TECHNISCHE HOCHSCHULE OSTWESTFALEN-LIPPE
UNIVERSITY OF APPLIED SCIENCES AND ARTS

Radar sensors

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Content

- Basics radar technology
  - Wavelengths
  - Generating radar signals
  - Characteristics: Reflection, range, aperture angle, resolutions
  - Multipath propagation
- Measurement principles
  - Modulation / Demodulation
  - Amplitude modulation / Frequency modulation
  - Doppler effect
- Examples

Radar systems

- Radar : **Ra**dio **D**etection **a**nd **R**anging
  - Origin in military technology of the 2nd World War
  - First use in traffic: speed monitoring in the 50s
  - First projects for driver assistance in the 70s for rear-end collision protection
  - First series introduction in 1998: adaptive cruise control ACC

  - Four frequency ranges for road traffic applications
    - 24.0 - 24.5 GHz
    - **76-77 GHz main frequency range by today**
    - 77-81 GHz (not yet fully regulated)
    - 21.65-26.65 GHz (for short-range applications only, no longer used)

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Frequency spectrum

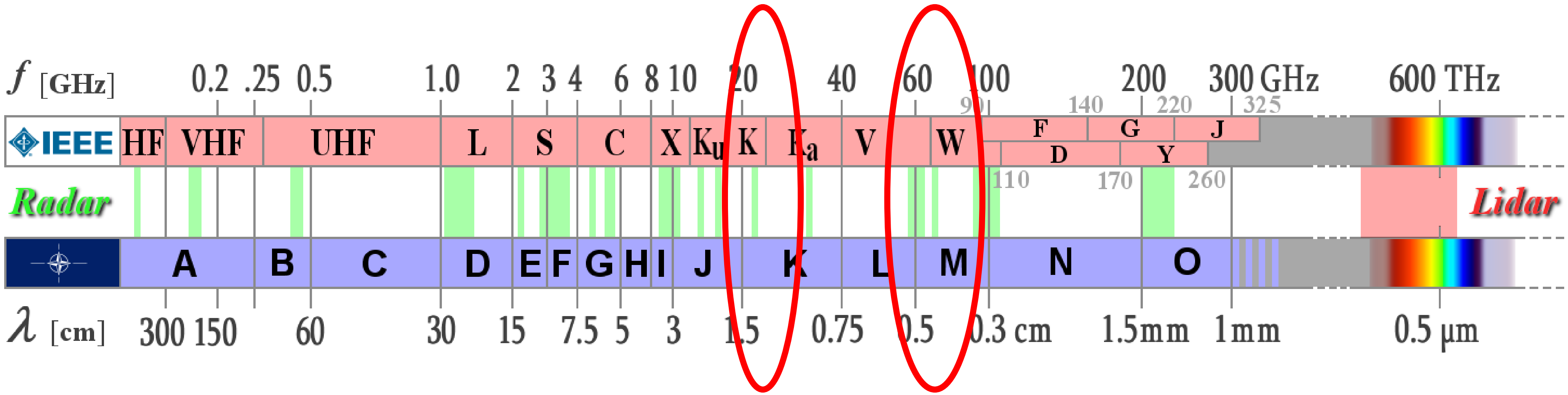


Image:www.radartutorial.eu

Frequencies in automotive application

Frequency range	Pro	Con
24,0 GHz – 24,25 GHz 21,65 GHz – 26,65 GHz (UWB)	• low line losses • low cost component	• poor radiation characteristics • small antenna gains • poor angular resolution • no further approval since 2013 for UWB systems
76 GHz – 77 Ghz main frequency band	• usable worldwide • long range • high angular resolution	• Expensive components • High line losses
77 Ghz – 81 GHz	• Alternative range for systems with UWB technology	• Expensive components • High line losses

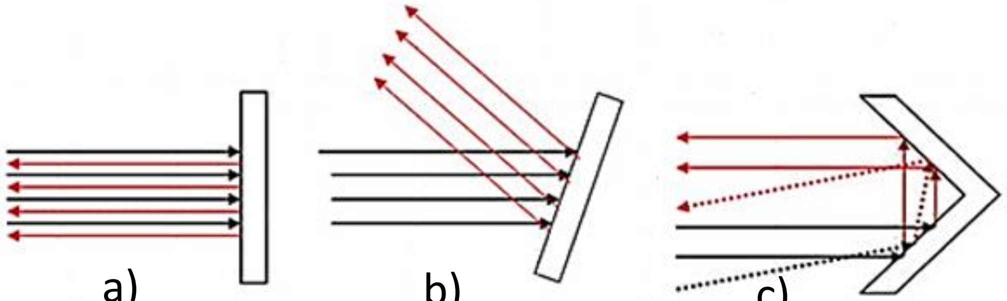
Electromagnetic waves and their propagation

- Electromagnetic waves
  - E.G.: Radio waves, X-rays, thermal radiation, light, etc.
- No medium is needed for movement
- Speed depends on medium
  - Vacuum -> speed of light
  - Air -> approximate speed of light
  - Water -> approx. 1/9 of the speed of light
- Sender/Transmitter and receiver paths

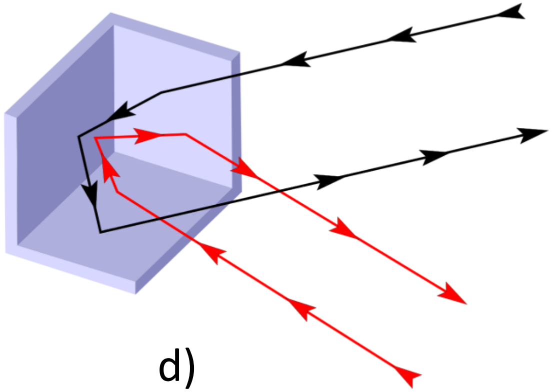
Image: Gamba, J. Radar Signal Processing for Autonomous Driving

Electromagnetic waves and their reflection

- Reflected signal depends on objects size, shape and reflectivity
- Shape of the reflecting surface has a great influence on the reflection
    a) 90° reflection at a plate
    b) 90° reflection at a tilted plate
    c) 90° double mirror
    d) Corner (Cube) reflector (ideal reflection)



a) b) c)



d)

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The radar equation

- Radar equation describes the relationship between
  - transmitted signal power P_t
  - received signal power P_r
  - antenna properties defined by gain G_t, G_r, signal wavelength λ
  - characteristics of the reflecting object σ_s (Radar Cross Section, RCS)
  - distance to reflecting object R

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma_s}{(4\pi)^3 R^4}$$

  - Additionally to be considered: atmospheric losses (rain, pollution,…)

Measurement with electromagnetic waves

- Measurements are made by reflected electromagnetic waves

- Vehicle is sending radar signal and is receiving the reflected signal
- Two main measurements
  - Distance
  - Relative speed

Disturbances due to environmental influences

- Disturbances at the reflection target:
  - Spoiler on vehicles
  - Radiator grille on vehicles
  - Entrance steps on SUVs
- Interference in the immediate vicinity of the vehicle:
  - Various angular reflectors such as U-profiles of crash barriers
  - Weather influences such as rain, fog or snow
- Interference from sensor housings:
  - Media such as water on the sensor housing, causing distortion of the exit and entry angle.
- Lead to sometimes severe reduction of radar performance and non-optimal functioning of the radar system

Performance and frequency range

- Influence of the frequency on the performance

  - Size of the hardware
  - Proportional to wavelength
  - low frequency = large wavelength ➔ large hardware

  - Radiated power
  - Limited by voltage gradient and heat losses
  - Large systems ➔ high power possible (but also cost issue)

  - Beam width / aperture angle
  - Beam width proportional to ratio of wavelength to width of antenna
  - High frequencies ➔ small antenna

Performance and frequency range

- Atmospheric attenuation
  - Influenced by absorption and scattering by oxygen, water vapor, water droplets
  - Increasing with frequency
- Ambient noise
  - Electrical noise decreasing with frequency
  - Above 10 GHz atmospheric noise becomes dominant
- Frequency shift
  - Frequency shift (Doppler effect) proportional to frequency

Basic building blocks

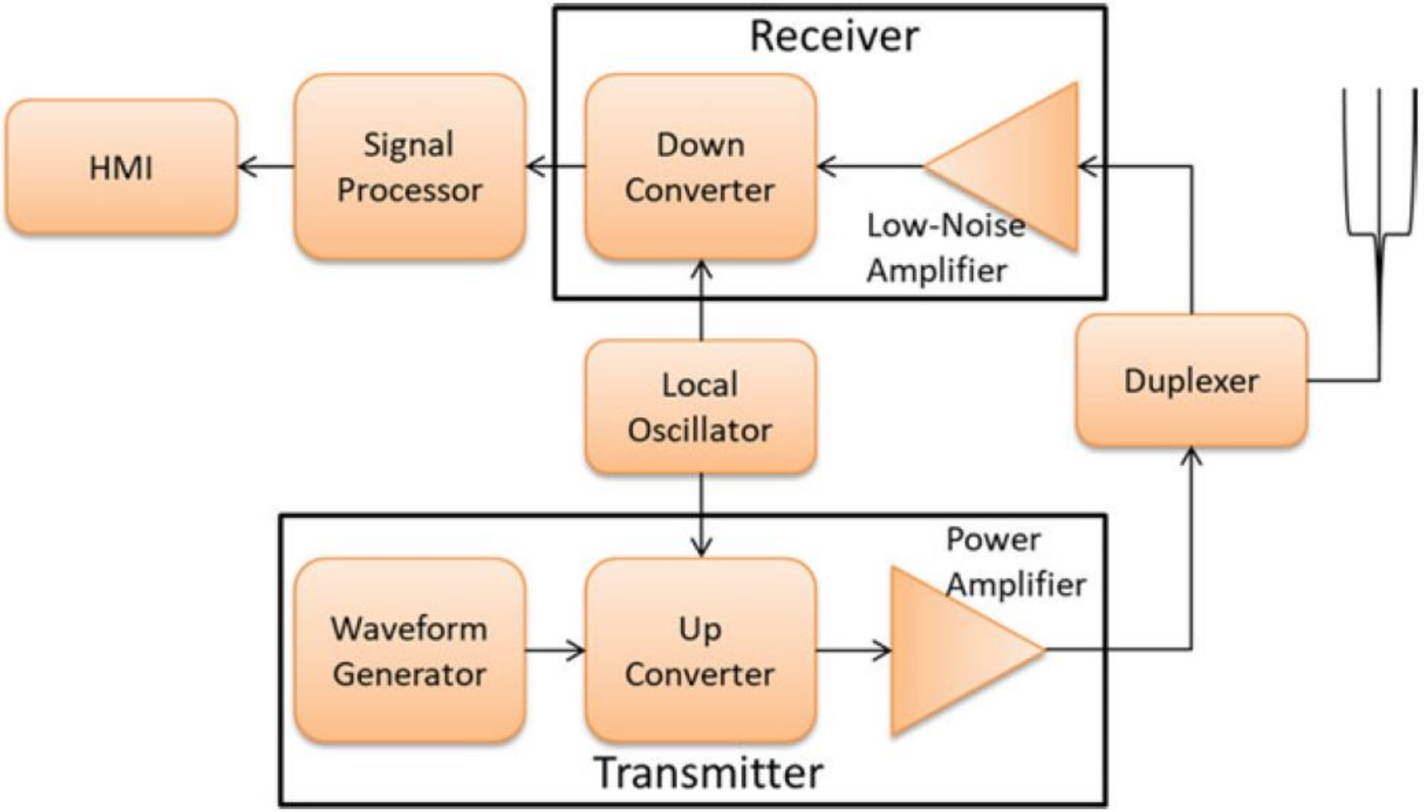
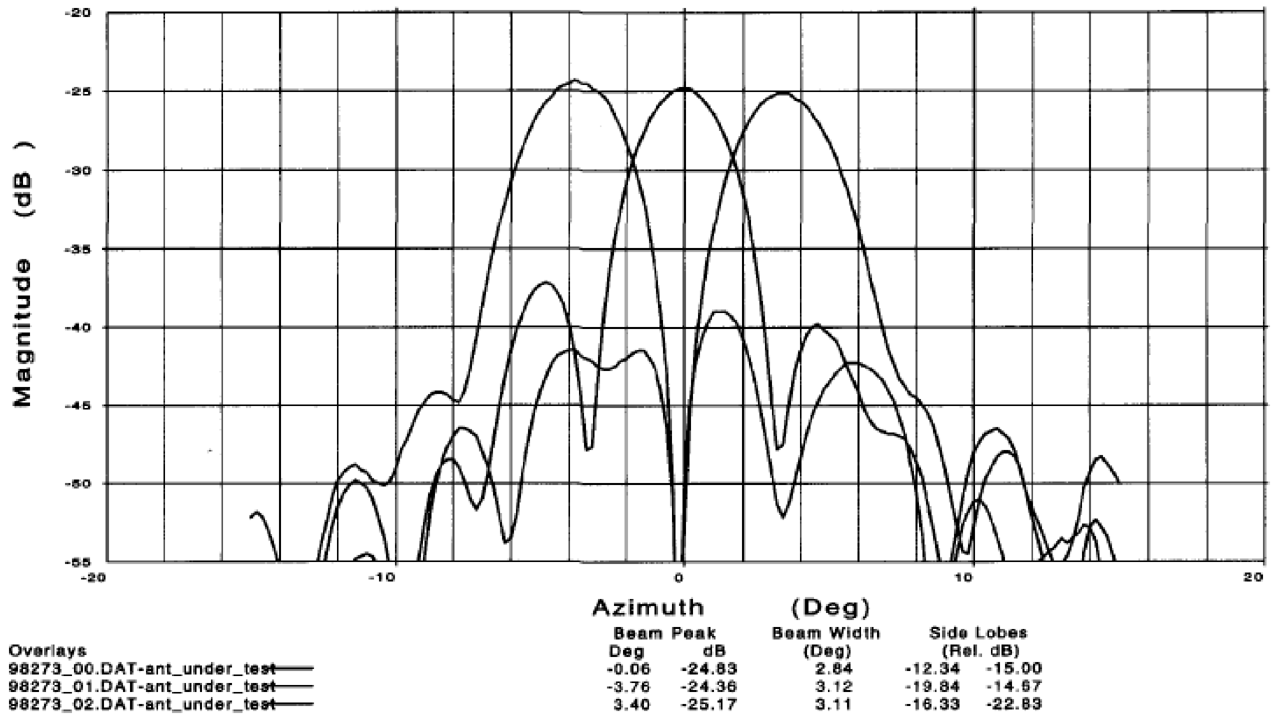


Image: Gamba, J. Radar Signal Processing for Atonomous Driving

Beam patterns

- 3-beam sensor

Figure 1: Typical Radiation Patterns, Beams 1 – 3



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Measuring Distance

- Basic principle: using the echo effect of electromagnetic waves.
- Necessary data:
  - the speed of propagation of the waves
  - the time from sending the waves to receiving them again (measured **value)**

- Distance to target = speed of light * travel time / 2

$$s = \frac{c * t}{2}$$

- Similar behavior to light waves
  - Straight line propagation
  - Reflection, refraction, diffraction

The Doppler effect to measure the relative velocity

- Predicted in 1842 by Austrian mathematician and physicist Christian Doppler
- Electromagnetic wave undergoes frequency shift when observer and transmitter move relative to each other
- Measurement of relative velocities
- Distinction between moving and fixed targets

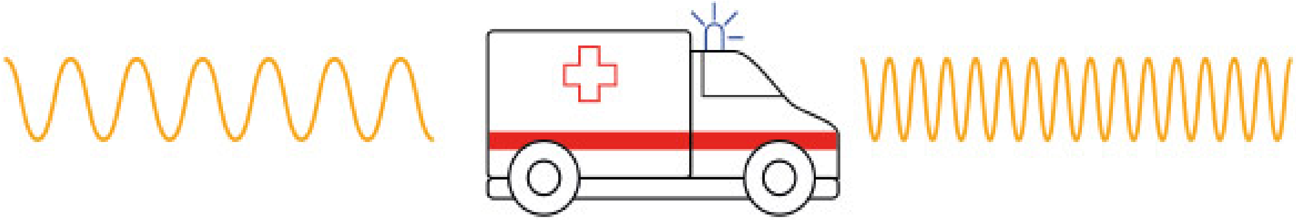


Image: https://www.christian-doppler.net/dopplereffekt/

Image: https://de.wikipedia.org/wiki/Christian_Doppler#/media/File:Cdoppler.jpg

The Doppler effect to measure the relative velocity

- Frequency change due to Doppler effect

$$f_{Doppler} = -2r' \frac{1}{\lambda} = -2r' \frac{f_0}{c}$$

  - Approaching object (r'< 0) ➔ positive
  - Departing object (r' > 0) ➔ negative

r : distance
r‘: first derivative of distane (velocity)
λ : wave length
c : speed of light
f_0 : frequency

Measuring speed

- Example
  - Carrier wave: 76,5GHz ➔ $f_{Doppler}$= $-510Hz \cdot r'$
  - Approaching object: r' = - 250 km/h ≈ $-70m/s$ ➔ $f_{Doppler}$= 35,7 kHz

- Nyquist sampling theorem must be satisfied
  - f_{sampling}=71,4kHz

Modulation

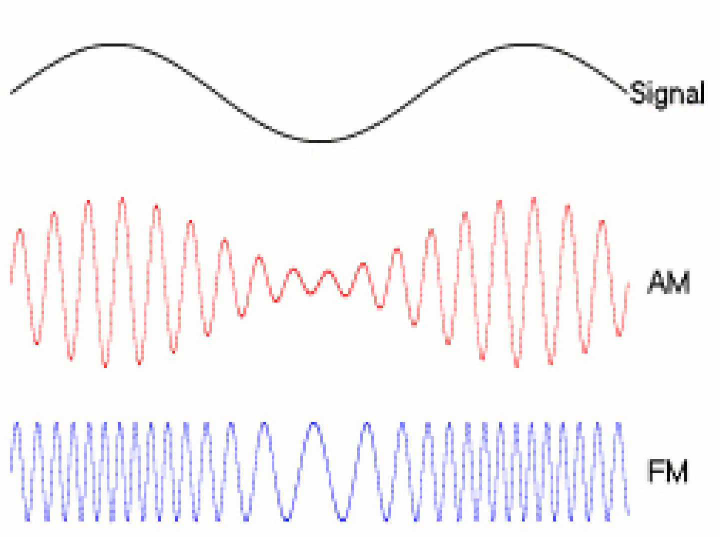
- Carrier signal is not sufficient for measuring distance and speed

- Transmitting constant wave
- Receiving constant wave
- Which elements of the signal do match?
- Resolution: $\Delta f = {}^{1}/_{T_{CW}}$, T_{CW} period of the constant wave

- Example
  - Frequency: 76 GHz ➔ period 1,3 * 10^{-11} s
  - Speed of light : c= 299.792.458 m/s ➔ Range d=0,39 cm

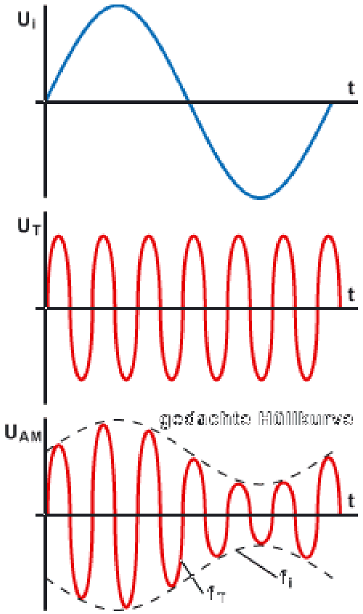
Modulation

- Electromagnetic waves only carriers of information
- $u(t) = A_t \cdot \cos(2\,\pi\, f_0\, t \pm \Phi_0)$
- Modifying the carrier wave with an information signal ➔ modulation
- Modulable variables:
  - Amplitude A_t
  - Frequency f_0
  - Phase Φ_0
- Automotive: amplitude modulation, frequency modulation

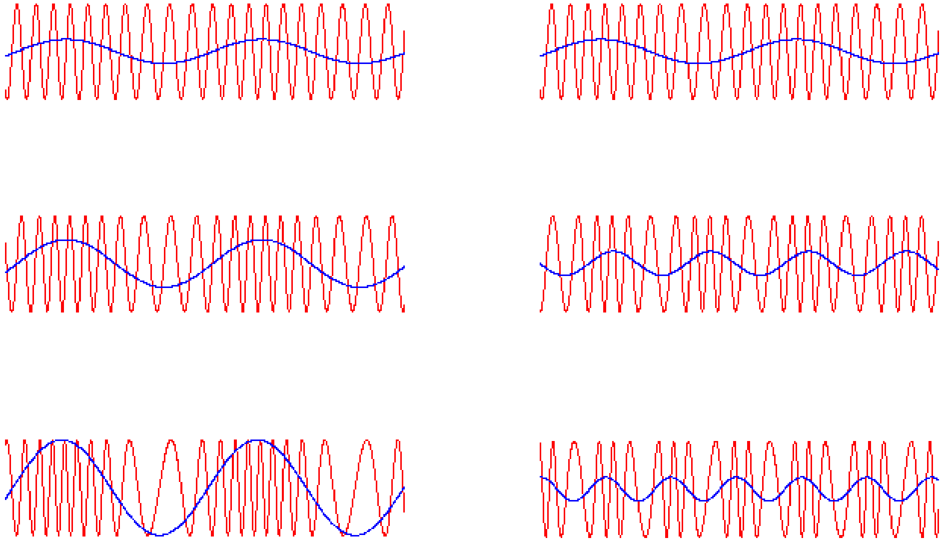


Modulation

- Examples



Amplitude modulation


Frequency modulation

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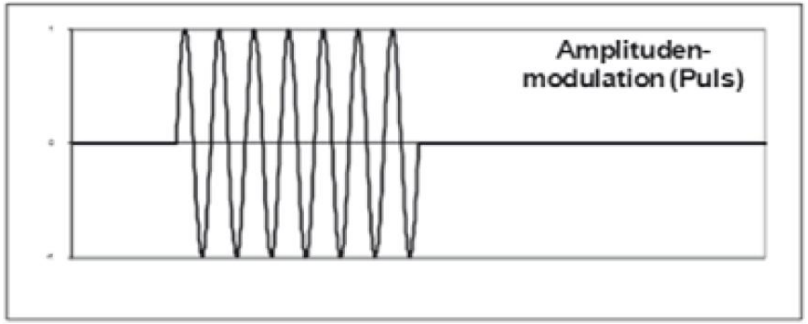
Amplitude modulation

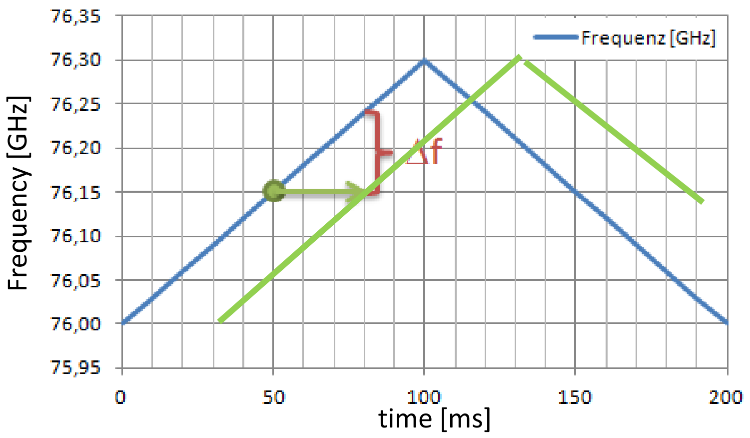
- Most common version: Pulse modulation
- Multiplication with square wave signals
- Used to measure distance and relative velocity
  - spatial resolution depends on pulse duration
  - maximum range depends on repetition frequency of pulses

- Advantages: Simple concept
- Disadvantage:
  - Higher sensitivity to interference
  - High bandwidth ➔ high costs



Frequency modulation - FMCW

- **FMCW - Frequency Modulated Continuous Wave**
  - Continuous radiation of the modulated transmission frequency
  - Modulation is ramped
  - Frequency shift from e.g. 76.0 GHz to 76.3 GHz
  - Phase is not changed



Example:

f_{Ramp}= 300 MHz and t_{Ramp}= 100 ms.

Distance to object:

runtime: t2 - t1= 30 ms

frequency: f2 - f1= 100 MHz

➔ Δf is measure for distance

Problem:

The Doppler effect is also influencing the received signal

Frequency modulation - FMCW

Problem statement:

- Equation with two unknown variables (distance, velocity)

Solution:

- Two independent measurements
  - during ramp-up
  - during ramp-down

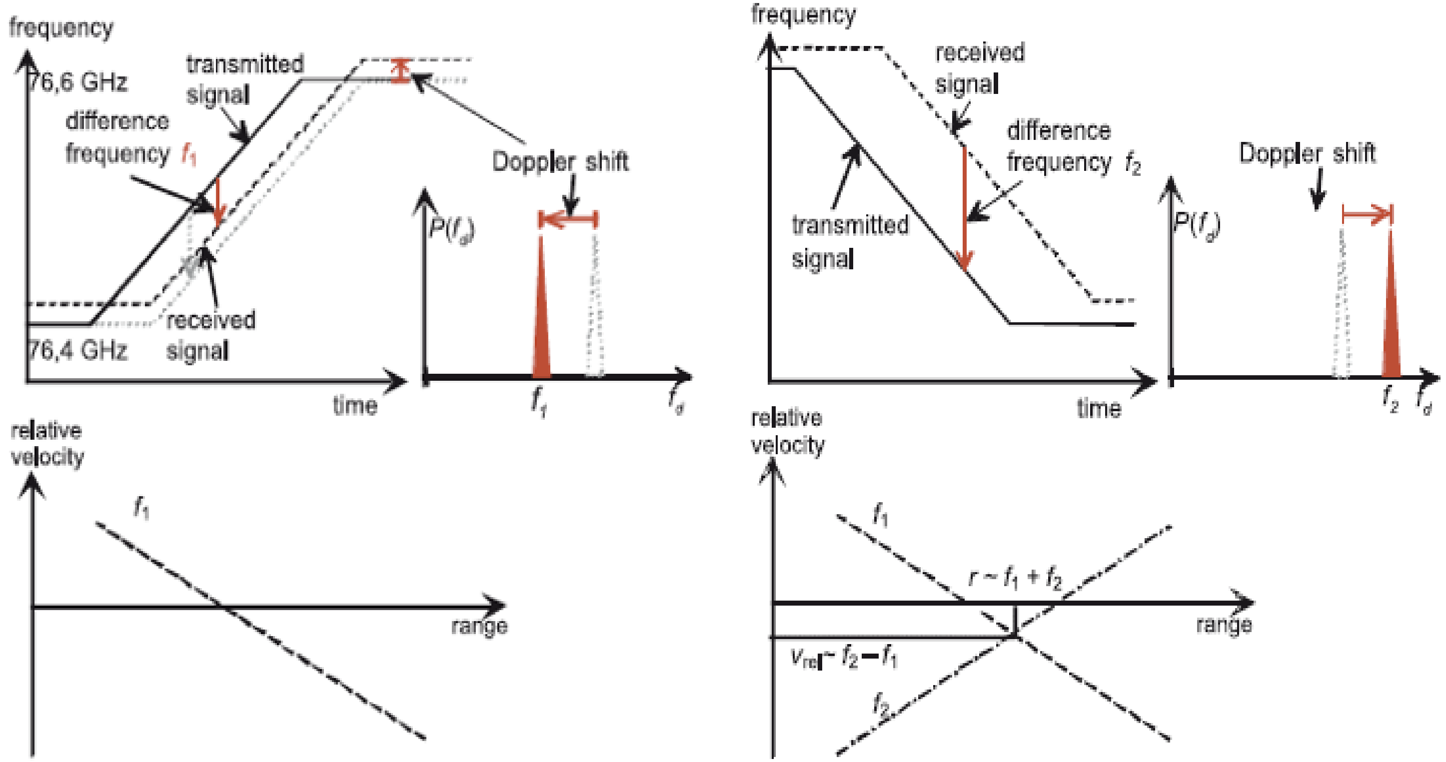
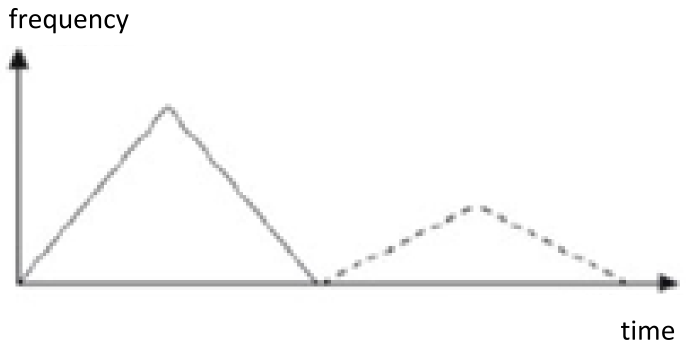
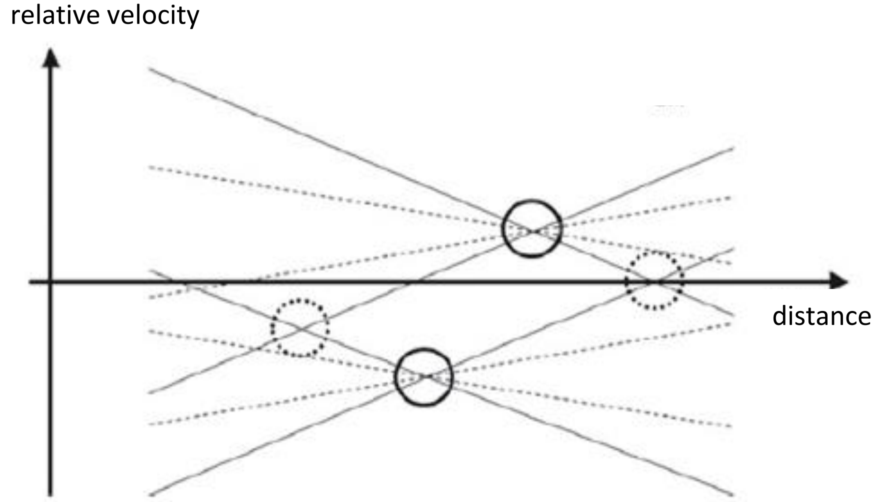


Image: Handbuch FAS 2015

Handling multiple objects

- Multiple intersections occur with multiple objects
- Using multiple ramps with different slopes
- Two additional ramps cause four straight lines to intersect at one point

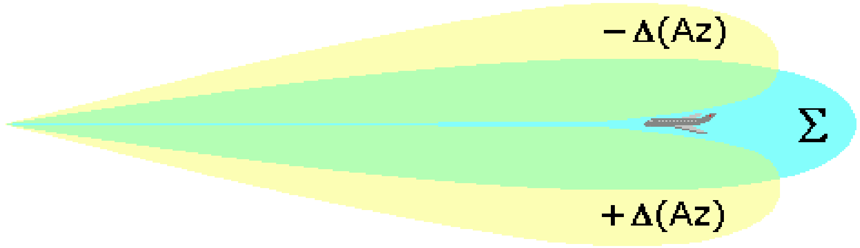


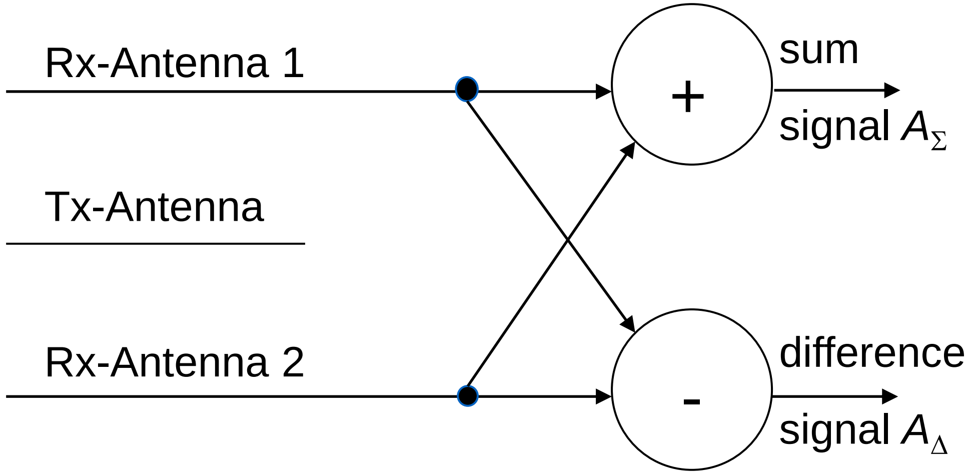


Images: Handbuch FAS 2015

Azimuth angle

- Angle measurement
  - Scanning
  - Fast panning of the antenna (lobe)
  - Performing multiple angle-dependent measurements
- Monopulse method
  - One transmitting antenna
  - Double antenna arrangement for reception





$$\phi = \frac{1}{2\pi\Gamma} \arcsin\left(\arctan\left(\frac{A_\Delta}{A_\Sigma} \right) \right)$$

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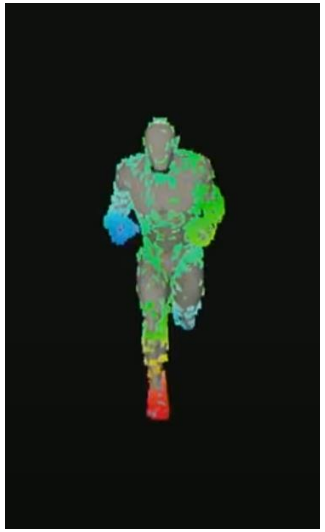
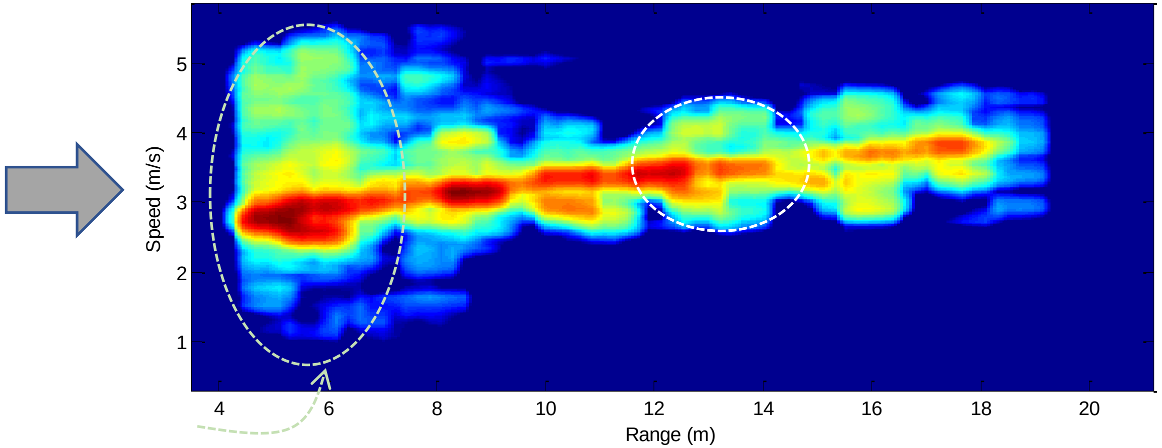
Micro-Doppler

- Doppler-Effect can be used to measure the velocity of an object.
- Not all elements of an object have the same speed ➔ Micro-Doppler
- Micro-Doppler allows us to recognize details of an object
  - Feet, arms, wheel, pedals

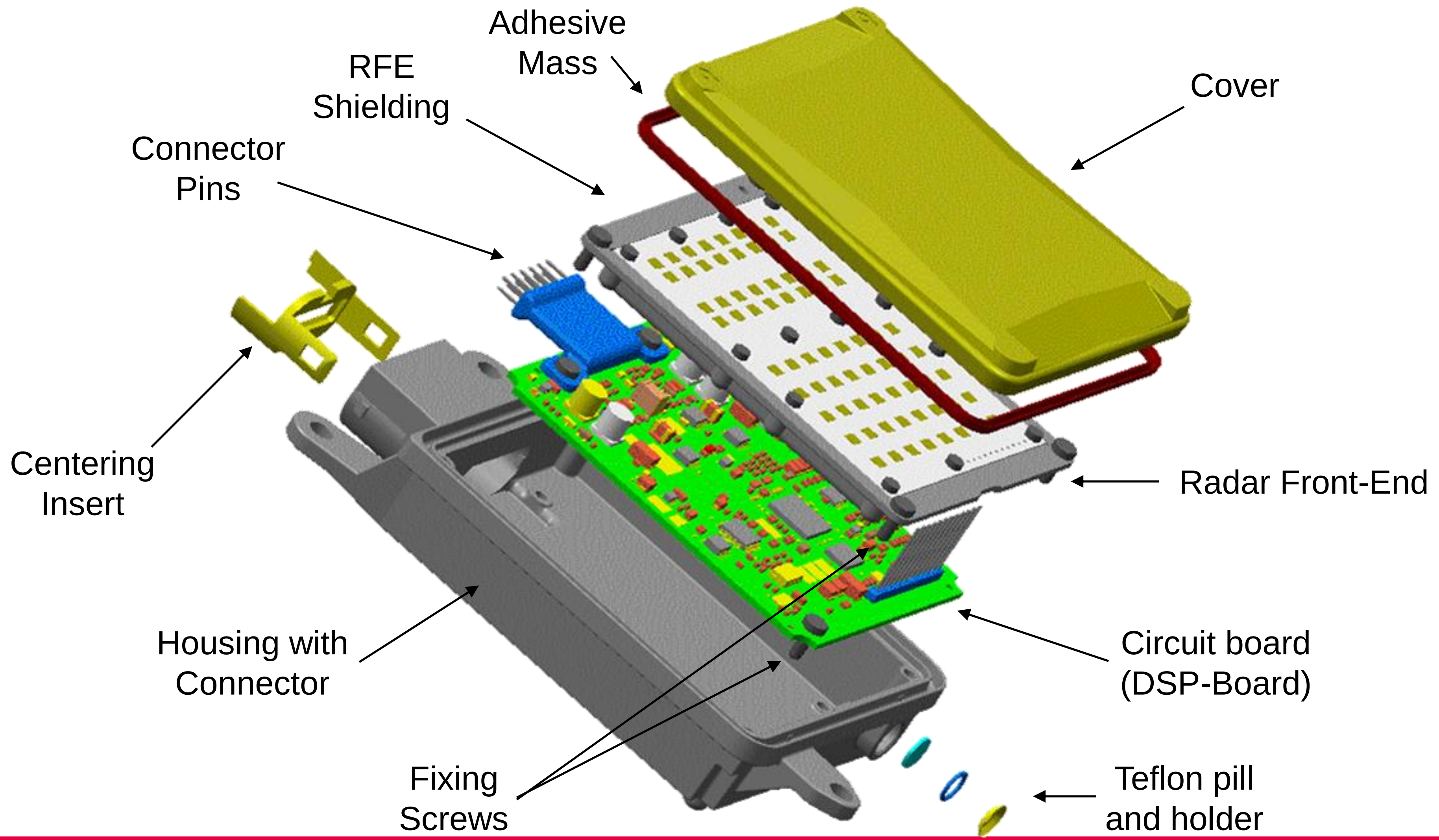




Images: dSPACE, APTIV

Examples

Radar system



4D Imaging radar

- Latest development in automotive radar technologies

- Earlier versions:
  - Horizontal angle
  - Distance
  - Relative Speed

- 4th dimension:
  - Vertical angle

Continental: ARS540

- Important to decide about passability : under- / over-drivability
  - Bridges, tunnels, low obstacles
- Usually combined with higher horizontal angle resolution

Conclusion

- Mature technology, proven in practice
- Small installation dimensions
- High range compared to many other sensors
- More expensive than, for example, ultrasound

➔ One of the most important components in driver assistance and autonomous driving for the detection and measurement of objects