Automotive Sensors

Radar

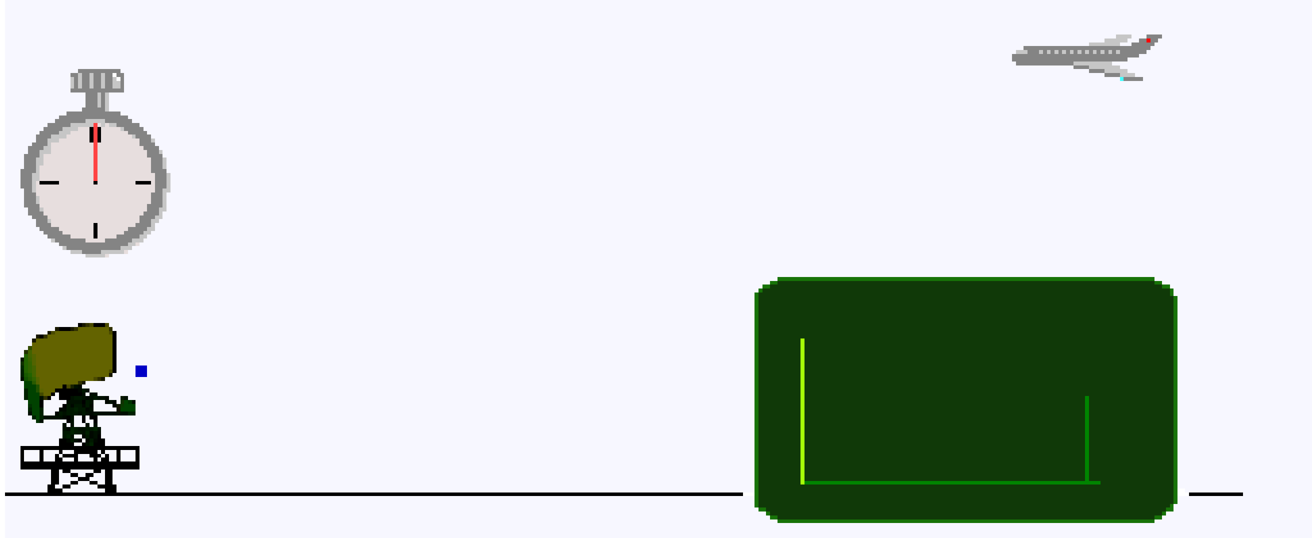
Automotive Intelligence Lab.

Contents

Introduction to Automotive Radar

Radar (Radio Detection and Ranging)

- **Radar is a detection system that uses radio waves to determine the range, direction, or relative velocity of objects.**
- **Principle**
  - A source transmitting the radio wave ➔ being reflected by a surface ➔ received and processed by a receiver system.
  - The **range** to the target is evaluated from the travelling time of the wave.
  - The **direction** of the target is determined by the arrival angle of the echoed wave.
  - The **relative velocity** of the target is determined from the Doppler shift of the returned signal.

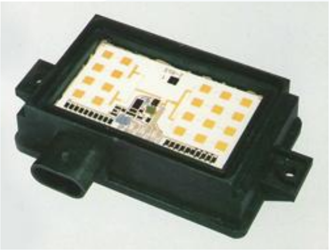


History of Automotive Radar

10GHz automotive radar
built by VDO

16GHz automotive radar
built by Standard Electric Lorenz (SEL)

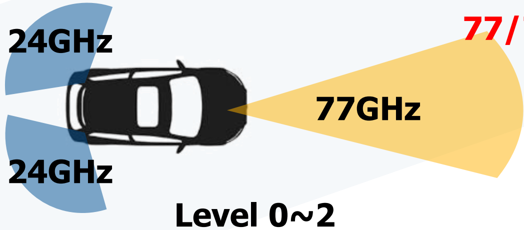
35 GHz automotive radar
built by AEG-Telefunken



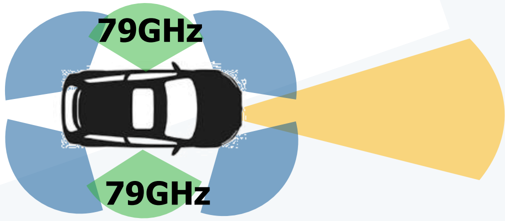
24 GHz SDS system
built by HE Microwave

24 GHz CWS system
built by EATON-VORAD

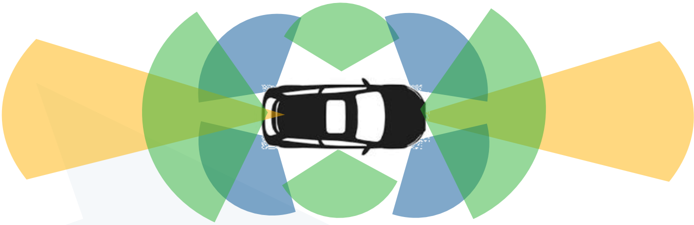
"Distronic"
First radar-assisted ACC
built by Mercedes-Benz



Level 0~2
Adaptive Cruise Control
24+77GHz Radar



Level 3
Highway Driving Assistance
77/79GHz Radar



Level 4-5
Autonomous driving
4D Imaging Radar

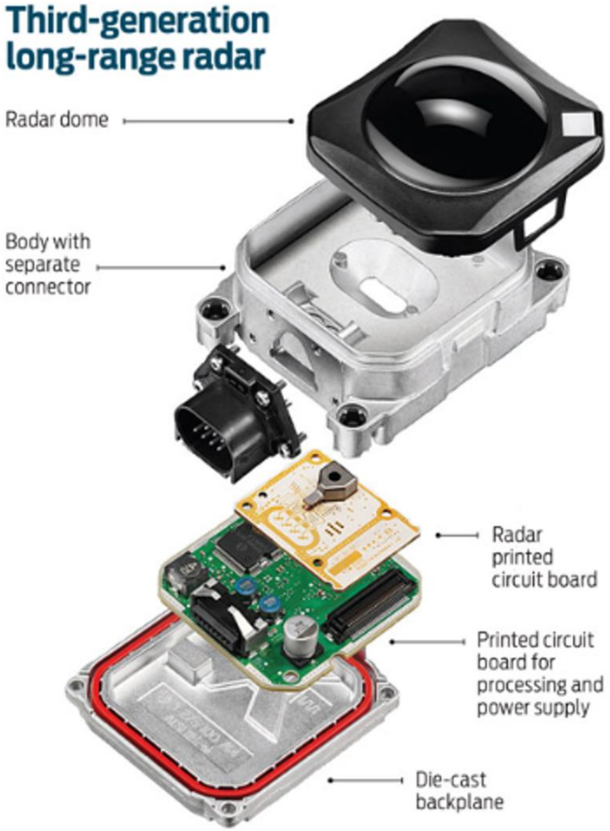
1970 **1990** **2010** **2020~**

Radar Construction

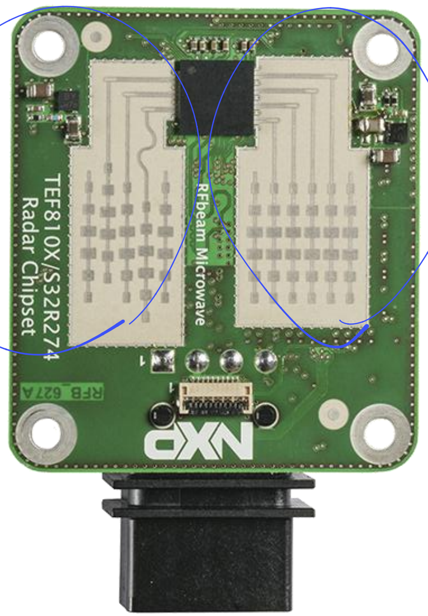
- **Radar dome (Radome)**
  - A *radome* is a structural, weatherproof enclosure that protects a radar antenna.
  - The radome is constructed of material that minimally attenuates the electromagnetic signal transmitted or received by the antenna, effectively transparent to radio waves.

- **Radar printed circuit board**
  - Analog hardware that includes the radar transceiver and antenna needed for radio wave generation.

- **Printed circuit board and processing**
  - Including Digital Signal Processing Unit (DSP).

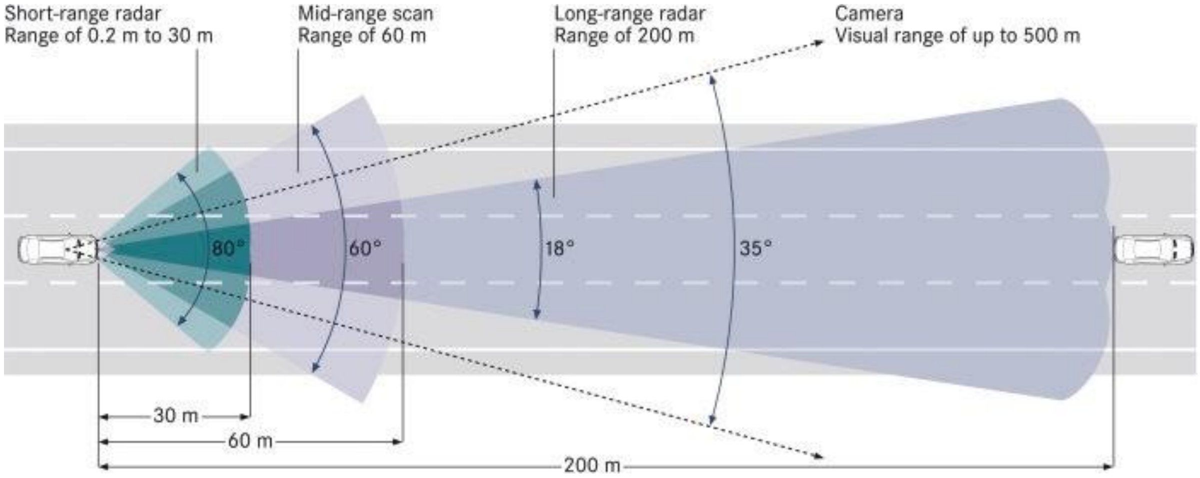


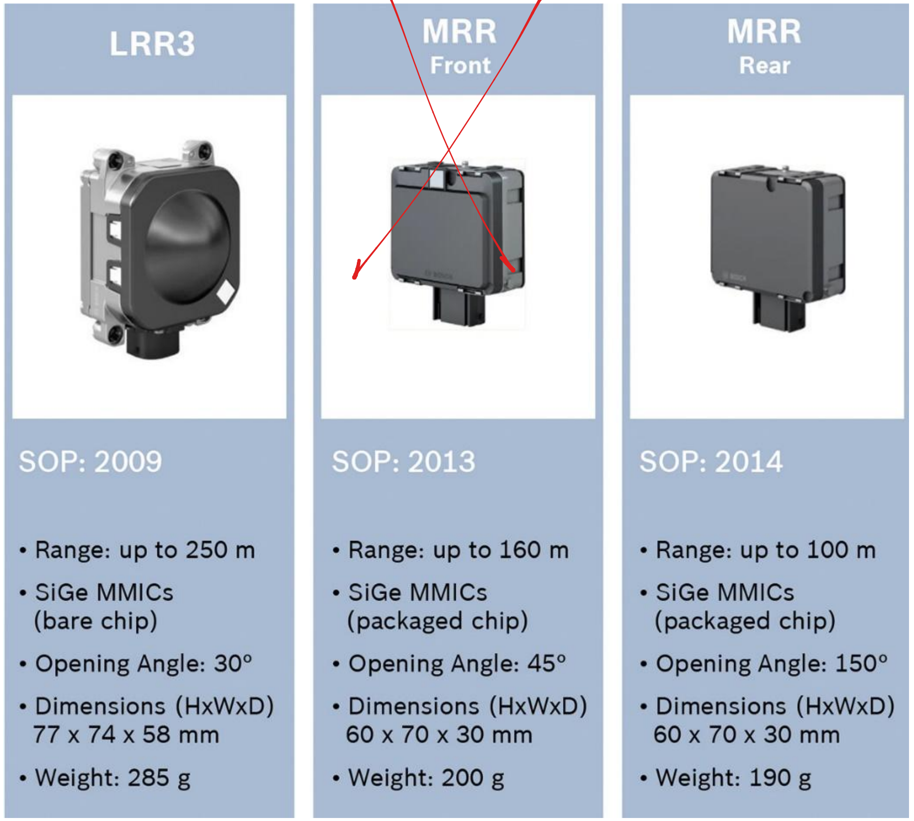
안테나



Types of Radar

- **Automotive radar typically works on near 77GHz and falls into three categories:**
  - Short range radar (SRR) – 0.5 to 20 meters
  - Medium range radar (MRR) – 1 to 60 meters
  - Long range radar (LRR) – 10 to 250 meters





Pros and Cons

- **Pros**
  - All-weather solution.
  - Night or day.
  - Long range radar systems can see far (10 to 250 meters).
  - Accurately measure velocity of the object using radio waves.

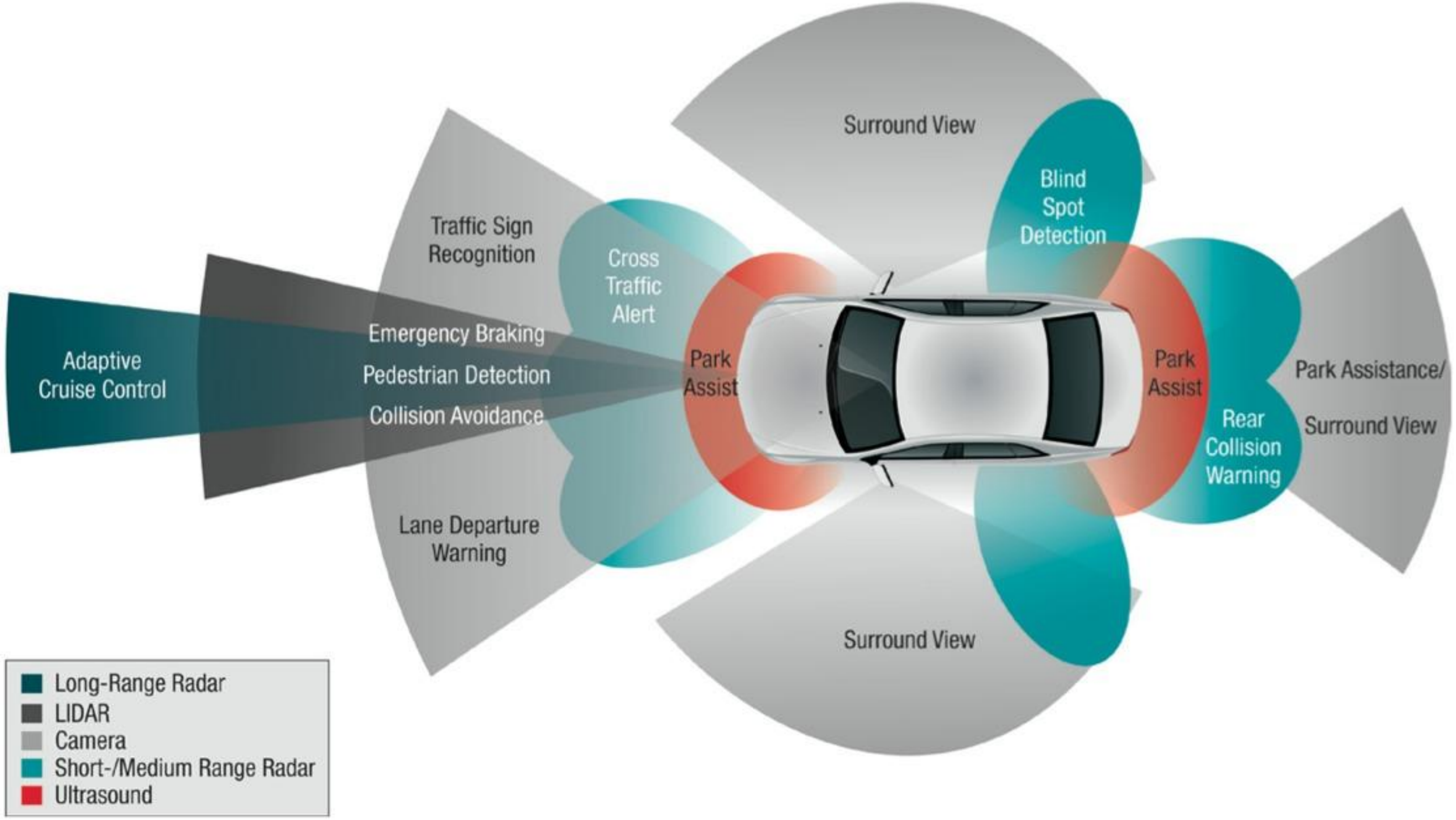
- **Cons**
  - Detecting small objects with radar is relatively difficult for shorter wavelengths.
  - Existing radar-based ADAS systems do not work well in closed environments such as tunnels and usually go into standby mode.
  - Radar based systems have their limitations when it comes to recognizing and classifying objects.
  - Processing time taken in actual detection.

multipass problem

Applications of Radar

- **SRR**
  - Lane change assist
  - Blind spot detection
  - Rear collision warning

- **LRR**
  - Adaptive cruise control
  - Autonomous emergency braking

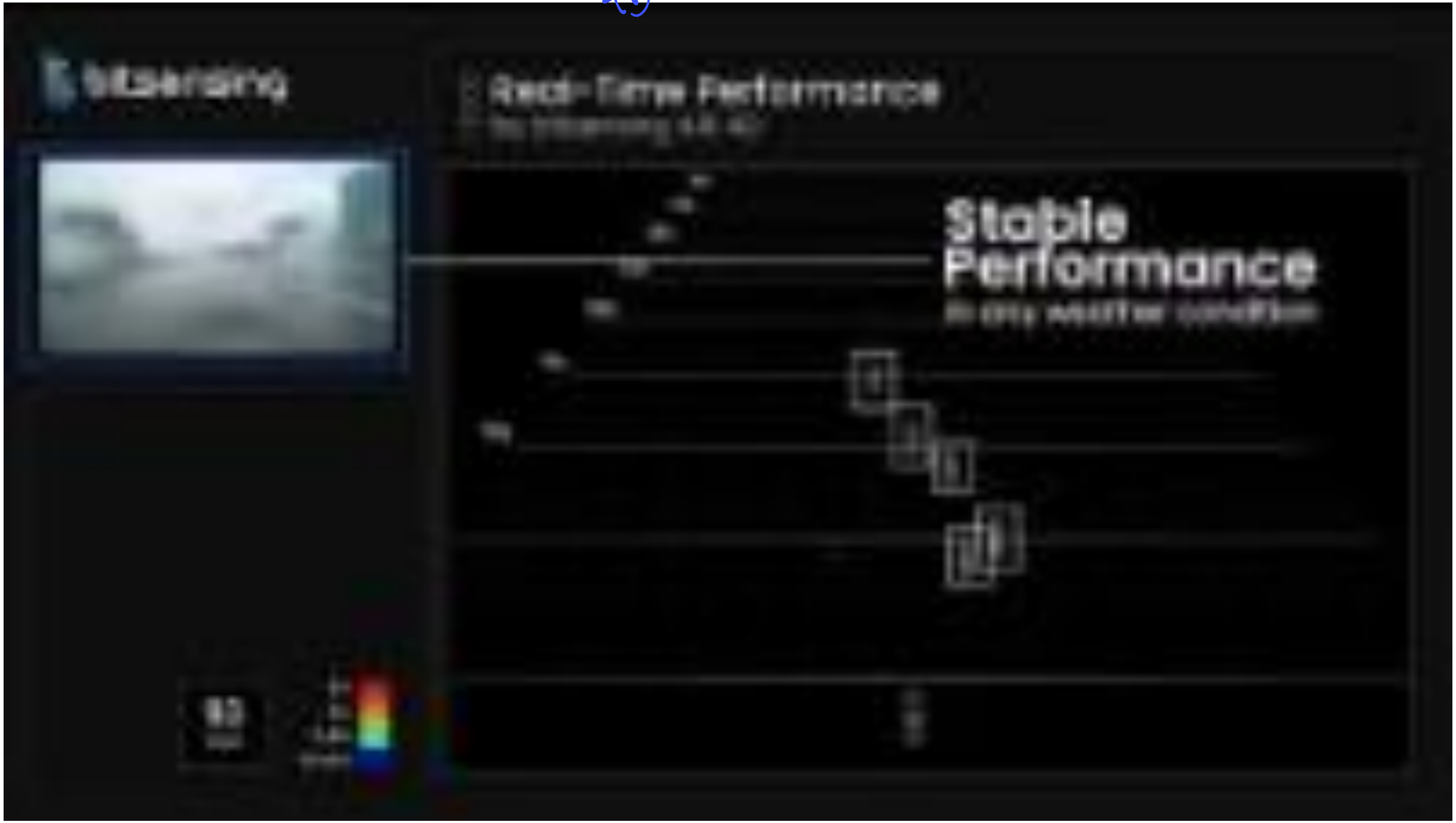


Radar for Automotive

https://www.youtube.com/watch?v=FjDn1DWfRjI

Radar for Automotive - Imaging Radar

4D



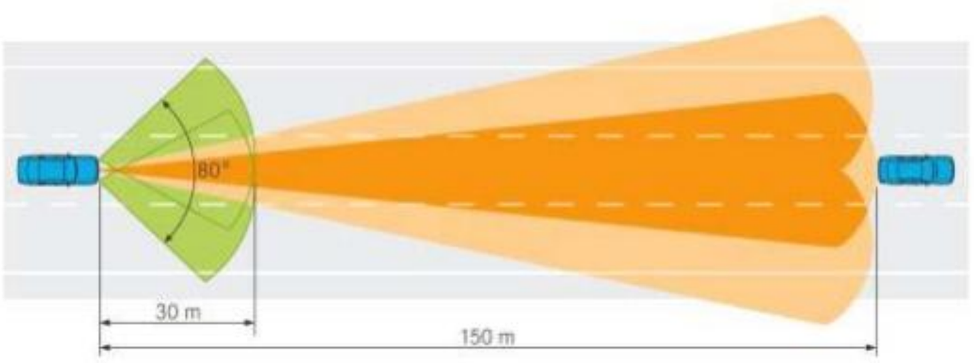
Traffic RADAR

Radar for Automotive In-Cabin Applications

Automotive Radar Basics

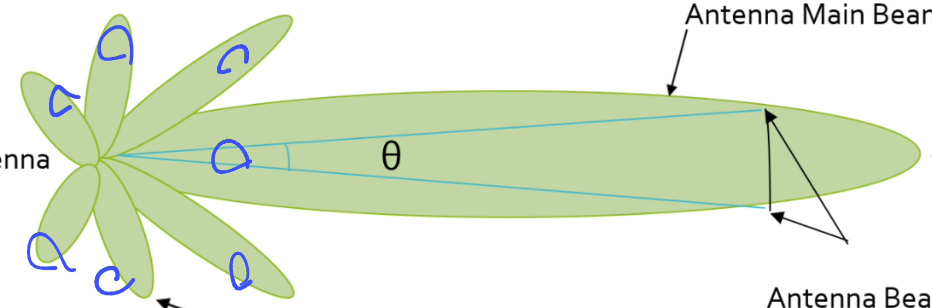
Antenna

- The *antenna pattern* is the geometric pattern of the strengths of the relative field emitted by the antenna.



- The beamwidth of the antenna determines the field of view.

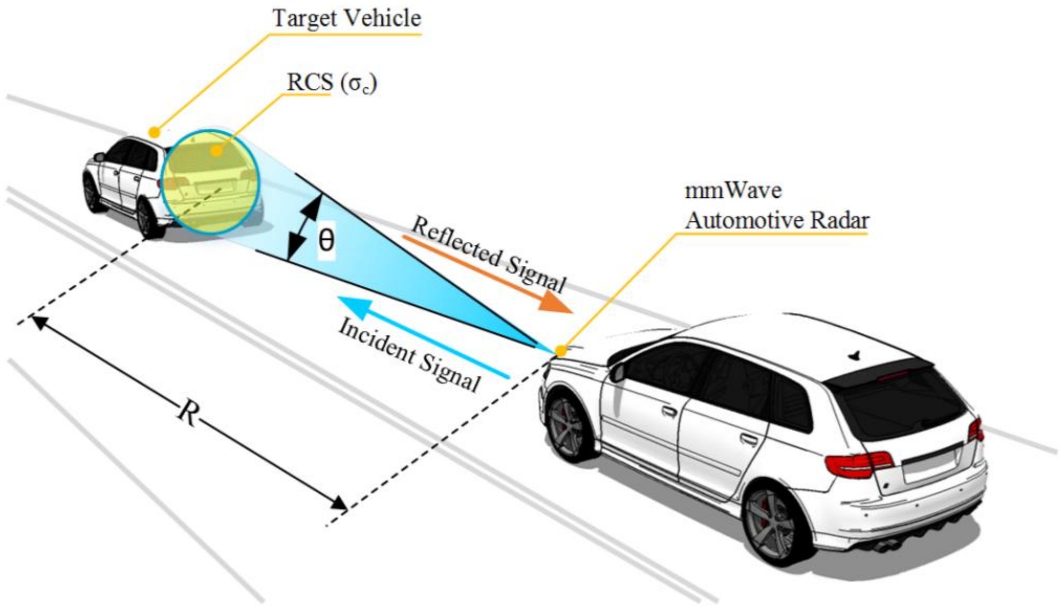
간끼리가 상쇄되도록
발생함.

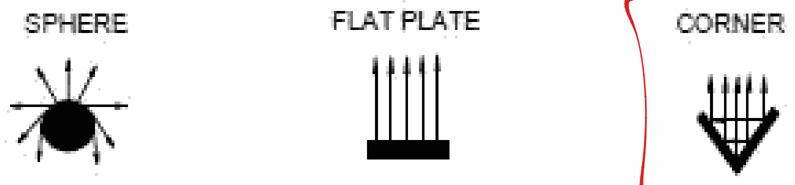


Radar Cross Section (RCS)

- **Ability of a target to reflect radar energy (σ).**
  - unit : m^2

- **Target radar cross sectional area depends on**
  - target's physical geometry and exterior features.
    - Smooth edges or surface would scatter the waves in all directions.
  - direction of the illuminating radar.
  - radar transmitter's frequency.
  - material.



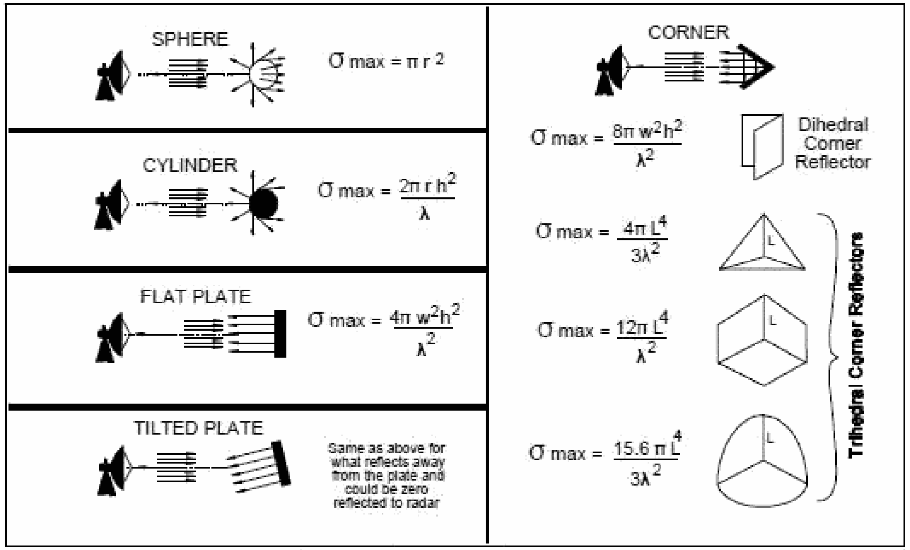


Biggest RCS

RCS Units

■ Example

- ▶ Stealth aircraft
  - ● Smooth surface + non-reflective Surface + geometry



Typical radar cross section values

Target	RCS (m^2)
Large commercial airplane	100
Large fighters	5-6
Small fighters	2-3
Man	1
Small bird	0,01
Bug	0,00001
F-117 fighter	0,1
B-2 bomber	0,01

The Radar Power Equation

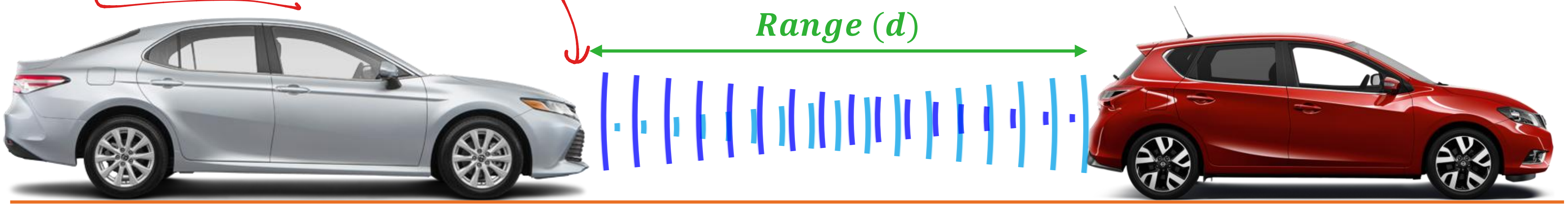
안테나 gain

- **Radiated power density**
  - $\frac{P_t G_{TX}}{4\pi d^2}\ W/m^2$
- **Power reflected by object**
  - $\frac{P_t G_{TX}\sigma}{4\pi d^2}\ W$
- **Power density at RX antenna**
  - $\frac{P_t G_{TX}\sigma}{(4\pi)^2 d^4}\ W/m^2$
- **Power captured at RX antenna**
  - $\frac{P_t G_{TX}\sigma A_{RX}}{(4\pi)^2 d^4}\ W = \frac{P_t G_{TX}\sigma G_{RX}\lambda^2}{(4\pi)^3 d^4}\ W$
    - $\boxed{A_{RX} = \frac{G_{RX}\lambda^2}{4\pi}}$

P_t	: Output power of device
$G_{TX/RX}$	: TX/RX Antenna Gain
σ	: Radar Cross Section (RCS) of target
A_{RX}	: Effective aperture area of RX antenna
d	: Range

Power ↓

Pt

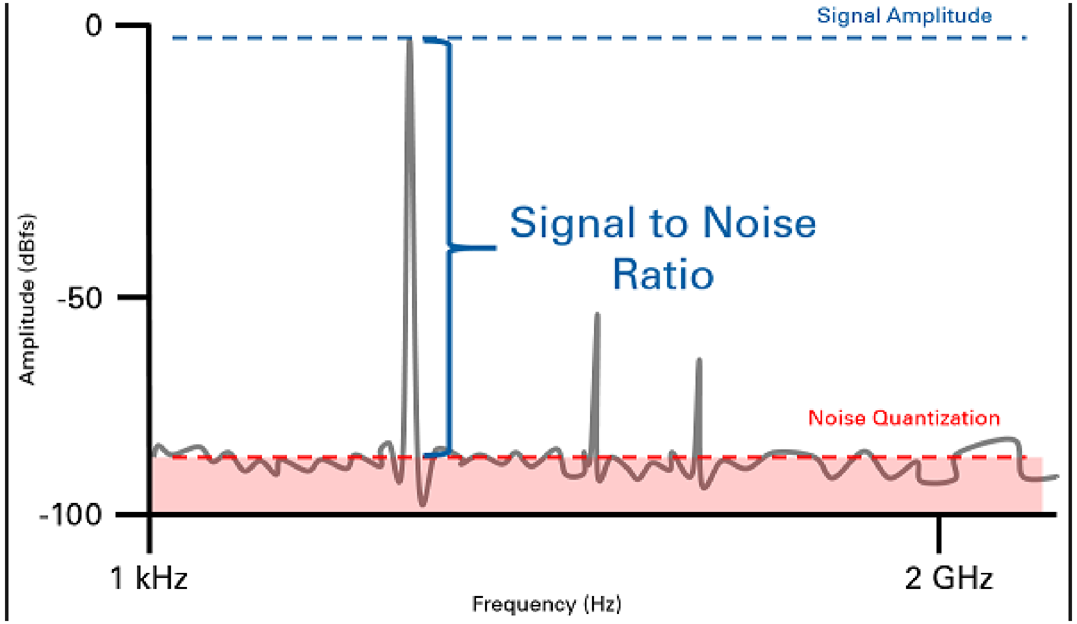


Signal to Noise Ratio (SNR)

SNR ↑ Good

- **SNR is a quantitative measure of a signal strength as compared to the level of** Noise
  - Lower SNR is difficult for a radar to distinguish the signal from noise.
  - Higher SNR is desirable for successful detection of the target.
    - 7-13 dB SNR ensures successful detection in a road scenario.

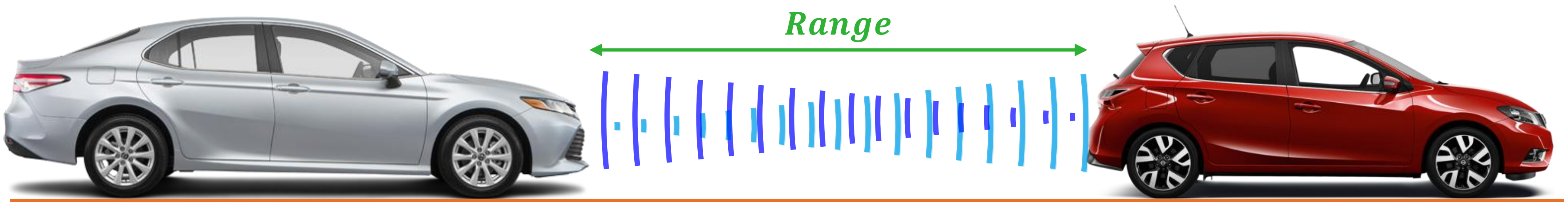
- **SNR = power level (in dBm) - noise level (dBm).**



Range Estimation

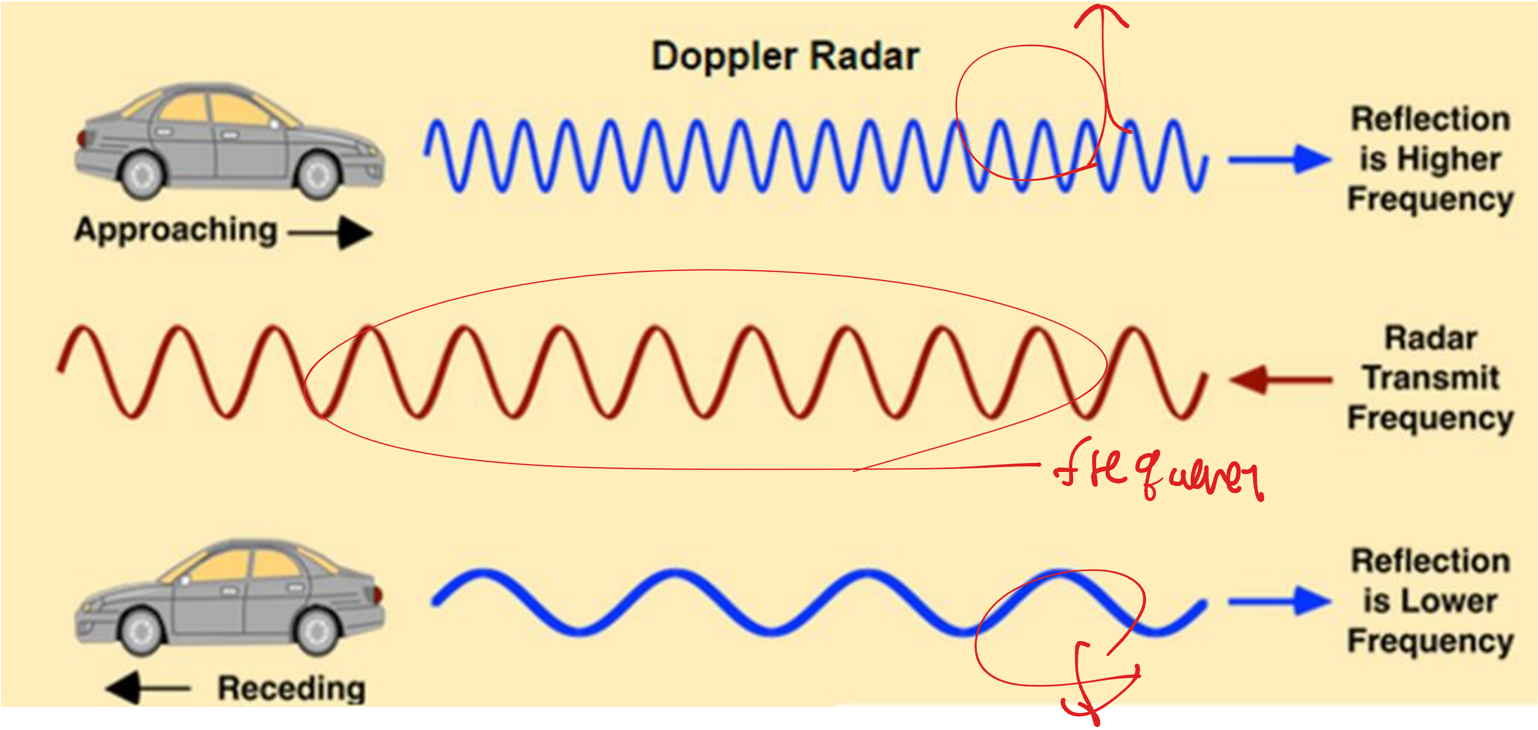
- Signal trip time (t) = $\frac{2Range}{c}$

$Range = \frac{t \cdot C}{2}$



Doppler Estimation

- **Doppler effect is a change in frequency of a wave reflected off a moving target.**
  - Receding target
    - Reflection is lower frequency.
  - Approaching target
    - Reflection is higher frequency.

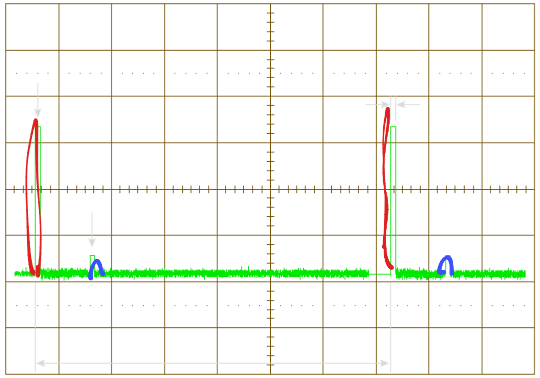


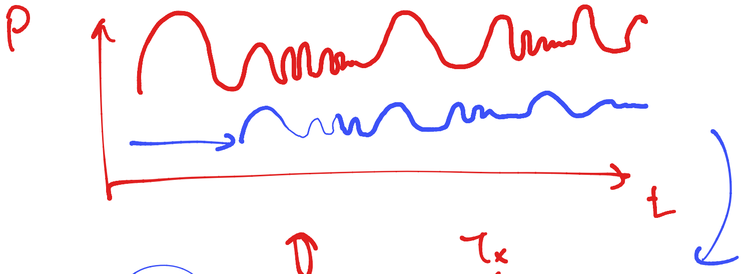
FMCW Radar

Types of Distance Measurement for Radar

Pulse radar

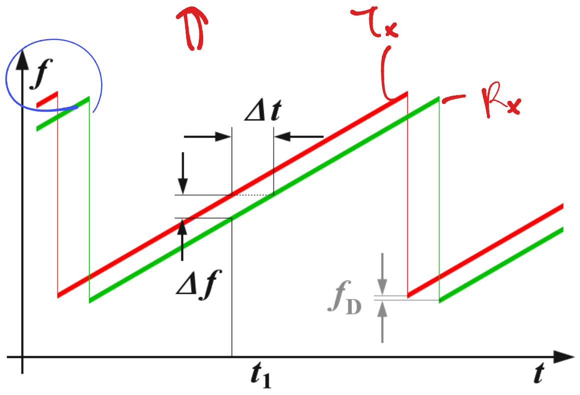
- Pulse radar emits short and powerful pulses and receives the echo signals.
- The transmitter is turned off before the measurement is finished.
  - Difficult to make powerful pulses. (warmup time needed)
  - Lower resolution.





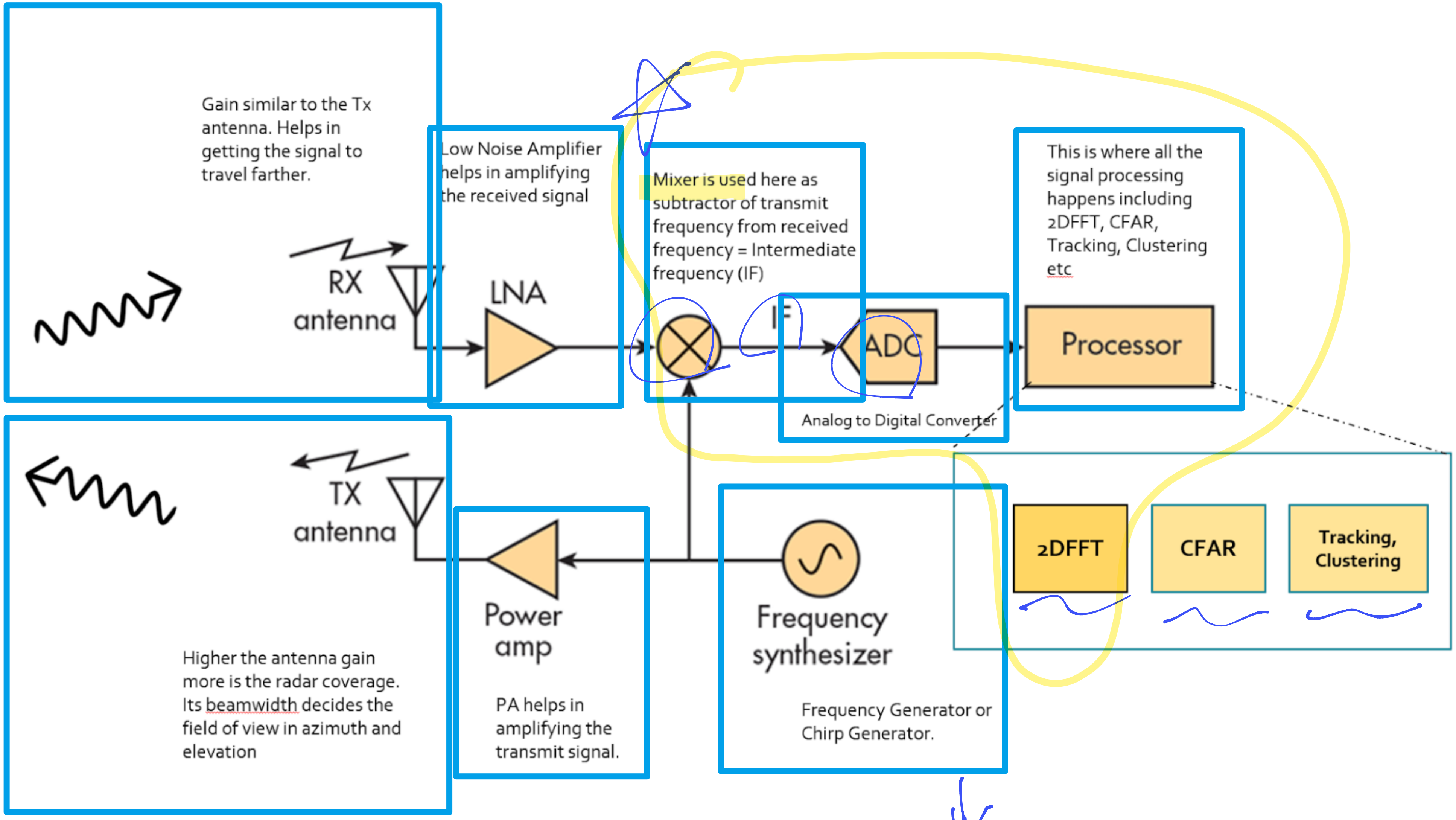
FMCW (Frequency Modulated Continuous Wave) radar

- FMCW radar can change its Operating frequency during the measurement.
  - Transmission signal is modulated in frequency (or in phase).
- Easy to calculate distance and velocity directly.



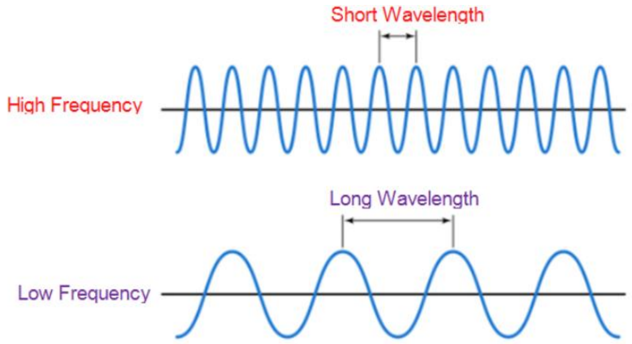
frequency domain

FMCW (Frequency Modulated Continuous Wave) Radar

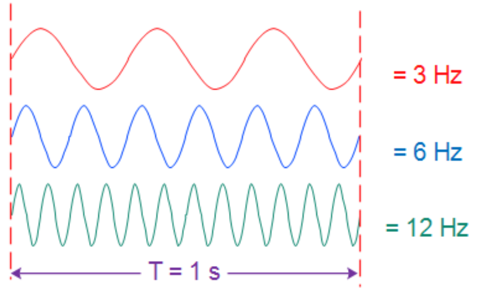


Signal Properties (1/3)

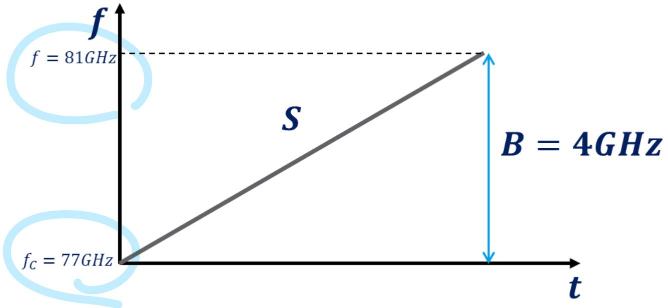
- Wavelength (λ) is the **physical length** from one point of a wave to the same point on the next wave.
  - $\lambda = \dfrac{speed\ of\ light}{frequency}$
  - The higher frequency the smaller wavelength.



- The frequency of a wave is the **number of waves that pass** by each second. (Hz)
  - Automotive radar generally operates at W band(76GHz ~ 81GHz).

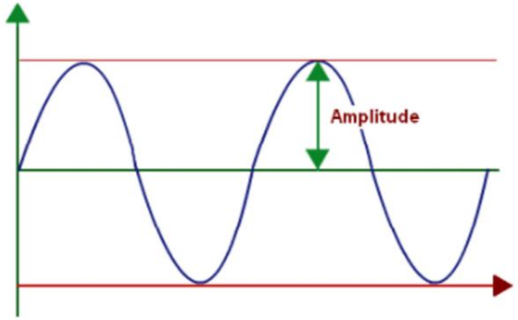


- Band Width of a signal is the **difference between the highest and the lowest frequency components** in a continuous band of frequencies.



Signal Properties (2/3)

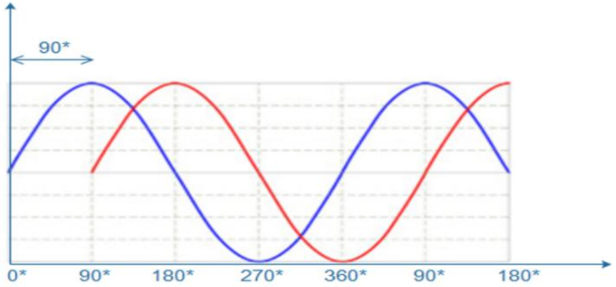
- Amplitude is the **strength** of the signal.



Amplitude of a signal

- Phase is a particular point in time on the cycle of waveform, measured as an angle in degrees.

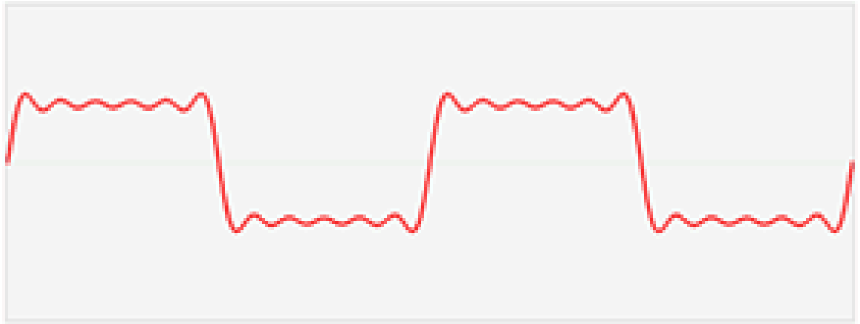
- Phase difference is the difference between of two periodic signals.
  - When the difference is zero, the two signals are said to be in phase, otherwise they are out of phase with each other.

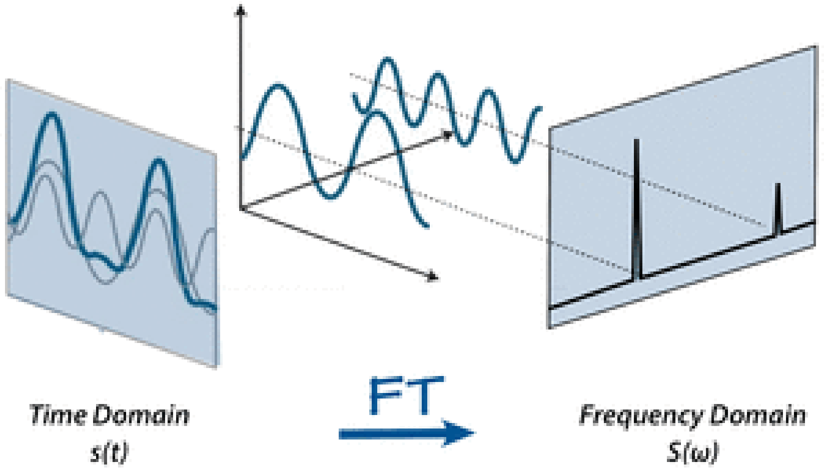


Signal Properties (3/3)

Fourier Transform (FT)

- Convert time-domain signal into frequency domain signal.
- Periodic waveform can be expressed as the sum of an infinite set of sine waves.

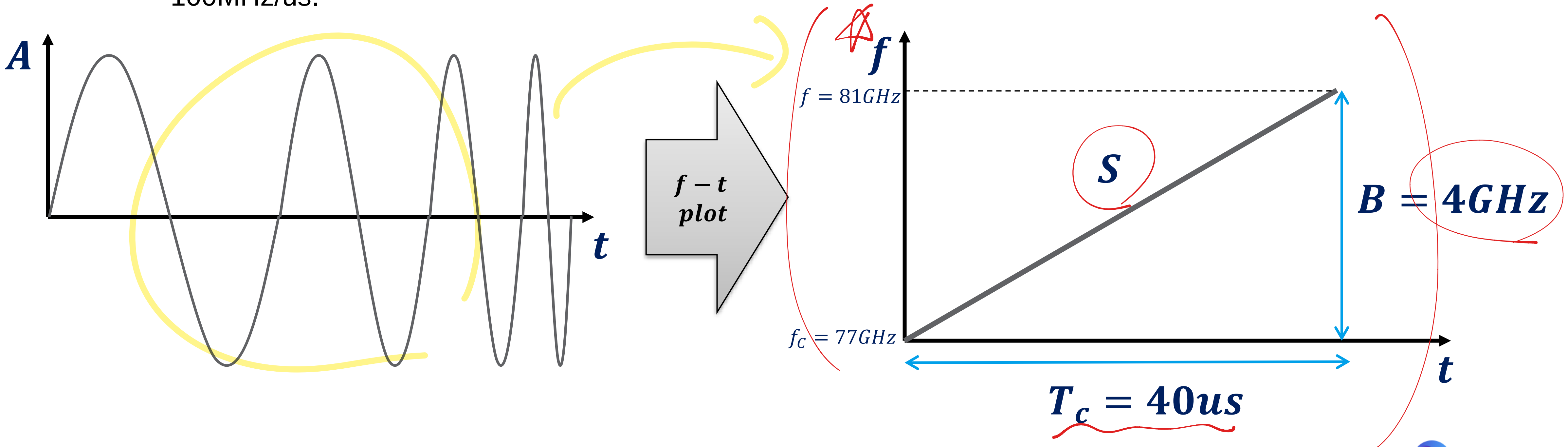




What is Chirp?

Chirp

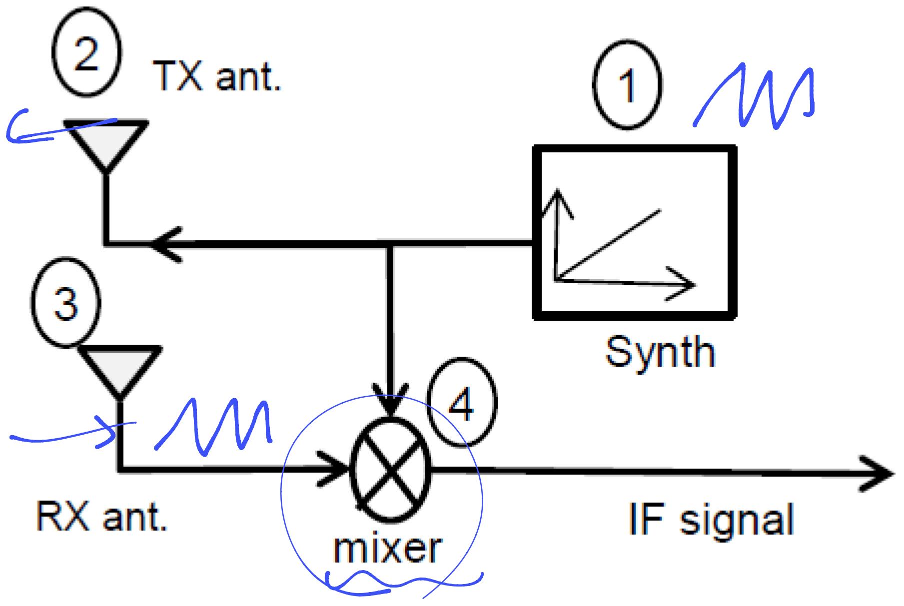
- An FMCW radar transmits a signal called a **“chirp”.**
- A chirp is a sinusoid whose frequency increases linearly with time, as shown in the Amplitude vs time.
- A chirp is characterized by a $\boxed{\text{Start frequency } (f_c)}$, $\boxed{\text{band width } (B)}$ and $\boxed{\text{duration } (T_c)}$
- The slope (S) of the chirp defines the rate at which the chirp ramps up.
  - In this example the chirp is sweeping a bandwidth of 4GHz in 40us which corresponds to a slope of 100MHz/us.



IF (Intermediate Frequency) Signal (1/2)

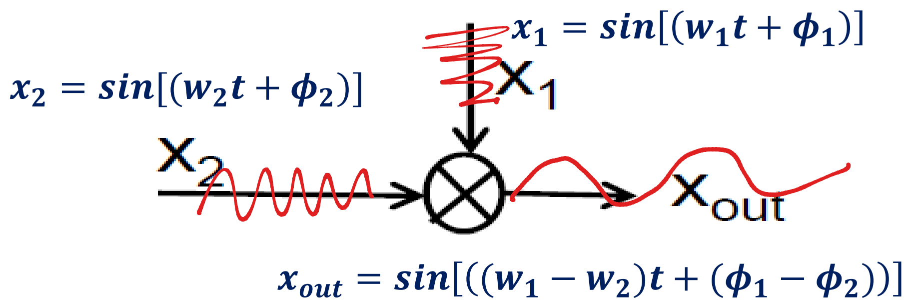
Principle of generate IF signal

1. A Synthesizer generates a chirp.
2. The chirp is transmitted by the TX antenna.
3. The chirp is reflected off an object and the reflected chirp is received at the RX antenna.
4. The RX signal and TX signal are 'mixed' and the resulting signal is called an IF Signal



Mixer

- Mixer produces new signals at the Sum and difference of the original frequencies.
- The frequency result of the mixer equals the difference between the instantaneous frequencies of the two input sinusoids.
- The phase result of the mixer is equal to the difference in the phase of the two input sinusoids.



IF Signal (2/2)

IF signal

- Frequency of the signal at the mixers output.
- Difference of the instantaneous frequency of the TX-chirp and RX-chirp.

Intermediate frequency

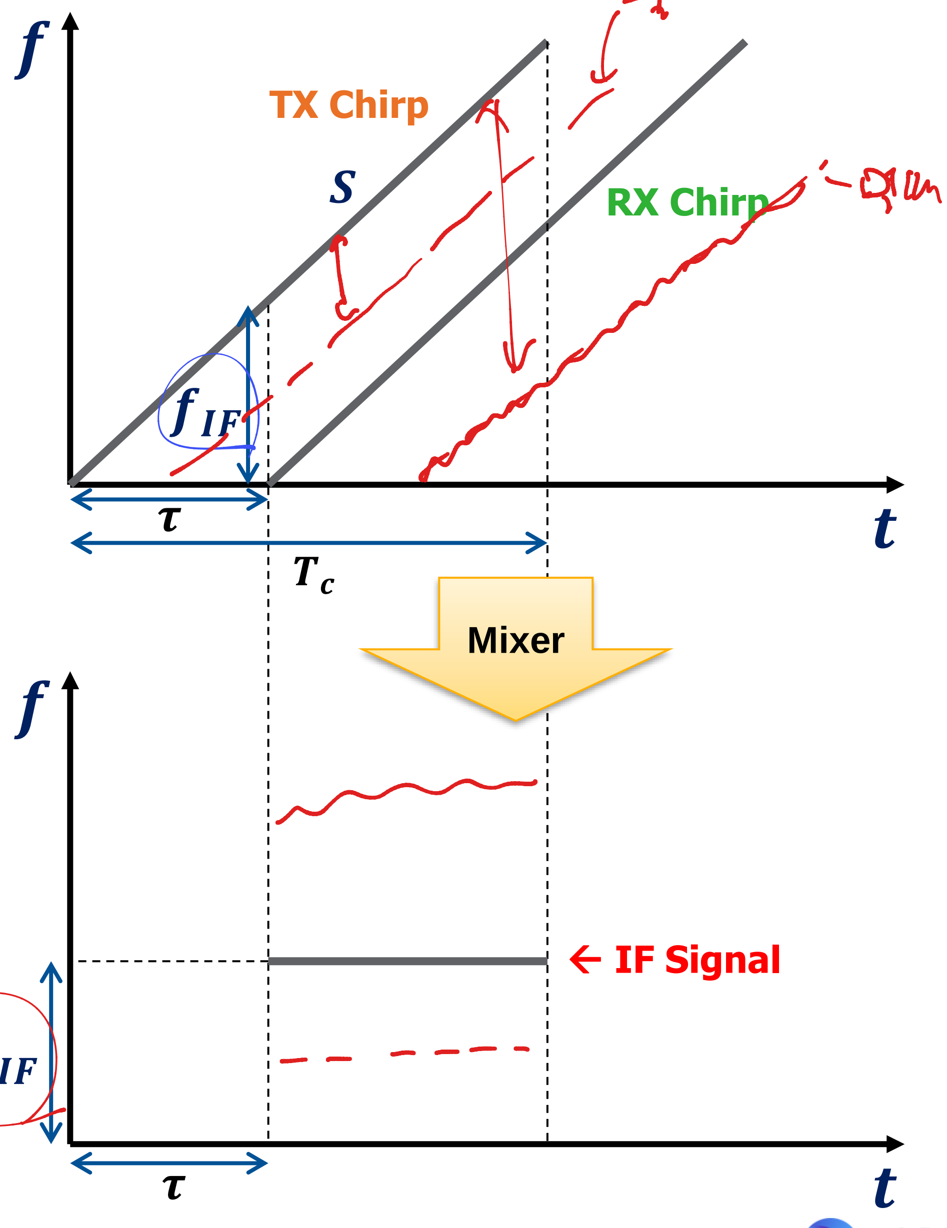
IF

τ

- Round-trip time
- $\tau = \boxed{\frac{2d}{c}} \rightarrow d = \frac{2c}{2}$
  - d: distance, c: speed of light

f_{IF}

- Frequency of the IF signal
- $f_{IF} = \boxed{S \cdot \tau = S \cdot \frac{2d}{c}}$
- $\boxed{d = \frac{f_{IF}\, c}{2S}}$

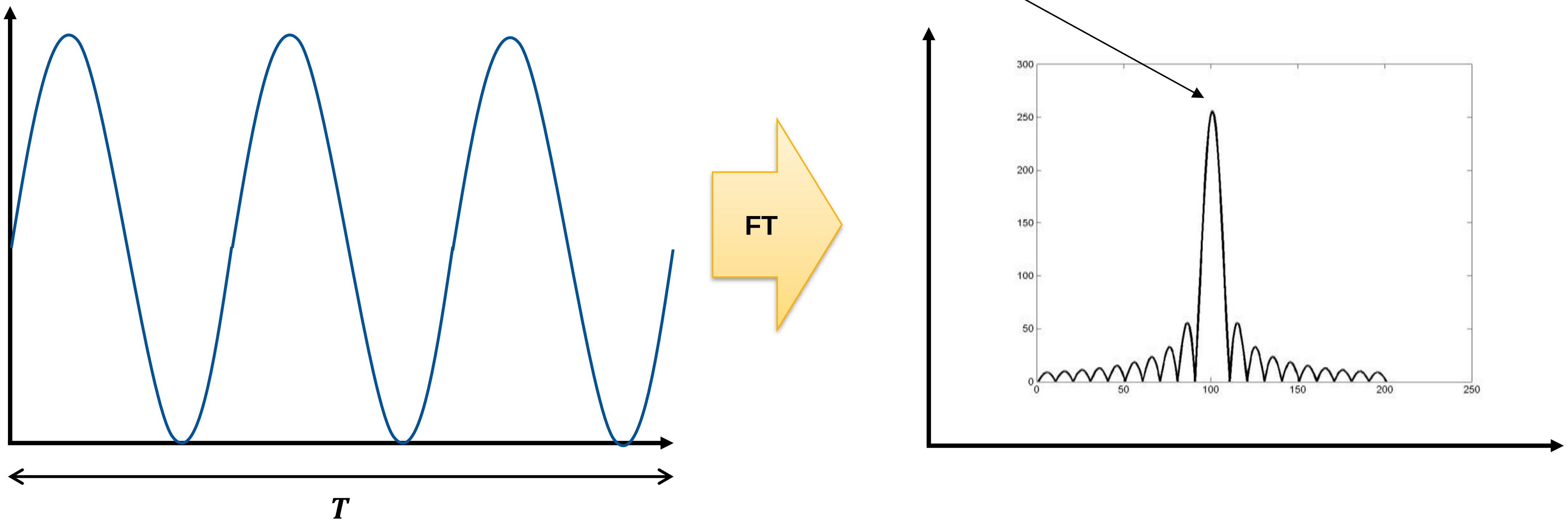


Fourier transform

Range Resolution in Radar (1/5)

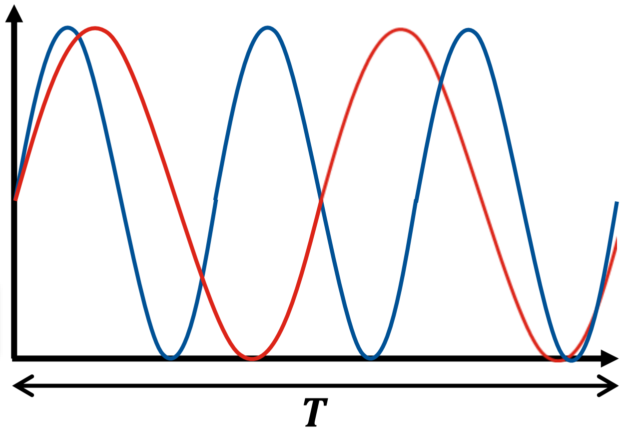
Fourier transform

- Fourier transform converts a time domain signal into the frequency domain.
- A sinusoid in the time domain produces a single peak in the frequency domain.



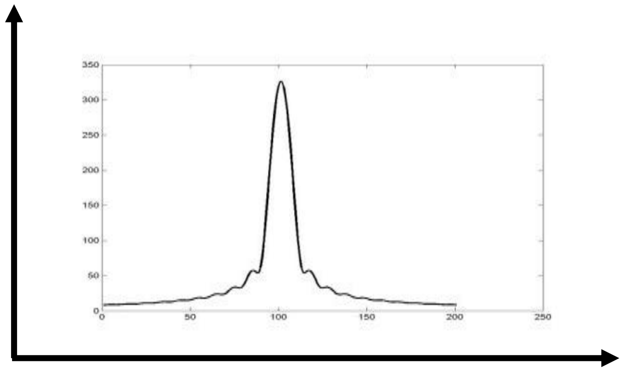
Range Resolution in Radar (2/5)

- **Two tones case: red tone (2 cycles), blue tone (3 cycles) in time window T.**
  - The difference of 1 cycle is not sufficient to resolve the tones in the frequency spectrum.

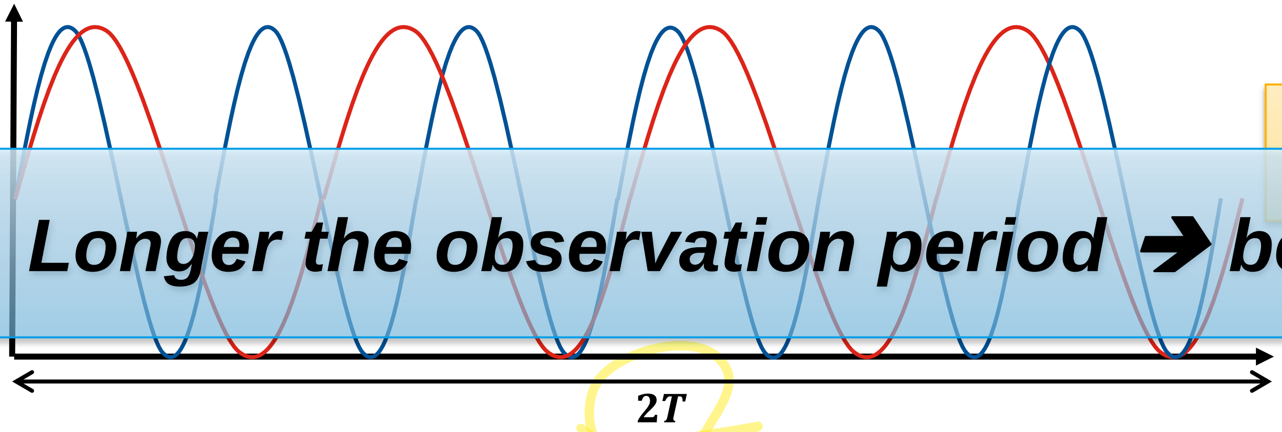


Not sufficient to resolve the two tones!

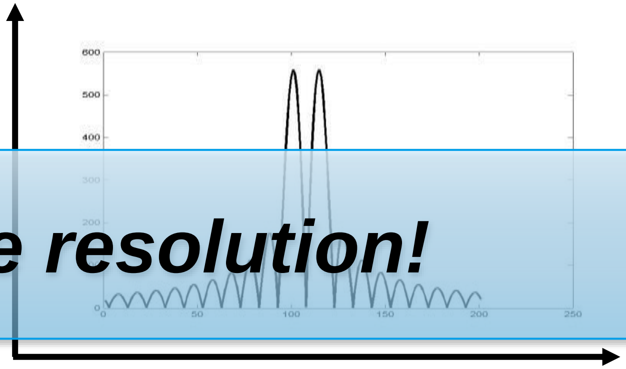
FT



Doubling observation window



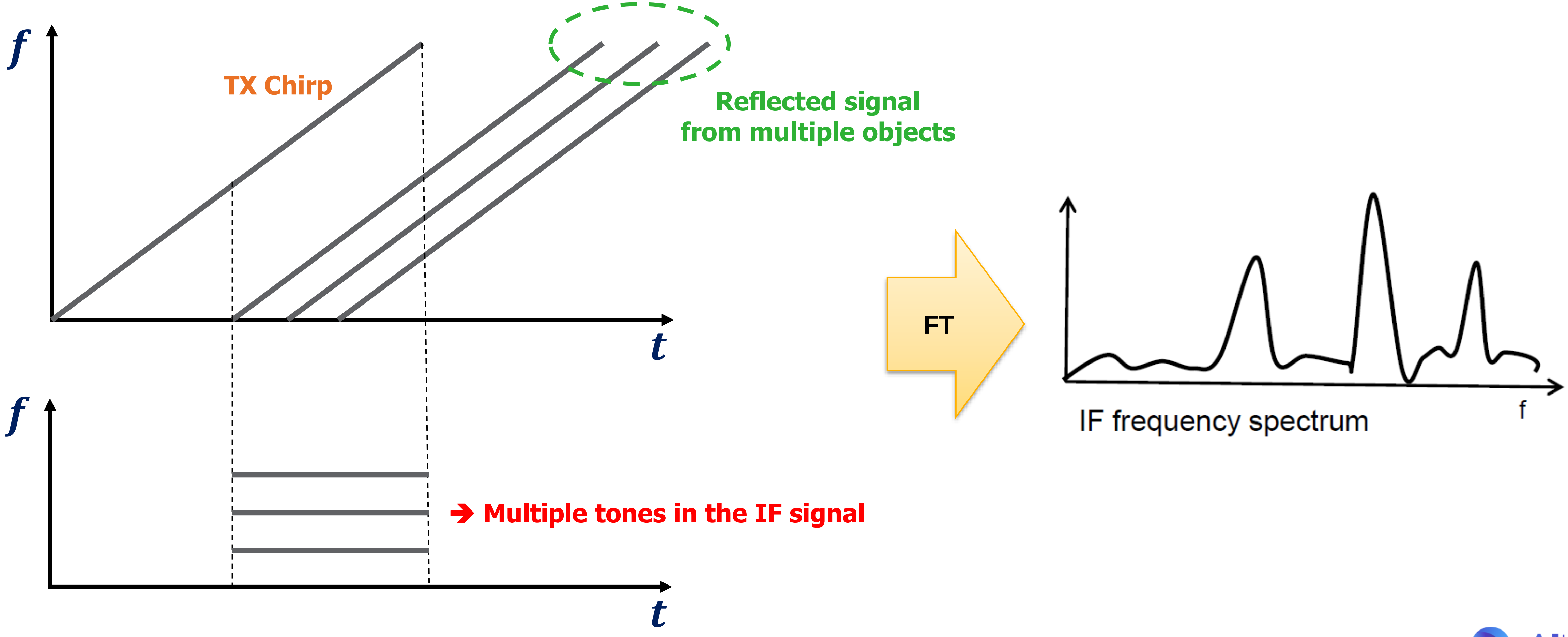
FT



Longer the observation period ➔ better the resolution!

Range Resolution in Radar (3/5)

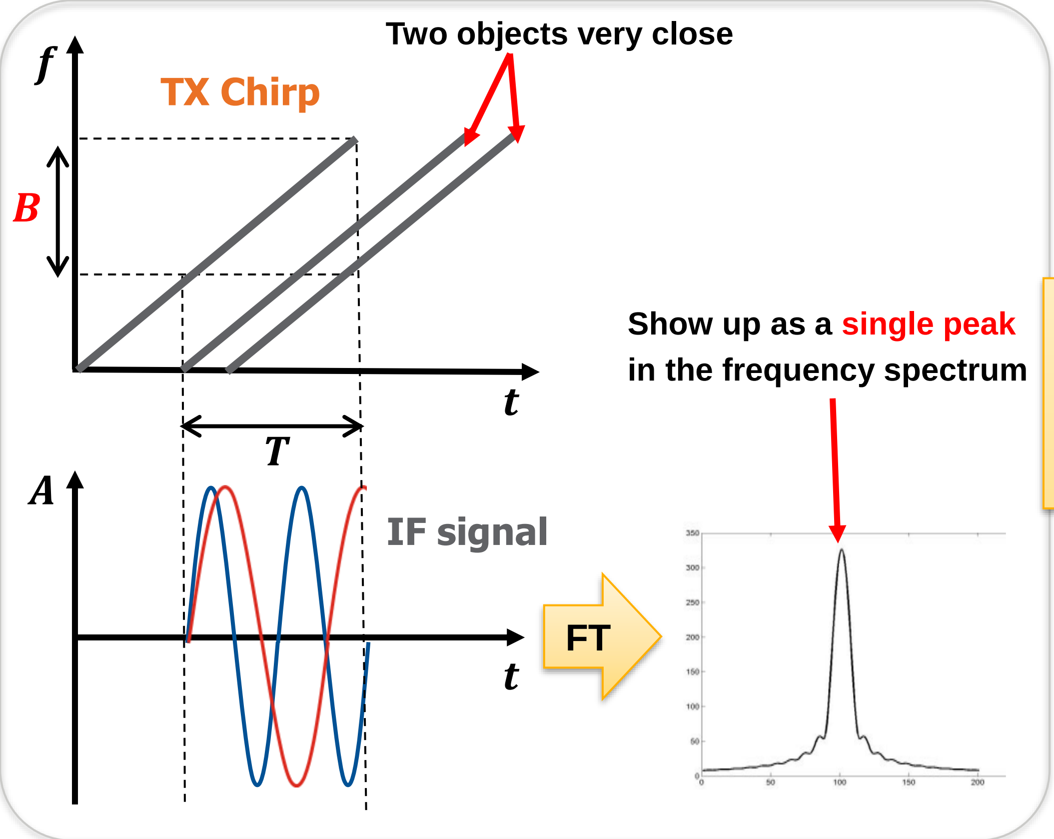
- **Multiple objects in front of radar generate multiple reflected chirps at the RX antenna.**
  - A frequency spectrum of the IF signal will reveal multiple tones, the frequency of each being proportional to the range of each object from the radar.



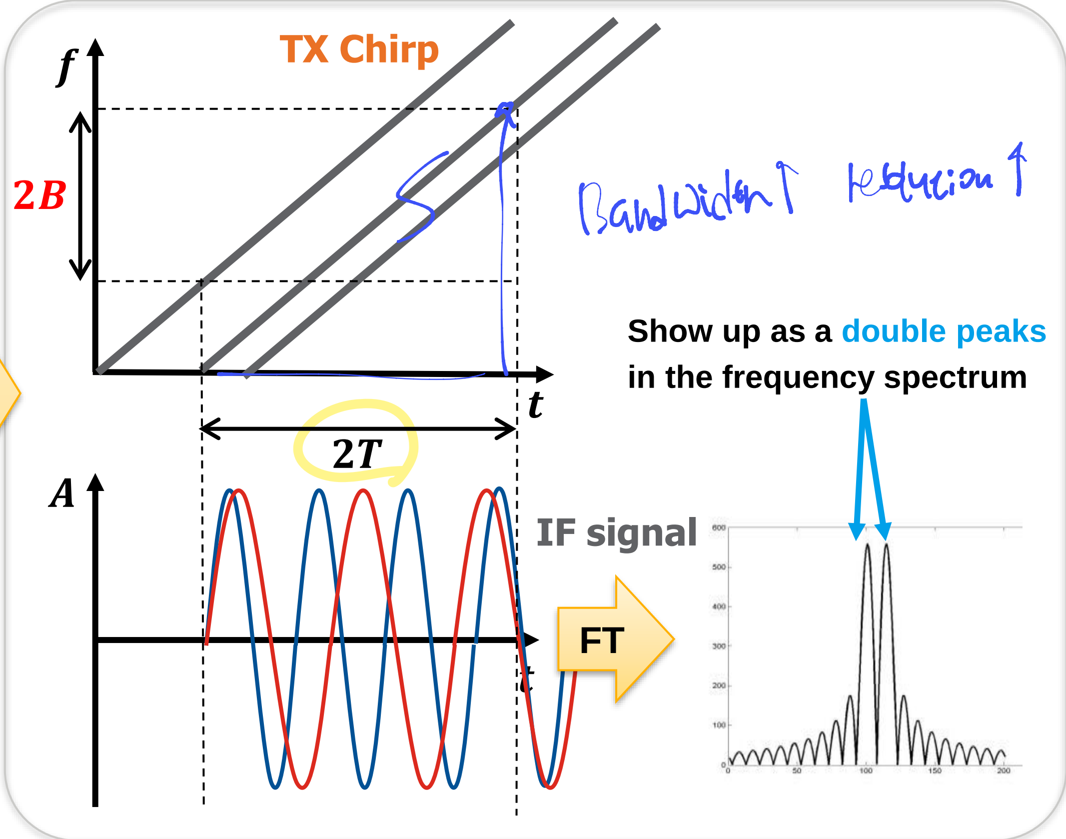
Range Resolution in Radar (4/5)

Range resolution

- Ability to resolve two closely spaced objects.
- The two objects can be resolved by increasing the length of the IF signal.
- It also proportionally increases the bandwidth, thus **"Greater bandwidth ➔ Better resolution"**.



Increase the length of IF signal



Range Resolution in Radar (5/5)

Difference of IF frequencies

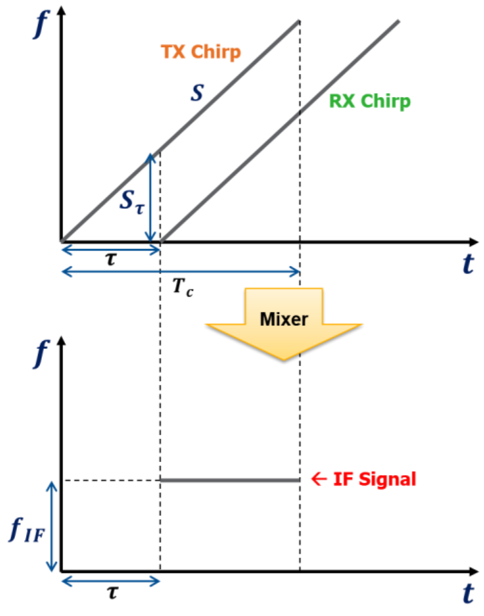
- $\Delta f = \frac{S2\Delta d}{c}$
  - Δd : distance between two objects
  - T_c : Observation interval
- $\Delta f > \frac{1}{T_c}$
- $\boxed{\frac{2S\Delta d}{c} > \frac{1}{T_c}}$
- $\boxed{\Delta d > \frac{c}{2ST_c}}$
- $\boxed{\Delta d > \frac{c}{2B}}$ (since $\boxed{B = ST_c}$)

Frequency formula

$$f = \frac{1}{T}$$

$T_c \propto$ Bandwidth

Review of Frequency of the IF signal



$$f_{IF} = S \cdot \frac{2d}{c}$$

Range resolution equation

- The range resolution depends only on the bandwidth swept by the chirp!

$$\boxed{d_{res} = \frac{c}{2B}}$$

Maximum Range

- **The bandwidth of interest of the IF signal depends on the desired maximum distance.**

$$\boxed{f_{IF_{max}} = \frac{S\,2d_{max}}{c}}$$

- **IF bandwidth is limited by the ADC sampling rate (F_S).**

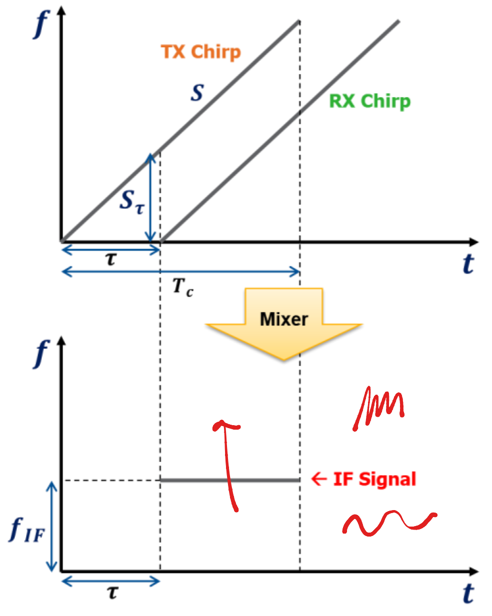
$$\boxed{F_S \geq \frac{S\,2d_{max}}{c}}$$

얼마나 빨리 측정하는?

- **Maximum range equation**
  - An ADC sampling rate of F_S limits the maximum range (d_{max}) of the radar!

$$\boxed{d_{max} = \frac{F_S c}{2S}}$$

Review of Frequency of the IF signal



$$f_{IF} = S \cdot \frac{2d}{c}$$

Summary

- An object at a distance d produces an IF frequency of:

$$f_{IF} = \frac{S2d}{c} \Rightarrow d = \frac{f_{IF}c}{2S}$$

- Range resolution (d_{res}) depends on the bandwidth (B):

$$d_{res} = \frac{c}{2B}$$

- The ADC sampling rate F_s, limits the max range (d_{max}) to:

$$d_{max} = \frac{F_s c}{2S}$$

THANK YOU
FOR YOUR ATTENTION