Provizio

FINAL PRESENTATION

IMPROVED LOCATION MAPPING USING IMAGING RADARS, GNSS AND POINT-CLOUD REGISTRATION

esa

SALES@PROVIZIO.AI

WHO ARE PROVIZIO?

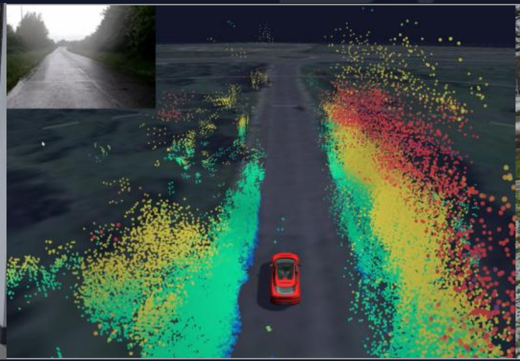
WORLDWIDE TEAM

Carnegie Mellon University The Robotics Institute

FUTURE MOBILITY CAMPUS IRELAND

QUEEN'S UNIVERSITY BELFAST

ECIT THE INSTITUTE OF ELECTRONICS COMMUNICATIONS AND INFORMATION TECHNOLOGY



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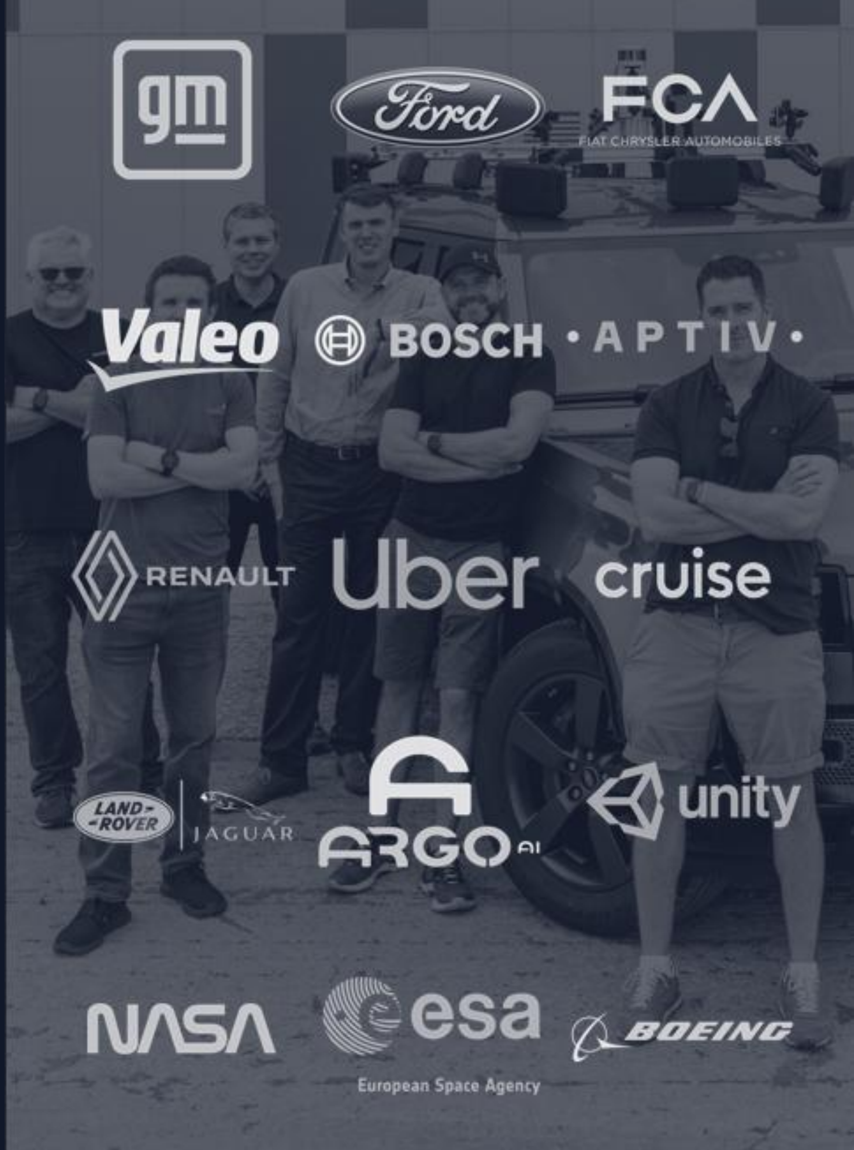
OUR PEDIGREE



OUR MISSION

- Every year over 1.35 million lives are lost, with over 50 million more lives maimed on our roads.
- Advanced Driver Assistance Systems (ADAS) aim to prevent both road deaths and injuries by actively reducing the number of car accidents or the seriousness of the impact of accidents that cannot be avoided.
- ADAS systems deploy perception services which assist the driver to make quicker and safer driving decisions.
- Provizio enhance these systems by deploying AI/ML models to make ADAS systems better and in that way aim to reduce this number further.

AUTOMOTIVE RADAR LANDSCAPE

Mobility is being commoditised

Autonomy is the path to disruption, but…

manufacturers are challenged to achieve full autonomy

86% of consumers don't trust autonomy, but…

human drivers cause a road death every 30 seconds

Provizio's solution is to solve the challenging corner cases faced by the industry in a cost-effective manner

THE PROVIZIO APPROACH

Improve sensors by using our 5D PERCEPTION® AI / ML models to augment human drivers; build trust…and data

Train our AI using crowdsourced data…in real-time

Deliver ubiquitous, safe autonomous driving…incrementally,

EVERYWHERE

5D PERCEPTION®

THE PROBLEM

- When PNT is lost, SLAM is lost
- When SLAM is lost, inputs to 5D PERCEPTION® are corrupted
- Corrupted inputs mean a corrupted output…
- Corrupted outputs mean safety features are lost

TECHNICAL OBJECTIVES

- To allow 5D PERCEPTION® microservices to be maintained when PNT signals are occluded on an automotive radar
  - Requires the maintenance of SLAM

- To predict the location change, from a previously known point, using the dead-reckoning technique
  - Requires the near instantaneous calculation of speed, angle change and distance

- The change in position must calculated by ONLY using radar data point detections
  - No other sensors or components such as an IMU should be used

- Total processing and calculation time must be maintained within the 100ms limit per frame i.e. the 10 FPS radar streaming rate and the radar nominal performance must be maintained

- The algorithm must be able to work using existing radar processors (or one having a similar cost)

EXISTING POINT CLOUD REGISTRATION TECHNIQUES

These include:

- **Fourier-Mellin Transform –** this is often used in the context of visual images (in this case the images would be consecutive point cloud images) and their alignment using translation, rotation angle, and scale factor. It therefore requires a significant computational overload for real-world applications, which is unsuitable for real-time applications.

- **Registration with Existing Radar Maps –** these systems register a current radar point cloud, or a window of several radar point clouds, with an existing radar point cloud-based map, which may have been obtained over multiple vehicle passes. A major drawback of this approach is the need for prior maps to have been generated, which along with being time-consuming, is also impractical.

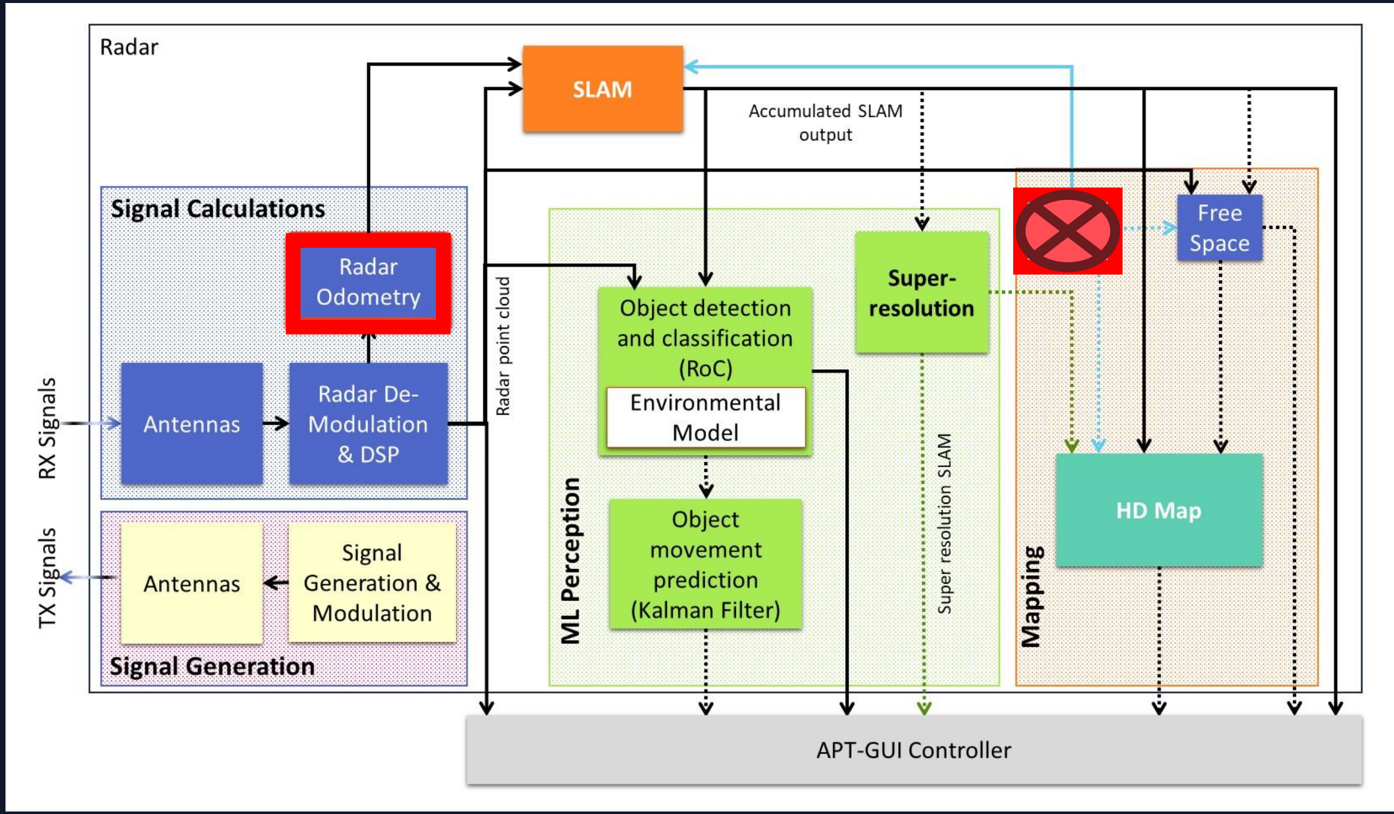
- **Feature Extraction and Iterative Closest Surface Point –** uses filtering to extract key features of the radar point cloud through only keeping the strongest range returns for each azimuth angle, calculating surface points and the normal axes from the filtered point cloud and then registering with closest surface points and normal axes in location and angle within a sliding window of previous point cloud frames. This method requires no existing map data and can be operated at a relatively fast rate. However, for best performance, parameters need optimised for the specific radar sensor and operational environment thus making it impractical for general use.

EXISTING POINT CLOUD REGISTRATION TECHNIQUES

- **Instantaneous Ego-Motion Estimation using Doppler Radar** – where the sinusoidal relationship between the radial velocity and azimuth angle of radar point cloud detections from stationary objects is used to enable the ego-vehicle (the vehicle on which the radar is positioned) velocity and yaw rate to be determined. However, it is not possible to directly extract the velocity vectors of the detections as a doppler radar can only measure the radial velocity component, which adds a considerable computation time to resolve.

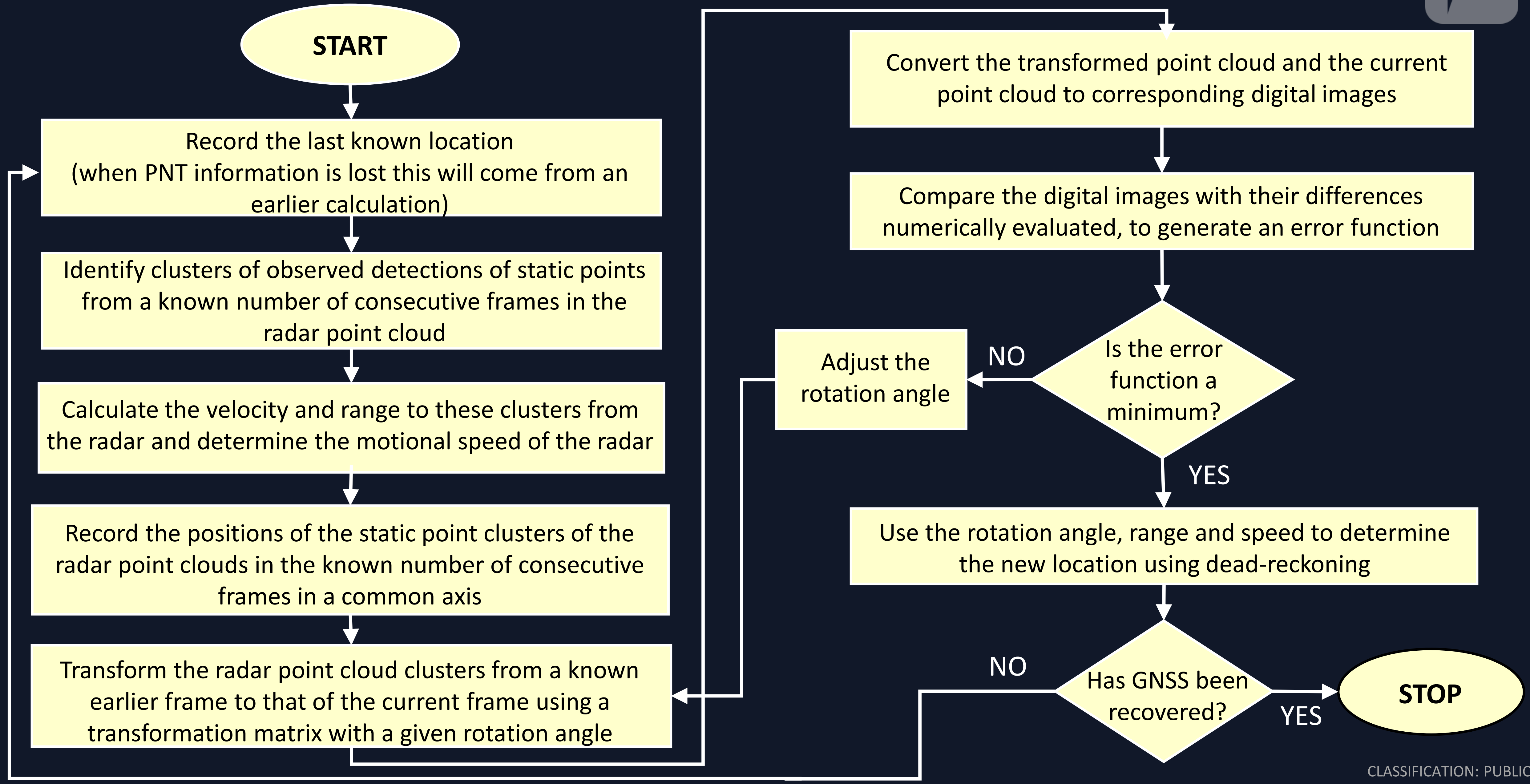
- **Use of an Inertial Measurement Unit and Accelerometer** – the use of additional components add further cost and redundancy as some information is already available from measured radar data.

RADAR ODOMETRY ALGORITHM

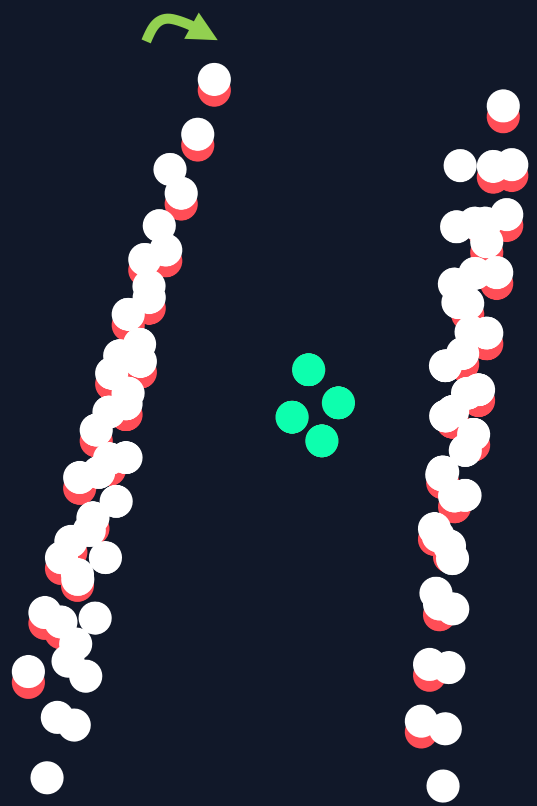


- The radar odometry algorithm is a scan matching-type algorithm that estimates the transform between measurements in the current frame and those in a previous frame.
- Designed to use a measurement of the ego-velocity, obtained from the radar point cloud, to make the extraction of the transform between scans easier and faster.
- Uses an adaptable Kalman Filter to ‘de-noise’ the calculation otherwise a location ‘jitter’ appears.
- Designed to be independent from an accurate radar extrinsic calibration and to need only a low number of operations for a quick implementation in real-time.

ODOMETRY ALGORITHM



ODOMETRY ALGORITHM DEVELOPMENT



SPECIFICATIONS

	ID	Parameter	Min.	Typ.	Max.	Unit
Sensor	RR1	**OPERATING FREQUENCY:**	76		81	GHz
		DETECTION RANGE:				
	RR2	10 dBsm target (car)	0.2		300	m
	RR3	-10 dBsm target (pedestrian)	0.2		60	m
		RANGE RESOLUTION:				
	RR4	Short-range mode (0 – 50 m)		0.05		m
	RR5	Mid-range mode (0 – 100 m)		0.39		m
	RR6	Long-range mode (0 – 200 m)		0.78		m
	RR7	Ultra-long-range mode (0 – 400 m)		1.56		m
	RR8	**RANGE ACCURACY (depending on range mode):**	±0.007		±0.22	m
		FIELD OF VIEW:				
	RR9	Azimuth		120		°
	RR10	Elevation		40		°
		ANGULAR RESOLUTION:				
	RR11	Azimuth		1		°
	RR12	Elevation		11		°
		PERCEPTION:				
	N/A[2]	Radar based Odometry	Radar only SLAM or with GNSS			
	RR13	**SUPPLY:** Voltage (dc)	9.5	12	32	V
	N/A[3]	**CYCLE TIME:**			100	ms
	N/A	**INTERFACE:**	1 GBPS Ethernet			
Output	RR14 RR15	Plug-and-play with API provided for parsing of radar data and Provizio APT GUI for visualisation. 4D point cloud (x, y, z location plus velocity) in all locations.				

ID	Parameter	Min.	Typ.	Max.	Unit
MR1	Computation time			50	ms
	ANGLE DEVIATION:				
MR2	Straight road			0.1	° / frame
MR3	Roundabout (3rd exit out of 4)			0.2	° / frame
	DISTANCE ACCURACY:				
MR4	Straight road	±0.007		±0.22	m

INITIAL TESTING

- The first step was to test the original algorithm (pre updates) using a test radar.

- Tests were conducted using the ‘first-build’ engineering test radar to:
  - Allow further engineering data to be gathered if errors were observed.
  - Enable quick software updates to made due to availability of additional connection points to the radar processor, if required.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Capture Number	Modulation Scheme	Range	Start Frequency (GHz)	Bandwidth (GHz)	Target Distance (m)	Completed?
1	TDMA	SHORT	76	3.2	6	YES
2	TDMA	SHORT	76.5	3.2	6	YES
3	TDMA	SHORT	77	3.2	6	YES
4	TDMA	SHORT	77.5	3.2	6	YES
5	TDMA	MEDIUM	76	0.5	6	YES
6	TDMA	MEDIUM	76.5	0.5	6	YES
7	TDMA	MEDIUM	77	0.5	6	YES
8	TDMA	MEDIUM	77.5	0.5	6	YES
9	TDMA	MEDIUM	78	0.5	6	YES
10	TDMA	MEDIUM	78.5	0.5	6	YES
11	TDMA	MEDIUM	79	0.5	6	YES
12	TDMA	MEDIUM	79.5	0.5	6	YES
13	TDMA	MEDIUM	80	0.5	6	YES
14	TDMA	MEDIUM	80.5	0.5	6	YES
15	DDMA	SHORT	76	3.2	6	YES
16	DDMA	SHORT	76.5	3.2	6	YES
17	DDMA	SHORT	77	3.2	6	YES
18	DDMA	SHORT	77.5	3.2	6	YES
19	DDMA	MEDIUM	76	0.5	6	YES
20	DDMA	MEDIUM	76.5	0.5	6	YES
21	DDMA	MEDIUM	77	0.5	6	YES
22	DDMA	MEDIUM	77.5	0.5	6	YES
23	DDMA	MEDIUM	78	0.5	6	YES
24	DDMA	MEDIUM	78.5	0.5	6	YES
25	DDMA	MEDIUM	79	0.5	6	YES
26	DDMA	MEDIUM	79.5	0.5	6	YES
27	DDMA	MEDIUM	80	0.5	6	YES
28	DDMA	MEDIUM	80.5	0.5	6	YES

RADAR PERFORMANCE TESTING

- Range Accuracy

Capture Number	Mode	Range 1 (m)	Detection Bin 1	Range 2 (m)	Detection Bin 2
1	SHORT	15	301	14.95	300
2	MID	15	39	14.6	38
3	LONG	15	20	14.2	19
4	ULTRA-LONG	15	11	13.4	10

- Bias Interface

Bias Setting (V)	Testpoint T101 (Required)	Testpoint T101 (Measured)	Bootup?
9	1.2	1.2	YES
12	1.2	1.21	YES
32	1.2	1.21	YES

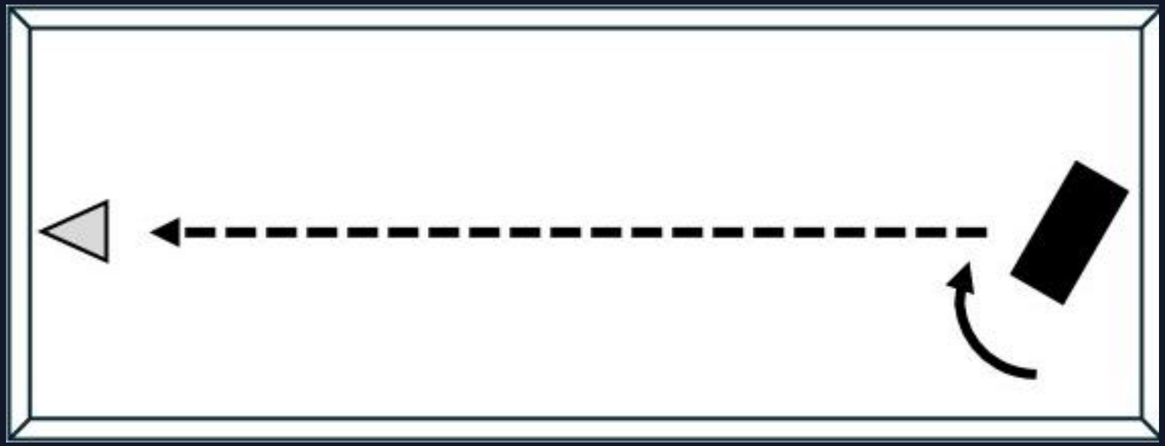
RADAR PERFORMANCE TESTING

- Detection Range

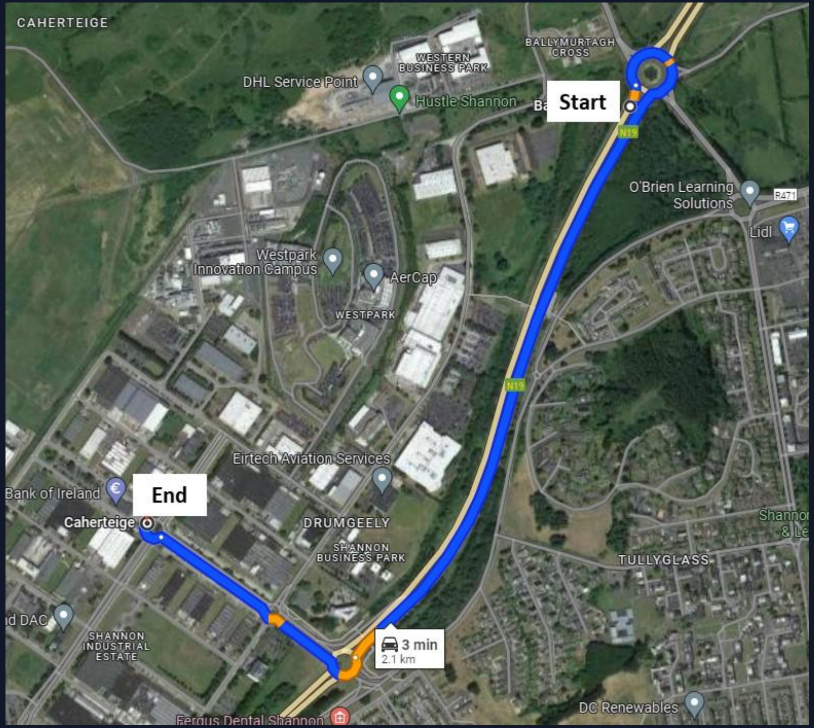
RADAR PERFORMANCE TESTING

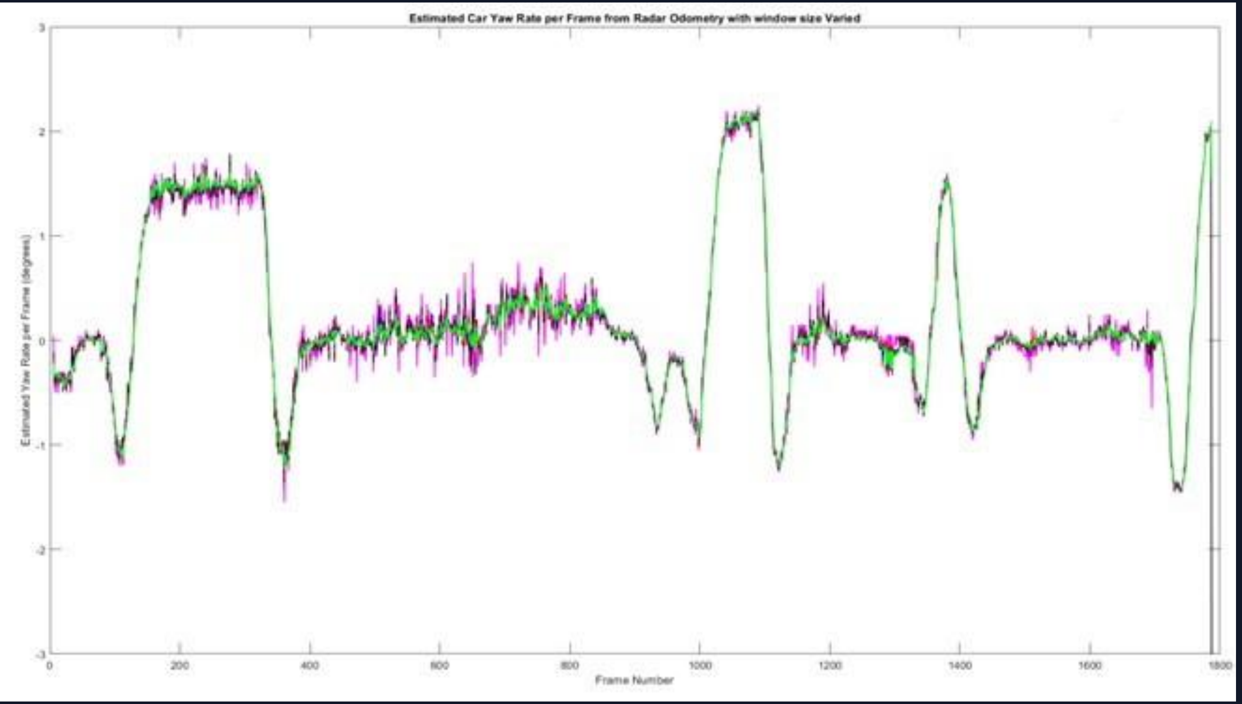
- Field of View Tests

Capture Number	Range (m)	Az Angle (deg)	El Angle (deg)	Reflector SNR level (dB)	Pass / Fail
1	6	0	0	-53.57	PASS
2	6	60	0	-37.33	PASS
3	6	0	20	-48.15	PASS



INITIAL RADAR PERFORMANCE OVERVIEW





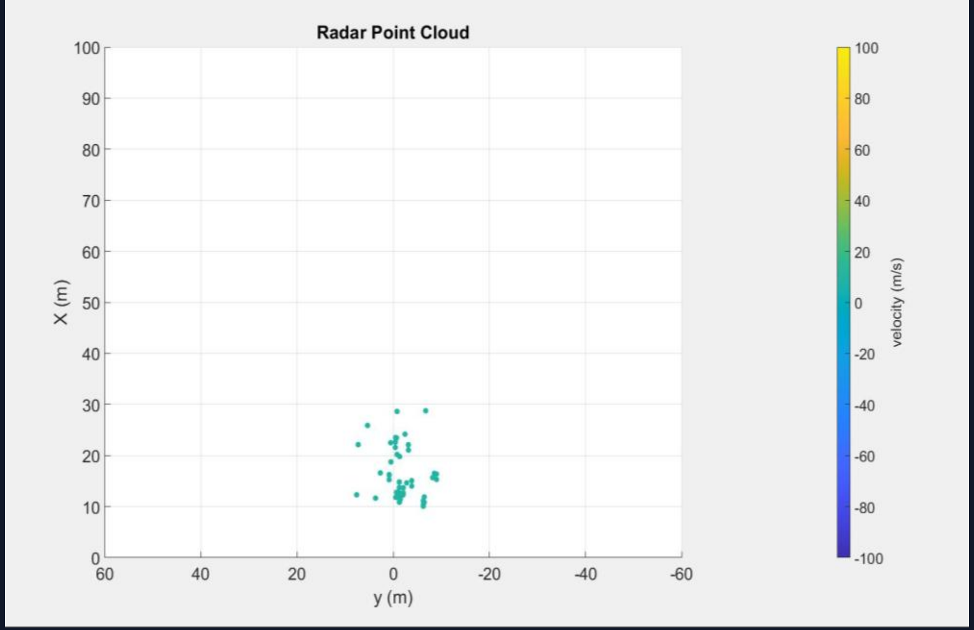
CLASSIFICATION: PUBLIC

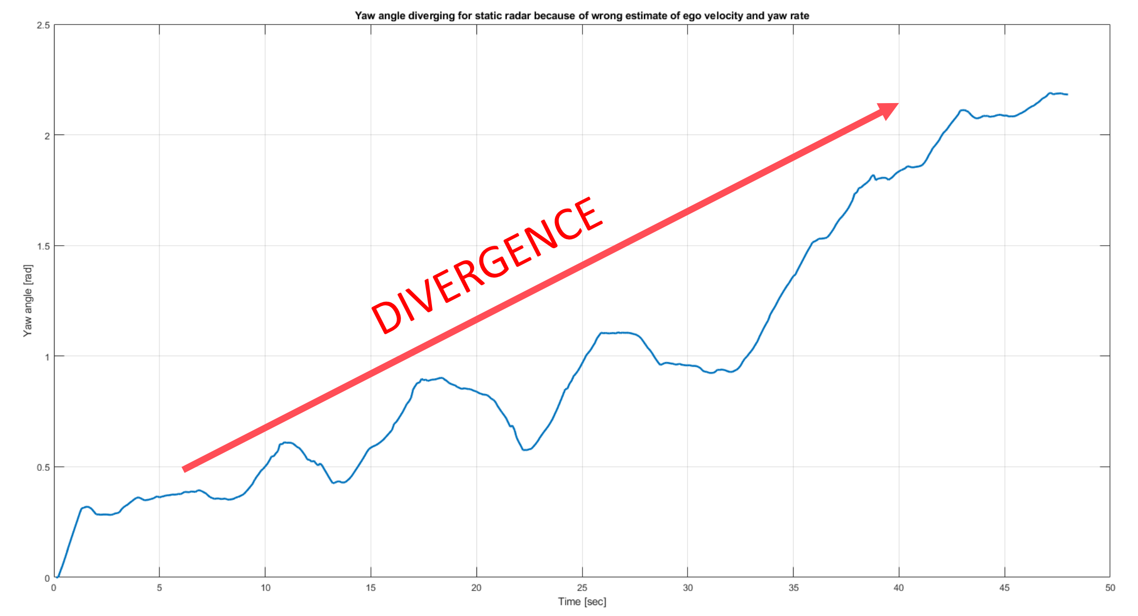
DIVERGENCE

- While initial testing showed promising results, it was noticed that after some time, the yaw rate was seen to start diverging and constantly increase / decrease:

DIVERGENCE

- To investigate this further, analysis was conducted on a static radar in an indoor scene.
- Results showed a non-coherent detection plot appearing over time, so was proven not to be introduced by the test setup:

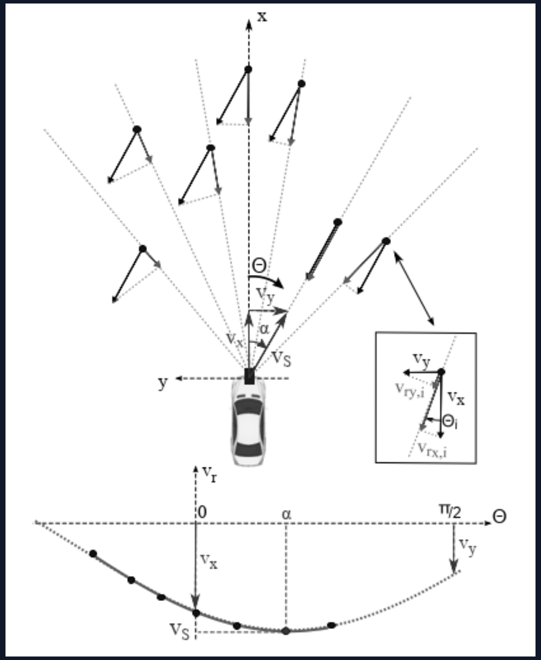


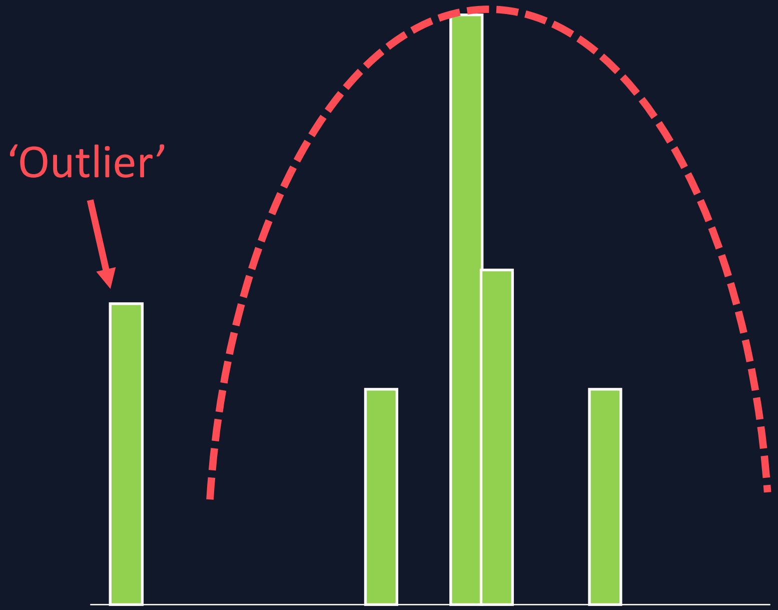


DIVERGENCE ANALYSIS

Analysis showed that:

- Divergence appeared when the ground velocity was missing (from a noisy point cloud) and a histogram. velocity estimation is used which does not follow a cosine function as a lot of 'outliers' appear.





- It appeared when most of the point cloud was filtered as 'dynamic', leaving less than 10 points from static objects in the scene.
- Both effects were needed to occur simultaneously for divergence to occur.

DIVERGENCE SOLUTION

Use a *Hybrid Solution* to calculate the ego-velocity:

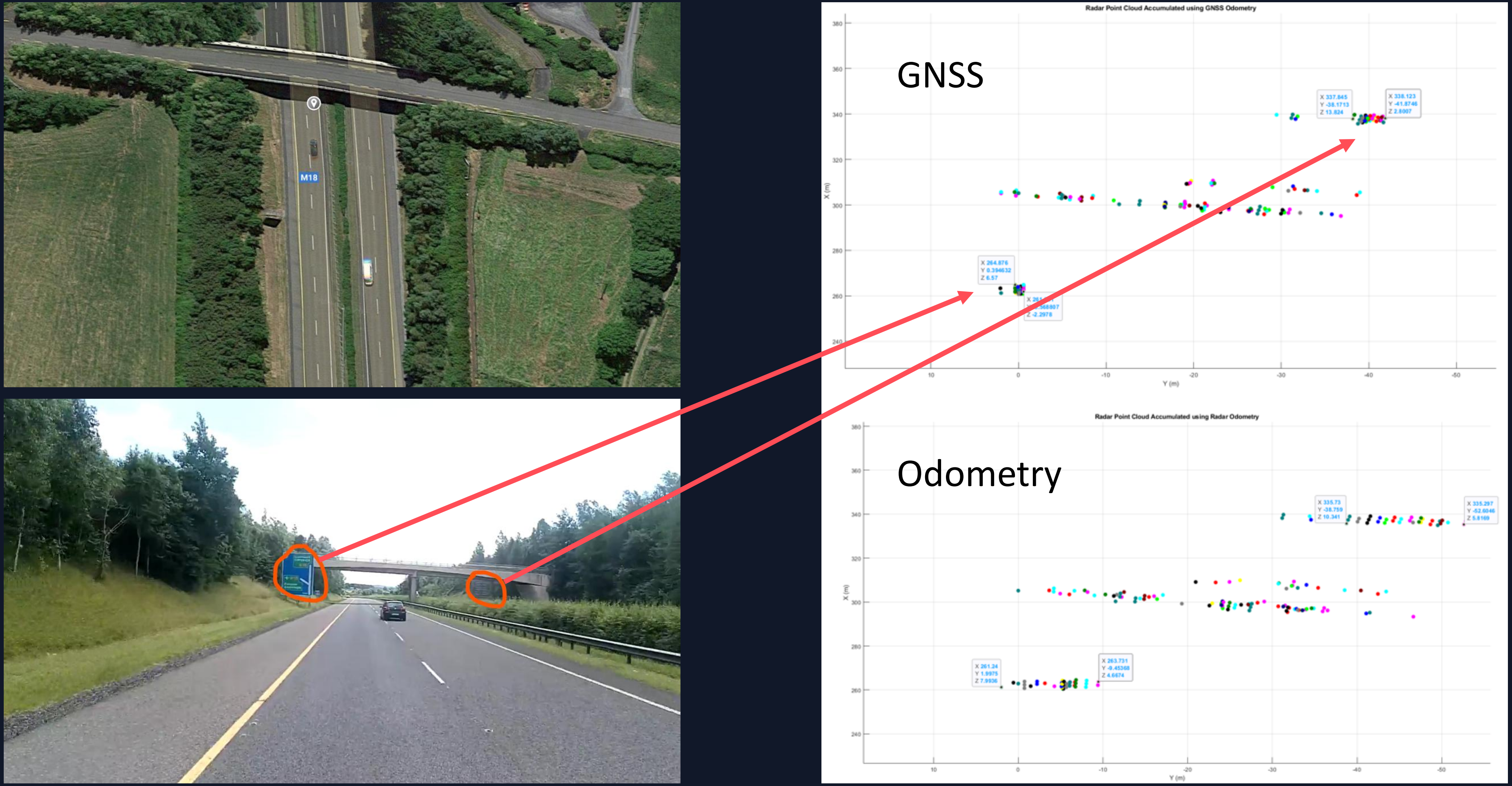
- Uses both the ‘Histogram Estimate’ and the one calculated from the complied radar processor code.
- As both estimates produce outliers at different frames, their combination greatly improves the ground velocity estimation.

In *noisy* environments:

- Ensure that the analysis is conducted over the full angle bandwidth, by:
  - Checking if the minimum located by the error function is improved from the previous calculation.
  - If this is not the case for 5 consecutive frames, the algorithm is reset to search over the full span of the possible yaw angles.

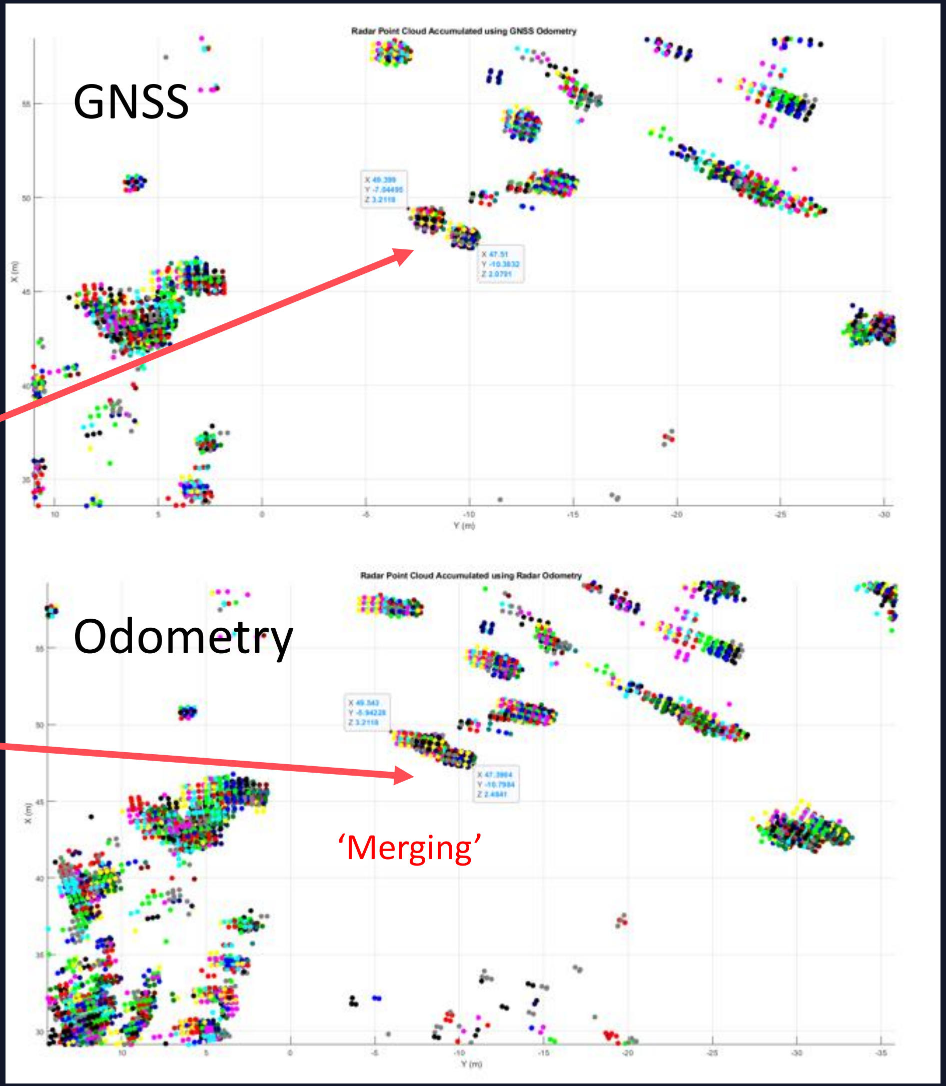
ODOMETRY DEVIATION – STRAIGHT ROAD

- By using accumulation on fixed reference points over time, the deviation of the points in the point cloud can be measured.



ODOMETRY DEVIATION - CORNERING

- Again, by using accumulation on fixed reference points over time, the deviation of the points when cornering can be measured.



DEVIATION - RESULTS

	Straight Road	Cornering
Total Measured Offset (m)	15	23
Delta (m)	7.5	11.5
Range (m)	300	47.4
Offset Angle (deg)	1.44	1.36
Number of Frames	20	10
Deg / frame	0.072	0.136

- Deviations were measured to be well within the specifications.

COMPUTATION TIME ERROR

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COMPUTATION TIME ERROR

- Due to the more challenging calculation, the processor was unable to calculate the yaw angle quick enough as the computation time was limited on the radar processor to prevent other services from being disrupted.
    - Several code improvements would solve this problem in future updates.
    - High-framerate interpolation was also introduced between the last odometry frames in APT-GUI (SW3), to improve SLAM precision (without adding extra lag).

- Time-stamping was also neglected at the frame trigger point meaning that the yaw rate could be calculated over an incorrect time period.
    - Identified as introducing the possibility of an incorrect calculation.
    - Time-stamping was therefore implemented in future code updates to remove this potential error.

TEST RADAR PERFORMANCE OVERVIEW

	ID	Parameter	Min.	Typ.	Max.	Unit	Test Result
Sensor	RR1	**OPERATING FREQUENCY:**	76		81	GHz	PASS
	RR2 RR3	**DETECTION RANGE:** 10 dBsm target (car) -10 dBsm target (pedestrian)	0.2 0.2		300 60	m	PASS PASS
	RR4 RR5 RR6 RR7	**RANGE RESOLUTION:** Short-range mode (0 – 50 m) Mid-range mode (0 – 100 m) Long-range mode (0 – 200 m) Ultra-long-range mode (0 – 400 m)		0.05 0.39 0.78 1.56		m	PASS PASS PASS PASS
	RR8	**RANGE ACCURACY (depending on range mode):**	±0.007		±0.22	m	PASS
	RR9 RR10	**FIELD OF VIEW:** Azimuth Elevation		120 40		°	PASS PASS
	RR11 RR12	**ANGULAR RESOLUTION:** Azimuth Elevation		1 11		°	PASS PASS
	N/A[2]	**PERCEPTION:** Radar based Odometry	Radar only SLAM or with GNSS				
	RR13	**SUPPLY:** Voltage (dc)	9.5	12	32	V	PASS
	N/A[3]	**CYCLE TIME:**			100	ms	
	N/A	**INTERFACE:**	1 GBPS Ethernet				
Output	RR14 RR15	Plug-and-play with API provided for parsing of radar data and Provizio APT GUI for visualisation. 4D point cloud (x, y, z location plus velocity) in all locations.					PASS PASS

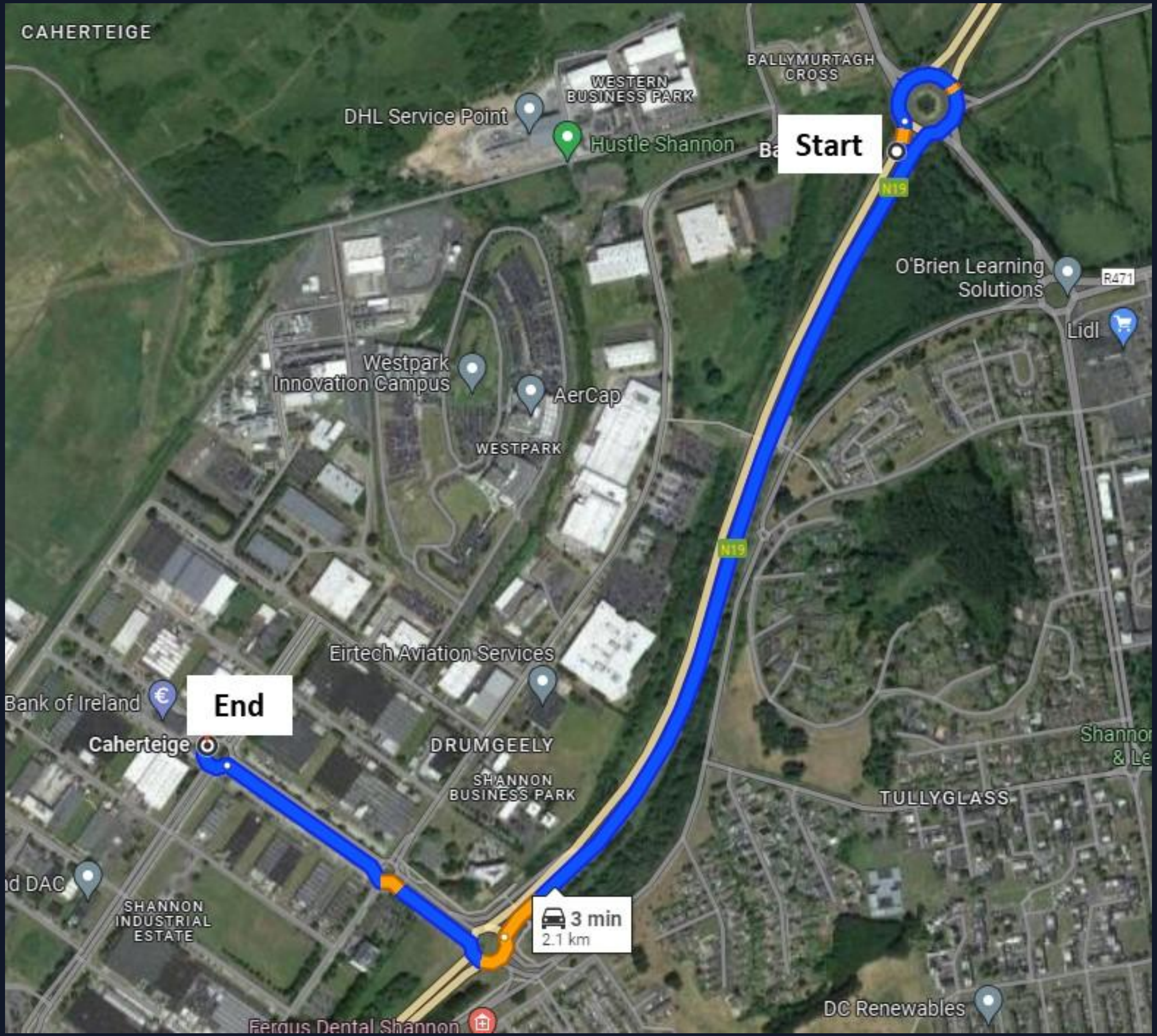
ID	Parameter	Min.	Typ.	Max.	Unit	Test Result
MR1	Computation time			50	ms	FAIL
MR2 MR3	**ANGLE DEVIATION:** Straight road Roundabout (3rd exit out of 4)			0.1 0.2	° / frame	PASS PASS
MR4	**DISTANCE ACCURACY:** Straight road	±0.007		±0.22	m	PASS

IDENTIFIED ALGORITHM IMPROVEMENTS

- A number of algorithm improvements were identified and tested on pre-recorded data before being implemented on the test radar and later on the final radar.

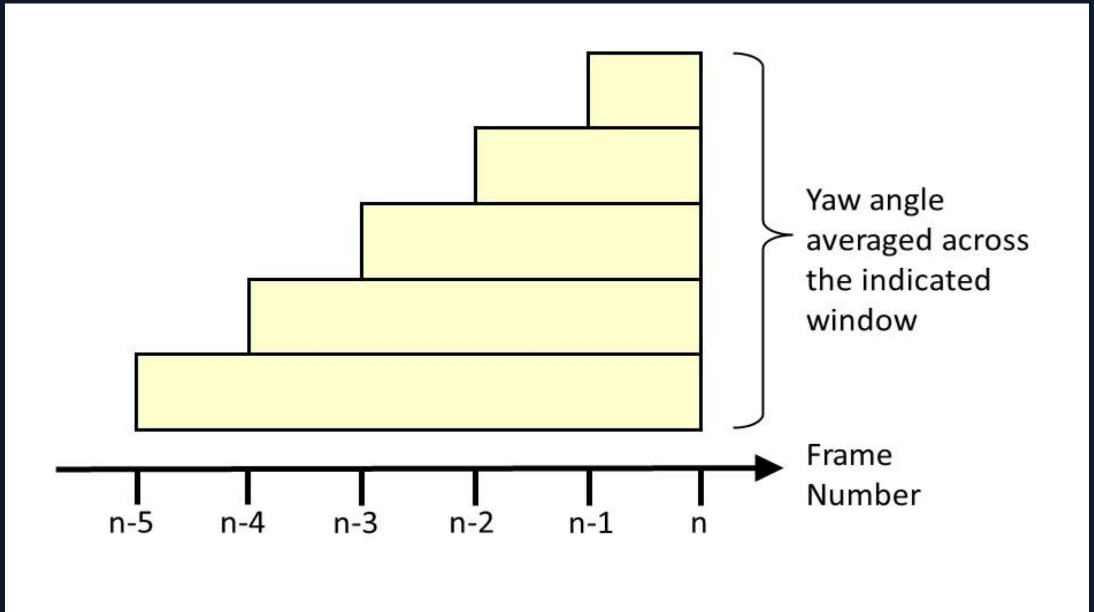
- Updates were assessed based on the following principles:
  - Is the yaw-rate noise level reduced and thereby more stable?
  - Is it comparable to the GNSS yaw rate?
  - Is the processing time improved?
  - Is the algorithm refactored, or simplified, to allow an easier / quicker implementation on the radar processor?

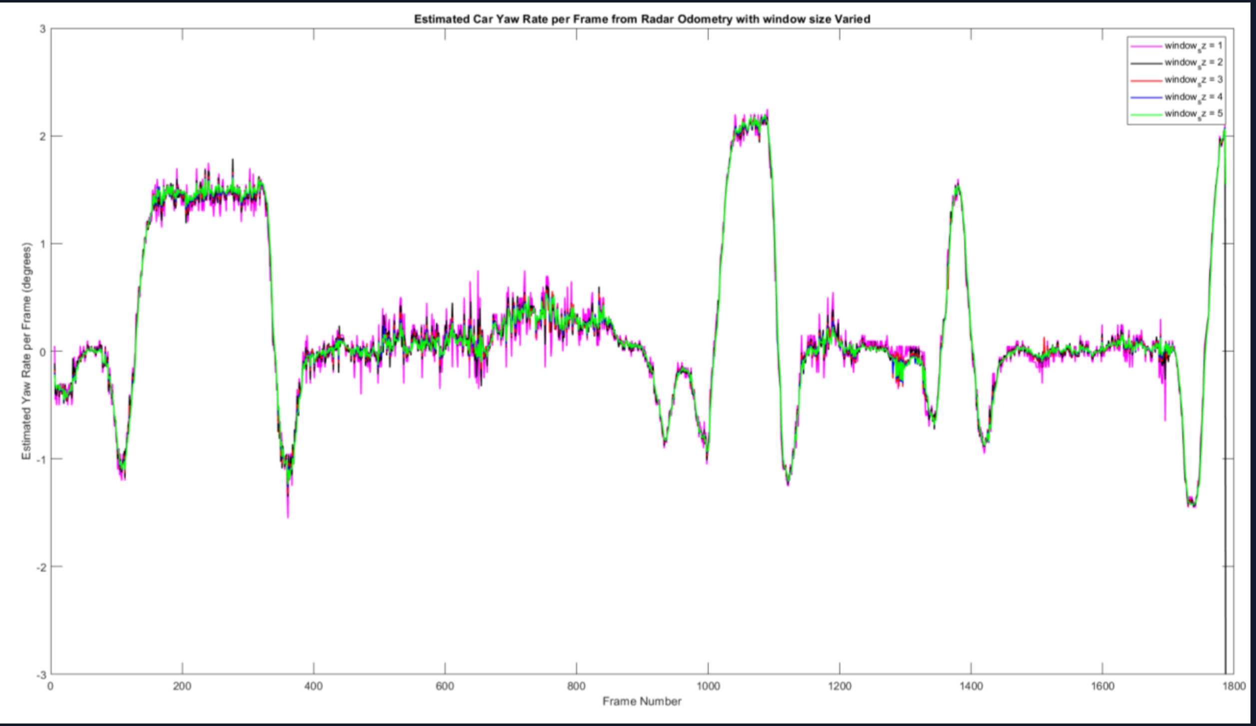
VALIDATION CASE (PRE-RECORDED)



WINDOWING

- Introducing the concept of point cloud translation over a number of frames rather than single frames
- Finding the best offset number of frames



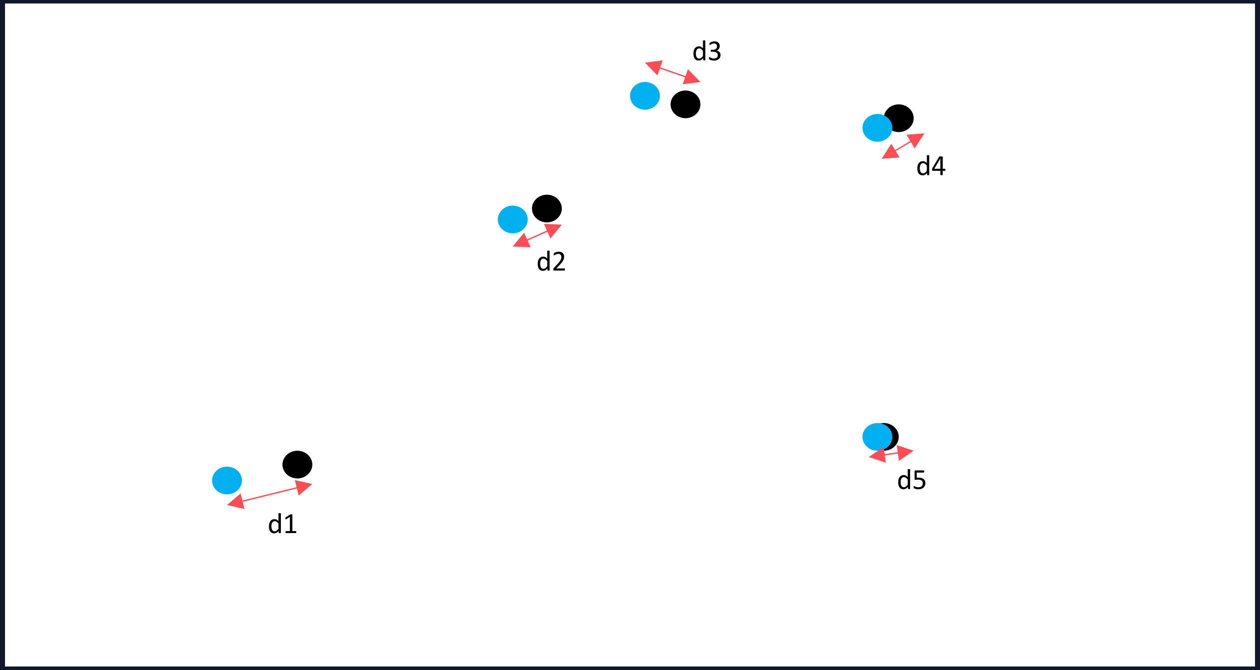


- CONCLUSION: A window of size of 5 or more should be used

ERROR FUNCTION ESTIMATION METHODS

Absolute Difference Method

- Calculate the absolute difference from a transformed point to the current point. Sum the differences from all points

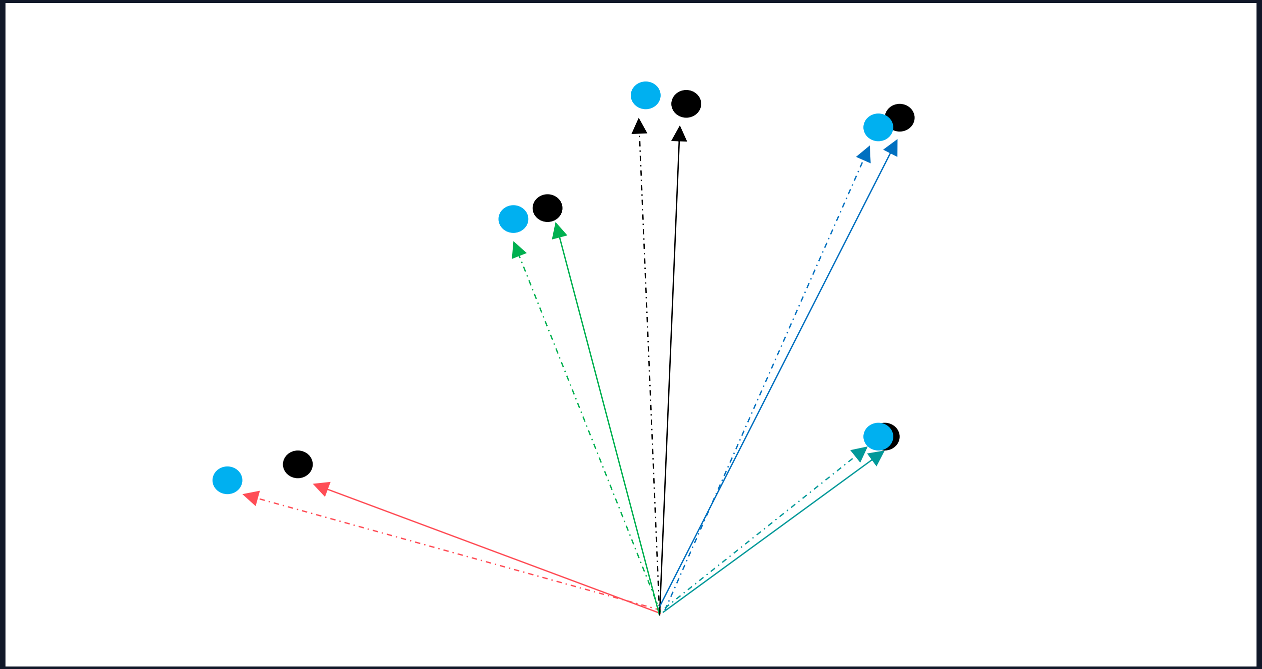


- Error = d1 + d2 + d3 + d4 + d5

ERROR FUNCTION ESTIMATION METHODS

Pairwise Multiplication Method

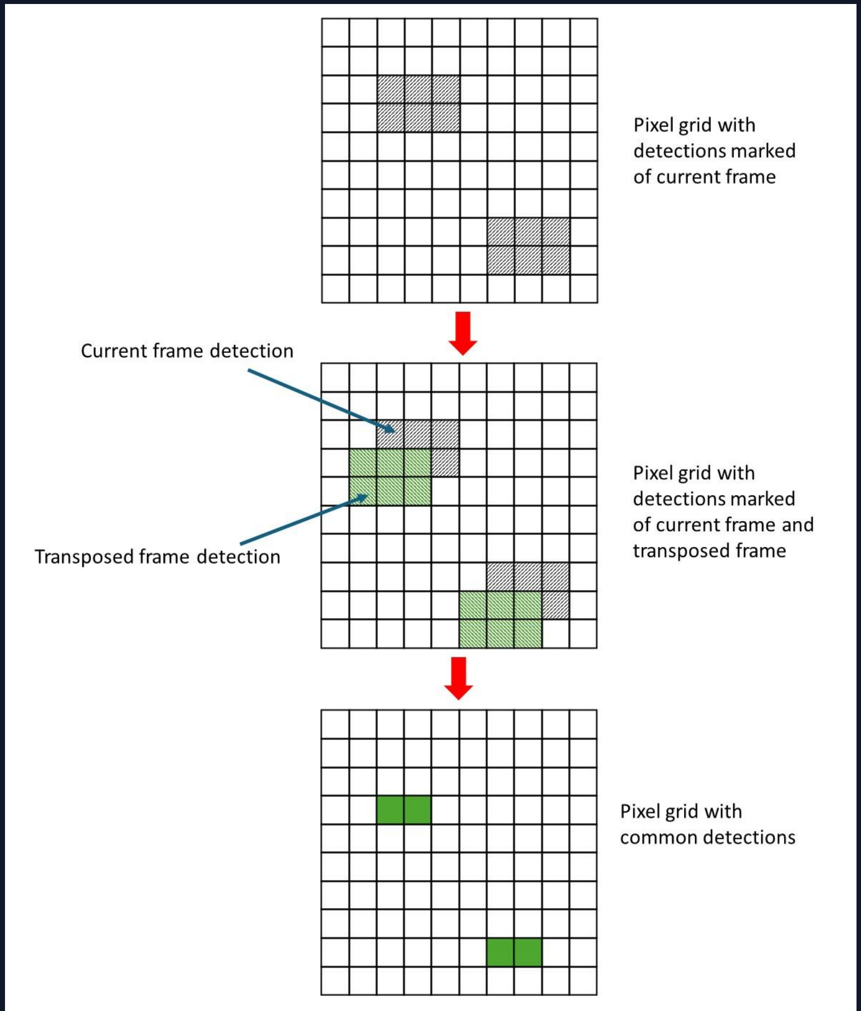
- The dot product or scalar product of a vector is a measure of how closely two vectors align (in terms of the directions they point). Assume the measured and transposed points are the end points of the vectors from origin and assess the alignment.



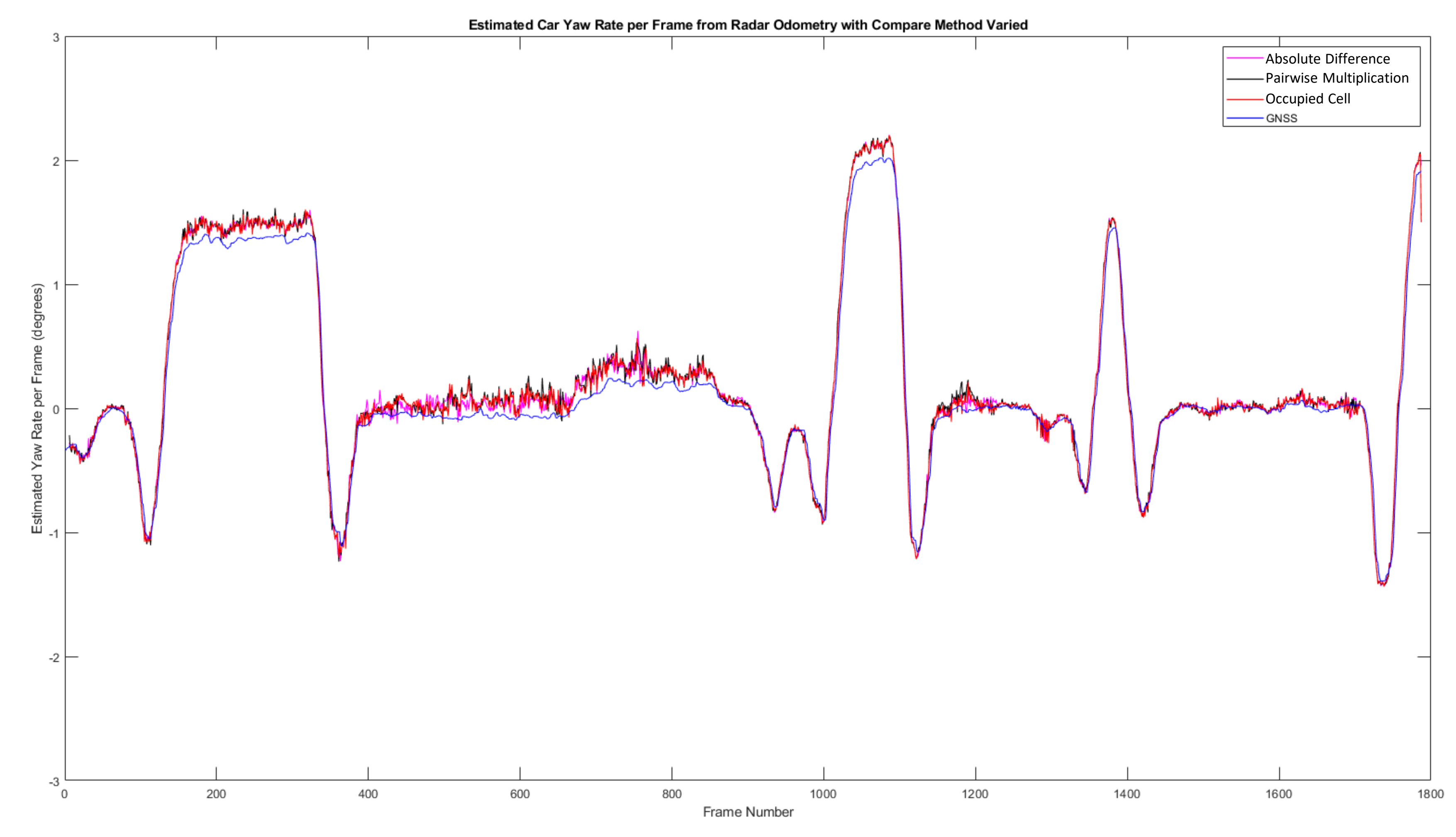
ERROR FUNCTION ESTIMATION METHODS

Occupied Cell Method

- Number of common cells when both point clouds are converted to a 'pixel grid'.



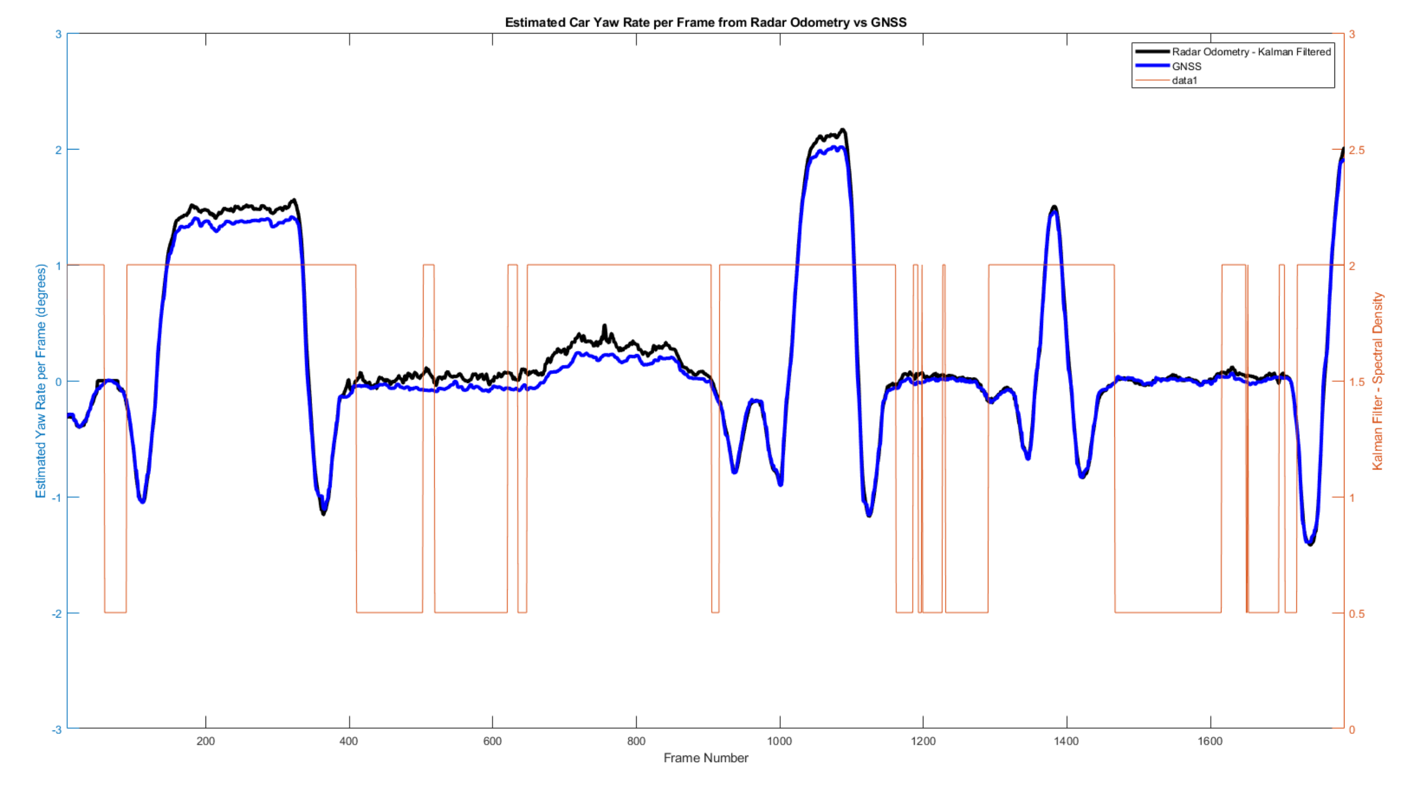
ERROR FUNCTION ESTIMATION METHODS



- CONCLUSION: The absolute difference method should be used

ADAPTIVE KALMAN FILTERING

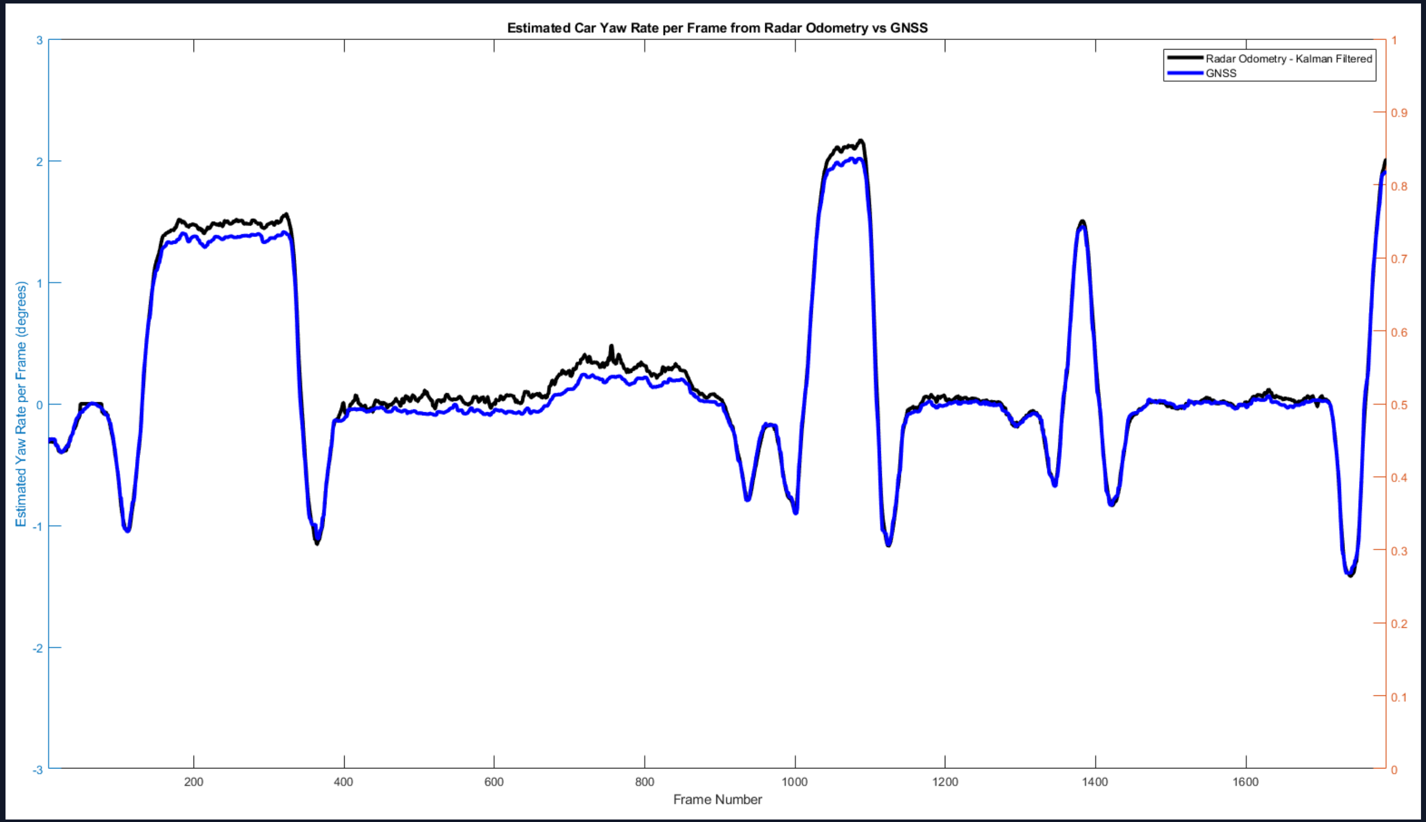
- A Kalman filter greatly improves the accuracy of the algorithm. However, this introduces an additional computational effort that, at times, causes the required FPS parameter to fail. Computation time / accuracy is a trade-off and is set by the spectral density coefficient (when q_0 is low, noise is reduced but the calculation is longer; and when q_0 is high, noise is higher, but the calculation is shorter).
- Rules were developed in the algorithm to set when q_0 can be changed (when turning or driving straight) to reduce the calculation time.



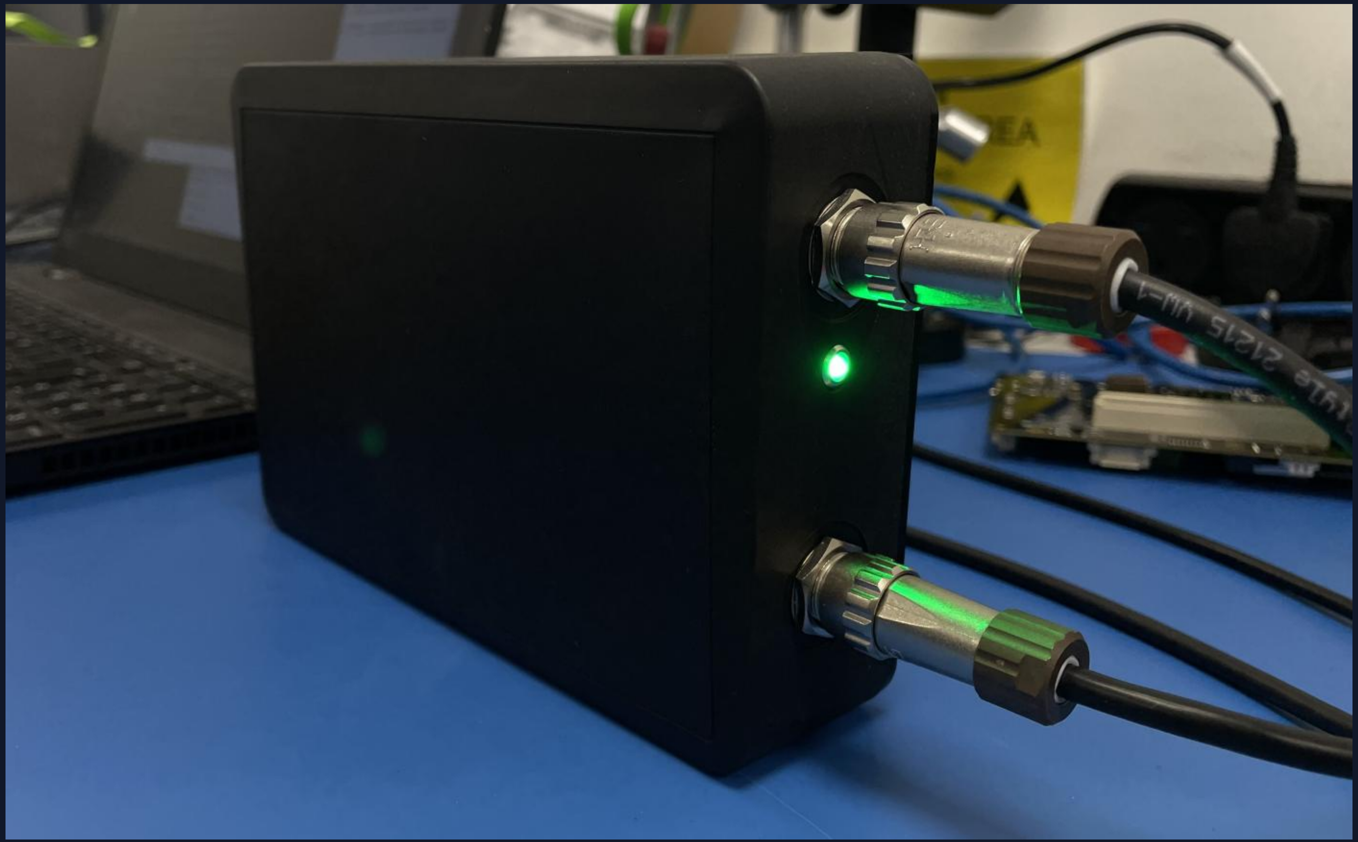
ERROR FUNCTION ESTIMATION METHODS

Dynamic Search Range

- Implement a dynamic rotation angle search range that depends on the calculated yaw rate from the previous frame, as this will not vary significantly between frames.
- Reduction in computation time, for no loss in accuracy.



RADAR UNIT



TURN ON TESTING

FINAL CALIBRATION

Radar	Capture Number	Modulation Scheme	Range	Start Frequency (GHz)	Bandwidth (GHz)	Target Distance (m)	Completed?
RA1_1	1	TDMA	SHORT	76	3.2	6	YES
	2	TDMA	SHORT	76.5	3.2	6	YES
	3	TDMA	SHORT	77	3.2	6	YES
	4	TDMA	SHORT	77.5	3.2	6	YES
	5	TDMA	MEDIUM	76	0.5	6	YES
	6	TDMA	MEDIUM	76.5	0.5	6	YES
	7	TDMA	MEDIUM	77	0.5	6	YES
	8	TDMA	MEDIUM	77.5	0.5	6	YES
	9	TDMA	MEDIUM	78	0.5	6	YES
	10	TDMA	MEDIUM	78.5	0.5	6	YES
	11	TDMA	MEDIUM	79	0.5	6	YES
	12	TDMA	MEDIUM	79.5	0.5	6	YES
	13	TDMA	MEDIUM	80	0.5	6	YES
	14	TDMA	MEDIUM	80.5	0.5	6	YES
	15	DDMA	SHORT	76	3.2	6	YES
	16	DDMA	SHORT	76.5	3.2	6	YES
	17	DDMA	SHORT	77	3.2	6	YES
	18	DDMA	SHORT	77.5	3.2	6	YES
	19	DDMA	MEDIUM	76	0.5	6	YES
	20	DDMA	MEDIUM	76.5	0.5	6	YES
	21	DDMA	MEDIUM	77	0.5	6	YES
	22	DDMA	MEDIUM	77.5	0.5	6	YES
	23	DDMA	MEDIUM	78	0.5	6	YES
	24	DDMA	MEDIUM	78.5	0.5	6	YES
	25	DDMA	MEDIUM	79	0.5	6	YES
	26	DDMA	MEDIUM	79.5	0.5	6	YES
	27	DDMA	MEDIUM	80	0.5	6	YES
	28	DDMA	MEDIUM	80.5	0.5	6	YES

Radar	Capture Number	Modulation Scheme	Range	Start Frequency (GHz)	Bandwidth (GHz)	Target Distance (m)	Completed?
RA1_2	1	TDMA	SHORT	76	3.2	6	YES
	2	TDMA	SHORT	76.5	3.2	6	YES
	3	TDMA	SHORT	77	3.2	6	YES
	4	TDMA	SHORT	77.5	3.2	6	YES
	5	TDMA	MEDIUM	76	0.5	6	YES
	6	TDMA	MEDIUM	76.5	0.5	6	YES
	7	TDMA	MEDIUM	77	0.5	6	YES
	8	TDMA	MEDIUM	77.5	0.5	6	YES
	9	TDMA	MEDIUM	78	0.5	6	YES
	10	TDMA	MEDIUM	78.5	0.5	6	YES
	11	TDMA	MEDIUM	79	0.5	6	YES
	12	TDMA	MEDIUM	79.5	0.5	6	YES
	13	TDMA	MEDIUM	80	0.5	6	YES
	14	TDMA	MEDIUM	80.5	0.5	6	YES
	15	DDMA	SHORT	76	3.2	6	YES
	16	DDMA	SHORT	76.5	3.2	6	YES
	17	DDMA	SHORT	77	3.2	6	YES
	18	DDMA	SHORT	77.5	3.2	6	YES
	19	DDMA	MEDIUM	76	0.5	6	YES
	20	DDMA	MEDIUM	76.5	0.5	6	YES
	21	DDMA	MEDIUM	77	0.5	6	YES
	22	DDMA	MEDIUM	77.5	0.5	6	YES
	23	DDMA	MEDIUM	78	0.5	6	YES
	24	DDMA	MEDIUM	78.5	0.5	6	YES
	25	DDMA	MEDIUM	79	0.5	6	YES
	26	DDMA	MEDIUM	79.5	0.5	6	YES
	27	DDMA	MEDIUM	80	0.5	6	YES
	28	DDMA	MEDIUM	80.5	0.5	6	YES

FINAL PERFORMANCE TESTING

- Range Resolution

Radar	Capture Number	Mode	Range 1 (m)	Detection Bin 1	Range 2 (m)	Detection Bin 2
RA1_1	1	SHORT	15	301	14.95	300
	2	MID	15	39	14.6	38
	3	LONG	15	20	14.2	19
	4	ULTRA-LONG	15	11	13.4	10
RA1_2	1	SHORT	15	300	14.95	299
	2	MID	15	38	14.6	37
	3	LONG	15	20	14.2	19
	4	ULTRA-LONG	15	10	13.4	9

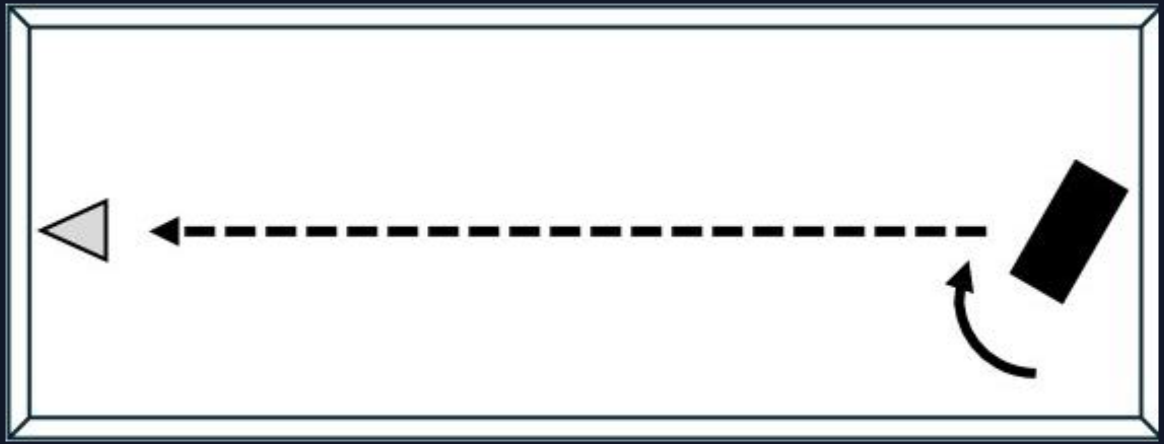
- Range Accuracy

Radar	Mode	Measured Range (m)	Detected Range (m)
RA1_1	SHORT TDMA	45	45
	ULTRA-LONG DDMA	45	45.15
RA1_2	SHORT TDMA	45	45
	ULTRA-LONG DDMA	45	45.11

FINAL PERFORMANCE TESTING

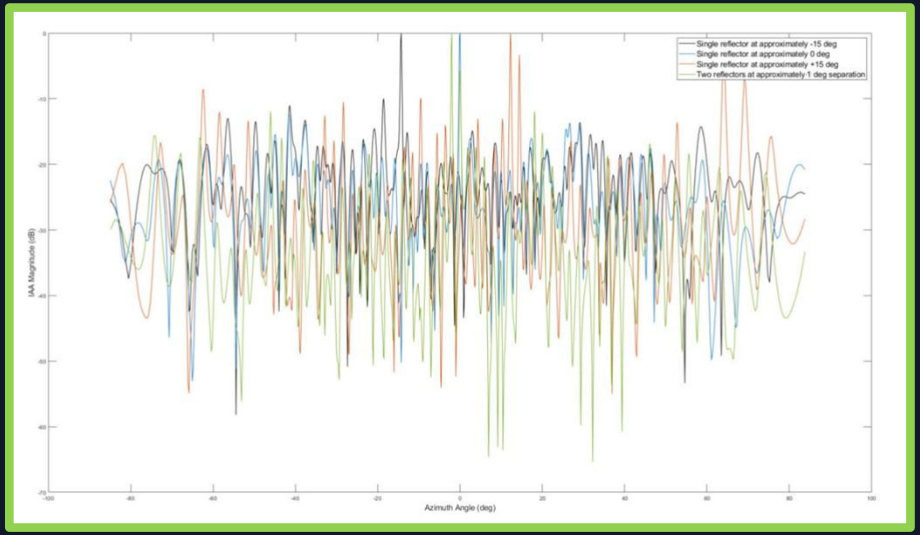
- Field of View Tests

Radar	Capture Number	Range (m)	Az Angle (deg)	El Angle (deg)	Reflector SNR level (dB)	Pass / Fail
RA1_1	1	6	0	0	-35.31	PASS
	2	6	60	0	-52.93	PASS
	3	6	0	20	-49.25	PASS
RA1_2	1	6	0	0	-36.57	PASS
	2	6	60	0	-51.04	PASS
	3	6	0	20	-52.29	PASS

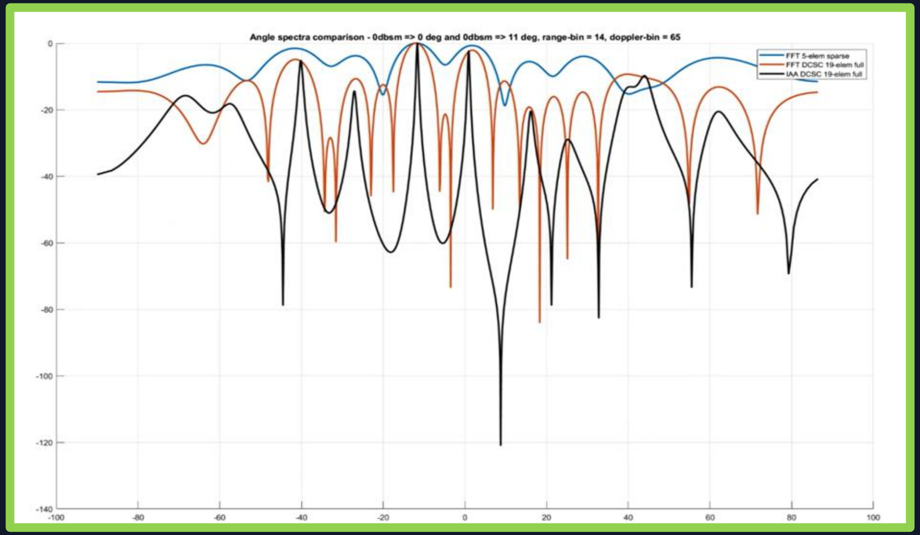


FINAL PERFORMANCE TESTING

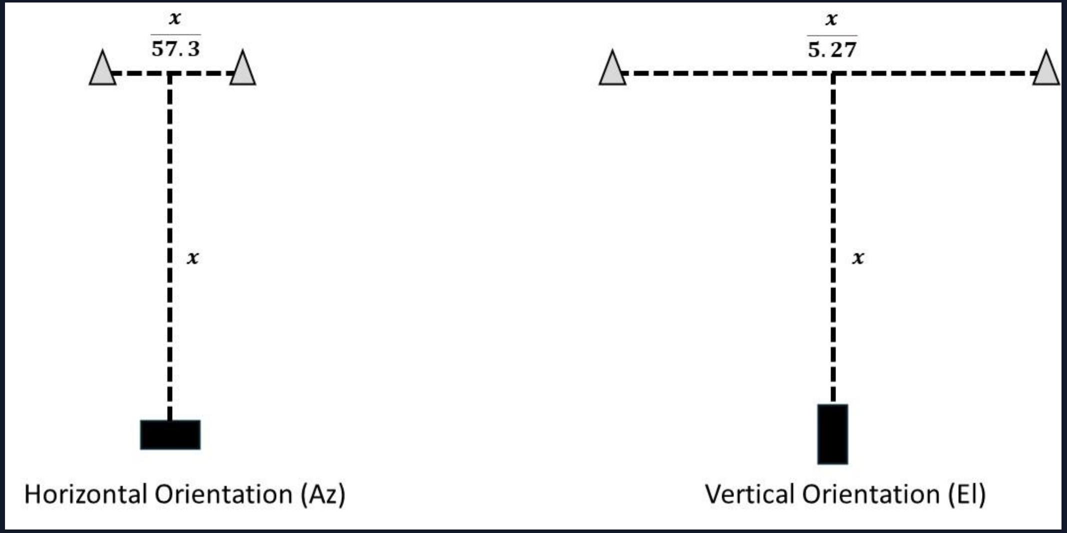
- Angular Resolution



Horizontal (Azimuth)



Vertical (Elevation)



FINAL PERFORMANCE TESTING

- Bias Test

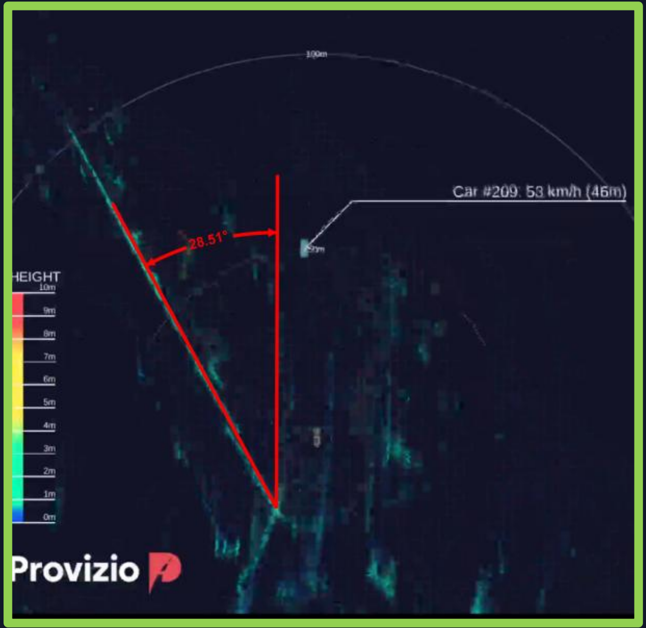
Radar	Bias Setting (V)	Testpoint T101 (Required)	Testpoint T101 (Measured)	Bootup?
RA1_1	9	1.2	1.2	YES
	12	1.2	1.21	YES
	32	1.2	1.19	YES
RA1_2	9	1.2	1.19	YES
	12	1.2	1.2	YES
	32	1.2	1.2	YES

- Display Test

FINAL PERFORMANCE TESTING

- Drift Test

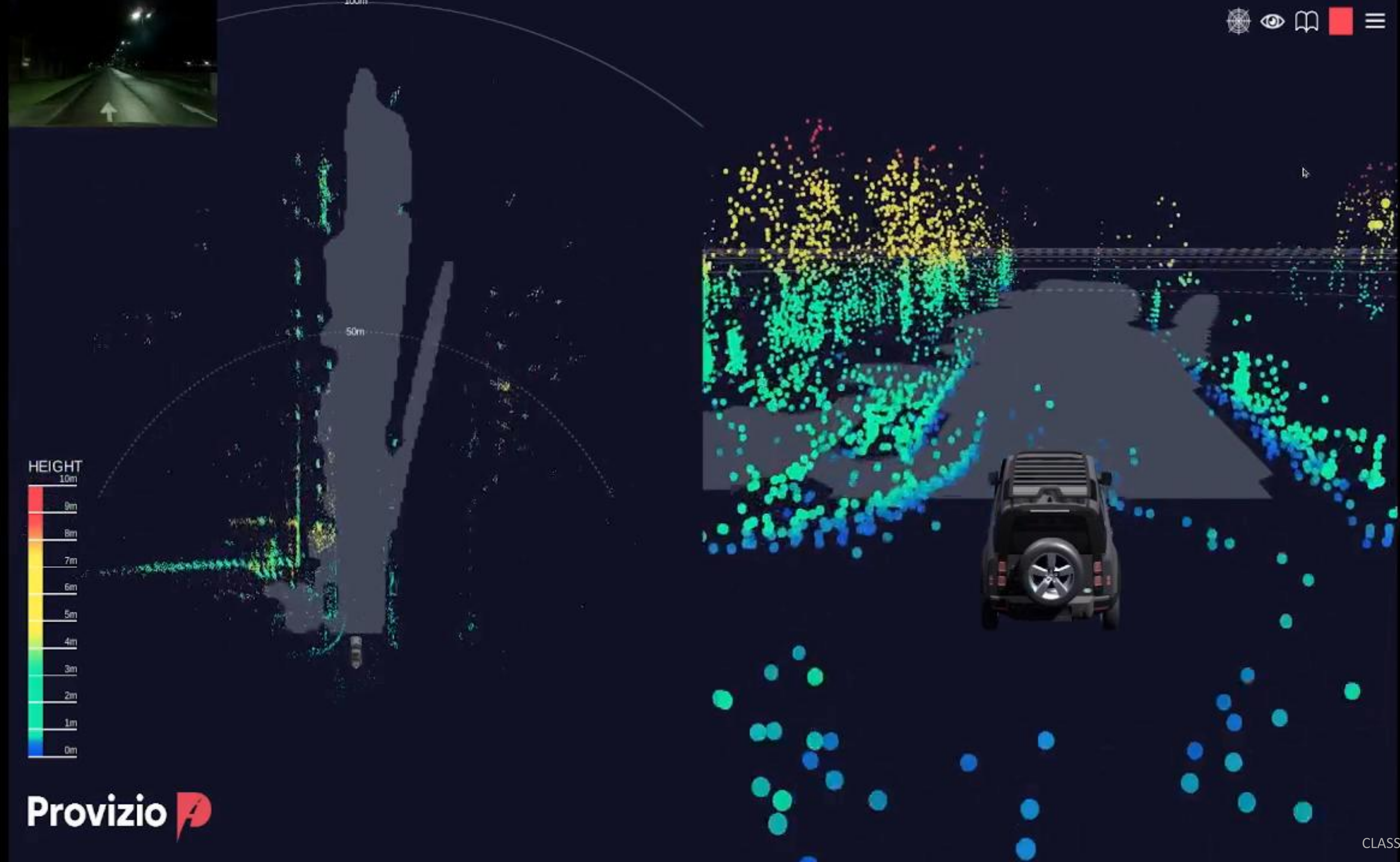
Radar	Turning Angle (deg)	Number of Frames	Angle Deviation (deg)	Deviation per frame (deg/frame)	Pass / Fail
RA1_1	0	100	8.9	0.09	PASS
	360	190	28.51	0.15	PASS
RA1_2	0	100	9.0	0.09	PASS
	360	190	29.24	0.15	PASS

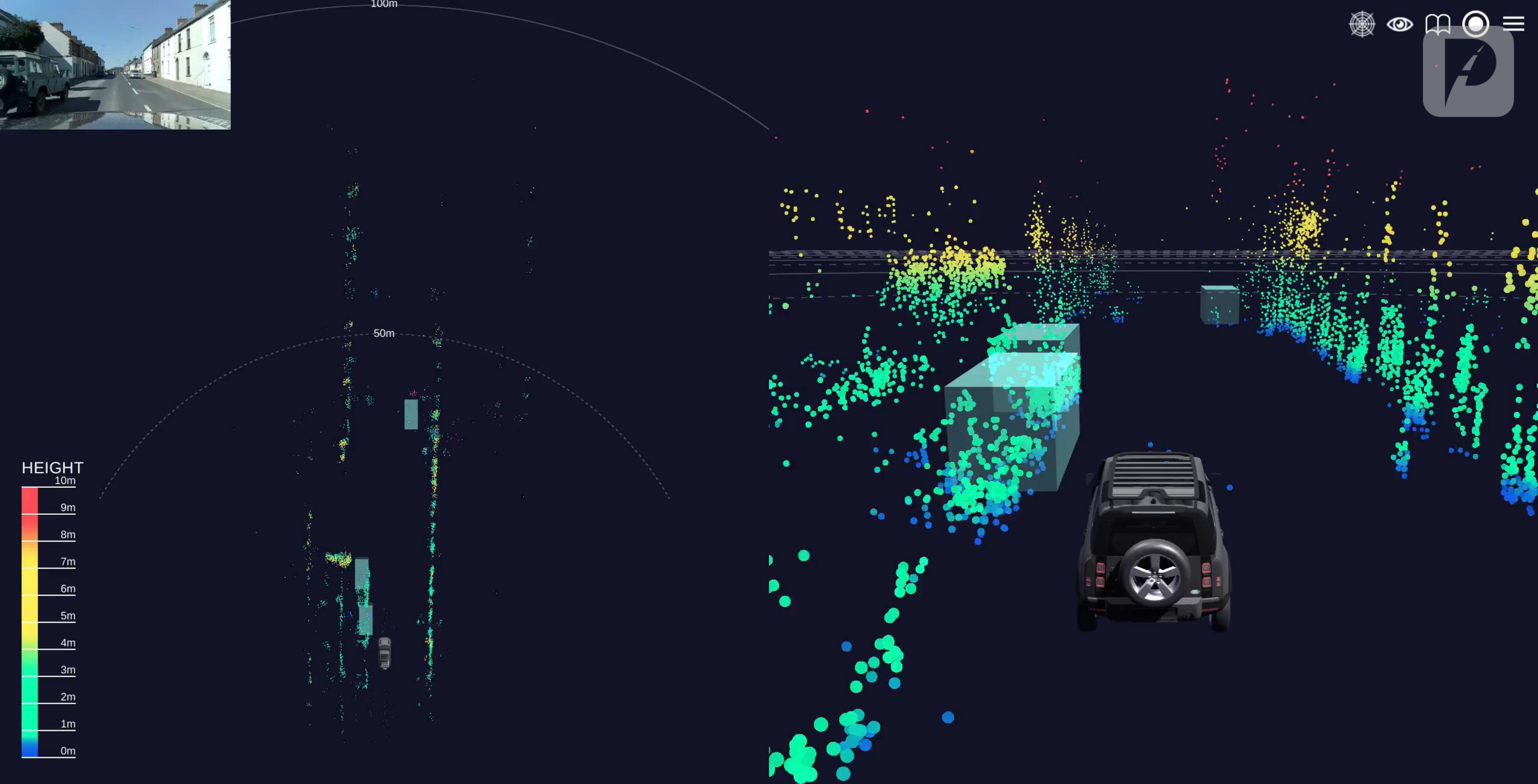


FINAL RADAR PERFORMANCE OVERVIEW

	ID	Parameter	Min.	Typ.	Max.	Unit	Test Result
Sensor	RR1	**OPERATING FREQUENCY:**	76		81	GHz	PASS
		DETECTION RANGE:					
	RR2	10 dBsm target (car)	0.2		300	m	PASS
	RR3	-10 dBsm target (pedestrian)	0.2		60		PASS
		RANGE RESOLUTION:					
	RR4	Short-range mode (0 – 50 m)		0.05		m	PASS
	RR5	Mid-range mode (0 – 100 m)		0.39			PASS
	RR6	Long-range mode (0 – 200 m)		0.78			PASS
	RR7	Ultra-long-range mode (0 – 400 m)		1.56			PASS
	RR8	**RANGE ACCURACY (depending on range mode):**	±0.007		±0.22	m	PASS
		FIELD OF VIEW:					
	RR9	Azimuth		120		°	PASS
	RR10	Elevation		40			PASS
		ANGULAR RESOLUTION:					
	RR11	Azimuth		1		°	PASS
	RR12	Elevation		11			PASS
		PERCEPTION:					
	N/A[2]	Radar based Odometry	Radar only SLAM or with GNSS				
	RR13	**SUPPLY:** Voltage (dc)	9.5	12	32	V	PASS
	N/A[3]	**CYCLE TIME:**			100	ms	
	N/A	**INTERFACE:**	1 GBPS Ethernet				
Output	RR14	Plug-and-play with API provided for parsing of radar data and Provizio APT GUI for visualisation.					PASS
	RR15	4D point cloud (x, y, z location plus velocity) in all locations.					PASS

ID	Parameter	Min.	Typ.	Max.	Unit	Test Result
MR1	Computation time			50	ms	PASS
	ANGLE DEVIATION:					
MR2	Straight road			0.1	° / frame	PASS
MR3	Roundabout (3rd exit out of 4)			0.2		PASS
	DISTANCE ACCURACY:					
MR4	Straight road	±0.007		±0.22	m	PASS


50m
HEIGHT
10m
9m
8m
7m
6m
5m
4m
3m
2m
1m
0m
Provizio



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CLASSIFICATION: PUBLIC

CONCLUSIONS

- The fundamental radar functions were all observed to be within specifications.
- Odometry measurements were all observed to be within specifications.
- Outputs when using the algorithm or PNT signals compared well.
- SLAM and Perception functions were able to operate alongside the algorithm.
- The algorithm therefore fulfils its design purpose and is able to allow safety perception functions to run over short periods of time when PNT signals are occluded.

Thank you!

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