac{\Delta f}{\Delta t}}$$

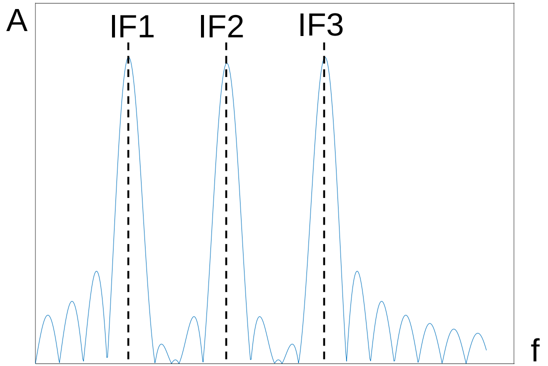


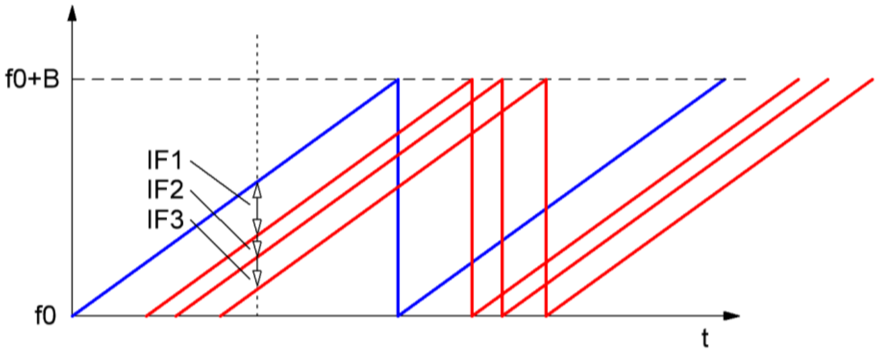
Radar Basics

But how can we measure multiple objects?

Multiple objects cause multiple tones!





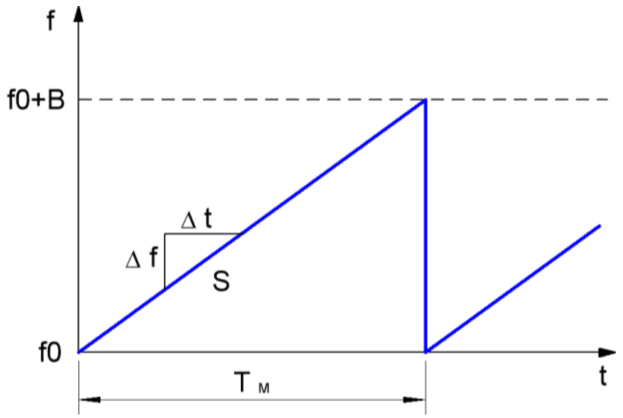


Radar Basics
Resolution of distance d

The smallest measurable intermediate frequency (IF) is equal to the modulation frequency ($\rightarrow \Delta IF > \frac{1}{T_M}$). The bandwidth of modulation determines the smallest distance. (e.g. $B = 1GHz \rightarrow \Delta d = 15cm$)

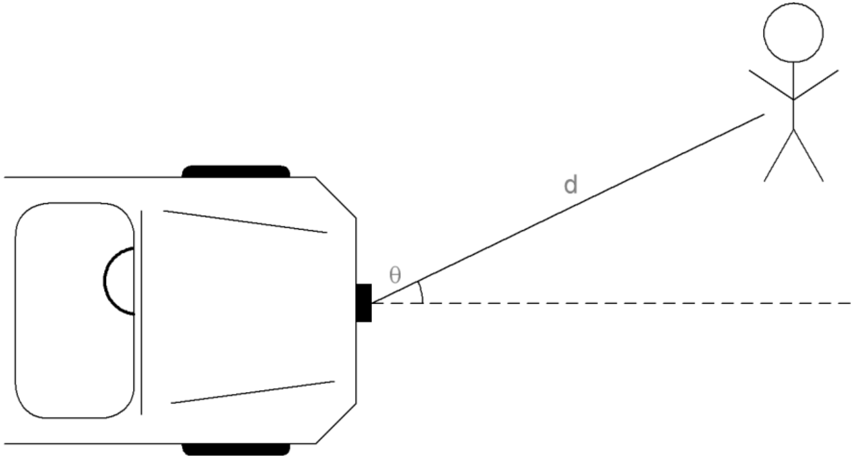
$$\Delta IF > \frac{1}{T_M}, \qquad \Delta d = \frac{c_0 \cdot \Delta IF}{2 \cdot S}, \qquad S = \frac{\Delta f}{\Delta t} \; (Slope)$$

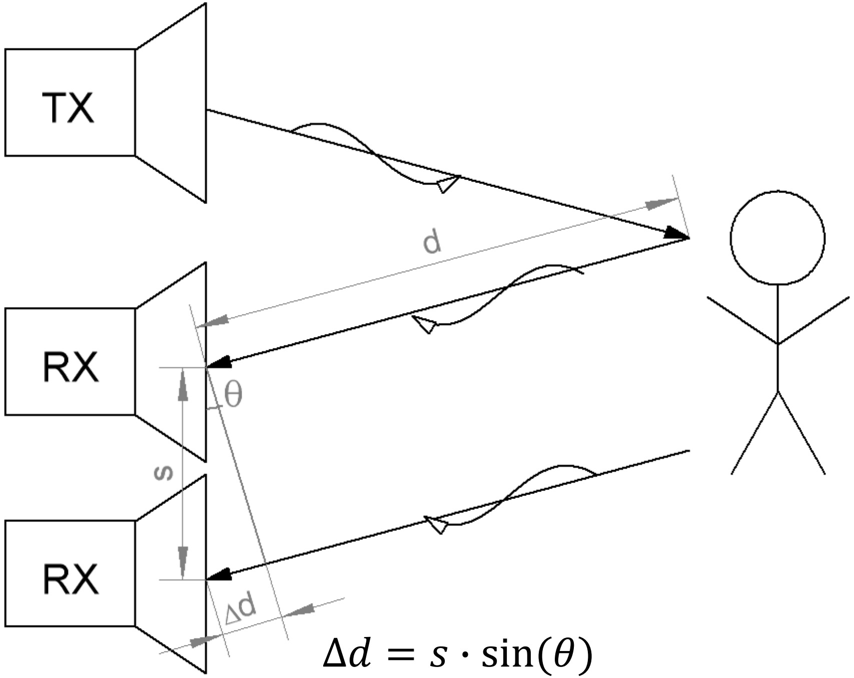
$$\frac{2 \cdot \Delta d \cdot S}{c_0} > \frac{1}{T_M} \Rightarrow \boldsymbol{\Delta d} > \frac{c_0}{2 \cdot S \cdot T_M} = \frac{\boldsymbol{c_0}}{\boldsymbol{2 \cdot B}}$$



Radar Basics

If we spent at least one additional receiver, we can measure the angle from sensor to object.





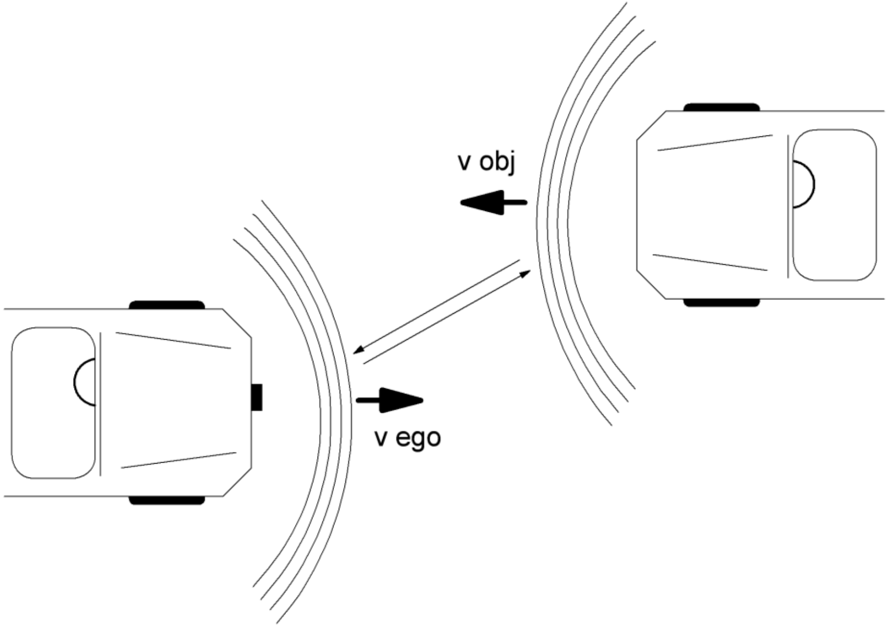
$$\Delta d = s \cdot \sin(\theta)$$

Radar Basics

To measure the velocity of an object we measure the frequency shift (f_D) caused by the Doppler-effect.

$$f_D = 2 \cdot f_0 \cdot \frac{v_{rel}}{c_0} \; {*})$$

$$v_{rel} = v_{ego} + v_{obj}$$



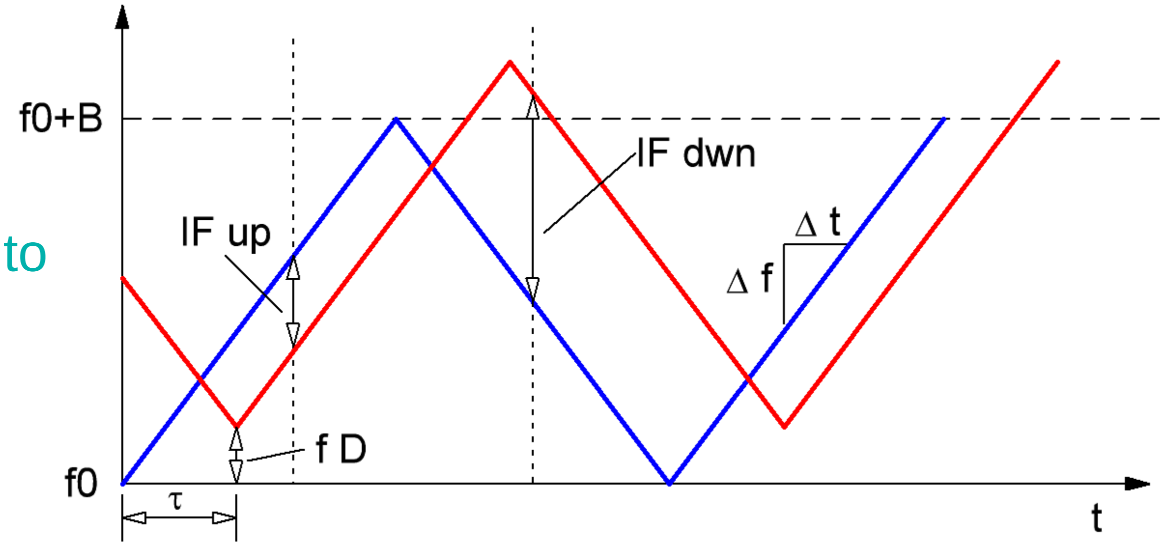
$*$) f_0 radar frequency, c_0 light‘s speed,
Factor 2 because we have Doppler‘s effect twice: on travel of the wave there and back

Source: F. Hüning, Sensoren und Sensorschnittstellen, DeGruyter, 2016

Radar Basics

But how can we separate the frequency shift caused by distance from frequency shift caused by velocity?

One way:
We move from sawtooth to triangle and do a 2nd IF measurement to get a second equation!



Source: F. Hüning, Sensoren und Sensorschnittstellen, DeGruyter, 2016

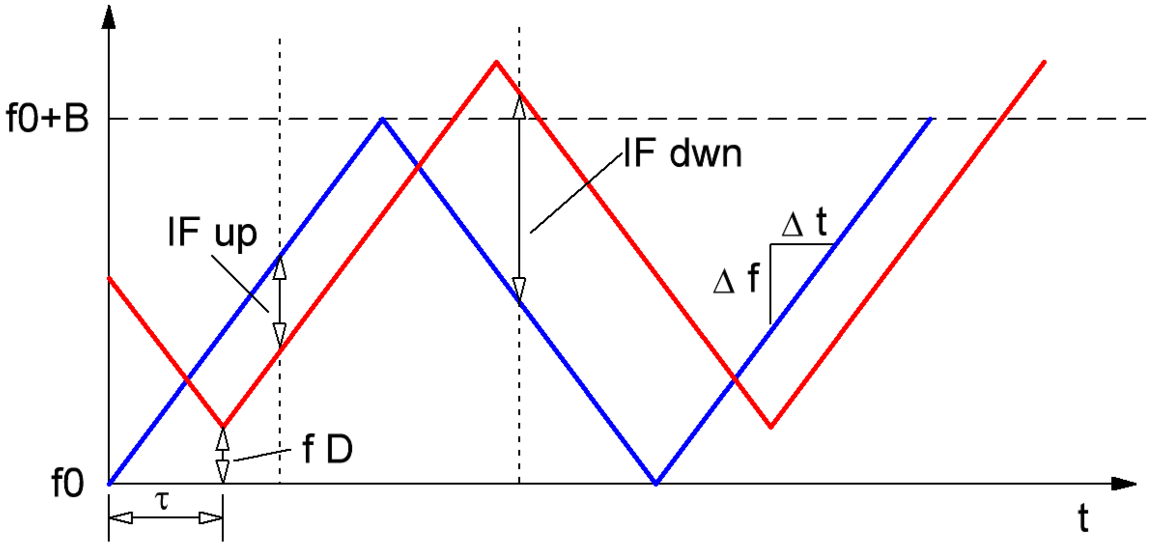
Radar Basics

$$v \sim f_D = \frac{|IF_{up} - IF_{dwn}|}{2}$$

$$d \sim \Delta f_D = \frac{IF_{up} + IF_{dwn}}{2}$$

$$v = \frac{c_0 \cdot |IF_{up} - IF_{dwn}|}{4 \cdot f_0}$$

$$d = \frac{c_0 \cdot (IF_{up} + IF_{dwn})}{4 \cdot \frac{\Delta f}{\Delta t}}$$



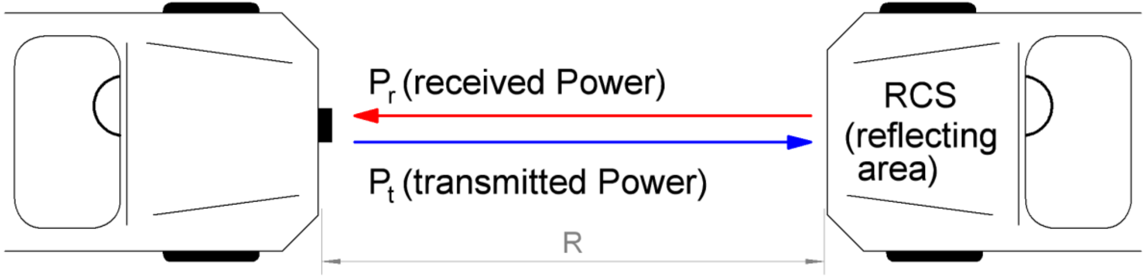
Source: F. Hüning, Sensoren und Sensorschnittstellen, DeGruyter, 2016

Radar Basics

The Radar Cross Section (RCS, σ) is based on a signal power measurement and calculation by the radar range equation.

$$P_r = \frac{P_t G_t}{4\pi R^2} \frac{\sigma A_{e,r}}{4\pi R^2}, \qquad \sigma = \frac{P_r}{P_t} \frac{(4\pi)^2 R^4}{G_t A_{e,r}}$$

G_t transmitting antenna gain
$A_{e,r}$ effective receiving antenna area



Radar Basics

Object [1][2][3]	**RCS [m²]**	**RCS [dBm²]**
small bird	0.01	-20
Stealth bomber (B-2)	0.01	-20
Human	1	0
Passenger car	100	20
Truck	200	23
Container ship	~50.000	~47
Corner reflector	20.000	43

Corner reflector on boats

[1] M. Skolnik, „Introduction to radar systems", McGraw-Hill
[2] http://www.mar-it.de/Radar/RCS/Ship_RCS_Table.pdf
[3] Stonier, R. A. Stealth aircraft & Technology From World War II to the Gulf. Part II: Applications and Design. SAMPE Journal

Radar Basics

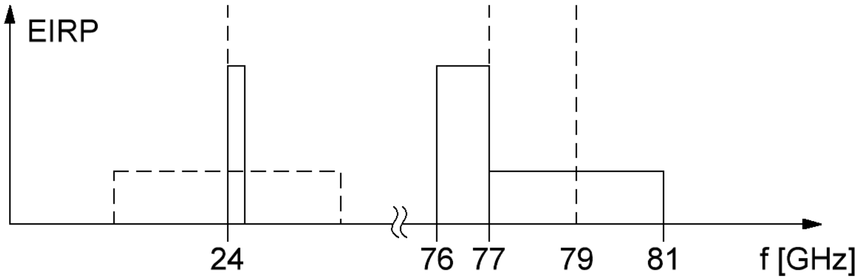
The resolution of RCS measurement is reduced by the the Signal-to-Noise ratio (SNR). While the noise power is almost constant, only optimizing the received signal power can optimize the SNR. But this is reduced by the allowed emitting signal power.

$$SNR = \frac{P_r}{P_N} \sim \frac{1}{kT_{eff}B} f\left(P_t, G_t, A_{e,r}\right), k = Boltzmann\ constant$$

Radar Basics

By regulation allowed frequencies

SRR : Short Range Radar
MRR: Mid Range Radar
LRR: Long Range Radar



Base f	Bandwidth	EIRP *)	Applications (examples)
24 Ghz	0.2 Ghz	high	MRR: Collision Avoidance
24 GHz	5 Ghz	low	SRR: Blind Spot Det. (until 2022)
77 GHz	1 GHz	high	LRR, MRR: Adaptive Cruise Control
79 GHz	4 GHz	low	SRR, MRR: Stop&Go Ass., Perception

*) EIRP: equivalent isotropically radiated power

Radar Basics

In summary for a sufficient radar we need:

> High radiated power for RCS measurement
>
> High bandwidth for good d and v resolution
>
> Multiple antennas for good angle resolution
>
> Powerful signal processing

Radar based Object Detection

Radar based Object Detection

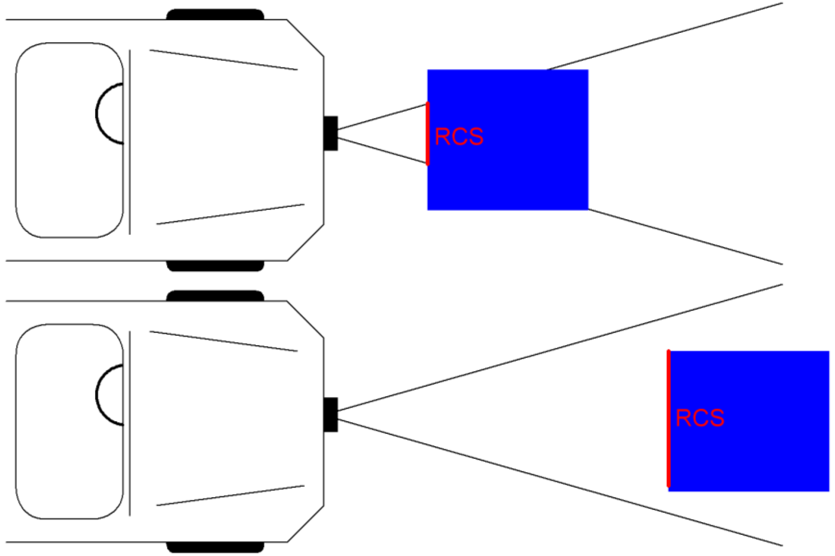
For each detected object the sensor measures:

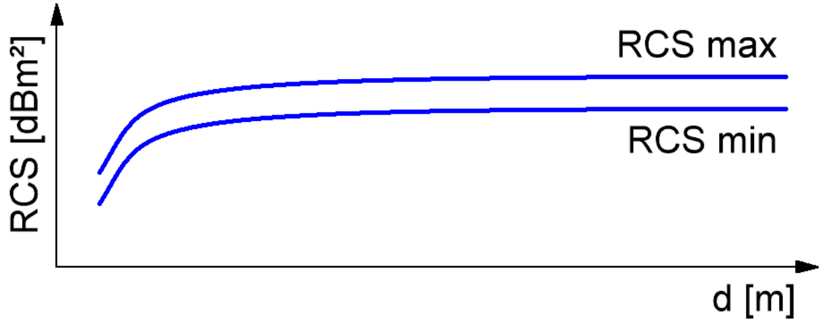
- Distance
- Velocity
- Angle
- RCS

With these parameters objects can be classified, e.g. an object with $100m^2 < RCS < 200m^2$ and $v = 50km/h$ must be a car.

Radar based Object Detection

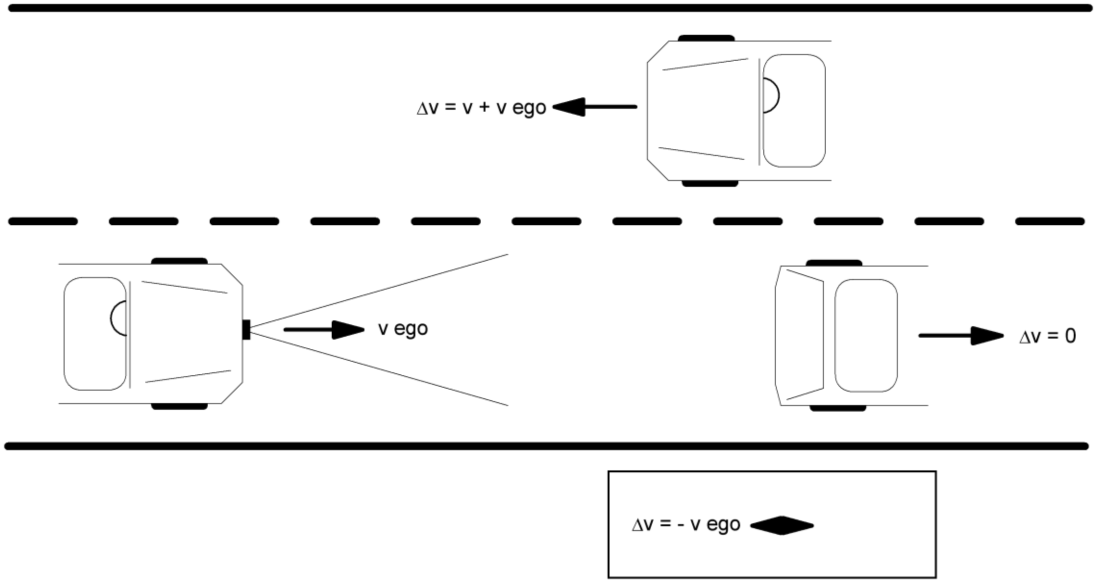
The RCS has to be correlated with the distance, because RCS is lower for nearer objects.





Radar based Object Detection

The velocity of objects has to be correlated with the velocity of the ego car.



Radar based Object Detection

With multiple measurements one after another objects are tracked and further classified.

An object with a RCS around $1m^2$ and variations in RCS due to arm and leg movement crossing the street must be a pedestrian.

Radar based Object Detection

Summary for object detection:

> possible by correlating various parameters

> classification to only a few known classes

> works in environments, where other sensors struggle (e.g. fog)

> Significance for classification is much lesser than e.g. camera or lidar

Available Sensors and Integration

Available Sensors and Integration

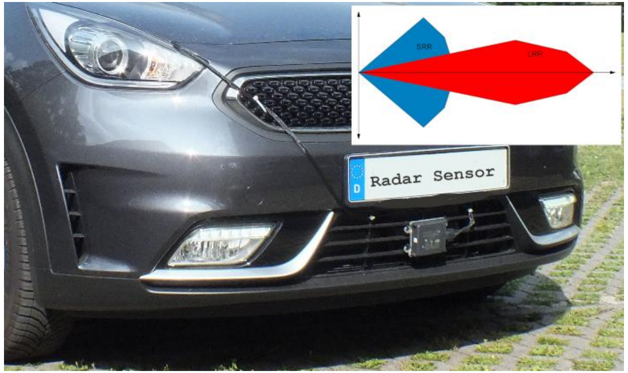
Typical technical data:

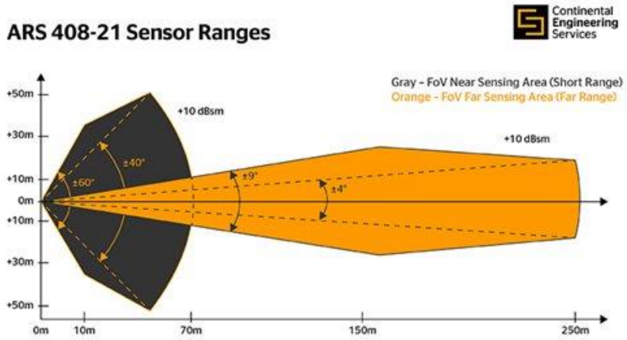
	SRR	MRR	LRR
Technology	77/1GHz, 24/0.2GHz	77/1GHz 79/5GHz	77/1GHz
Mounting	Rear, Side	Front	Front
Range	max. ~70m ± ~60°	Max. ~150m ± ~45°	Max. ~250m ± ~10°
Applications	Blind spot detection Parking assist Vehicle exit assist	Traffic Jam assist	Adaptive cruise control Emergency breaking

Available Sensors and Integration

Example Continental ARS 408-21:

> 77GHz w/ 1GHz Bandwidth
> Integrated Signal Processing
> LRR and SRR combination
> Antenna setup (24 chan.)
>> 2TX/6RX far and 2TX/6RX near
> Object Detection & Classification:
>> 250 untracked / 100 tracked





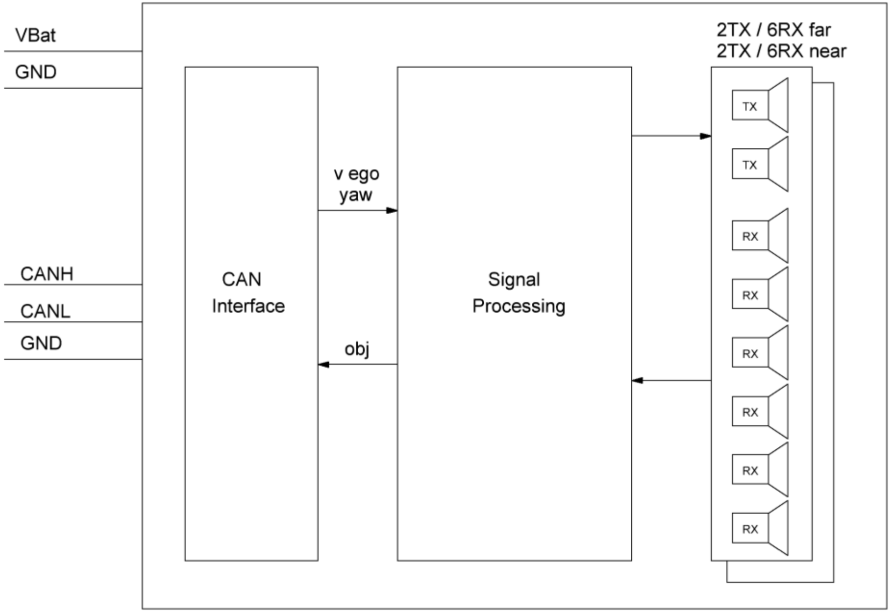
Available Sensors and Integration

Continental ARS 408-21

> v ego and yaw rate as input

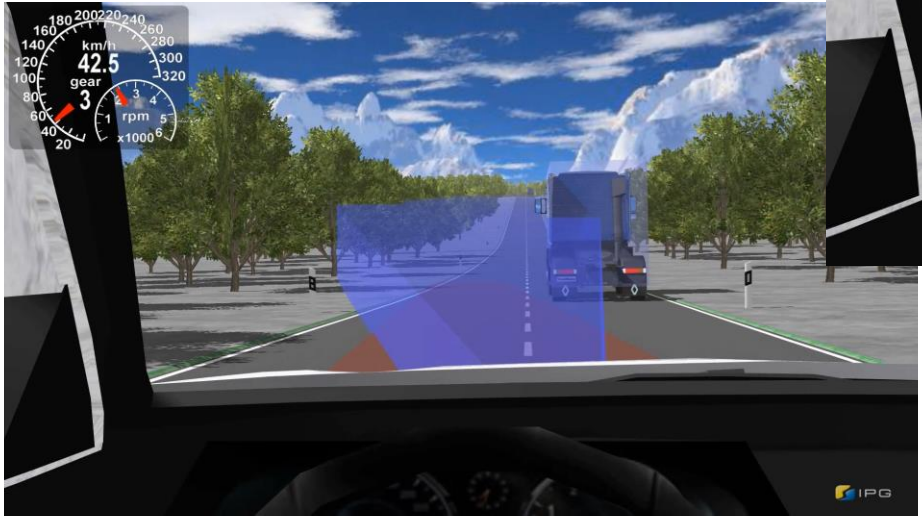
> Detected object list as output

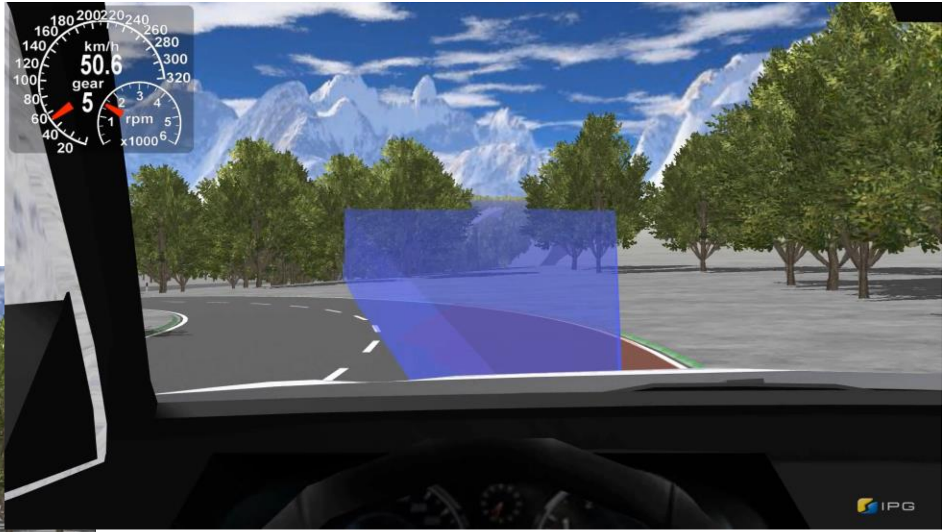
> Individual parametrization



Available Sensors and Integration

Plausibilisation due to current traffic situation necessary!





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