AUTOMOTIVE ENVIRONMENT SENSORS

Lecture 10

Radars

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MŰEGYETEM 1782

BME KÖZLEKEDÉSMÉRNÖKI ÉS JÁRMŰMÉRNÖKI KAR
32708-2/2017/INTFIN SZÁMÚ EMMI ÁLTAL TÁMOGATOTT TANANYAG

Radar History

- Radio Detection and Ranging
- Christian Hülsmeyer 1904 creates the Telemobiloscope
  - Approx. 1 m wavelength
  - Horn antenna with parabolic reflector
  - Rang a Bell
  - Could not directly measure distance.
  - The first patented device using radio waves for detecting the presence of distant objects.

- Albert Wallace Hull around 1920 invented the magnetron .
  - Leads to the generation of high power shortwave signals
- Spreads from the 40s, naturally WW II gave a large motivation

Automotive Radar History

- First tentative automotive radar since 70’s
  - Too large, too expensive
  - VDO, 10 GHz, early 1970’s
  - Standard Electric Lorenz, 16 GHz, 1975
  - AEG-Telefunken, 35 GHz, 1974
- First series production was the Mercedes-Benz Distronic in 1999.
- High frequency allows small size and weight.
  - 77 and 79 GHz frequency bands
  - Highly integrated with SiGe chipset
  - The costs can be reduced drastically

Principles

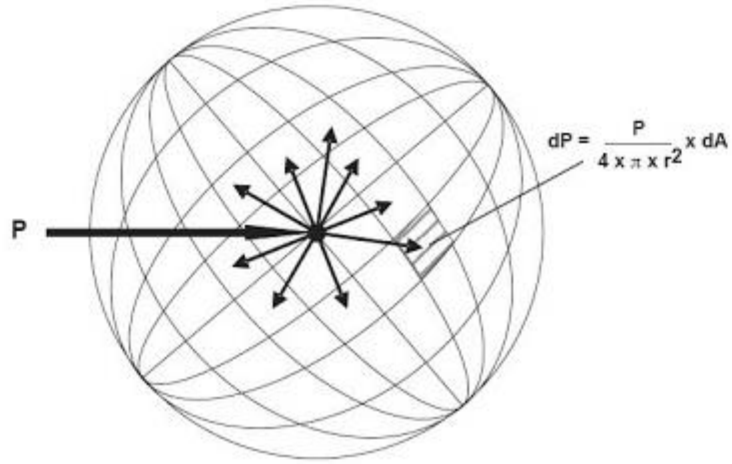
- When electromagnetic waves come into contact with an object they are usually reflected or scattered in many directions.
  - This is particularly true for electrically conductive materials
  - Radar absorbing materials also exist, containing resistive and sometimes magnetic substances.
- Radar waves scatter in a variety of ways depending on the size (wavelength) of the radio wave and the shape of the target.
  - If the wavelength is much shorter than the target's size, the wave will bounce off in a way similar to the way light is reflected by a mirror.
  - If the wavelength is much longer than the size of the target, the target may not be visible because of poor reflection.

Radar Equation I.

- An isotropic radiator is a theoretical, lossless, omnidirectional (spherical) antenna.

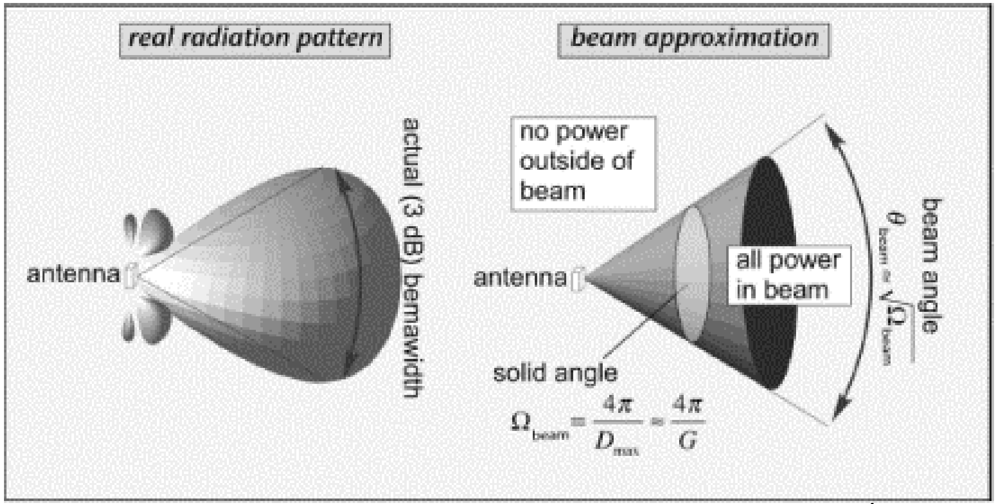
- The nondirectional power density:
  - at distance R,
  - with P_{Tx} transmitter power:

$$S_t = \frac{P_{Tx}}{4\pi R^2}\left[\frac{W}{m^2}\right]$$



Radar Equation II.

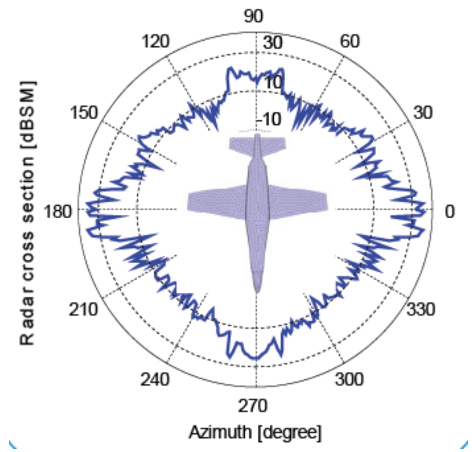
- Radars use directional antennas to channel most of the radiated power in a particular direction.
  - The Gain (G) of an antenna is the ratio of power radiated in the desired direction as compared to the power radiated from an isotropic antenna
- The power density at a distant point from a radar with an antenna gain of G_{Tx} is the power density from an isotropic antenna multiplied by the radar antenna gain.
- $S_t = \frac{P_{Tx} G_{Tx}}{4\pi R^2} \left[\frac{W}{m^2}\right]$



source: eetimes.com

Radar Cross-Section

- Radar cross-section (RCS) determines how well the object can be detected by the radar.
- The unit is m^2
- The factors that influence RCS:
  - Material
  - Absolute and relative size
  - Incident and reflected angles
  - Polarization of the transmitted and the received radiation with respect to the orientation of the target.



- Insect: 0.00001 m^2
- Human: 1 m^2
- Motorcycle: 10 m^2
- Car: 30-200 m^2
- Cargo aircraft: up to 100 m^2
- B-26 Invader bomber aircraft: 3100 m^2
- F-22 Raptor stealth fighter: 0.0001 m^2

Radar Equation III.

- With the radar cross section (σ) the power can be calculated on a given object in a given distance:

$$P_t = \frac{P_{Tx} G_{Tx}}{4\pi R^2} \sigma \; [W]$$

- In the common case where the transmitter and the receiver are at the same location:

$$S_r = \frac{P_{Tx} G_{Tx} \sigma}{(4\pi R^2)^2} \left[\frac{W}{m^2}\right]$$

Radar Equation IV.

- The received power depends on the effective aperture of the receiving antenna (A_r):

$$P_{Rx} = \frac{P_{Tx} G_{Tx} \sigma A_r}{(4\pi R^2)^2} \; [W]$$

- which can be expressed with wavelength and antenna gain:

$$A_r = \frac{G_{Rx} \lambda^2}{4\pi}$$

- Results in:

$$P_{Rx} = \frac{P_{Tx} G_{Tx} G_{Rx} \lambda^2}{(4\pi)^3 R^4} \sigma [W]$$

In monostatic case the transmitter and the receiver is the same

$$G_{Tx} = G_{Rx}$$

Radar Equation V.

- Solving for range R, we obtain the classic radar equation

$$R = \sqrt[4]{\frac{P_{Tx} G^2 \lambda^2 \sigma}{P_{Rx} (4\pi)^3}} \; [m]$$

- For a given radar most values can be regarded as constant. The radar cross-section varies heavily.
- The maximum range can be calculated with the smallest received power. (Smaller power cannot be used since it lost in the noise.)
- When calculating the radar equation we assume that the EM waves propagate under ideal conditions. But in practice the equation is extended by the loss factor L.

$$R_{max} = \sqrt[4]{\frac{P_{Tx} G^2 \lambda^2 \sigma}{P_{Rx\_min} (4\pi)^3 L}} \; [m]$$

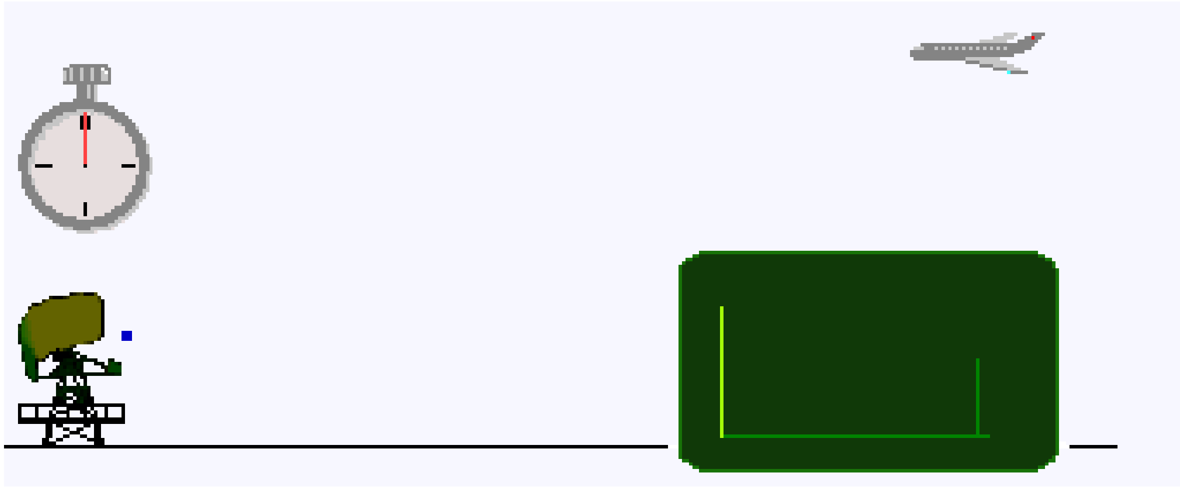
- The loss factor includes:
  - Internal attenuation of the radar
  - Fluctuation losses: the temporal changes of the object course cause fluctuation of the reception field
  - Atmospheric losses

Pulse radars

- Emitting short and powerful pulses and receiving echo signals.
  - Transmit pulse duration $\tau = 0.1 \ldots 1\ \mu s$
  - Period time $T \approx 1ms$
- Distance measurement
  - Pulse time-of-flight

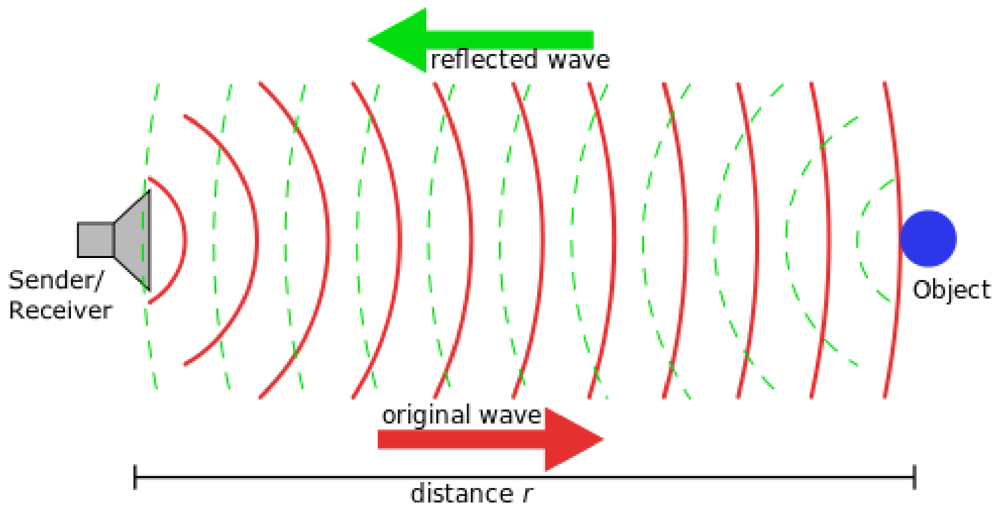
$$R = \frac{ct}{2}$$

  - Example: d=1km,c=2.99e8 m/s -> 6.67 µs
- Applications
  - Designed for long distances, air traffic control, meteorology, military



CW radars

- Continuous-wave radar is a type of radar system where a known constant frequency and constant amplitude continuous wave radio energy is transmitted and then received from any reflecting objects.
- It cannot measure a range and it cannot differ between two or more reflecting objects.
- It can measure the speed only by using the Doppler-effect.
- Typical application in transportation is traffic control radar.

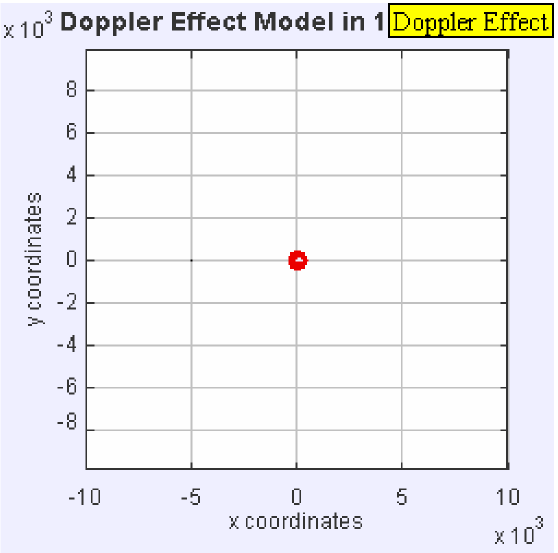


Doppler-effect

- Doppler-effect is the change in frequency caused by motion between the source and the reflector. Christian Doppler (1803-1853) was an Austrian mathematician and physicist.
- The relation between the detected frequency ***f*** and the emitted frequency f_0 :

$$f = \left(\frac{c + v_r}{c + v_s}\right) f_0$$

- where ***c*** is the velocity of waves in the medium; v_r is the velocity of the receiver relative to the medium; positive if the receiver is moving towards the source; v_s is the velocity of the source relative to the medium;



By Lookang many thanks to Fu-Kwun Hwang and author of Easy Java Simulation = Francisco Esquembre - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16444998

By Zátonyi Sándor, (ifj.) Fizped - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=15626717

Doppler-effect in practice

- If the speeds are small compared to the speed of wave:

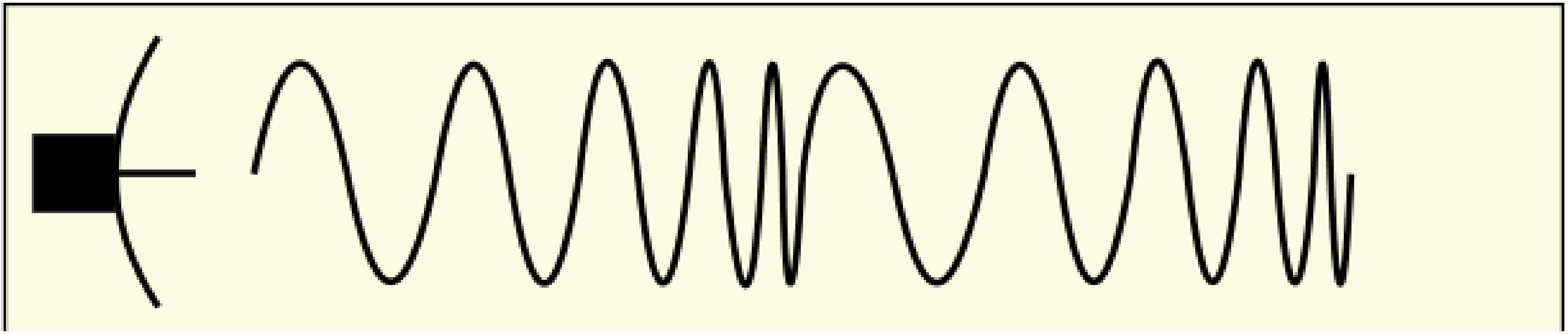
$$f = \left(1 + \frac{\Delta v}{c}\right) f_0$$

$$\Delta f = \frac{\Delta v}{c} f_0$$

- In case of radars the Doppler-effect affects the wave toward the target as well as back to the radar.

$$\Delta f = \frac{2\Delta v}{c} f_0$$

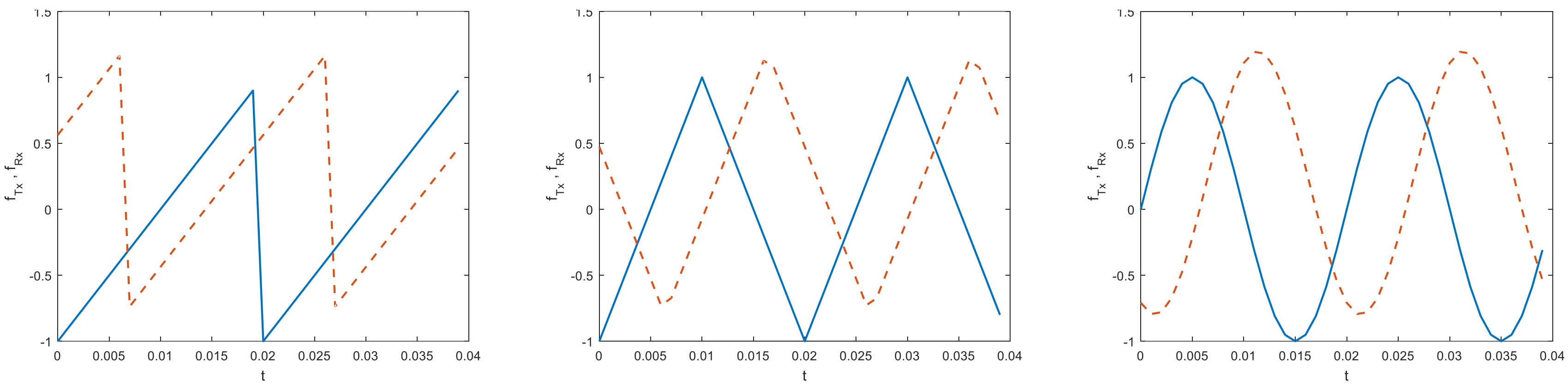
Vehicle Industry: FMCW radar

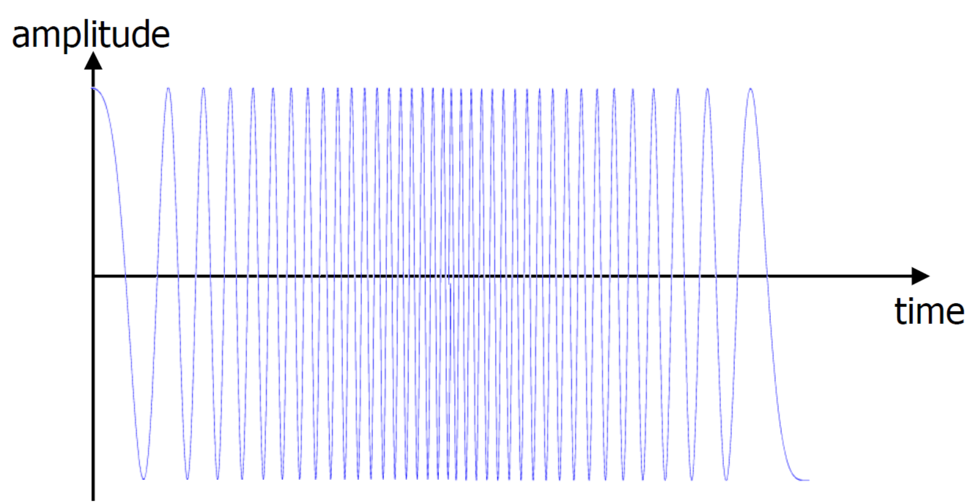


Source: Nautical Software

- Another form of distance measuring radar is based on frequency modulation.
  - Continuous wave radar without modulation, cannot determine target distance.
  - Pulse radars need high power
- Nowadays in the vehicle industry, the mainly used radar technology is FMCW:
  - Frequency Modulated Continuous Wave
  - Smaller, cheaper, lower power
  - Lower distance
  - Enables distance and speed measurements
- The carrier frequency is modulated with a periodic signal.
  - Most commonly sawtooth

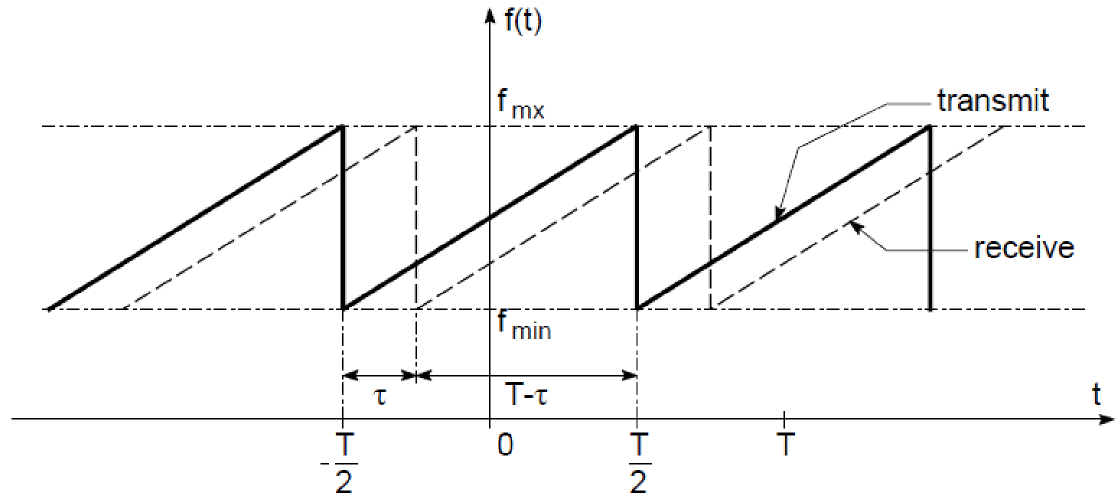
FM modulation signals and differences



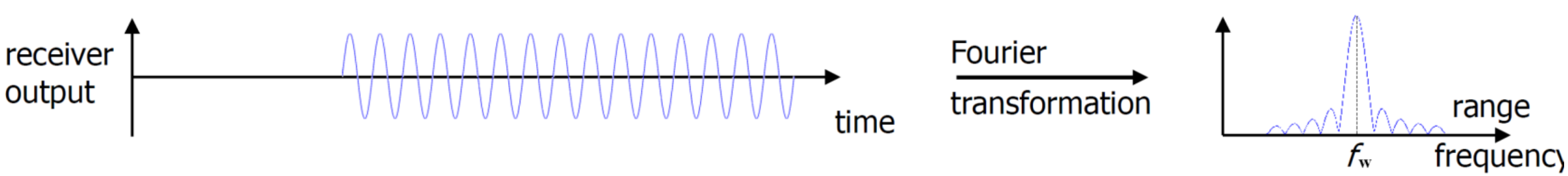


FMCW signal processing basics (static)

$$\tau = \frac{2R}{c}$$
$$f_w / B_s = \tau / T$$
$$B_s = f_{max} - f_{min}$$
$$R = \frac{cTf_w}{2B_s}$$



- Sawtooth modulation signal is assumed.
- Ideally, the wave reflected from distance **R** is the copy of the emitted wave with delay $\boldsymbol{\tau}$ proportional with the distance
- The receiver output signal is a sinusoid and its $\boldsymbol{f_w}$ frequency is constant in $\boldsymbol{T- \tau}$.
- Determining the frequency is also determining the distance of the resulting signal

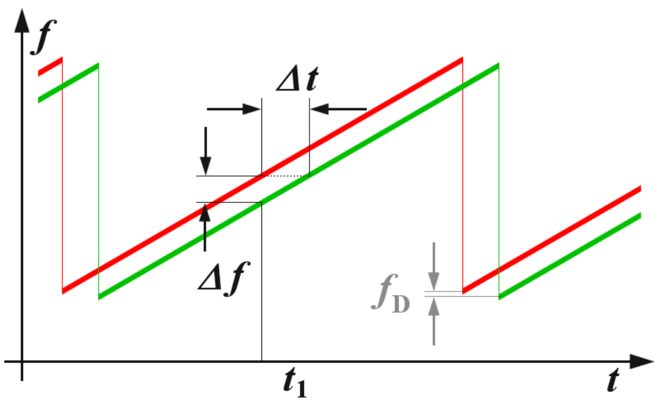


FMCW (moving object) I.

- In case the object moves from distance $\boldsymbol{R_0}$ with $\boldsymbol{v_r}$ velocity, the delay is not constant. Assuming that $\boldsymbol{v_r} \boldsymbol{<<} \boldsymbol{c}$, then the delay is a linear function of time:

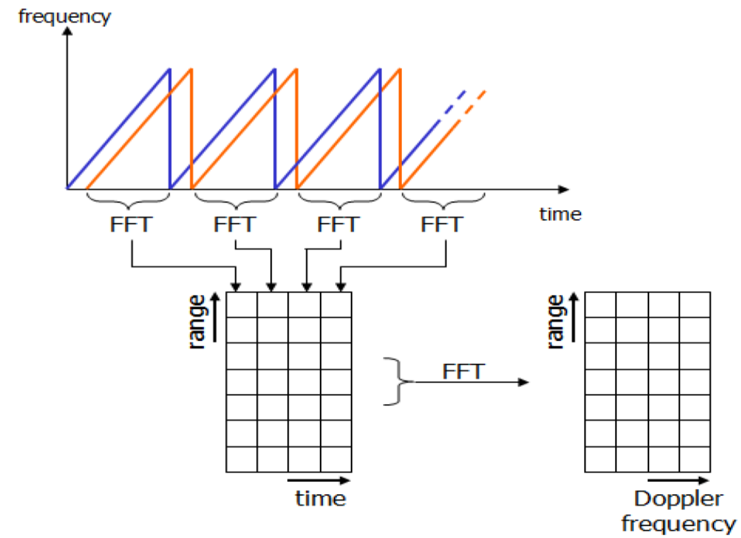
$$\tau \approx \frac{2}{c}(R_0 + vt)$$

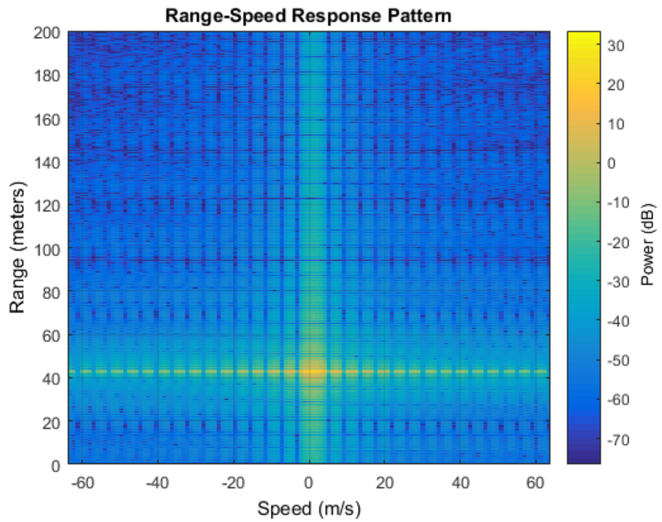
- The change in delay is a quite slow process, therefore it can be detected in the change in the phase response. By evaluating more modulation period, the Doppler frequency can be estimated.
- Therefore estimation need to be made for $\boldsymbol{f_w}$, and $\boldsymbol{f_d}$ (Doppler) frequencies. Now the two sums up in the beat signal (Δf).



2D discrete Fourier-transformation

- In case of sawtooth modulation
- Fast Fourier Transformation (FFT)
- FFT for all chirp resulting in (f_w+f_d). Since $f_w>>f_d$, approx. for distance is given.
- FFT from multiple periods FFT results in the 2D spectrum of the signal.
- From this, distance and speed can be evaluated.





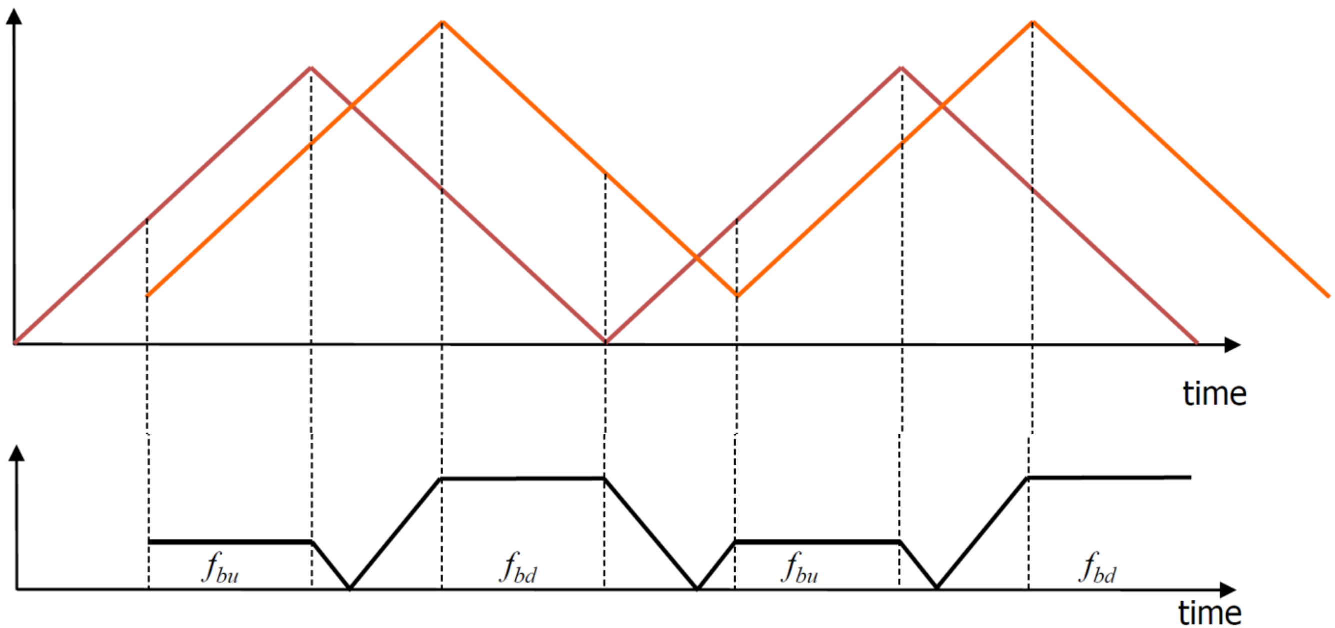
FMCW (moving object) II.

- In case of triangular modulation
- Allows easy separation of the difference frequency (f_b) and Doppler frequency (f_d)

$$f_b = \frac{2B_sR}{cT}$$

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

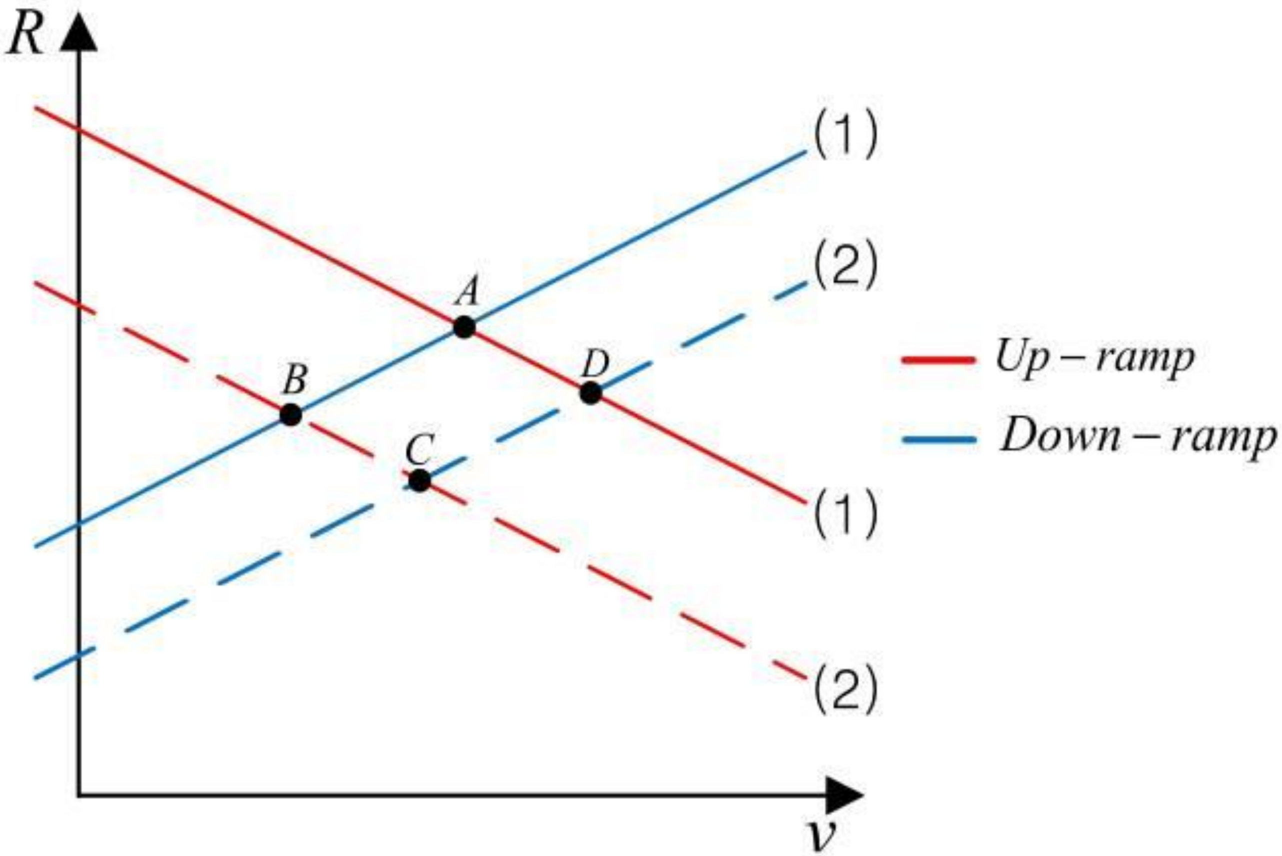
$$f_{bu} = f_b - f_d$$
$$f_{bd} = f_b + f_d$$



$$R = \frac{cT}{4B_s}(f_{bd} + f_{bu})$$
$$v_r = \frac{\lambda}{4}(f_{bd} - f_{bu})$$

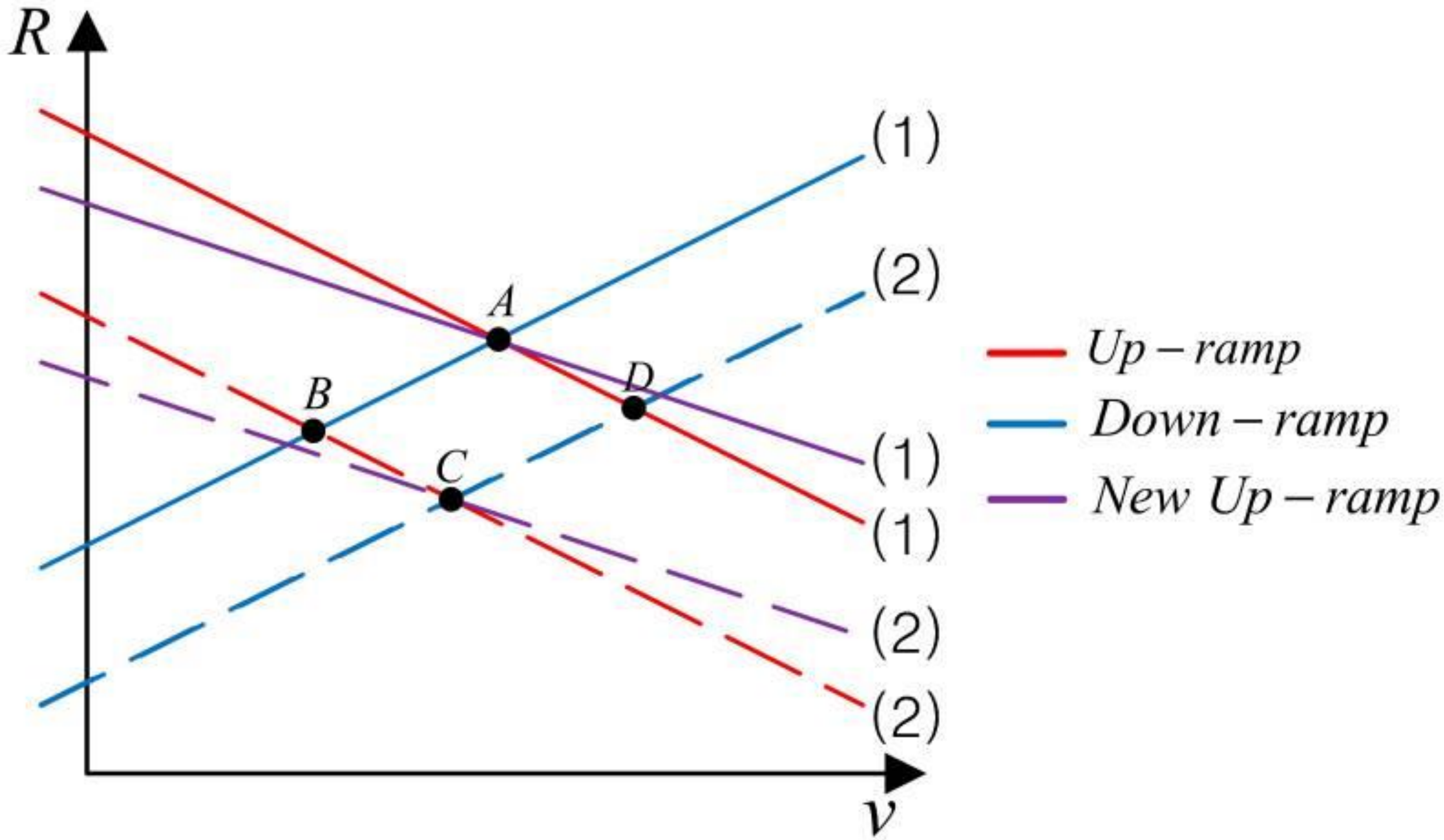
Multi-Target Problem

- Two targets
- Both pairs of linear slopes give a total of four intersections, two of which are the ghost targets



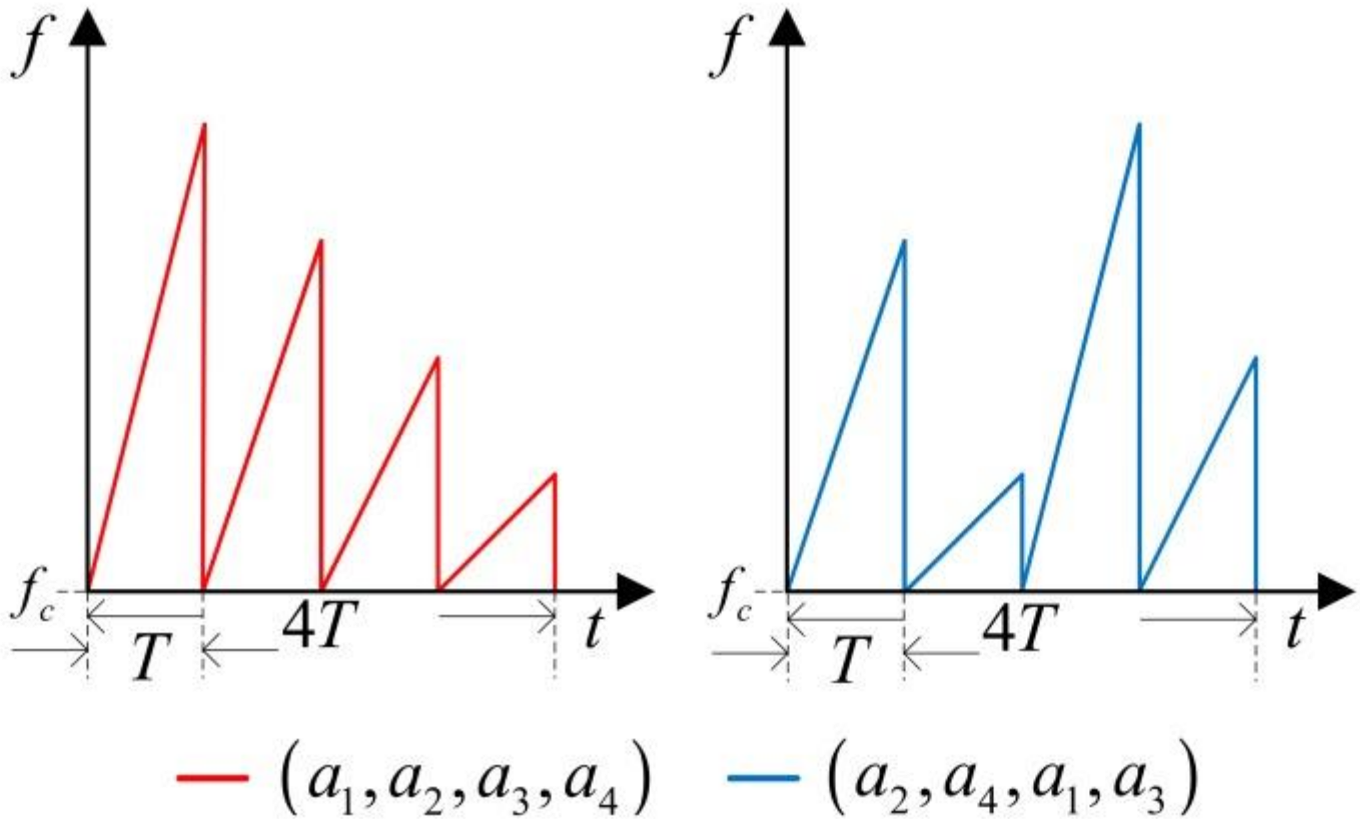
Multi-Target Solution

- The problem can be resolved by measuring cycles with different slope steepness's



Example Multi-Target Solution

- A single period of chirp sequence is composed of four short chirp sequences with different frequency slopes.



Angle of Arrival (AoA) estimation

- Angle Estimation requires at least 2 RX antennas.
- The differential distance from the object to each of the antennas results in a phase change in the Fourier-transformation peak.

$$\omega = \frac{2\pi \Delta d}{\lambda}$$

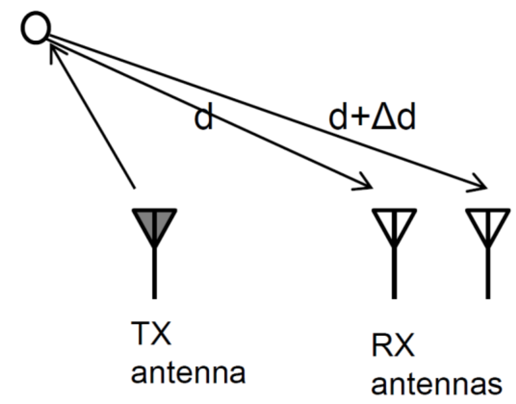
$$\omega = \frac{2\pi d sin(\theta)}{\lambda}$$

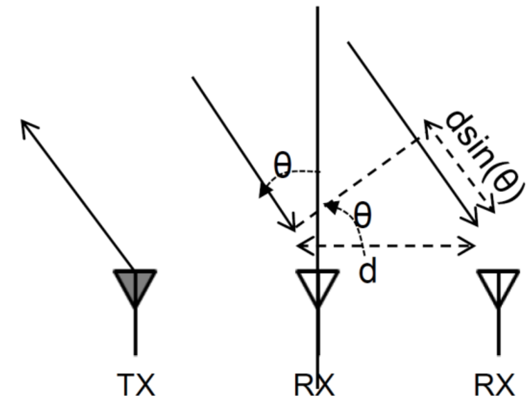
$$\theta = sin^{-1}\left(\frac{\lambda}{2\pi d}\right)$$

- The maximum FoV that can be serviced by two antennas spaced d apart is

$$\theta_{max} = sin^{-1}\left(\frac{\lambda}{2d}\right)$$

(|ω| should be less than π)





FMCW Radar Design

- Carrier frequency: 76-81 GHz, mm wavelength
- Max distance: determines chirp length ***T*** (min. 2R/c)
- Distance resolution
  - Distinguish between two close targets.
  - R_1 and R_2 distance, the frequency distance:

$$\Delta f_{\mathrm{w}} = |f_{w1} - f_{w2}| = \frac{2B_s}{cT}|R_1 - R_2| = \frac{2B_s}{cT}\Delta R$$

  - To separate two targets with Fourier transform minimal $\boldsymbol{f_w}$ frequency have to be at least ***1/T*** :

$$\Delta f_{wmin} = \frac{1}{T} = \frac{2B_s}{cT}\Delta R_{min} \rightarrow \Delta R_{min} = \frac{c}{2B_s}$$

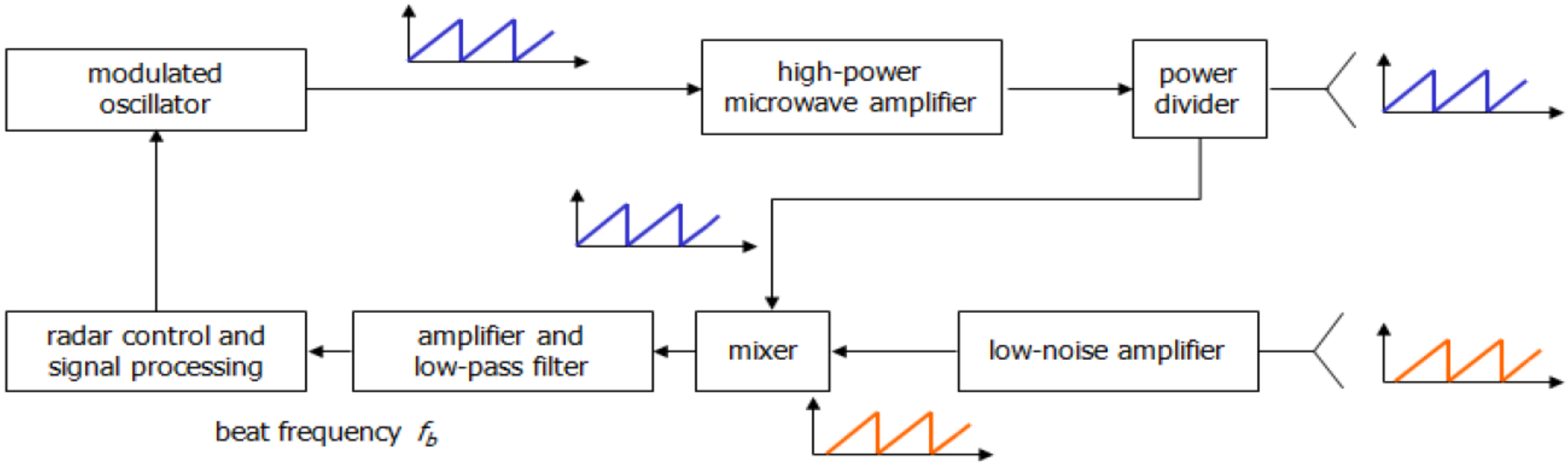
  - Bandwidth: $B_s = \frac{c}{2\Delta R_{min}}$
- Maximal speed: based on speed and wave length, the Doppler-frequency:

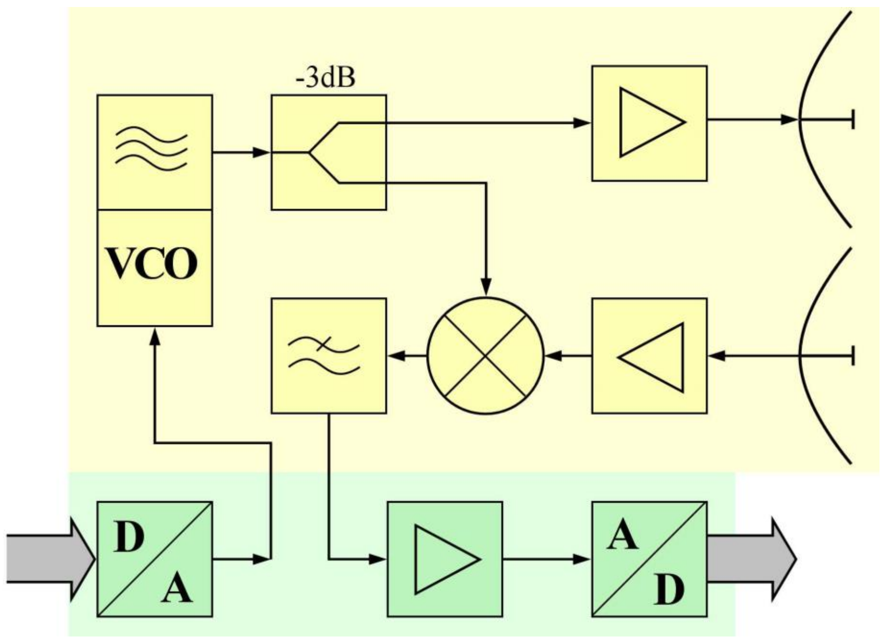
$$f_{dmax} = \frac{2v_{max}}{\lambda}$$

- Sampling: at least the double of the BW or the beat frequency

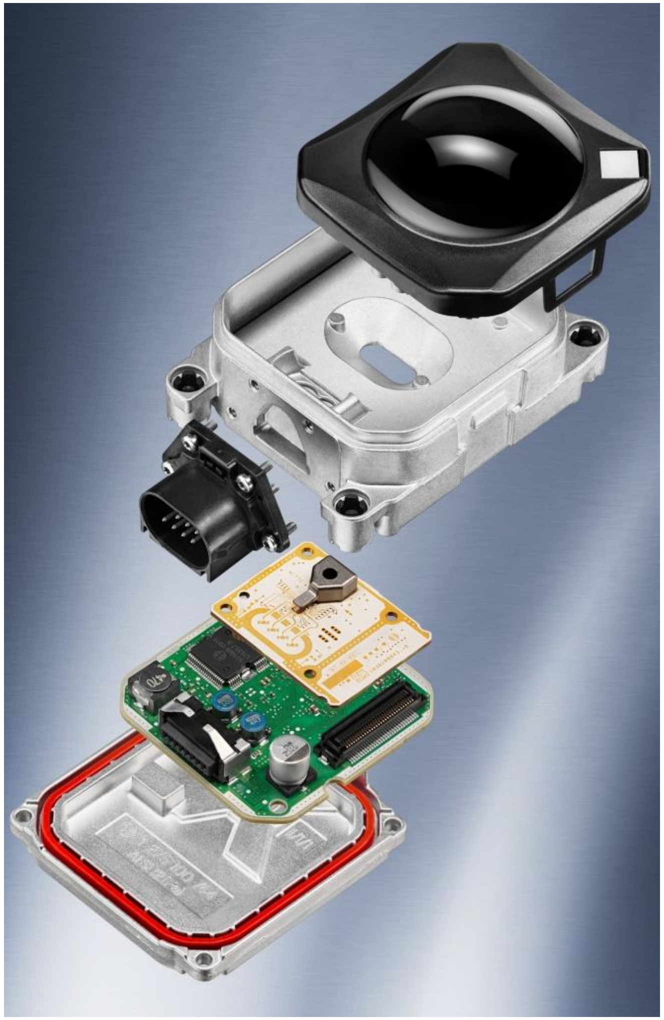
$$f_{bmax} = f_{wmax} + f_{dmax}$$
$$f_s = \max(2 \cdot f_{bmax}, B_s)$$

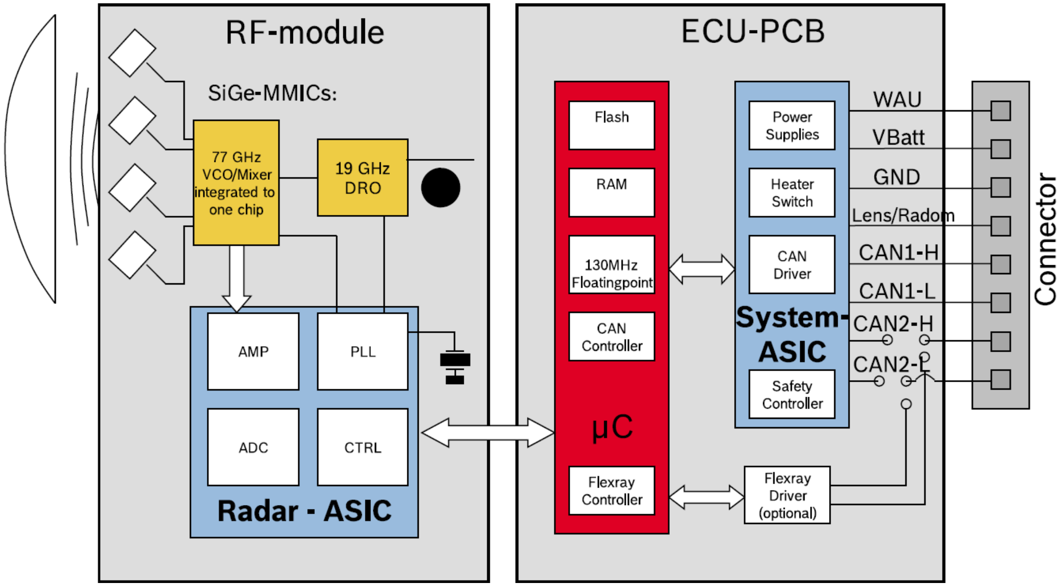
FMCW radar block diagram





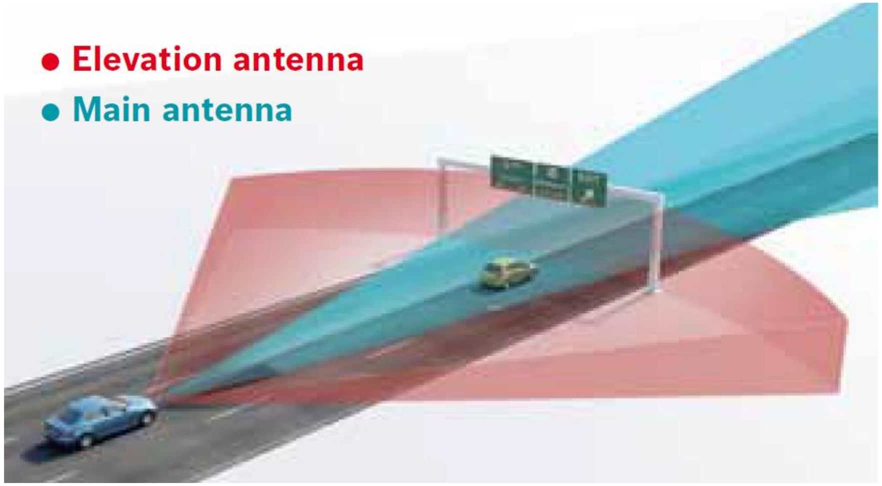
FMCW radar HW architecture





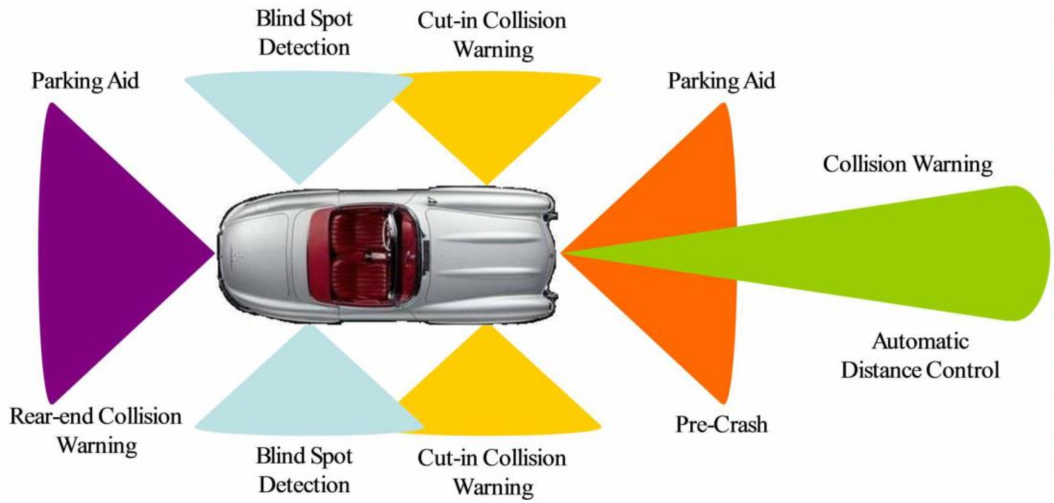
Bosch MRR Specs

Features	MRR	MRR rear
Frequency	76…77 GHz	76…77 GHz
Range	0.36…160 m	0.36…80 m
FoV (hor.)	±6° (160 m); ±9° (100 m); ±10° (60 m); ±25° (36 m); ±42° (12 m)	±5° (70 m); ±75° (close range)
Accuracy	0.12m, 0.11 m/s, ±0,3°	0.12 m, 0.14 m/s, ±0.8°
Resolution	0.72 m, 0.66 m/s, 7°	0.72 m, 1.4 m/s, 7°
Max. number of objects	32	
Dimensions in mm	70 x 82 x 30 (with connectors)	70 x 82 x 30 (with connectors)
Weight	190 g	190 g
Power consumption	4.5 W	4.5 W



Radar Functions

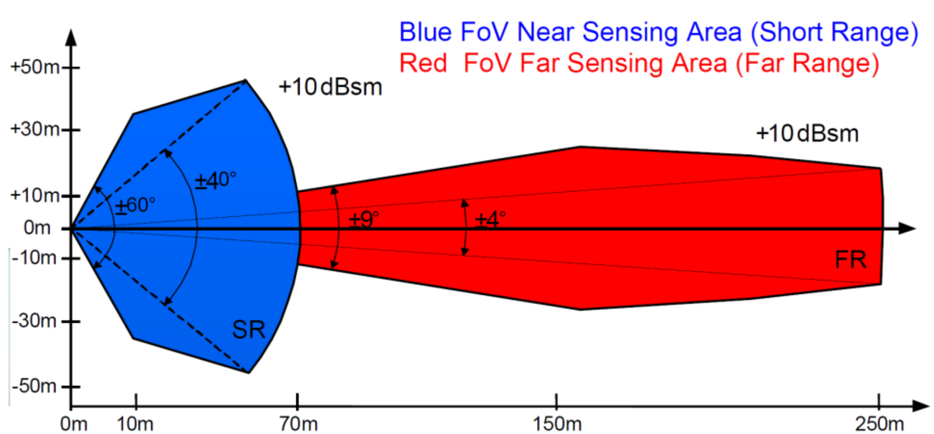
- Radar is the core sensor of driver assistance systems
- Functions
  - Object detection and classification
    - Adaptive cruise control (distance control)
    - Collision warning and avoidance
    - Blind spot detection
    - Parking Aid
- Pros
  - Low sensibility to weather conditions, not sensible to light
  - For safety critical applications
  - Small size and low price
- Cons
  - Object classification is hard
  - Reflections can cause disturbance



Forrás: Maria S. Gerco: Automotive Radar, 2012 IEEE Radar Conference, May 7-11, Atlanta

Continental Radar Specs

Features	ARS 408-21
Frequency	76…77 GHz
Range	0.20…250 m
FoV (hor.)	±9° (250 m); ±40° (70 m); ±60° (20 m);
Accuracy	0.12m; 0.03 m/s; ±0.1° (250 m), ±1° (70 m), ±5° (20 m)
Resolution	1.79 m (250 m), 0.39 m (70 m); 0.10-0.12 m/s; ±1.6° (250 m); ±4.5° (70 m); ±12.3° (20 m);
Max. number of objects	100
Dimensions in mm	138 x 91 x 31 (with connectors)
Weight	320 g
Power consumption	6.6 W

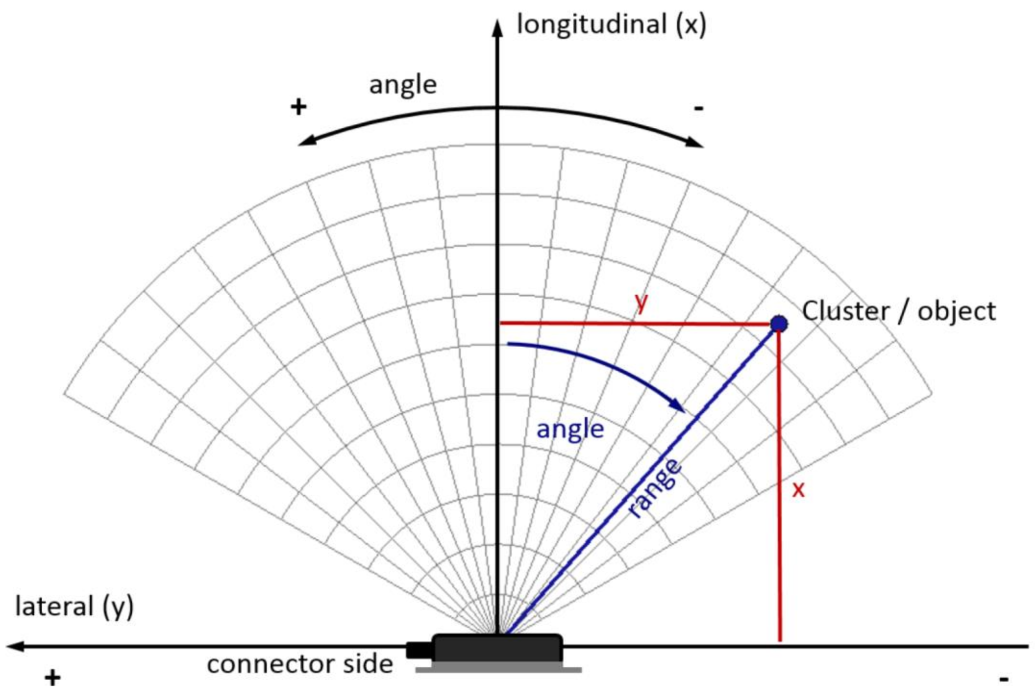


Conti ARS 408-21 I.

- The sensor uses FMCW radar technology to analyse its surroundings.
- The reflected signals are available in form of clusters and objects.
  - Clusters are radar reflections
    - Position, velocity and signal strength
    - Newly evaluated every cycle
  - Objects have a history and dimension
    - They consist of tracked clusters

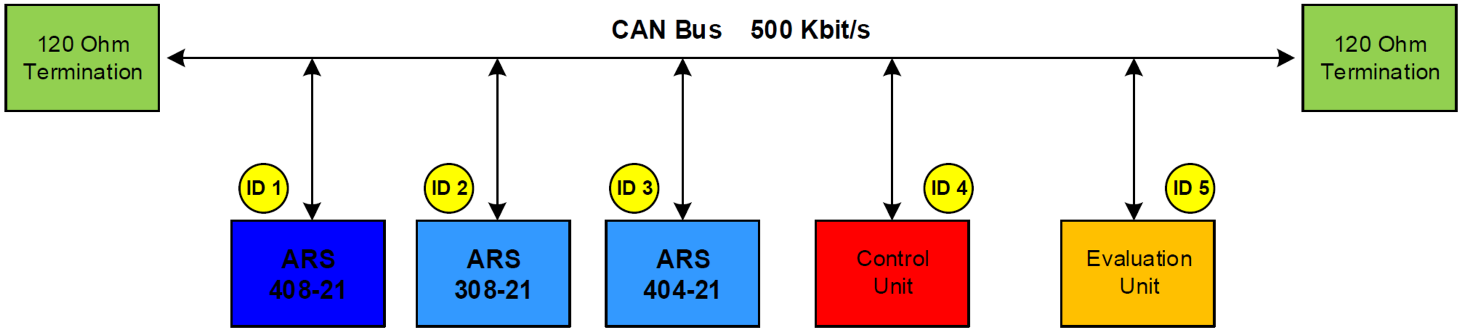
Conti ARS 408-21 II.

- The position is given in a Cartesian Coordinates System relative to the sensor.
- The velocity is calculated relative to an assumed vehicle course.
- The course is determined by using the speed and yaw rate information
- The output cluster and object lists can be filtered by setting filter criteria based on their attributes.
  - The clusters or objects of interest that are sent on the CAN-bus can be selected.



Conti ARS 408-21 III.

- The sensor has one CAN interface with a transmission rate of 500 kbits/s. It is used for
  - configuration
  - sensor state output
  - other data input and output (e.g. yaw rate and velocity information)
- Up to eight sensors can be added to one CAN bus
  - The sensor ID can be configured, which will change the message IDs.
  - E.g. the configuration message 0x200 for sensor ID 0, will be 0x210 for sensor ID 1.



Conti ARS 408-21 IV.

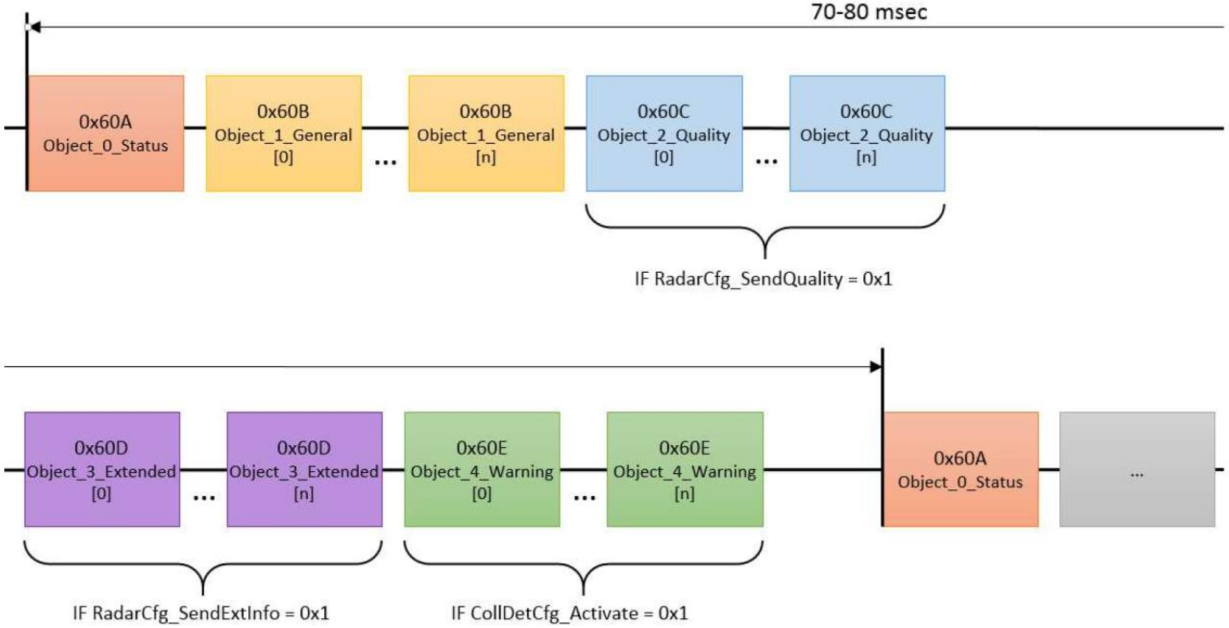
- Configuration of the radar sensor is very simple
  - It can be set with one CAN message
  - It is enough to send once
  - The config can be stored in the non/volatile memory (NVM), if it is activated in the config message
  - The parameters can be changed individually or in combinations.
- Which parameters can be configured?
  - Sensor ID (modifies the CAN IDs)
  - Maximum far distance
  - Radar power
  - Output type
  - Quality information
  - Extended information
  - Sort index
  - Relay control
  - RCS threshold
  - Store in NVM

Conti ARS 408-21 V.

- The sensor can filter the output data.
- Multiplexed message is used
  - filter clusters or objects
  - filter criteria (filter index)
- The filters are designed as pass though filters
  - min – max
- Filter criterion
  - Number of object
  - Distance, azimuth, signed relative vel. (abs. , x, y)
  - RCS, size, lifetime
  - Probability of existence
  - X, Y
  - Object class: point, car, truck, motorcycle, bicycle, wide

Conti ARS 408-21 VI.

- One can choose from clusters and objects
- Clusters and objects are sent in a similar way, but with different CAN IDs and data.
- Object information
  - Status
  - General
  - Quality
  - Extended
  - Warning



Conti ARS 408-21 VII.

- Object general information
  - ID
  - Longitudinal and vertical distances
  - Longitudinal and vertical relative velocities
  - Dynamic property: moving, stationary, oncoming, stationary candidate, unknown, crossing stationary, crossing moving, stopped
  - RCS
- Object quality information
  - ID
  - Standard deviation of every distances, velocities, accelerations and orientation angle
  - Measurement state: new, predicted, measured and deleted
  - Probability of existence
- Object extended information
  - ID
  - Longitudinal and vertical relative accelerations
  - Class (See slide 35!)
  - Orientation angle
  - Dimensions

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Thank you for your attention!