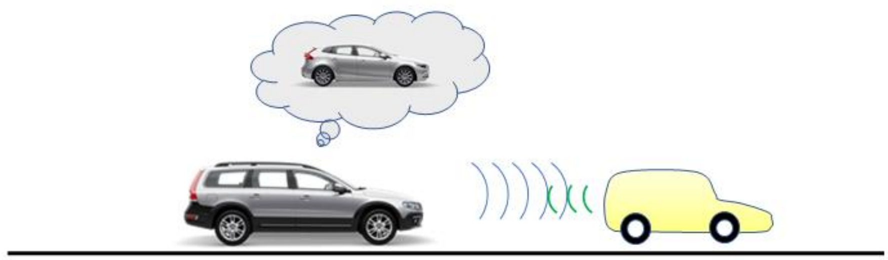
HiFi Radar Target

High fidelity soft targets and radar simulation for more efficient testing (real and virtual)

Public report



Project within FFI - Elektronik, mjukvara och kommunikation

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Content

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1. Summary

The 77 GHz radar is a crucial sensor in the Advanced Driver Assistance System (ADAS) and Autonomous Driving (AD) system due to its ability to detect and track objects at distances up to 200 meters. To ensure high reliability of the radar function, extensive testing with soft surrogate targets is needed. However, the radar response of a surrogate target may differ from that of real targets, causing unexpected reactions of the ADAS and AD functions in real traffic situations. The first project goal was therefore to develop and validate realistic soft surrogate targets, a work which was performed in several steps. First radar reference targets were designed and verified. Secondly procedures for calibration of automotive radars were developed. Finally, a thorough investigation on Radar Cross Section (RCS) characterization methods for large test objects on the test track was conducted resulting in several measurement setups and measurement procedures including uncertainty analysis. Now, with the ability to perform repeatable and reliable RCS characterizations, several real and surrogate targets were characterized and work on improving RCS profile of surrogate targets were conducted.

Strong competition in the automotive industry and the need to validate more and more complex functions (including autonomous drive) drives the development of virtual test methods. The ability to test the ADAS or AD functions virtually early in the development will save considerable time and cost. However, there were no such tools available with full radar simulation in-loop available prior to the project, which was the reason for the second goal of this project: an ADAS/AD system simulation tool-chain with radar simulation in-loop.

The HiFi Radar Target project (diarienr. 2015-04852) was an FFI project within the Electronics, Software and Communications program. After prolongation it was a 30-month project that started 2015-12-31 and ended 2018-06-30. The project had a total budget of 15.9 MSEK.

2. Sammanfattning på svenska

Radarsensorn på 77 GHz är en vital komponent för ADAS (Advanced Driver Assistance System) samt system för autonom körning (AD) tack vare sin förmåga att detektera och följa objekt på avstånd upp till 200 meter. För att säkerställa hög tillförlitlighet hos fordonets funktioner baserade på radarn krävs omfattande tester med mjuka surrogatmål. Radarresponsen hos ett surrogatmål kan dock skilja sig från det för reella mål, vilket i förlängningen kan orsaka oväntade reaktioner från ADAS- och AD-funktioner i verkliga trafiksituationer. Det första projektmålet var därför att utveckla och validera mjuka surrogatmål så att de blir mer realistiska, ett arbete som utfördes i flera steg: referensmål togs fram och verifierades, metoder för *on site* kalibrering av radarsensorer utvecklades, och slutligen togs metoder fram för karakterisering av radarmålarea (RCS) av stora objekt på testbana (AstaZero, high speed area). Detta resulterade i flera mätuppställningar och mätprocedurer inklusive osäkerhetsanalys. Nu, med förmågan att utföra repeterbara och pålitliga RCS-mätningar, karakteriserandes ett antal reella mål (verkliga bilar) samt surrogatmål och arbetet med att syntetisera radarmålarean hos surrogatmål genomfördes.

Stark konkurrens inom bilindustrin och behovet av att validera mer och mer komplexa funktioner (inklusive autonom körning) driver utvecklingen av virtuella testmetoder. Möjligheten att testa ADAS eller AD-funktioner tidigt i utvecklingscykeln kommer att spara tid, kostnad och vara en konkurrensfördel. Dock fanns inga verktyg med kapacitet att utvärdera radarsensorn tillsammans med resten av bilens hård- och mjukvara virtuellt tillgängliga före projektet, vilket var orsaken till det andra målet: ett simuleringsverktyg för ADAS/AD-system inklusive simulering av radarn.

HiFi Radar Target-projektet (diarienr. 2015-04852) var ett FFI-projekt inom programmet Elektronik, programvara och kommunikation. Efter förlängning blev det ett 30-månaders projekt med start 2015-12-31 och slut datum 2018-06-30. Projektet hade en total budget på 15,9 MSEK.

2.1 Mål

Utvecklingen av radarsystem, en nödvändig sensor för aktiv säkerhet och autonoma fordon, kräver pålitlig och effektiv testning för validering av systemprestanda. Effektiv utveckling kräver att man tidig upptäcker och löser möjliga problem, något som testinfrastrukturen måste stödja. Målet med projektet var därför att möjliggöra effektiv och tillförlitlig verifiering av radarsystem, inklusive ADAS och AD-system som är beroende av radarsensorer, genom:

- Utveckling samt validering av repeterbara RCS mätmetoder.
- Utveckling av mer realistiska surrogatmål för säker provning av bilradarsystem.
- Utveckling av simuleringsverktyg för radarsystem i virtuell miljö.
- Demonstration av förbättrad verifiering med hjälp av de utvecklade verktygen och metoderna.

- Stödja internationell standardisering (ISO) i deras arbete för framtida verifiering och kalibrering av surrogatmål.

Projektresultaten kommer att:

- Bidra till nollvisionen, det vill säga noll dödliga trafikolyckor.
- Stärka svensk bilindustris konkurrenskraft i ett globalt perspektiv.
- Bidra till att utveckla AstaZero till en testplats i världsklass för ADAS och AD system.
- Ge verktyg och metoder för AD-testning till VCC.

2.2 Resultat och leveranser

Målen som beskrivits i föregående kapitel har alla (i olika utsträckning) blivit uppfyllda:

- Utveckling och validering av noggranna och repeterbara RCS mätmetoder: detta mål uppnåddes mycket väl och konsortiet har arbetat internationellt.
- Utveckling av mer realistiska surrogatmål för säker provning av bilradarsystem: projektet har fått kunskap om vilka egenskaper som påverkar radarresponsen för ett specifikt mål och har förbättrat surrogatmål inklusive den automatiserade mobila plattform som förflyttar surrogatmålen under test.
- Utveckling av simuleringsverktyg för virtuell testning av radarsystem: verktygskedjan för trafiksimulering av AD och ADAS funktioner hos VCC har uppdaterats med nya realistiska (mätbaserade) klustermodeller för radarmål. För framtida utveckling definierades också ett interface som möjliggör implementering av nya modeller.
- Demonstration av metoder framtagna i projektet: projektresultat presenterades och demonstrerades vid AstaZero.
- Stödja internationell standardisering (ISO) i utvecklingen av metoder för framtida verifiering och kalibrering av surrogatmål: projektet har bidragit till arbetet i ISO genom att öka förståelsen för RCS hos riktiga fordon och surrogatmål, definierat representativa egenskaper hos radarmål, tagit fram metoder för repeterbar och noggrann karakterisering, samt tagit fram en osäkerhetsbudget.

3. Background

There are three grand challenges the transportations of tomorrow face: environment, safety and congestion. One key element in meeting these challenges, and to reach the VisionZero stated by the Swedish government in 1997, is development of active safety systems and AD systems assisting or replacing the driver in both normal traffic situations as well as critical situations. These systems have already proven to decrease the number and severity of injuries and insurance cost [1]. The development of higher degree of AD puts stronger requirements on reliability, and therefore on its sensory input and the interpretation of this input. There exist several sensor types that typically are employed in sensor systems in ADAS and AD, such as visible spectrum and infrared cameras, laser scanners, ultrasonic sensors, and radars. In this project we focused on radars.

Millimeter wave radars have important advantages over other technologies, e.g., ability to detect objects such as humans and vehicles at large distances (up to 200 meters), and to measure their instantaneous positions and velocities. Furthermore, they allow convenient and discreet installation behind bumpers and show low sensitivity to adverse weather conditions and contamination of their cover. Because of this, radar sensors are, or are a part of, sensing solution of most high-end ADAS systems, and multiple radar sensors are included in practically all AD sensor setups. In the AD vehicles that Volvo Car Corporation (VCC) has built within the DriveMe project, as many as seven radar sensors are used among other sensors for unprecedented traffic situation awareness[1].

However, there are still factors that limit the accuracy and reliability of the automotive radar systems, among which the most critical ones are:

- Clutter from atmosphere, road and background objects, that create false returns that need to be separated from the returns from "relevant" traffic objects.
- Internal inaccuracies in the radar hardware, such as noise, nonlinearities, crosstalk in radio frequency (RF) components, etc.
- Directivity of transmission and reception antennas, which are strongly influenced by geometries and materials of antennas, radar packaging, fasteners, cover, and other vehicle body elements in vicinity of antennas.
- Complex nature of radar returns from different traffic objects, which poses challenges for detection and tracking of relevant object returns.

Validation of the radar systems and identification of possible performance issues caused by the above factors, require extensive testing of the systems, both during radar system development, and during verification of ADAS and AD vehicles.

[1] https://www.media.volvocars.com/global/en-gb/media/pressreleases/158276/volvo-cars-presents-a-unique-system-solution-for-integrating-self-driving-cars-into-real-traffic

3.1 High fidelity surrogate objects

Controllability and safety of testing dictates that most testing is performed at closed test tracks. Since it is not possible to test situations that may result in collision with real vehicles, pedestrians etc. as targets, surrogate objects are used. These are typically mock-up objects made of soft materials that can be repeatedly hit without damage to themselves or the test vehicle [2]. In order to make testing with surrogate targets to be valid, radar response of the surrogate target must be consistent with the response of the corresponding real target.

Surrogate targets are typically designed to mimic the real objects by appearance to human eye (shape, color, etc.) and this may be claimed sufficient for camera sensors. However, this approach fails when it comes to radar sensors, as the radar “image” is very different from the camera image. Radars typically see an aggregated response from “hot spots” on objects, the locations that reflect the radar radiation strongly in the direction of the radar receiver. The strength of the response is determined by the RCS - “effective” area of the object, which is a complex function of object shape, viewing angle and material. Dielectric fabrics that soft surrogate targets usually are made of are nearly transparent at 77 GHz, and thus generate a much weaker radar response compared to a metallic car body. On the other hand, the metallic support structures, measurement equipment installed in targets, as well as propulsion systems, may create unnaturally strong reflections. This results in large discrepancy between appearances of surrogate targets and real ones for radar sensors, which reduces the quality and reliability of testing and thereby limits the development of next generation AD systems.

3.2 Virtual radar testing tool chain

Virtual testing of ADAS and AD systems is an emerging trend that reflects the growing need for earlier assessment of system design and performance (e.g. before the system is installed in vehicle) enabling more complex and dangerous scenarios (easier and cheaper to perform in virtual worlds), larger parameter space for situations that vehicles need to cope with (highly parallelized simulations), and reduced testing cost (reduced amount of physical prototypes and reduced amount of test driving). Accurate simulation tools are needed, that can predict the performance of active functions in real traffic situations, and how these are influenced by radar detection performance.

To attain these tools, advanced simulators that capture performance of radar sensor, need to be integrated in-loop with ADAS/AD traffic simulators that model the dynamic behavior of the host vehicle and other objects in complex traffic situations.

Radar simulators need to reproduce operation of the real radar system, including propagation of signals and generation of object returns, processing of analogue antenna signals and conversion to digital form, and finally digital processing of these signals to attain object tracks.

[1] I. Isaksson-Hellman, M. Lindman. "Real-World Performance of City Safety Based on Swedish Insurance Data," 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV). No. 15-0121, Gothenburg, Sweden, June 8-11, 2015.
[2] M. Rabben, R. Henze, and F. Küçükay, "Dynamic Crash Target for the Assessment, Evaluation and Validationof ADAS and Safety Functions". Proc. 3rd International Symposium on Future Active Safety Technology Towards zero traffic accidents, 2015; and references therein.

4. Purpose, research questions and method

4.1 High fidelity surrogate objects

The need for understanding radar signatures of real targets, and for synthesis of surrogate targets with realistic RCS have been acknowledged in the field of automotive testing. While several studies have been conducted where radar responses of cars and humans have been measured [3] or simulated [4, 5], few measurements and analyses of radar responses of surrogate targets have been performed. National Highway Transportation Safety Administration (NHTSA) has measured their foam car version 1 for tail aspects and compared to a representative set of real vehicles, showing acceptable statistical RCS properties of the former [6]. However, analysis of tail aspects only provides validation for back-end scenarios. The aspects that might emerge in more complex traffic scenarios, for example, intersection collision avoidance [7], or merging, overtaking and cut-in cases for AD vehicles, where the amplitudes and locations of the scattering centers on target vehicles may vary rapidly, are not covered, limiting the applicability of the studied surrogate target for testing of these situations.

Moreover, analyses of other types of surrogate targets available on the market, as well as studies of possible improvements of the latter, are lacking. This poses limitations for OEMs, radar developers and test tracks who need reliable surrogate targets for increasing need for reliable and safe radar testing.
In order to address these issues, this project will consider the following questions:

1. How can the radar signatures of surrogate targets be assessed and validated against the real targets' signatures by measurements and simulations? This, in turn, leads to the following question: What are the radar signatures of real targets (that the signatures of surrogate targets must be similar to)?
2. How can surrogate targets be improved so that their radar signatures would better agree with real targets' ones?

The radar signature of an object should not depend on the particular radar technology. It should show how an ideal radar perceives it, rather than how a specific automotive radar does. Therefore, signature measurements have to be performed in controlled environment using accurate and thoroughly calibrated "reference" radar setup rather than an off-the-shelf automotive radar installed in-vehicle.

During test track testing, surrogate targets can be deformed by repeating collisions. While their appearance can be inspected visually, internal deformations may lead to their radar signature changing in an unpredictable way, making further testing unreliable. Validation methods developed in this project can be applied to validate the targets after collisions and to identify when the signature has deteriorated, and repair is needed, either after the tests or by periodical calibrations.

To address the first question, measurement facilities and simulation methods for radar signatures have been developed that are applicable to both real and surrogate targets. By using these measurement and simulation methods, we can assess the signatures of real targets. This provides requirements on the surrogate targets (what should their signatures be) and the results can be used to define how the surrogate targets need to be improved in order to fully function as valid test object for radar development. We have investigated different strategies of how to improve the surrogate targets and have implemented the most suitable ones.

4.2 Virtual radar testing tool chain

Realistic radar returns from the traffic object is a crucial component in radar simulation as these excite the virtual radar system. Full-scale simulation of traffic situations with multiple objects represented by accurate CAD models is time inefficient[2] and therefore another approach will be exploited in the project. Instead of full electromagnetic simulation, knowledge of radar signatures obtained in the 1st part of the project needs to be combined with radar-specific propagation models in order to provide correct excitation of the radar simulator. Furthermore, propagation models should include both noise and background clutter that is inevitably present in real world.
Therefore, to build up the virtual radar testing tool chain, we have addressed the following research questions:

1. How can accurate radar simulators be developed and integrated in software-in-loop (SIL) and/or hardware-in-loop (HIL) simulation environments, and how can different radar components be included in these?
2. How can realistic models of target signatures be developed based on measurements and simulations of real targets, and how can these models be combined with signal propagation simulation to excite simulated radar systems?

As specifics of the radar performance are often know-how of the radar manufacturer, certain components of radar simulation tool-chain were obtained from radar manufacturers[3] and integrated in the simulation tool rather than developed by the OEM.

While tools for generation of realistic raw image stream for prototyping camera detection algorithms are available in several commercial traffic simulation environments (such as

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[2] At typical radar repetition frequency of 20 Hz, returns have to be simulated 20 times per second, while a single accurate simulation typically takes minutes to hours to compute on a PC.
[3] VCC has reached agreement with one of its radar system suppliers that the latter would provide VCC with radar front-end model and signal processing SW components for integration into VCC's traffic simulation environment.

Vires Virtual Test Drive [8], Prescan [9], IPG Carmaker [10], possibilities for simulation of accurate radar response from traffic objects in commercial simulators are still limited (to the best of our knowledge, mature solutions are available from Oktal-SE [11] and recently Vires). In the named tools, radar simulation is based on generic ray-tracing simulation, tailored for real-time performance rather than accuracy, which can be complemented by sensor-specific tracking algorithms. The aim of this project was to attain a more accurate yet efficient radar simulation by combining signal propagation with accurate models for object signatures and sensor specific non-ideal front-end model.

[3] Yamada. ”Three-Dimensional High Resolution Measurement of Radar Cross-Section for Car in 76 GHz Band”, R&D Review of Toyota CRDL Vol. 36 No 2, Toyota Central R&D Labs, Inc., H. Suzuki, “Radar cross section of automobiles for millimeter wave band,” JARI research Journal, Vol. 22, No. 10, pp. 475-478, 2000.; N. Yamada, “Radar cross section for pedestrian in 76 GHz,”Proceedings of 2005 European Microwave Conference, Vol. 2, 4-6 Oct. 2004, pp.46-51.
[4] K. Schuler, D. Becker, and W. Wiesbeck, “Extraction of vertical scattering centers of vehicles by ray-tracing simulations,” IEEE Transactions on Antennas and Propagation, Vol. 56, No. 11, November 2008, pp. 3543-3551.
[5] H. Buddendick, T Eibert, J. Hasch, "Bistatic scattering center models for the simulation of wave propagation in automotive radar systems," in Microwave Conference, 2010, Germany, vol., no., pp.288-291, 15-17 March 2010.
[6] W.T. Buller and D.J. LeBlanc, “Radar Characterization of Automobiles and Surrogate Test-Targets for Evaluating Automotive Pre-Collision Systems," in Antennas and Propagation Society International Symposium (APSURSI), 2012 IEEE , vol., no., pp.1-2, 8-14 July 2012.
[7] City Safety by Volvo Cars – outstanding crash prevention that is standard in the all-new XC90, press release from 2014, December 5. Available at: https://www.media.volvocars.com/global/en-gb/media/pressreleases/154717/city-safety-by-volvo-cars-outstanding-crash-prevention-that-is-standard-in-the-all-new-xc90
[8] Test Drive: http://www.vires.com/products.html. Accessed on September 14th, 2015.
[0] Prescan: https://www.tassinternational.com/prescan. Accessed on September 14th, 2015.
[10] IPG Carmaker: http://ipg.de/simulationsolutions/carmaker/. Accessed on September 14th, 2015.
[11] Oktal-SE: http://www.oktal-se.fr/. Accessed on September 13th, 2015.
[12] ISO/TC 22/WG 16 for Active Safety Test Equipment. Accessed on September 14th, 2015.

5. Objective

The development of radar system technology, a necessary sensing technology for active safety and AD vehicles, relies on reliable and efficient testing to validate the system performance. Efficient development requires early detection and solution of possible issues which the testing infrastructure must support.

The objective of the project was to enable more efficient and reliable verification of radar systems, including ADAS and AD systems that rely on the radar sensors, through:

- Development and validation of accurate and repeatable RCS measurement methods for radar targets.
- Development of more realistic surrogate targets for safe testing of automotive radar systems.
- Development of a radar simulation tool for virtual testing of radar systems.
- Demonstration of improved verification with the developed tools and methods.
- Supporting international standardization (ISO) with standard methods enabling future verification and calibration of radar signatures of active safety soft surrogate targets.

The project results will:

- Contribute in reaching the goal of VisionZero, i.e., zero deadly traffic accidents.
- Strengthen the Swedish automotive industry's competitiveness in a global perspective.
- Be part in developing AstaZero to a world class test site for ADAS and AD.
- Provide tools and methods for AD testing to VCC.

6. Results and deliverables

The objectives as described in previous chapter have all, to different extent of course, been met:

- Development and validation of accurate and repeatable RCS measurement methods for radar targets: This objective is very well achieved, and the consortium has worked on an international level.
- Development of more realistic surrogate targets for safe testing of automotive radar systems: The project has gained knowledge about which properties that influence the radar response of a specific target and have improved soft targets as well as their corresponding carrier platform.
- Development of radar simulation tool for virtual testing of radar systems: The radar simulation tool chain at VCC has been updated with novel realistic (measurement based) cluster models. For versatility, a framework was also defined enabling easy implementation of new models.
- Demonstration of improved verification with the developed tools and methods: Project results were presented and successfully demonstrated at AstaZero.
- Supporting international standardization (ISO) with standard methods enabling future verification and calibration of radar signatures of active safety soft surrogate targets: The project has made substantial contributions to the work in ISO in understanding RCS of real vehicles and surrogate targets, and in defining representative and repeatable measures including input to uncertainty budget calculation.

In sub-chapters below follows a summary of project results.

6.1 Test setup and verification methods

In the beginning of the project a literature study was conducted collecting information on a range of different subjects crucial to the success of the project. A project internal reference document was created which contained information useful for basic understanding of general radar technology as well as more specific information on Frequency Modulated Continuous Wave (FMCW) type radars, the most common type of radar used in automotive applications. State-of-the-Art in solutions for antennas and beam steering for angular resolution of detection origin was mapped. Furthermore, the

State-of-the-Art of the main objects of interest in the project, the surrogate vehicle targets, was also assessed. In order to be able to properly choose simulation tools used, e.g., for improving the surrogate targets, information on different simulation tools for radar simulations was also collected and a summary of the advantages and disadvantages of the respective tools was made.

Several different physical reference targets with known theoretical radar response were developed and characterized. Among the reference targets were several trihedral corner reflectors, a sphere, metal plates and a cube. These were used to verify and calibrate the radar sensors used as well as for verification of simulation and measurement methods. An example of comparison between simulation and measurement on a metallic cube performed on AstaZero High Speed Area (HSA) at 30 m radius is shown in Figure 1.

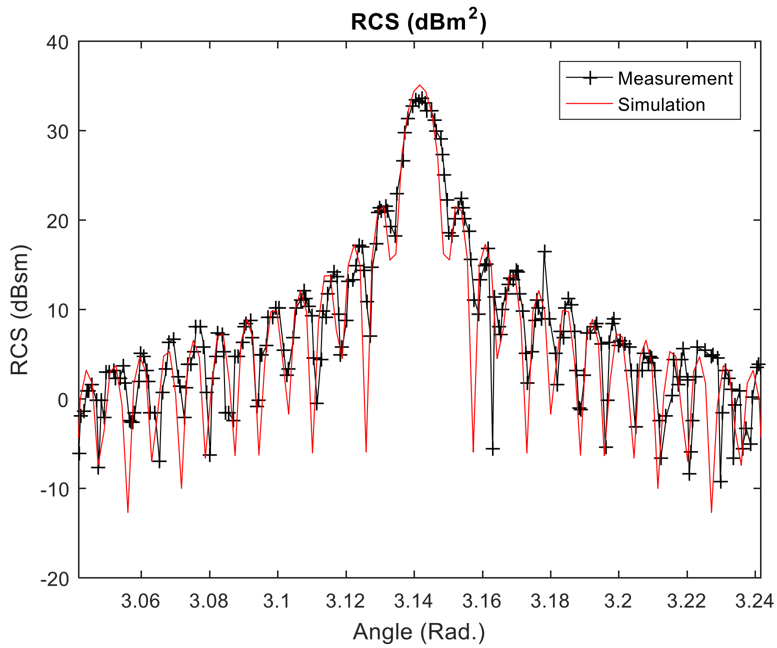

Figure 1. Verification of test method: monostatic RCS over angle of measured and simulated reference cube.

A reference target for improved calibration of the radar over range was developed in the project. This reference target has the advantage of suppressing the most significate error contribution during calibration: the ground reflection. See Figure 2.

Figure 2. Dihedral corner reflector with reduced reflection into ground.

6.2 Target signature measurement facility

A central part of the project was to find measurement methods to correctly characterize RCS of large test objects such as surrogate targets or real vehicles. These methods should be repeatable and with known uncertainty, and if uncertainty is large, means to reduce the uncertainty should be taken. It was known prior to the project that RCS of surrogate targets or real vehicles depend a lot on measurement distance and Angle of Arrival (AoA). In the project those variations have been thoroughly investigated, and deterministic as well as statistical measures have been developed to enable classification of targets. E.g., the distance dependence is investigated in terms of target size, radar-field-of-view, influence of ground reflection and range. That the radar response does change with AoA is easy to understand due to the non-rotational symmetry of the targets, but the actual change in RCS response over angle is however not straightforward to predict and much effort has been put into characterization methods and statistical evaluations of such. Two main methods for characterization of targets have been developed:

- Fixed radius RCS characterization as function of incidence angle.
- Fixed incidence angle RCS as function of distance.

Depending on test object (large target or calibration of reference target) three different test facilities have been used:

- RISE Hertz 5m fully anechoic chamber with rotational platform to measure RCS over angle of reference targets with different radars.
- RISE Faraday 15 m semi-anechoic chamber with rotational platform to measure RCS over angle of up to vehicle sized objects with different radars.
- AstaZero/HSA with radars placed on different positioning equipment (trolleys) to access target over angle, or over distance.

To accomplish all measurement tasks described in the project, several different radars have been used:

- A reference measurement setup utilizing a 77GHz Continuous Wave (CW) signal in combination with a spectrum analyzer with high frequency mixers. Both source and mixers were connected to horn antennas which were placed in parallel and close to each other constituting a monostatic RCS measurement setup. This setup is used for calibration of reference targets.
- An ISAR measurement setup with a 77GHz FMCW radar from Sivers IMA.
- Several 77GHz automotive graded radars from different vendors such as Autoliv (now called Veoneer).

To access the target over angle and range several positioning equipment’s were developed:

- A post-crash target validation setup where access to the target from different angles is enabled by a moving trolley with fixed yaw rate. This trolley moves around the target at a radius of 5.5m and carries an Autoliv (Veoneer) automotive radar.

- A trolley which can position and move the radar along user defined tracks, e.g., around the target or along straight lines approaching the target from different directions (range measurement). The trolley is positioned with a (Radio-Controlled) RC-car equipped with enhanced precision of position GPS (Real-Time Kinematic RTK-GPS), developed in the iTransit project. This setup conforms with the methods described in ISO for certification of surrogate soft (3D) targets (to date). The project has contributed a lot in the development of those ISO methods.
- Radar mounted on test vehicle positioned by RTK-GPS using the recorded RTK-GPS position as reference for the target location along with a Velodyne HDL-64 lidar to localize the target edges.

For repeatable and calibrated measurement result a strategy for calibration of the test system was defined, see Figure 4.

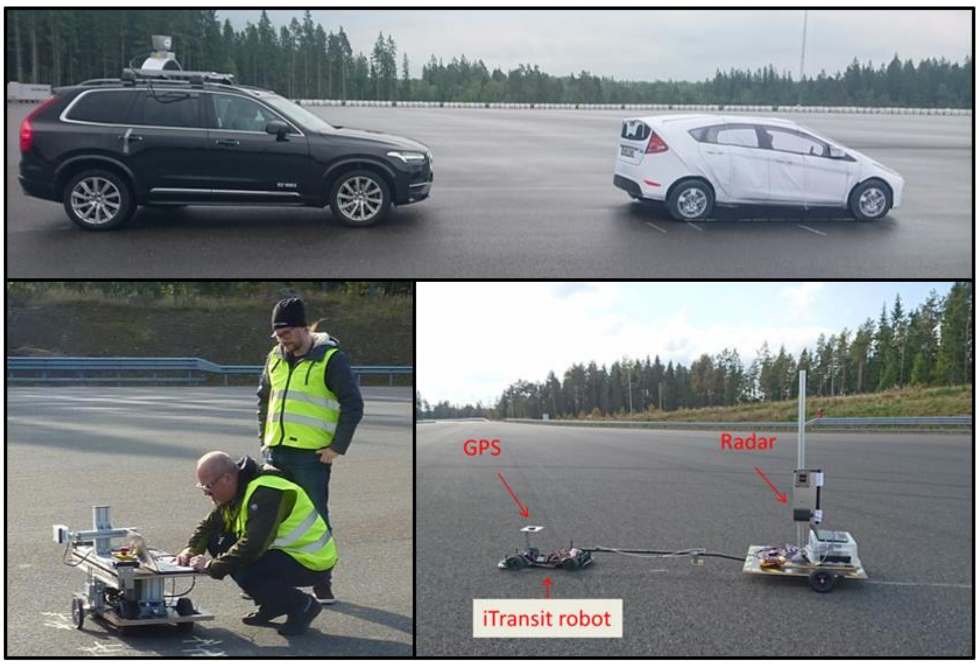

Figure 3. VCC test setup measuring on a DRI surrogate target (upper), the Autoliv RCS measurement chart (lower left), and RISE automotive radar carried by a trolley positioned by the iTransit robot (lower right).

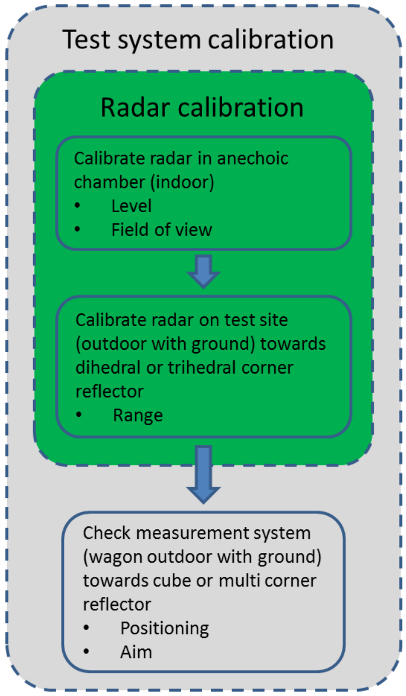

Figure 4. Measurement radar calibration procedure established in the project.

6.3 Measurement, simulation and analysis of target signatures

In the project the capabilities of analyzing RCS at frequencies around 77 GHz has been evaluated for several electromagnetic simulators. Properties such as accuracy and efficiency has been analyzed for several targets, both for smaller reference targets as well as for CAD models of large objects (surrogate targets and real vehicles). The CAD model of the surrogate target was achieved by a 3D scan with help of our sister project: HiFi Visual Target.

Figure 5. CAD model of DRI target.

Besides monostatic RCS also Inverse Synthetic-Aperture Radar (ISAR) images and hot sports have been simulated and compared with measurements. Good accuracy between measurements and simulations has been found (Figure 6), but we have also identified situations where electromagnetic simulations goes wrong, or don't converge at all.

To facilitate measurement system analysis a MATLAB model was developed were RCS of a canonical target of certain size can be calculated taking into account radar antenna beam width, range, and the ground reflection of the test site.

Several measures were investigated for analyzing the radar response of targets; back projection (Figure 7), multiple scattering centres, ISAR, representation by cumulative density function, a sliding max algorithm, smoothing over range (Figure 8 and Figure 9), and a new measure named radar reflectivity spatial profile (Figure 10 and Figure 11).

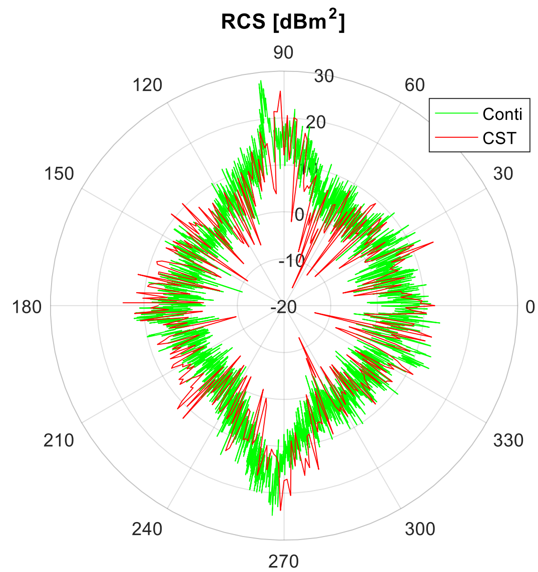

Figure 6. Measured RCS (green) compared with simulation (red).

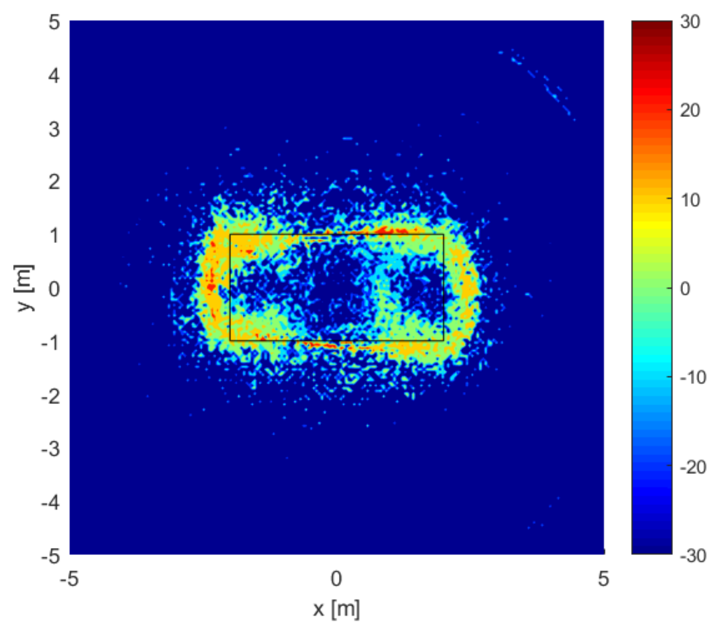

Figure 7. Back projected RCS of a real vehicle.

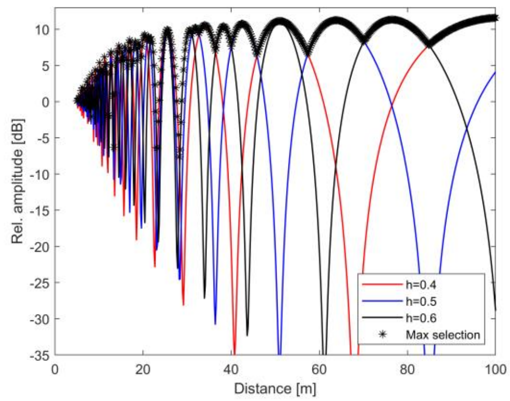

Figure 8. Simulated RCS over range for three different radar heights and height diversity by max selection at each distance.

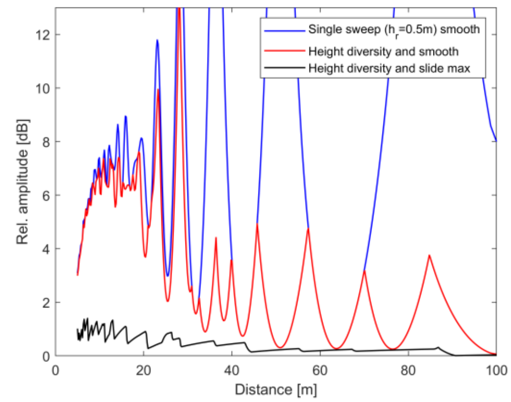

Figure 9. Estimate of the error originating from ground reflection for three approaches to characterize RCS as function of range. Sliding max outperform smoothing method and single height measurement.

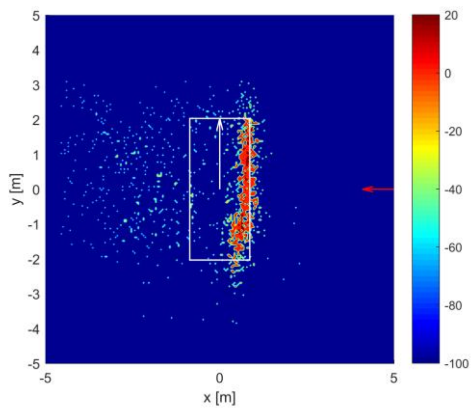

Figure 10. Grid summation RCS image of back projected detections for the surrogate target with the radar located at 90°±15° relative to the target. The color is the calculated RCS in dBm2

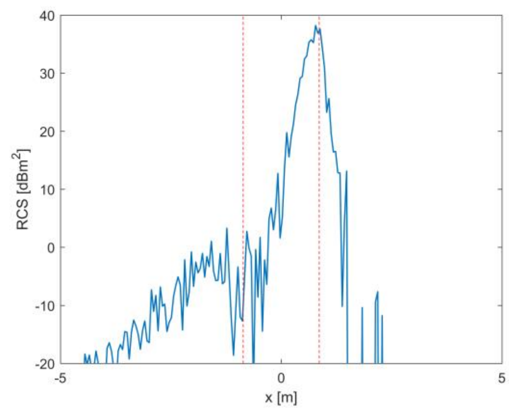

Figure 11. Compared to the figure on the left, RCS spatial profile can easily be completed with limits. This figure shows RCS spatial profile for the surrogate target when the radar is located at 90°±15° relative to the target (positive x is closer to the radar). The dashed red lines mark the approximate physical dimensions of the target.

1.1.1. Back projection with overlayed lidar response

Back projection of the radar detections onto the target's coordinate system allows analysis of where on the target the detections originate. The detections are recorded in the coordinate system of the radar and subtracted from the relative position of the radar from the target. This position is recorded using an RTK GPS system with accuracy of less than 2 cm in both lateral and longitudinal. This enables a study of where in relation to the base of the target's reference system the detection comes from. To understand better where on the target the detections come from, a lidar point cloud is recorded along with the radar and RTK GPS in order to overlay the point cloud over the radar detections and thereby confirm where the edges of the target are. Using this method, a more informed feedback to the target manufacturers can be made about where the radar signature should be adjusted and in what way. The measurements used for this type of analysis are fixed angle approaches using a XC90 test vehicle with a FLR (Forward Looking Radar) behind the windshield. An example of this method of back projection can be seen in Figure 12 where a Volvo V40 was measured using the method.

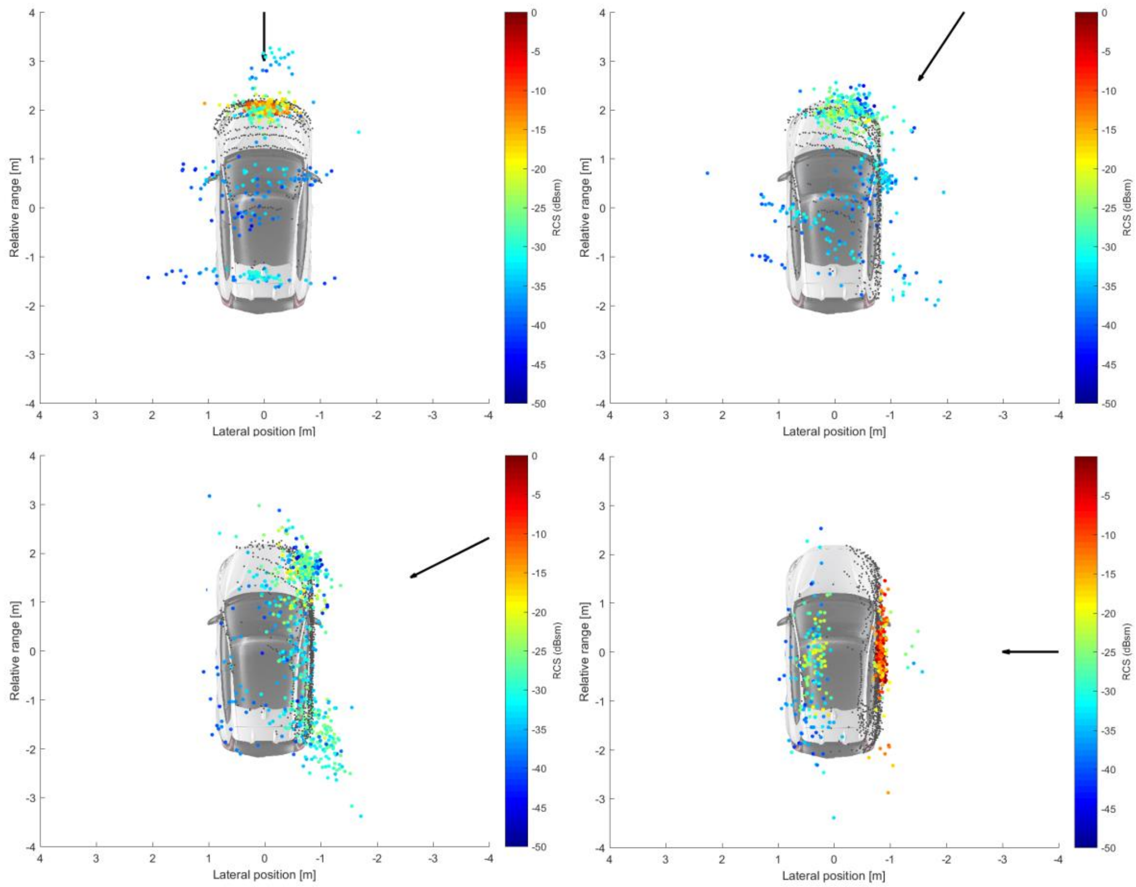

Figure 12. Back projected detections overlayed on a lidar point cloud of a Volvo V40 for four different approach angles. The upper left is an approach at 0°, the upper right at 30°, lower left at 60° and the lower right at 90°. The grey points overlayed on the image of the target are the point cloud from the Velodyne HDL64 lidar.

1.1.2. Vårgårda measurement campaign

During the project several measurement occasions took place at the HSA at AstaZero and also on an airfield in Vårgårda. Highlighted could be the measurement campaign coordinated by Autoliv (Veoneer) where 37 real vehicles and four targets were characterized. The measurement campaign was performed to understand how the 360º RCS measurement of various vehicles of different models and sizes looked to the radar. This data was then used to evaluate the RCS of current vehicle targets. The vehicles were from 16 different manufactures (Figure 13), covering 32 different vehicle models (Figure 14), and ranging in years from 2002 – 2017. There was at least one vehicle from each of the nine European car segments (Figure 15).

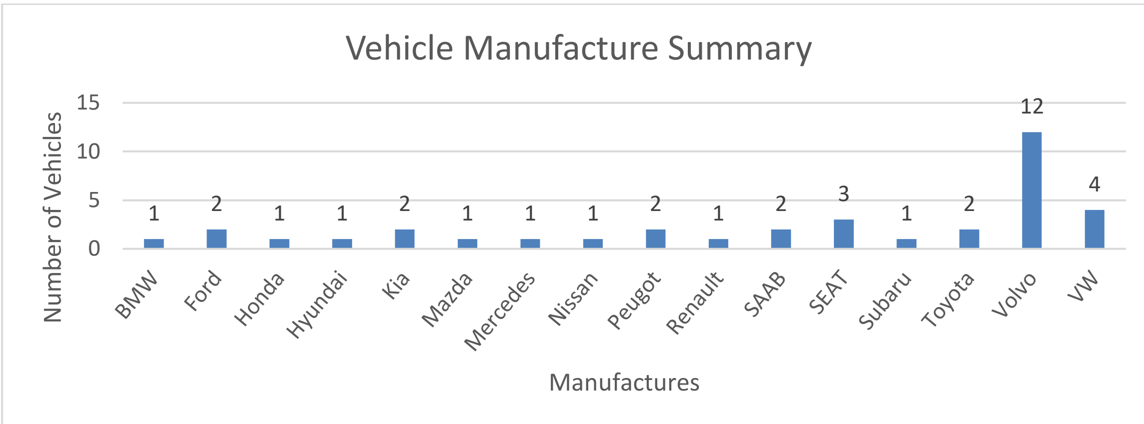

Figure 13. Distribution of the vehicles in the study for the different car manufacturers.

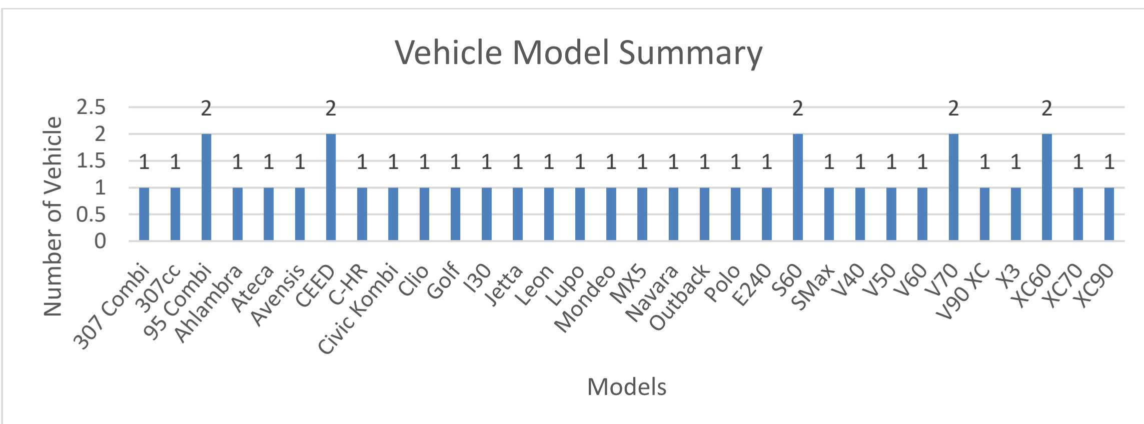

Figure 14. Distribution of the vehicles in the study for the different car models.

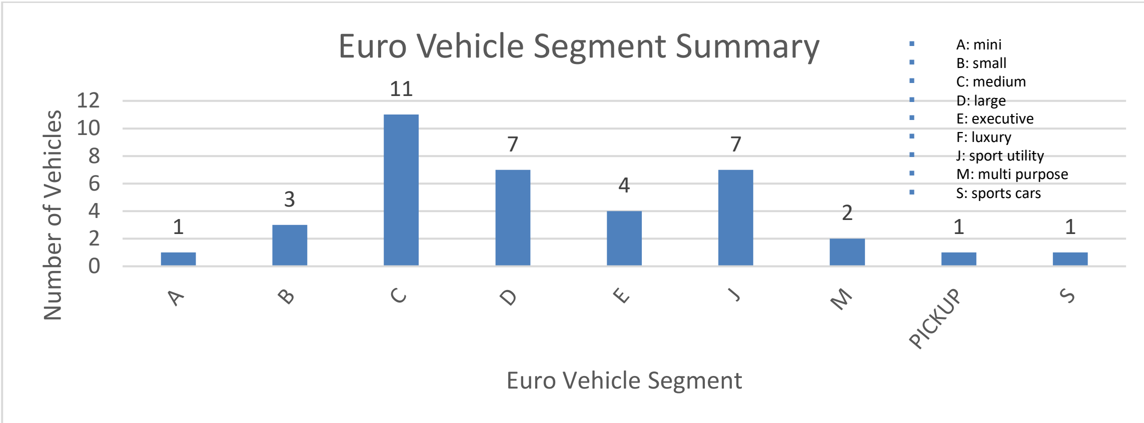

Figure 15. Distribution of the vehicles in study in terms of European Car Segments.

A 360º measurement of each vehicle was made and the angle of the radar to the vehicle along with the radar data (magnitude, distances, and angle) were sampled (Figure 16).

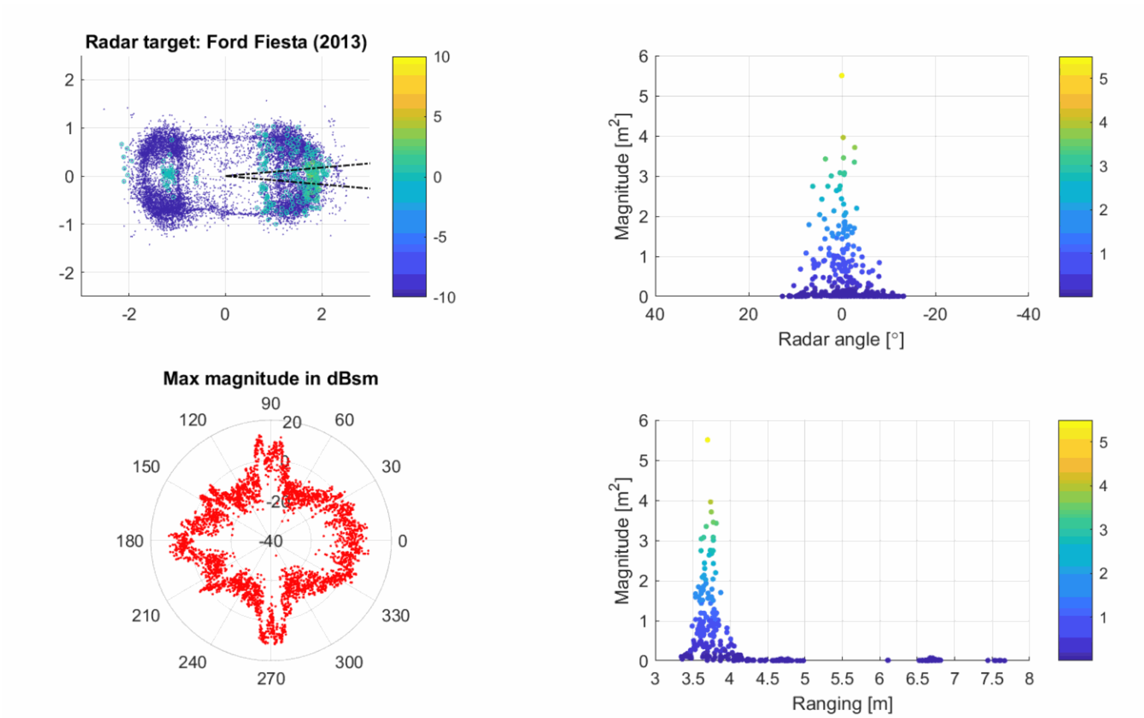

Figure 16. Example of measurement result on a Ford Fiesta. Back projection, RCS as function of angle, RCS spatial distribution as function of radar angle and as function of radar range for a given AoA window.

The first comparison was to look at the magnitude in RCS of the for the different car segments and see how they compared to the 3D targets. The measured 3D targets were modeled after vehicles in B to C category (Figure 17).

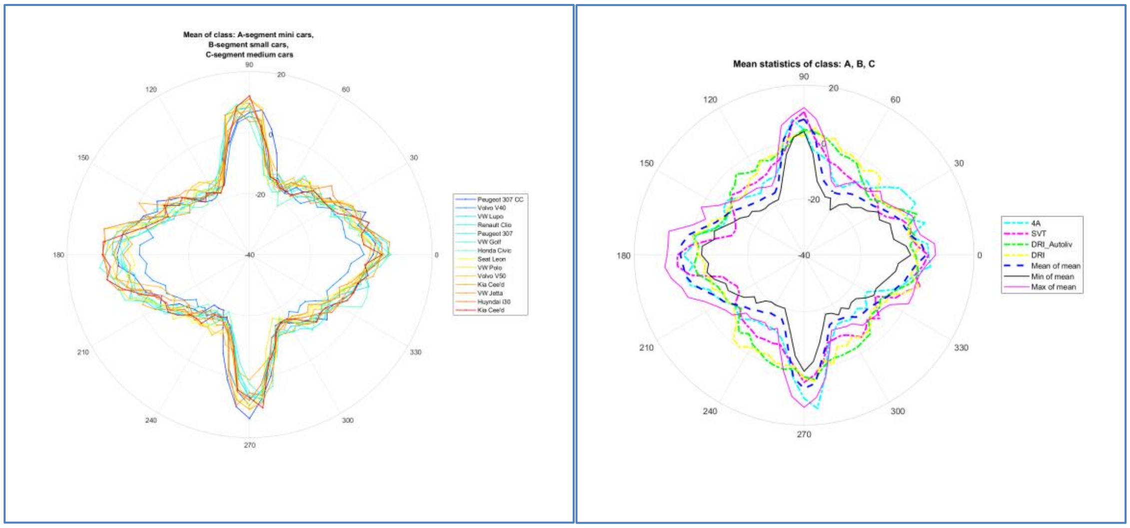

Figure 17. Measured RCS of vehicles from the A-C segment (left). Comparison of the real vehicles RCS to a couple of 3D targets (Right).

Next a summation of the location of the magnitudes in 10 cm squares was made for the 37 vehicles at 10º intervals over 180º from the front to the back was made and compared to the targets. It was assumed that the vehicles were symmetrical (Figure 18 - Figure 20). The dashed line in the plots represent the average width, length and wheel position of the 37 vehicles in the study.

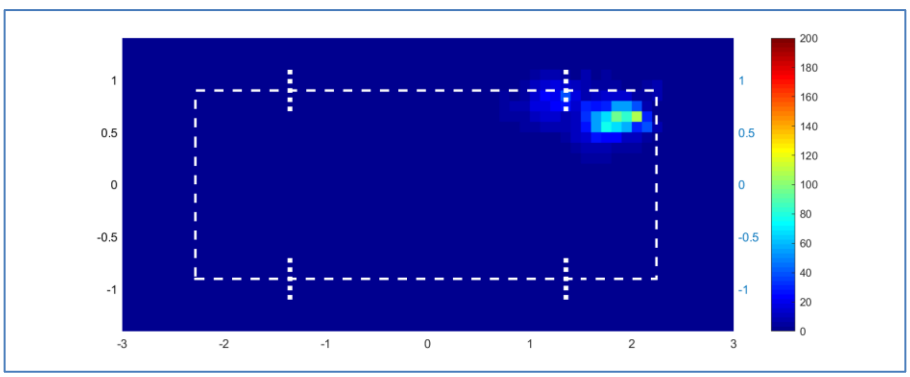

Figure 18. Example plot of the measurement of the magnitude locations as a function of the summary of 37 sampled vehicles at 30º.

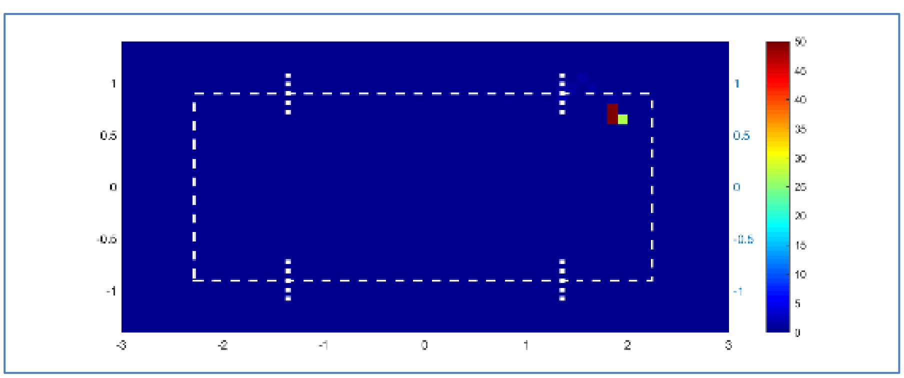

Figure 19. Example plot of the measurement of the magnitude locations of the 4a target at 30º.

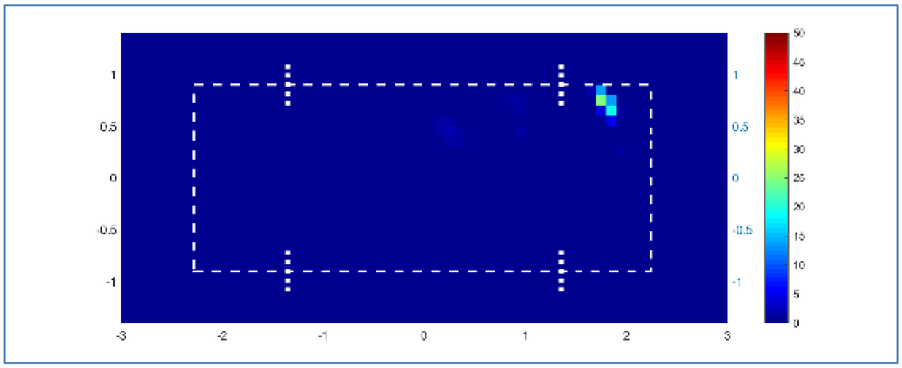

Figure 20. Example plot of the measurement of the magnitude locations of the DRI Version E target at 30º.

Also, a summation of the location of detections in 10 cm squares was made for the 37 vehicles at 10º intervals over 180º from the front to the back was made and compared to the targets. (Figure 21 - Figure 23).

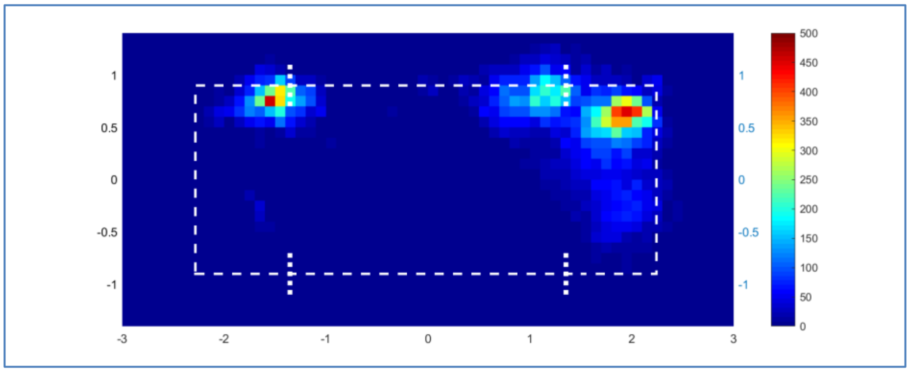

Figure 21. Example plot of the measurement of the detection locations as a function of the summary of the 37 sampled vehicles at 30º.

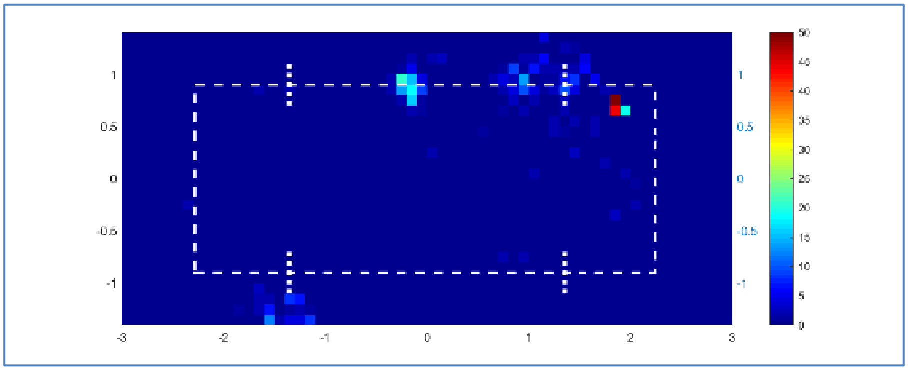

Figure 22. Example plot of the measurement of the detection locations of the 4a target at 30º.

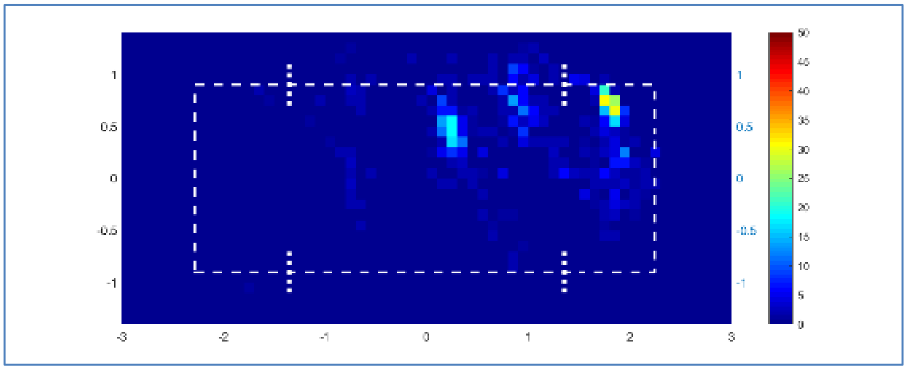

Figure 23. Example plot of the measurement of the detection locations of the DRI Version E target at 30º.

Finally, a comparison of the measurements of the B class vehicles was made and compared to the targets. The measurements were summed in 10º intervals over the first 90º from the front to the back. (Figure 24)

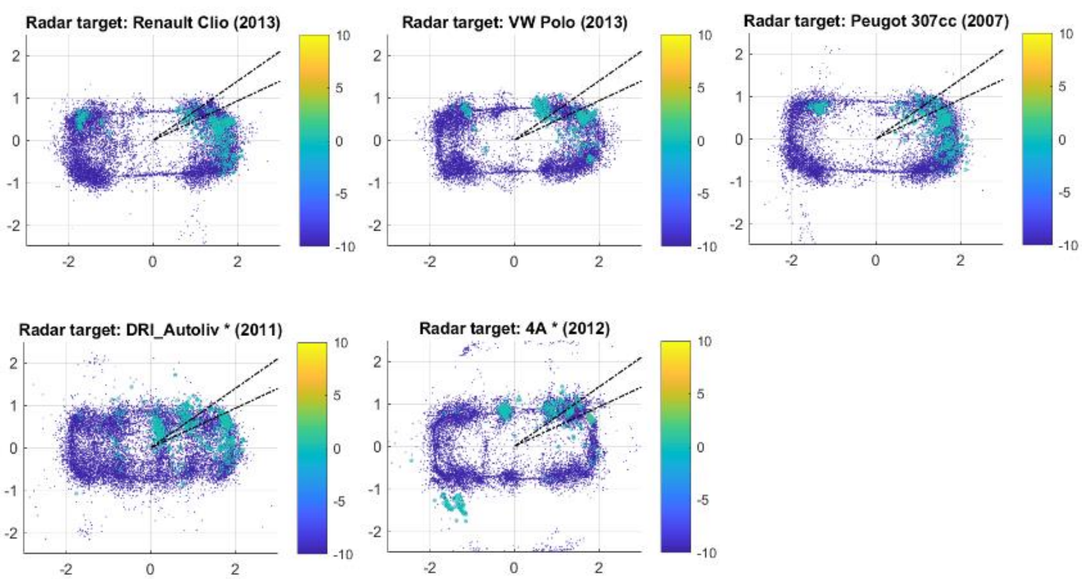

Figure 24. Example of the detection locations and magnitudes of the B class vehicles and some 3D targets at 30º.

6.4 Scenario based radar target characterization

During scenario-based tests on the test track, surrogate targets are sometimes moving at high speeds, and due to the soft nature of surrogate targets it is not certain that they are able to maintain their radar properties of their stationary state due to wind, accelerations, vibrations etc. Scenario-based testing can also include several surrogate targets and real vehicles simultaneously, moving or passing close to each other.

For these reasons, we have started to investigate strategies for testing the targets in more complex test scenarios in which it would be possible to add several real and/or surrogate targets that could be either stationary or moving.

The test system at AstaZero makes it possible to add tracking of position and heading to all targets involved in a test scenario. It is also possible to register the positions of stationary objects such as walls or guard rails. A radar, with all the wanted read out data accessible, has been mounted on a carrier test vehicle and its data is synchronized with the positions and headings of all the targets as well as the position and heading of the carrier vehicle. This way the detections recorded by the radar could be projected onto the targets.

Figure 25 shows an example with two targets and a real vehicle carrying a forward-looking radar which moves towards the targets and then passes between the two. For this both the target separation and radar speed has been used as variables and the difference in ability to separate the targets has been evaluated. In Figure 26 all the detections recorded during this test have been collected and projected onto the targets in scatterplots to show where on the targets the radar finds detections.

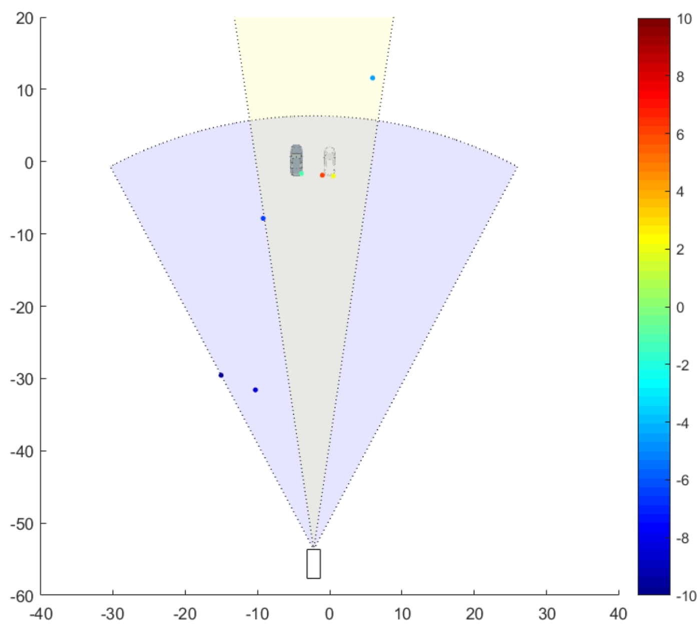

Figure 25. Detections at one time instance of a test scenario with a vehicle carrying the radar (white square) passing between two targets (left car represents a real vehicle and the right a surrogate target). The vehicle carrying the radar has two range modes (medium and far) shown in blue and yellow. Colormap shows RCS [dBsm] for each detection.

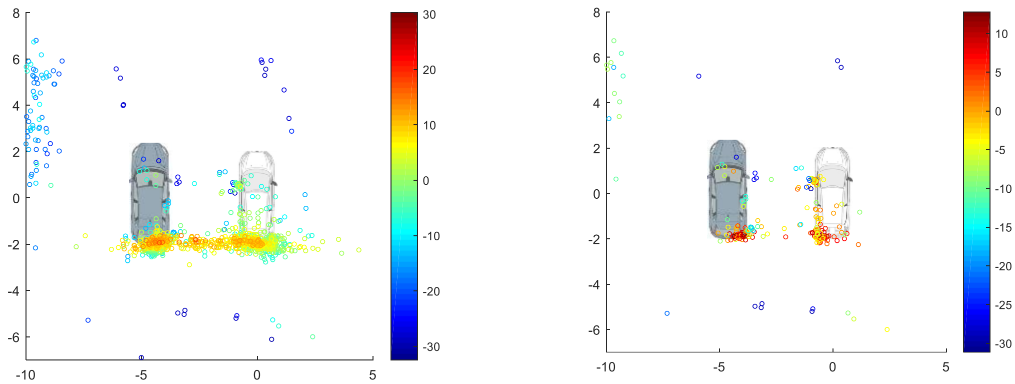

Figure 26. Back projection, onto the targets, of all detections registered during one testcycle with the radar passing between the two targets. The blue/grey target on the left represents a real car and the white target on the right a surrogate. Colorbar shows RCS [dBsm] for individual detections. x- and y-axis show distance [m] from centre. Left: all data. Right: data filtered to only show data from when the radar is closer than 20 m from the target.

Another scenario that was evaluated was when both the radar and the target were moving. In this test the measurement vehicle carrying the radar passed the moving target (Figure 27). This could be useful e.g. for evaluating if the surrogates radar properties are affected by vibrations or wind deformation when travelling at high speed. Preliminary results from one such measurement, where the target and measurement vehicle were travelling at 50 kph and 70 kph respectively, can be seen in Figure 28.

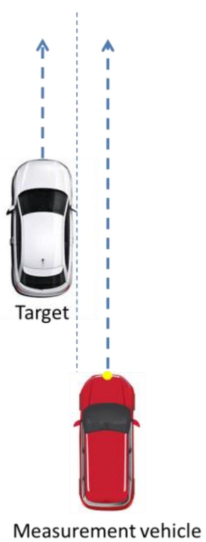

Figure 27. Scenario with the vehicle carrying the radar passes the moving target.

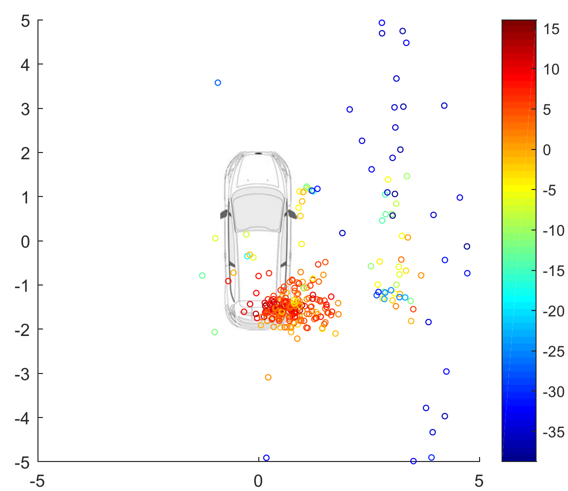

Figure 28. All detections collected during one test with the forward-looking radar mounted on a vehicle passing to the right of the moving target. x-and y-axis shows distance[m] from target center. colormap shows RCS [dBsm] of each detection.

The progress in this WP in the project was limited to measurement setup, evaluating a few measurement scenarios and early analysis. A detailed analysis has not been performed in the project, neither was such included in the project plan. This could be a proposal for future work.

6.5 Surrogate target synthesis

The surrogates can usually be viewed as compound objects constituted by the surrogate itself and the carrier platform needed to make the surrogate mobile. To achieve representative radar signatures both parts can be individually considered, but even more importantly both parts together as the two parts influence each other.

Within the project efforts in improving both platform and surrogate individually, as well as platform and surrogate together has been made.

6.5.1 Surrogate target model

A method for early evaluation of possible approaches towards improving or changing the radar signature of surrogate targets has been developed. The method consists of a Styrofoam cube that can be covered in different layers of materials to mimic the empty structure with a functional shell-like structure common in the soft surrogate targets. In addition to the cover materials, the effect of a small reflecting ramp placed under the cube (in analogy to the ramp like features of the target carrier platform) were investigated.

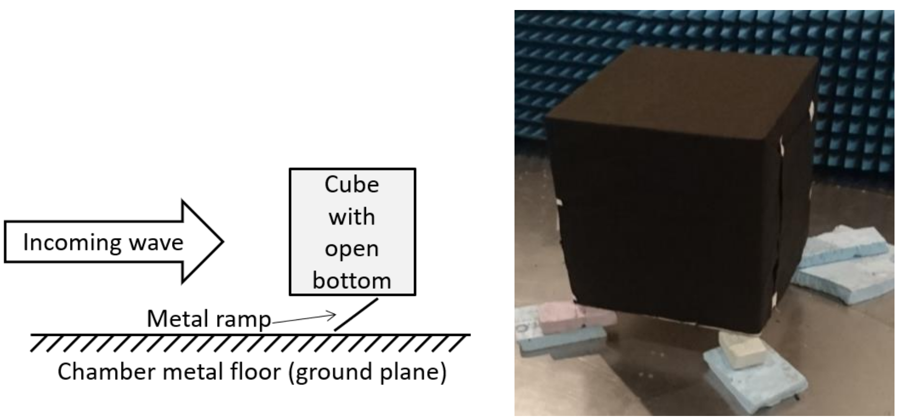

Figure 29. Left: Schematic drawing of test set up. Right: Cube covered in only the RF-absorbing textile inner lining. Layers can be changed or added.

Several studies were performed, e.g., the use of a textile with RF absorbing properties (from Eeonyx with surface resistivity 510 Ω/m), exemplified here. The sides and top of the cube was during test covered in model material, while the bottom was left open.

This example shows the model tested in two cases: with only the reflective aluminum foil, as well as with the textile absorber mounted as the innermost layer. To create internal reflections a metallic ramp (~22° angle to the ground plane) was placed underneath the cube to reflect energy into the interior, which is what happens to a surrogate target when placed on a moving platform.

In Figure 30 resulting RCS-probability is shown for the two cases. It can be seen that the absorbing textile reduce the density of the detections. Note: due to the measurement methodology “ghost” detections were also recorded. These are due to multiple reflections occurring between the radar fixture and the exterior of the cube (aluminum cover) and is not part of what is studied here.

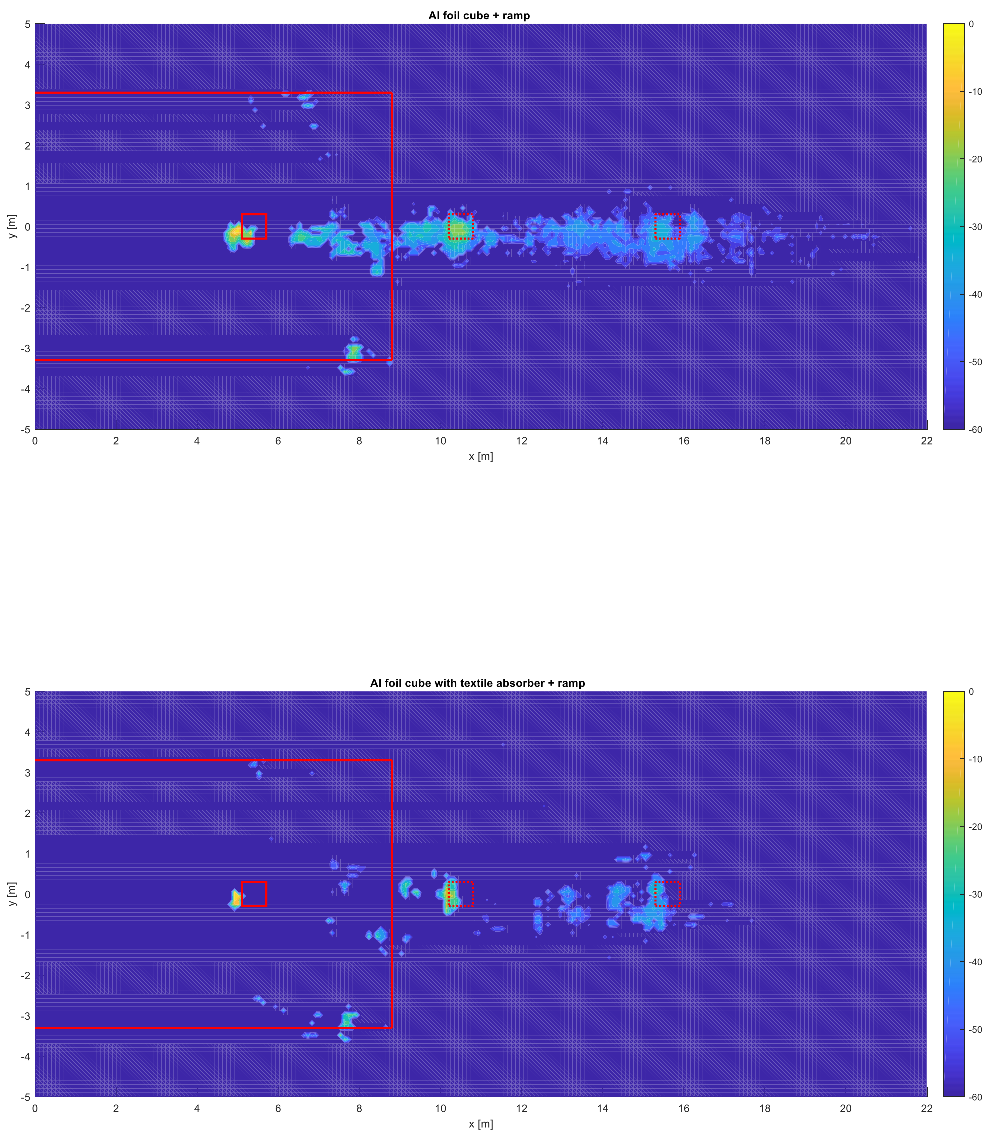

Figure 30. Resulting RCS-probability of the cube when covered in aluminum foil and with a reflecting ramp present underneath (upper), and with an inner lining of RF-absorbing textile (lower). Red squares mark the cube (solid) and the first two predicted "ghost" reflections of it (dotted lines).

6.5.2 Addition of a ramp to the target carrier platform

Originally, the target carries had huge monostatic RCS along the ground, at normal directions to its sides. To improve that, a ramp was added to the target carrier platform reflecting incoming waves upwards. The carrier platform with modifications on two out of four sides can be seen in Figure 31, and in Figure 32 measured RCS with and without ramp is shown and it can be concluded that RCS is significantly reduced by the ramp. Note: Even though the initial reflections are reduced, there is a risk of inner reflections (as seen in previous chapter).

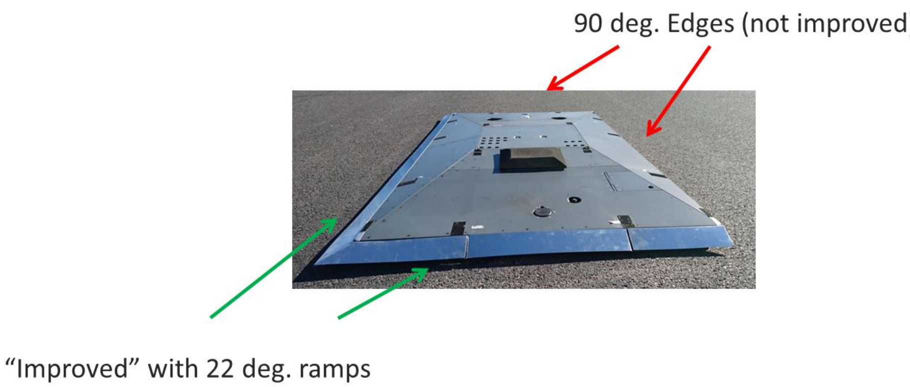

Figure 31. GST platform with 22 degree ramps.

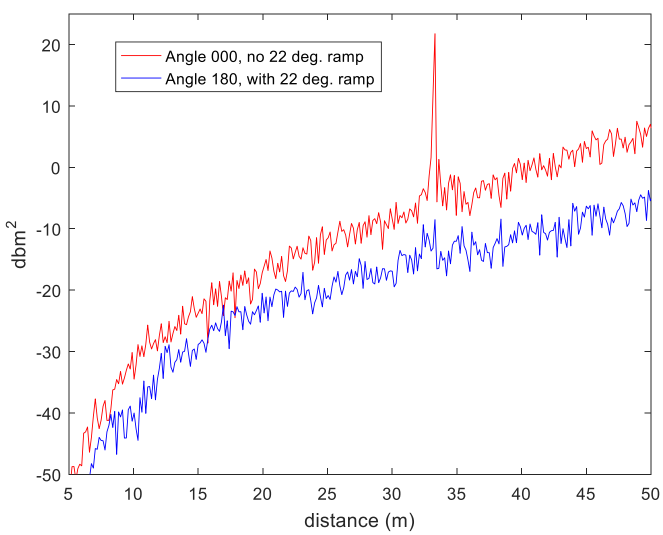

Figure 32. GST platform with and wtihout 22 degree ramp.

6.6 Virtual radar testing tool-chain

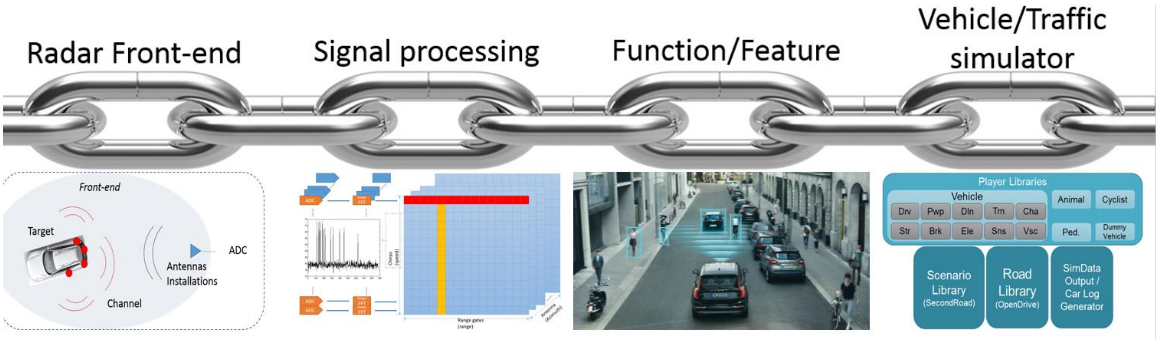

Figure 33. Radar virtual verification tool chain.

In order to simulate more realistic automotive radar behavior to test ADAS/AD function performance, a series of tools are needed to cover difference aspects or stages of the working process of the radar. In this project, the virtual verification environment for a production rear-side radar has been analyzed and different links of the tool chain have been presented.

Generally, the tool chain can be divided into radar front-end, signal processing, function/feature and vehicle/traffic simulator. Each of the link requires different methods and resources. In front-end model, we use commercial Electro Magnetic (EM) simulation software to simulate the radar installation radiation pattern and the scattering centre list of the target. These results provide the basic radar signature about where and how strong the radar is going to see from the target. Moreover, if multi-path reflection from the ground is considered, the radar signature needs to be adjusted accordingly. Then Analog-To-Digital (ADC) modelling can be built based on the specific design of the radar waveform. After acquiring the low-level ADC data cube of the radar, the signal processing algorithm kicks in. As this is the main part under test of the radar, we often treat it as a black box. ADC data is fed into the signal processing. The tracked objects and function actuation signal will be generated. Under the circumstance that certain suppliers are not able to provide the full signal processing software component for PC environment, we have to provide the higher level of signal flow than ADC data to enable the verification of downstream processing algorithm. Typically, it happens at point detection level. Two detection models has been developed showing two basic direction, statistic model based on the measurement and physical model based on radar characteristic plus simulation results. The pros and cons have been discussed for both types of models. The project uses a VCC-in-house developed traffic simulator as the integration platform of all the tools. The tool is Simulink based but there also exits the C code version. At last, the structures of integrated virtual verification tool chains have been presented for both SIL and HIL.

The front-end model, detection model and EM simulations on the target has been benefited from this project. The work in this project filled the gaps of the full tool chain that makes the close loop complete. Moreover, part of the work such as propagation channel analysis and modelling described in chapter 4.2 has improved the accuracy of the simulation. The tool chain has been provided to the testers, and the result shows some consensus with the real measurement from the radar/function verification. In the future of next production radar project, we will continue to improve the quality/accuracy of the links of the virtual verification tool chain and hope more issues with the radar system can be identified at an early stage of the product process.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Increased knowledge in RCS characterization of real vehicles and surrogate targets, RCS simulation at 77 GHz and RCS models.
Be passed on to other advanced technological development projects	X	RISE: Passed on to radar target simulator project. RISE: Knowledge transferred to a project specifying a weather protected test facility at AstaZero (SPICE). VCC: Virtual verification tool chain and soft target development. Autoliv: Soft target and simulation development.
Be passed on to product development projects	X	VCC: Virtual verification tool chain and RCS verification methods on test track. Autoliv: RCS verification methods on test tracks. AstaZero: Validation of novel cardboard target.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions	X	We have supported ISO with investigations, knowledge in writing of “ISO WD 19206-3 Requirements for passenger vehicle 3D target” in ISO/TC 22/WG 16.

On February 21, 2018 a project seminar was held at AstaZero, which included both presentations of the project results as well as demonstrations of a few of the measurement methods developed within the project. The event had around 30 participants.

The project has also been presented at two other external events:

- HiFi Visual Target demo day at AstaZero on June 20th, 2018.
- IEEE EMC Society, Sweden Chapter, Mjölby, September 14th, 2018.

7.2 Publications

W. Buller, N. Lundin, K. Karlsson, D. Alio, ”Evaluation of 3D Surrogate Vehicles for Automotive Safety Tests,” ESV, 25th International Technical Conference on the Enhanced Safety of Vehicles, June 5-8, Detroit, USA.

I. Vakili, E. Marel, G. Panahandeh, ”Scattering Center Analysis of Surrogate Targets,” FAST-zero’17, Nara Kasugano International Forum, September 18-22, 2017, Nara, Japan

K. Karlsson, H. Toss, F. Costagliola, “Reducing influence from ground reflection during RCS characterization of automotive targets,” submitted to EuCap, 13th European Conference on Antennas and Propagation, March 31-April 5, 2019, Krakow, Poland.

K. Karlsson, H. Toss, “Radar reflectivity spatial profile of 3D surrogate targets and real vehicles,” submitted to EuCap, 13th European Conference on Antennas and Propagation, March 31-April 5, 2019, Krakow, Poland.

8. Conclusions and future research

The project has worked with, and fulfilled, all deliverables and goals defined in the application. Some goals were more than well reached, and some others were only fulfilled to a lower level. E.g., the work with ISO on surrogate target characterization methods took a lot of resources and resulted in good impact as well as deliverables, while on the other hand, work with improvement of surrogate targets did not reach that far. One reason for less success in that area was that to be able to verdict an improved surrogate target compared to a standard target, precise and repeatable measurement procedures are needed and those were not ready until late in the project. However, the basic understanding of how to analyze and tweak radar response from a surrogate target was established and several improvements of surrogate target structures were proposed and implemented during the project.

During the time of the project the interest and need for virtual environments for evaluation of ADAS functions has increased to the automotive community. And accordingly, so has the interest and need for realistic and efficient radar models. Even though some models were developed in the project a lot of work remains to be done in this area. Both for pure virtual simulators and for mixed environments combining e.g. a real automotive radar with a radar target simulator hardware and a virtual environment.

The proposed ISO method is quite time consuming as it requires several measurements at different radar heights. A test rig with an array of radars with synchronized sampling would significantly improve test quality and save time on the test track.

There will be an ongoing work within ISO for other target types such as trucks, bikes/motorcycles and animals. There will also be work on road infrastructure objects such as road signs and crash barriers. These planned work groups will need input from research projects for characterization methods and models for such targets and objects.

9. Participating parties and contact persons

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