

# **Radar Technology**

## **Signal Data Processing and Object Detection**

**AGCO GmbH Julian Sauter  
22nd of October, 2025**

**HS Kempten**

**Alle Daten sowie Unterlagen dürfen nur im Rahmen  
der Vorlesung Sensorik im Studiengang  
"Fahrerassistenzsysteme" verwendet werden**

# AGENDA

1. Introduction to FMCW Radar and Imaging Radar
2. FMCW / Imaging Radar explained with Texas Instruments Radar
3. Signal Processing in Software and Mathematical Background
4. Introduction to PSA
5. Datasets for PSA

# TABLE OF CONTENTS

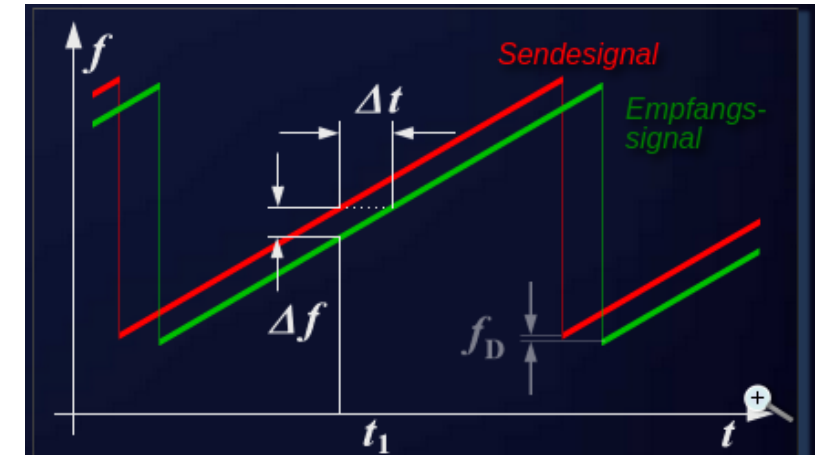
1. Introduction Radar
  1. Current stand
  2. FMCW function principle
  3. MIMO FMCW cascade radar
  4. Imaging Radar
2. Texas Instruments Development Board
  1. Structure
  2. Antenna configuration
  3. Radar / chirp configuration
  4. Signal processing and radar raw data

# INTRODUCTION RADAR – FMCW RADAR

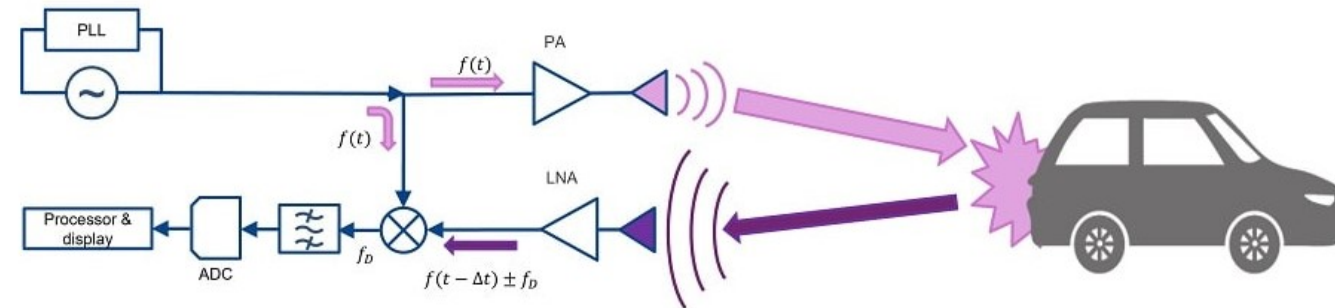
## Function principle

FMCW = Frequency-Modulated Continuous Wave

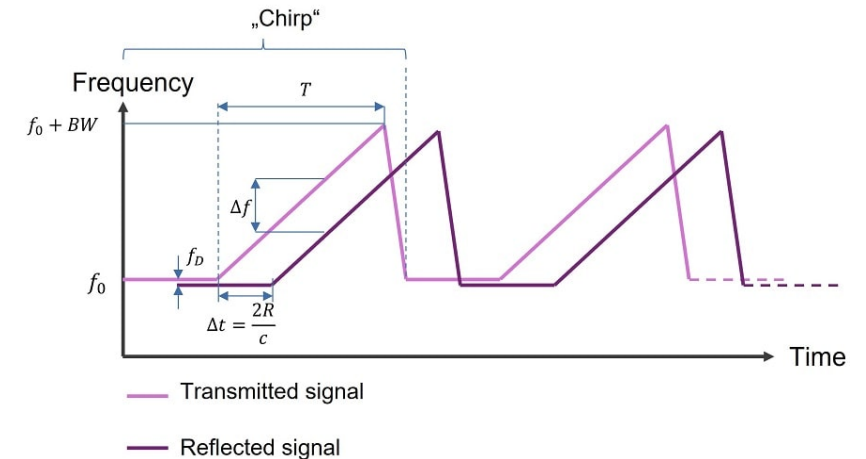
- Continuous transmitting signal
- Frequency is modulated in range of bandwidth
- Modulation often done by chirp sequence modulation



[4]



[5]



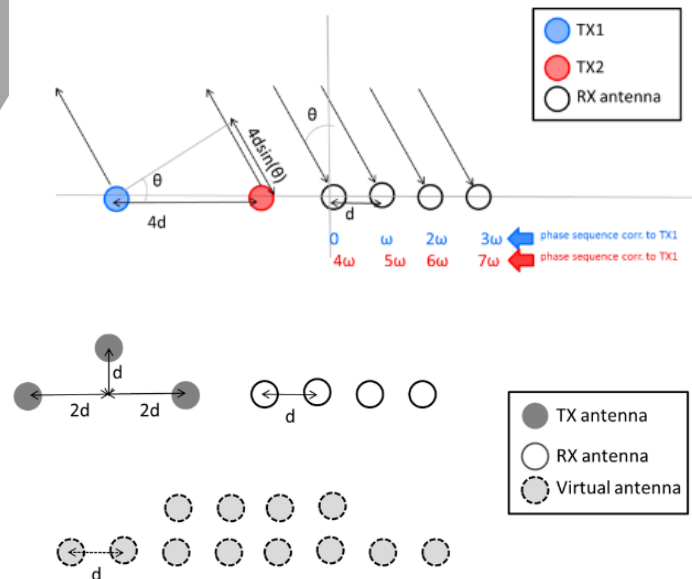
# INTRODUCTION RADAR – MIMO FMCW RADAR

## Function principle

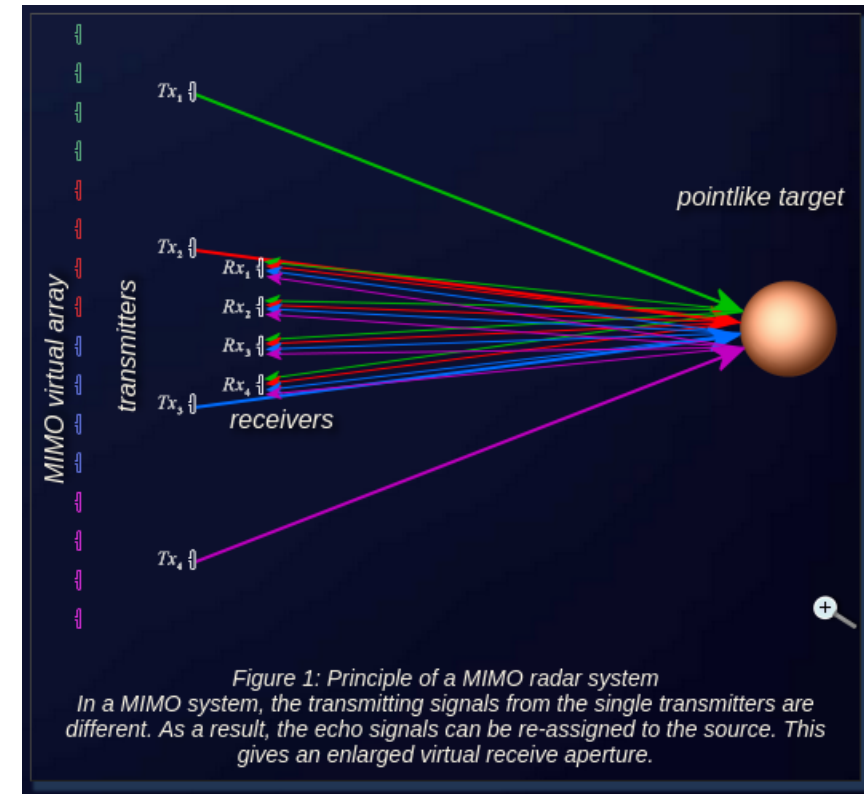
MIMO = Multiple Input Multiple Output Antennas

## Advantages

- Improve spatial resolution
- Improve SNR -> probability of detection increased



[1]

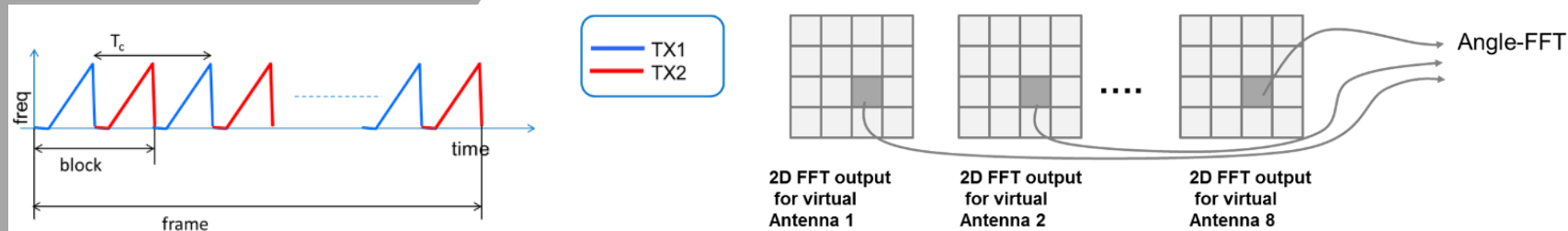


[2]

# INTRODUCTION RADAR – MIMO FMCW RADAR

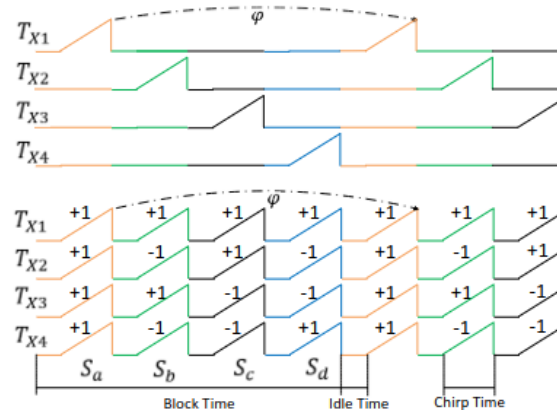
## Multiplexing Strategies for MIMO

- Time Division Multiplexing (TDM-MIMO)
- $NTX = 2$ ;  $NRX = 4$



[1]

- Binary Phase Modulation (BPM-MIMO)



[3]

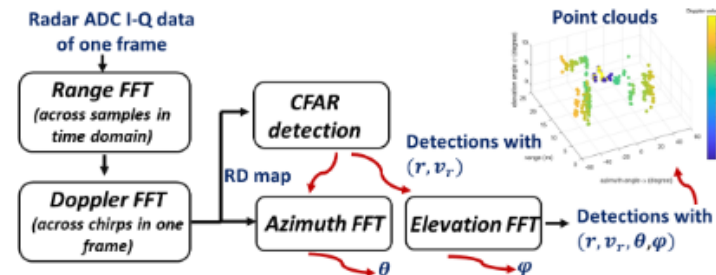
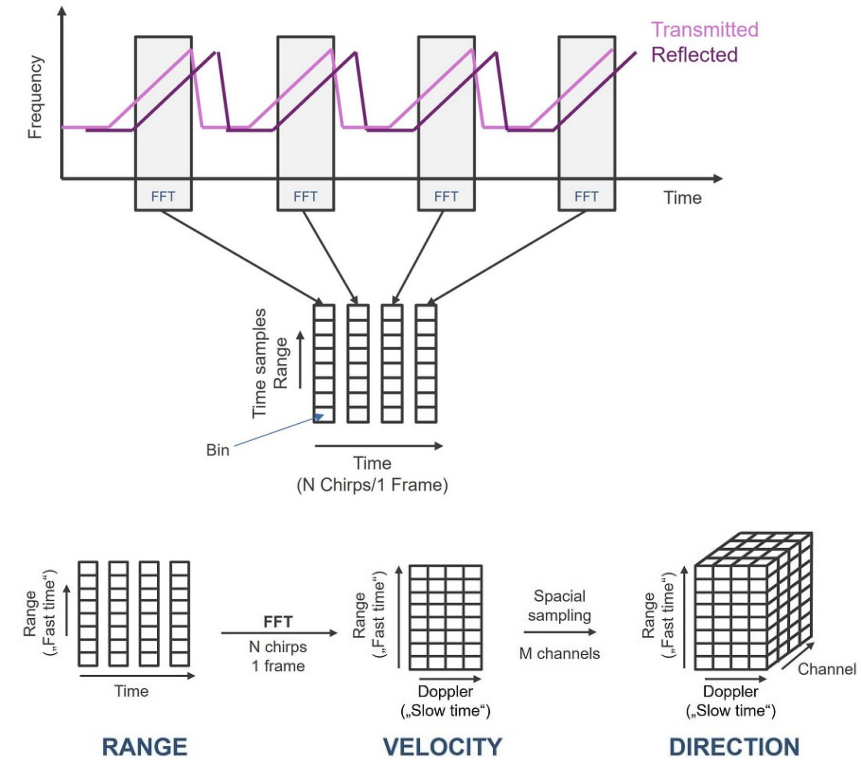
# INTRODUCTION RADAR – IMAGING RADAR

## Function

- Increasing of Antennas to create higher point cloud density
- Density of MIMO array is increasing proportional
- Including 4 dimensions (range, doppler, azimuth, elevation)

## Signal Processing 3 and 4 Dimensions

- Space-time Processing
- Need for space-time processing:
  - Signal frame needs to be saved and digitalized

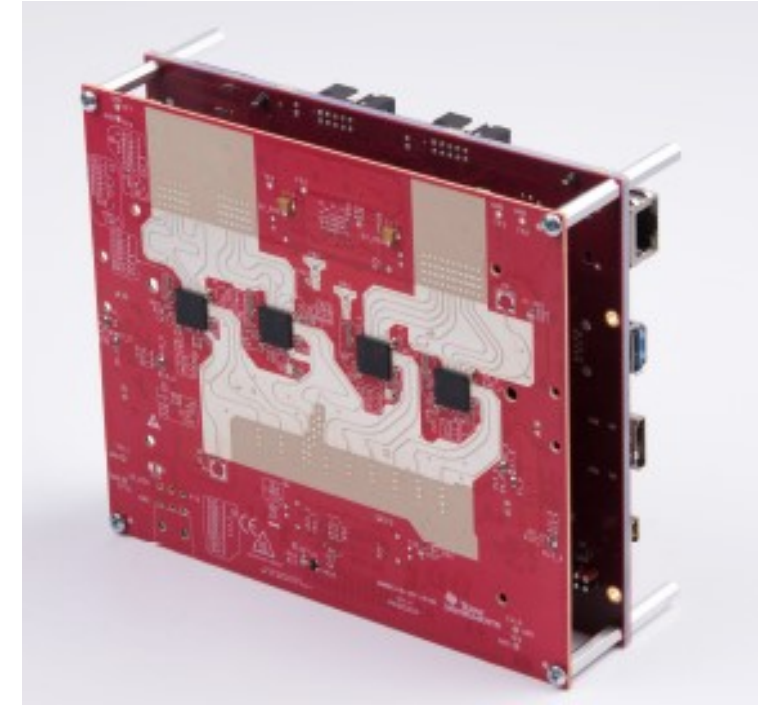


# TI RADAR DEVELOPMENT BOARD

***Ti Radar Board:*** AWRx Cascaded Radar RF Evaluation Module  
+  
***Ti DSP Board:*** MMWCAS-DSP-EVM  
=  
***Imaging Radar Using Cascaded mmWave Sensor Reference Design***

Table 1. Key Features

Cascade Radar RF Board	
4x AWRx 76-81GHz Radar SoC	Integrated VCO, LO distribution, PA, LNA, ADC, 3 TX and 4 RX ARM MCU R4 Controller
<b>AWRx RF/LO Peripherals</b>	
12x TX, 16x RX Antennas	<ul style="list-style-type: none"><li>• 12 total transmitters across all 4 AWRx devices</li><li>• 16 total receivers across all 4 AWRx devices</li><li>• 86 non-overlapping Azimuth virtual array (<math>\lambda/2</math>)</li><li>• 4 minimum redundancy array (MRA) Elevation</li></ul>
Embedded Antenna	<ul style="list-style-type: none"><li>• 4-element series-fed patch antenna, 12dBi</li><li>• <math>\pm 60</math> deg Azimuth 3dB</li><li>• <math>\pm 30</math> deg Elevation 3dB</li></ul>
20 GHz LO Star-Network Distribution	2x Wilkinson power dividers fed by the Master AWRx device LO output to Master and Slave AWRx devices
<b>AWR Digital Peripherals</b>	
CSI2.0 4-lane	600Mbps/Lane for 2.4 Gbps ADC IF data per device
QSPI Flash	16 Mbit QSPI flash for AWR firmware updates/deveopment
Serial Peripherals	SPI, I2C, UART, GPIO
System Temperature	TMP112 I2C Temperature Sensors
<b>Power</b>	
Radar Power Management IC (PMIC) Solution	<ul style="list-style-type: none"><li>• 2x LP87524P Quad-Channel, Integrated FET, Buck Converters, secondary LC filtering solution powering all 4 AWRx devices</li><li>• TPS73733 LDO generating 3.3V system power</li></ul>



# TI RADAR DEVELOPMENT BOARD

## Architecture

- **One master device**
- **Three slave devices**
- **12 transceive channels (TX)**
- **16 receive channels (RX)**

Figure 5. Device and Antenna Array Groups

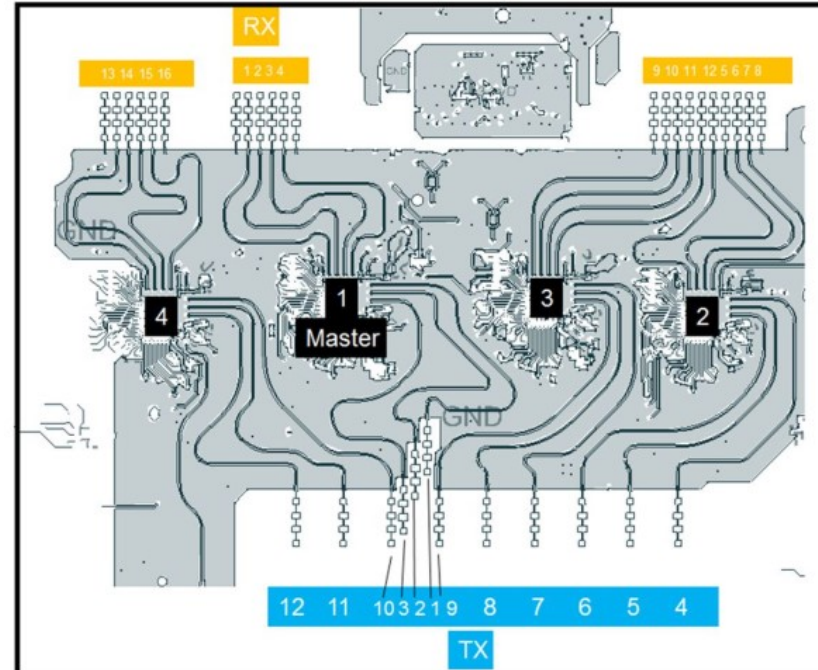
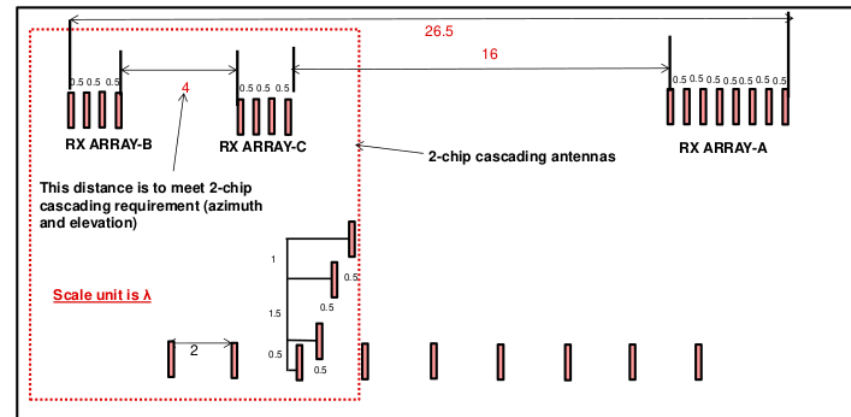


Figure 6. Antenna Array Positions



# TI RADAR ANTENNA APERTURE

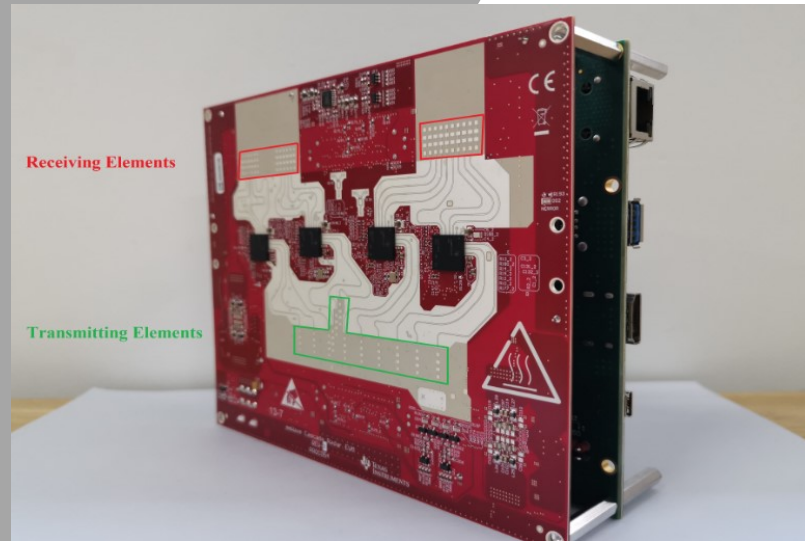


Figure 5. Device and Antenna Array Groups

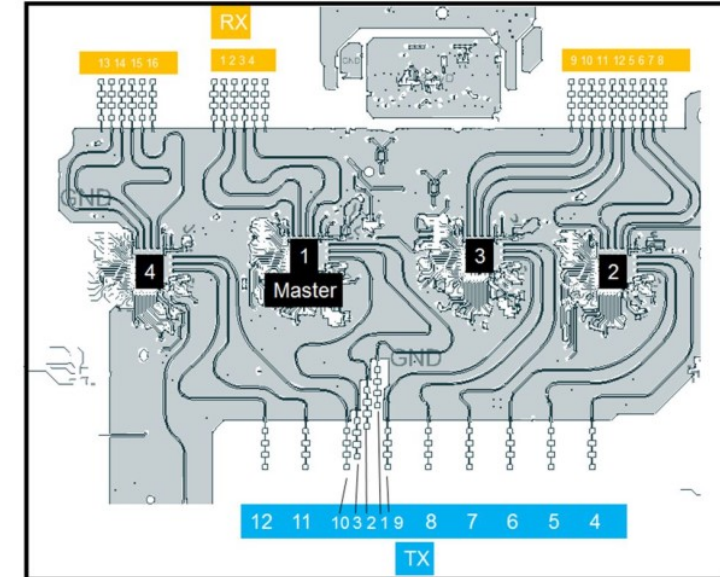
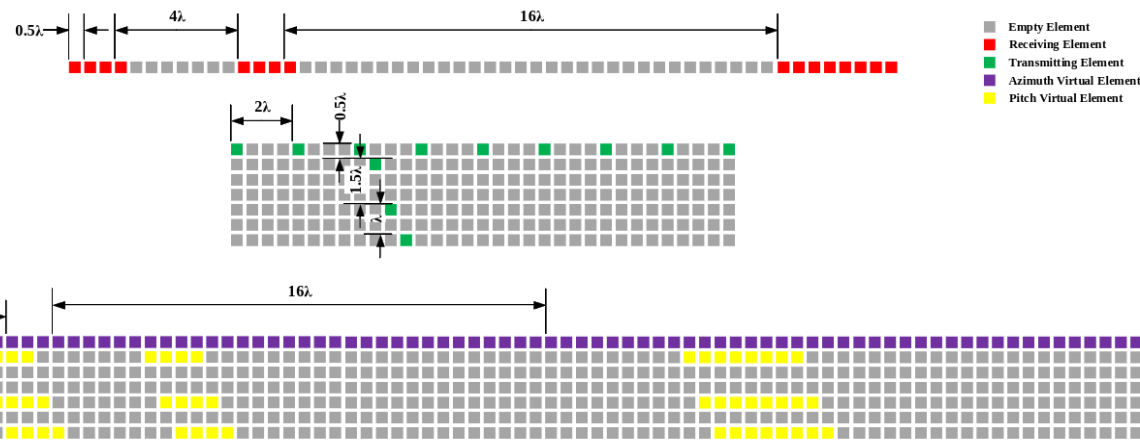
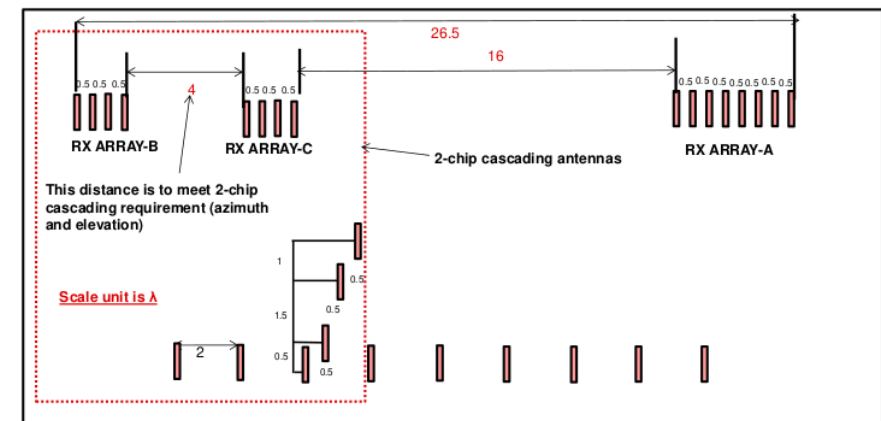


Figure 6. Antenna Array Positions



# TI RADAR DEVELOPMENT BOARD

## Radar configuration

- MIMO configuration
- TX Beamforming

## MIMO configuration

- Short-range radar SRR
- Mid-range radar MRR

Table 1. Key System Specifications

PARAMETERS	SPECIFICATIONS (MIMO)	SPECIFICATIONS (TXBF)	DESCRIPTION
Maximum Range	150 m	350 m	This represents the maximum distance that the radar can detect an object representing an RCS of approximately 10 m <sup>2</sup> .
Range Resolution	60 cm	150 cm	Range resolution is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges. The resolution is configurable, so the provided number is just an example.
Azimuth Angle Resolution	1.4 degrees	1.4 degrees (with multiple beam steering)	Angle resolution is the ability of a radar system to distinguish between two or more targets with the same range and velocity but different angles. The resolution is equivalent in both applications.
Elevation Angle Resolution	18 degrees	n/a	Elevation angle resolution is only available for MIMO application given the antenna design on the TI cascade EVM board.
Maximum Velocity	133 kmph	133 kmph	This is the native maximum velocity obtained using a two-dimensional FFT on the frame data. For TDM MIMO case, velocity compensation algorithm is applied to recover the native maximum velocity. This specification will be improved over time by showing how higher-level algorithms can extend the maximum measurable velocity beyond this limit.
Velocity Resolution	0.53 kmph	0.53 kmph	This parameter represents the capability of the radar sensor to distinguish between two or more objects at the same range but moving with different velocities.

# TI RADAR DEVELOPMENT BOARD

## *Chirp configuration*

### ***Ultra-Short-Range Radar***

#### Parameters

TDM-MIMO (12 Tx, 16 Rx)

Center Frequency: 78.26375 GHz

Radar Bandwidth: 2.5275 GHz

Sampling Rate: 8 MHz

N samples per chirp: 256

Chirp time: 55  $\mu$ s

N Chirps per CPI: 128

Rx Gain: 48 dB

Waveform: Sawtooth, positive

#### Resulting Performance:

Max range: 15.18 m

Range res: 0.06 m

Max velocity: approx. 2.893 m/s

Velocity res: 0.0226 m/s

## *Chirp configuration*

### ***Mid-Range Radar***

#### Parameters

TDM-MIMO (12 Tx, 16 Rx)

Center Frequency: 77.27 GHz

Radar Bandwidth: 0.26 GHz

Sampling Rate: 15 MHz

N samples per chirp: 256

Chirp time: 45  $\mu$ s

Chirp slope 15MHz/ $\mu$ s

N Chirps per CPI: 64

Rx Gain: 48 dB

Waveform: Sawtooth, positive

#### Resulting Performance:

Max range: 150 m

Range res: 0.56 m

Max velocity: approx. 1.80m/s

Velocity res: 0.06 m/s

# TI RADAR DEVELOPMENT BOARD

## Chirp configuration

### Parameterizable sizes:

- Start frequency
- Frequency slope
- Idle time
- ADC start time
- Ramp end time (ADC start, ADC sampling, excess ramping time)

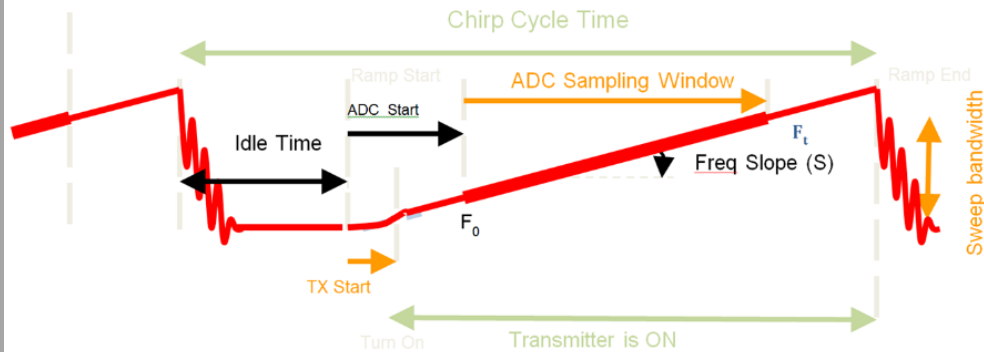
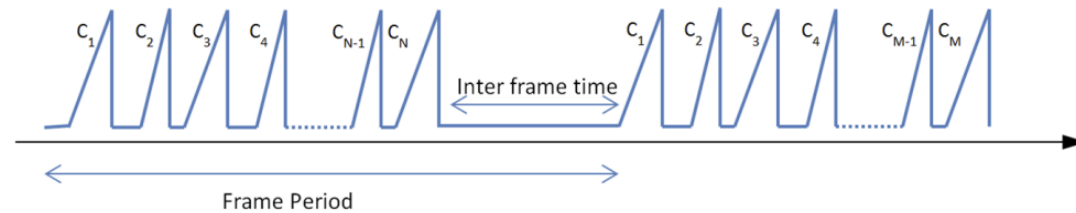


Figure 1. Typical FMCW Chirp



# RADAR EQUATIONS

## Calculation of key parameters

### Range key parameters

Calculation of maximum range

$$\begin{aligned} \text{Range max} &= \frac{f \text{ sampling} * c}{2 * \text{chirp slope}} \\ \text{Range max} &= \frac{c * t_c * f \text{ sampling}}{2 * B} \end{aligned}$$

Calculation of range resolution

$$\text{Range resolution} = \frac{c}{2 * B}$$

### Velocity key parameters

Calculation of maximum velocity

$$\text{velocity max} = \frac{c}{4 * f_0 * t_c * 12}$$

Calculation of velocity resolution

$$\text{velocity resolution} = \frac{c}{2 * f_0 * t_c * N * 12}$$

Calculation of chirp slope

$$\text{Chirp slope} = \frac{B}{\frac{1}{f \text{ sampling}} * Nc}$$

Character	Meaning	Unit
f sampling	Sampling frequency	Hz
c	Light speed	m/s
B	Bandwidth	Hz
t <sub>c</sub>	Complete chirp time (ramp end time + idle time)	µs
Chirp slope	Slope of chirp	Hz/µs
F <sub>0</sub>	Start frequency	Hz
N <sub>c</sub>	Number of samples from ADC	
N	Number of chirps per frame	

# RADAR EQUATIONS – REFERENCE LECTURE

## Calculation of key parameters

Basics: Calculation as FMWC Radar with square receiver

Equation	TI-Radar	Lecture
Range max	$Range\ max = \frac{f\ sampling * c}{2 * chirp\ slope}$	$Range\ max = \frac{f\ s * tc * c}{2 * B}$
Range resolution	$Range\ resolution = \frac{c}{2 * B}$	$\Delta d = \frac{c}{2 * B}$
Velocity max	$velocity\ max = \frac{c}{4 * f0 * tc * 12}$	$velocity\ max = \frac{c}{4 * f0 * tc}$
Velocity resolution	$velocity\ resolution = \frac{c}{2 * f0 * tc * N * 12}$	$velocity\ resolution = \frac{c}{2 * f0 * tr * N}$

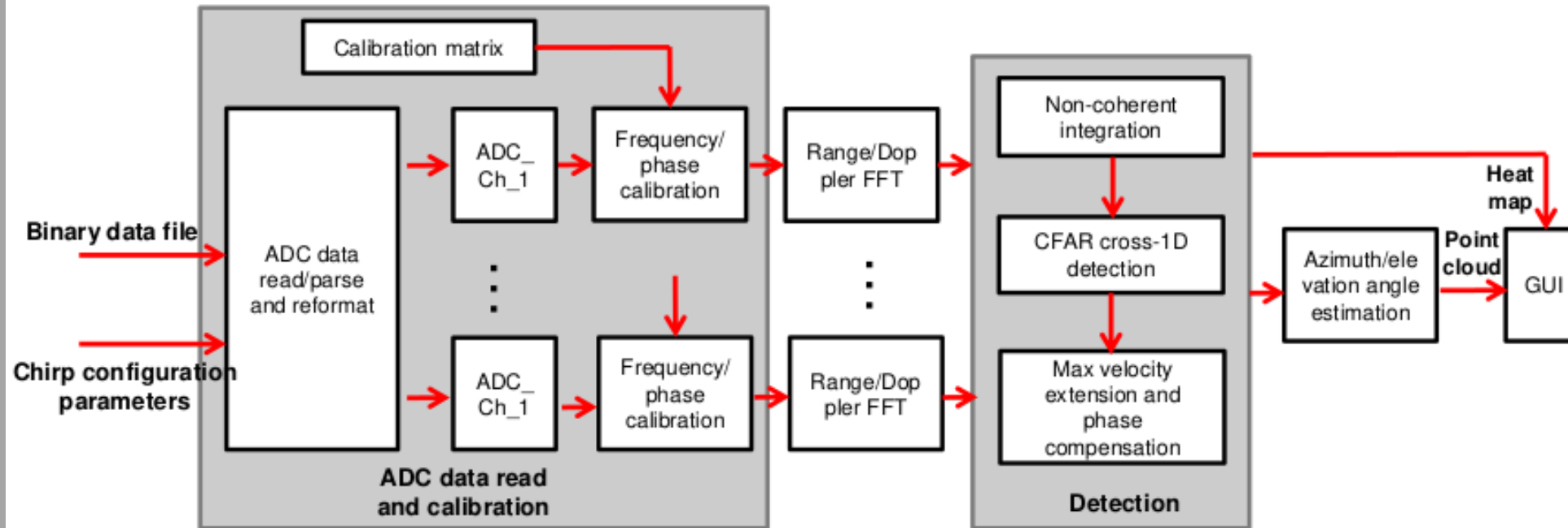
# SIGNAL PROCESSING – TABLE OF CONTENTS

1. Radar Signal Processing
2. Raw Data Processing
  1. Raw Data Processing 3D Radar
  2. Raw Data Processing 4D Imaging Radar
3. Point Cloud Processing

# RADAR SIGNAL PROCESSING

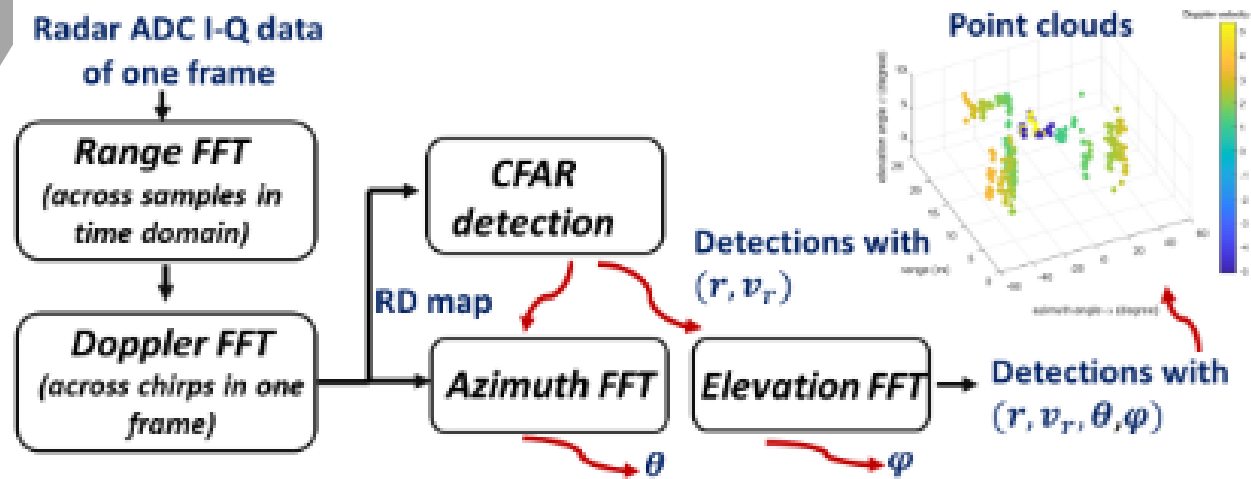
## Raw data processing

Figure 16. MIMO Signal Processing Chain



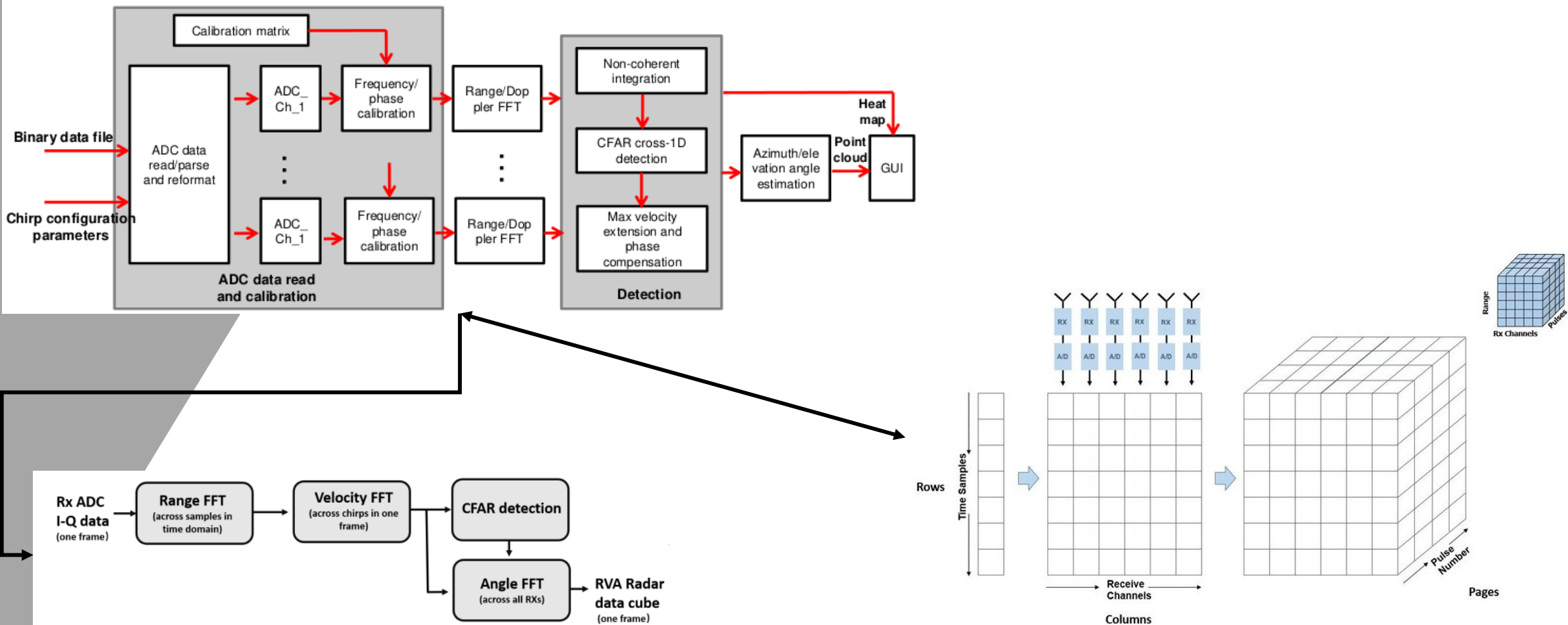
# RADAR SIGNAL PROCESSING

## Raw data processing



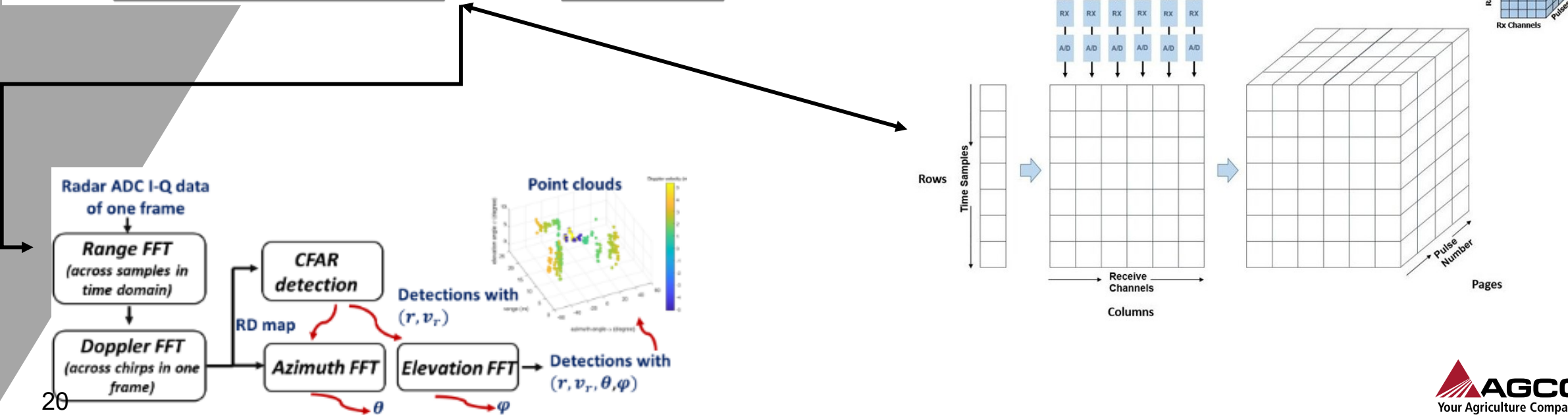
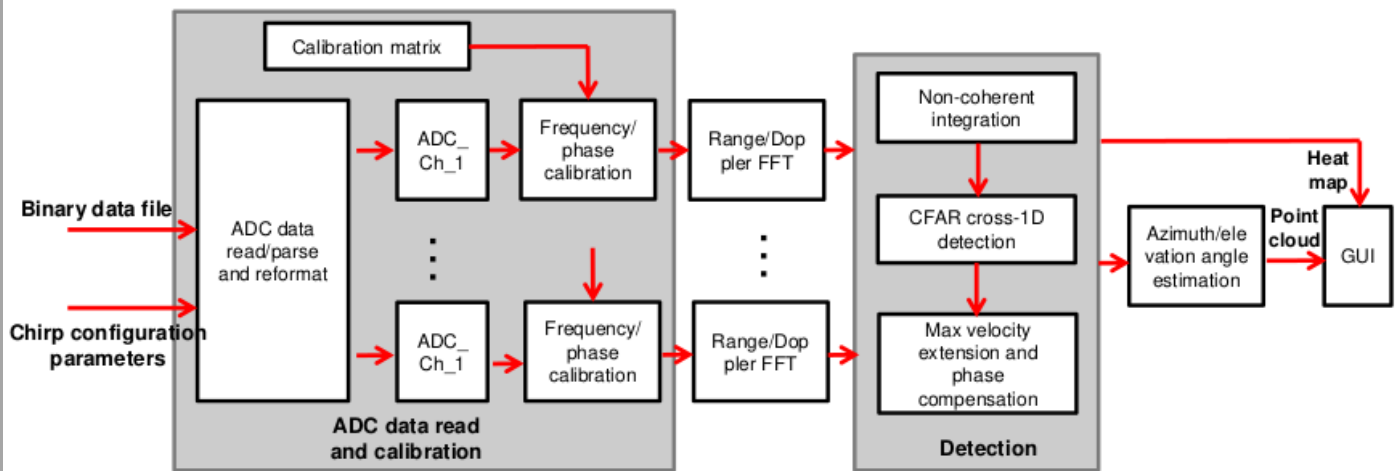
# RAW DATA PROCESSING 3D RADAR

Figure 16. MIMO Signal Processing Chain

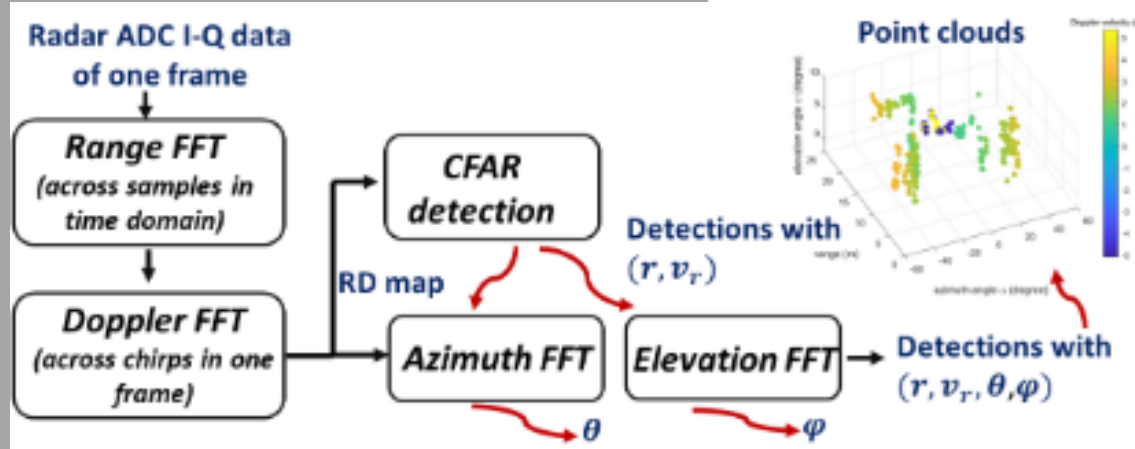


# RAW DATA PROCESSING 4D RADAR

Figure 16. MIMO Signal Processing Chain



# POINT CLOUD PROCESSING



## Point Cloud Information

### Simple Use Case

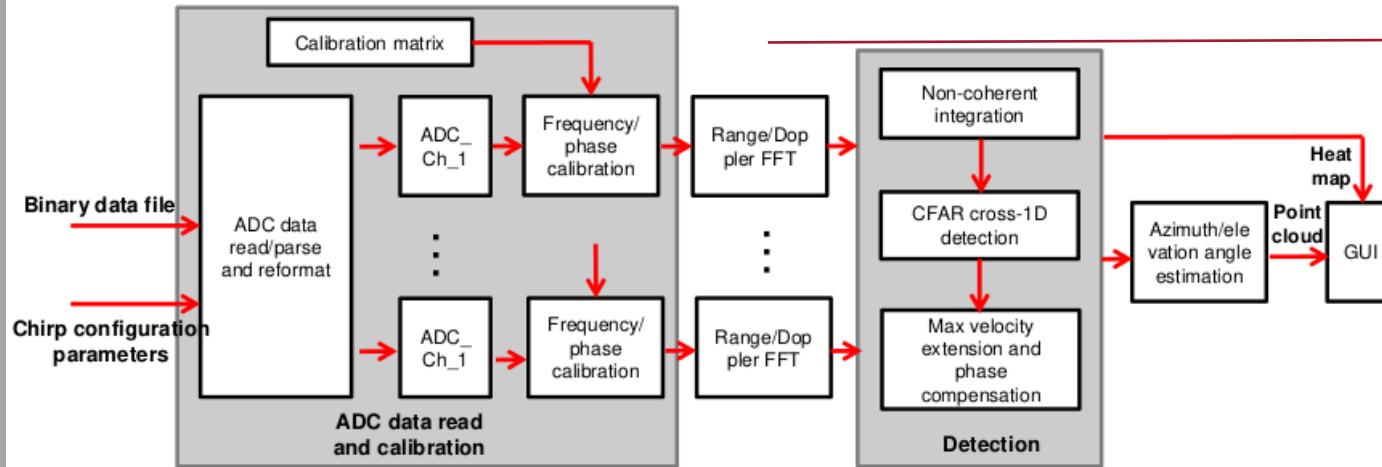
- Contains x, y, and z information of a detected point
- Contains velocity information of this point

### Advances use case

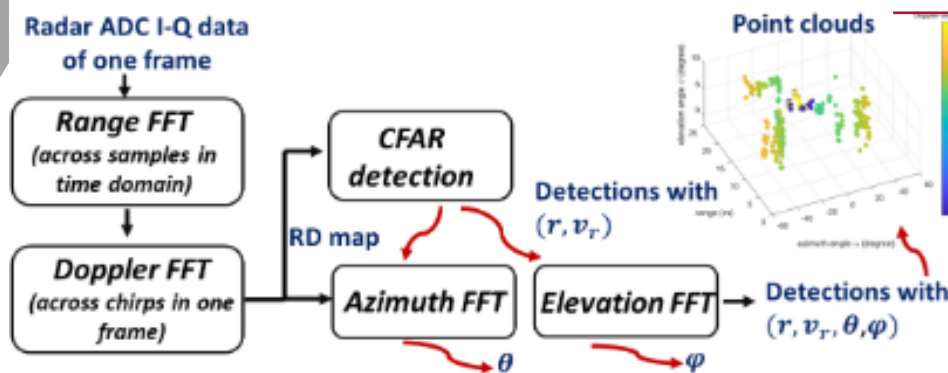
- Contains additional information for each point like:
- SNR, RCS, Heading information, direction

# RADAR SIGNAL PROCESSING – OBJECT DETECTION

Figure 16. MIMO Signal Processing Chain



Process/Option 1 and Option 3  
Object Detection based on 3D Radar Cube consisting of  
Range-angle, Range-velocity, Velocity-angle heatmap



Process/Option 2  
Based on existing available 3D point cloud

# PSA – TABLE OF CONTENTS

1. PSA - Objection Detection based on Radar Raw Data
  1. Classic Object Detection based on Radar Cube
2. PSA – Object Detection based on Point Cloud Data
  1. Object Detection based on 4D Point Cloud Data
3. PSA – Infineon Development Board

# OBJECT DETECTION 1 – BASED ON RADAR CUBE DATA

## Process/Option 1

- Based on 3D Radar Cube Data
- Combination of spatial and temporal data frame

Additional Information

<https://arxiv.org/pdf/2103.16214.pdf>

<https://arthouroaknine.github.io/codeanddata/>

## Targets of Option 1

Process for each frame

### Step 1

- Load each frame with the corresponding radar cube
- Apply different windowing functions
- Implementation of a two-dimensional Fast Fourier Transformation
- Plot two dimensional FFT data without axes scaling

### Step 2

- Calculation of key parameters like max. Distance and velocity and their resolutions
- Visualization of the two-dimensional FFT results mapped to calculated characteristics
- Range-Doppler Plot
- Range-Doppler Plot over summed up virtual channels

### Step 3

- Implementation of CFAR Filtering (or other peak detection algorithms)
- Testing of different parameters and their effects on the algorithm
- Visualization of detected targets after peak detection (visualize CFAR results)
- Calculation of the corresponding range and velocity

## Additional Tasks

- Process third dimension FFT along all Azimuth Antennas
- Visualization of Range / Cross-Range Plot in cartesian coordinates

# OBJECT DETECTION 1 – BASED ON RADAR CUBE DATA

## Process/Option 1

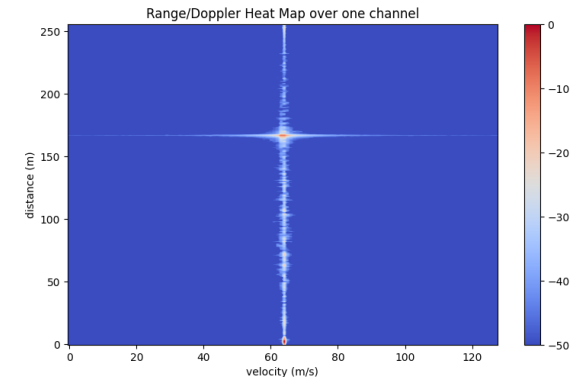
- Based on 3D Radar Cube Data
- Combination of spatial and temporal data frame

## Targets of Option 1

### Process for each frame

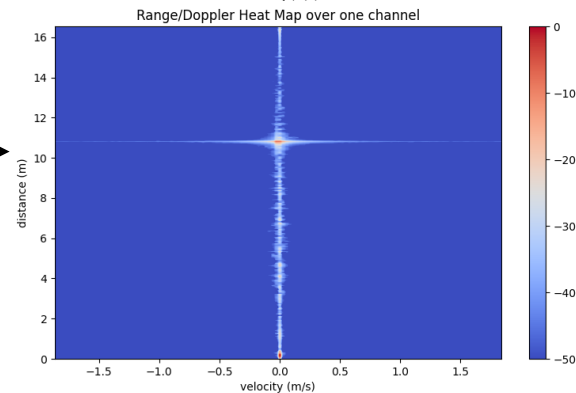
#### Step 1

- Load each frame with the corresponding radar cube
- Apply different windowing functions
- Implementation of a two-dimensional Fast Fourier Transformation
- Plot two dimensional FFT data without axes scaling



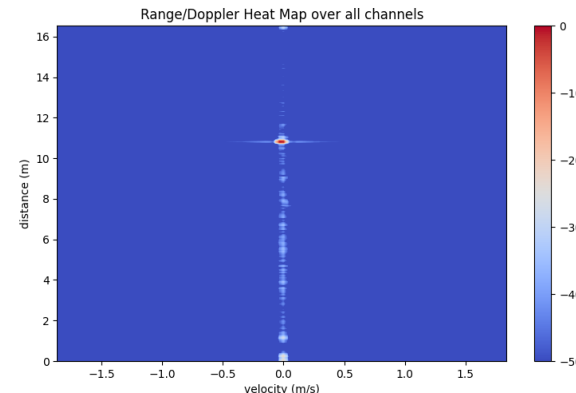
#### Step 2

- Calculation of key parameters like max. Distance and velocity and their resolutions
- Visualization of the two-dimensional FFT results mapped to calculated characteristics
- Range-Doppler Plot
- Range-Doppler Plot over summed up virtual channels



#### Step 3

- Implementation of CFAR Filtering (or other peak detection algorithms)
- Testing of different parameters and their effects on the algorithm
- Visualization of detected targets after peak detection (visualize CFAR results)
- Calculation of the corresponding range and velocity



### Additional Tasks

- Process third dimension FFT along all Azimuth Antennas
- Visualization of Range / Cross-Range Plot in cartesian coordinates

# OBJECT DETECTION 1 – BASED ON RADAR CUBE DATA

## Process/Option 1

- Based on 3D Radar Cube Data
- Combination of spatial and temporal data frame

## Targets of Option 1

Process for each frame

### Step 1

- Load each frame with the corresponding radar cube
- Apply different windowing functions
- Implementation of a two-dimensional Fast Fourier Transformation
- Plot two dimensional FFT data without axes scaling

### Step 2

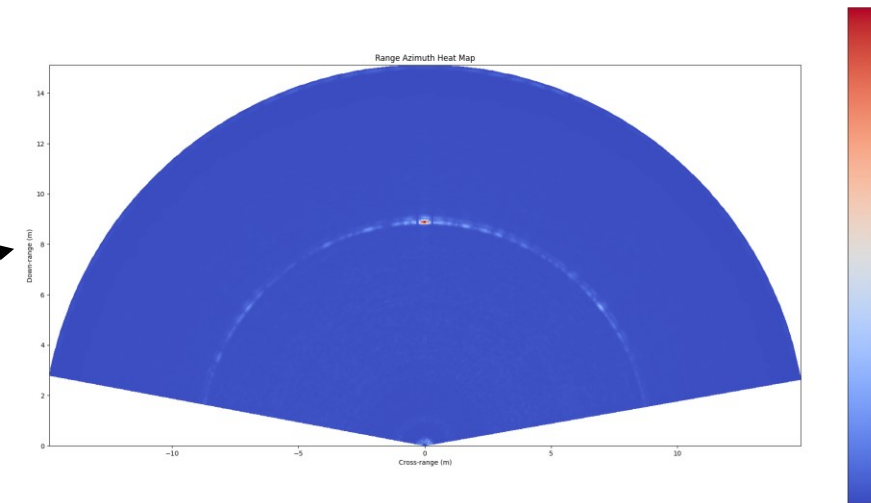
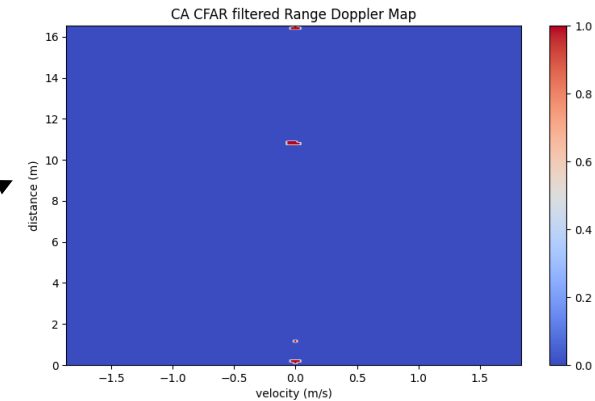
- Calculation of key parameters like max. Distance and velocity and their resolutions
- Visualization of the two-dimensional FFT results mapped to calculated characteristics
- Range-Doppler Plot
- Range-Doppler Plot over summed up virtual channels

### Step 3

- Implementation of CFAR Filtering (or other peak detection algorithms)
- Testing of different parameters and their effects on the algorithm
- Visualization of detected targets after peak detection (visualize CFAR results)
- Calculation of the corresponding range and velocity

### Additional Tasks

- Process third dimension FFT along all Azimuth Antennas
- Visualization of Range / Cross-Range Plot in cartesian coordinates



# OPTION 1 DATASETS

Datasets for Object Detection based on Radar Cube Measurements TI Radar

Ultra Short Range Radar

- Single dynamic target with movements towards radar

Mid Range Radar

- Static target

# DATASET – RAW DATA CHIRP CONFIGURATION

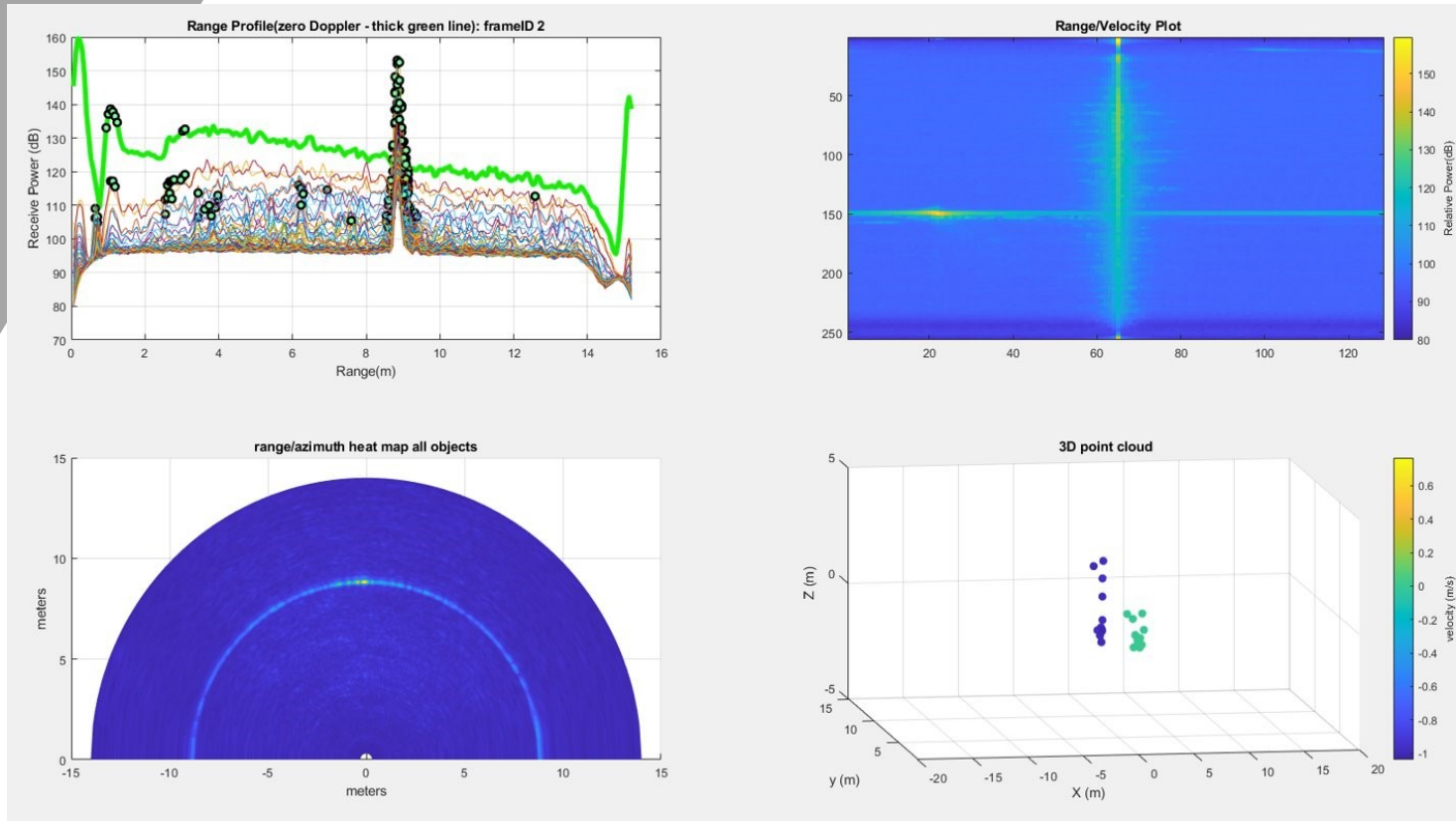
Parameter	Unit	Ultra-Short Range Configuration	Mid-Range Configuration
Function principle		TDM-MIMO (12Tx; 16Rx)	TDM-MIMO (12Tx; 16Rx)
Start frequency	GHz	77	77
Center frequency	GHz	78.26375	77.27
Radar bandwidth	GHz	2.5275	0.54
Sampling Rate	MHz	8	10
Number samples per chirp		256	256
Chirp interval complete	μs	55	47
Number chirps per loop		128	128
Frequency slope	MHz/μs	79	12
Idle time	μs	5	2
ADC start time	μs	6	4
Ramp end time	μs	50	45
Rx gain	dB	48	48
Waveform		Sawtooth, positive	Sawtooth, positive

# USRR DATA 1

Ground truth: static object at range 10 m, velocity approx. -5 km/h

Point Cloud ground truth

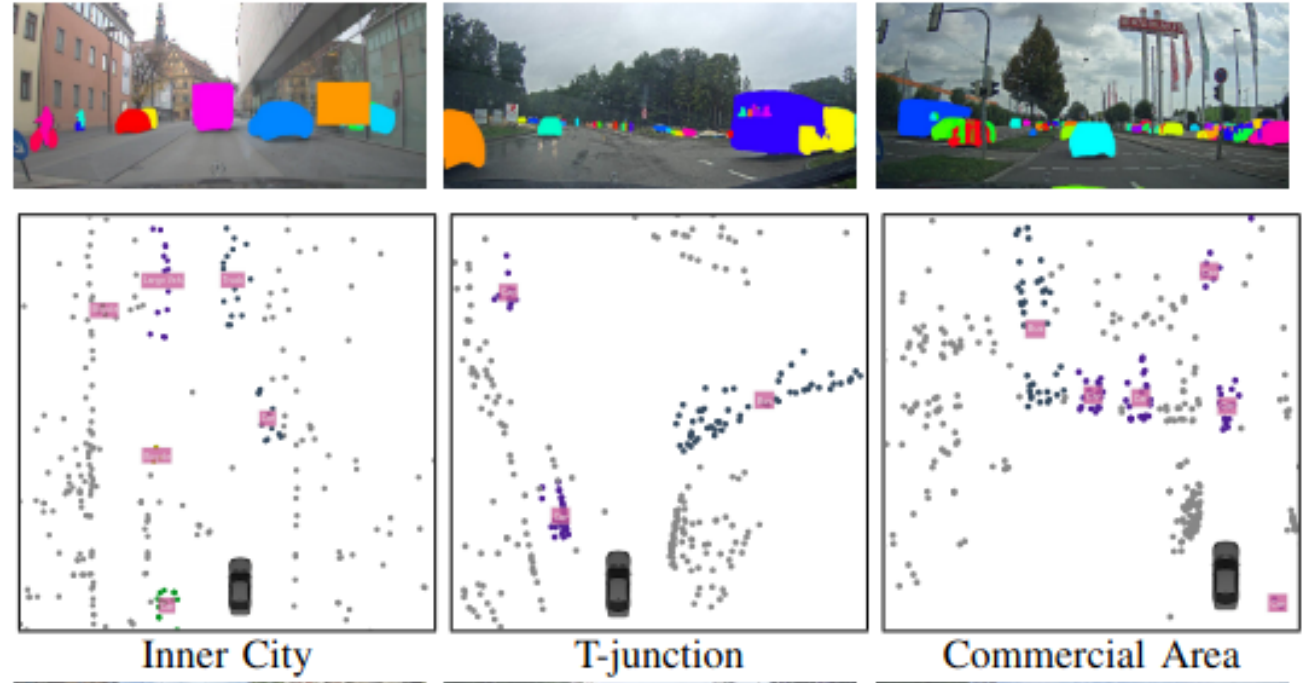
y=approx. 8 to 9.5m, x=0m, z=0 and velocity = -5 km/h



# OPTION 2 – OBJECT DETECTION BASED ON POINT CLOUDS

## Expectation

- Analyse and Understand the data set
- Extract the data of the data set
- Implement different clustering solutions
- Cluster the points to objects
- Classify the objects
- Compare the different algorithms
- Visualize the results



# OPTION 2 – DATASET AND PAPER

## Datasets for point cloud detection (clustering)

- <https://radar-scenes.com/>
- Radar scenes data set

## Paper

- Paper: <https://arxiv.org/abs/2104.02493>
- Contains point cloud data from Ulm, Germany

### *radar\_data.h5*

In this file, both the radar and the odometry data are stored. Two data sets exist within this file: "odometry" and "radar\_data".

The "odometry" data has six columns: timestamp, x\_seq, y\_seq, yaw\_seq, vx, yaw\_rate. Each row corresponds to one measurement of the driving state. The columns x\_seq, y\_seq and yaw\_seq describe the position and orientation of the ego-vehicle relative to some global origin. Hence, the pose in a global (sequence) coordinate system is defined. The column "vx" contains the velocity of the ego-vehicle in x-direction and the yaw\_rate column contains the current yaw rate of the car.

The hdf5 data set "radar\_data" is composed of the individual detections. Each row in the data set corresponds to one detection. A detection is defined by the following signals, each being listed in one column:

- timestamp: in micro seconds relative to some arbitrary origin
- sensor\_id: integer value, id of the sensor that recorded the detection
- range\_sc: in meters, radial distance to the detection, sensor coordinate system
- azimuth\_sc: in radians, azimuth angle to the detection, sensor coordinate system
- rcs: in dBsm, RCS value of the detection
- vr: in m/s. Radial velocity measured for this detection
- vr\_compensated: in m/s: Radial velocity for this detection but compensated for the ego-motion
- x\_cc and y\_cc: in m, position of the detection in the car-coordinate system (origin is at the center of the rear-axle)
- x\_seq and y\_seq: in m, position of the detection in the global sequence-coordinate system (origin is at arbitrary start point)
- uuid: unique identifier for the detection. Can be used for association with predicted labels and debugging
- track\_id: id of the dynamic object this detection belongs to. Empty, if it does not belong to any.
- label\_id: semantic class id of the object to which this detection belongs. passenger cars (0), large vehicles (like agricultural or construction vehicles) (1), trucks (2), busses (3), trains (4), bicycles (5), motorized two-wheeler (6), pedestrians (7), groups of pedestrian (8), animals (9), all other dynamic objects encountered while driving (10), and the static environment (11)

# OPTION 3 – OBJECT DETECTION WITH RADAR SDK

## Expectation

- Create test bench / measurement setup
- Create radar measurements with a simple test case
- Signal processing based on the sensor setup (analog to Option 1 with own data)
- Doppler Velocity spectrum
- Classification of objects
- Gesture recognition

# CONTENT SOURCES

- [1] Texas Instruments Documentation [https://www.ti.com/tool/TIDEP-01012?utm\\_source=google&utm\\_medium=cpc&utm\\_campaign=sdm-auto-null-58700008225888860\\_refdesdynamic\\_automotive-cpc-rd-google-eu\\_int&utm\\_content=refdesdynamic&ds\\_k=DYNAMIC+SEARCH+ADS&DCM=yes&gclid=EAIaIQobChMIn8DWtYSTgQMVSJbVCh391AHAEAAAYASAAEgKhs\\_D\\_BwE&gclidsrc=aw.ds#tech-docs](https://www.ti.com/tool/TIDEP-01012?utm_source=google&utm_medium=cpc&utm_campaign=sdm-auto-null-58700008225888860_refdesdynamic_automotive-cpc-rd-google-eu_int&utm_content=refdesdynamic&ds_k=DYNAMIC+SEARCH+ADS&DCM=yes&gclid=EAIaIQobChMIn8DWtYSTgQMVSJbVCh391AHAEAAAYASAAEgKhs_D_BwE&gclidsrc=aw.ds#tech-docs)
- [2] <https://www.radartutorial.eu/02.basics/MIMO-radar.en.html>
- [3] <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9360348>

# IMAGE SOURCES

- [1] [https://www.ti.com/lit/an/swra554a/swra554a.pdf?ts=1693896020053&ref\\_url=https%253A%252F%252Fdev.ti.com%252F](https://www.ti.com/lit/an/swra554a/swra554a.pdf?ts=1693896020053&ref_url=https%253A%252F%252Fdev.ti.com%252F)
- [2] <https://www.radartutorial.eu/02.basics/MIMO-radar.en.html>
- [3] <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9360348>
- [4] <https://www.radartutorial.eu/02.basics/Frequenzmodulierte%20Dauerstrichradarger%C3%A4te.de.html>
- [5] <https://www.renesas.com/us/en/blogs/basics-fmcw-radar>