Intelligent vehicles and autonomous driving

PERCEPTION SYSTEMS 2022 / 2023

Lesson 3

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RECAP

- HD maps
  - 5-layer organization
  - simplification of perception
  - industry standards (NDS, OpenDRIVE)
- Proprioceptive sensors
  - GNSS, trilateration
  - GNSS + IMU + odometry


SONAR

SONAR (ULTRASONIC SENSOR)

***SO**und **N**avigation **A**nd **R**anging*

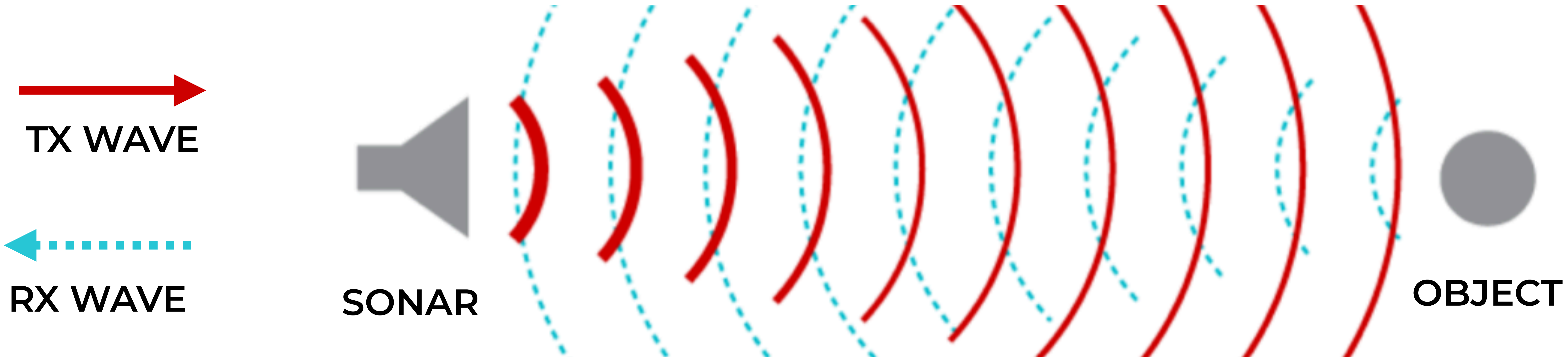
Used in many sectors (maritime, military, medicine) since early 20th century. First use in automotive in 1980 by Toyota's parking assistance system.

Low-cost sensor that measures short-range distances and is not affected by adverse weather and lighting.

SONAR

Ultrasonic sensors by Bosh (parking assist)

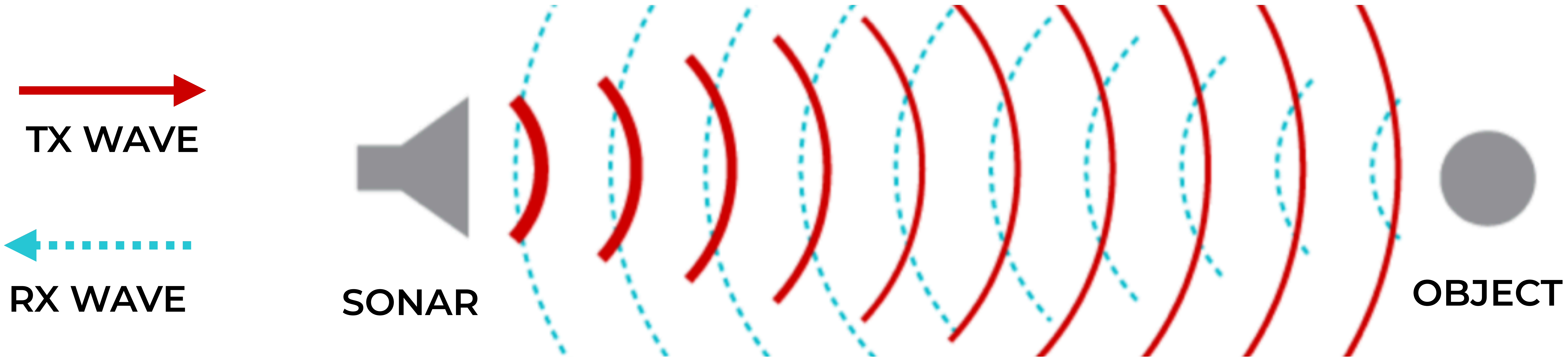
OPERATING PRINCIPLE - TIME OF FLIGHT



A transmitter emits an acoustic wave. The wave hits an obstacle and gets reflected. A receiver detects the reflected wave after a period of time Δt.

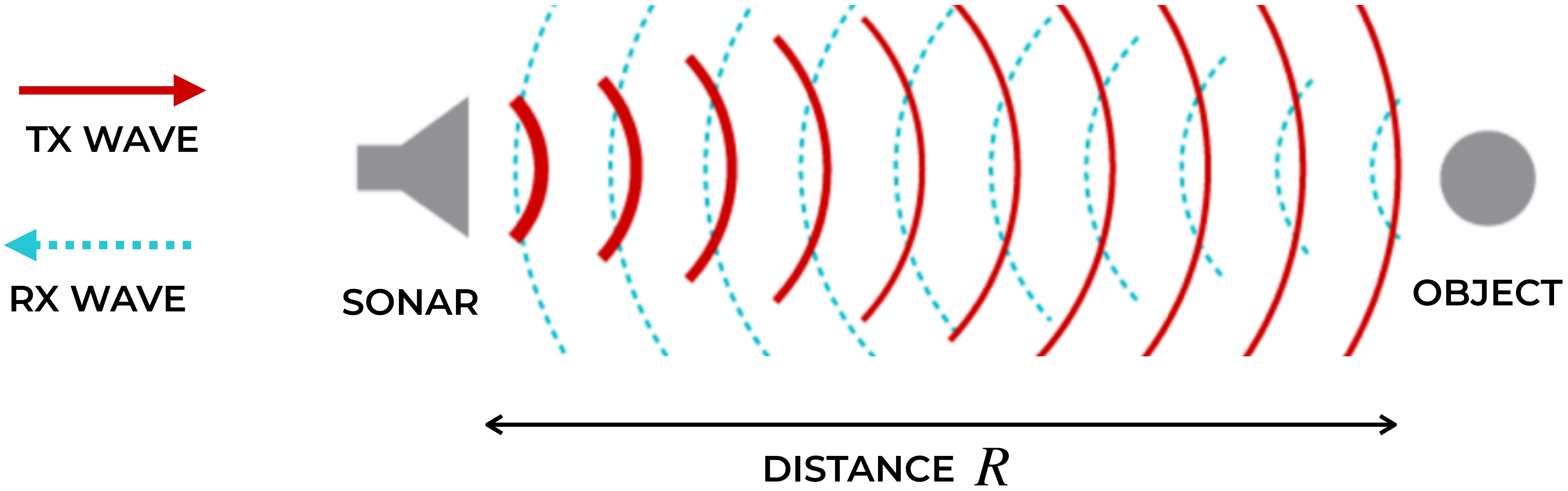
Ultrasonic waves have frequency from 20 kHz up, above the upper audible limit of human hearing.

OPERATING PRINCIPLE - TIME OF FLIGHT



Since the propagation of ultrasonic waves happens at constant speed c_s, the range R between the object and the sensor is determined from the runtime Δt of the acoustic signal.

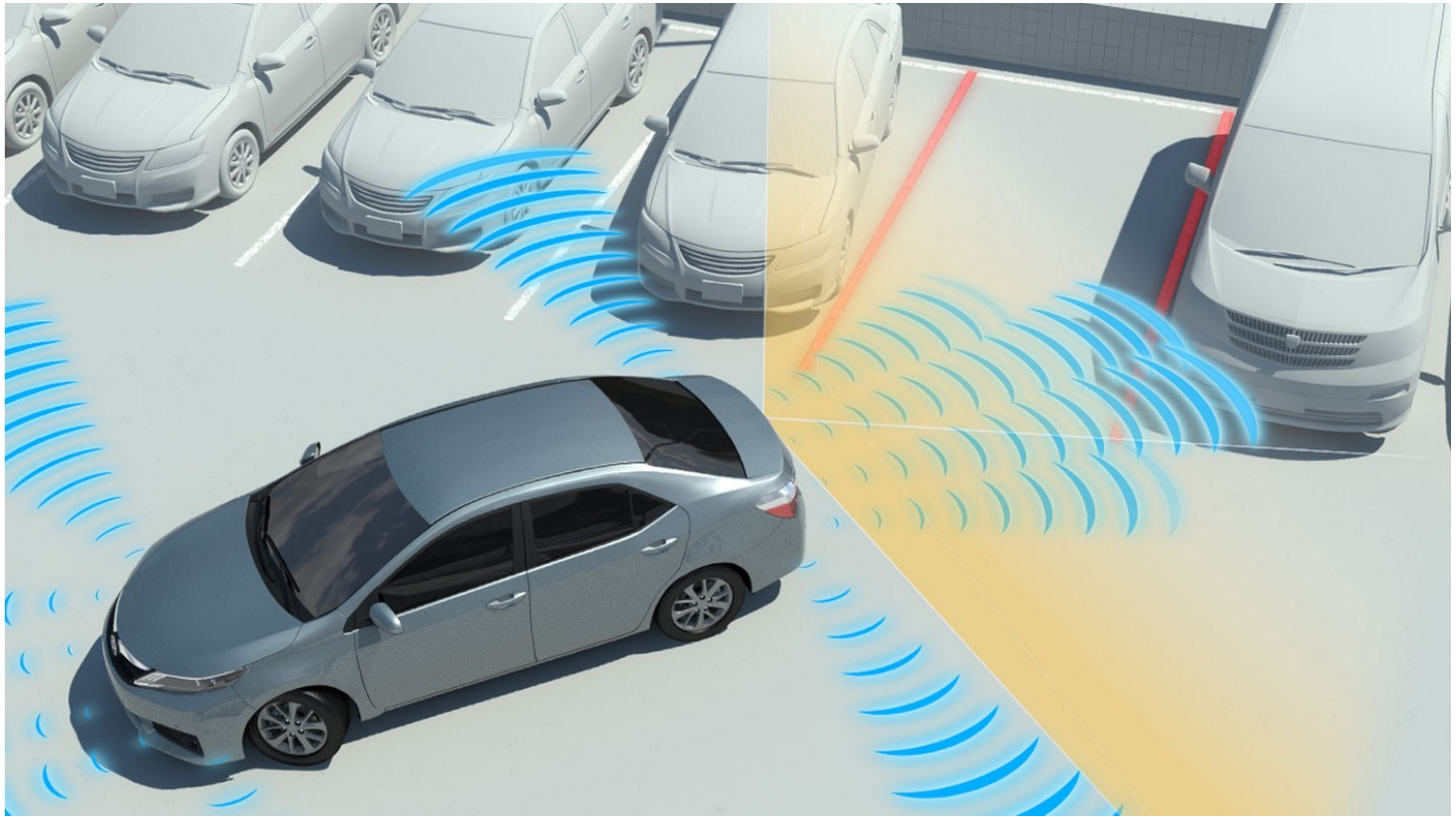
OPERATING PRINCIPLE - TIME OF FLIGHT

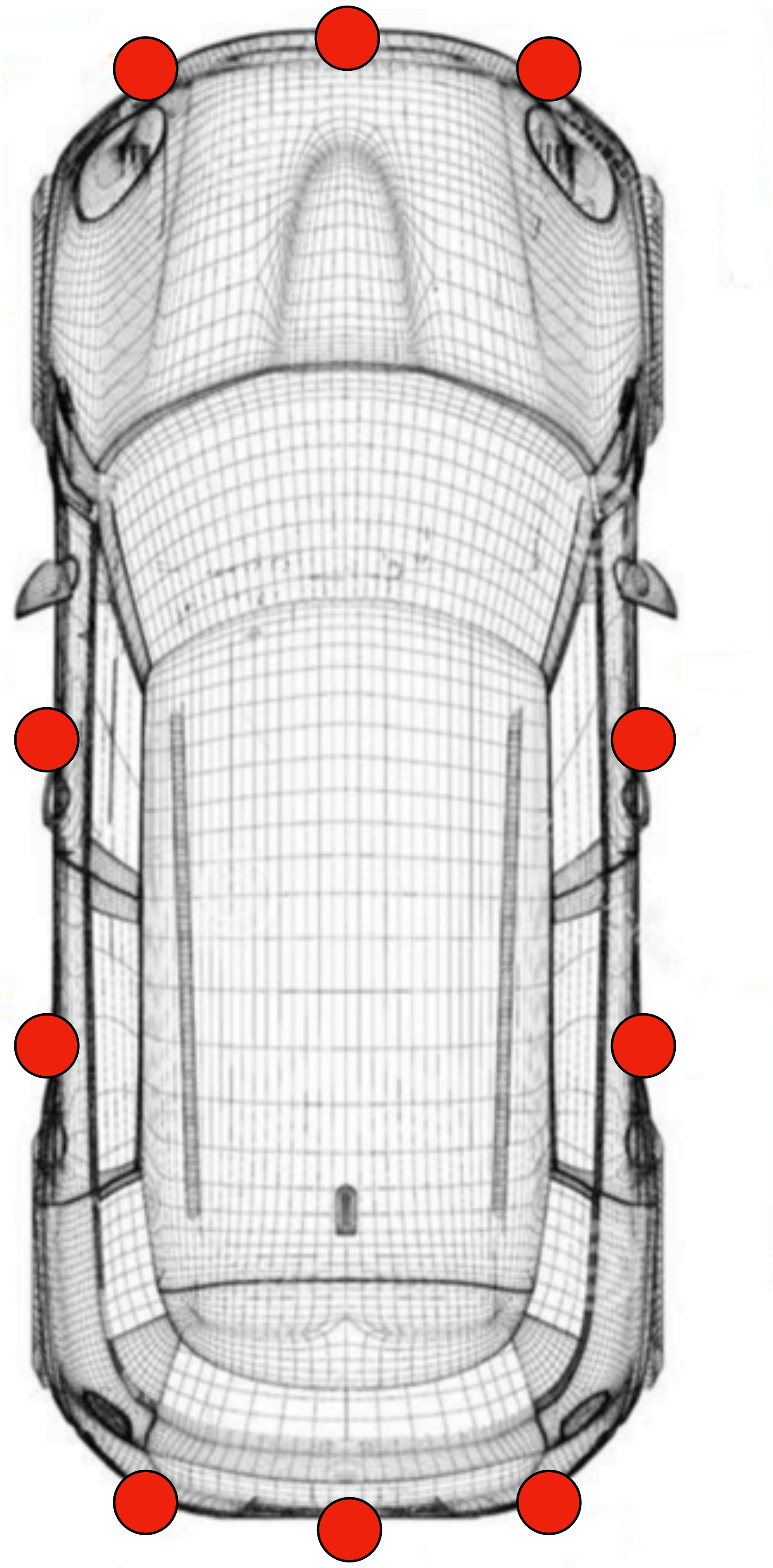


$$c_s = \frac{2R}{\Delta t} \implies R = \frac{c_s \, \Delta t}{2}$$

c_s = speed of sound (~300 m/s)

APPLICATION





PROS AND CONS

PROS

- cheap (~$20)
- good in any light conditions (direct sunlight and darkness)
- good in any weather conditions (rain, fog, snow)
- work even with non-metallic objects

CONS

- low resolution and low range
- sensitive to high speed

RADAR

RADAR

***RA**dio **D**etection **A**nd **R**anging*

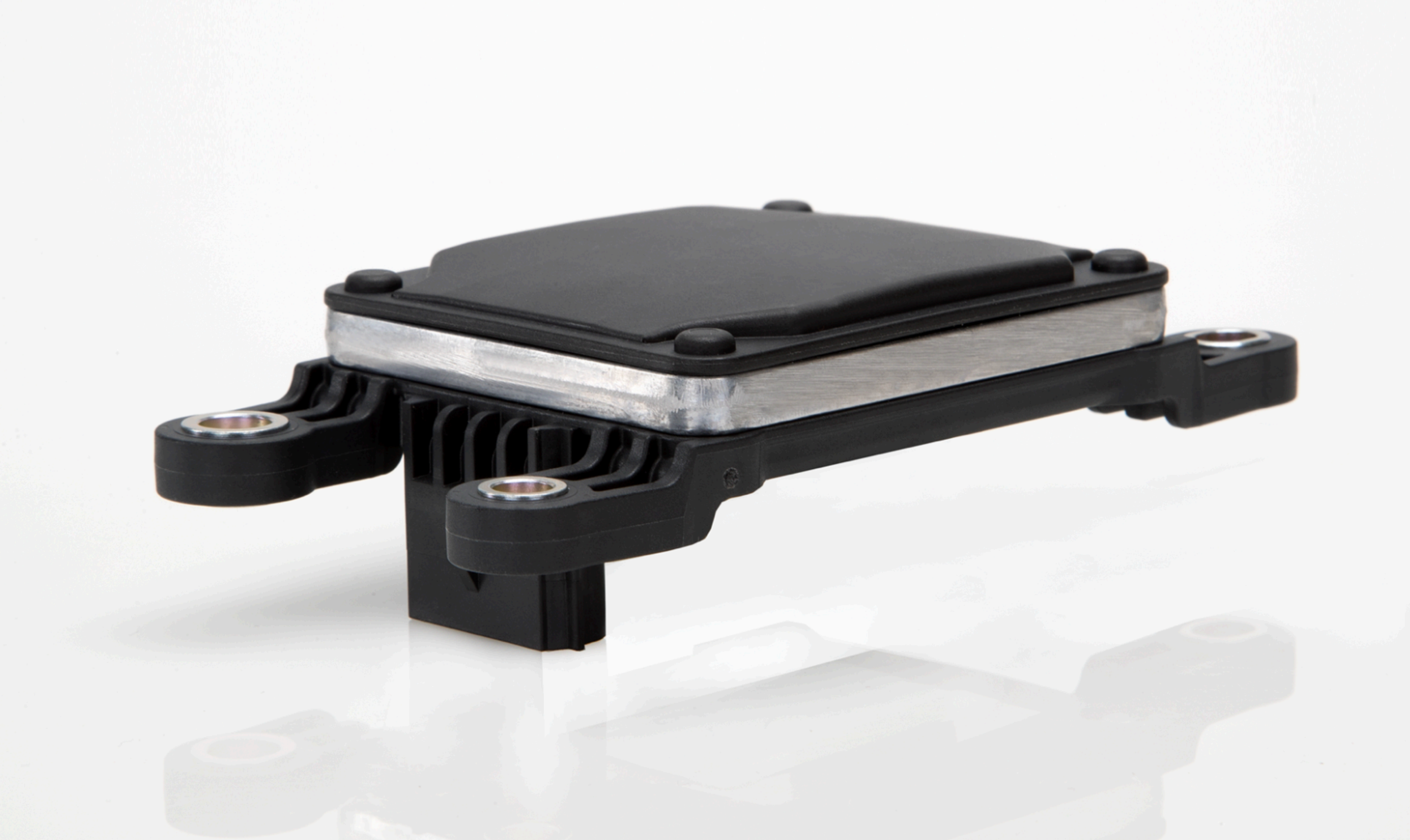
Used in military and civil aviation since 1940. Adopted in automotive since 1990.

Measurements of objects:

- distance
- speed
- relative angle
- cross section (reflecting area)

Robust sensor to detect obstacles, rather than classify objects.
Works in bad weather/light conditions.

RADAR



Long-range radar by Continental
(adaptive cruise control)

Mid-range radar by Bosh
(lane change assist)

OPERATING PRINCIPLE (TOF)

A transmitter emits an electromagnetic wave. The wave hits an object and gets reflected. A receiver detects the reflected wave after a period of time.

In automotive, radio waves between 24GHz and 79 GHz.

MAIN SYSTEMS

PULSE RADAR emits a pulsed signal, followed by a longer pause in which the echoes can be received before a new transmission signal is transmitted.

CONTINUOUS WAVE RADAR (CW RADAR) emits a continuous signal without interruption. The received signal gets mixed with the transmitted signal.

- **UNMODULATED CW RADAR** emits a signal that is constant in frequency.
- **FREQUENCY MODULATED CW RADAR (FMCW RADAR)** emits a signal that is modulated in frequency.

PULSE RADAR

Since the propagation of EM waves happens at constant speed c, the range R between the illuminated object and the radar is determined from the runtime Δt of the signal.

$$c = \frac{2R}{\Delta t} \qquad \Longrightarrow \qquad R = \frac{c\ \Delta t}{2}$$

UNMODULATED CW RADAR

It measures only speed of objects. It cannot measure distance. Typical application is speed gauges (autovelox).

The emitted wave has constant frequency. The received wave either has exactly the same frequency or is shifted by the ***Doppler frequency***.

UNMODULATED CW RADAR

To measure the speed v_o of an object, the radar measures the frequency shift f_D caused by the doppler effect.

$$\left.\begin{aligned} \frac{f_T}{c} &= \frac{f_R}{c + v_r} \\ f_R &= f_T + \frac{1}{2} f_D \\ v_r &= v_e + v_o \end{aligned}\right\} \implies f_D = 2\,\frac{v_r\, f_T}{c} \implies v_o = \frac{c\, f_D}{2 f_T} - v_e$$

f_T = transmitted frequency

f_R = received frequency

v_r = relative speed

v_e = ego speed

UNMODULATED CW RADAR

Since the signal is continuous and with constant frequency, there is no way to get accurate time references to measure the distance of stationary objects.

This is why unmodulated CW radar cannot determine target range.

Such time references can be generated by modulating the frequency of the transmitted signal.

FMCW RADAR

The transmitted signal increases/decreases in the frequency linearly and periodically.

When an echo signal is received, the change of frequency arrives with a runtime delay Δt (similar to the pulse radar).

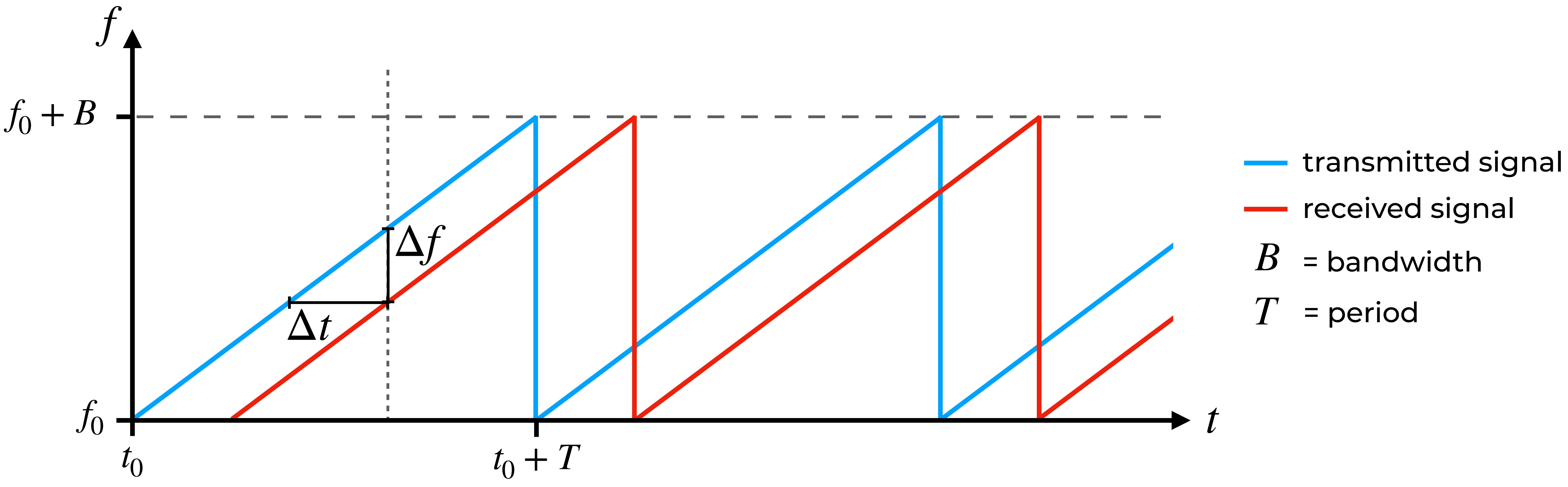
While the pulse radar measures the runtime directly, the FMCW radar measures the differences in frequency between the transmitted and the received signals instead.

FMCW RADAR

Features:

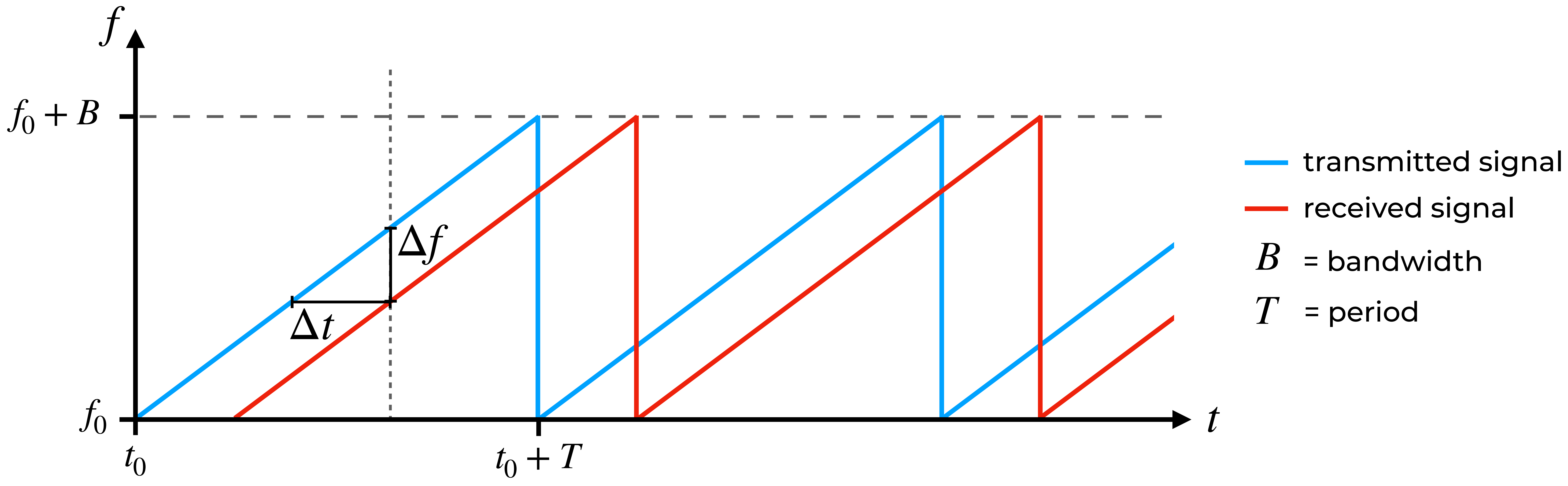
- simultaneous target range and relative speed measurement
- high accuracy and resolution of range measurement
- most adopted in AV applications

FMCW RADAR (NO RELATIVE SPEED)



The distance is measured by comparing the frequency of the received signal to the frequency of the transmitted signal. The frequency shift Δf is proportional to the distance R.

FMCW RADAR (NO RELATIVE SPEED)



$$\frac{\Delta f}{\Delta t} = \frac{B}{T}, \quad R = \frac{c\,\Delta t}{2} \quad \Longrightarrow \quad R = \frac{c\,\Delta f\,T}{2\,B}$$

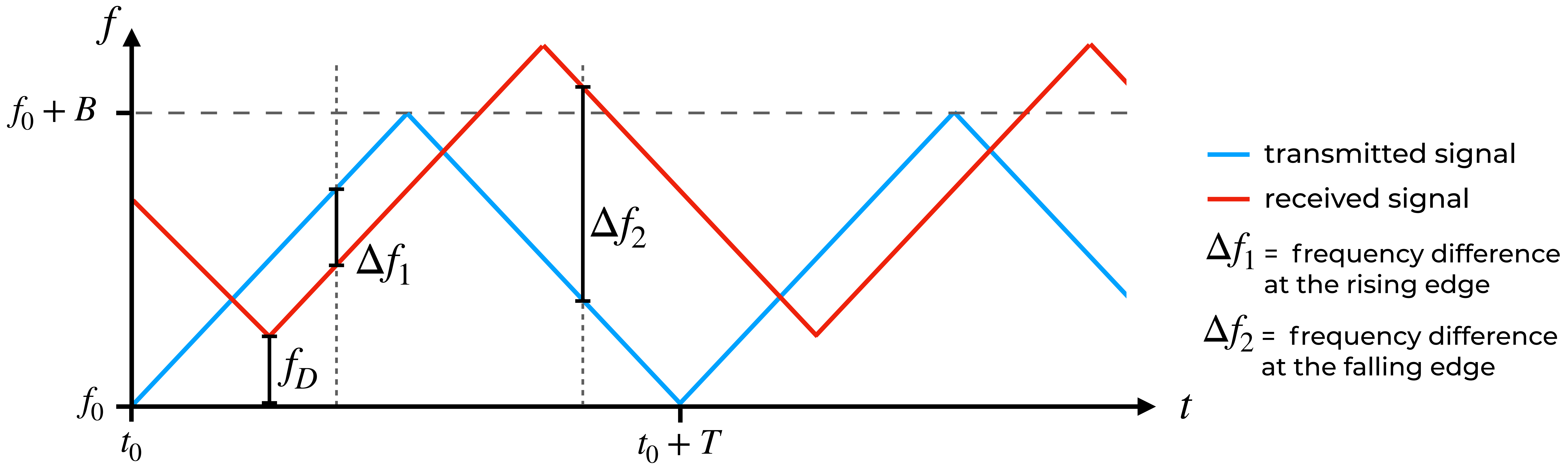
FMCW RADAR (WITH RELATIVE SPEED)

If the reflecting object has a radial speed with respect to the receiver, then the received signal has two frequency shifts:

1. Δf caused by the runtime
2. the Doppler frequency f_D

To separate between the two shifts, it is possible to use the triangular modulation pattern. In this way, two measurements can be performed on the rising and on the falling edge of the signal.

FMCW RADAR (WITH RELATIVE SPEED)



$$\left.\begin{aligned}\Delta f_1 &= \Delta f - f_D \\ \Delta f_2 &= \Delta f + f_D\end{aligned}\right\} \implies \Delta f = \frac{\Delta f_1 + \Delta f_2}{2}, \qquad f_D = \frac{\left|\Delta f_1 - \Delta f_2\right|}{2}$$

FMCW RADAR (WITH RELATIVE SPEED)

$$\Delta f = \frac{\Delta f_1 + \Delta f_2}{2} \quad , \qquad f_D = \frac{\left| \Delta f_1 - \Delta f_2 \right|}{2}$$

$$\left. \begin{aligned} R &= \frac{c\, \Delta f\, T}{2\, B} \\ v_r &= \frac{c\, f_D}{2\, f_T} \end{aligned} \right\} \Longrightarrow \begin{aligned} R &= \frac{c\, T}{4\, B} \left(\Delta f_1 + \Delta f_2 \right) \\ v_r &= \frac{c}{4\, f_T} \left| \Delta f_1 - \Delta f_2 \right| \end{aligned}$$

MAX RANGE AND RANGE RESOLUTION

The ***maximum unambiguous range*** is the longest distance the radar can measure reliably. It is determined by the necessary temporal overlap of the (delayed) received signal with the transmitted signal.

The ***range resolution*** is the minimum variation in range the radar can measure. It is determined by the bandwidth of the signal. In addition, it is limited by the period of the signal because of the Discrete Fourier Transform.

EXAMPLE

A radar sends a signal with period $T = 1\ \mu s$ and bandwidth $B = 1\ GHz$. Find the maximum range R_M and the range resolution R_Δ.

We find the maximum range when there is almost no temporal overlap.

$$\Delta t \approx T \quad \Longrightarrow \quad R_M = \frac{c\,T}{2} = 150\ m$$

R_Δ is directly proportional to the minimum measurable runtime, which depends from the minimum measurable frequency shift.

EXAMPLE

A radar sends a signal with period $T = 1\ \mu s$ and bandwidth $B = 1\ GHz$.
Find the maximum range R_M and the range resolution R_Δ.

The minimum frequency shift depends from T because of the DFT.

$$\Delta f_m = \frac{1}{T} = 1\ MHz \quad \Longrightarrow \quad \Delta t_m = \frac{\Delta f_m\ T}{B} = 1\ ns$$

From the minimum measurable runtime we can find the range resolution.

$$c = \frac{2\,R_\Delta}{\Delta t_m} \quad \Longrightarrow \quad R_\Delta = \frac{c\ \Delta t_m}{2} = 0.15\ m$$

RADAR FOR AUTOMOTIVE

	SHORT-RANGE	MID-RANGE	LONG-RANGE
frequency	24 GHz, 77 GHz	77 GHz, 79 GHz	77 GHz
bandwidth	0.2 GHz, 1 GHz	1 GHz, 5 GHz	1 GHz
range	~ 70 m	~ 150 m	~ 250 m
field of view	~ 120°	~ 90°	~ 20°
mounting	rear, side	front	front
application	blind spot detection, parking assist	traffic jam assist	emergency braking, adaptive cruise control

APPLICATIONS

Given an object, a radar can measure: distance, speed, angle, cross section (surface area). With this information, it is possible to roughly classify the object.

Example: an object with cross section ~ 1 m^2 moving at 1 m/s is likely a pedestrian (and not a vehicle).

PROS AND CONS

PROS

- work in any light conditions (direct sunlight, darkness)
- work in any weather conditions (rain, fog, snow)
- good resolution even at long ranges (up to 250 m)
- cheap ($50 - $150)

CONS

- less robust with non-metallic objects
- bad at recognizing types of objects (compared to LIDAR and camera)