Cascaded Radar And Body&Chassis Automotive Applications

Dan Wang, System Manager, Radar & Analytics, EP

TEXAS INSTRUMENTS

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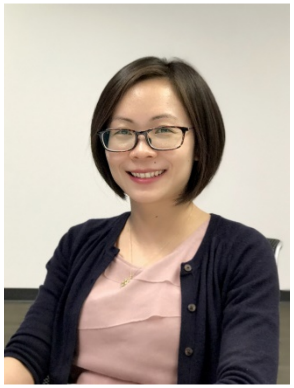


- **Career**
  - PhD, Electrical Engineering, University of Texas at Austin
  - System Engineer, Perception Processing & Analytics Lab, Radar & Analytics, EP, 2012~2017
  - System manager, Radar & Analytics, EP, 2018

- **Expertise**
  - Radar signal processing algorithms
  - System analysis/development
  - Multi-core DSP programing/optimization

TI training – summary

Cascaded Radar and Body&Chassis Automotive Applications:

This presentation will cover two topics. The first session describes how to cascade multiple TI single chip radars to a high performance radar sensor with enhanced angle and range detection performance. A cascade radar system proposal will be presented followed by some demonstrate results based on TI 4-chip cascade radar system. The second session introduces multiple body and chassis automotive applications based on TI single chip radar. For each application, the corresponding hardware EVM and basic signal processing chain will be introduced.

What you'll learn:

- Why need cascade radar and how to cascade based on TI radar chip
- What the performance of cascade radar
- What are the automotive application for body & chassis

Training level: Intermediate

Course Details:

Audience: All

Specific TI Designs & Parts Discussed:

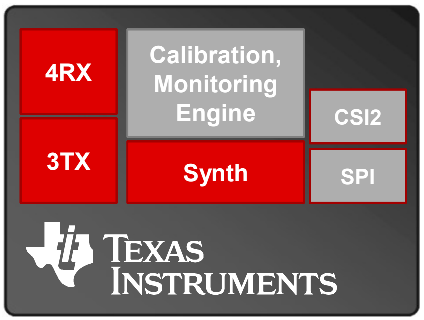
- AWR1243, AWR1443, AWR1642

Agenda

- Cascade Radar
  - What/Why cascade radar
  - How to cascade multiple radar chips
  - What TI cascade radar can achieve
- Body&Chassis Automotive Applications
  - Driver vital sign monitoring: hardware, signal processing chain
  - Obstacle detection for door/chunk opening: hardware, signal processing chain
  - Occupancy detection: hardware, signal processing chain

76 – 81 GHz mmWave Sensors (Sampling)

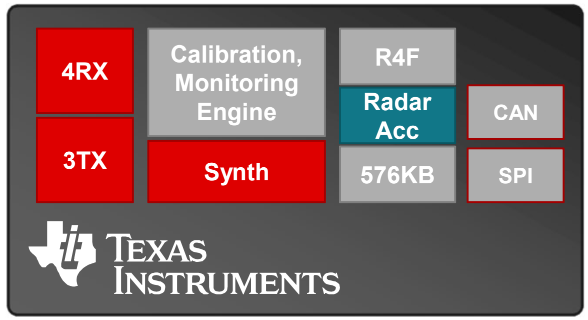
AWR1243



Radar Sensor

- **Use Cases**
  - Imaging Radar Sensor
    - 2x or 4x AWR12 (cascade) + External DSP
  - MRR and LRR

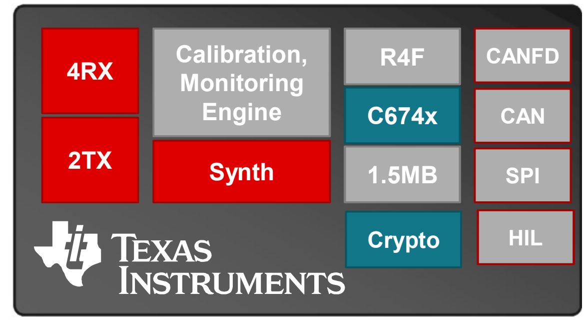
AWR1443



Radar Sensor + HW Accelerator

- **Use Cases**
  - Entry-level Single-chip Radar
    - Proximity warning
  - Free space sensor in and around the vehicle
  - Occupant detection, driver monitoring

AWR1642

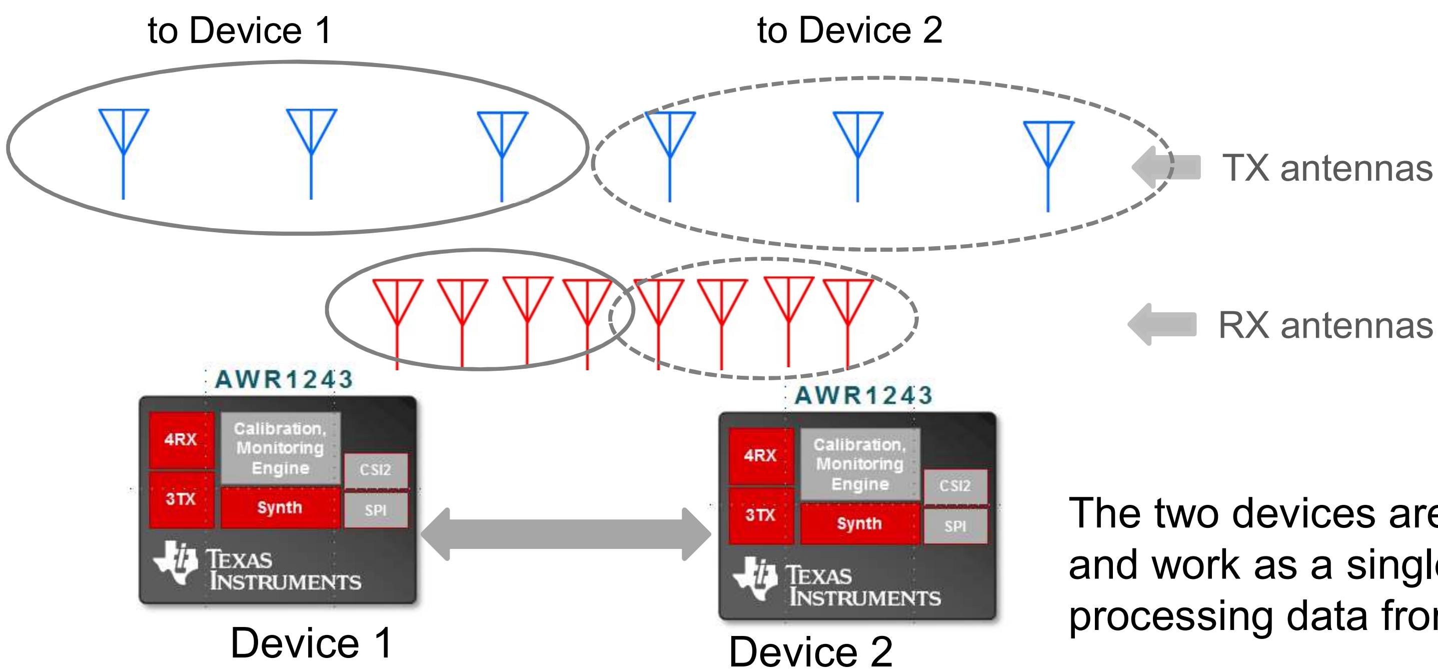


Radar Sensor + DSP

- **Use Cases**
  - USRR Single Chip Radar
    - 160 Degree, 40m
  - SRR Single chip Radar
    - 120m Cross traffic Alert

Cascaded Radar

What is Cascaded Radar?



The two devices are synchronized and work as a single unit, coherently processing data from all the antennas

Why Cascading?

- **Range resolution:**
  - Directly proportional to the bandwidth (B) spanned by the chirp.
  - TI's AWRxxxx solution : chirp bandwidth of 4GHz=> 4cm range resolution

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

- **Velocity resolution:**
  - Velocity resolution can be improved by increasing frame time (T_f)=> No hardware cost.
  - A T_f of 5ms => v_{res} of 1.5 kmph

$$v_{res} = \frac{\lambda}{2T_f}$$

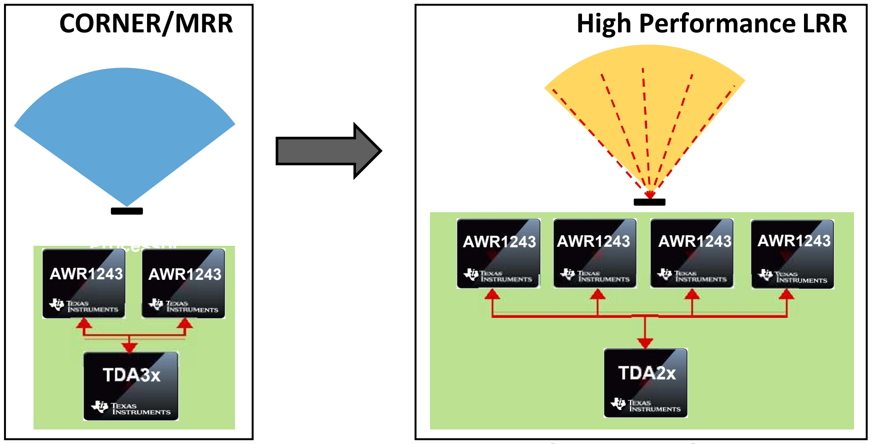
- **Angle resolution (improved by cascade):**
  - Improving angle resolution requires increasing the number of TX/RX antennas
  - Cost & area constraints limits the number of TX/RX chains per chip
  - A device with 2TX and 4 RX can achieve a theoretical angle resolution of only 15^o

$$\theta_{res} = \frac{2}{N_{TX}N_{RX}}$$

- **Maximum detection range (improved by cascade):**
  - Larger number of TX/RX antennas improves maximum detection range
  - Detection range can be more than 300 meters with 4 chip cascade board

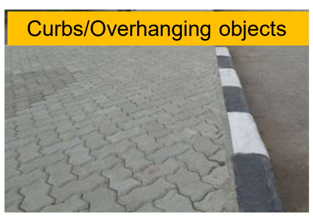
Cascading of multiple radar chips (e.g. 2,4) provides a cost effective and scalable solution to address the differing angle resolution requirements of various applications

Enabling Level 2 and Beyond of Automated Driving



4x angular resolution
Virtual array of 48 channels

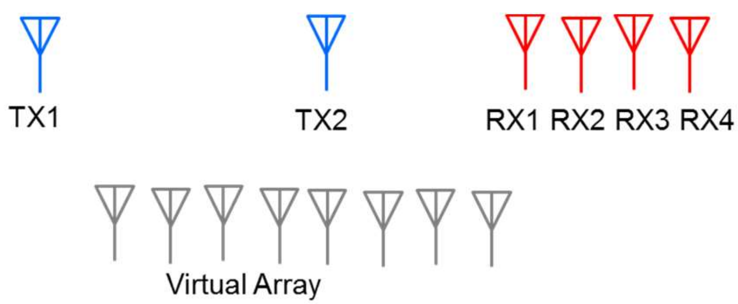
beam steering
< 1° angular resolution
> 300 meters range
Virtual array of 192 channels



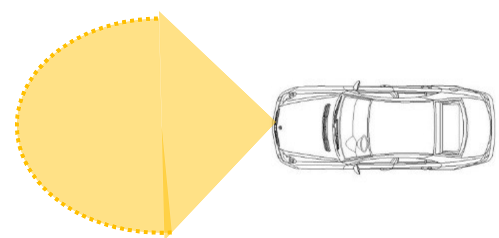
Modes of operation of cascade radar: MIMO

- Multiple TX antennas transmit independently
- Multiplexing of the transmitters can be in frequency (FDM), time (TDM), code-space (BPM) or a combination of the above.
- A single snap-shot with independent transmissions from all TX's, can illuminate the entire scene.
- Suitable for applications which require a high angular resolution over a wide field of view. (such as in MRR/SRR/USRR Imaging radar)

MIMO Operation



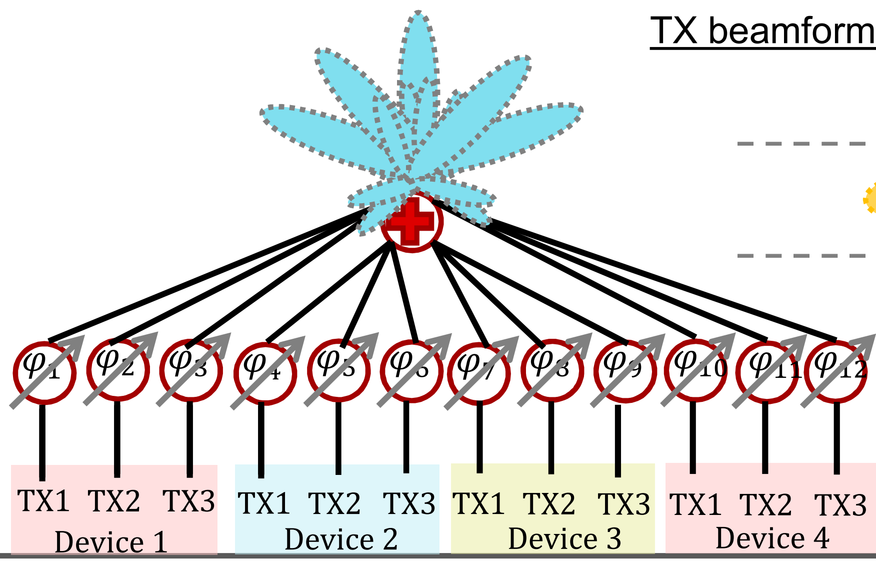
In this example, an independent transmission from each of the two TX's (with all the RX's receiving) , generates a virtual array of length 2x4=8 antennas.

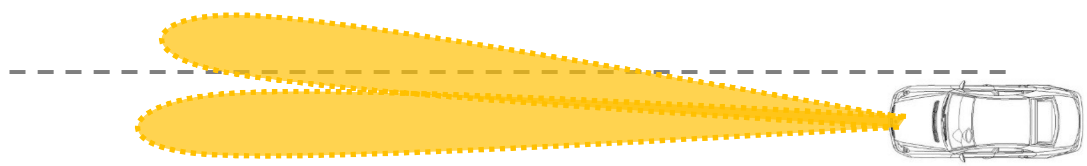


Modes of operation of cascade radar: TX beamforming

- Multiple TX antennas transmit simultaneously & coherently to create a focused beam.
- Phase shifts across TX antennas can steer the beam in a desired direction
- Coherent gain across the N_{TX} antennas improves SNR ($20\log_{10}(N_{TX})$ vs. $10\log_{10}(N_{TX})$ in MIMO)
- Suitable for applications which require maximum range and high angular resolution over a narrow field of view (such as in LRR)

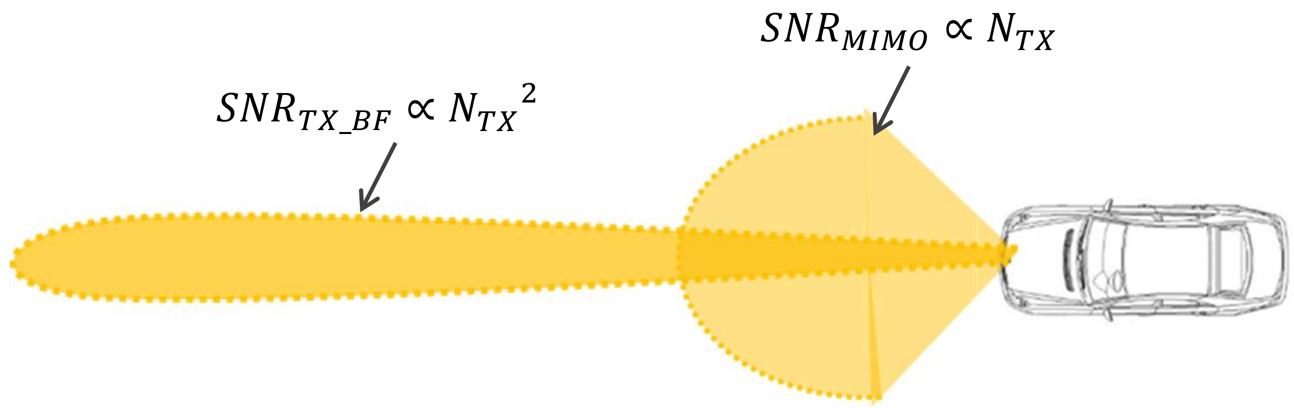
TX beamforming operation





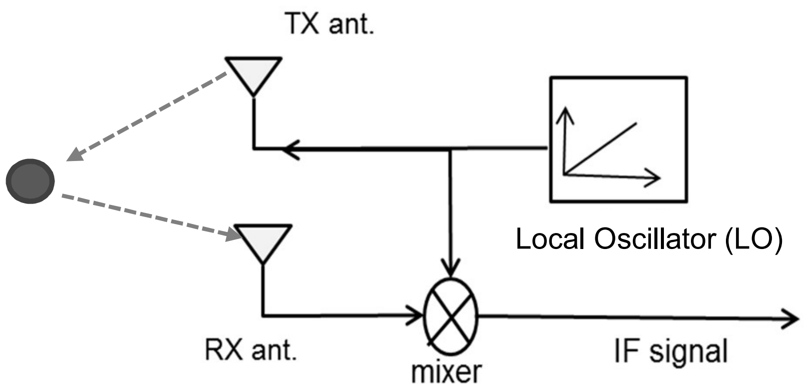
- A single snap-shot illuminates a narrow FOV.
- Multiple snap-shots (scanned sequentially) to cover a wider FOV

MIMO vs TX beamforming

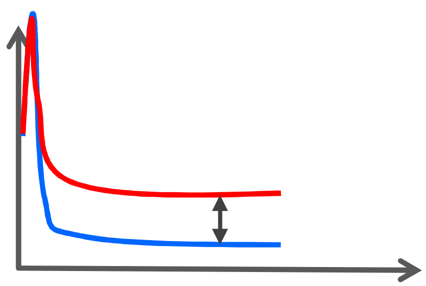


Cascade challenges: shared LO

Why shared LO?

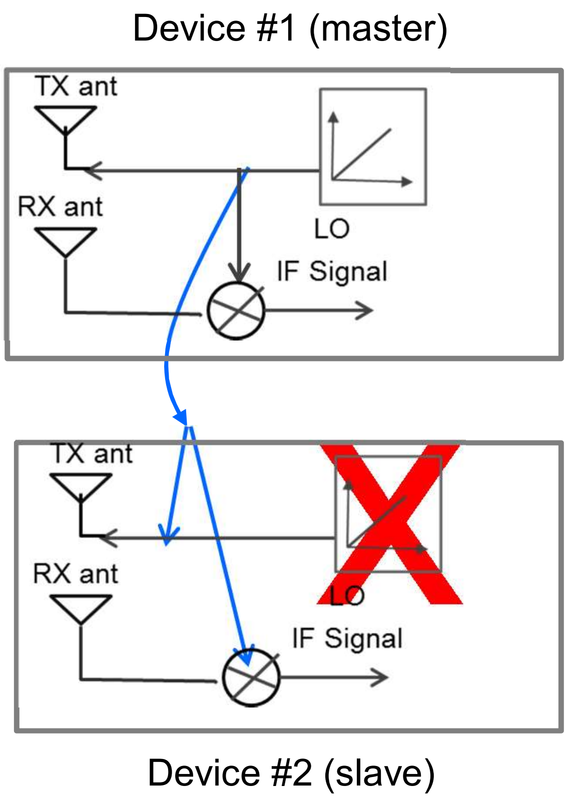


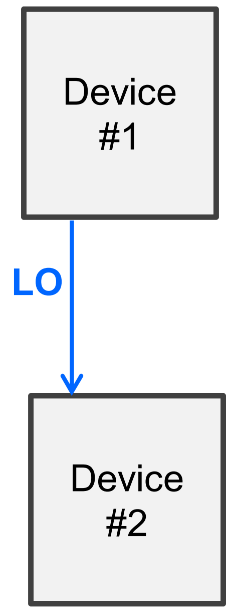
- The chirp generated by the LO, also has associated phase noise.
- Ensuring that transmit and receive signal originate from the same LO, results in "phase noise cancellation" => mitigates the adverse impact of phase noise in the IF signal



The bumper reflection/antenna coupling signal is typically the most dominant IF signal. A shared LO source reduces the associated phase noise by several 10's of dB (red- independent LO vs blue shared LO)

Cascade challenges: shared LO

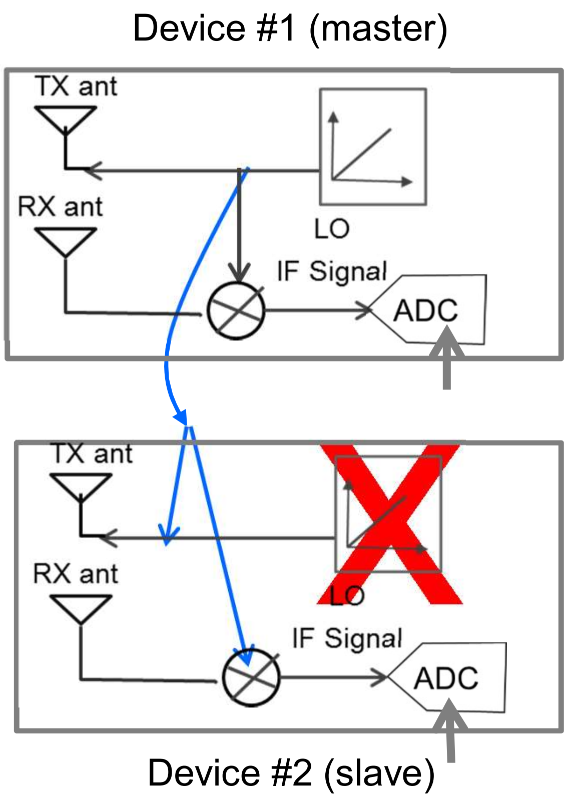


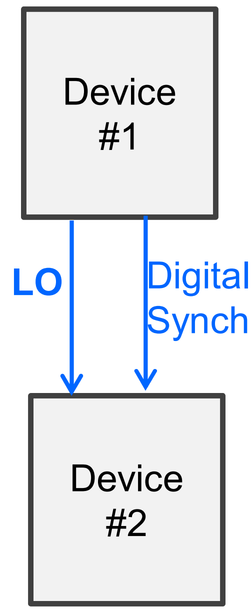


- Shared LO => LO routed from master to slave(s)

Note: LO is generated and routed at ~ 20GHz . Slave does a 4x to 77 GHz band. Routing at 20GHz (instead of 77GHz eases routing)

Cascade challenges: shared LO



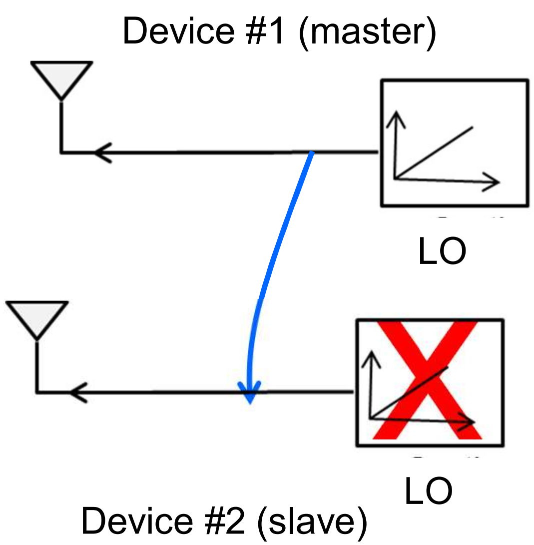


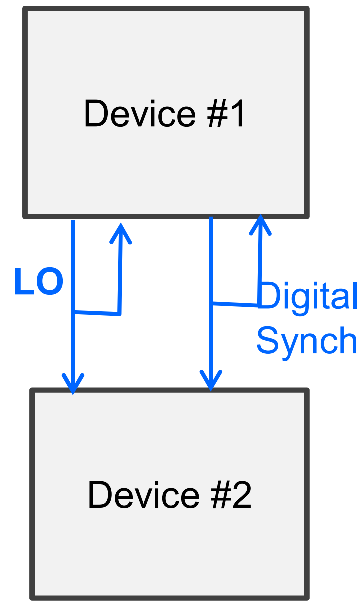
- Shared LO => LO routed from master to slave(s)
- Additionally ADC sampling and transmission time across devices needs to be synchronized => Digital synch signal from master routed to all slaves.

Cascade challenges: LO length matching

- In the TX beam forming mode of operation, TX antennas across multiple devices are fired simultaneously to create a stronger and more focused beam.

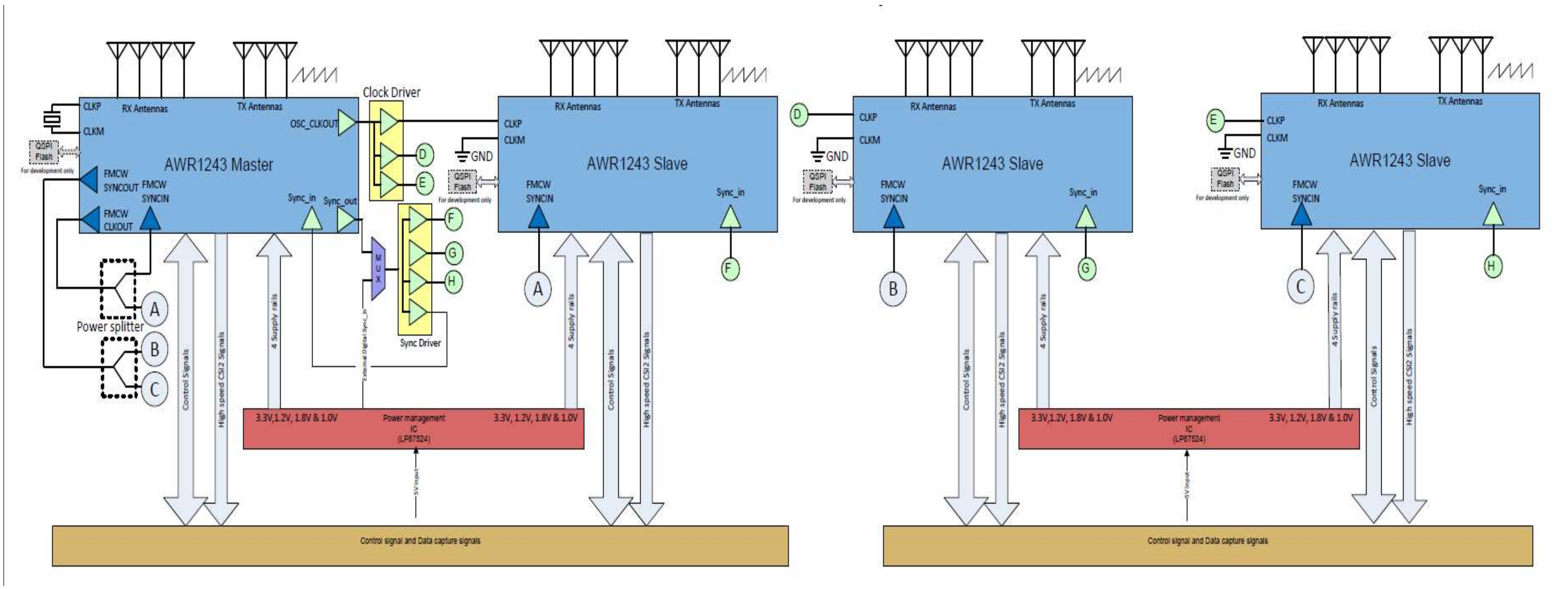
- All TX's should transmit in phase => LO routing from master to all the slaves needs to be length matched.





Master has the capability to use LO signal routed from an external pin. This can be used to achieve inter-chip delay matching.

4 Chip Cascading Scheme

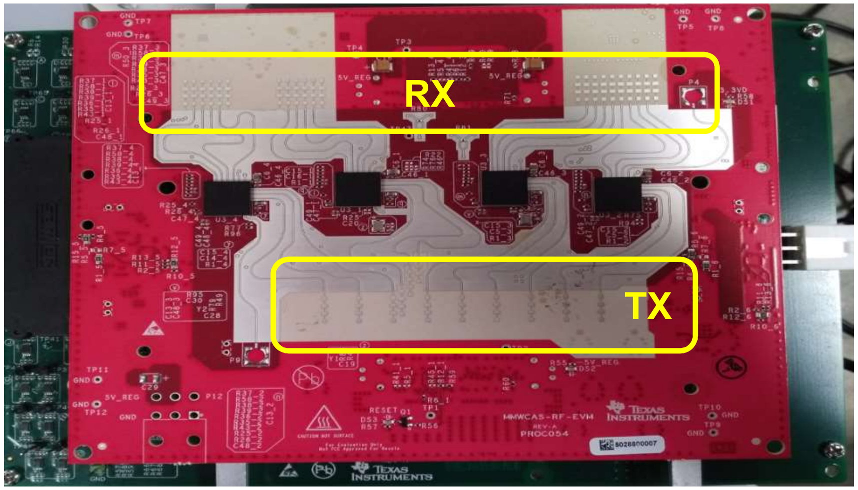


Cascade Radar : TI offering

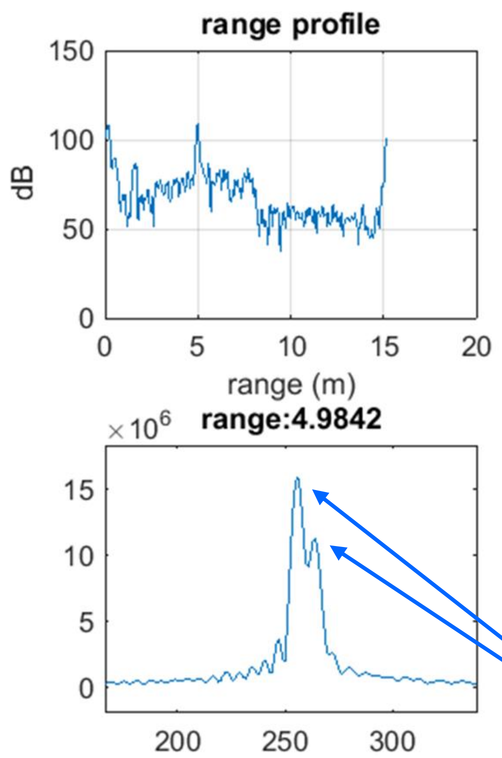
	AWR1243 features that enable cascading		PINS
1	Ref clock synchronization	• Reference clock from master is shared with all the slaves.	OSC_CLKOUT, CLKP
2	LO synchronization	• LO from master is shared with all the slaves. • LO is output from the master through two different delay matched pins	FMCW_ SYNCOUT, FMCW_CLKOUT,
3	Frame Synchronization	• Start of frame synchronized between master and all slaves.	SYNC_IN , SYNC_OUT
4	TX Phase shifter	• Can be programmed in steps of 5.6°	
5	Collateral	• TI 4-chip EVM board • Accompanying digital board which can stream ADC data via Ethernet to PC • Sample Matlab Code for TX beamforming/MIMO	

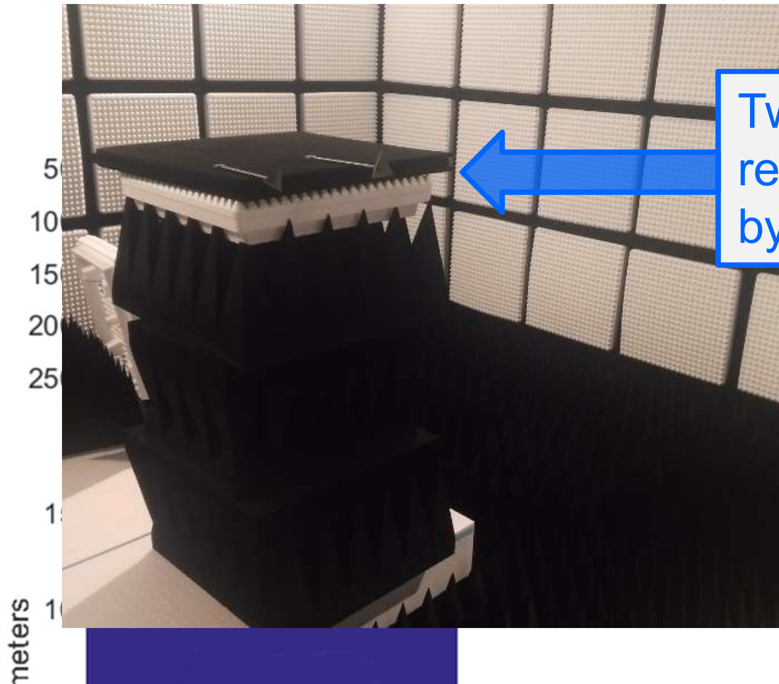
Imaging Radar System Demonstrator

- 4-chip cascade prototype implemented on a multi-layer PCB with Rogers 3003 top layer
- 3-D antenna pattern supporting MIMO and TX beamforming
- Tested in anechoic chamber and in multiple indoor/outdoor environments
  – Pedestrian detection at > 140m
  – Car detection at > 270m
  – Azimuth angular resolution 1.4°



Lab Test





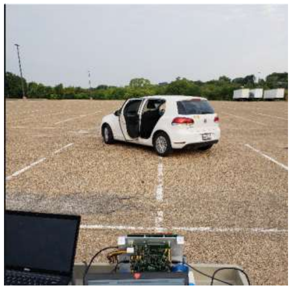
Two corner reflectors separated by 1.7 degrees

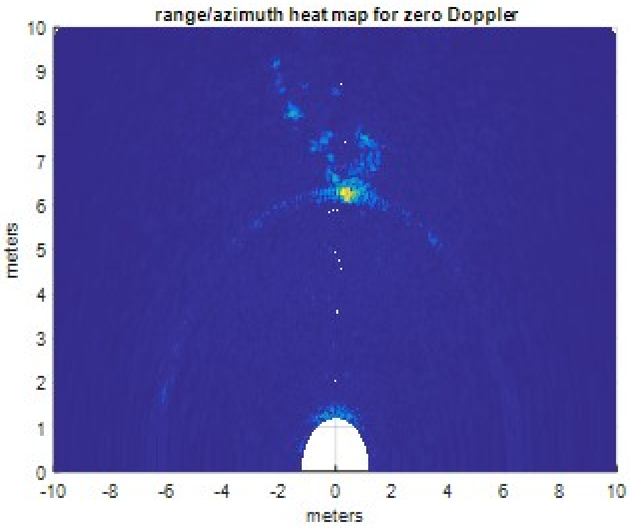
Two separate peaks detected at 1.7 degree separation (in the angle-FFT). Close to the expected angle resolution of 1.4 degree

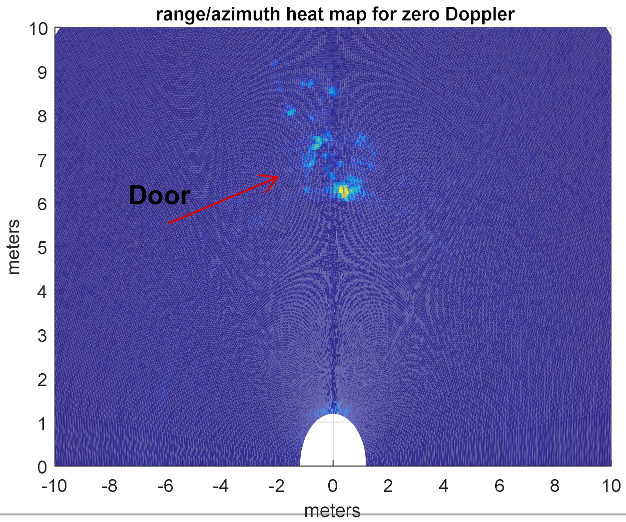
Single Car with car door open

45 degrees

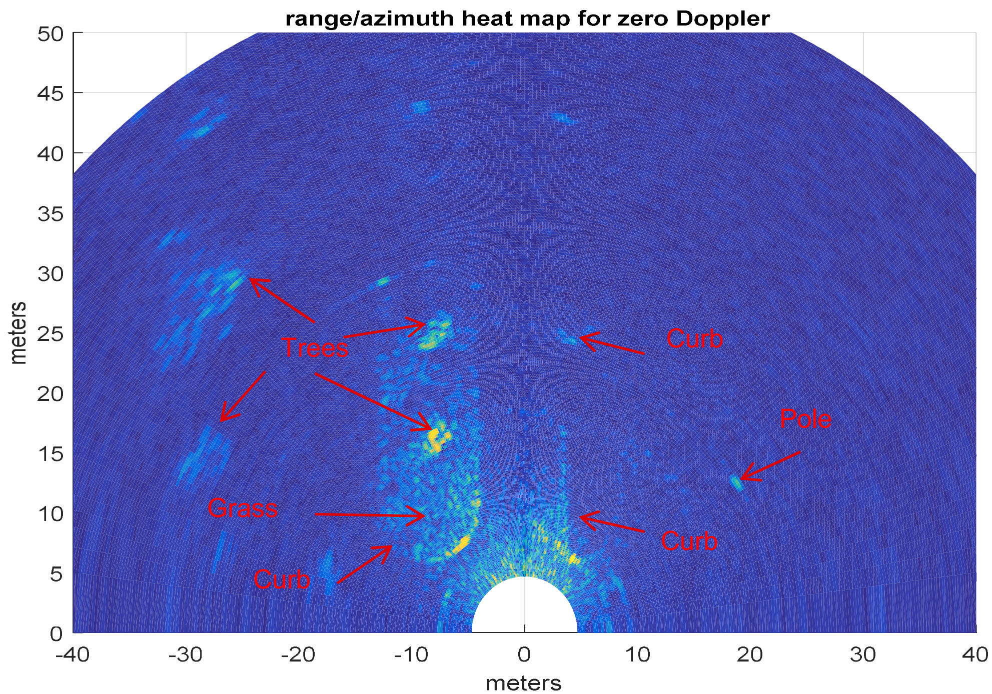
45 degrees with door open



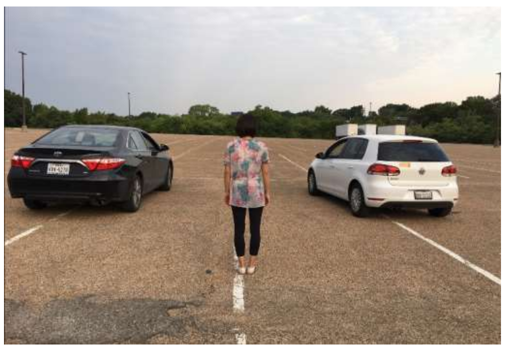


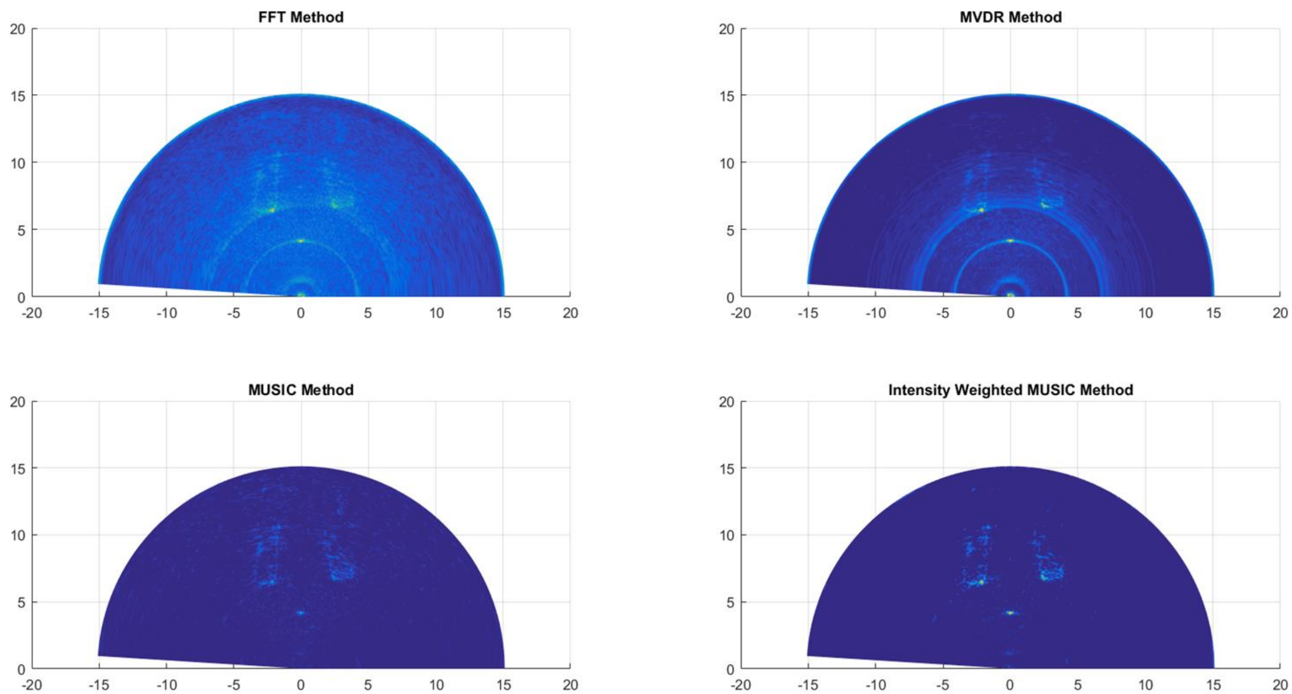


Contour of Curb

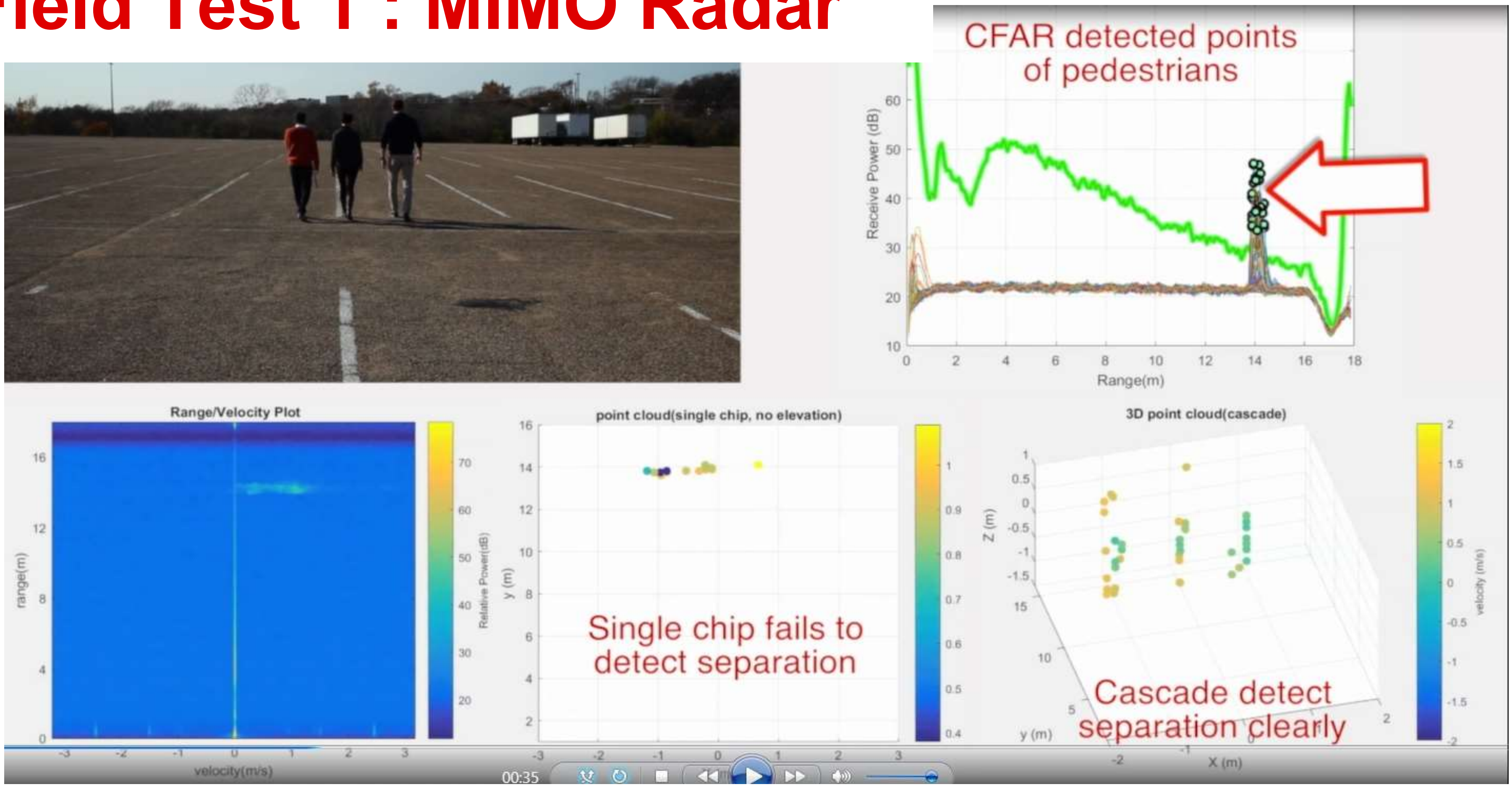


Comparison – Angle estimation methods

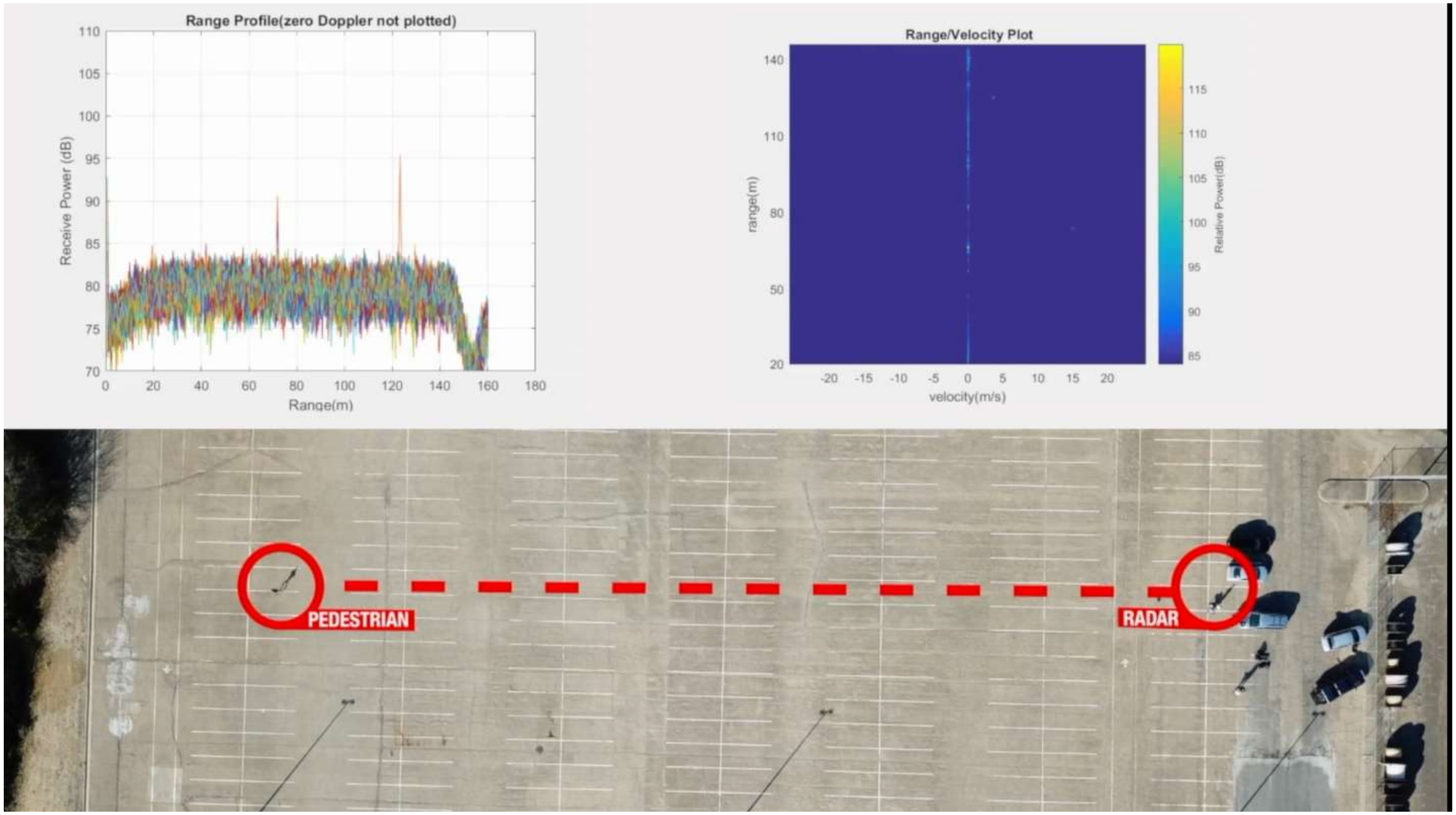




Field Test 1 : MIMO Radar

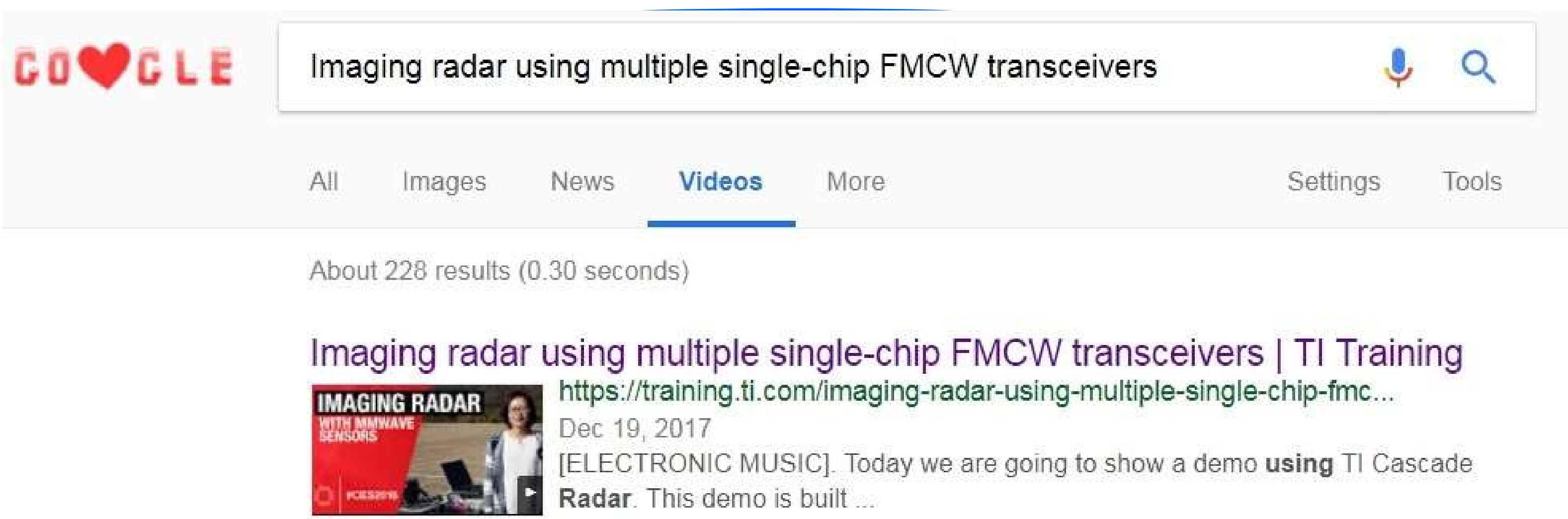


Field Test 2 : TX beamforming (pedestrian)



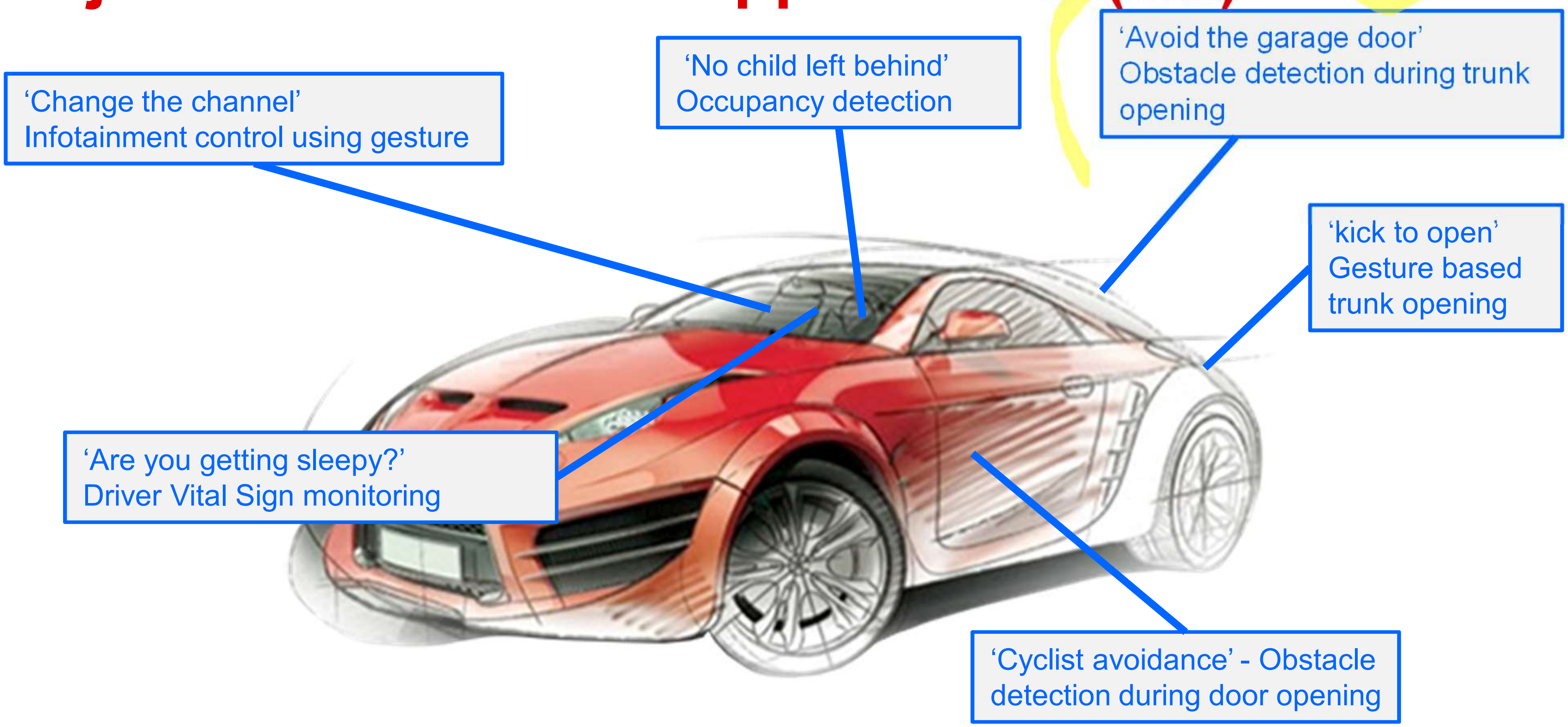
Field Test 3 : TX beamforming (car)

To see the entire video covering all field tests :



Body&Chassis Automotive Applications

Adjacent Automotive Applications (1/2)



Agenda

- Adjacent automotive applications using radar
  - Obstacle detection.
  - Driver vital sign monitoring.
  - Occupancy detection.
  - Gesture recognition.

Adjacent Automotive Applications (2/2)

- Why Radar:
  - Fine Range and velocity resolution
  - Robust under weather
  - Aesthetics: can be placed behind a façade
  - Multi-use : E.g. parking sensor doubles as a ‘kick-to-open’ sensor
  - High Sensitivity to small movement.

- The AWR1642 76-81 GHz integrated radar sensor is ideally suited for these applications:
- Chirp with 4GHz bandwidth
- 2 TX – 4 RX
- C6748 DSP @600MHz
- ARM R4F @200MHz
- 1.5MB on-chip

- Application note
http://www.ti.com/lit/wp/spry315/spry315.pdf

Obstacle Detection Sensor

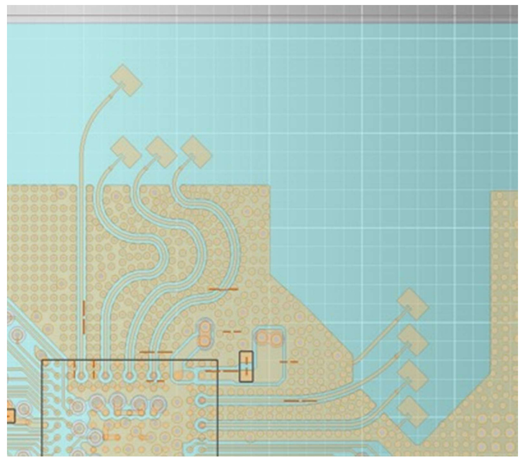
Obstacle Detection Sensor (1/4) – Applications

- **Car Door Opening**
  - Detect obstacles around car door and lock movement to avoid damage
- **Trunk Opening**
  - Detect obstacles around trunk to avoid damage while opening
- **Parking assistance**
  - Detect objects like plastic, metal cones, curb, tree, mesh, other cars, motorcycle, pedestrian while parking a car
- **Detect potholes/Speed bumps**
  - For smoother driving by tuning the suspension based on the road ahead.

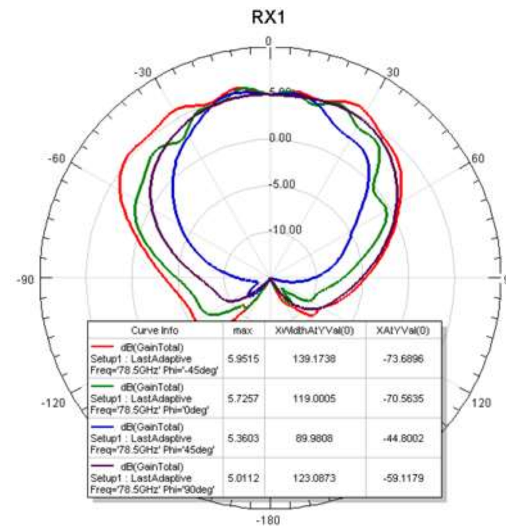
Obstacle Detection Sensor (2/4) –Hardware Platform

- Newly designed antenna
  - Wide field of view $\pm 80^{o}$, Elevation measurement.
  - Detection range of 15m,
- Otherwise similar to AWR1642BOOST EVM

ODS EVM Board

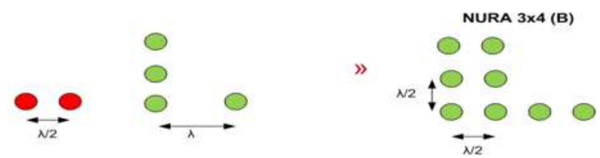


Antenna layout



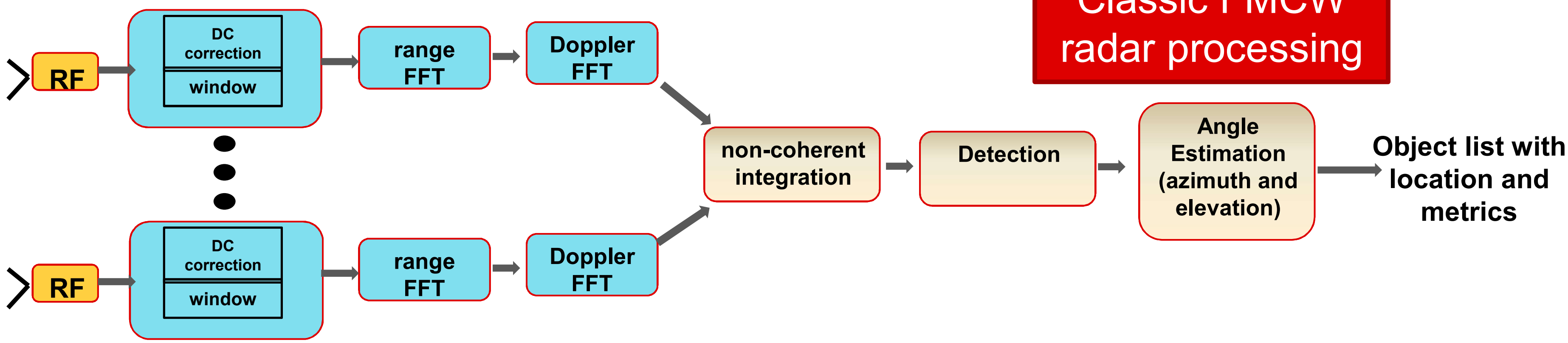
Radiation Pattern

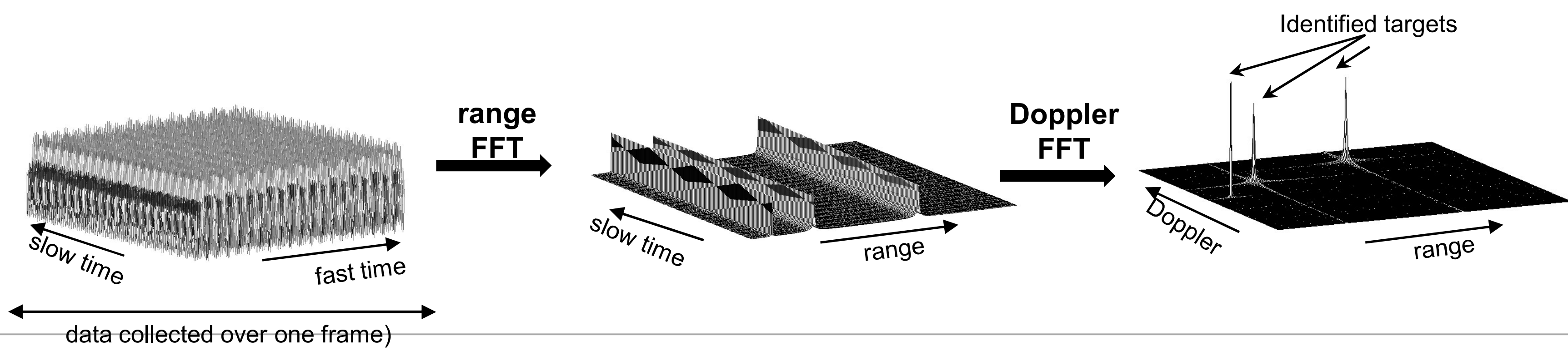
- Non-uniform Receiver array NURA 3x4 (B):
- Using 2Tx and 4Rx a virtual array of 3 x 4 is generated



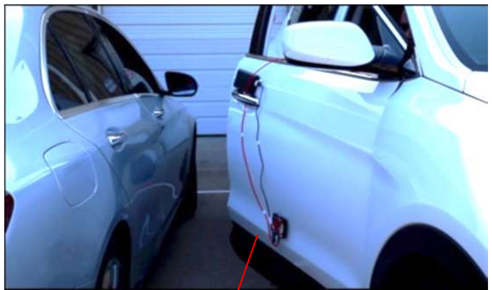
Obstacle Detection Sensor (3/4) - Processing Chain

Classic FMCW radar processing





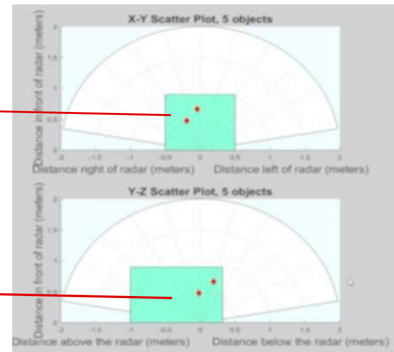
Obstacle Detection Sensor (4/4) – Evaluation



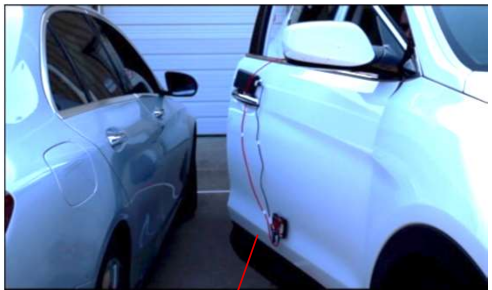
Sensor 50cm from ground

Car door detection in horizontal plane

Car door detection in vertical plane

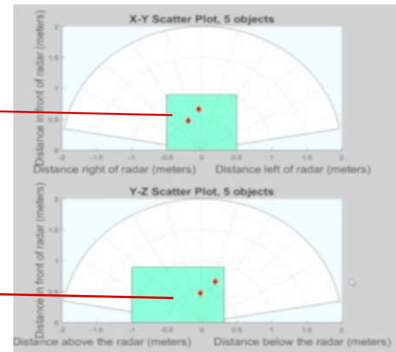


Obstacle Detection Sensor (4/4) – Evaluation

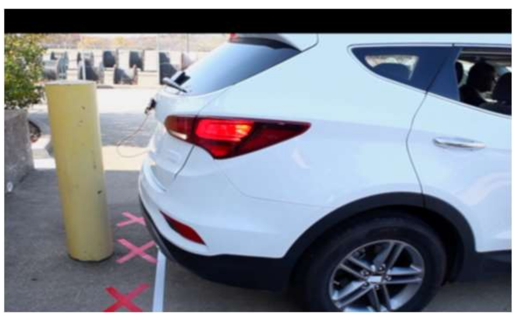


Car door detection in horizontal plane

Car door detection in vertical plane

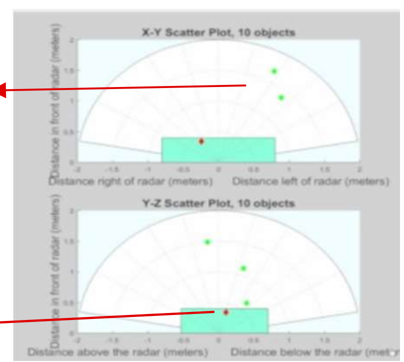


Sensor 50cm from ground

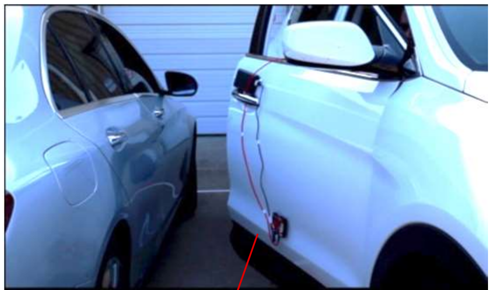


Objects detected not as obstacles

Pole detected as obstacle

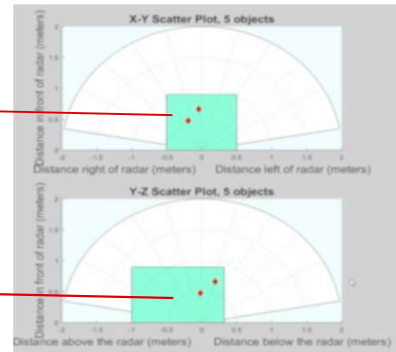


Obstacle Detection Sensor (4/4) – Evaluation



Car door detection in horizontal plane

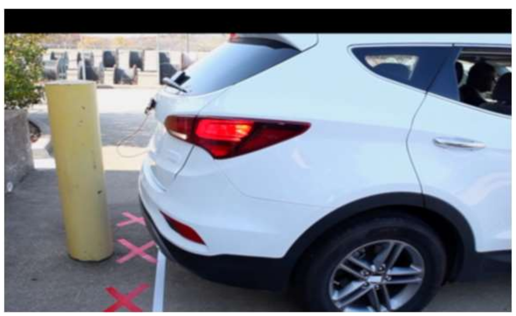
Car door detection in vertical plane



Sensor 50cm from ground

Chirp configuration

Parameter	Value
Chirp bandwidth	4GHz
Chirp periodicity	100µs
Number of chirps per frame	32 (interleaved between TX1 and TX2)
Maximum velocity	17kmph
Range resolution	~4cm
Maximum range	4m
Velocity resolution	1kmph
Memory requirement	~100KB



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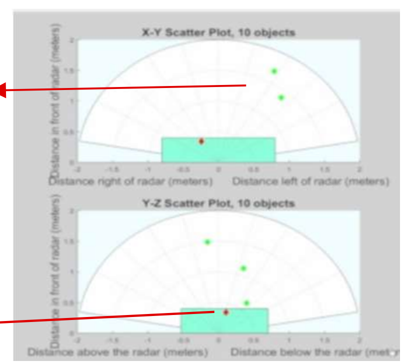
Pole detected as obstacle



Reference :

- Early evaluation code and EVM schematics available now at mySecureSW

Driver Vital Sign Monitoring

Driver Vital-Signs Monitoring (1/4) - Application

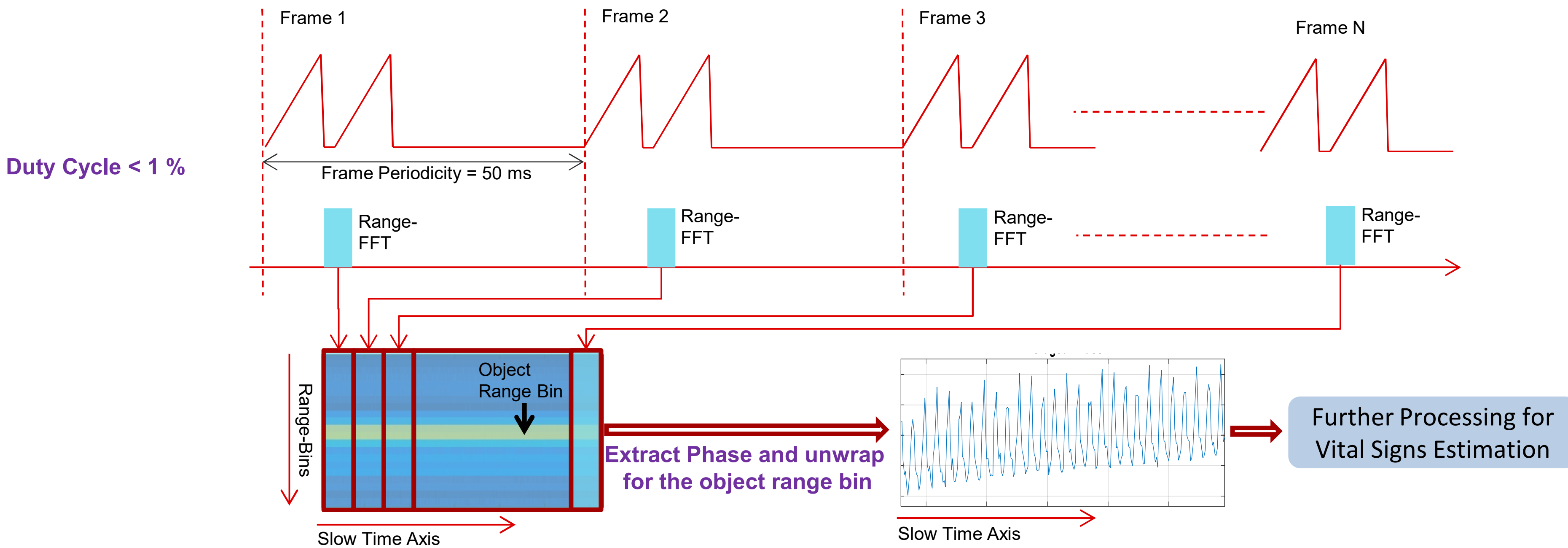
- **Targeted application :** Monitoring of heart and breathing rate of driver.
  - Heart-rate variability,
  - If driver is falling asleep, the heart/breathing rate would slowly decrease.
- How does Radar measure heart-rate ?
  - 77Ghz radar doesn’t penetrate the skin.
  - Radar can measure body surface movements due to breathing/heartrate.
  - Uses the sensitivity of 77Ghz radar to small movements (1mm => 180 degrees phase shift).

Typical vital sign parameters

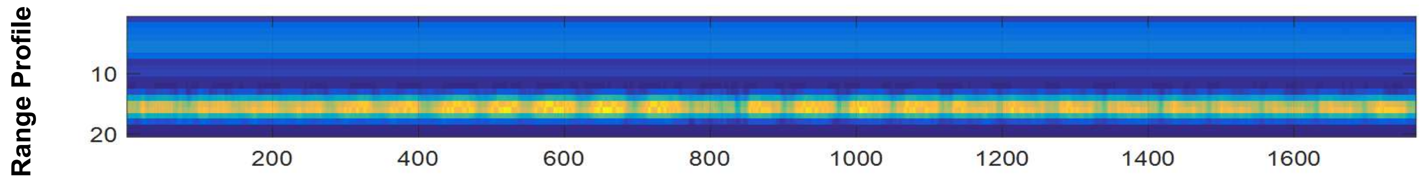
		From Front	From Back
Vital Signs	**Frequency**	**Amplitude**	**Amplitude**
Breathing Rate (Adults)	0.1 – 0.5 Hz	~ 1- 12 mm	~ 0.1 – 0.5 mm
Heart Rate (Adults)	0.8 – 2.0 Hz	~ 0.1 – 0.5 mm	~ 0.01 – 0.2 mm

Driver Vital-Signs Monitoring (2/4)

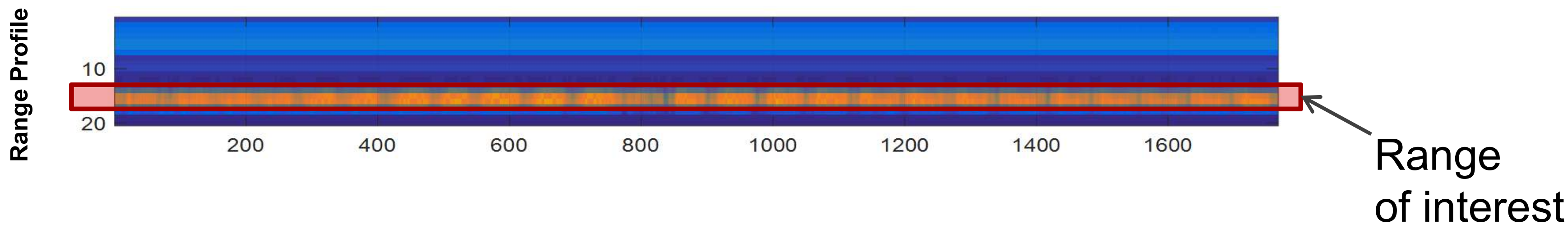
- 100 ADC Samples per chirp. Chirp duration is 50 μs based on the IF sampling rate of 2 MHz
- Each frame is configured to have 2 chirps. However only the 1st Chirp in the frame is used for processing
- A single TX-RX antenna pair is currently used for processing (Although all the RX antennas are enabled)
- Vital signs waveform is sampled along the “slow time axis” hence the vital signs sampling rate is equal to the Frame-rate of system



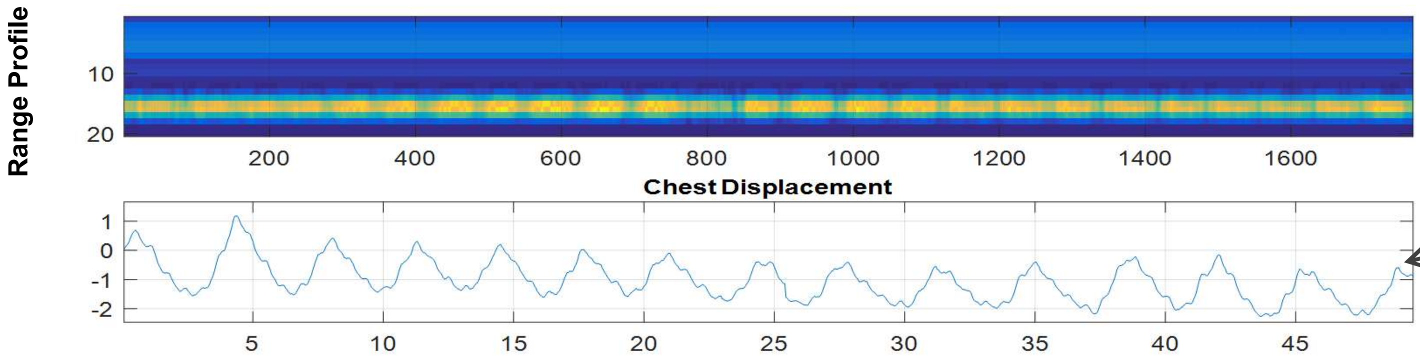
Driver Vital-Signs Monitoring (2/4) – Processing



Driver Vital-Signs Monitoring (2/4) – Processing

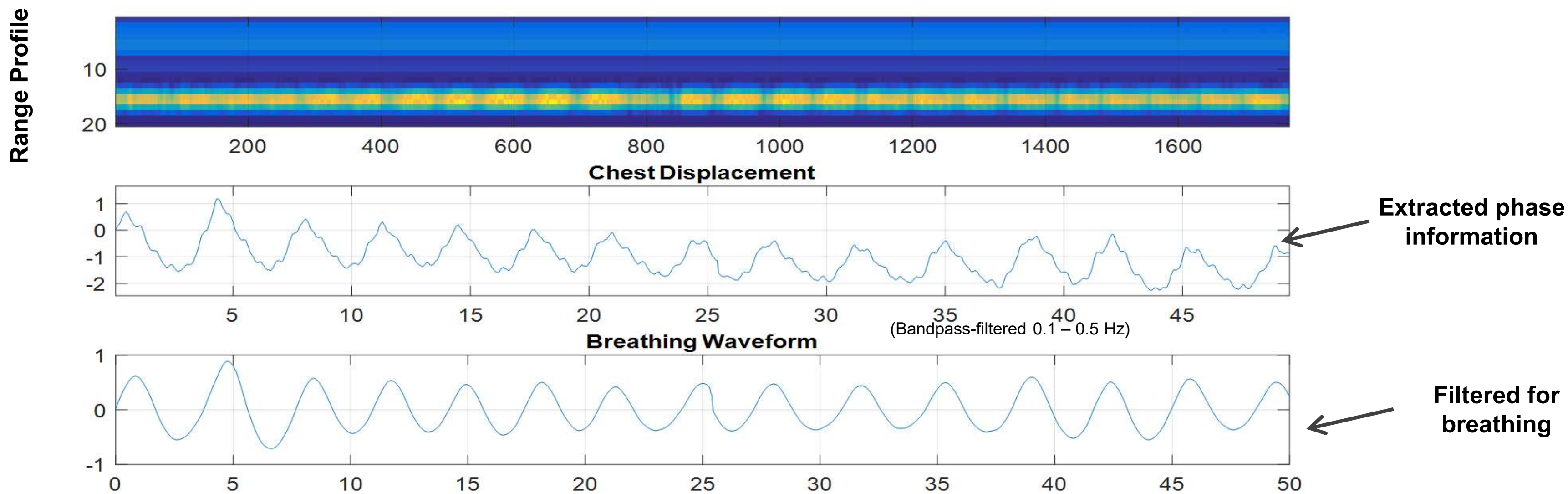


Driver Vital-Signs Monitoring (2/4) – Processing

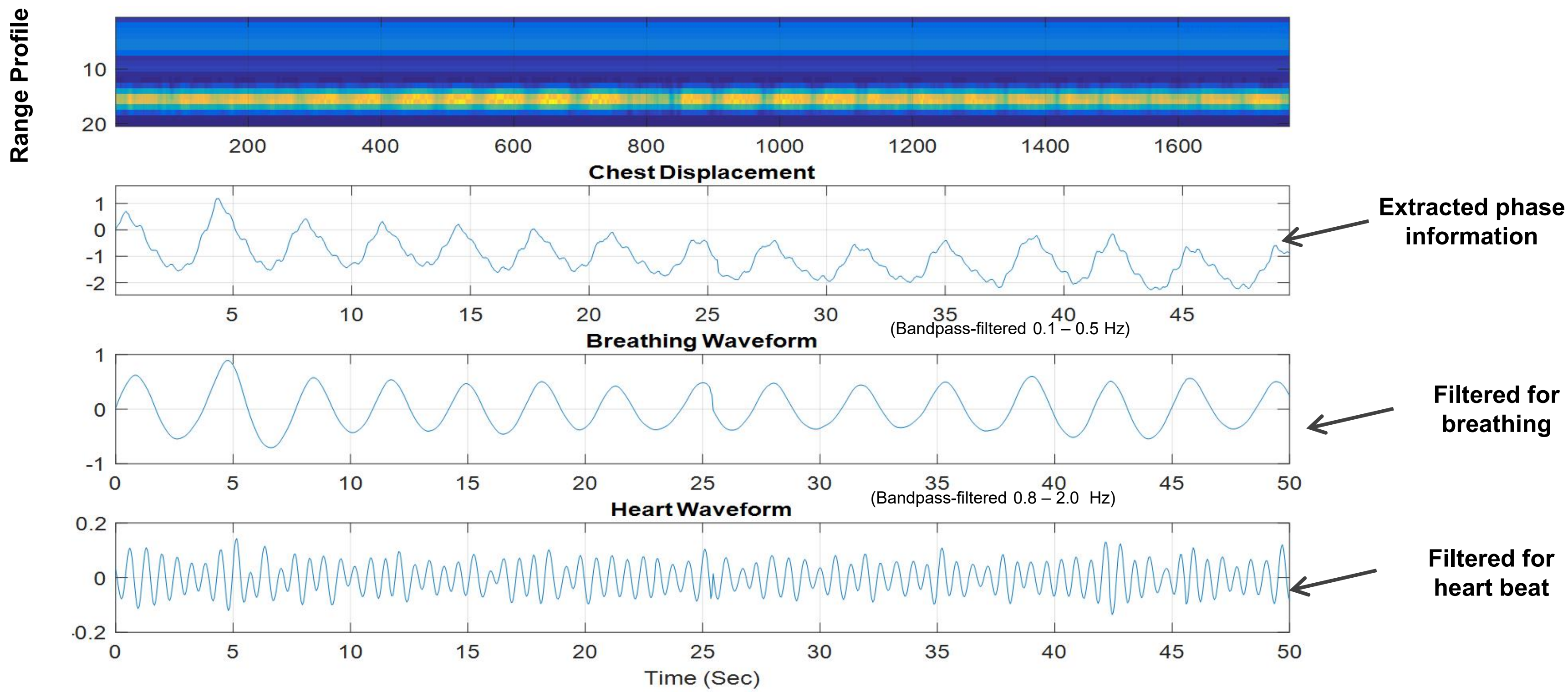


Extracted phase information

Driver Vital-Signs Monitoring (2/4) – Processing

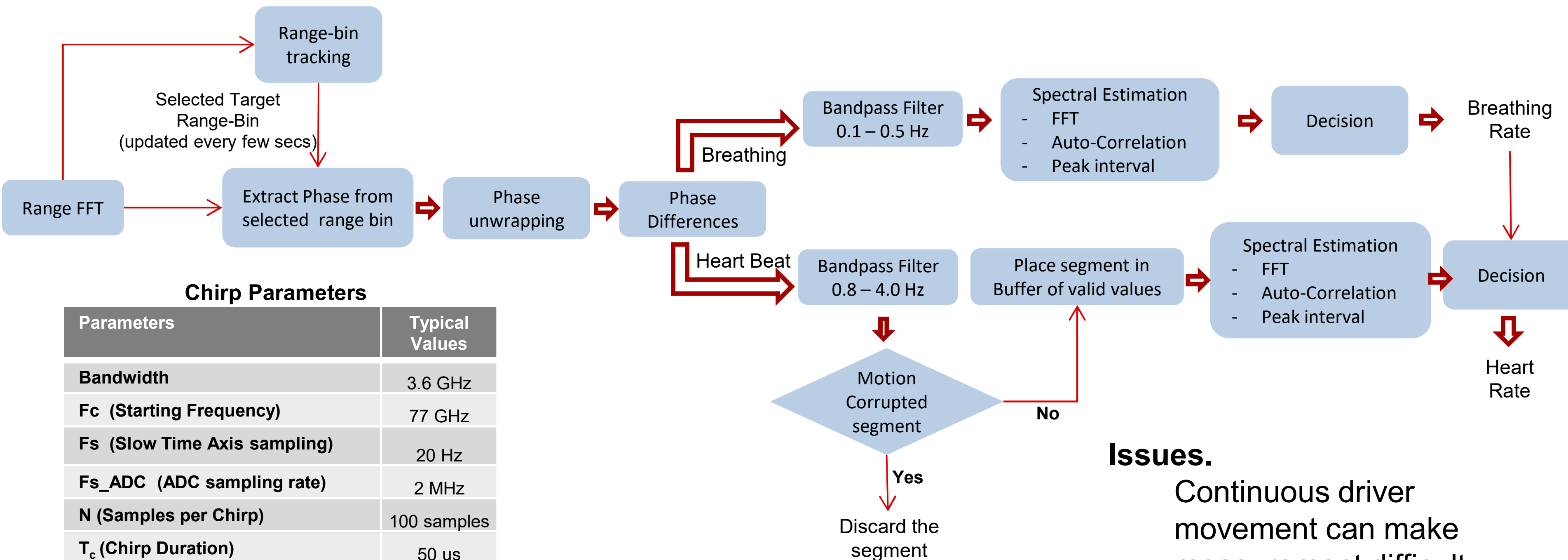


Driver Vital-Signs Monitoring (2/4) – Processing



Driver Vital-Signs Monitoring (3/4) – Processing

- Real-time implementation (20 fps) on the C674x DSP Processing Core
- Processing done over a running window of *T* ~ 16 seconds. New estimates are updated every 1 second
- Memory Requirements ~ 16 kB, CPU Processing time for a single estimate ~ 4 ms



Chirp Parameters

Parameters	Typical Values
Bandwidth	3.6 GHz
Fc (Starting Frequency)	77 GHz
Fs (Slow Time Axis sampling)	20 Hz
Fs_ADC (ADC sampling rate)	2 MHz
N (Samples per Chirp)	100 samples
T_c (Chirp Duration)	50 us

Issues.

Continuous driver movement can make measurement difficult.

Driver Vital-Signs Monitoring (4/4) – Evaluation

- AWR1642 BOOST sensor is used for testing
- The sensor is embedded into the seat, behind the driver.

Driver Vital-Signs Monitoring (4/4) – Evaluation

Driver Vital-Signs Monitoring (4/4) – Evaluation

GUI showing heart rate and breathing rate

Reference Code:

- Link
- Video

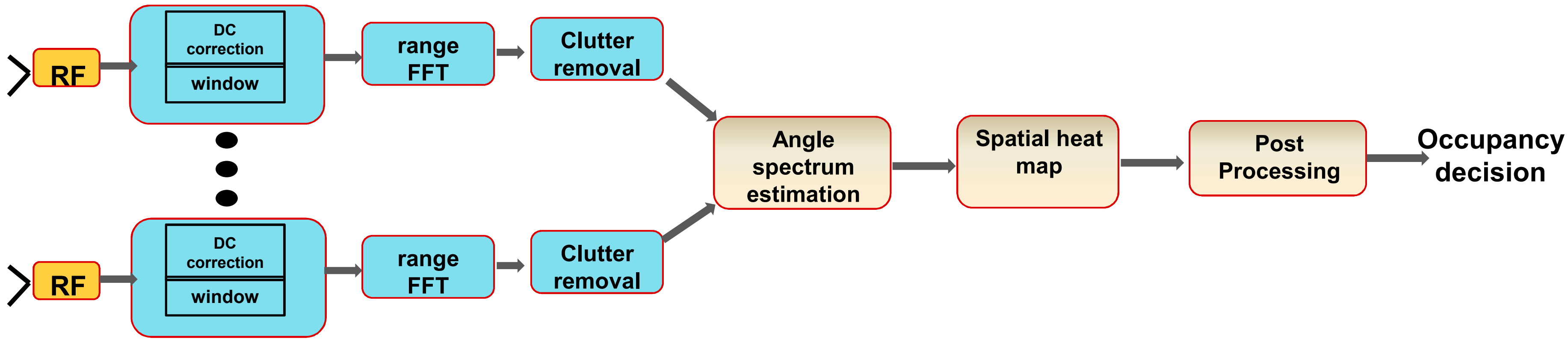
Texas Instruments

Vehicle Occupant Detection

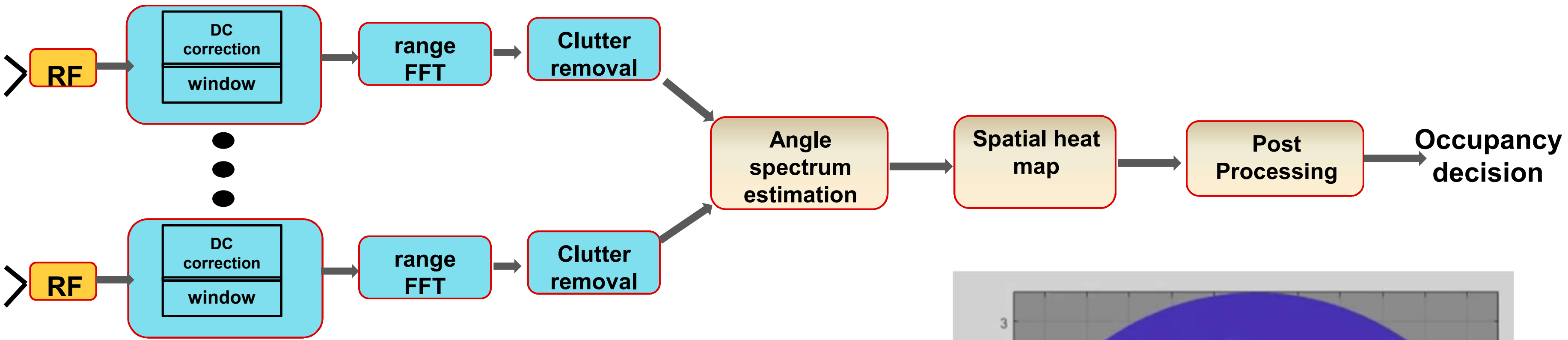
Vehicle Occupant Detection (1/3) - Applications.

- **Child left behind in car detection**
  - Detect the presence of a child in car when a caregiver locks the car door forgetting to take the child outside
- **Occupancy detection**
  - Detection of a lifeform in any seat to determine the force of airbag deployment in case of crashes
- **Intruder detection**
  – Detection of a intruder breaking into a car

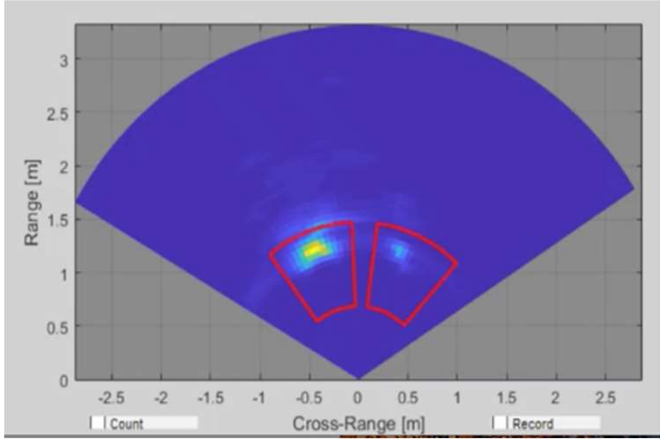
Vehicle Occupant Detection (2/3) - Processing chain.



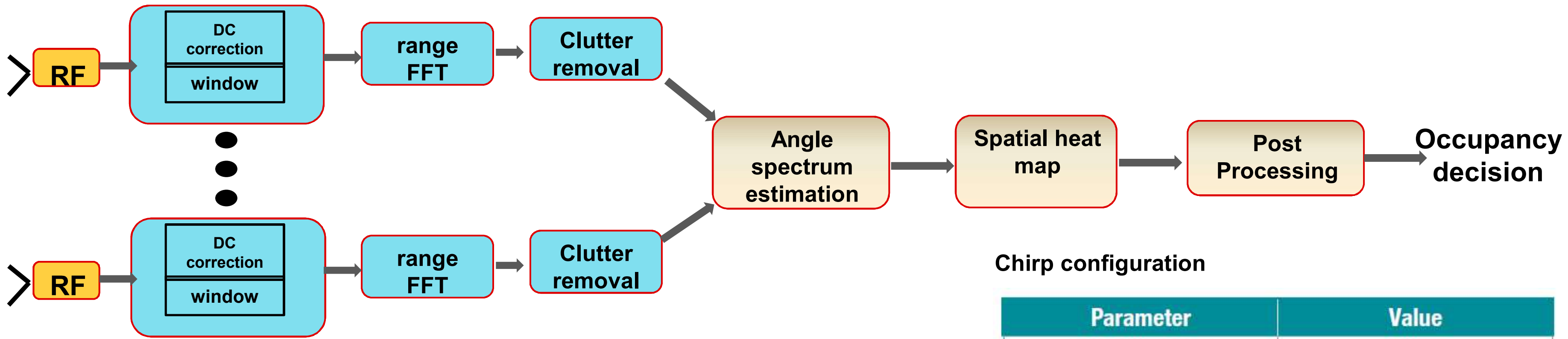
Vehicle Occupant Detection (2/3) - Processing chain.



- Main difference with OOB is that
  - No doppler processing is performed.
  - Angle estimation is performed using MVDR.
    - Provides better angular resolution assuming targets are slowly moving.



Vehicle Occupant Detection (2/3) - Processing chain.



- Main difference with OOB is that
  - No doppler processing is performed.
  - Angle estimation is performed using MVDR.
    - Provides better angular resolution assuming targets are slowly moving.

Chirp configuration

Parameter	Value
Chirp bandwidth	4GHz
Chirp periodicity	340µs
Number of chirps	512 (256 each of TX1 and TX2)
Range resolution	~4cm
Maximum range	3m
Maximum velocity	2.28m per second (10kmph)
Velocity resolution	0.02m per second (0.08kmph)
Memory requirement	600KB

Vehicle Occupant Detection (3/3) - Evaluation.

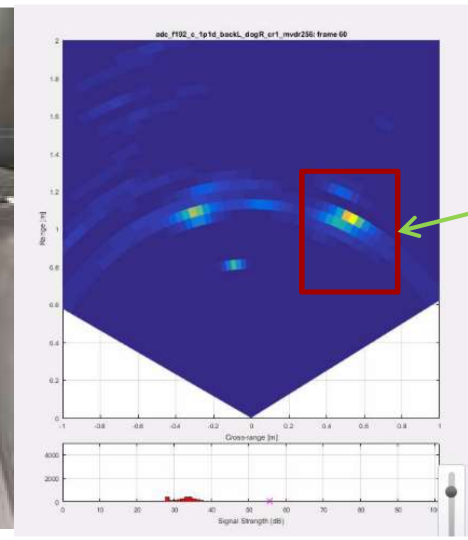
User defined zone.

- Demo can perform zone-based detection.
  - Is a seat occupied?

Vehicle Occupant Detection (3/3) - Evaluation.

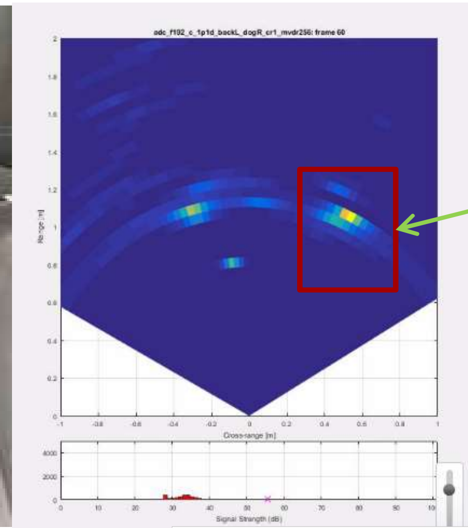
- In-car test, demonstrating the detection of pets.
  - Pets have very small RCS

Vehicle Occupant Detection (3/3) - Evaluation.



- In-car test, demonstrating the detection of pets.
  - Pets have very small RCS

Vehicle Occupant Detection (3/3) - Evaluation.



- In-car test, demonstrating the detection of pets.
  - Pets have very small RCS

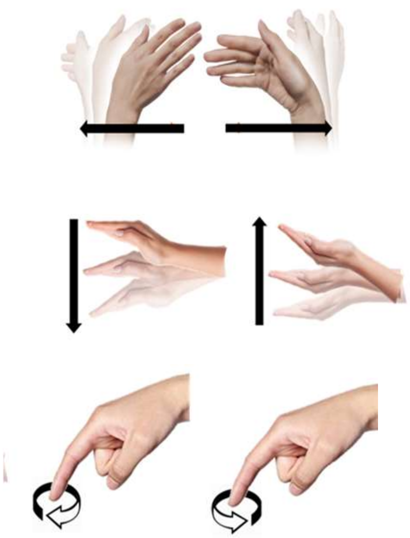
Collateral :

- Source code : link
- white paper : link
- Evaluation module : AWR1642BOOST

Gesture Inference

Gesture Inference (1/4) – Applications

- ‘Kick to open’
  - Detect the kick “gesture” to open the trunk of a car – hands-free.
- In-cabin gestures
  - Swipe up and down to open and close the sun roof.
  - Swipe left and right to change radio channels.
  - Rotate finger to control radio volume.

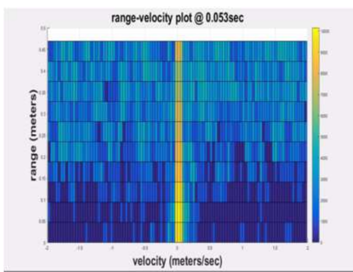


Gesture Inference (2/4) – Processing

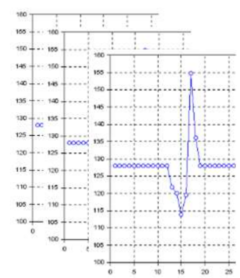
2D FFT → Feature Extraction → Feature Classification → Post Processing

Input:
ADC samples

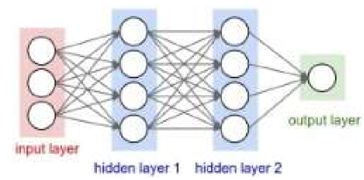
Intermediate O/P:
Range Doppler Image (RDI)



Intermediate O/P:
Per frame
Feature Vector



Intermediate O/P:
Classified Gesture



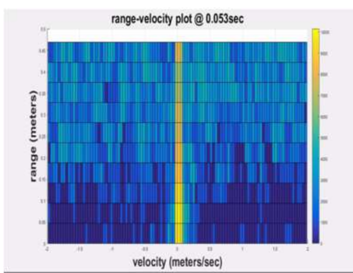
Output:
Filtered
Gesture

Gesture Inference (2/4) – Processing

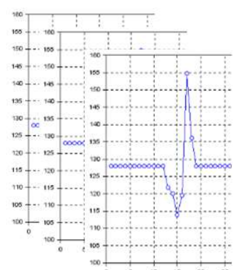
2D FFT → Feature Extraction → Feature Classification → Post Processing

Input:
ADC samples

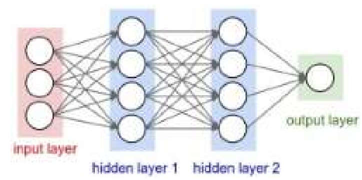
Intermediate O/P:
Range Doppler Image (RDI)



Intermediate O/P:
Per frame
Feature Vector



Intermediate O/P:
Classified Gesture



Output:
Filtered Gesture

- Radar advantages over camera
  - Fine velocity estimation.
    - Enables detection of fine motion
  - Unaffected by light..

Gesture Inference (2/4) – Processing

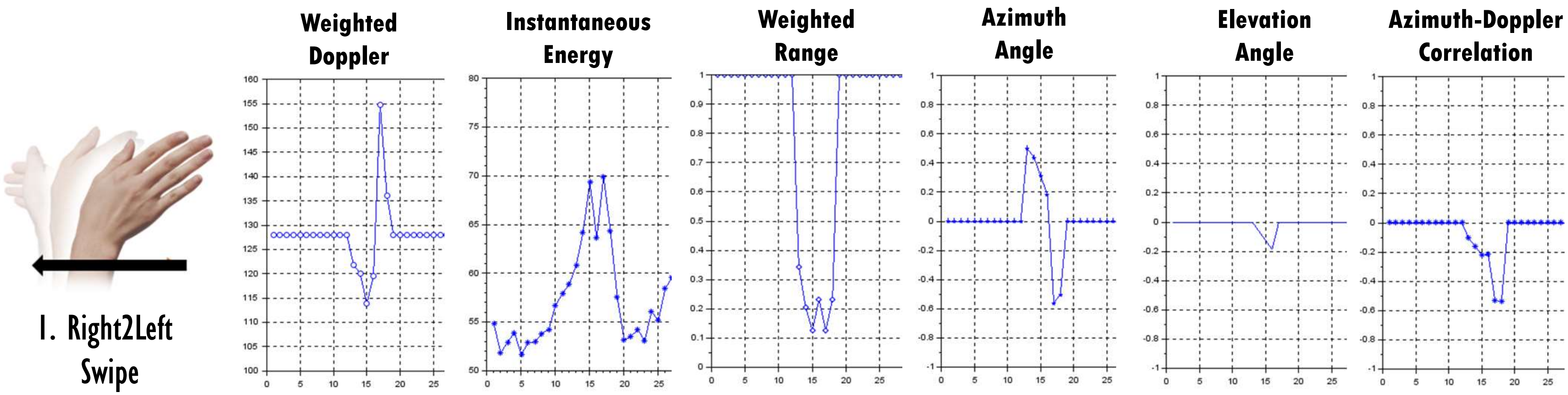
Input:
ADC samples

Output:
Filtered Gesture

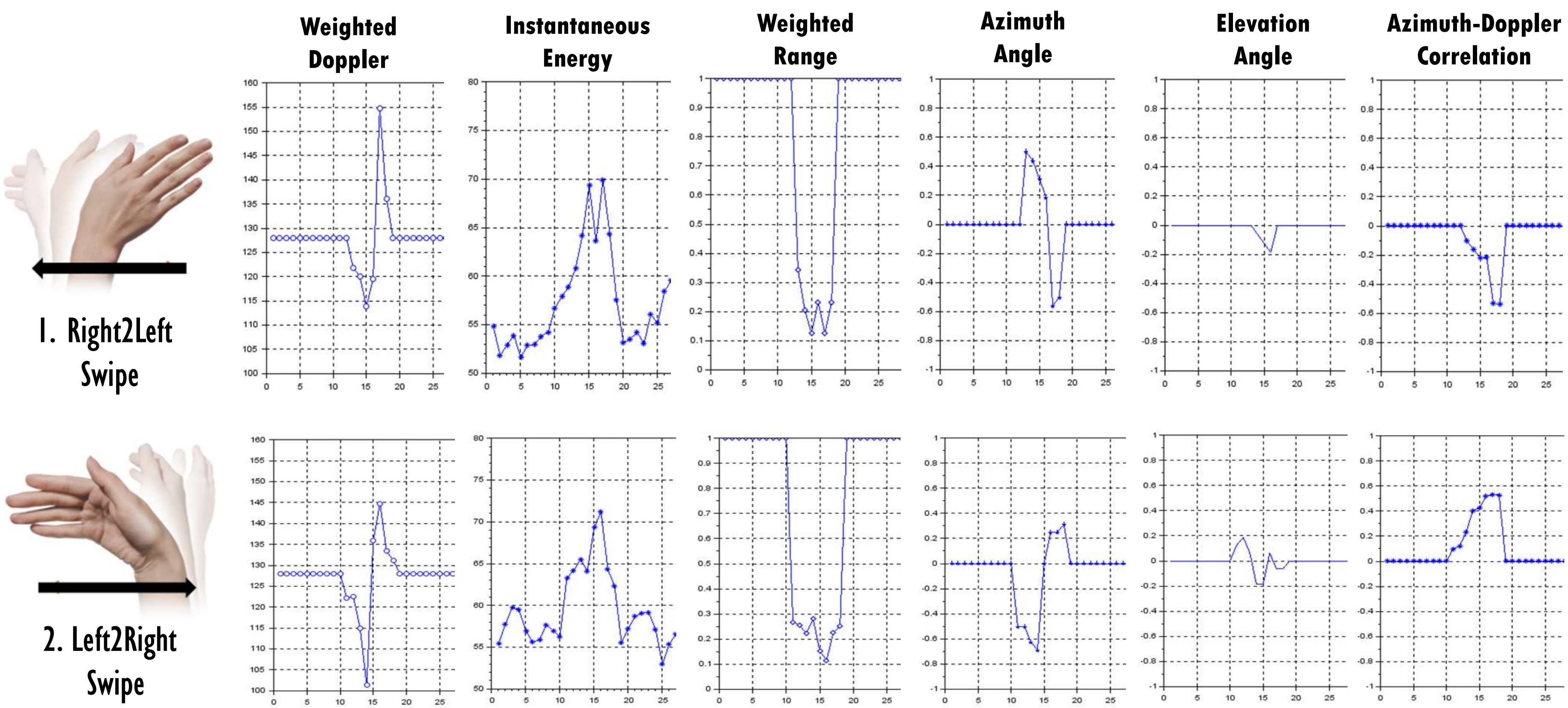
Chirp Parameters

Specifications	Gesture Recognition
Max. Range (m)	3.35 m (ROI limited to 80 cm)
Range Resolution (m)	0.05 m
Absolute Velocity (m/s)	2.5 m/s
Velocity Resolution (m/s)	0.039 m/s
Range Dimension	64
Doppler Dimension	256
Frames/sec	19.6

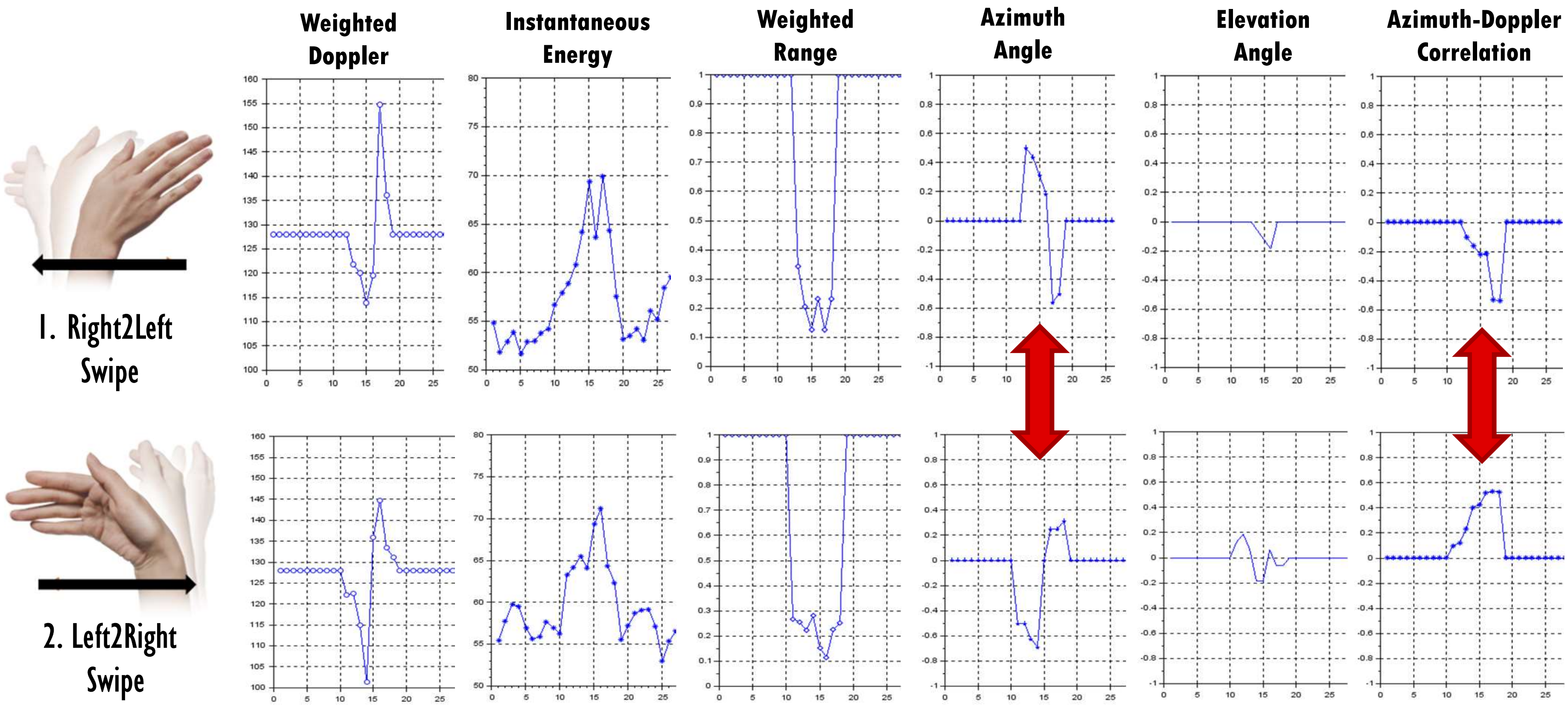
Gesture Inference (3/4) – Signatures



Gesture Inference (3/4) – Signatures



Gesture Inference (3/4) – Signatures



Gesture Inference (4/4) – Evaluation

- AWR1642 ODS sensor is used for testing.
- Neural network runs on the chip.
- Current Status
  - Upto 6 gestures can be detected.
  - Reference processing chain and training feature set
    - Available in May 2018

Summary

- Cascade Radar
  - Why cascade? Higher angle resolution and longer distance
  - Multimode cascade radar: MIMO and TX beamforming
  - Master/slave share LO for frequency/phase synchronization
  - TI 4-chip cascade demonstration(https://training.ti.com/imaging-radar-using-multiple-single-chip-fmcw-transceivers)

- Body&Chassis Automotive Applications
  - Obstacle detection for door opening
  - Driver vital sign monitoring
  - Occupancy detection
  - Gesture recognition

Reference

- “Automotive body and chassis applications”, http://www.ti.com/lit/wp/spry315/spry315.pdf
- “AWR1243 Cascade”, http://www.ti.com/lit/an/swra574a/swra574a.pdf
- “MIMO Radar”, http://www.ti.com/lit/an/swra554/swra554.pdf
- “Cascade Video”, https://training.ti.com/imaging-radar-using-multiple-single-chip-fmcw-transceivers
- “Obstacle Detection”, https://training.ti.com/free-space-sensor-demonstration-using-tis-mmwave-sensor?cu=1135109
- “Vital Sign Monitoring”, https://training.ti.com/driver-vital-sign-detection-demonstration-using-mmwave-radar-sensors?cu=1135109

THANK YOU