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Introduction to Modern Radar for Machine Perception

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Content

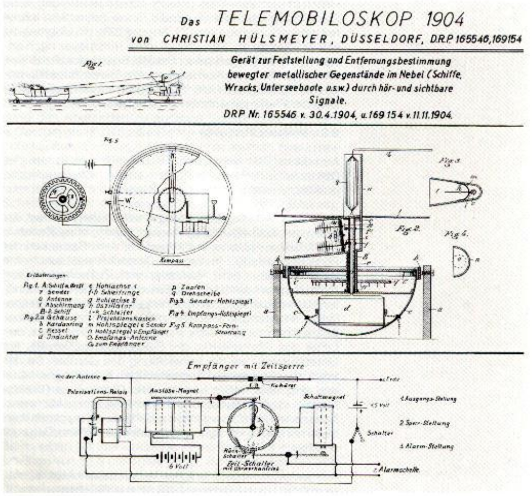
1. Radar: fundamental principle
2. Radar history and modern radar development
3. Technology for radar: time of flight, continuous wave radar, frequency modulation
4. FMCW radar: the chirp signal, signal mixing
5. FMCW signal processing: range, Doppler, direction of arrival
6. The Range-Azimuth-Doppler signal
7. Detection from radar: constant false alarm rate algorithms
8. Pros and cons of radars
9. Conclusion

Radar development

- Radar is a relatively old technology
  - Mature solid-state design, very reliable
- New applications emerged in recent years
  - Occupancy detection
  - Gesture recognition
  - Automotive (ADAS and AV)
- Almost every aspect of radar performance has improved
  - Cost, size, power, resolution, etc.

Radar history

- 1886-1889, German physicist Heinrich Hertz experimentally prove the existence of radio waves
  - Predicted by Maxwell’s theory of electromagnetism (1865)
- 1904, German engineer Christian Hülsmeyer invented Telemobiloscope
  - First patented device to use radio waves for detecting objects
  - 18th May 1904 first public demonstration
- World War II stimulated the development and large-scale deployment of Radar

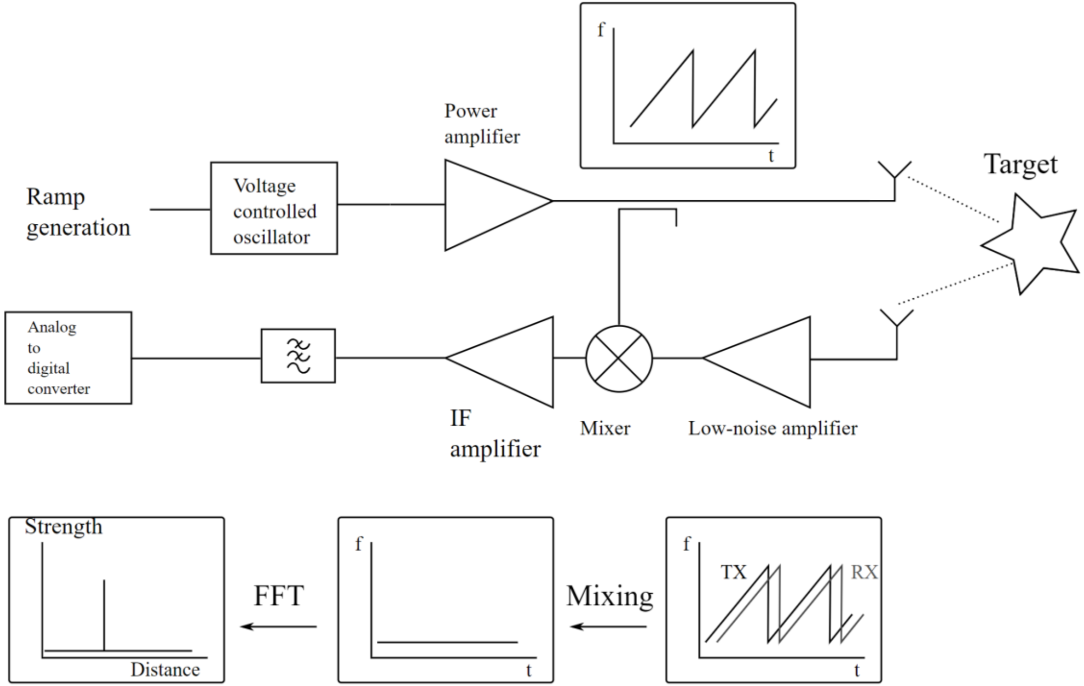


radarworld.org/huelsmeyer.html

Three technologies for radar

1. Time of Flight (ToF)
2. Continuous Waves (CW)
3. Frequency Modulation (FM)

➢ **FMCW Radar**



https://hforsten.com/third-version-of-homemade-6-ghz-fmcw-radar.html

1. Time of flight (ToF) for distance estimation

- In its simplest form, an impulse signal is sent
- Measuring time to receive the echo yield to distance estimate according to:

$$R = \frac{c \cdot \Delta t}{2}$$

R , Range estimation
Δt , Time duration
c , Light speed: $3 \times 10^8 \; m/s$

monostatic radar

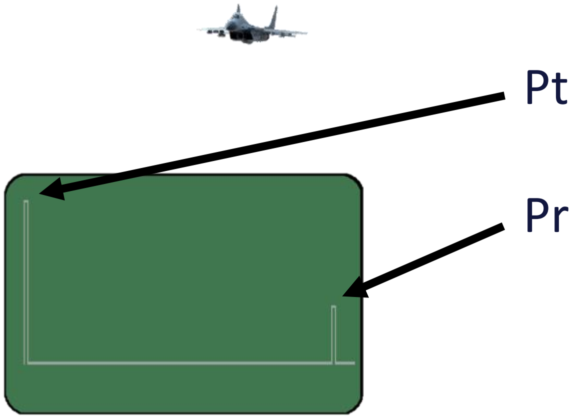
www.radartutorial.eu/01.basics/Distance-determination.en.html

Radar cross section

- The power received **Pr** is a fraction of the power transmitted **Pt**

$$\mathbf{Pr} = \mathbf{Pt} \times (\text{gain}) \times \left(\frac{\text{spread factor}}{4\pi r^2}\right) \times (\text{losses}) \times \boldsymbol{\sigma} \times \left(\frac{\text{spread factor}}{4\pi r^2}\right) \times (\text{aperture}) \times (\text{dwell time})$$

- **σ** is the radar cross section (expressed in m^2) defines how detectable is the target; it depends on:
  - Target material
  - Target shape
  - Target size
  - Incident angle



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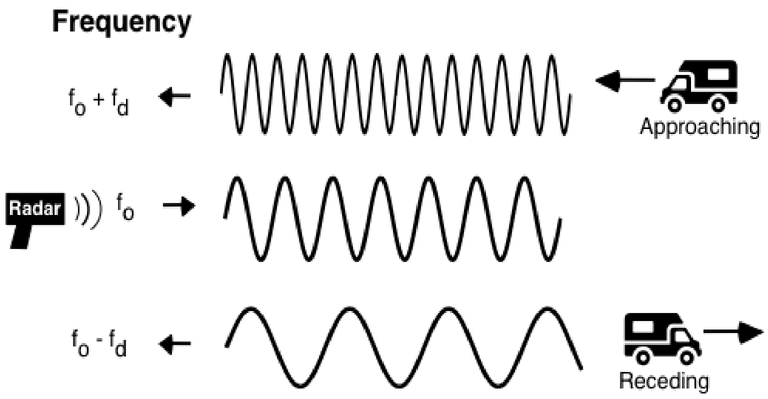
2. Continuous wave (CW) and the Doppler effect

- A continuous signal is transmitted
- The Doppler effect provides target velocity information
  - The Doppler frequency is the difference between the transmitted signal frequency and the received signal frequency

$$f_r = \frac{1 + v/c}{1 - v/c} f_t$$

$$f_d = f_r - f_t = 2v\frac{f_t}{c - v} \approx 2v\frac{f_t}{c}$$

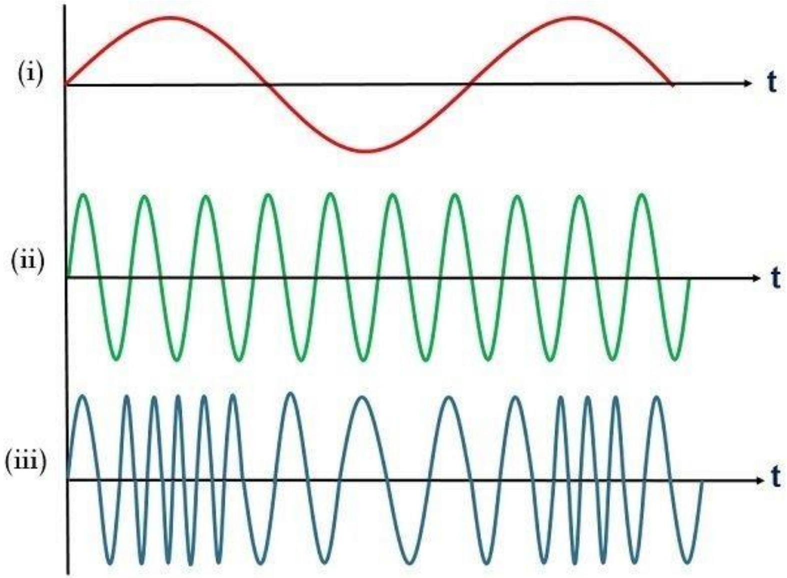
f_d , Doppler frequency
f_t , Transmitted frequency
f_r , Received frequency
c , Light speed: $3 \times 10^8\ m/s$
v , Target velocity



copradar.com/chapts/chapt3/ch3d1.html

3. Frequency modulation (FM) signal encoding

- Technique for encoding of information into a wave signal by varying its instantaneous frequency
- For radar this is a way to add information
    - To better estimate velocity and range via Doppler shift
    - To reduce interference by making the signal more distinctive

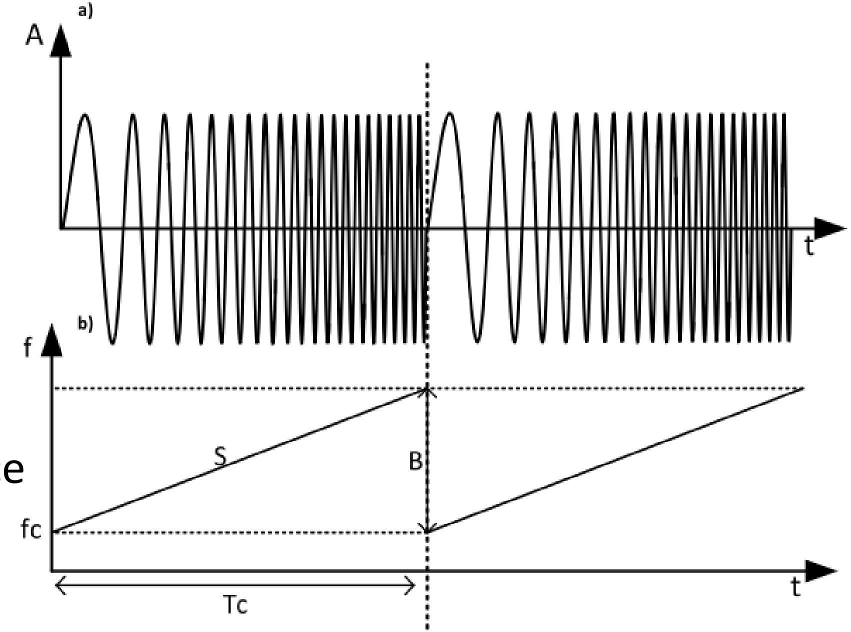


(i) Modulating signal
(ii) Carrier waveform
(iii) Frequency modulated signal

Electronics Coach

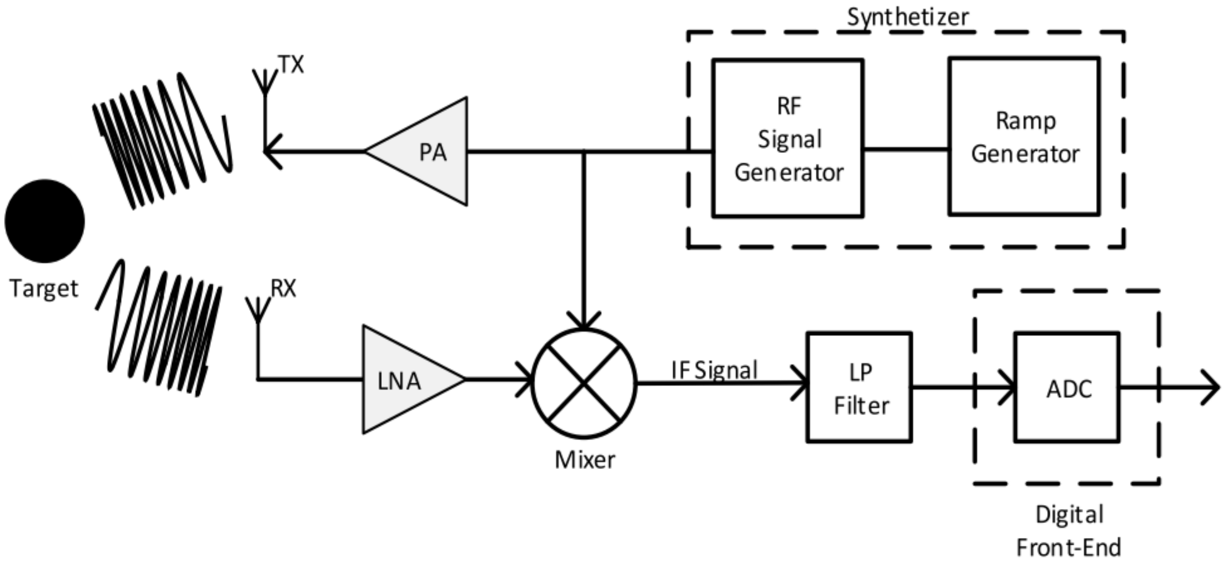
FMCW signal

- FMCW radars transmit and receive a signal that combine FM and CW techniques
- The signal frequency changes periodically w.r.t time, one period is often referred to as one "chirp"
- Signal parameters:
  - Chirp periodicity T_c;
  - Frequency slope S;
  - Frequency bandwidth of one chirp B.
  - As we will see, the choice of the signal parameters will affect the radar performance
- A radar frame is made of N chirps



FMCW signal mixing

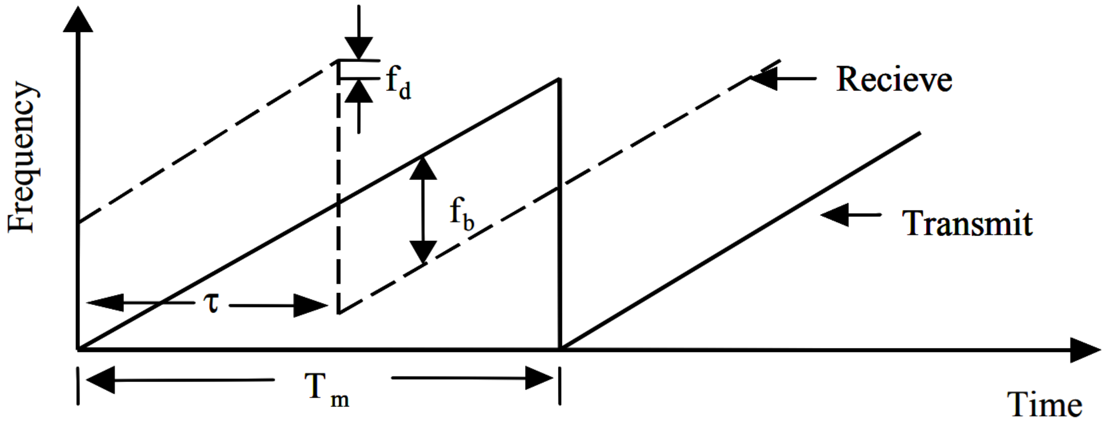
- The transmitted (Tx) and received (Rx) signals are mixed by an onboard mixer
- The resulting signal is then digitized by an analog to digital converter (ADC)



www.radartutorial.eu/01.basics/Distance-determination.en.html

The mixed signal

- The frequency difference f_b between the Tx and Rx signals is called the beat frequency
  - The beat frequency carries range and velocity information
  - The frequency shift (or Doppler shift) f_d is proportional to velocity
  - The time shift τ is proportional to the distance of the target



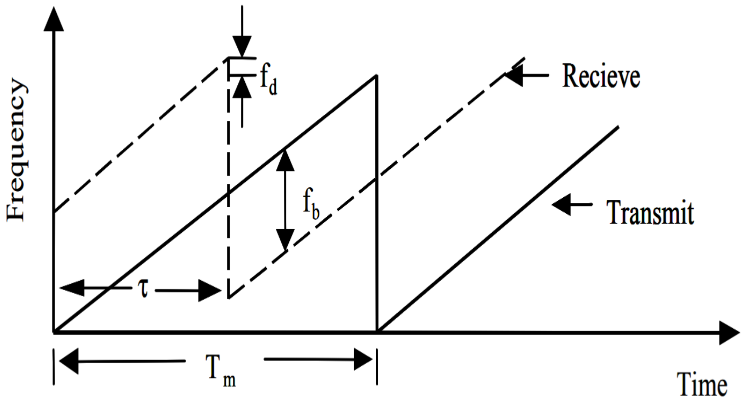
uwaterloo.ca/centre-for-intelligent-antenna-and-radio-systems/sites/ca.centre-for-intelligent-antenna-and-radio-systems/files/uploads/files/fmcwradarsystem.pdf

FMCW digital signal processing

- The input signal is a radar frame composed of N Chirps
  - This is the ADC signal
    - i.e., the signal from the Analog-to-Digital converter
- The Fast Fourier Transform (FFT) is the main tool for the analysis of FMCW radars
- Traditional FMCW DSP is normally divided into 3 steps:
  - Range FFT
  - Doppler FFT
  - Direction of Arrival (DOA)
- The resulting signal is three-dimensional and is therefore designated as the:
  - **Radar Data Cube**

The range FFT

- The beat frequency f_d (a.k.a. intermediate frequency) is computed by FFT from ADC signals.
  - The theoretical maximum range is limited by the chirp periodicity ($\tau < T_m$).
  - In practice it is limited by the power of the signal and the ADC sampling rate.
  - To increase the range resolution, you must increase the chirp frequency bandwidth B.
- This range FFT is conducted with the signals collected in one chirp.



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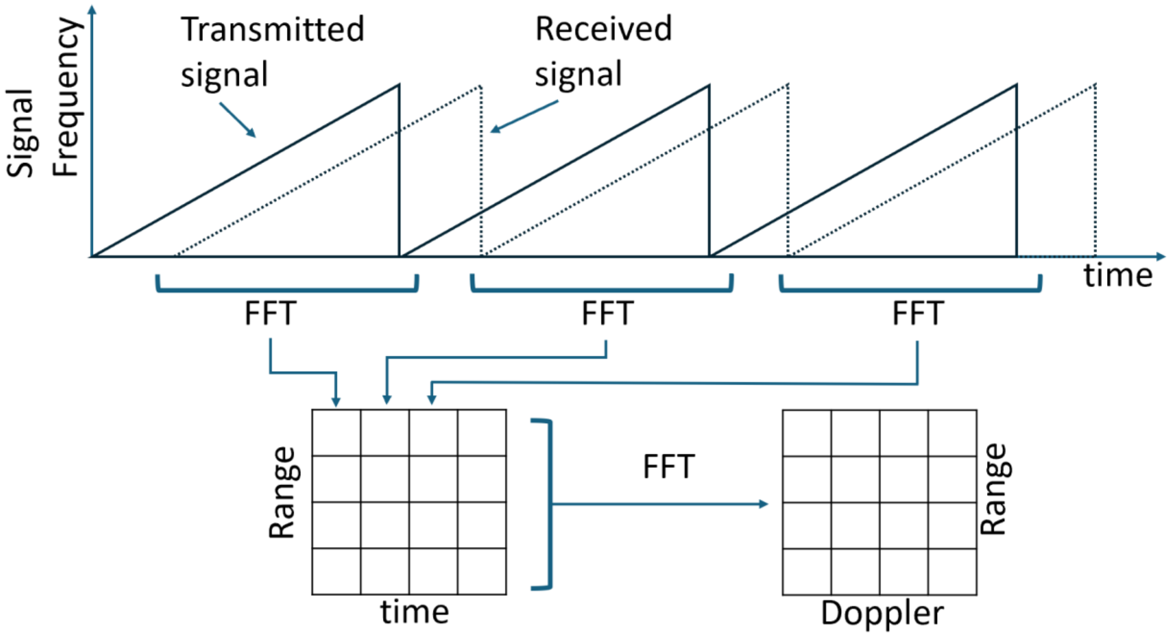
Doppler FFT

- The velocity is extracted by observing the change in phase of the beat frequency between consecutive chirps.
- This Doppler FFT is therefore computed over the series of chirps in a radar frame.
- To increase the range resolution, you must increase the number of chirps in the radar frame.



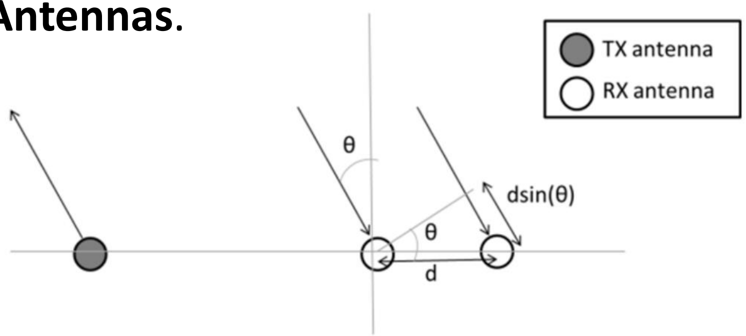
Range and velocity estimation summary

	Range [m]	Velocity [m/s]
Definition:	$\frac{c \cdot IF_{tone}}{2S}$	$\frac{\lambda \Delta \Phi}{4\pi T_c}$
Resolution:	$\frac{c}{2B}$	$\frac{\lambda}{2T_f}$
Maximum:	$\frac{F_s c}{2S}$	$\frac{\lambda}{4T_c}$

$\Delta\Phi$, Phase Shift (Doppler Frequency)
λ , Signal Wavelength
v , Target Velocity
c, Speed of light
IF_{tone}, Beat frequency
S, Chirp frequency slope
Tc, Chirp period
D, Chirp frequency bandwidth
T_f, Frame period
F_s, ADC sampling frequency

Direction of arrival (MIMO)

- MIMO radars use multiple transmitting (Tx) and receiving (Rx) antennas
  - Creating (Tx) x (Rx) virtual antennas (i.e. mixed signals)
- The angle estimation is based on the phase differences between the signals received from different onboard receivers.
- Signals transmitted from different transmitters and received at different receivers are rearranged into an array called **Virtual Antennas**.
- Based on the physical arrangement of the antennas, you can measure both
  - Vertical (Elevation) and
  - Horizontal (Azimuth) directions

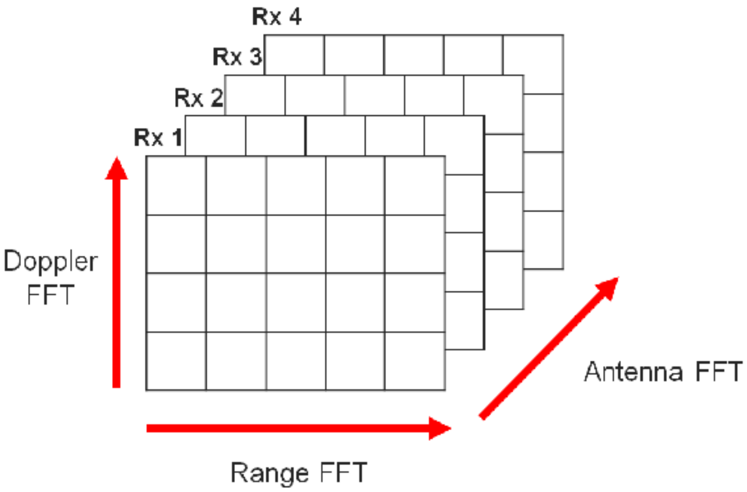


- 3Tx and 4Rx antennas = 12 channels is a common configuration

www.ti.com/lit/an/swra554a/swra554a.pdf?ts=1616040203534

Range-Azimuth-Doppler: the RAD cube

- The ADC signal is pre-arranged into a 3D tensor
  - Number of digital samples per chirp X
    number of chirps X
    number of virtual antennas.
- The output from 3D-FFT is called range-azimuth-Doppler (RAD) tensor
  - **The RAD Cube**

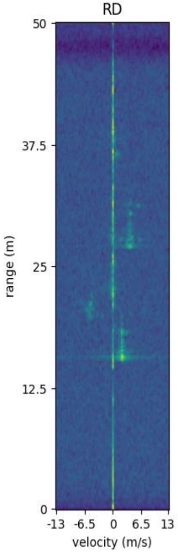


www.semanticscholar.org/paper/79-GHz-wideband-fast-chirp-automotive-radar-sensor-Sturm-Li/3d0fb8b52e40bf870bccc908217065ec7a15311a/figure/1

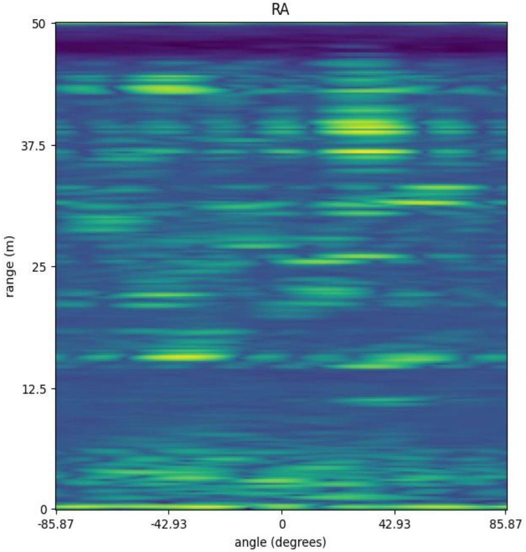
Range-Azimuth-Doppler: the RAD cube

- Range-azimuth-Doppler (RAD) tensors are usually projected onto 2D planes for visualization.
- The two most practical planes for visualizing RAD tensors are:
  - Range-Doppler (RD) spectrum
  - Range-Azimuth (RA) spectrum

Range vs Velocity



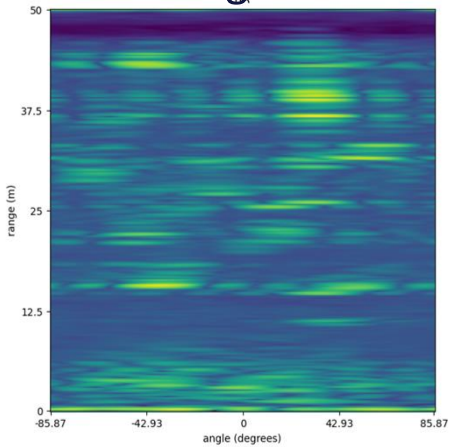
Range vs Angle



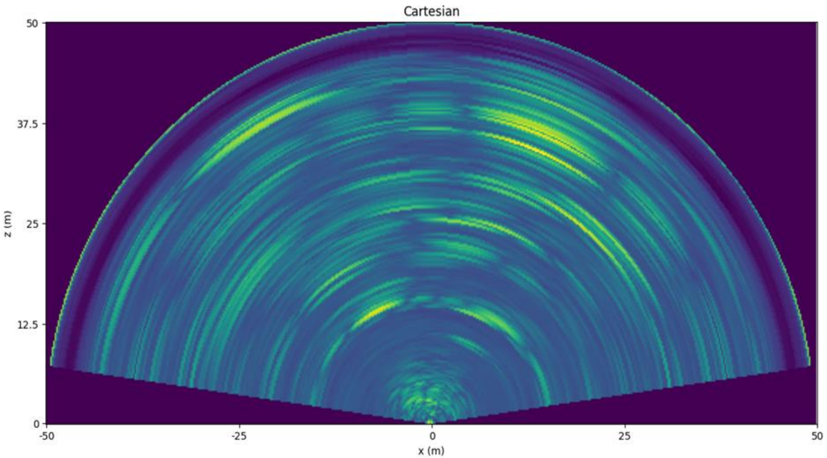
Polar to Cartesian

- RA spectrum is presented with [range, angle] representations in polar coordinates.
- To increase the readability, RA data can also be transformed into top-view coordinates.

Range vs Angle



Cartesian coordinates [X,Z]



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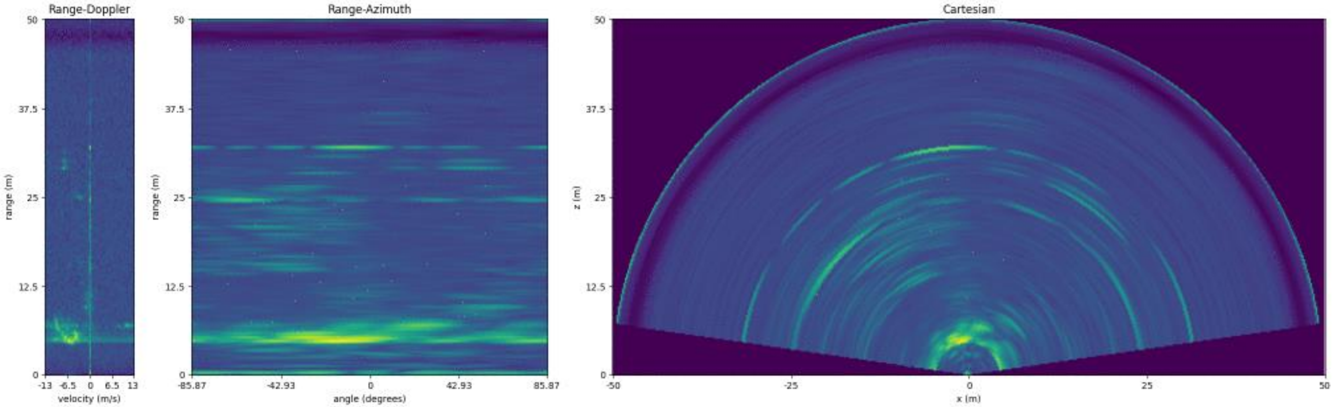
Detection from radar

- From the information embedded in the RAD cube, it is possible to detect objects.
  - But this signal is complex to analyze.

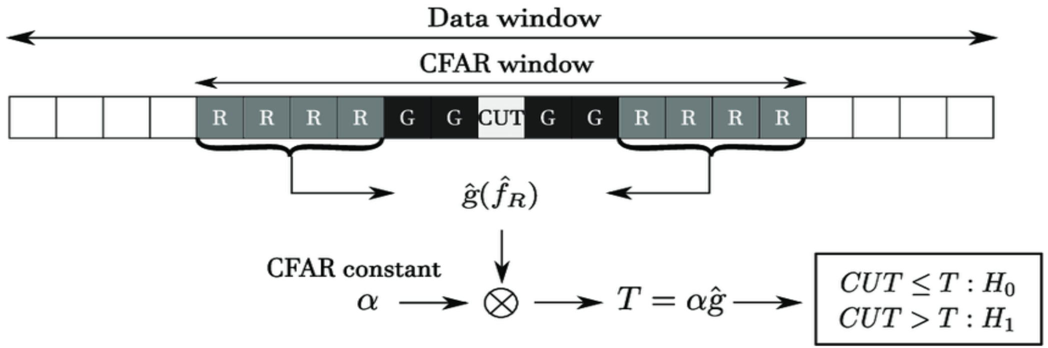


The next step is generally to perform thresholding and clustering operations to extract meaningful objects.

- The main algorithm to accomplish this objective is the **CFAR.**

Constant false alarm rate (CFAR) algorithm

- Constant false alarm rate (CFAR) is the most popular denoise algorithm for FMCW radars.
  - Usually used for the detections on RD spectrum.
  - It is a sliding window-based algorithm.
- Different thresholding variants exist:
  - Cell averaging: CA-CFAR
  - Ordered statistics: OS-CFAR



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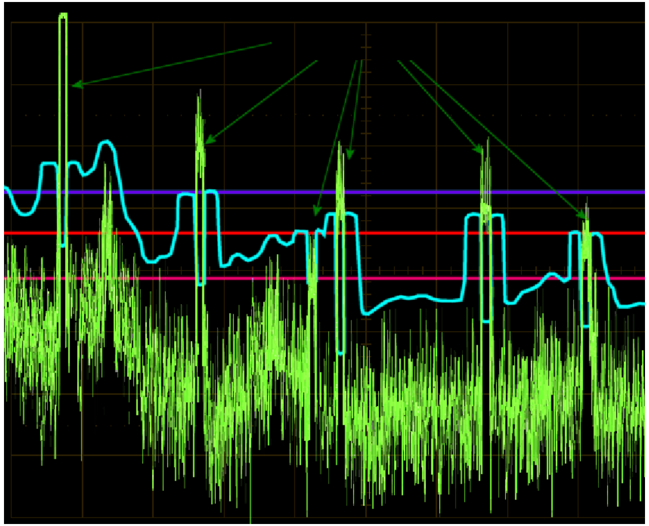
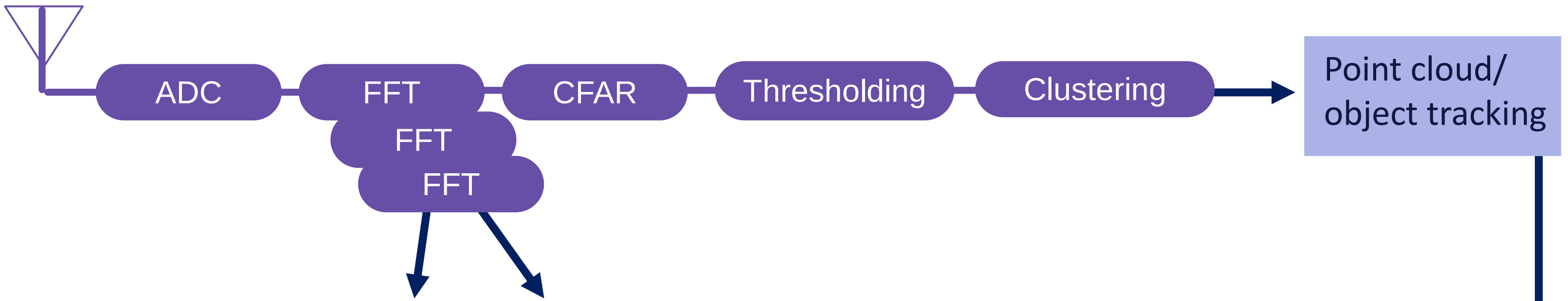


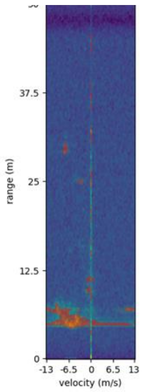
www.radartutorial.eu/01.basics/False%20Alarm%20Rate.en.html

CUT: Cell under test
G: Guard cells
R: Reference cells

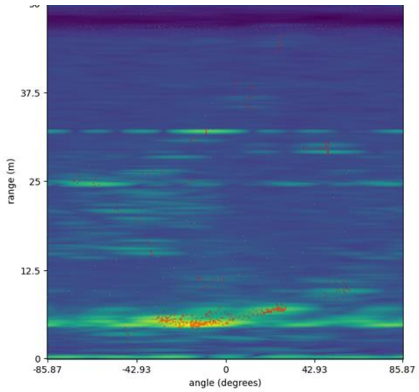
Traditional radar pipeline



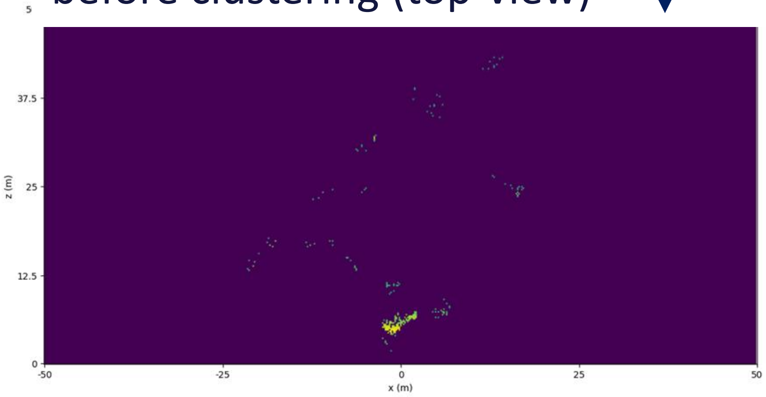
Range-Doppler



Range-Azimuth



This is the radar point cloud before clustering (top-view)



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Pros of FMCW radars

- Weather-proof:
  - FMCW radars can penetrate mediums such as clouds, fogs, mist and snow
- Illumination-proof:
  - The signal frequency is specially designed and not affected by other visible light sources
- Rich detection:
  - FMCW radars can detect the positions and speeds of the targeted objects simultaneously
- Large Field of View (FoV):
  - The FoV of FMCW radars is approximately 180 degrees
- Economically friendly:
  - FMCW radars are normally cheaper than other sensors in autonomous driving.

Cons of FMCW radars

- Noisy:
  - The noisy signals lead to difficulties of distinguishing target objects from background noise
- Unintuitive representations:
  - The detection outputs are not visually intuitive to human observers
- Ignorance of some objects:
  - Because FMCW radars can penetrate certain materials such as glasses, those objects are sometimes not visible in radar frames
- No visual details:
  - Radars cannot reveal the details of different objects, such as colors, surface properties, etc.
  - For example, it cannot read road signs

Conclusion

- Radars are cheap, reliable, robust solid-state sensors
  - Its claimed robustness to adverse weather condition is assumed but still must be fully demonstrated
- Radars are becoming an essential component of complex perception systems
  - e.g., autonomous vehicles
- Radars are improving in resolution and accuracy
- Deep neural networks (artificial intelligence) can be applied to radar
- Multi-sensor integration is the future of perception
  - Radars will be part of it

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