Radar Sensors

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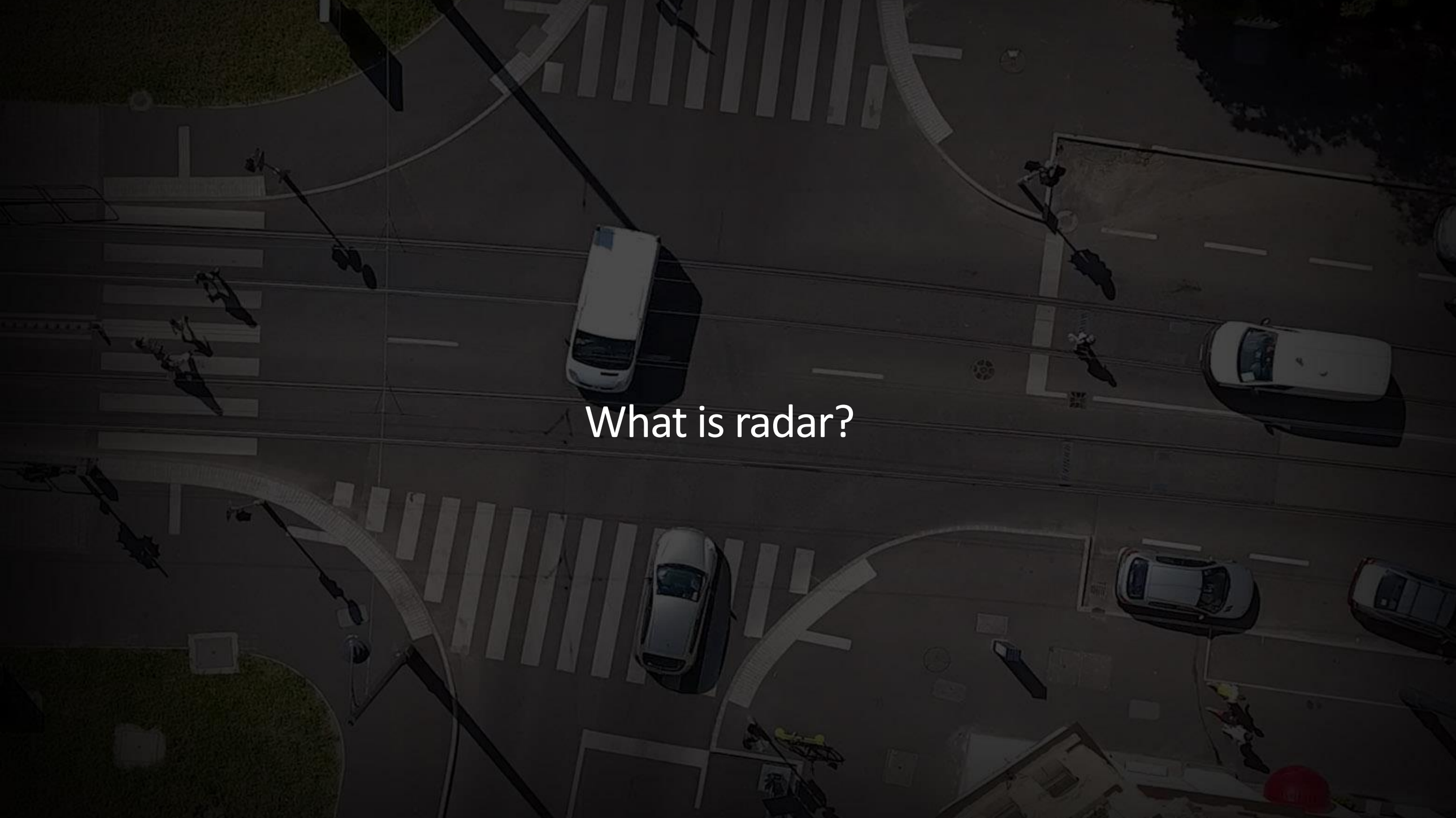
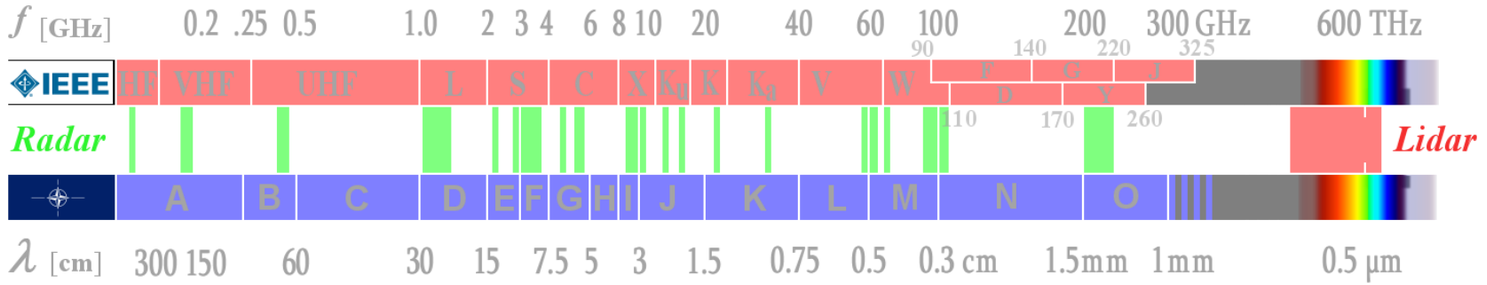
Content overview

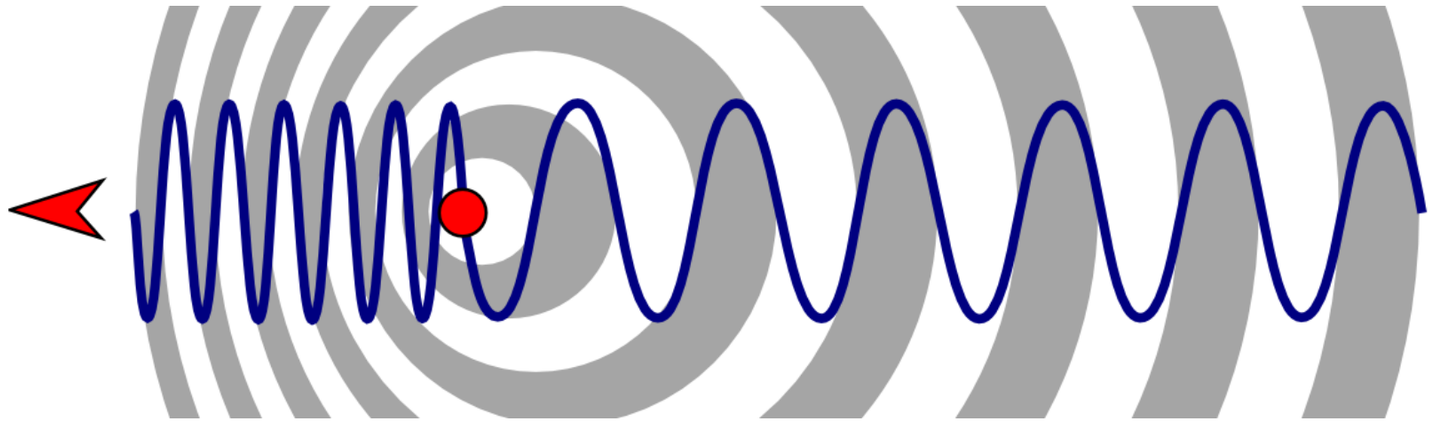

What is radar?

Radar wave and Doppler shift

- Radar wave
  - Electromagnetic (EM) radiation
  - From 3 MHz up to 300 GHz
  - From ~ 100 m down to ~ 1 mm
  - Speed of radiation: ~ 3 x 10^8 m/s
  - Radar bands (IEEE, NATO)

- Doppler effect
  - Frequency shift of EM radiation due to the relative velocity of
    - Source
    - Observer

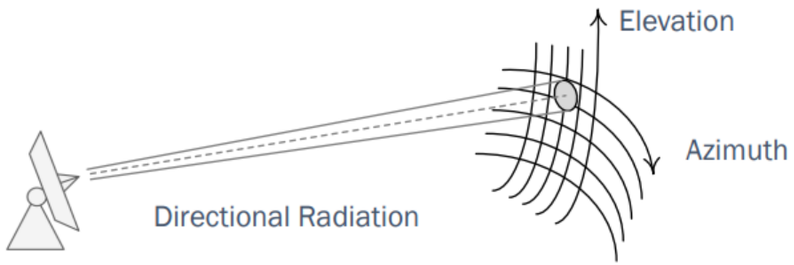


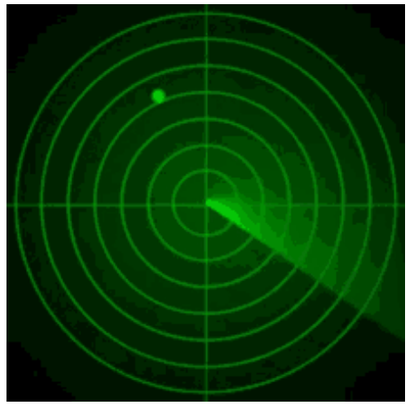


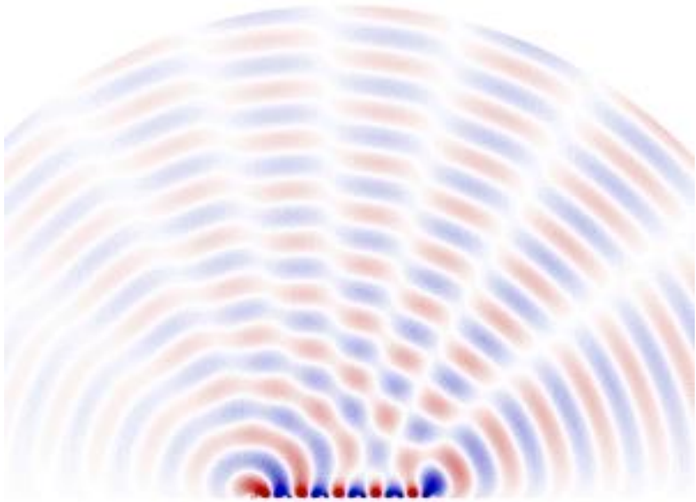
Classical radar measurement

- Radar (Radio Detection and Ranging) emits electromagnetic radiation and measures
  - Distance (e.g.: time-of-flight, modulation)
  - Direction (e.g.: rotation, beam deflection)
  - Radial speed (frequency shift)

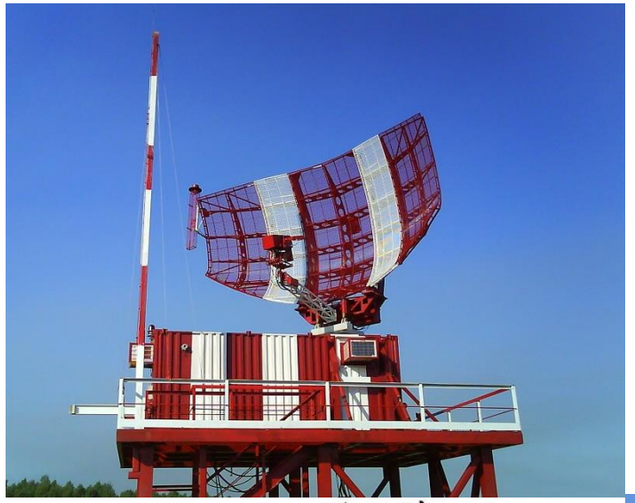
- The output:
  - 1D: range/velocity
  - 2D: range-azimuth/velocity
  - 3D: range-azimuth-elevation/velocity
  - 4D: range-azimuth-elevation-velocity





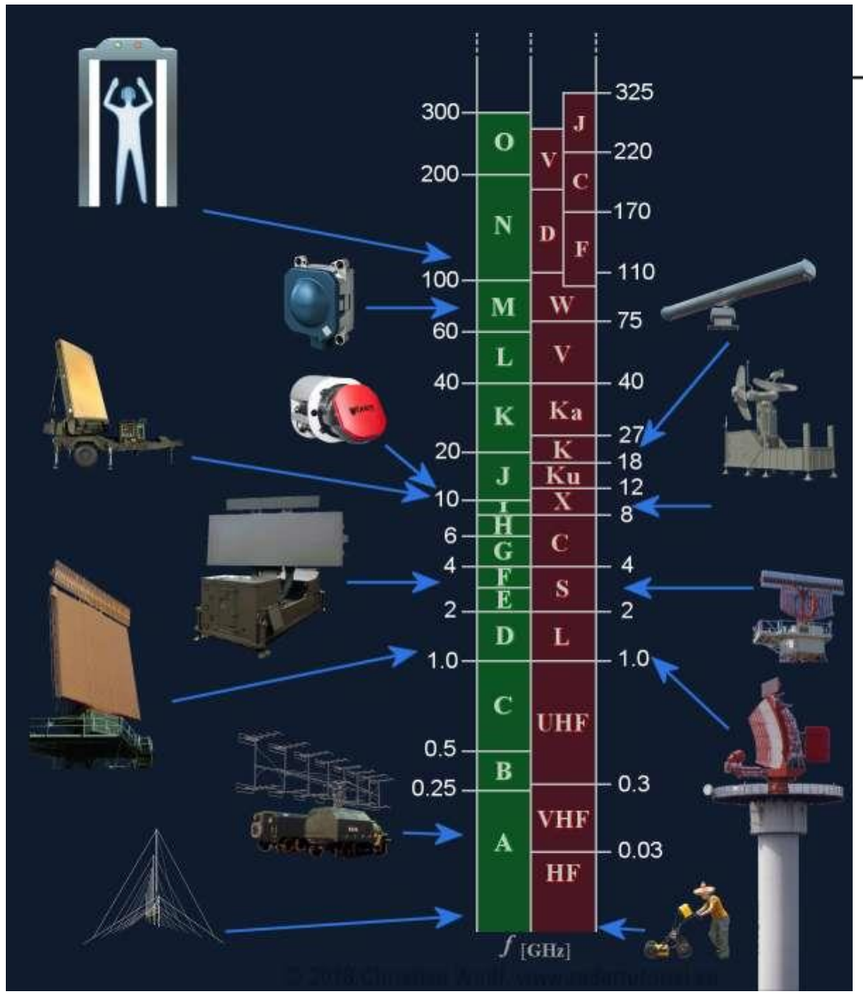


Different radars



Applications

- Some relevant application fields
  - Agriculture
  - Automotive *
  - Aerospace and aviation
  - Geology and environmental studies
  - Law enforcement and security
  - Ocean surveillance
  - Maritime traffic control
  - Meteorology
  - Military and defense
  - Space exploration



Band Designation	Frequency Range
HF	3–30 MHz
VHF	30–300 MHz
UHF	300–3000 MHz
L	1–2 GHz
S	2–4 GHz
C	4–8 GHz
X	8–12 GHz
Ku	12–18 GHz
K	18–27 GHz
Ka	27–40 GHz
V	40–75 GHz
W	75–110 GHz
mm	110–300 GHz

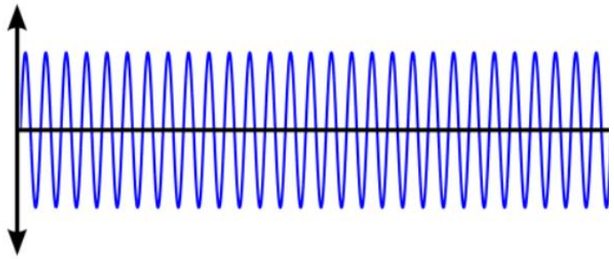
λ [millimeter]	λ [meter]
Better angular res.	Longer det. range


How do radars work?

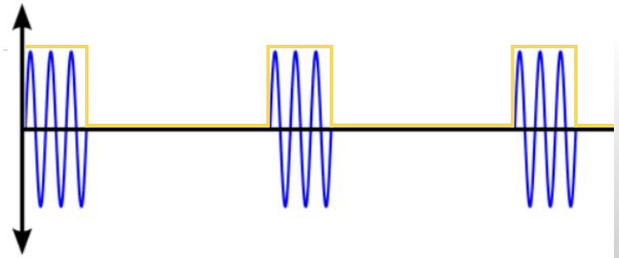
Unmodulated radars

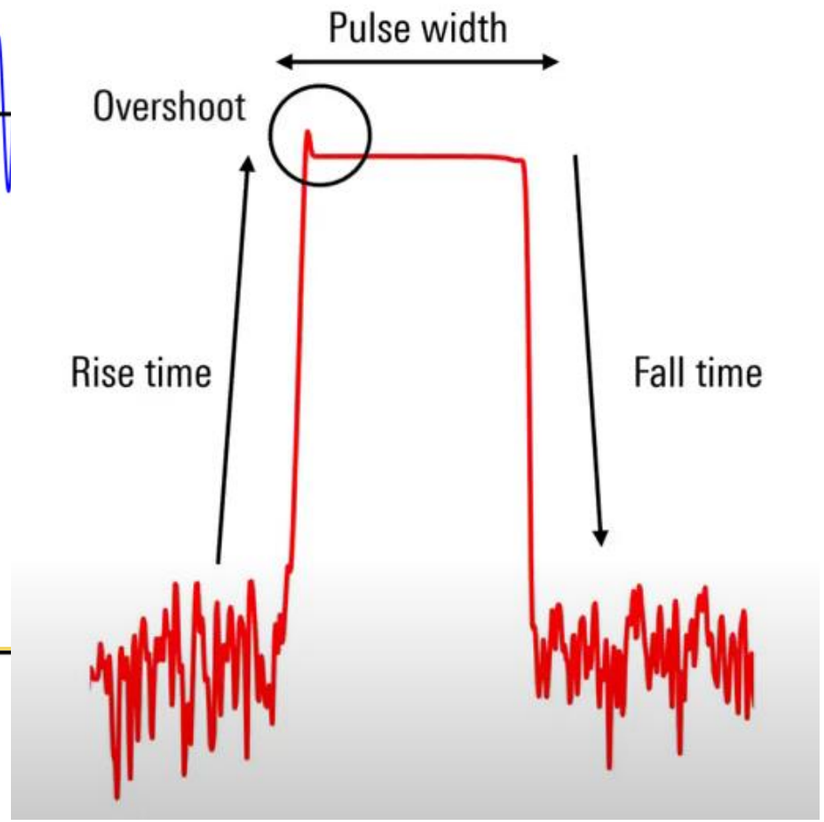
- Unmodulated continuous wave radar
  - EM wave is continuously emitted
  - Return signal (echo) is collected
  - Frequencies are compared
  - Relative speed (v) is calculated
- Unmodulated pulsed radar
  - EM pulse is emitted
  - Return signal (echo) is collected
  - Time-of-flight (τ) is measured
  - Distance (r) is calculated

unmodulated continuous wave



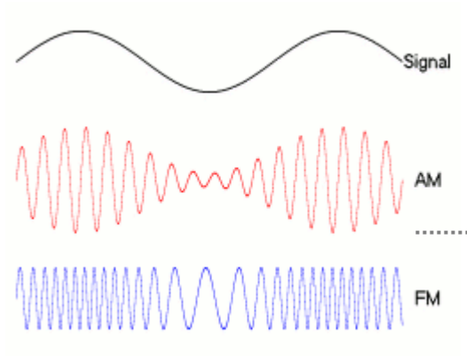
unmodulated short pulses

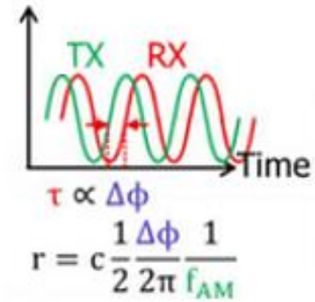


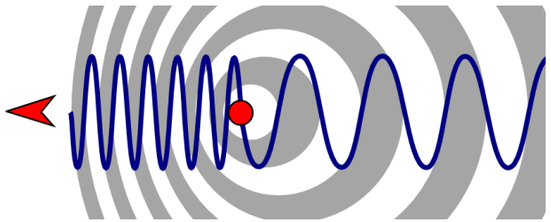


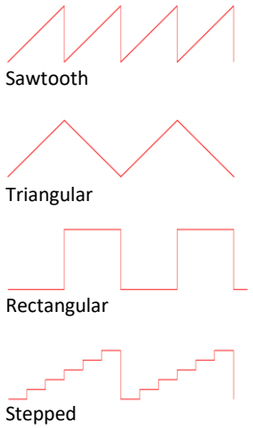
Modulated radars

- Amplitude Modulated Continuous Wave (AMCW)
  - AMCW signal is emitted
  - Return signal is collected
  - Phase difference (ΔΦ) is measured
    - Lock-in detection method
  - Distance (r) is calculated



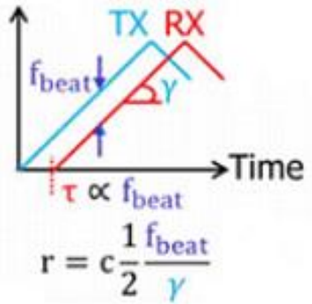




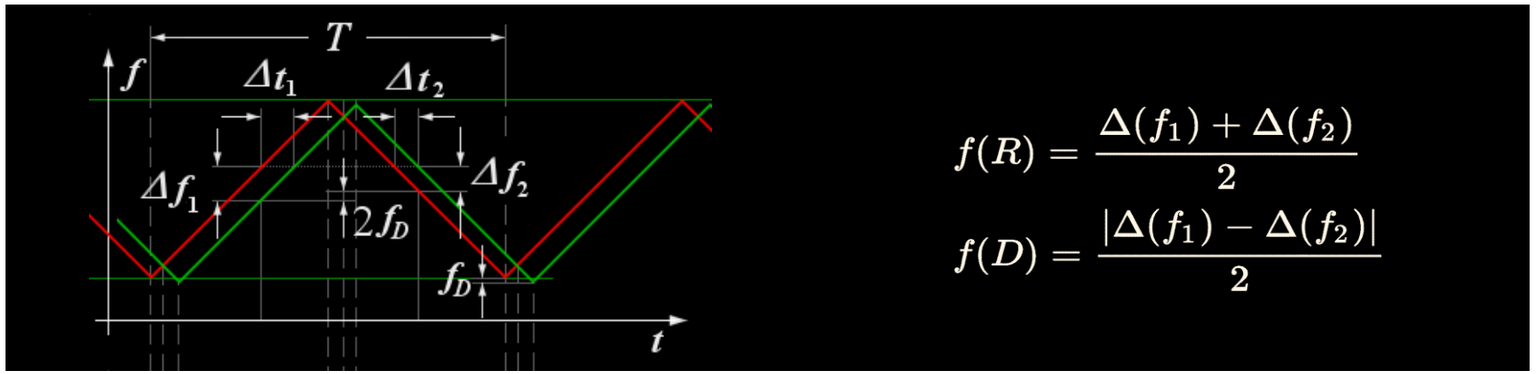


Automotive radars

- Frequency Modulated Continuous Wave (FMCW)
  - FMCW signal is emitted
  - Return signal is collected
  - Beat frequency (f_{beat}) is measured
  - Doppler shift (f_d) is measured
  - Distance (r) and rel. radial speed (v) are calc.



$$v = \frac{c}{2}\frac{f_d}{f_s}$$

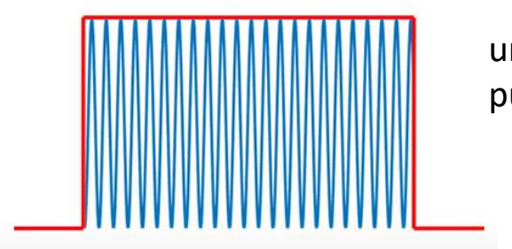


$$f(R) = \frac{\Delta(f_1) + \Delta(f_2)}{2}$$

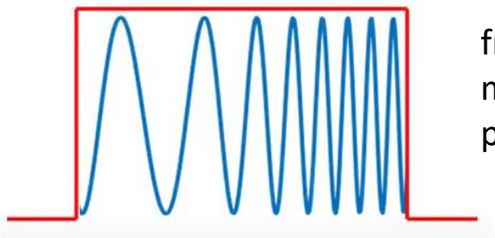
$$f(D) = \frac{|\Delta(f_1) - \Delta(f_2)|}{2}$$

Intrapulse modulated radars

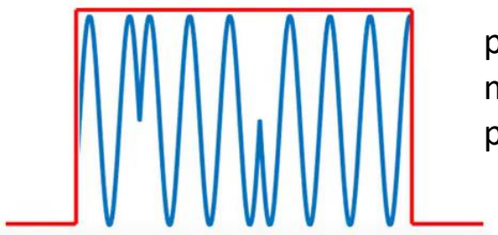
- Short unmodulated pulses
  - shorter pulses → better range resolution
  - shorter pulses → more difficult to create
  - no direct radial speed measurement
- Intrapulse modulation (pulse compression)
  - Within a pulse the EM wave is modulated
    - frequency
    - phase
  - longer pulses with the same results
  - easier to detect and correlate modulated pulses



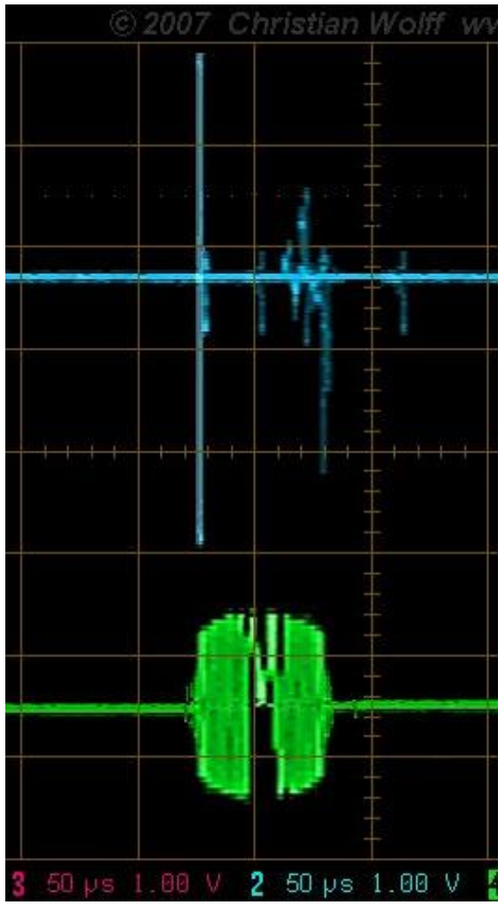
unmodulated pulse



frequency modulated pulse

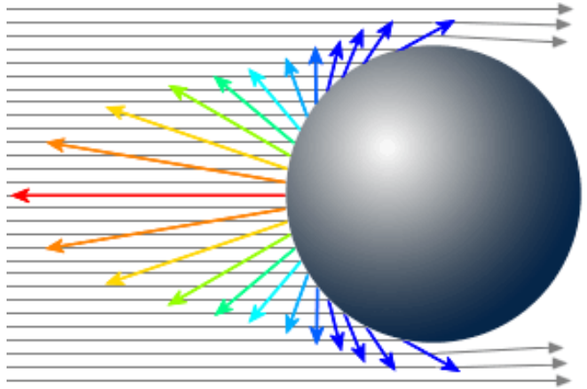


phase modulated pulse



Radar cross section

- Radar cross section (RCS, σ) of an object is the cross-sectional area of a perfectly reflecting sphere that would produce the same strength reflection as would the object.
- σ is the function of
  - target material
  - target size
  - incident angle
  - polarization direction
- Radar equation: connection between transmitted- and received power

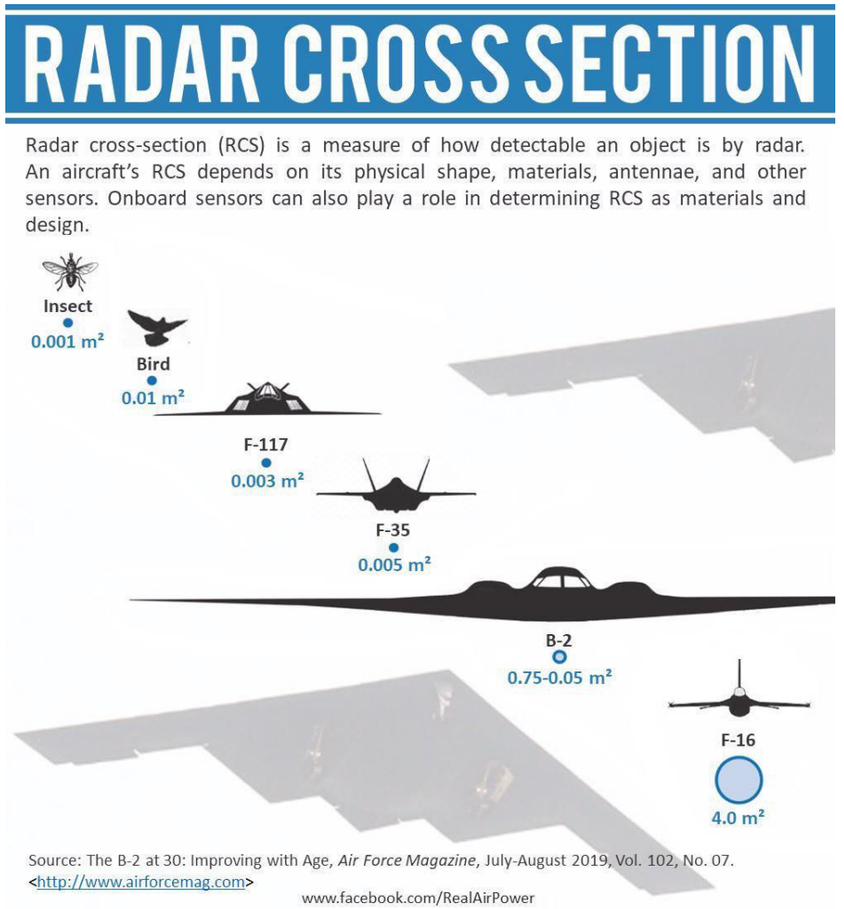


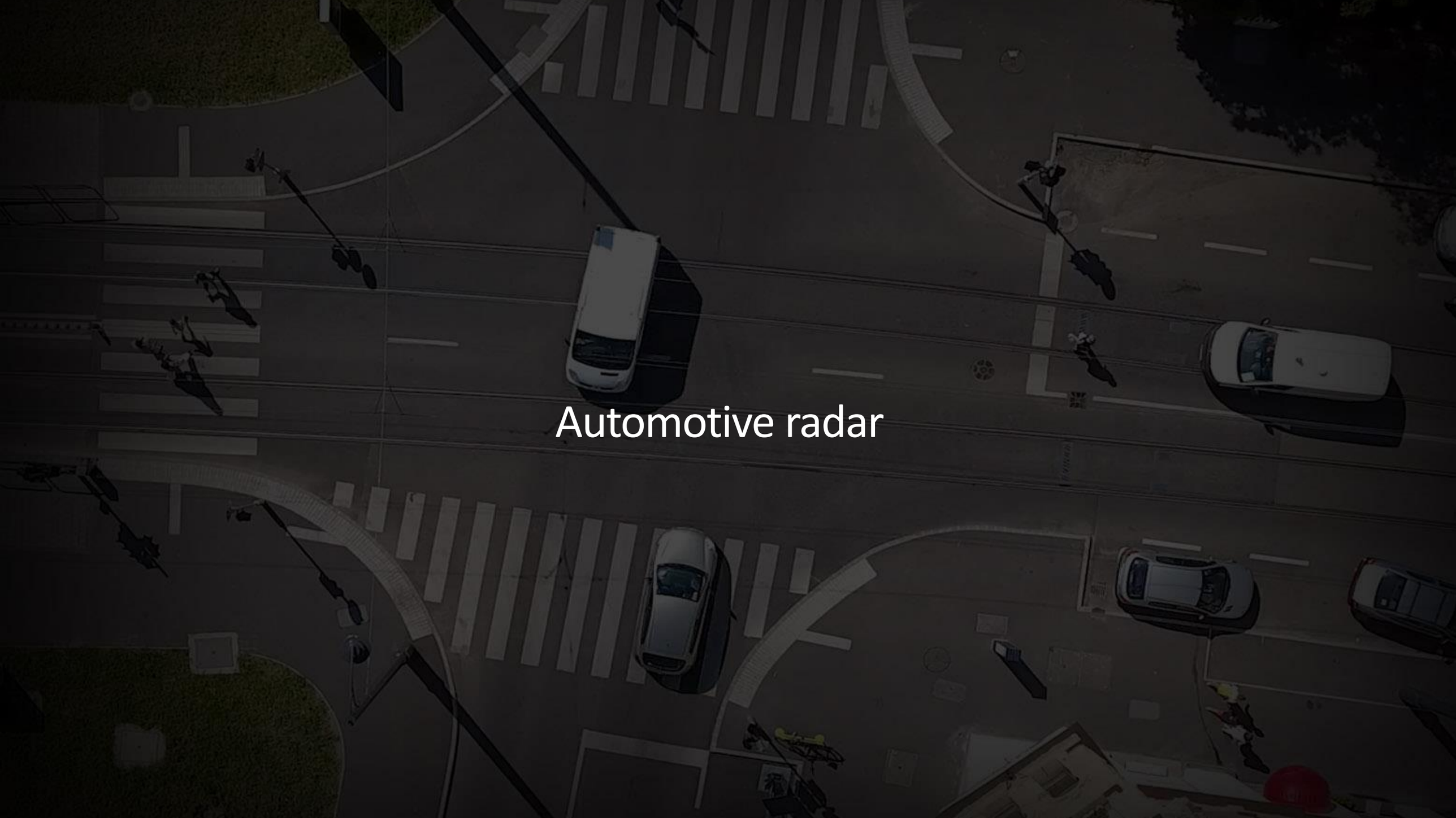
$$P_r = \frac{P_t G_t}{4\pi r^2} \sigma \frac{1}{4\pi r^2} A_{\text{eff}}$$

Power density at the target

Isotropic spreading (backward)

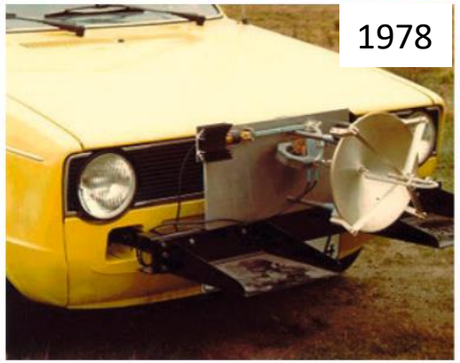
Reflected power density at the receiver



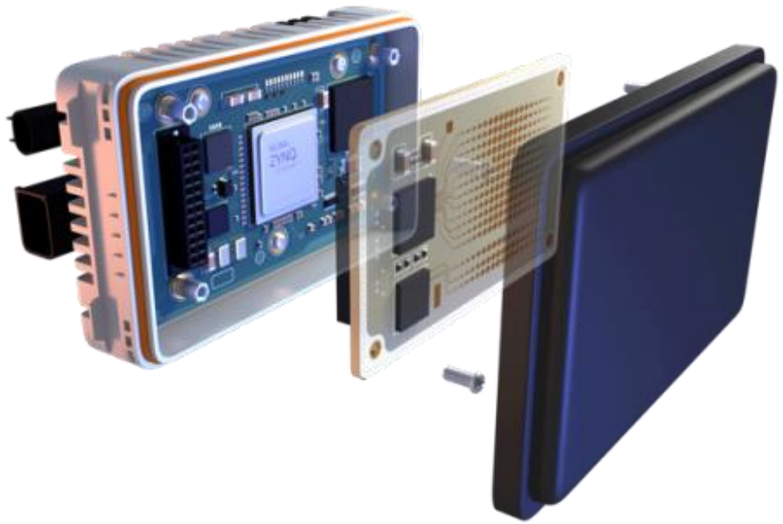

Automotive radar

Automotive radars

- Automotive radars today are typically
  - fully integrated and invisible
  - compact devices
  - FMCW wave modulation
  - millimeter wave regime (76–81 GHz)
  - high measurement rate (25 – 100 Hz)
  - 4D: range, azimuth, elevation, radial speed
  - high resolution
  - new cars are equipped with radar(s)

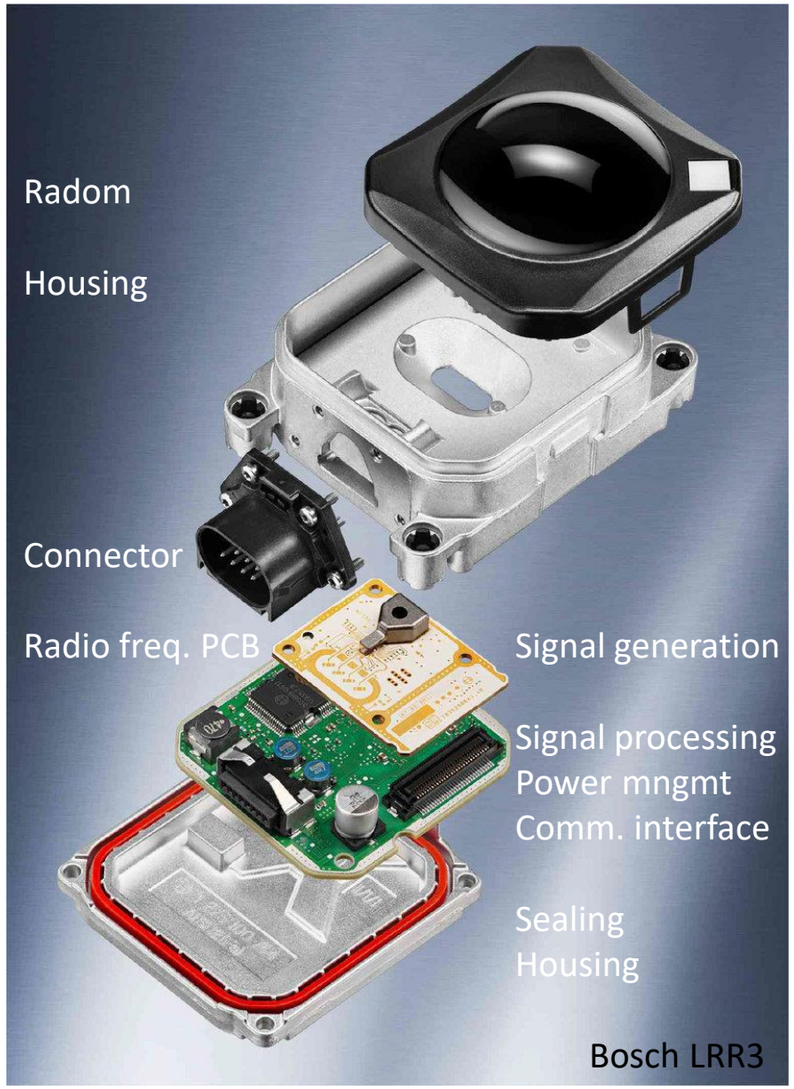


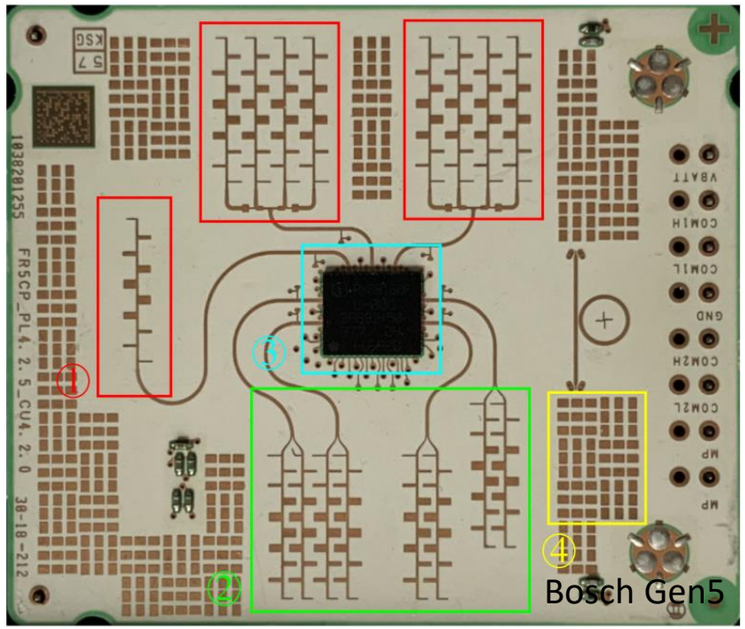
Continental ARS540



MIMO radar components

- Radom
  - Weatherproof
  - Transparent for radio waves
    - Fiberglass or plastic
- Housing
  - Weatherproof
  - Metal
- Electrical components
  - Printed circuit board (PCB)
  - Stacked PCBs
- Connector
  - High speed
    - Fakra, Automotive Ethernet, HSD
  - Low speed
    - CAN Bus





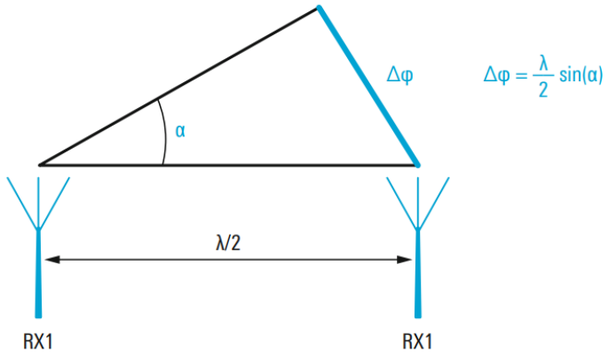
3x transmitters, 4x receivers,
1x frontend MMIC, 1x reflection reduction

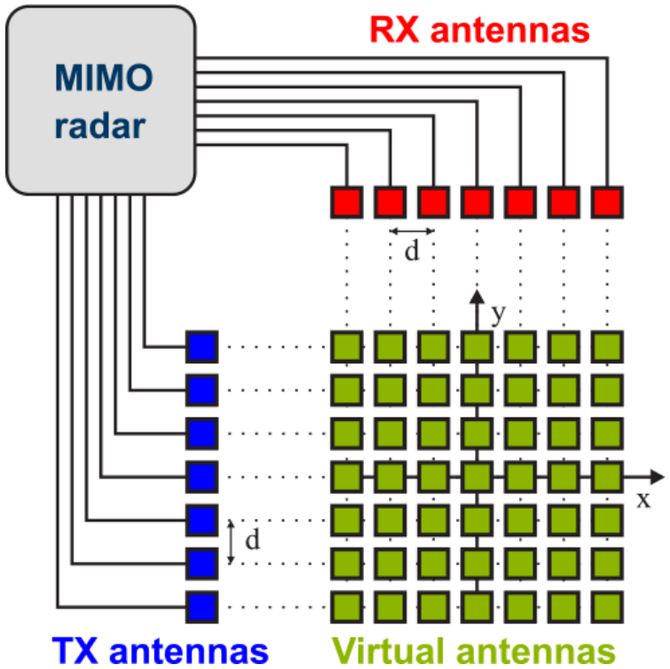
MMIC:
monolithic microwave intergrated circuit

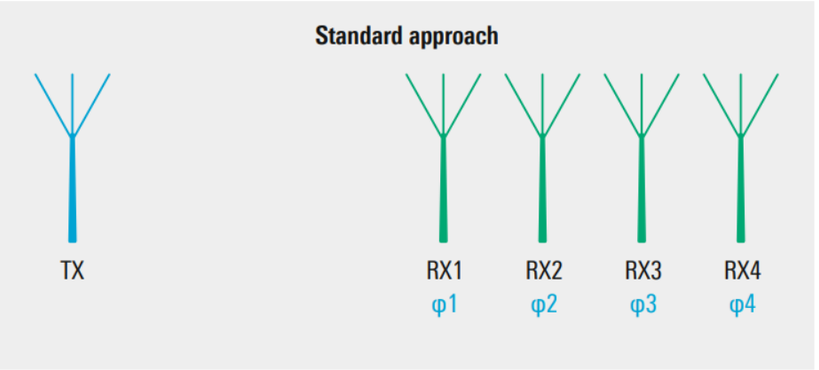
Azimuth and elevation

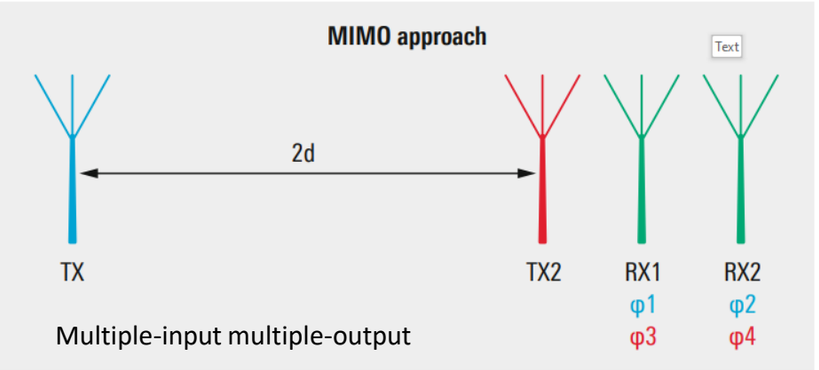
- TX (transmitter) antenna
- RX (receiver) antenna
  - Phase difference measurement
    - 1D array: azimuth
    - 2D array: azimuth and elevation
- MIMO radar signal processing
  - # of virtual antennas: #_TX × #_RX
  - Enlarged virtual aperture
  - Improved angular resolution
  - Improved immunity to interference
  - Full time on target (no scanning)

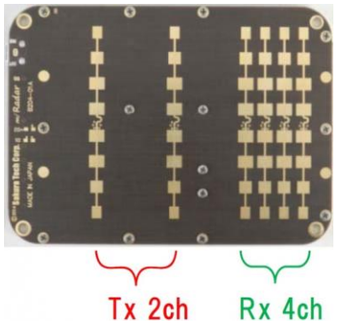
Spatial convolution

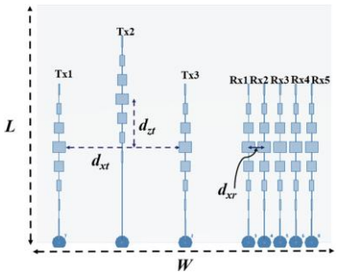






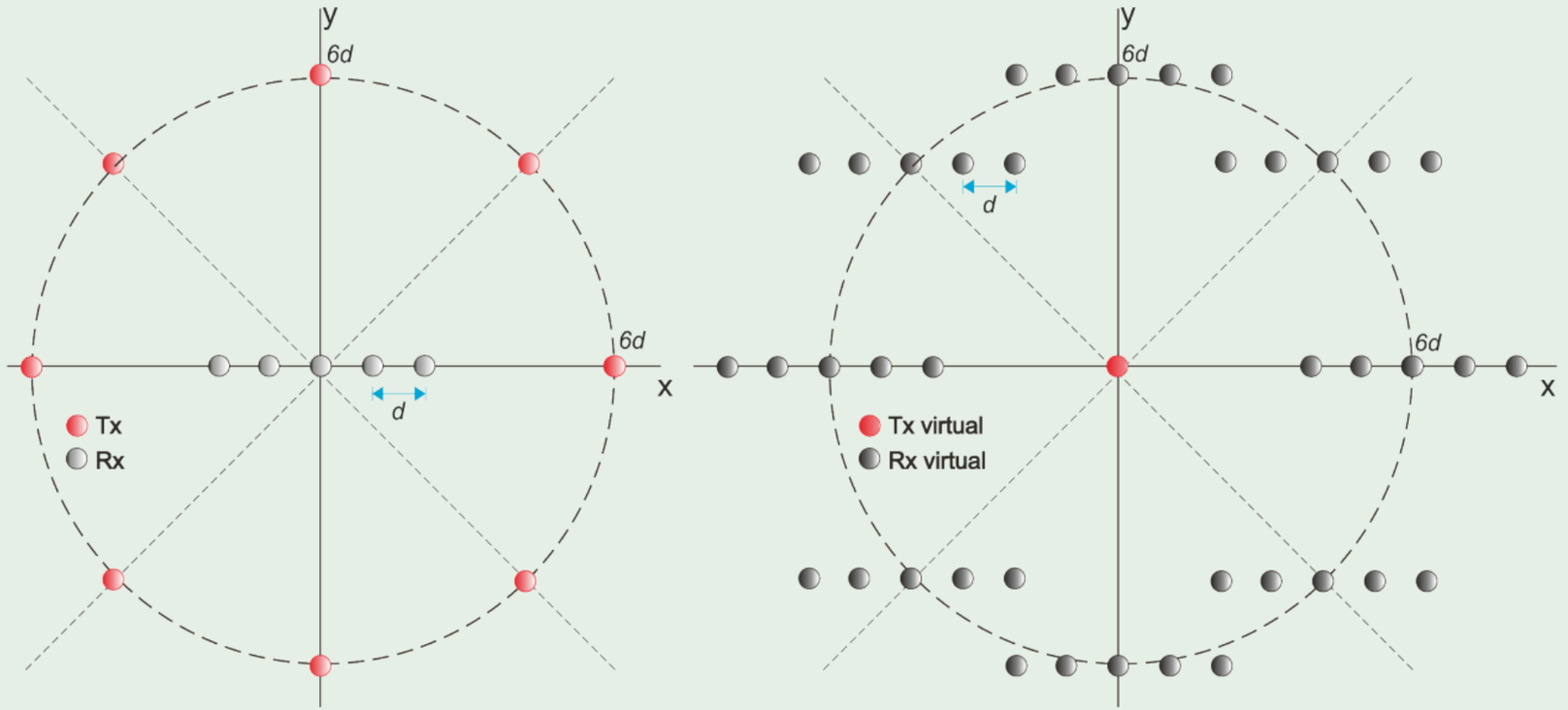






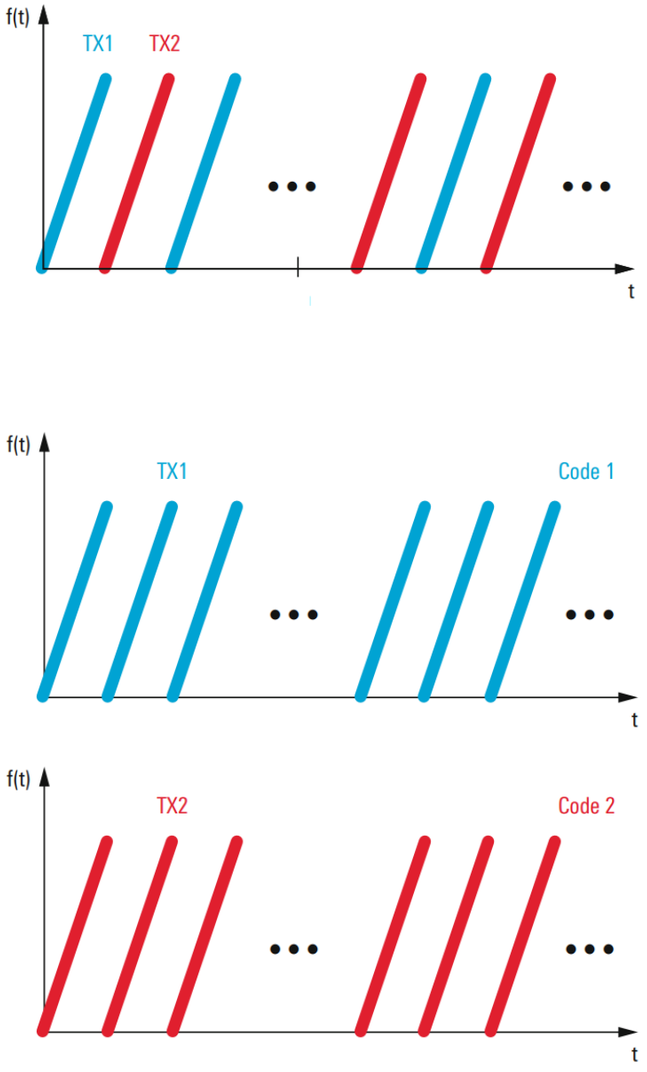
Examples of virtual arrays

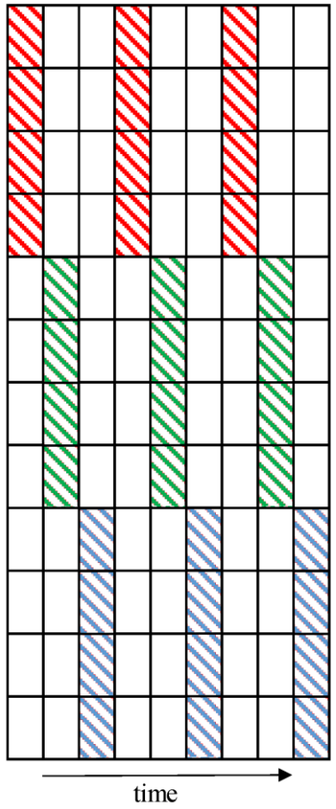
Example (MIMO: Tx=circular; Rx=Linear)

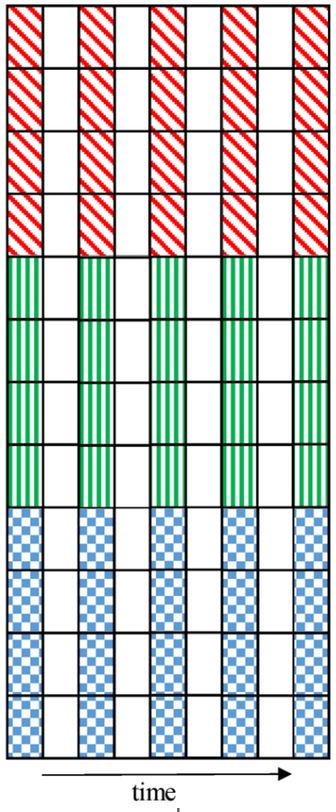


Transmitter signals

- To distinguish between the various transmitter signals each Tx antenna has its own arbitrary baseband waveform generator
  - Time division multiplex (typical)
    - Sequential activity
    - Timing-based signal separation
- Emerging technologies (not yet typical)
  - Frequency division multiplex
    - Parallel activity
    - Frequency-based signal separation
  - Code division multiplex
    - Parallel activity
    - Code-based return separation

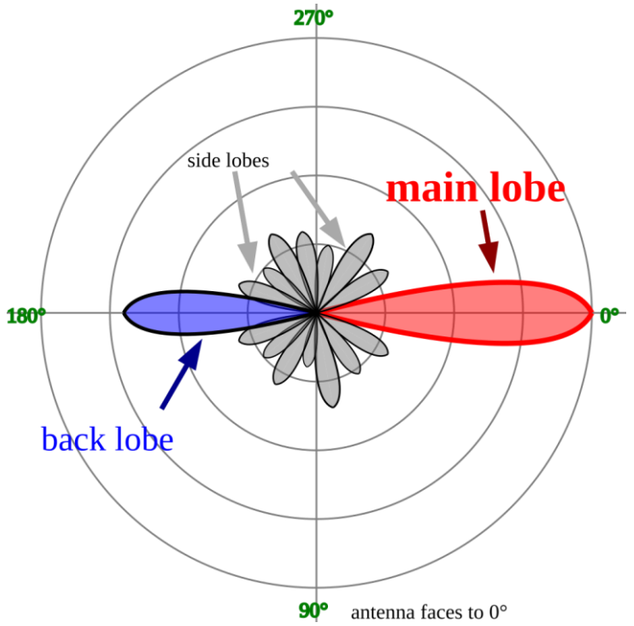


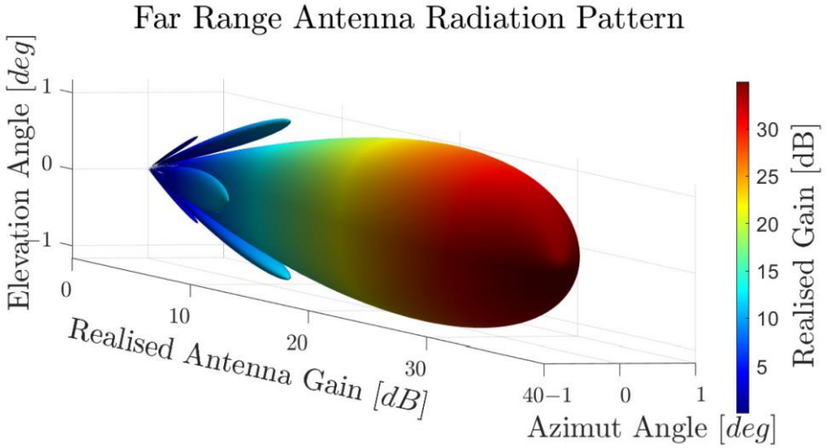


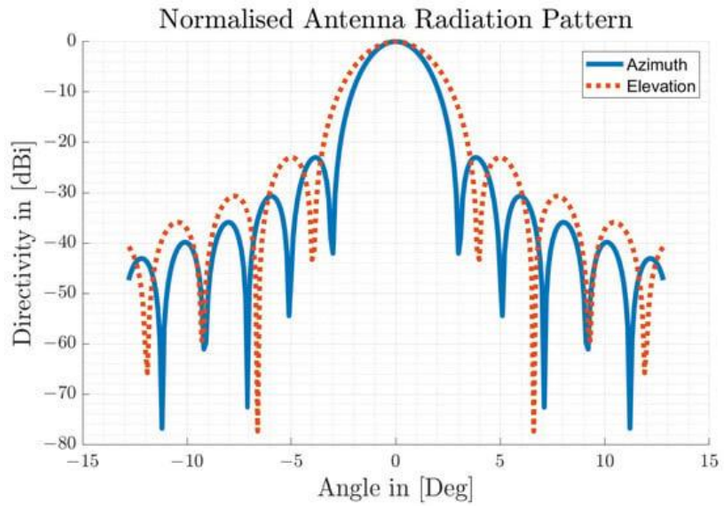


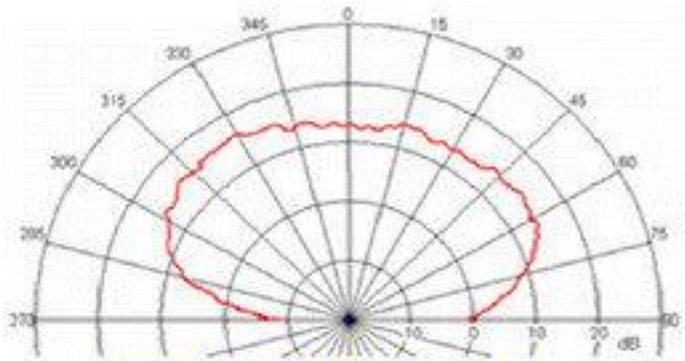
Antenna radiation pattern

- Radar detection in the FoV
  - Radiation pattern
  - Defines the application
  - In case of a directional antenna:

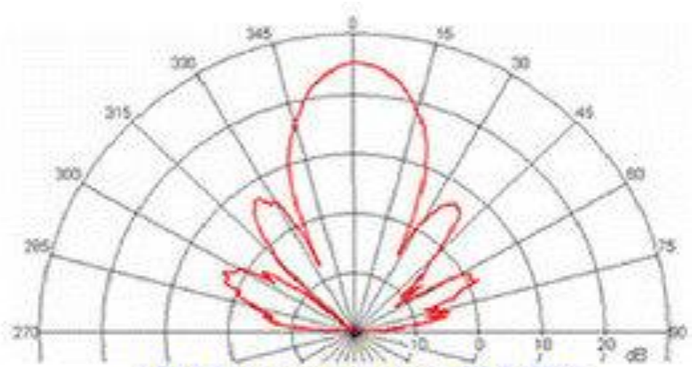








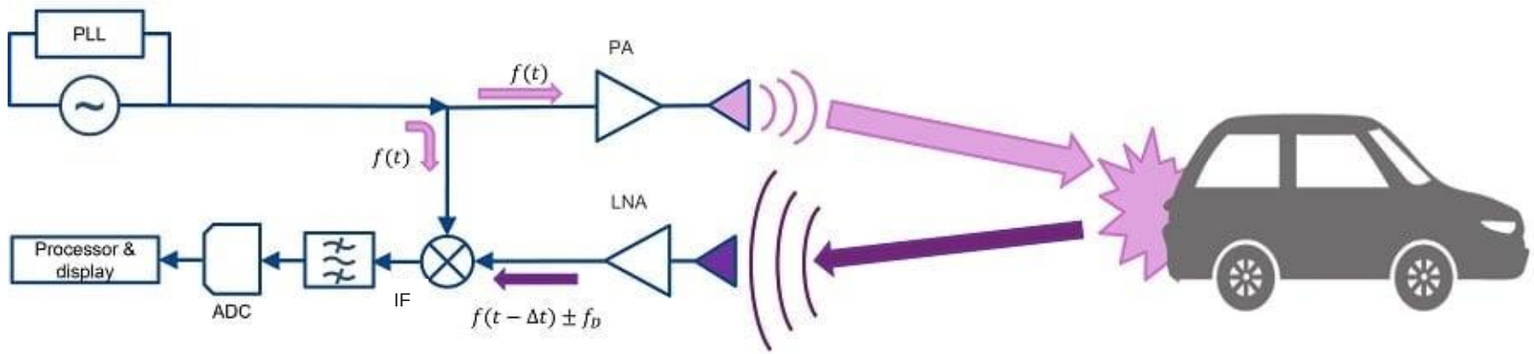
(a)

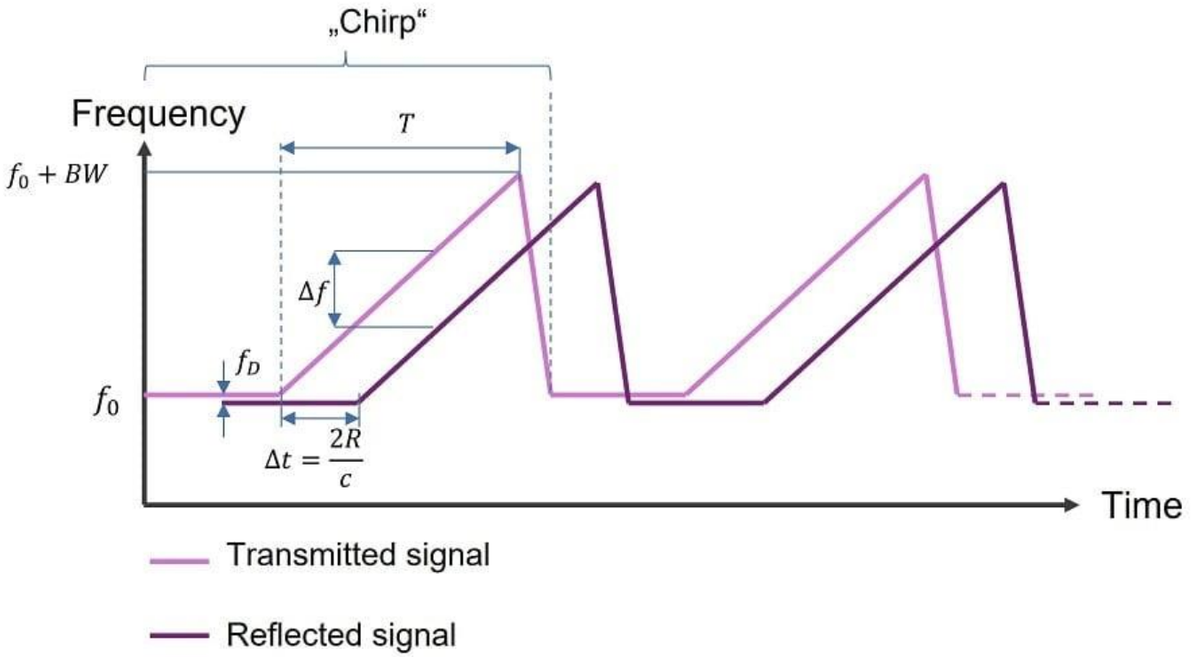


(b)

Range – Doppler map calculation

- FMCW „chirp” signal is emitted
- Reflected signal is mixed with the original one
- 4D detection
  - Range: beat frequency
  - Velocity: Doppler shift
  - Azimuth and elevation: channels
- Components:
  - PLL: phase-locked loop oscillator
  - PA: power amplifier
  - LNA: low noise amplifier
  - IF: intermediate frequency
  - ADC: analog-to-digital converter

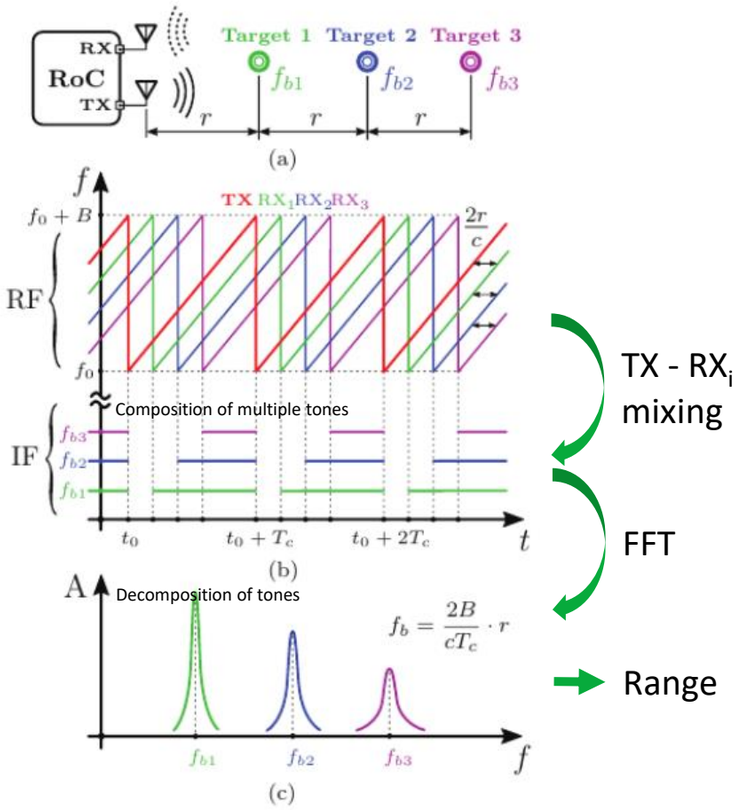




„Sterile” case (devoid of real-world complexity)

Range – Doppler map calculation

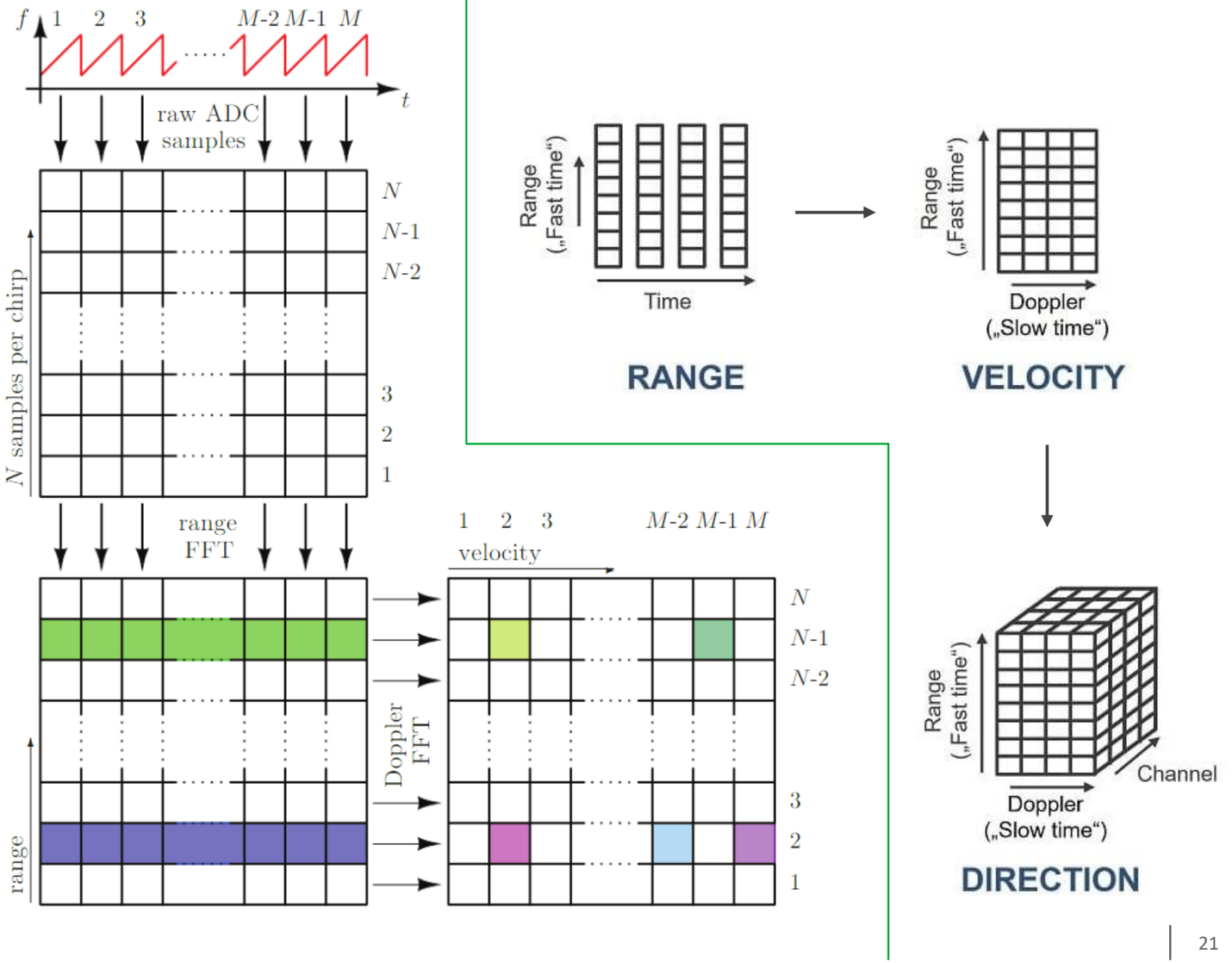
- Real-world scenario is more complex
  - Multiple reflections
  - Different orientations
  - Different radar cross sections



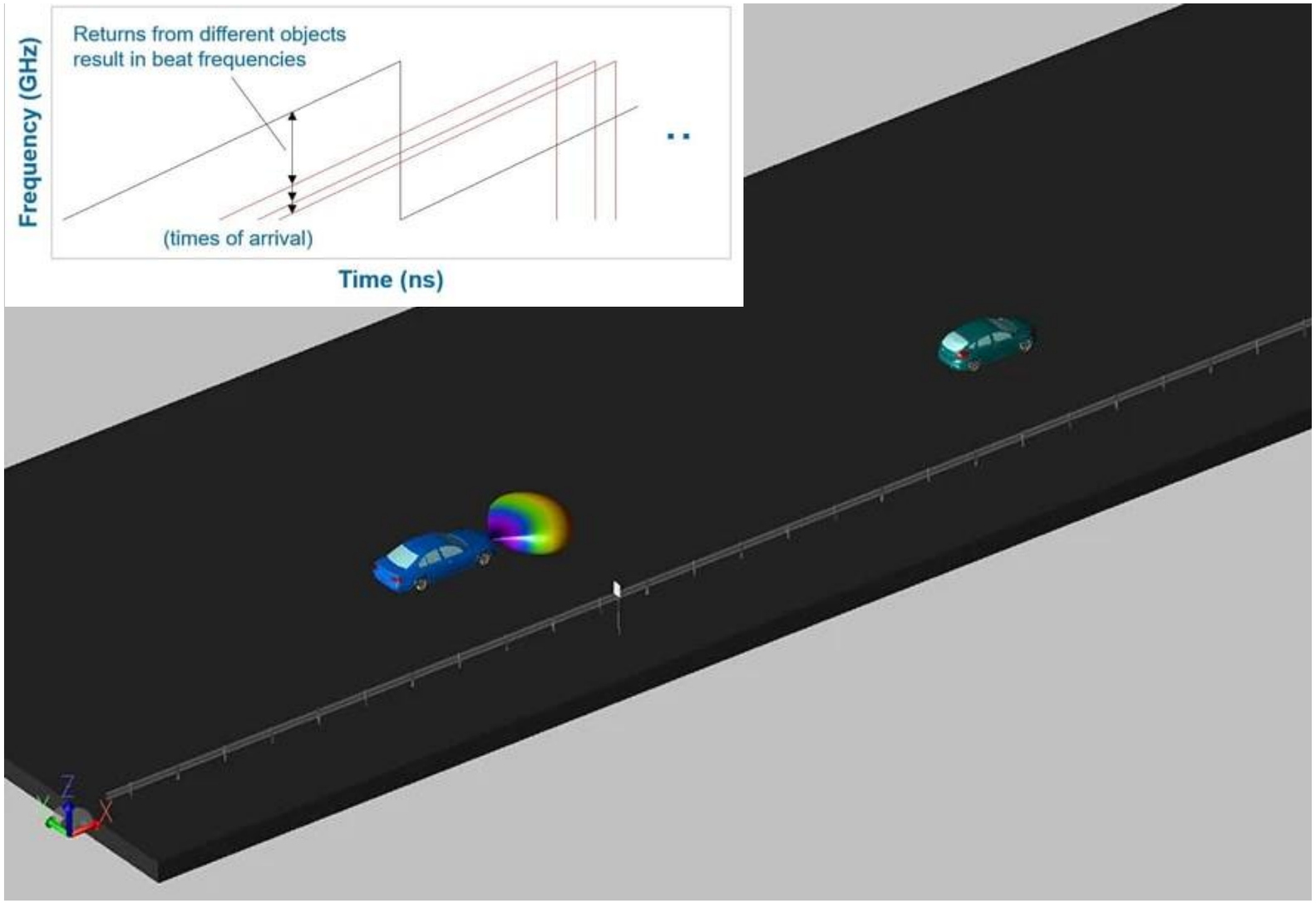
TX - RX$_i$ mixing

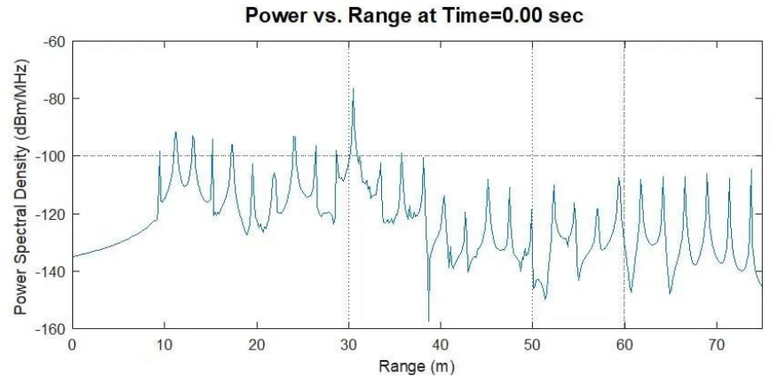
FFT

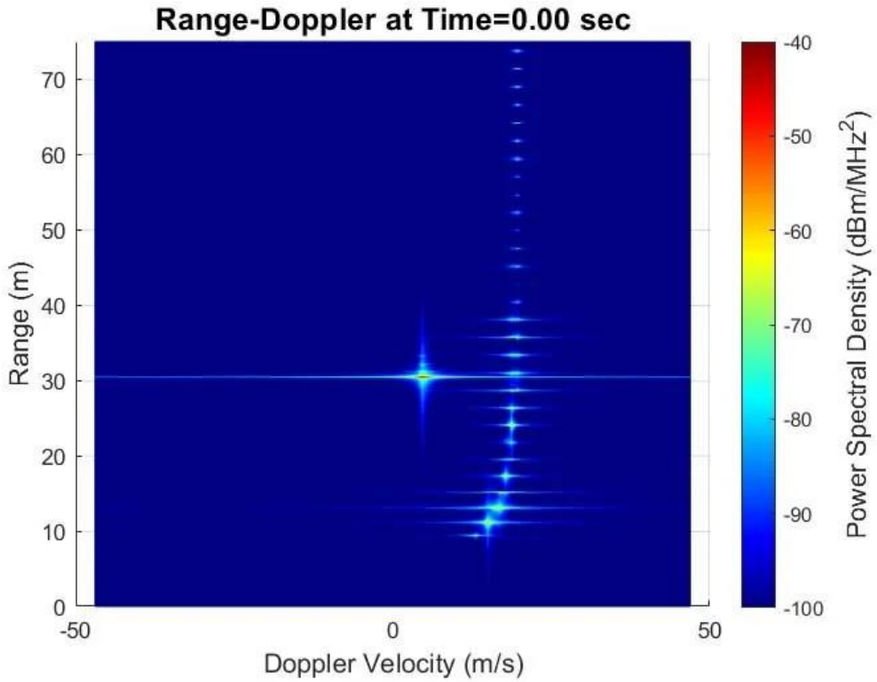
Range



Range – Doppler map calculation





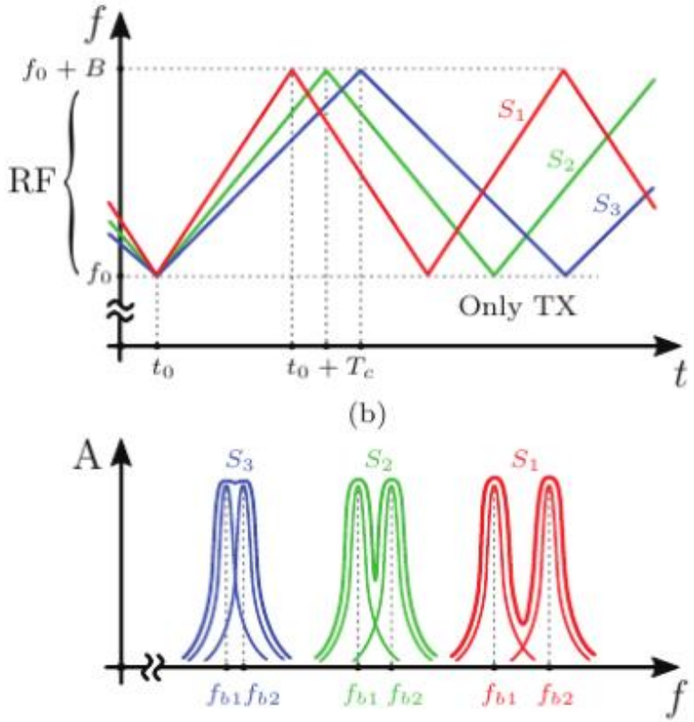


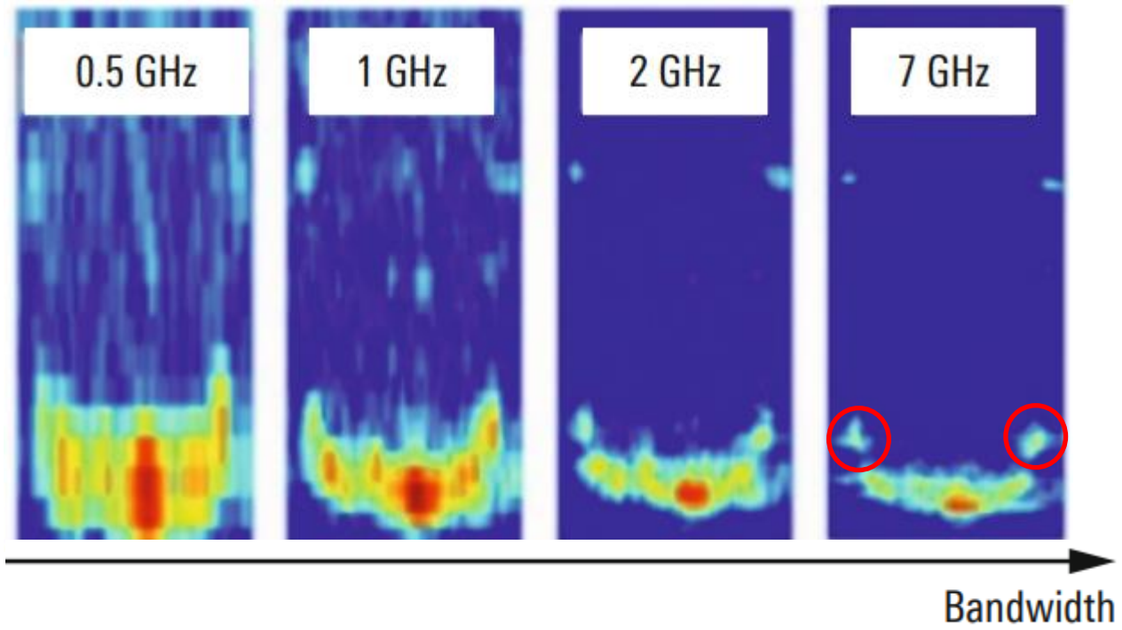
Signal bandwidth

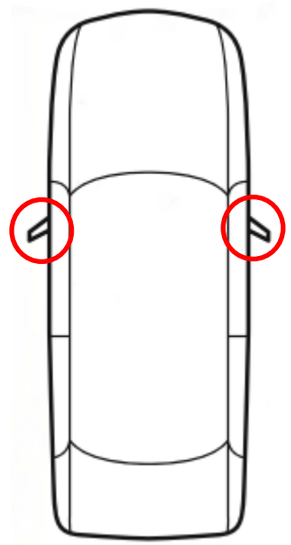
- Range resolution (ΔR)
  - depends on the signal bandwidth (B)

Within the same T_c

$$\Delta R = \frac{c}{2B} = \frac{c}{2ST_c}$$

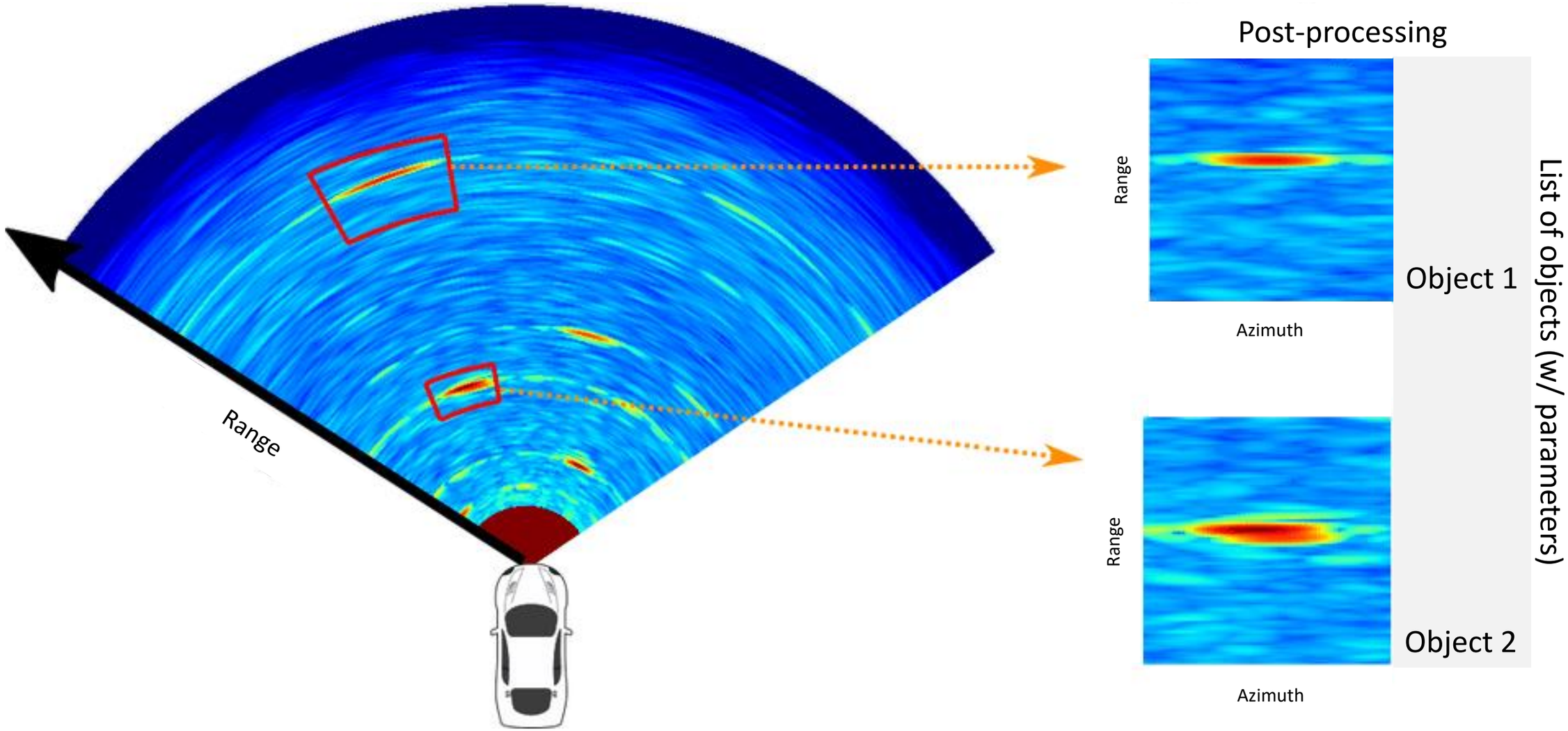






mmWave picture taken by Rohde&Schwarz,
frequency 70 GHz to 80 GHz,
several thousand transmitting and receiving antennas

Object list



Automotive radar performance

Performance metrics

- Some relevant performance metrics
  - Detection range, resolution, accuracy
  - Velocity range and resolution, accuracy
  - Field of view and angular resolution (A, E)
  - Angular resolution, accuracy
  - Antenna channels
  - Cycle time
  - Operating frequency band
  - Power consumption
  - Ingress protection rating (wiki)
  - Mechanical resistance
  - Operating temperature
  - Communication interface
  - Compliance (ISO, IEC, RoHS, etc)

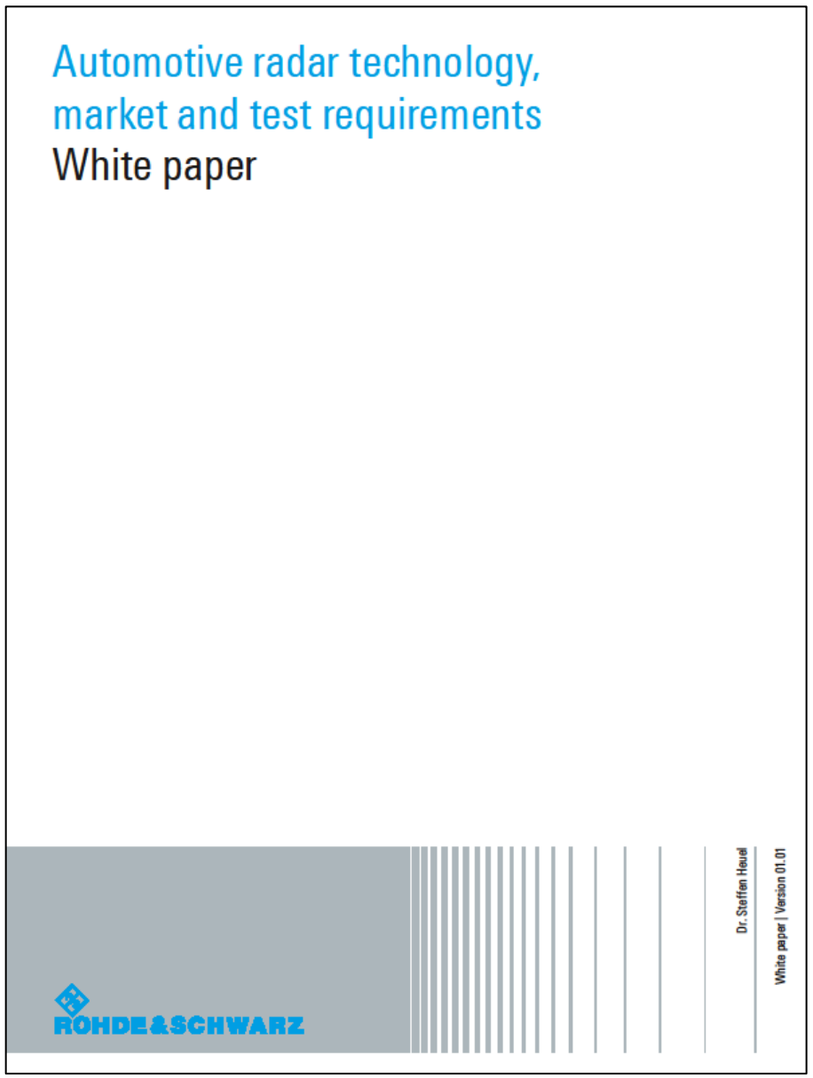
  +

  - Extra features, e.g.
    - Elevation measurement capability
    - Different operation modes

Parameter		Long-Range Mode	Medium-Range Mode	Short-Range Mode
Operating Frequency		77…81GHz | 3 center frequencies (bands)	77…81GHz | 3 center frequencies (bands)	77…81GHz | 3 center frequencies (bands)
Range	Min./Max.[1]	0.8m/120m | 2.6ft/394ft	0.4m/55m | 1.3ft/180ft	0.15m/19.3m | 0.5ft/63ft
	Separation	< 1.2m | < 3.9ft	< 0.6m | < 2.0ft	< 0.3m | < 1.0ft
	Accuracy	< 0.5m | < 1.64ft or 1% (bigger of)	< 0.3m | < 1.0ft or 1% (bigger of)	< 0.15m | < 0.5ft or 1% (bigger of)
Speed	Min./Max.	-340…+140km/h | -211…+87mph	-340…+140km/h | -211…+87mph	-400…+140km/h | -249…+87mph
	Separation	< 0.3m/s	< 0.3m/s	< 0.3m/s
	Accuracy	< 0.15m/s	< 0.15m/s	< 0.15m/s
Angle	Field of View: Azimuth[2]	-50…+50° (squint beam)	-65…+65° (straight beam)	-65…+65° (straight beam)
	Field of View: Elevation[2]	-7.5…+7.5°		
	Separation: Azimuth	~30° (optional)		
	Accuracy: Azimuth[3]	≤ 1° (at <50° from bore sight)		
	Accuracy: Elevation[3]	≤ 2° (at <10° from bore sight)		
Mechanical Details				
Weight		≤ 153g | ≤ 5.4oz		
Dimensions (H/W/D)		97 x 76 x 17.7mm | 3.8 x 2.99 x 0.7in (plus connector)		
Further Information				
Initialization Time		< 4s		
Update Cycle Time[4]		≤ 55ms		
Processing Latency		2-4 cycles		
Operating Voltage[5]		8…24V		
Power Consumption[6]		3.75…5W		
Bandwidth		< 2000MHz		
Max. Transmit Power (EIRP)		≤ 31dBm		
Operating & Storage Temperature		-40…+85°C | -40…+185°F		
Interfaces[7]		Ethernet 100Mbit (2-wire); 2xCAN V2.0b (passive)		
Connector		TE 1411001-1 series		
Shock / Vibration		$100g_{rms}$ / $14g_{rms}$		
Relative Humidity		0…95% (non-condensing)		
IP		67		
Pressure or Transport Altitude		0…10000m | 0…32800ft		

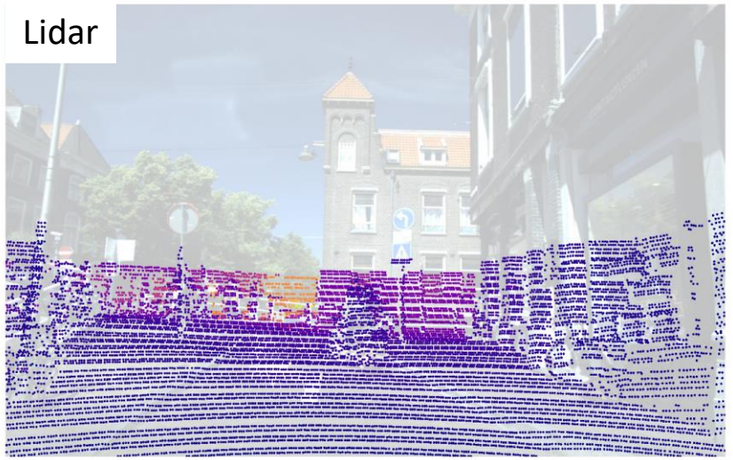
Performance test

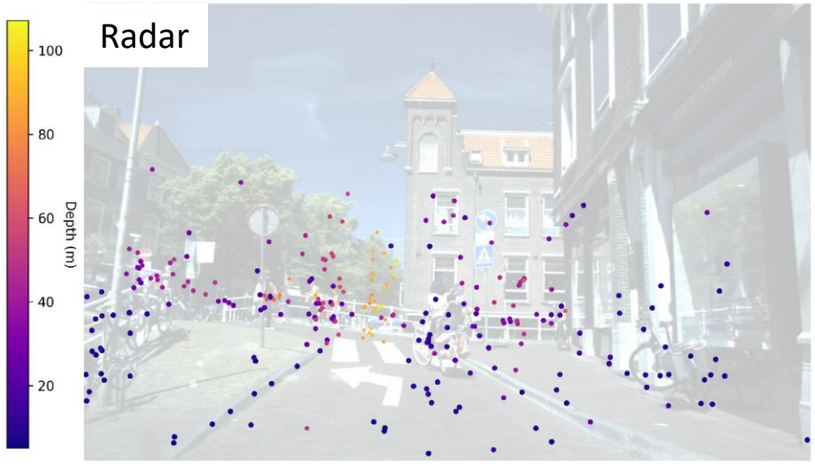
- Radar performance tests standards
  - European Telecommunications Standards Institute
    - ETSI EN 303 396 (Meas. techniques)
    - ETSI EN 302 858 (24.05 – 24.25 GHz radars)
    - ETSI EN 301 091-1 (76 – 77 GHz radars)
    - ETSI EN 302 264 (77 – 81GHz radars)
  - Institute of Electrical and Electronics Eng.
    - IEEE SA P3116
    - Approved in 2021 (not available)
  - Individual, application-tailored evaluations
    - Muckenhuber et al.

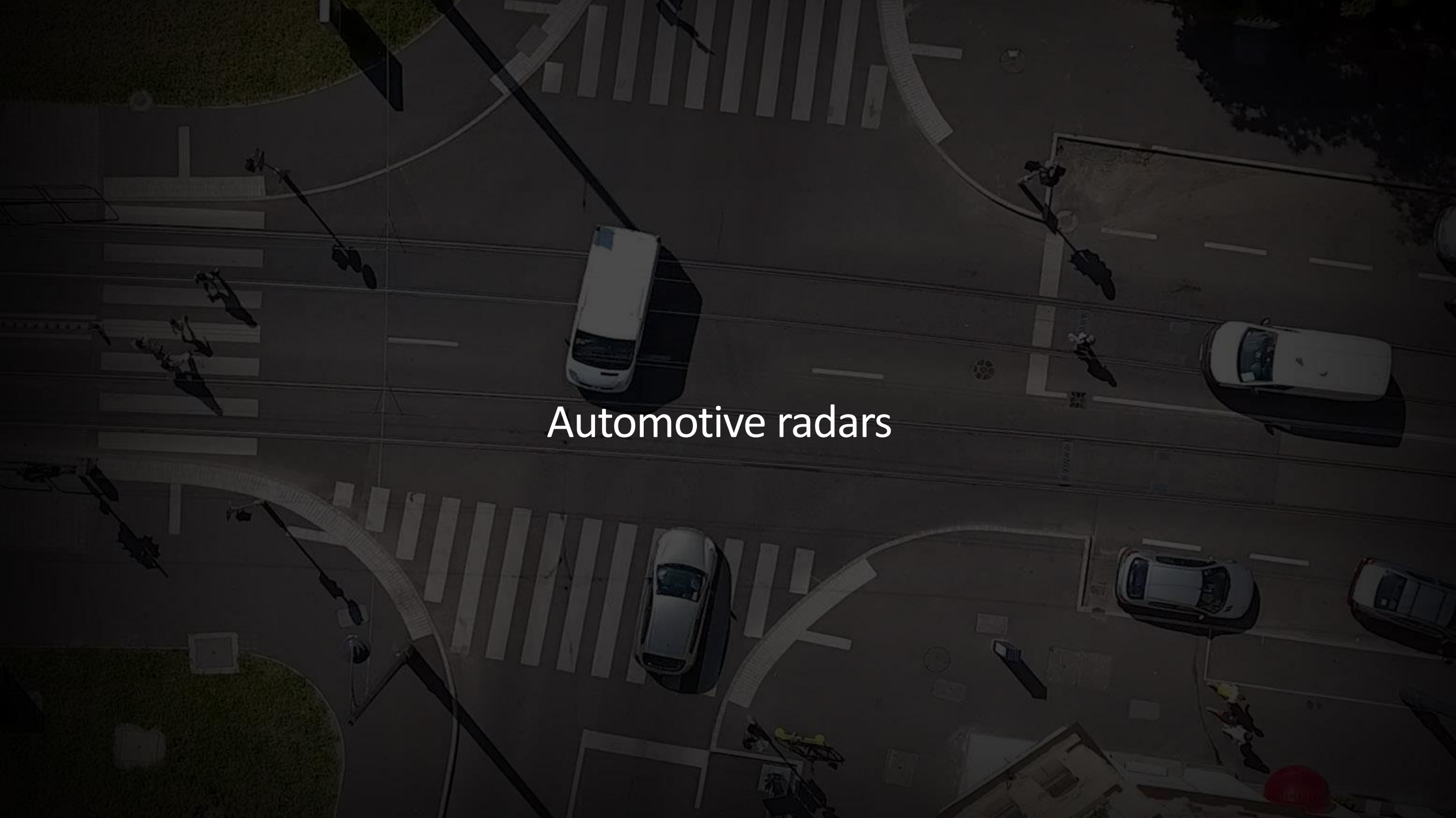


Performance limitations

- Detection range, resolution, accuracy
- Velocity range and resolution, accuracy
- Field of view, angular resolution, accuracy
- Ambiguity (range, velocity, angle)
- Frame rate and chirp time
- Bandwidth regulations
- Radar cross section
- Reflections
- Interference and crosstalk
- Environmental conditions
- Data latency
- Power consumption






Automotive radars

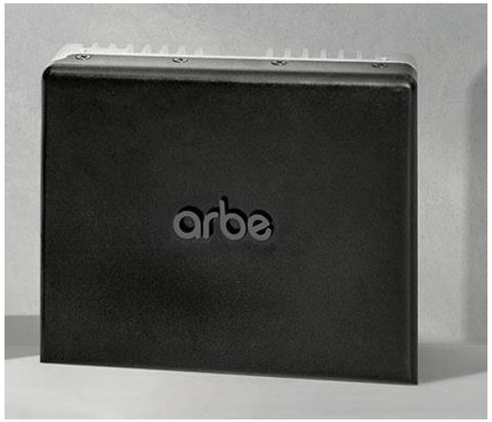
Relevant manufacturers

- Some relevant automotive radar manufacturers

  OEMs
  - Bosch
  - Continental
  - Aptiv (formerly Delphi)
  - Denso
  - Hella
  - Infineon
  - Magna
  - NXP
  - Texas Instruments
  - Veoneer (formerly Autoliv)
  - Valeo
  - ZF Friedrichshafen

  Startups
  - Altos
  - Arbe
  - Metawave
  - Oculii (acquired by Ambarella)
  - Uhnder
  - RadSee
  - SmartMicro



4D Radar Tensor & Lidar Point Cloud Calibration Results

K-Radar: 4D Radar Object Detection Dataset and Benchmark for Autonomous Driving in Various Wearher Conditions

Dong-Hee Paek*, Seung-Hyun Kong*†, Kevin Tirta Wijaya

*:equal contribution, †:corresponding author

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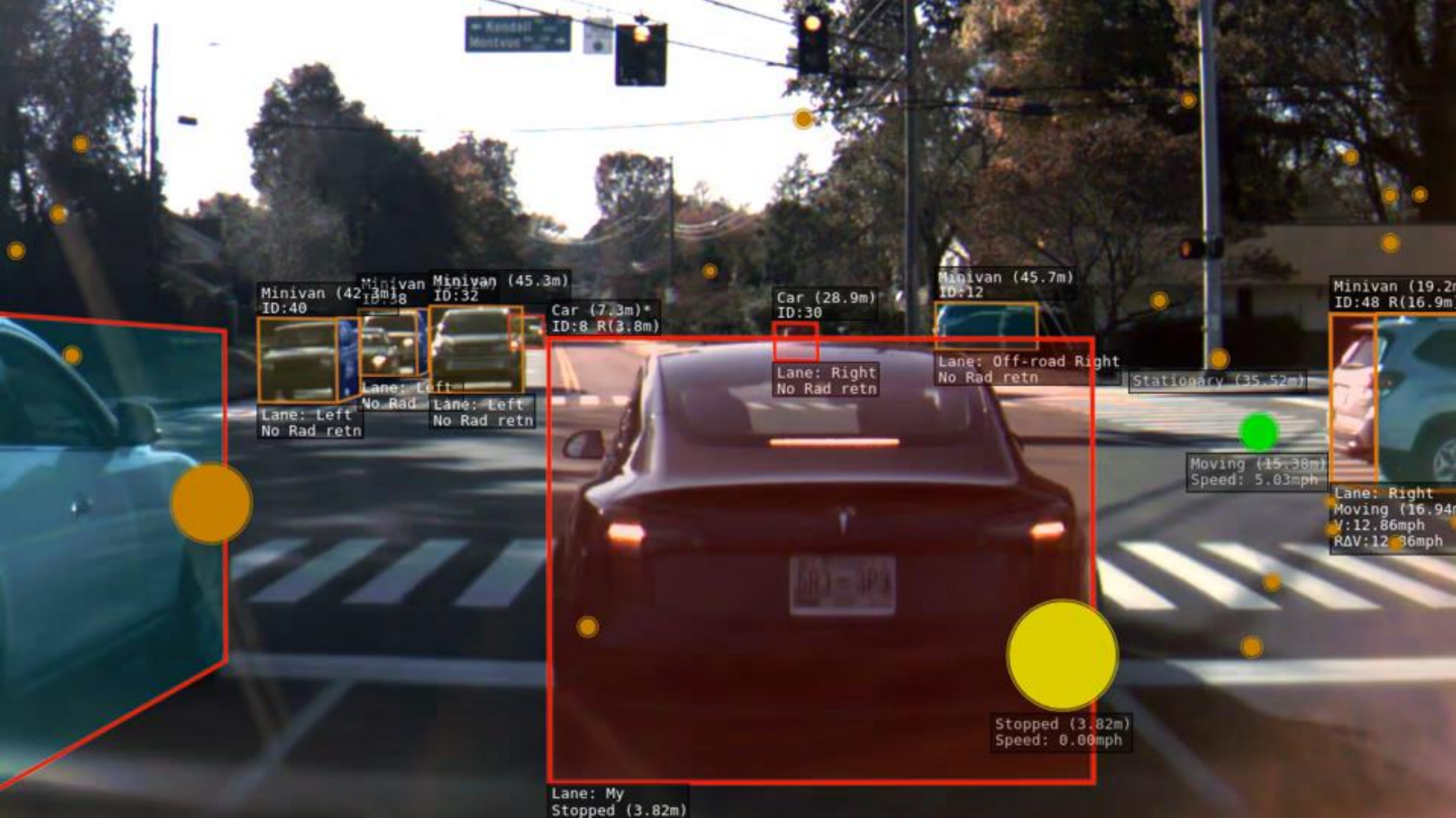
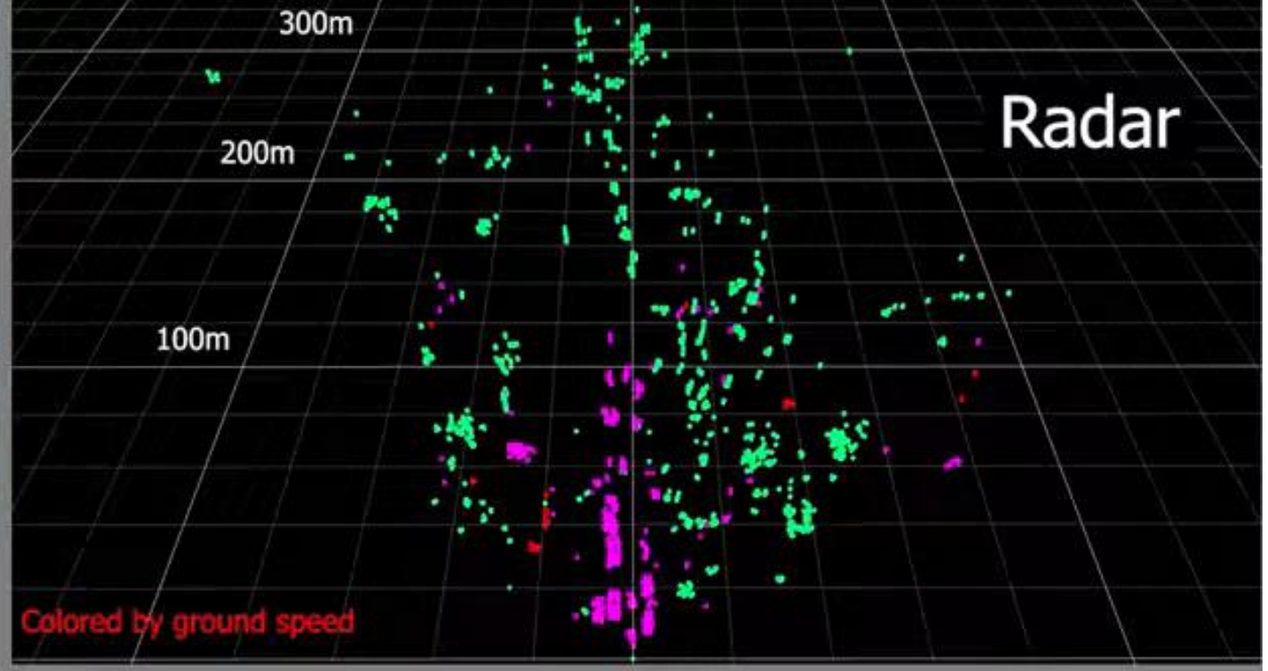
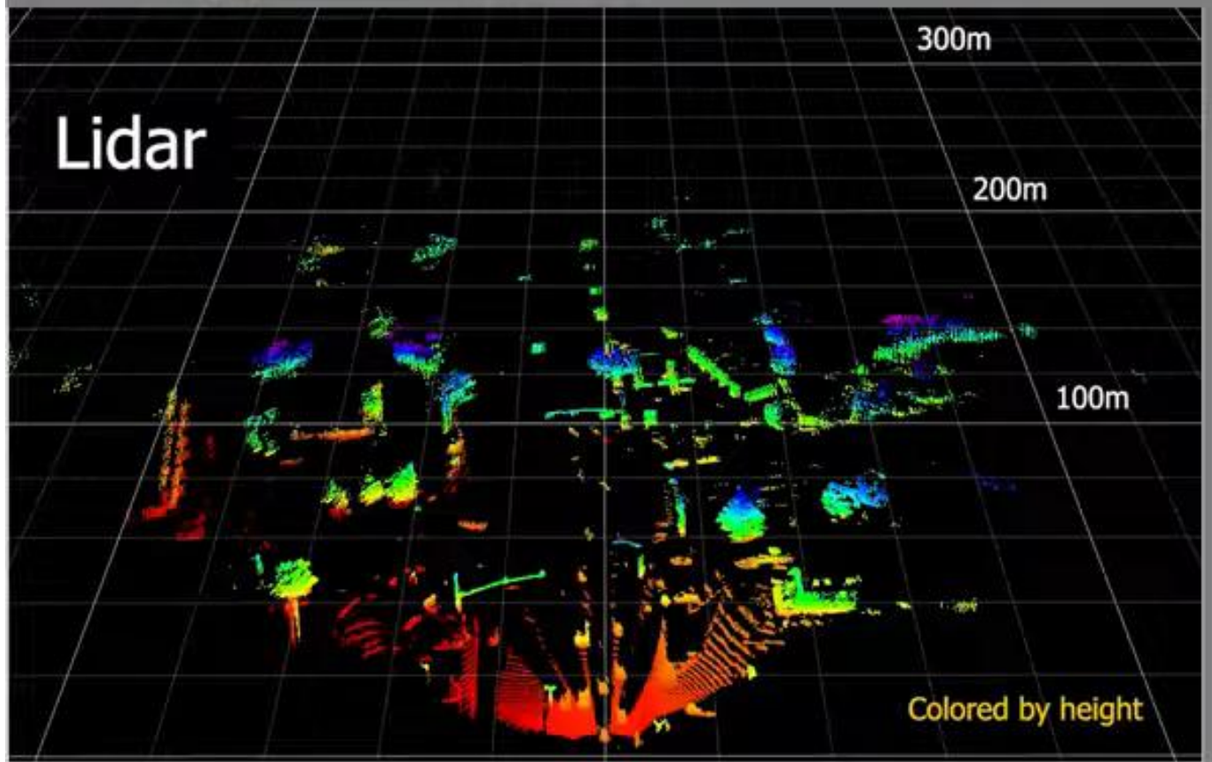
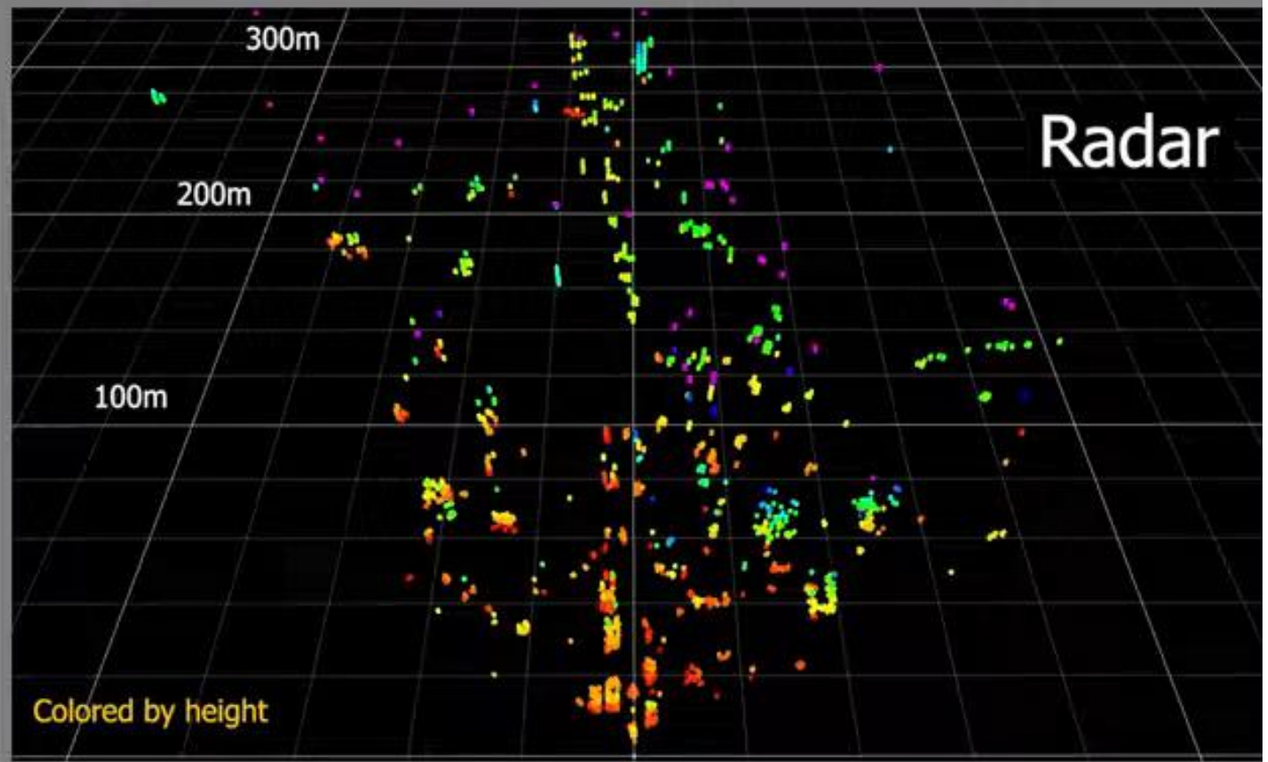

Minivan (42.3m)
ID:40
Lane: Left
No Rad retn
Minivan
ID:38
Lane: Left
No Rad
Minivan (45.3m)
ID:32
Lane: Left
No Rad retn
Car (7.3m)*
ID:8 R(3.8m)
Car (28.9m)
ID:30
Lane: Right
No Rad retn
Minivan (45.7m)
ID:12
Lane: Off-road Right
No Rad retn
Stationary (35.52m)
Moving (15.38m)
Speed: 5.03mph
Minivan (19.2m
ID:48 R(16.9m
Lane: Right
Moving (16.94m
V:12.86mph
RΔV:12.86mph
Stopped (3.82m)
Speed: 0.00mph
Lane: My
Stopped (3.82m)


smartmicro
SMART MICROWAVE SENSORS


Lidar vs Altos V1 Radar
Point Cloud Comparison
Jan-5th-2024


300m
200m
100m
Radar
Colored by ground speed


Lidar
300m
200m
100m
Colored by height


300m
200m
100m
Radar
Colored by height

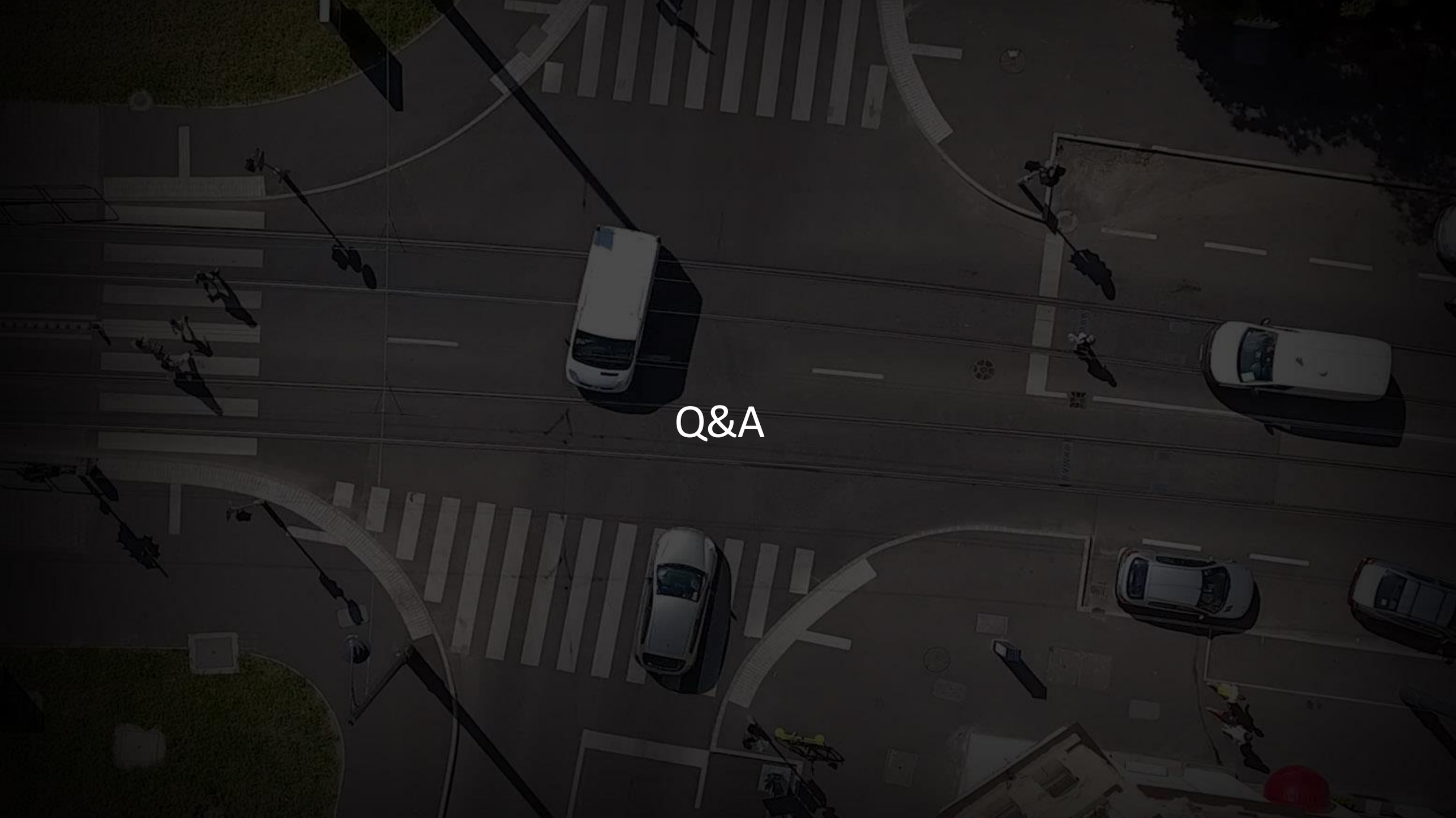

arbe
Radar Revolution. Delivered.

RadSee

METAWAVE

SPEKTRA™

RADAR


Q&A