



SOLUÇÃO AUTOMATIZADA PARA TESTE E VALIDAÇÃO RADARES AUTOMÓVEIS

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AUTOMATIZED SOLUTION TO TEST AND VALIDATE AUTOMOTIVE RADAR UNITS

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Resumo

Com a necessidade crescente da produção de automóveis, gerada pelo aumento populacional em junção com as tentativas de inovação e introdução de novas tecnologias na indústria automóvel, verifica-se um surto de novas funcionalidades disponibilizadas ao consumidor. A maioria destas têm como principal foco a segurança rodoviária, uma preocupação em crescimento dado que mais pessoas circulam nas estradas públicas diariamente, aumentando as chances de possíveis acidentes. Algumas das funcionalidades que vêm a surgir incluem, por exemplo, aviso de colisão, deteção de ângulo morto e assistência à mudança de faixa, um conjunto de funcionalidades com grande dependência de sistemas de deteção. Atendendo a que alguns sistemas de deteção já são considerados comuns em veículos, para auxílio ao estacionamento, por exemplo, o conceito não é novo, mas os sistemas já existentes apresentam limitações quanto ao clima, alcance e resolução, entre outros. Para ultrapassar estas dificuldades, a indústria automóvel iniciou a implementação de sistemas baseados em radar.

A tecnologia radar é capaz de cobrir a maioria das necessidades da indústria automóvel para sistemas de deteção e, considerando o foco acrescido que tem sido dado pelos fabricantes automóveis aos sistemas avançados de auxílio à condução (ADAS), outras tecnologias são também consideradas e usadas em junção com o radar, como é o caso do LiDAR, uma solução com custos mais elevados e mais apropriada para desenvolvimentos na área dos veículos autónomos e não tanto para os veículos orientados ao consumidor. Com o crescimento da procura por radares automóveis, os fabricantes dos mesmos procuram também sistemas de testes para os seus produtos.

Tendo em conta o potencial do mercado do radar automóvel, múltiplos desenvolvedores de testadores procuram uma forma de incorporar testadores de radar nas fábricas dos seus clientes, um desafio para este tipo de sistemas. Para cumprir com as normas europeias de teste, um engenheiro de testes deverá encontrar complicações com o tamanho da câmara anecoica necessária para realizar os testes, assim como as larguras de banda necessárias. As dimensões elevadas da câmara anecoica aumentam o testador para tamanhos

inapropriadas à inserção em linhas de produção e a solução, tipicamente, requer ignorar as indicações ergonómicas para operação do sistema, um problema por si só. Para ultrapassar este problema, este documento propõe uma solução automatizada para deslocamento da unidade, disponibilizando posições ergonómicas e reduzindo as dimensões da máquina.

Apesar do quão vantajosas sejam estas funcionalidades, este tipo de implementação adiciona complexidade ao sistema, dificultando o desenvolvimento e aumentando o custo para o cliente final. Apesar do desagradável aumento no preço, o tamanho mais compacto e a conformidade com as normas europeias são razões suficientes para considerar este tipo de sistema de teste em detrimento de outros.

Para validar o conceito do testador, o mesmo deve ser capaz de gerar objetos para o radar detetar durante o teste num ambiente de espaço aberto simulado, como numa câmara anecoica blindada. Para simular estes objetos, é necessário utilizar um gerador de objetos radar, um dispositivo capaz de ser colocado próximo do radar e de gerar objetos mais distantes. Este é também essencial para garantir que a totalidade da largura de banda da unidade é testada, sendo que tipicamente estão disponíveis nas duas larguras mais usadas nos radares automóveis: 76-77 GHz e 77-81 GHz.

Neste documento, os radares AWR1642 da Texas Instruments e o ARS408-21 da Continental são utilizados para validação do testador. Alguns testes iniciais são necessários em bancada de teste onde é expectável maior ruído e um rácio *signal-to-noise* pior. Outros testes deverão ser realizados com os restantes componentes do testador, como a espuma absorvente de RF, a câmara anecoica blindada e o gerador de objetos radar. Deverão ser identificadas melhorias em cada fase e, em última instância, o comportamento no interior do testador deverá ser claramente superior aos testes iniciais.

Palavras-Chave

Radar automóvel, Sistema de testes, ADAS, RCS, Ergonomia, AREG100A, Testador, ETSI, Automação, Gerador de objetos radar, Linha de produção, Laboratório.

Abstract

The rising need for more cars to be produced, induced by the population growth, allied to the attempts at innovation and introduction of new technologies in the automotive industry, originated the surge of new features available to the consumer. Most of these are road safety focused, a growing concern as more people circulate in the public roads daily, increasing the likelihood of accidents. Some of those features include, for example, collision warning/prevention, blind-spot detection and lane-change assist, a group of features which rely heavily on detection systems. With some forms of detection systems already common in vehicles, for parking assistance, for instance, the concept isn't new, but the existing systems have limitations related to weather, range and resolution. To overcome these issues, the automotive industry implemented detection systems based on radar.

Radar covers most needs in the automotive industry for detection systems and, as such, becomes a growing presence in cars, being a core component in new and improved features. Having advanced driver assistance systems (ADAS) become such a major focus for cars developers and manufacturers, some other technologies are also considered and implemented in conjunction, like LiDAR, a more expensive solution, best suited for autonomous driving development and not consumer-focused vehicles. As the demand for automotive radars rises, so does the demand for radar test systems by the manufacturers.

Considering the potential growth for the automotive radar market, multiple tester developers are focusing in the most efficient way to incorporate such a tester into their clients manufacturing plants, a challenge for this type of systems. A test engineer who wishes to comply with the European standards for automotive radar testing faces complications with the required anechoic chamber size where the tests will be carried out and the frequency bandwidths required. Its large dimensions tend to grow the test system into sizes not suited for a manufacturing plant and the solution is typically to disregard ergonomic guidelines for the system operation, an issue in itself. To overcome the size issue, this paper presents a proposed solution based on automated unit transposing,

allowing for the operator to work in ergonomic positions and for the machine to reduce in size.

As advantageous as these features may be, this type of implementation adds complexity to the system, increasing the difficulty in development and the cost for the final client. Despite the non-appealing increase in price, the more compact size and standard compliance, are enough reasons to consider the system over others.

In order to assure the concept for the tester is a valid one, the tester must be capable of generating targets for the radar sensor under test to detect in an emulated open-space environment, *i.e.* inside a shielded anechoic chamber. The objects generated must cover most of the sensor's range, which can typically reach the hundreds of meters. To emulate these objects, a radar echo generator must be used, a device capable of being placed close to the radar sensor and generating targets further away. These devices are also the core component to assure the entirety of the radar frequency bandwidth is tested, as they are usually available in the two most used in automotive radar: 76-77 GHz and 77-81 GHz.

To test the correct functioning of the system, a radar sensor must be inserted in the system and its data analysed, throughout the entirety of development. For this paper, the Texas Instruments' AWR6142 and Continental's ARS408-21 radar sensors are used to evaluate the tester performance. Some initial tests must be carried out in a testbench where clutter and a worse signal-to-noise ratio are expected. Some other tests must then be done with the gradual introduction of tester components, *i.e.* RF absorbent foam, shielded anechoic chamber and radar echo generator. Improvements must be seen in each phase and, ultimately, the performance inside the full tester must be clearly superior to the initial tests.

Keywords

Automotive radar, Test system, ADAS, RCS, Ergonomic, AREG100A, Tester, ETSI, Automation, Radar target generator, Production-line, Laboratory.

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List of Abbreviations

ACC	–	Adaptive Cruise Control
ADAS	–	Advanced Driver Assistance Systems
AEB	–	Autonomous Emergency Break
CAN	–	Controller Area Network
CW	–	Continuous Wave
DUT	–	Device Under Test
EIRP	–	Effective Isotropic Radiated Power
EMC	–	Electromagnetic Compliance
EN	–	European Standard
ETSI	–	European Telecommunications Standards Institute
FCC	–	Federal Communications Commission
FPGA	–	Field-Programmable Gate Array
FMCW	–	Frequency Modulated Continuous Wave
GPIO	–	General Purpose Interface Bus
ITU	–	International Telecommunication Union
IEEE	–	Institute of Electrical and Electronics Engineers
JTAG	–	Joint Test Action Group
MSD	–	Musculoskeletal Disorders

- PLC – Programmable Logic Controller
- PXI – PCI eXtensions for Instrumentation
- RAM – Radar Absorbent Material
- RCS – Radar Cross-Section
- SDK – Software Development Kit
- TTT – Transport and Traffic Telematics
- UART – Universal Asynchronous Receiver-Transmitter
- UUT – Unit Under Test
- WHO – World Health Organization

1. INTRODUCTION

Transportation has become an essential aspect in everyday life for humans in nowadays. The growth of the population intensified the need for more means of transportation, and, most importantly, the need for an increased number of pre-existent vehicles of transportation. Either by personal taste of the consumer or by offering better conditions than other means of transportation, these rise in needs propelled the automotive industry to continuous growth, both in amount manufacturing and in purchasing by the consumer. According to the World Health Organization (WHO), the number of registered vehicles in the world grew by 16% between the years 2010 and 2013¹. This massive increase in number of users of both the public roads and the vehicles manufactured comes with its

¹ Data available in WHO's Global Health Observatory data on registered vehicles.

disadvantages, raising concerns with road safety and pushing manufacturers into developing new and improved features to attract such a large number of possible customers. To cover both situations, the inclusion of new technologies in vehicles for both safety, comfort and performance is becoming a focus for car developers attempting to innovate and offer an answer to public needs and wants.

The radar has been one of the main technological supports for some of the top-of-the-line applications that have been showing up in the recent years. Automatic emergency braking, adaptive cruise control (ACC), lane-change assist and other advanced driver assistance systems (ADAS) are some of these applications in which radar plays a major role in the effective performance of the system [1] [2]. As these applications are expected to represent a consistently larger part of the automotive industry companies' annual budget, being prepared to test them thoroughly is a priority for any companies responsible for developing test systems. This fact allied to the very rigorous specifications and needs of the system as well as the complexity of the technology make the development of a testing solution a very interesting challenge [3].

As the need for automotive radar units raises, the need of a fast, reliable and compact testing solutions also raises. One can then assume that a system that can be insert into production lines, capable of validating all major radar functionalities of the UUT according to all technical requirements will, very shortly, become mandatory in the industry.

The document that follows describes the development of a solution for automotive radar units testing at CONTROLAR's Test Systems department. Being the focus of this department the testing and validation of a variety of products, researching new types of faster, more reliable and less expensive solutions for the systems that run the tests is a must. As most of the companies that purchase and use CONTROLAR's test systems are very well established in the automotive industry and are pioneers in the integration of new technologies in the industry, CONTROLAR must keep up with this development and offer solutions to test these new technologies. One of these more recent technologies is the radar.

The testing of radar devices requires a multitude of factors to be met, *e.g.* the space surrounding the radar sensor, the working frequencies of the instrument generating objects for the radar, the ability to position the radar at different angles in relation to said instrument and others. Despite the tester complexity that may rise from the demanding the requirements, the concept of the radar test itself is well defined. The signals emitted by the radar device should be delayed, either by a passive device or an active device, and then return to the UUT with different characteristics, emulating longer travel times and the reflection with objects, where the target information would be obtained and analysed. Since, normally, the unit under test (UUT) is the emitter of radio waves, said device should be in an anechoic chamber during testing, avoiding interferences and excess reflections from the surrounding environment [4]. A more detailed explanation of the working concept of radar and its testing strategies may be found later in the document.

1.1. MOTIVATION

Although some systems and devices, like the echo generator Rohde & Schwarz's AREG100A, that help radar testing are already in the market, there are still a lot of limitations in said devices. The ideal testing of automotive radars would consist in having the unit to test inside an anechoic chamber with a device generating targets for the radar to detect. For a more capable system the generator should be able to generate multiple and variable targets on-the-fly. This is one of the limitations in the current automotive radar testing scene as most generators are only able to generate a fixed low number of targets with an also fixed distance as the processing for more active generators is highly demanding.

However, for a testing system designed to be inserted in a production line, a fixed number of known targets might be exactly what is expected of the system, the reason being that this type of tester offers the same test conditions for all products throughout its life. When testing in mass-production environments the goal revolves around assuring all units pass the same tests in the same conditions, so if the test conditions were able to change, then

the viability of the tester would decrease. For this reason, the development of the system needs to consider the environment in which it will be implemented. Since it is expected that both the development and the production of automotive radar units will increase in the future, both types of testing will be important.

CONTROLAR aims at consolidating its workers knowledge in the technology and its ability to develop reliable test systems.

1.2. OBJECTIVES

The main goal of this project is to research the needs of the automotive radar units when it comes to technical specifications and how is it possible to test and validate such requirements. There should then be a well-defined of the concept responsible for said testing and validation. Keeping these points in mind, the major objectives to take in account are:

- Research of automotive radar units and testers state-of-the-art;
- Development of a conceptual testing system;
- Implementation and validation of the main components of the concept;
- Definition of possible improvements of the system and concept;
- End up with a reliable and satisfactory architecture for automotive radar testing.

2.AUTOMOTIVE RADAR

In the next chapter, the surge of the radar, more specifically of the automotive radar, is described. After the description of the technology's first steps, a more in-depth explanation of the current applications and principle of use can be found. The chapter ends with some details about the automotive radar, describing aspects like expected developments in the automotive industry, current products in the market, the industry's testing requirements and regulations and the implications of said tests.

RADAR stands for **R**adio **D**etection **A**nd **R**anging, clearly exposing target detection and ranging employing radio waves as its main application. The main motivation for the technology's development was the World War II, with nations such as the Soviet Union, United States of America and Great Britain exploring the possible military advantages which the technology could bring [5]. As the prospective capability for targeting enemy troops

and vessels arose, so did the investment into finding and improving new functionalities. Some of these, such as portability, would bring to light the potential use of radar in civil scenarios, including the cars, commercial flights and passenger boats [6].

According to the World Health Organization, WHO, approximately 1.35 million people die each year as a result of road traffic crashes and said crashes cost most countries 3% of their gross domestic product.² These numbers show the need for improvements in vehicle safety and reduction in the impact of human error. One of the possible ways to accommodate for human error is the implementation of advanced driver assistance systems (**ADAS**) [7] [8]. These are electronic systems incorporated into the vehicle with the goal to aid the driver while driving. These allow to increase the degree of automation associated to driving, diminishing the chance of crashes caused by human error. Radar plays an essential role in some of these systems, such as adaptive cruise control (**ACC**), autonomous emergency break (**AEB**), rear collision warning and blind spot detection. Further development of the technology may even be one of the key phases in reaching full autonomous driving, one of the current automotive industry's main goals [9].

2.1. RADAR WORKING PRINCIPLE

In the following chapter a description of the working principle of radar and similar technologies can be found, as well as the decomposition into different types of radar and the advantages and disadvantages of each. It is also important to highlight which characteristics of the radar and its types that make the technology a major asset for the automotive industry in the upcoming years. Once the reasons for the surge of the automotive radar are established, it is critical to understand the safety standards for testing said radars.

² Data related to the year of 2018, available in the WHO's *Global Status Report on Road Safety 2018*.

The working principle of radar is very similar to the one present in **Sound Navigation Ranging (Sonar)** and **Light Detection And Ranging (LiDAR)**: the device sends electromagnetic waves, or sound waves in the case of sonar, which will reflect in objects and return to the device (Figure 1). Time spent between the emission and reception is used to calculate the distance to the object. The key difference between the exposed technologies is in the emitting waves. Radar emits radio waves, the lowest frequency waves from the electromagnetic radiation spectrum, ranging from 30 Hz to 300 GHz. LiDAR emits light waves, with the most common wavelength being between 905 nm and 1550 nm (± 193 THz to ± 331 THz) [10]. Sonar uses sound waves, typically ultrasonic (above 20 kHz), which are substantially slower than electromagnetic waves.

The difference in emitting waves means different advantages and disadvantages for each technology. LiDAR requires expensive components, such as motors and encoders, despite offering greater resolution [11]. Sound waves used by sonar are much slower than the electromagnetic waves used by the other technologies, however, being a mechanical wave with higher wavelength, is not as easily absorbed by sea water, making it a great solution for underwater applications [12]. Radar requires no moving parts, can be compressed to reasonably small sizes and achieves acceptable resolutions for automotive applications.

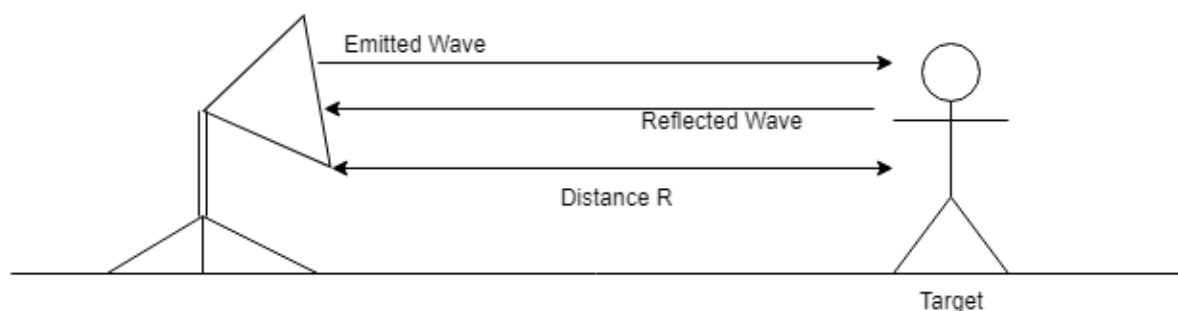


Figure 1 Simple example of either radar, sonar or LiDAR most basic application.

In the case of radar, the simplest method for detecting objects consists in the device emitting a signal through its transmitter, switching its antenna to a receiver using a duplexer and then capture the reflected waves from the objects within range of detection.

This principle varies in complexity as different types of devices are analysed with the key differences being the wave transmitted or the form of transmission. Said differences can be grouped into mainly two types: pulsed radars and continuous wave (**CW**) radars.

2.1.1. TYPES OF RADAR

The more basic version of the radar is the pulsed radar. These emit high frequency pulses which travel at the speed of light, c , and resort to the elapsed time, Δt , from the moment the signal is emitted and the instant its reflection is captured to obtain the distance to the target, R :

$$R = \frac{c\Delta t}{2} \quad (1)$$

Since the speed of light travelling through air is a known constant and the elapsed time, between the transmission and reception of the signal, can be computed by the device, the distance to the target can be easily obtained taking into consideration that the elapsed time refers to the waves travelling both ways, *i.e.* to the target and from the target, so the result shall be divided by 2. These types of radar allow the detection of targets and their distance, but do not allow for neither relative velocity acquiring nor knowledge of the direction the target is moving. These are important characteristics for an automotive application and put pulsed radar at a disadvantage for said applications [13].

A type of radar that covers more of the automotive industry needs than the pulsed radar is the continuous wave radars. In this sort of devices, the emitted wave is continuously transmitted at a known frequency, f_0 , which will then reflect in the targets and the returned wave is received with a different frequency, f . This variation in frequency is known as the Doppler-Shift and is explained by the Doppler Effect: a stationary object A detects waves with different frequencies depending on whether they originate from an object B moving towards the object A, away from object A or a stationary in relation to object A [14]. The Doppler effect shows the relationship between the observed frequency f , the velocity of the waves in the medium c , the velocity of the receiver in relation to the medium v_r , the velocity of the source in relation to the medium v_s and the emitted frequency f_0 as:

$$f = \left(\frac{c \pm v_r}{c \pm v_s} \right) f_0 \quad (2)$$

In the case of radars where the waves in the medium travel at the speed of light, one can assume that $c \ll v_r, v_s$, *i.e.* the speeds of the receiver and the source are significantly smaller than the speed of the wave, and the relationship can be simplified as:

$$f = \left(1 + \frac{\Delta v}{c}\right) f_0, \quad (3)$$

And the change in frequency is given by:

$$\Delta f = \frac{\Delta v}{c} f_0, \quad (4)$$

The different perception of the waves coming from an object depending on the direction it is moving (Figure 2) is important in automotive radars, allowing to detect whether another vehicle is moving towards the driver, for example [14].

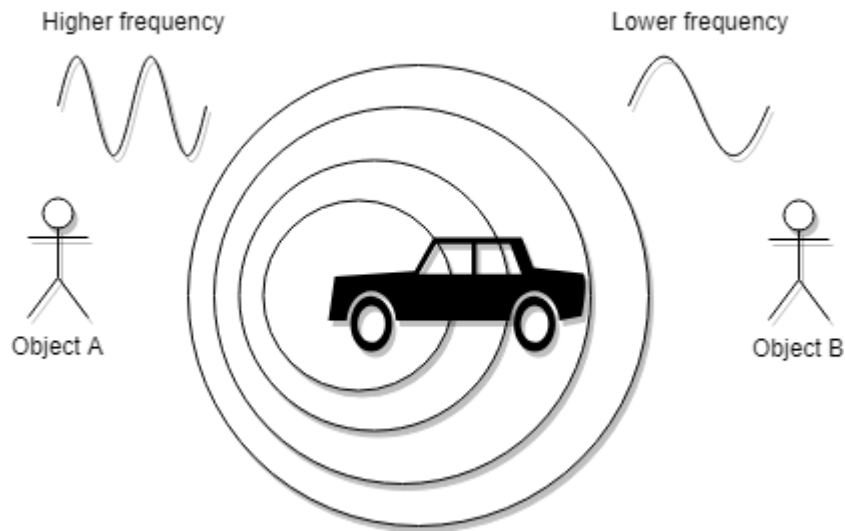


Figure 2 Doppler effect on waves generated by a moving object.

The relative velocity available through the application of the Doppler effect is the main characteristic of the non-modulated continuous wave radar, as it is solely capable of detecting the target relative velocity, Δv :

$$f = \left(1 + \frac{2\Delta v}{c}\right) f_0, \quad (5)$$

Despite the capacity to obtain a target relative velocity being an advantage in automotive radar, the CW radar cannot detect stationary objects as these do not generate a frequency shift. This inability renders this type of radars as useless in the automotive industry.

In order to overcome the issue of not detecting a stationary object, a new type of radar might be the solution: the frequency modulated continuous wave, FMCW, radar [15]. By modulating its emitted frequency, the device can obtain a time shift, Δt , between the transmission and the reception of the signal from the frequency shift, Δf . In such manner,

the FMCW radar combines the best of both worlds and answers most needs of the automotive industry for radars.

The FMCW radar consists in a continuous transmission, such as the simple continuous radar, yet, in order to define a time reference, modulates its frequency, which increases or decreases over a period. This frequency sweep allows the device to compare the received wave to the wave transmitted and thus obtain the elapsed flight time from the correlation between the perceived frequency shift and the time shift of the waves [16] (Figure 3).

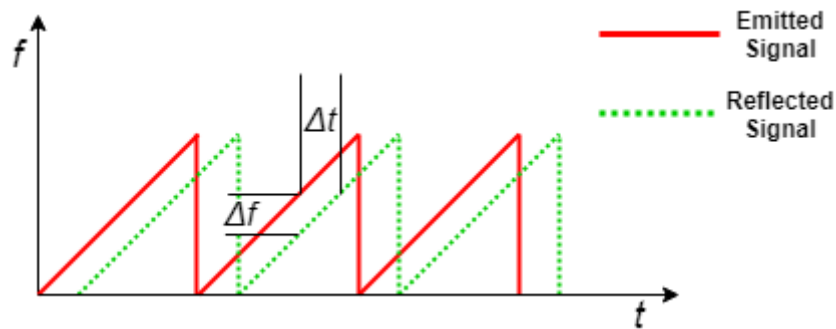


Figure 3 Frequency and time shift between the wave transmitted and received.

Assuming the radar is outputting a signal which the frequency, f_{out} , can be defined as:

$$f_{out}(t) = f_0 + k * t, 0 \leq t \leq T, \quad (6)$$

Where f_0 is the starting frequency, T is the time it takes for the frequency to complete a sweep and k , as the rate at which the frequency changes:

$$k = \frac{\Delta f_{sweep}}{T}, \quad (7)$$

As seen in the most basic applications of the radar concept, the elapsed time of flight, Δt , is given by:

$$\Delta t = 2 \frac{R}{c}, \quad (8)$$

With R being the distance between the radar and the target and c the speed of light in the medium. The frequency perceived by the radar in relation to the original signal can then be calculated as:

$$f_{in} = f_0 + k * (t - \Delta t), \Delta t \leq t \leq T + \Delta t, \quad (9)$$

The difference in frequency, Δf , between the transmitted wave, f_{out} , and the received wave, f_{in} , is then obtained as:

$$\Delta f = k * (-\Delta t) , \quad (10)$$

It is now possible to obtain a relation to the targets distance, assuming the absolute value of the time shift and, as such, omitting the minus sign:

$$\Delta f = k * 2 \frac{R}{c} , \quad (11)$$

Rearranging the equation to make d the subject:

$$R = \frac{\Delta f \cdot c}{2k} . \quad (12)$$

It is now proven that the FMCW radar can obtain the distance to a target without disregarding the advantages of applying the Doppler effect [4]. Aggregating both features paves the way for the implementation of this types of radar in the automotive industry.

The focus is now understanding what the limitations of these radars are and how to diminish them, especially in terms of resolution. Recalling equation 11 and decomposing k :

$$\Delta f = \frac{\Delta f_{sweep}}{T} * 2 \frac{R}{c} , \quad (13)$$

Now, taking into consideration that Δf_{sweep} corresponds to the frequency bandwidth B , and that for any rising time T , the minimum frequency shift will correspond to $1/T$, then:

$$\frac{1}{T} = \frac{B}{T} * 2 \frac{R}{c} , \quad (14)$$

In this situation, the distance R will also represent the minimum variation in distance ΔR detectable. As such, rearranging the equation gives:

$$\Delta R = \frac{c}{2B} . \quad (15)$$

Given that the speed of light c is a constant, the only limitation for the minimum resolution for detectable objects is the frequency bandwidth of the modulation [16]. One can conclude that increasing the sweep bandwidth improves the minimum resolution, while changing the base frequency of transmission has no impact at all.

2.1.2. RADAR CROSS SECTION

Despite the differing characteristics of various types of radars which make them suitable for different applications, some factors regarding a radar effectiveness are external to the radar sensor itself. One of the most predominant ones is the radar cross section (**RCS**) of an object [3]. In colloquial terms, the RCS is equivalent to the reflectiveness of an object, or how detectable said object is by radar and is expressed in squared meters (m^2). The determined value of reflectiveness may be compared to that of a perfect conducting sphere of cross sectional area of the same value. This parameter is influenced by a variety of factors, such as:

- The size of the object;
- The material of which the object is made;
- The shape of the object.

Typically, as an object size increases, so does the power of its reflections, resulting in a higher RCS. As such, assuming the remaining factors are the same, a larger object will be more easily detectable by a radar sensor than a smaller one.

Besides the target's size influence in the radar performance, objects of similar size may result in significant different reflections. A reason for this phenomenon is the object's material of construction. Different materials account for different reflectiveness, *e.g.* a metallic object is capable of much stronger reflections than the same object made of wood. The application of highly radar absorbent materials and highly reflective ones may be seen in aeronautics, while stealth based aircrafts will typically be seen covered in radar absorbent paint coats, whereas commercial airplanes will usually be composed of bare metal.

Some other applications exist may benefit from the implementation of absorbing material. In those cases, in order to minimize the reflectiveness of the object, the shape is also taken into consideration. As the radar waves hit the target, its shape will determine in which direction the waves will be reflected. This effect may result in most of the reflections returning to the source, or emitting radar, or in the same reflections following the opposite direction. Once again, the implementation of this characteristic may be observed in

aeronautics, *e.g.* a commercial airplane will typically have rounded surfaces in an attempt to maximize the amount of reflections which will return to the source, while a stealth based aircraft will tend to have more linear surfaces in order to achieve the opposite effect (Figure 4) [17].



Figure 4 A stealth aircraft (left) [18] and commercial airplanes (right) [19].

It is also typical to see the consideration of all these factors in the development of radar-absorbent materials (**RAM**), materials with an extremely low RCS. A highly valuable implementation of these materials in automotive radar testing is the absorbent foams used for covering shielded anechoic chambers. These tend to be shaped as square pyramids made of foam and with a high concentration of conductive carbon black particles. The pyramid shape pointed at the radar sensor reduces the number of waves which are reflected directly back to the source, scattering the radar waves. The purpose of the conductive particles resides in the absorption of the waves emitted by the radar device. The base of pyramid consists of a higher concentration of conductive particles when compared to the top, guiding the electromagnetic waves to the base (Figure 5) [20]. Other implications may be considered regarding the overall size of the pyramids in order to achieve higher absorption of more specific radio frequencies when the application so requires. These materials are typically of great importance in electromagnetic compliance (**EMC**) tests [4].

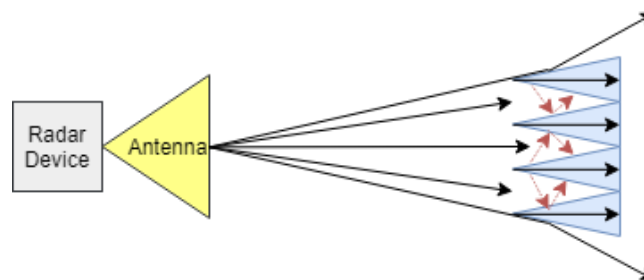


Figure 5 Pyramid foam absorbers reducing the number of reflected waves.

When used on the public road, automotive radars will face scenarios with multiple objects of varying RCS'. Some objects, like trucks or buildings, will result in high RCS values, while people and animals will present lower ones. Since automotive radars are mainly implemented for safety reasons, it is of substantial importance that the sensor can detect even the objects of low RCS values. As such, during production, products must undergo tests of not only multiple distances, but also of multiple RCS objects.

2.2. INTERNATIONAL REGULATIONS AND EUROPEAN STANDARDS

Despite the redundancy of the fundamental frequency used, due to regulations, the automotive radar must oblige to certain ranges. The International Telecommunication Union (ITU) in Article 5 of the ITU Radio Regulations [21], in the 66-81 GHz allocation table, specifies the 76-81 GHz range for radiolocation, since both the 74-76 GHz and the 81-84 GHz ranges are reserved for mobile broadcasting and space applications. Besides defining a fixed range for radiolocation applications, the document also restricts the 77.5-78 GHz range to short-range radar for ground-based applications, including automotive radars.

Despite this assignment, it is typical to find devices operating at a 24 GHz fundamental frequency. The reason for this is that older automotive solutions which employed radar used this frequency, as it includes two bandwidths: the narrowband (NB) of 250 MHz and the ultrawide band (UWB) of 5 GHz. The NB, as seen before, represents a much worse resolution, which for automotive applications could only be used for blind-spot detection, for instance. The UWB would be used in situations where much higher resolutions were necessary. Both these bandwidths were unlicensed and as such free to use, especially the NB band, an industrial, scientific and medical (ISM) [22] band, until the Auction 102 conducted by the Federal Communications Commission (FCC) [23]. In this event, the FCC auctioned part of the 5 GHz band (24.25-24.45 GHz and 24.75-25.25 GHz) to multiple bidders, licensing small parts of the band to different entities. In result of this auction, and due to the fact the solely the NB would not be enough for all type of applications, the automotive radar was forced to migrate to the 76-81 GHz range, which should be the standard range used in future applications.

Within this range, the European Telecommunications Standards Institute (ETSI) defines two bandwidths to be used and regulated: the 76-77 GHz band and the 77-81 GHz band. This results in two effective bandwidths, one of 1 GHz and one of 4 GHz. As exposed by equation 15, the bandwidth is the sole responsible for the minimum range resolution, and as such the minimum range resolutions for the given bandwidths may be obtained (Table 1).

Table 1 Minimum range resolution for different bandwidths.

Bandwidth (GHz)	Minimum Range Resolution (cm)
1	14,9896
4	3,7474
5	2,9979

As expected, the 4 GHz bandwidth offers a superior resolution than the 1 GHz bandwidth.

Despite the better performance of the 4 GHz bandwidth version of the radar, both may be used in conjunction in a vehicle, as multiple devices are expected to be implemented into cars for various applications and, ultimately, in autonomous driving (Figure 6) [24].

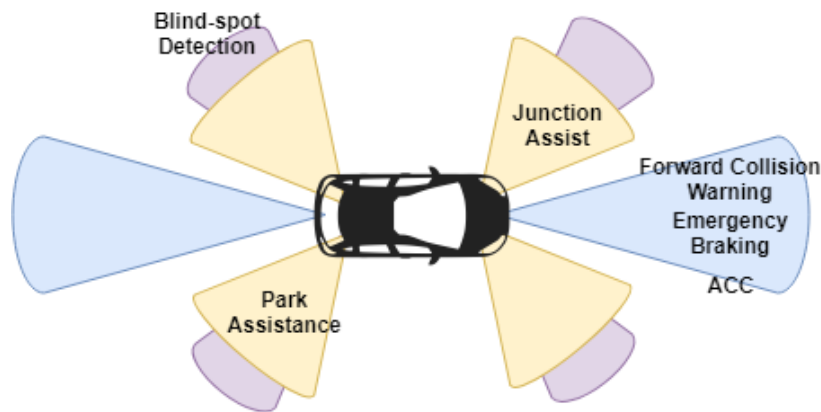


Figure 6 Possible applications for multiple radars in a single vehicle.

Since both bandwidths are viable for implementation, it is required to define standards and test conditions for both as, despite very similar, they do have different characteristics. For this reason, ETSI specifies multiple European standards.

2.2.1. EN 301 091

The EN 301 091 is an ETSI standard which covers transport and traffic telematics (TTT) and radar equipment operating in the 76 GHz to 77 GHz range [25]. The document is divided in two parts where the first one specifies the technical characteristics and methods of measurements for radar equipment operating in the 76 GHz to 77 GHz range for ground-based vehicle applications. The focus of the document is the signal power by the transmitter, the working frequency and the radiated power by the receiver. In terms of specific applications analysis, *e.g.* performance expected, range or relative speed, all specifications and requirements are to be declared by the manufacturer. The second part of the document covers the requirements for fixed infrastructure TTT applications and is, therefore, less relevant for automotive radar applications.

2.2.2. EN 302 264

The EN 302 264 is another ETSI standard for radar equipment, but in this case operating in the 77-81 GHz band and road transport and traffic telematics (RTTT), a possible application of automotive radars. This standard is also divided in two parts. The first one covers the essentials related to the tester for the devices, including critical information related to the limits of the tests and the tester assembly [26]. Some of the key notes in the document refer to the shielded anechoic chamber in which the test should be carried out and the pyramid absorbers that should be applied to the walls of said chamber. The second part of the document exposes the test suites and requirements and mainly recalls the first part for actual limits and methods to comply with article 3.2 of the R&TTE Directive [27].

2.2.3. EN 303 396

The EN 303 396 is, once again, an ETSI standard devoted to measurement techniques for automotive and surveillance radar equipment and short-range devices and, as such, includes valuable information for automotive radar testers [28]. The document refers the environment in which the tests should be carried out, as well as some of the characteristics of the device that should be tested and how they should be tested. Not all these characteristics must be necessarily tested in the same station but should be throughout the entire production of the device.

2.2.4. EN 301 489

The EN 301 489 is another ETSI standard for ElectroMagnetic Compatibility (EMC) for radio equipment and services. The document covers a vast range of equipment and applications, including, in part 51, automotive radar devices [29]. More specifically, said part refers to the specific conditions for automotive, ground based vehicles and surveillance radar devices using 24,05 GHz to 24,25 GHz, 24,05 GHz to 24,5 GHz, 76 GHz to 77 GHz and 77 GHz to 81 GHz. The standard aims to harmonise the different EMC requirements that result in compliance with the article 3.1b of Directive 2014/53/EU, a directive on the harmonisation of the laws of the European Union Member States in relation to the making of radio equipment [30]. The document covers multiple arrangements for tests related to automotive radars and mainly redirects the reader to the specific section in part 1 which details said test.

For an automotive radar tester to be capable of covering both radar equipment of 1 GHz bandwidth (76-77 GHz) and the 4 GHz bandwidth version (77-81 GHz), at least all the four of the European Standards presented must be taken into consideration.

Despite the well-documented test requirements, preparing a tester for covering all of them is not an easy task. Most tests require a great deal of complexity, *e.g.* in computing capacity for target simulation or in the development of an anechoic chamber which meets the criteria. Since high complexity usually comes hand in hand with high costs, most testers inserted into lines of mass production focus on testing the overall performance of the unit according to the manufacturer criteria. These methods of testing do not guarantee compliance with the standards that regulate radio equipment. In order to achieve compliance, the manufacturer might require a more complex test facility, usually done in laboratory environment, where the device is tested in earlier phases of development. The manufacturer should only allow the device to reach the mass production phase once it is assured that it meets the requirements established by the regulating institutions.

Various reasons exist that prevent the use of the same tester for both a development and a production environment. For example, the development type of testers might require space allocations impracticable for production lines, while also being of higher costs excluding the possibility of adding multiple testers to increase the capacity of a line. The

lower costs required, and the limited dimensions allowed for production line insertion push testers to mere functional testing that aim to assure that the product does not reach the market in faulty conditions.

3. TESTER CONCEPTUALIZATION

In order to conceptualize a machine attractive to manufacturers looking for testers for their radar units being produced, a list of guidelines must be defined. Such list must consider the relevant international standards and the specific characteristics of either a) a laboratory environment for development or b) a production line environment for mass production (Table 2). As such, some critical points might be defined early on:

- The product must be tested inside a shielded anechoic chamber;
- The tester must be able to generate known targets for the radar to detect in order to assess performance;
- The distance between the radar’s antenna and the antenna generating targets must be enough to assure realistic working conditions for the radar;
- The tester must be able to power the unit under test (UUT) and communicate with it (in the automotive industry, CAN is a typical communication protocol [31]).

These are some of the features the tester must assure despite whichever environment it is inserted into. In case the tester must be designed for a specific environment some other aspects must be considered:

Table 2 Difference in requirements for test environments.

Laboratory	Production Line
Capable of generating variable targets to detect;	Tester dimensions are of major importance and may be a limitation;
Capable of moving either antenna in relation to the other;	Cycle time for a complete test must be as low as possible;
Cycle time and dimensions are less relevant.	Tester may generate fixed targets.

Some of these features, despite almost obligatory in one of the environments and not required on the other, would be interesting to be added on both cases, such as the ability to generate multiple variable targets, and moving either of the antennas throughout the

test, simulating a more realistic environment. Besides that, keeping the tester as small as possible without compromising performance or life expectancy of the equipment would also be an advantage. In addition to the mentioned features, some others would increase the value of either testers, despite not required:

- Ability to test both bandwidths common in present and future automotive radar applications (1 GHz and 4 GHz);
- Highest degree of automation possible in the system;
- Possibility to change the housing of the UUT in order to accommodate a vast variety of products in the same machine;
- Capacity to change the default air gap between the tester's antenna and the UUT's antenna;
- Ability to generate realistic road scenarios in real-time for the radar to analyse.

A combination of the aforementioned features should originate in a robust tester capable of testing multiple products under controlled conditions. It is then important to analyse the compromises required to conceptualize said tester.

3.1. ANECHOIC CHAMBER

The most critical component of the tester, despite whatever goal it has, is without a doubt the shielded anechoic chamber. The chamber aims to diminish the impact of both the reflections inside the test environment and the interferences from radio waves outside the tester. Only in such a controlled environment can the tester assure that the objects detected by the radar correspond to the reality and its measurements are obtained in consistent conditions, independently of the product or the time of testing.

The EN 302 264 gives an example of a possible anechoic chamber for radar testing. In the proposed case, a 10 m long, 5 m broad and 5 m high chamber is used, coated with radio frequency (RF) absorbing material 1 m thick (Figure 7). As already mentioned, dimensions are one of the biggest limitations for production line machines and this type of anechoic chamber would require tester dimensions impracticable in said environment.

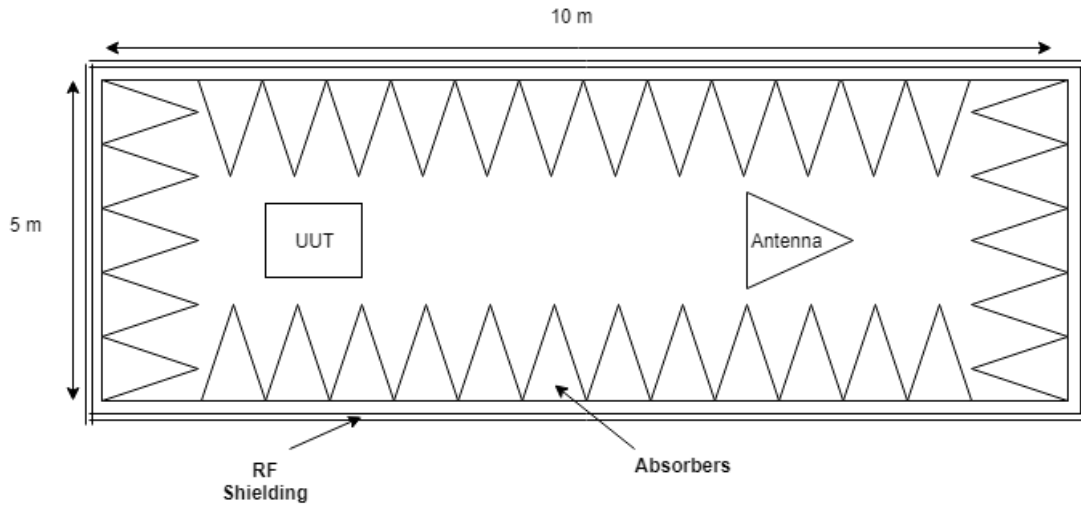


Figure 7 Anechoic chamber proposed by the EN 302 264 example.

Even in laboratory conditions, where dimensions might not be such a limitation, a tester of this size would be extremely difficult to accommodate.

As the solution proposed by the standard is not a viable one for the case study, the individual requirements exposed by the standard must be analysed and a more suitable anechoic chamber must be designed.

As the EN 302 264 document refers, the main reason for a lengthening of the anechoic has to do with the minimum distance between the transmitting and receiving antenna that shall guarantee mutual far-field conditions, also known as the Fraunhofer distance. At far-field conditions the transmitted electromagnetic waves become more consistent and predictable, making the tests carried out at this point more reliable, opposed to the Fresnel distance, or radiating near-field, where more scattering of the radio waves is present [32].

The Fraunhofer distance, d_F , can be obtained from the emitted wavelength, λ , and the largest dimension of the antenna aperture of UUT, d :

$$d_F = 2 \frac{d^2}{\lambda}. \quad (16)$$

The following Table 3 considers multiple values for the largest dimension of the antenna aperture, d , and transmitter wavelength, λ , and the resulting Fraunhofer distance.

Table 3 Fraunhofer Distances for multiple apertures and wavelengths.

Antenna Aperture, d (m)	Emitted Frequency (GHz)	Emitted wavelength, λ (m)	Fraunhofer distance, d_F (m)
0,04	76	0,00394	0,811
0,04	77	0,00389	0,822
0,04	78	0,00384	0,833
0,04	79	0,00379	0,843
0,04	80	0,00375	0,854
0,04	81	0,00370	0,865
0,03	76	0,00394	0,456
0,03	77	0,00389	0,462
0,03	78	0,00384	0,468
0,03	79	0,00379	0,474
0,03	80	0,00375	0,480
0,03	81	0,00370	0,486
0,02	76	0,00394	0,203
0,02	77	0,00389	0,205
0,02	78	0,00384	0,208
0,02	79	0,00379	0,211
0,02	80	0,00375	0,213
0,02	81	0,00370	0,216

The antenna apertures used are based of the Texas Instruments AWR1642EVM [33], a radar evaluation board in which the largest dimension of the antenna aperture is of 0,03 m.

As observed, for the relevant frequencies used in automotive radar, the Fraunhofer reaches its maximum value at 81 GHz. For the considered device, with 0,03 m antenna aperture, the Fraunhofer distance is of 0,486 m. If the antenna largest aperture dimension decreases by a centimetre to 0,02 m, the Fraunhofer distance decreases to 0,216 m. So, if the tester

is prepared for an antenna aperture of 0,03 m, this antenna aperture will also be accommodated. In case the antenna aperture increases 1 cm to 0,04 m, then the Fraunhofer distance increases to 0,865 m. As such, the tester should be prepared to test radar devices with such an antenna aperture.

The anechoic chamber can now be reduced in function of the required minimum distance to comply with the Fraunhofer distance for an 81 GHz wave transmitted by an antenna which its largest dimension of aperture is 0,04 m of 0,865 m. A variable air gap of 0,8 to 1,2 m between the product's antenna and the target generator's antenna should be enough.

With the reduced size of the anechoic chamber, the size of the pyramidal absorbers must be changed, since the 1 m high version proposed by the EN 302 264 is not a viable option. The guideline for the absorber performance in the standard is that the absorber must assure at least a 30 dB return loss. Analysing some of the options in the market, the 3640-50 – PU foam based pyramid absorbers from Holland Shielding [34], at a height of 50 mm, offers a 50 dB return loss for waves travelling at 40 GHz and 45 dB return loss for waves travelling at 100 GHz. Since the relevant frequencies for the automotive radar tester fall within this range, the minimum return loss required by the standard can be assured by some of the options in the market with smaller dimensions than the ones proposed in EN 302 264.

Considering the minimum air gap between the product's antenna and the target generator's antenna and the size of pyramid absorbers, a conservative height for the anechoic chamber could be 1,5 m with its width and length being less restrictive and vulnerable to change depending on the final solution for product placement.

3.2. TARGET GENERATOR

Having confirmed the viability of having a smaller anechoic chamber, another key feature to verify is the target generator. Since the ultimate goal of the tester is to assure the correct performance of radar devices, it is absolutely necessary for the tester to emulate objects for the unit to detect. This purpose can be achieved through the implementation of target

generators, also known as echo generators. These types of equipment usually consist of an antenna which receive the waves transmitted from the UUT and, either through passive echo reflectors like Luneburg lens' or active or semi-active echo generators who rely on FPGA's or electronic devices, respectively, to alter the signal in order to emulate targets.

3.2.1. PASSIVE TARGET REFLECTOR

One of the simplest ways to generate objects that can be detected by the unit under test consists in the use of passive target reflector. These normally rely on simple metallic structures with varying shapes and sizes (Figure 8) but can also be achieve using Luneburg lenses. Although these are fairly inexpensive ways of achieving a simple target emulator with the possibility for a vast variety of radar cross-sections (RCS), it is not an easy task to incorporate such structure into an anechoic chamber, since they are of great dimensions and require at least half of the distance to emulate the air gap.



Figure 8 Example of a corner reflector [35].

Since the objects emulated by this kind of reflectors can only be obtained through physical structures in which the space required increases with the distance desired to emulate, these are not a viable option for the type of tester in study.

3.2.2. SEMI-ACTIVE TARGET REFLECTOR

In order to tackle the issue of size, some target reflectors, known as semi-active target reflectors, rely on electronic devices to add delays to round-trip of the emitted signal. These sort of reflectors, typically, capture the signal emitted by the product, convert the electromagnetic wave to a light-based signal through the use of electro-optic converters, direct the signal to multiple fiber optic delay paths, reconvert it to electromagnetic waves at the correct frequency and transmit it back to the unit under test [36]. The distance to the object obtained by the radar in test will then be the sum between the air gap between the radar and the target emulator, the distance of the fiber optic path and the first air gap again. In some cases, the reflector also includes radial velocity emulation originated by frequency shifts (Doppler Effect) achieved by implying attenuators and phase-shifters in the fiber optic paths of lower distance.

The main advantage of these target generators may be found in their compact size and the possibility to be manufactured with multiple targets designed specifically for the application in mind. As this may be an advantage for the production line type of tester, for the testers aimed at development it reduces the versatility of the reflector. In case the tester is designed with a specific product in mind, and, consequently, so is the target generator, the tester will offer excellent performance for said product's production. As time progresses and new products require testing, the tester will become less relevant as other targets might be required. This disadvantage may be diminished by including multiple emulated objects, amplifying the number of cases covered by the reflector.

As it stands, the semi-active target reflector offers more advantageous features, versatility and robustness to change than the passive target reflector for the case study.

3.2.3. ACTIVE TARGET REFLECTORS

As exposed earlier in this document, fixed distances might cover the needs of mass production testers but get short for the requirements in development environments. In these scenarios, the tester would, ideally, be capable of generate more realistic scenarios in real-time for the unit under test, *e.g.* emulate the application in a road with heavy traffic. The target reflectors that pursue this goal are known as active target reflectors. The main

component of these reflectors is a FPGA responsible for the highly demanding processing needs of the application. The signal captured is normally interpreted by the FPGA and a transformation is applied for the signal to be retransmitted in such way that the radar will detect a target of specific characteristics [37].

This functionality might allow engineers responsible for the development of the product to generate multiple different scenarios that permit them to analyse the radar in various circumstances and correct issues in early phases of the product life.

Considering this type of reflector is, usually, also of compact size, it takes the lead as the best option for an automotive radar tester.

3.2.4. OPTIONS AVAILABLE IN THE MARKET

As much as the theoretical advantages and disadvantages might lead the reader into believing the active target reflector is without a doubt the most versatile option for the tester, it might be interesting to analyse the current options in the market.

For the semi-active, or in some cases considered passive, generators two options might be considered: the Keysight's E8707A Radar Target Simulator [38] and the Rohde & Schwarz's AREG100A Automotive Radar Echo Generator [39]. Some of the key features to retain from these generators:

- Compatibility with 4 GHz bandwidth for the AREG100A;
- Compatibility with 1 GHz for the E8707A;
- Possibility for 4 simultaneous emulated targets;
- Minimum total emulated distance ranging from 3 to 4 m;
- Maximum total emulated distance ranging from 300 to 400 m;
- Support for 24 GHz and/or 76 GHz to 81 GHz.

For the active target reflectors, less options are available as these are of higher complexity. One of the solutions available is the National Instrument's Vehicle Radar Test System, or VRTS [40]. Based on a PXI system with an onboard FPGA the emulator offers:

- 76 GHz to 81 GHz support;

- Emulated targets ranging from 4 m to 300;
- Maximum 4 objects emulated at full range;
- Limited to 1 GHz bandwidth.

Considering the specific features of actual solutions available in the market, the decision between the type of generator to use might not be so simple as once thought.

Despite the higher versatility for emulated scenarios, the active generator is limited to 1 GHz bandwidth, becoming unreliable for products working in the 77 GHz to 81 GHz band. Besides this, higher complexity usually means high costs. Once again, compromise is required. Weighting the pros and cons of each solution, excluding possible exceptions, the expected would be to use a semi-active generator for mass production and an active generator for laboratory applications, complemented with a semi-active one for 4 GHz bandwidth products (at least while a 4 GHz solution is not available).

3.3. ERGONOMICS AND DESIGN

One of the biggest issues for workers in assembly lines is the musculoskeletal disorders (MSD) that may occur from excessive force, repeated manipulation of objects and the continuous standing/sitting in a fixed posture. The WHO warns to the negative impacts of these conditions in the wellbeing of the workers, prejudicing the worker's health and increasing the costs for the public health system and the manufacturer [41]. The impact of most of these problems may be diminished by correctly designing the workstation and following some guidelines that aim to protect the workers during their shifts.

Multiple aspects might require analysis for an ergonomic design of an assembly line workstation, such as range of vision, height of loading position, reach zone, lighting, load weight and many more. Usually, not all these aspects are relevant for a single workstation. In the design phase of the station the possible future issues need to be identified and their impact reduced by applying the known recommendations (Table 4).

Considering the tester in study will be applied to an assembly line and will require a worker to operate it, some of the ergonomic requirements to be considered may be identified:

Table 4 Identifiable possible ergonomic issues.

Operator Action	Possible Issues
Load/Unload the unit on to the tester	<ul style="list-style-type: none"> • Repeated manipulation of objects; • Weight of the products; • Motion required; • Continuous standing; • Height of working position; • Possible visual inspection.
Fixture changeover	<ul style="list-style-type: none"> • Weight of the fixture; • Height of working position; • Motion required.
Monitor visualization	<ul style="list-style-type: none"> • Neck placement.

After identifying the possible issues that may incur from various elements of the tester, the step would be to tackle said issues in order to diminish its negative effects and, as such, make the tester as ergonomic as possible.

Since the discussed tester is aimed for the automotive radar, it might be relevant to analyse what guidelines do manufacturers in the automotive industry recommend. For instance, Bosch provides an Ergonomic Guidebook which cover most of the key factors for an ergonomic workstation in its infrastructures.

3.3.1. LOAD/UNLOAD THE UNIT

Loading and unloading the unit is the most recurrent activity in the tester’s working process. It represents the start of the process as well as its end. In a situation where the tester is working as intended, the testing process will occur continuously and uninterruptedly. The worker will then load and unload the unit to test multiple times throughout the time of the shift. This type of activity falls within the description for a

repeated manipulation of objects and continuous standing on a fixed posture which may result in MSD disorders in the long term.

To reduce the physical stress generated by these processes, the work position should be well-thought-out. Bosch recommends that the height of the general population be considered and recommends the ideal working position of 1125mm to cover all applications and heights. In the automotive radar case, the most important requirement is elbowroom and there is no need for fine motor skills and very low need for visual inspection. As such, the recommended working heights for the population overall population are within the range of 900-1150mm [42]. Since the type of tester in hand doesn't allow for an adaptable working height, a fixed one within 1000mm might be the best option (Figure 9).

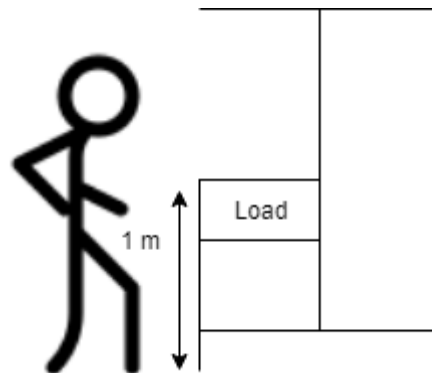


Figure 9 Possible ergonomic load position.

3.3.2. FIXTURE CHANGEOVER

One of CONTROLAR's focus when developing a tester is the design of fixture changeover capability. The fixture refers to the element that houses the product and it is designed specifically for each product. This means that if the manufacturer needs to test a new device in the same tester, the current fixture will be useless for the purpose and needs to be changed. When the production plan specifying which product to produce and in which amount changes weekly or even daily, being able to quickly and effortlessly switch the fixture in the tester is a considerable advantage. This ability reduces costs in both time and money to the manufacturer.

Despite the advantages it offers, the fixture changeover also represents another movement and load for the operator to do. Fortunately, the frequency of this amount is significantly lower than the load/unload unit action, resulting in less strict requirements for ergonomic considerations. The fixture is typically heavier than most handled objects (> 1kg) and, as such, these characteristics settle it as an Area C, according to the Bosch Ergonomic Guidebook [43]. In this case, the guidelines recommend that the action is performed the least amount of times possible and allow for shoulder and torso movement.

Although the restrictions are less strict for this sort of action, designing the solution in such a way that the load and the stress on the worker's body is reduced is a must. Some possible considerations might be the implementation of accessible handles, sliding guides, counterweights, and others (Figure 10).

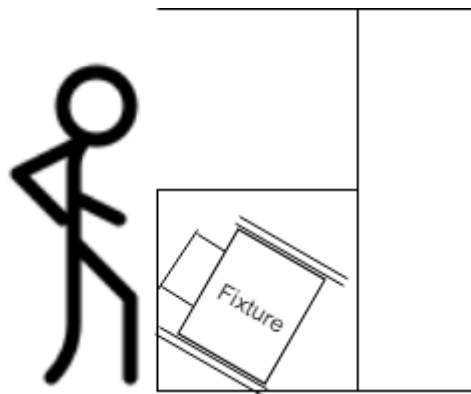


Figure 10 Fixture changeover aided by sliding guides.

3.3.3. MONITOR VISUALIZATION

As most assembly line machines are operated by workers that may not be specialized in the process of the machine or might frequently change between changes, it is important to guide the worker through the process. This is typically done with clear and step-by-step instructions that follow the process flow. The easiest and most intuitive way to achieve this is the implementation of indicative lights and/or a computer monitor. In the case of a monitor, since it holds such valuable information for the worker, they will spend an extensive amount of time looking at it for commands, hence it is important to place the monitor at a reasonable height. A correctly considered monitor will reduce unnecessary eyes and head movements, especially upwards, by the worker and reduce the stress

applied to its head and back. Once again, considering the height of the general population a conservative height would be within the 1650mm to 1750mm range (Figure 11).

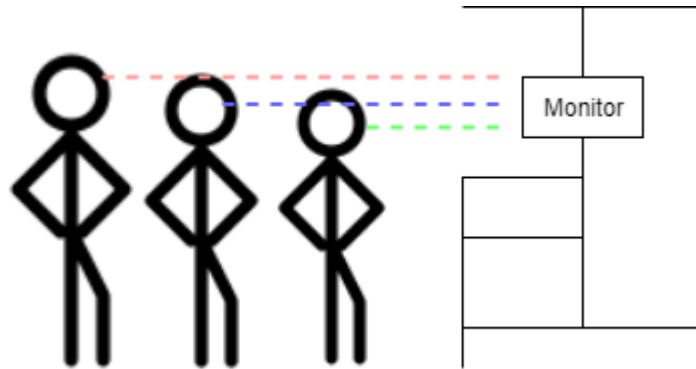


Figure 11 Monitor placement for multiple people heights.

After identifying the possible ergonomic issues of a system in the early phases of development these can be accounted for in the overall design.

Considering the requirements for the anechoic chamber, the largest main component of the tester, and the ergonomic features to consider, some implications may be deduced.

Since a conservative height for the anechoic chamber was identified in chapter 3.1 as 1,5 m, problems in the placement of the load/unload unit start to arise. In case a loading position at the top of the anechoic chamber is considered, it would require a height around 1500 mm (Figure 12) (considering a reserve of 20 cm for transportation wheels and leftover room in the bottom of the system, and an opening slightly lower than the maximum height of the anechoic chamber). In case the product is loaded at the bottom of the anechoic chamber, with the same assumptions, a height around 400 mm would be required (Figure 12). Neither of these options are within the 900 – 1150 mm deemed acceptable.

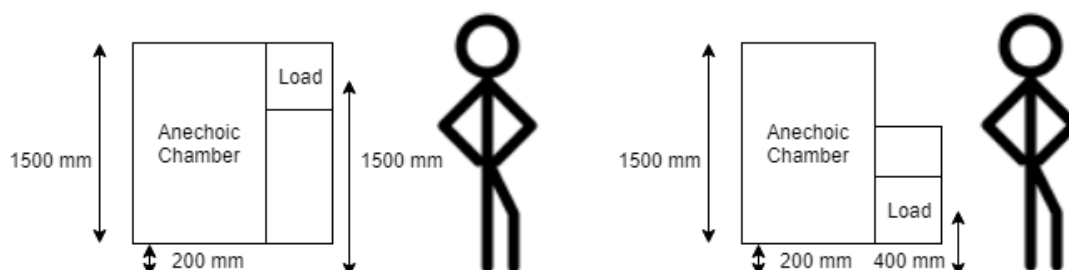


Figure 12 Load positions on top (left) and bottom (right) of the anechoic chamber.

The simplest way to comply with the requirements defined would be the placement of the loading position at 1000 mm while raising the anechoic chamber in such way that its bottom matches the loading position (Figure 13).

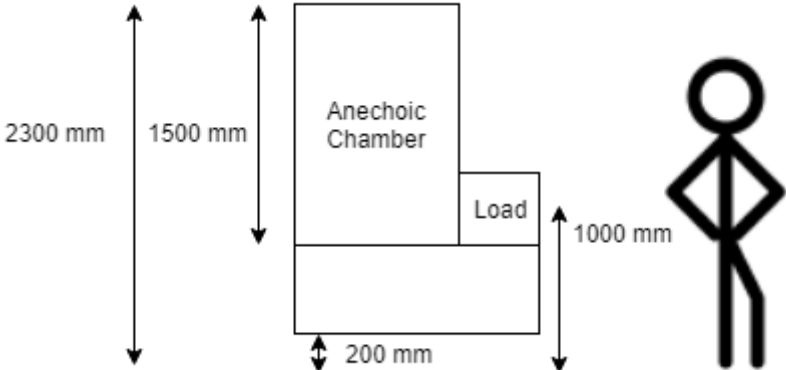


Figure 13 Anechoic chamber matching the load position at 1000 mm.

This approach would set the joint height of the wheels, base for the anechoic chamber and anechoic chamber at around 2300 mm. Considering more equipment needs to be implemented, *e.g.* industrial computer, target generator and power supply, as well as the exterior structure which covers the anechoic chamber, the overall height of the system would surpass the current height of 2300 mm, rendering the tester excessively tall for a production line. Incorporating both an anechoic chamber with standard compliance characteristics and ergonomic working positions is one of most challenging aspects of developing an automotive radar tester.

In order to complement both aspects, CONTROLAR proposes a solution with automated fixture movement (Figure 14). The main concept consists in keeping the loading position at the established ergonomic height and the anechoic chamber as low as possible and, once the product is placed, the system is responsible for lowering the fixture to the bottom of the anechoic chamber. As expected, this solution adds complexity to the overall tester.

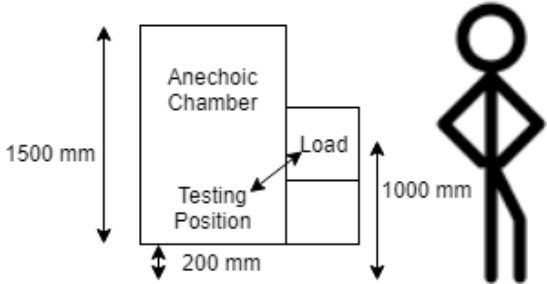


Figure 14 CONTROLAR’s automated product placement solution.

This solution substantially shortens the overall height required to accommodate a compliant anechoic chamber and an ergonomic load position. One of the arguments that may be made against the solution focus on the cycle time of the process. In a mass-production, time cycles must be kept as short as possible in order to maximize production. The addition of multiple automated movements tends to increase the cycle time when compared to a tester which only requires the operator to place the product in the testing position.

The second argument covers the cost of the solution. As expected, adding complexity and more equipment, like motors, axis and cylinders, also increases the overall cost of the tester. A higher price tag might make the tester less appealing to manufacturers looking for options in the market but in this case, it comes as a necessity to cover the issues already exposed.

As the development of the tester advances these issues must be considered and their impact diminished, especially in the case of the cycle time. Attending to covered problems and necessary solutions proposed, a first overall sketch of the tester design is presented (Figure 15 and Figure 16), credit to CONTROLAR's mechanical department:



Figure 15 Overall design of the tester.

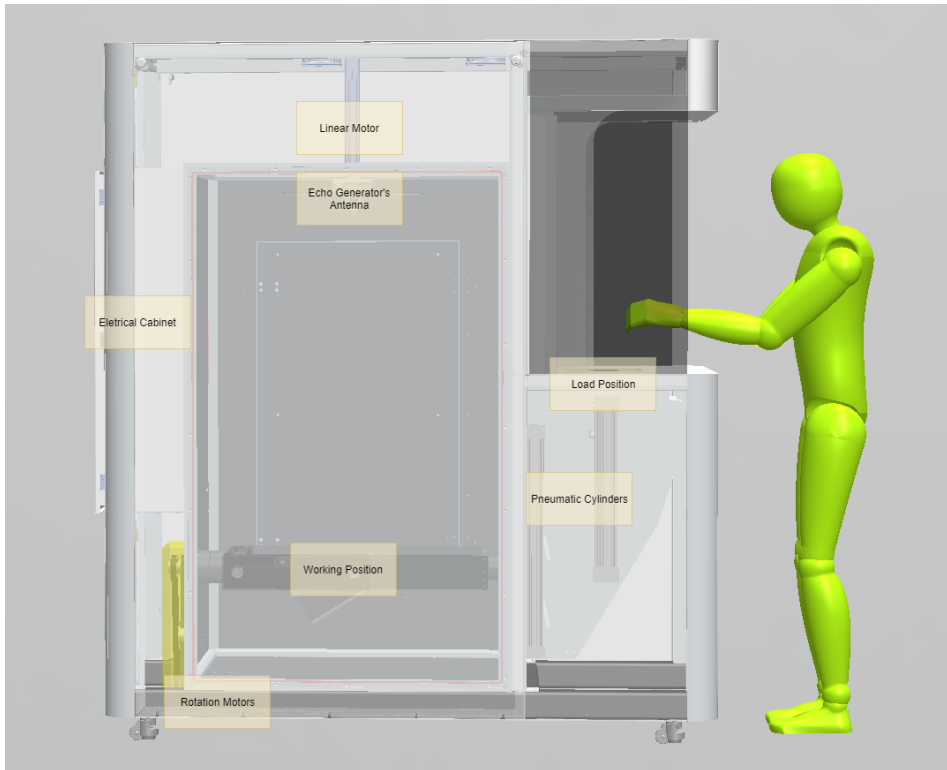


Figure 16 Transparent view to the inside of the tester.

The solution proposed consists of a tester with dimensions of 2030x1700x980 mm. These dimensions will, typically, not present any issues to the tester integration in a production line. The product placement is kept at an ergonomic height and after it is loaded will be lowered to the work position inside the anechoic chamber, aided by pneumatic cylinders. The anechoic chamber is home to the echo generator's antenna at the top capable of linear movement and a working position capable of rotation. The motors responsible for said movements are kept outside the anechoic chamber in order to reduce the electromagnetic interferences these could possibly generate. Behind the anechoic chamber can be found the electrical cabinet which will house most of the electrical connections of the system.

Reaching the later stages of the tester conceptualization, it is important to begin analysing the individual components that make up the system.

4. TESTER COMPONENTS

In this chapter, the most important individual hardware and software components are analysed more in-depth, including the target generator, PLC and motors, the product communication and the software which controls the machine.

4.1. R&S AREG100A

Considering the key features of a target generator for the automotive radar tester in development as exposed in chapter 3.2, and more specifically, the current market options analysed in chapter 3.2.4, the chosen target generator for the system is the Rohde & Schwarz's AREG100A (Figure 17). Despite being a semi-active target generator, not capable of generating real-time scenarios, it offers 4 GHz bandwidth compatibility, four simultaneous emulated targets and a short distance Doppler shifted target. This target generator is a well-rounded solution for mass production testers and allows measurements of the radar sensor effective isotropic radiated power (EIRP), regulated in the ETSI standards EN 301091-1 and EN 302264-1.

As specified by the manufacturer, the AREG100A receives the signal emitted by the radar under test, downconverts it to the intermediate frequency (IF) and applies the transformations required, such as a fixed time delay for range, Doppler shift for radial velocity and attenuation for radar cross section (RCS). The IF signal is then upconverted to the correct radio frequency and retransmitted to the unit under test. The new signal is captured by the radar device and analysed as an object with the characteristics corresponding to the transformations made.

The configuration of the equipment can be made manually or remotely, through either of the Ethernet interface (multiple communication protocols) or the IEEE 488 interface (GPIB).

For the application being studied, the remote control is the best option and the one to be implemented.

Other connections to consider are to the frontend module which houses the antenna. The connections on the frontend module are listed in Table 5:

Table 5 AREG100A Frontend connections.

Connection	Function	Correspondent in the base unit	Connector
RX IF Out	Receiver IF signal output to base unit	Frontend RX IF In	SMA Female
TX IF In	Transmitter IF signal input from base unit	Frontend TX IF Out	SMA Female
Control	Power and control connection	Frontend Control	26-pin ODU Mini-Snap series L
RX Power	Receiver IF signal output for power measurements	External Device (R&S NRP)	SMA Female

For the RX power measurement, the power meter R&S NRP must be applied, allowing for the EIRP measurement.



Figure 17 Rohde & Schwarz’s AREG100A and its frontend module [39].

In the tester being studied, the R&S’ AREG100A will be controlled remotely making use of the Ethernet port available in the back of the device. The echo generator can be controlled

through SCPI commands which may be sent to the device using any of the available protocols. In this specific case, the Virtual Instrument Software Architecture, or VISA, will be employed. VISA is a standard which encapsulates a multitude of protocols within a single API, allowing for more consistent software when communicating with instruments in the test and measurement industry [44]. VISA is readily open to use in NI LabVIEW, the programming language used in the tester [45].

From the entire SCPI commands list available in the instrument manual, only the basic units configuration, attenuation settings and air gap to the radar sensor setting are of interest for the tester in study (Table 6). These settings need to be set during the device's initialization device at the tester power up and during testing only the enable of the individual objects is required. When the tester moves the AREG100A's frontend module either closer or further away from the UUT, the over-the-air gap must be set accordingly.

Table 6 AREG100A used SCPI commands.

SCPI Command	Function
:SOUR:AREG:RAD:BASE:ATT	Set the AREG100A base attenuation (dB).
:SOUR:AREG:UNITS:RANG	Set the range units (m;cm;ft).
:SOUR:AREG:UNITS:SPE	Set the speed units (km/h;mph;mps).
:SOUR:AREG:UNIT:RCS	Set the RCS units (dBsm;sm).
:SOUR:AREG:OBJX:ATT	Set object X individual attenuation (dB).
:SOUR:AREG:OBJX:STAT	Activate or deactivate object X.
:SOUR:AREG:RAD:OTA:OFF	Set the air gap to the radar (m).

The combination of base attenuation and individual objects attenuation results in varying RCS values for each object. These values should be set regarding the client specifications for the performance tests of the radar sensor. Since the products used in this tester are merely demonstrative, the values will be defined through experimentation until a combination that springs in consistent results is achieved.

4.2. TEXAS INSTRUMENTS' AWR1642 EVM BOARD

Since the tester is being developed for demonstration purposes and not for a specific client's product, a radar device available in the market must be applied. Considering that demonstration is the sole purpose of the radar device, a very simple implementation of an automotive radar is the goal and, as such, the Texas Instrument's AWR1642 Evaluation Module (Figure 18) fits the criteria [33]. Some of the radar sensor module key features include:

- Onboard Antenna;
- Powered by a 5V power jack;
- Onboard CAN-FD transceiver;
- UART communication through USB port;
- JTAG emulation for flash programming;
- 60-pin HD connector for interfacing with other Texas Instruments' boards.

Texas Instruments offers software development kits (SDKs) for quick and easy implementation with the device. Some of these SDKs include demonstration examples which can display the sensors most basic features, like target detection. For the board in question, the software development kit used was the mmWave SDK version 2.1.0.4. Said SDK includes a firmware (`xwr16xx_radarss_rprc.bin`) for the board, as well as a demo file (`xwr16xx_mmw_demo.bin`) to flash onto the board, allowing for communication and basic operations from the board [46]. The evaluation module may be programmed with the various types of software with the help of the Texas Instrument's standalone application Uniflash [47].



Figure 18 Texas Instrument's AWR1642 Evaluation Module Board [33].

For validation of the correct functioning of the board, the mmWave Demo Visualizer application may be used (Figure 19) [48]. The Application allows for connection to the board and some basic configurations. The connection is done through two serial ports available in the same USB port, the XDS110 Class Application/User UART (115200 Baud Rate) and the XDS100 Class Auxiliary Data Port (921600 Baud Rate), for device configuration and data reception respectively. After the connection, the application can be configured in some respects, besides the device and SDK version to use, such as:

- Number of reception and transmission to use;
- Frame Rate (fps);
- Range Resolution (m);
- Maximum Unambiguous Range (m);
- Maximum Radial Velocity (m/s);
- Radial Velocity Resolution (m/s).

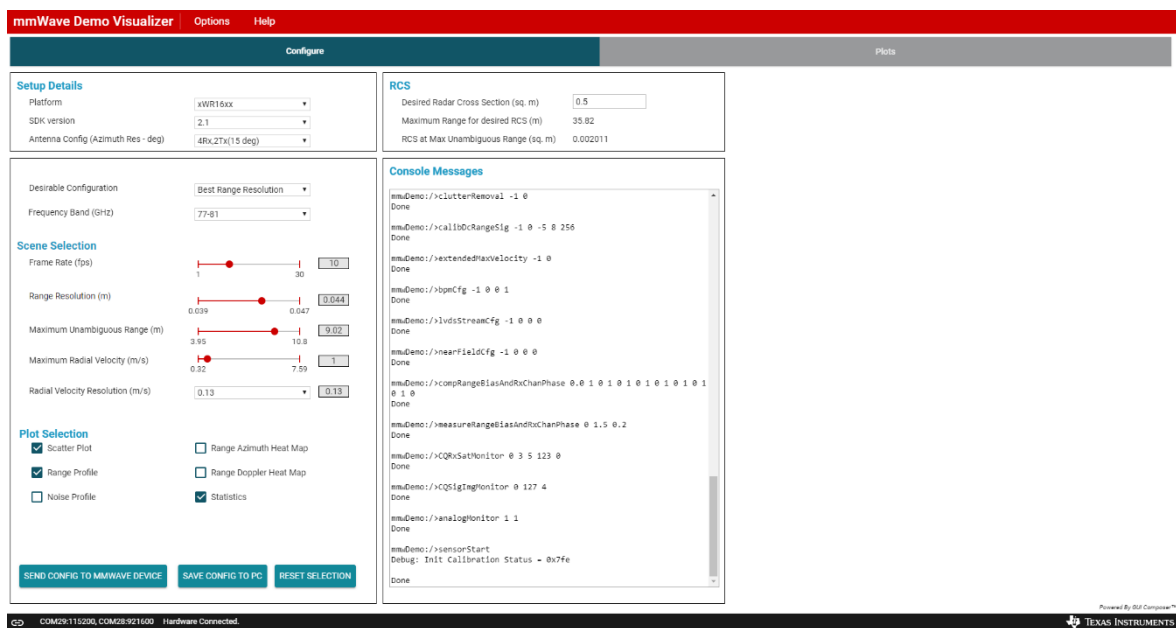


Figure 19 Configuration page on the mmWave Demo Visualizer [48].

After configured, the application treats the data frames returned from the sensor and displays the data in some user-friendly graphs. The graphs include plots for the detected objects in lateral and longitudinal axis, relative power along distance and the Doppler effect along distance (Figure 20). The mmWave Demo Visualizer version used was the 2.1, for compatibility with the SDK 2.1.0.4.

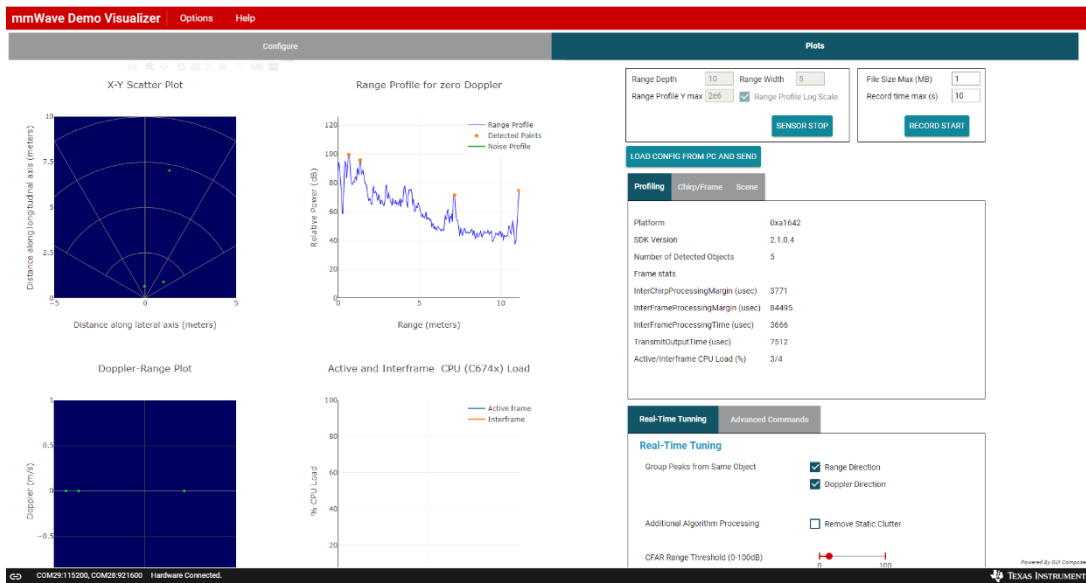


Figure 20 Plots page on the mmWave Demo Visualizer [48].

4.3. CONTINENTAL’S ARS408-21

The Texas Instrument’s AWR1642 EVM board is an adequate device to use as sample in the developing tester, allowing for analysis of its overall performance and behaviour. Despite this advantage, remains an evaluation board, developed and commercialized for testing of the AWR1642 radar sensor for possible companies which might use said sensor in a finished radar product of their own. As such, the board requires software and application development in order to mimic the performance of an automotive radar available in the market. Since for this tester the board was only employed with its demonstration software and most basic functionalities, a completer and more finished product would be an interesting addition to the set of tests and evaluations of the tester. A product that suits the described profile is the ARS408-21 manufactured by Continental (Figure 21) [49].



Figure 21 Continental’s ARS408-21 radar sensor [49].

The ARS408-21 is a long-range radar sensor included in a range of products designed for automotive radar applications by Continental. Some of its key features include:

- 76-77 GHz operating frequency band;
- 0.20 to 250 m far range;
- 1.79 m resolution for far range and 0.39 m for near range;
- CAN high-speed interface (500 kbit/s).

Continental recommends this radar sensor for a multitude of automotive applications such as:

- Distance Monitoring/Warning;
- Detection and tracking of people, vehicles, animals and equipment for collision avoidance in industrial, construction, agricultural and mining applications;
- Traffic monitoring for traffic management and safety applications;
- Monitoring and protection of vehicle and pedestrians on railway and passenger crossing.

According to the description, the ARS408-21 fits the needs for a product currently available in the market and ready for implementation in the developing tester.

4.3.1. RADAR PRINCIPLE

The radar device is based on a FMCW principle with a processing procedure which consists of sampling the individual chirps and processing them independently. Due to this approach, despite outputting a frequency modulated continuous wave, the sampling is done similarly to a pulse radar. For this reason, this radar sometimes referred to as pulse compression radar.³ Continental implements this solution in the basis that it allows for a higher amplitude RF energy output, resulting in a better signal-to-noise ratio. Another advantage, according to Continental, resides in the ability to more easily differentiate between range

³ Pulse compression is a waveshaping technique which does not have a direct impact in the radar's basis working principle.

and velocity data in the received signals as these are submitted to three consecutive Fast Fourier Transformations which will map the two data samples into a 2-dimensional frequency range. The modulation wave applied to the transmitting signal is a sawtooth wave (Figure 22).

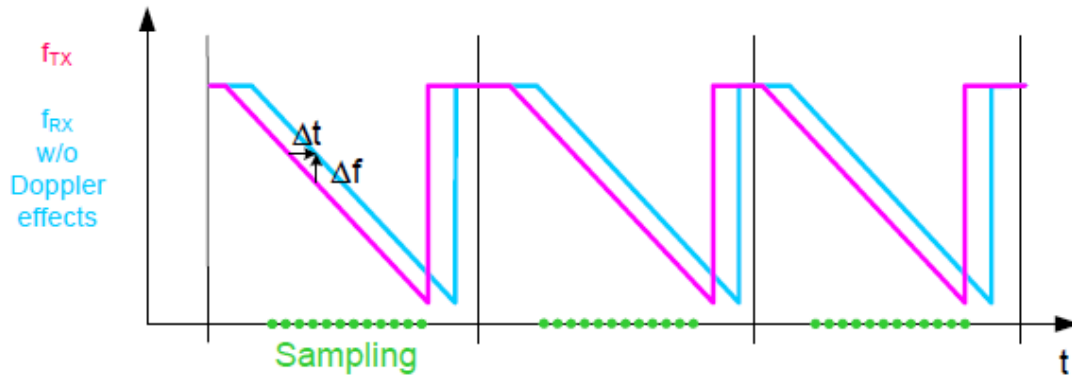


Figure 22 Representation of the transmitting signal of the ARS408-21 [50].

The radar sensor is also prepared for difference resolution configurations. The configurations may be applied through the CAN interface once for one single system cycle by altering the frequency sweep of the chirps. This feature allows the change the resolution of the sensor from its default values to a range of 1 m or above up to a resolution of 0.25 m.

4.3.2. ANTENNA PRINCIPLE

In the case of the ARS408-21, the antenna patch consists of two bundles of 2 TX and 6 RX antennas, one used for near range scanning and the other for far range. The incorporation of multiple receiving antennas allows for different phases being detected from signal reflected of the same target. As the amplitude variation should be neglectable, the phase variations may be used to obtain the azimuth angle in relation to the radar sensor (Figure 23). The sensor scans the near range and the far range sequentially by selecting different frequency chirps (Figure 24). Both data types are obtained in a single measurement cycle:

- one far range with a distance range of 0.25 m to 250 m and $\pm 9^\circ$ scan;
- one near range with a distance range of 0.25 m to 70 m and $\pm 60^\circ$ scan.

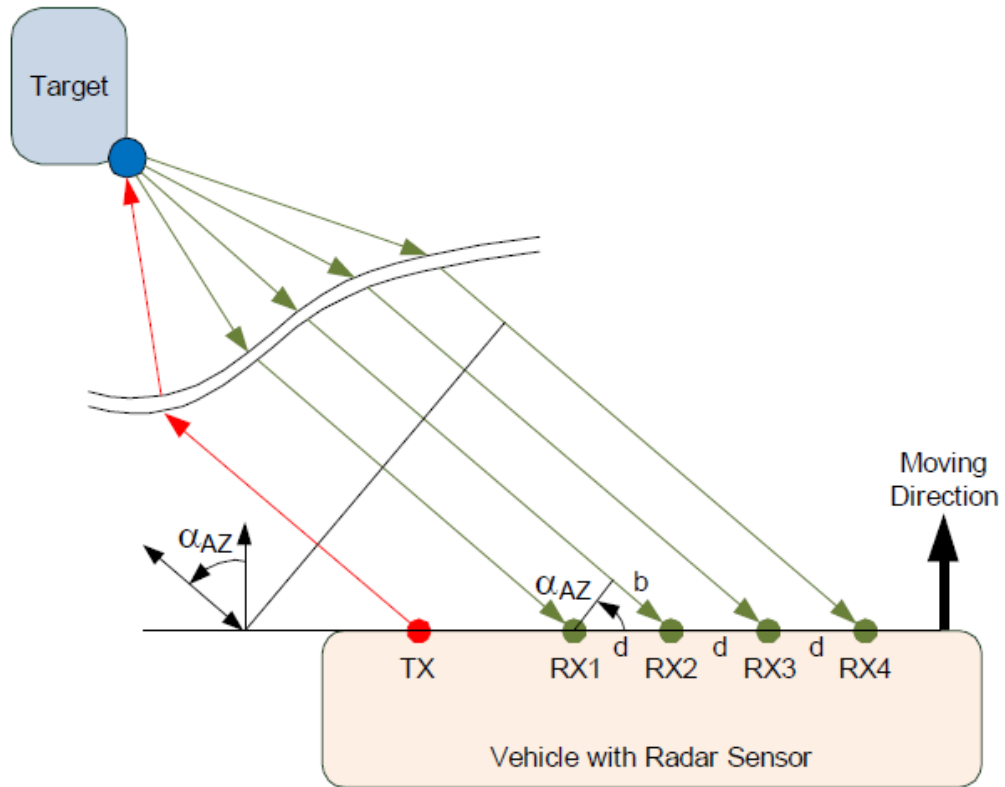


Figure 23 1TX/4RX antenna configuration for azimuth angle, α_{AZ} , calculation [50].

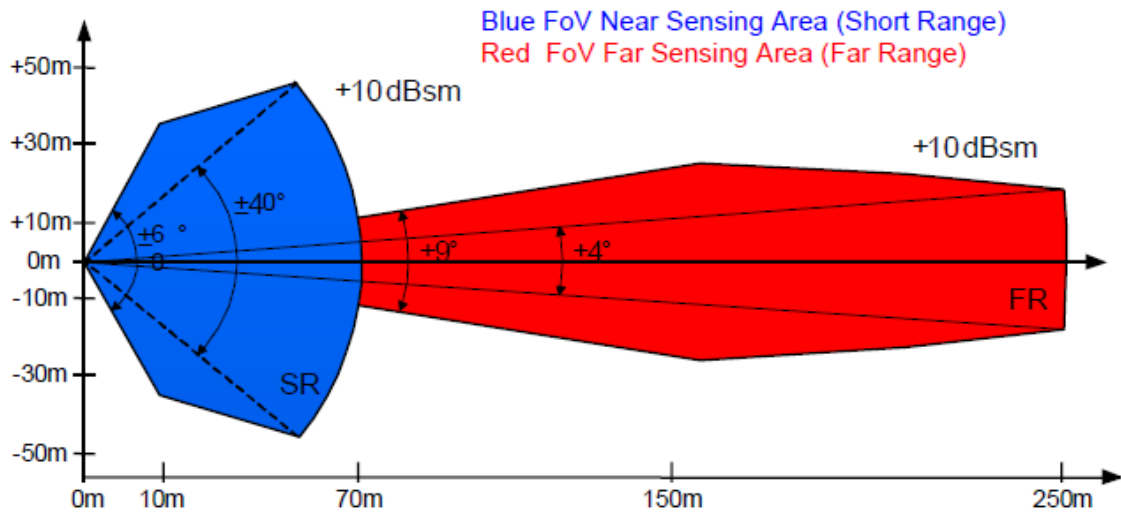


Figure 24 Continental's ARS408-21 field of view [50].

4.4. PNEUMATIC CYLINDERS AND ELECTRICAL MOTORS

As referred in 3.3 Ergonomics and Design, in order to comply with ergonomic requirements and typical tester dimensions, the system must move the unit from its load position to the test position. To achieve this a multitude of movements must be accomplished and automated.

4.4.1. PNEUMATIC CYLINDERS

The first step for transposing the unit to the inside of the anechoic chamber is to rotate the device nest, open the chamber's door and pushing the nest inside and then returning to the original position and closing the door (Figure 25 and Figure 26). These movements can be attained from the implementation of pneumatic cylinders (Table 7).

Table 7 Cylinder movements and references.

Movement	Cylinder Reference
Nest Rotation	SMC MY1B40TFG-200Z [51]
Door Movement	SMC MY1B32TFG-400Z [51]
Nest Overall Movement	UNIVER RT120-040-600L [52]
Nest Docking	SMC MY3A16-300 [53]

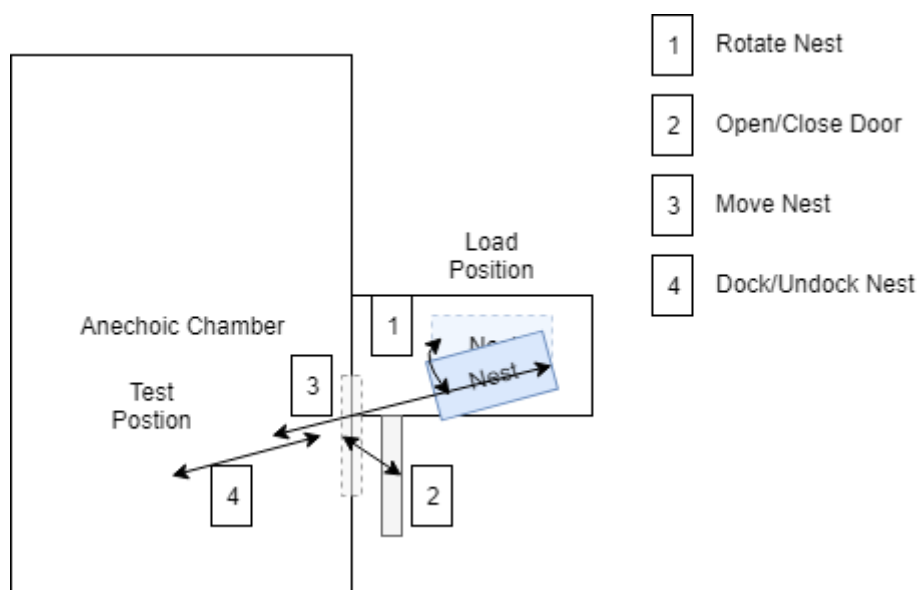


Figure 25 Pneumatic cylinder movements.

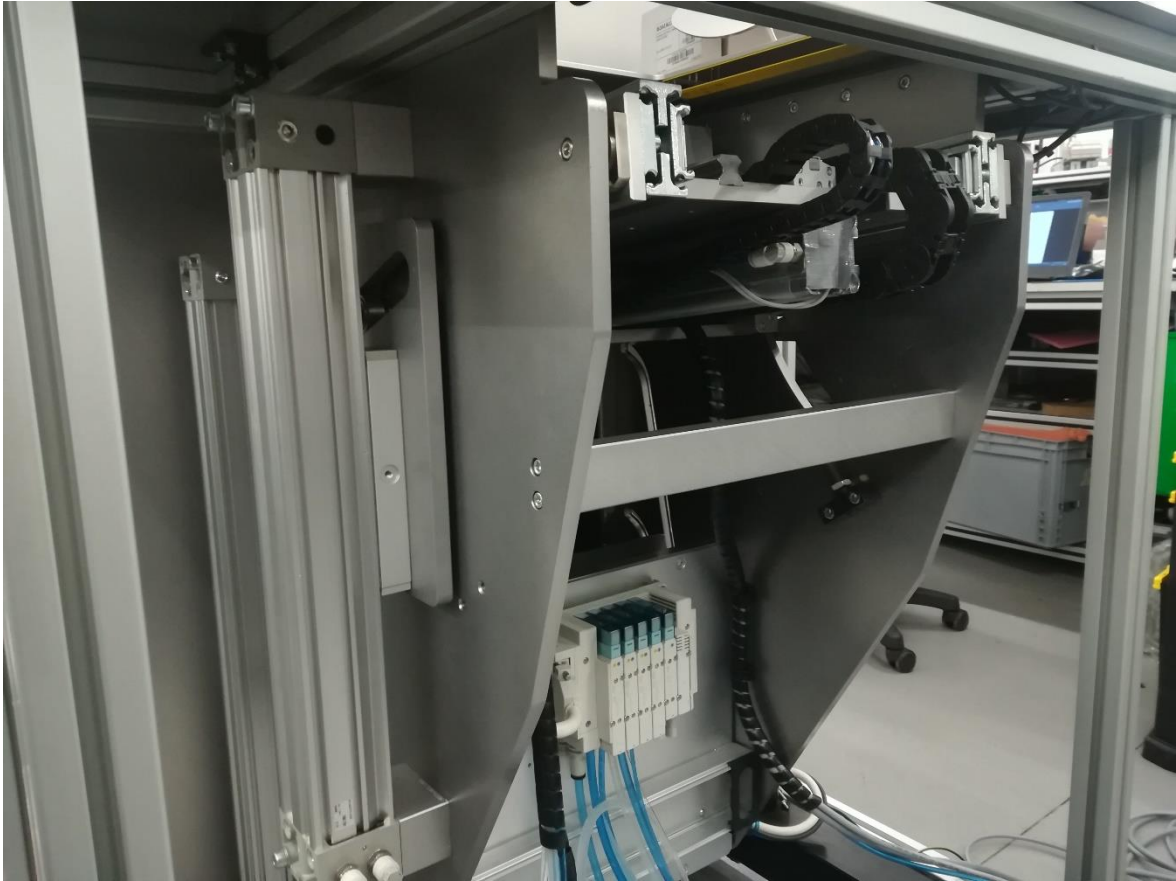


Figure 26 Pneumatic cylinders under the load position.

4.4.2. MOTORS AND MOTOR CONTROLLERS

The nest arrives at the docking position in an angle and, as such, the position must be able to rotate to accommodate the nest. This requirement is covered by an inner rotatory plate, which is also responsible for applying some rotation to radar sensor during testing to emulate various angles to the detected objects. This rotation is only available in one direction, with the other direction being achieved through an outer rotatory plate. Rotatory plates inside the anechoic chamber. (Figure 27 and Table 8).

Another motor may be found coupled to a linear axis at the top of the anechoic chamber (Figure 28). This motor is responsible for moving the AREG100A's frontend module, varying the air gap between the radar sensor and the antenna, accommodating for different manufacturer's requirements.



Figure 27 Rotatory plates inside the anechoic chamber.

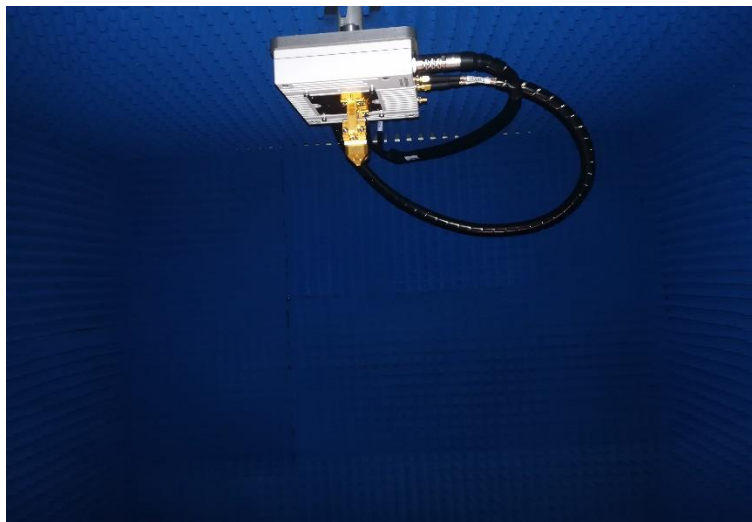


Figure 28 AREG100A's frontend module coupled to the linear axis.

Table 8 Motor movements and references.

Movement	Motor Reference	Axis Reference
Inner Rotation	Festo EMMS-ST-57-M-SEB-G2 [54]	-
Outer Rotation	Festo EMMS-ST-87-M-SEB-G2 [54]	-
Antenna Movement	Festo EMMS-ST-28-L-SEB [54]	Festo EPCC-BS-25-200-6P [55]

Each motor has its own motor controller, the CMMT-ST-C8-1C-EC-S0 [56], a servo drive responsible for supplying the load voltage to the motors and controlling its movements, handling the data returned by the motors' encoders and the configurations supplied by the end-user.

4.5. SOFTWARE ARCHITECTURE

As expected, the machine includes many different instruments and devices, such as power supply, PLC and others. All this equipment requires software to be controlled and to share data between each other. The correct sequence of steps to have all equipment functioning properly must be assured by the tester, which is also responsible to display information regarding its operations to the its operator. The information display is typically achieved through the inclusion of an operator graphical user interface in the monitor.

4.5.1. NI TESTSTAND

Besides the instrument control software and the user interface, the tester must also include a testing application, responsible for controlling the different steps to execute in order to correctly evaluate the UUT functionalities. These tests include, for example, the locking of the unit and its connection to the power supply and the communication device, *e.g.* a CAN controller, and the actual testing steps that compare the results returned by the unit to the limits specified by the manufacturer. This might be considered the central piece in the software architecture of the tester, as it is the responsible for concluding if the unit's performance is according to the requirements or not. In this tester the application which will handle these actions is National Instrument's TestStand [57].

TestStand is a step sequencer which includes multiple test sockets management, sequence modularity and ability for other software integration. These are the main reasons which make TestStand a valuable tool for test engineers, eliminating the need for developing a sequencer from scratch. The sequences may be created, executed and debugged using the Sequence Editor (Figure 29). In the Sequence Editor multiple sequences may be developed to run in conjunction or as a basis for other test software, *i.e.* a process model. TestStand allows the incorporation of different software languages through code modules. These modules are treated as single steps, despite the complexity that may be present inside them. Besides the incorporation of other software modules, the TestStand API may also be used in other programming languages to dynamically run test sequences, disregarding the use of the Sequence Editor interface.

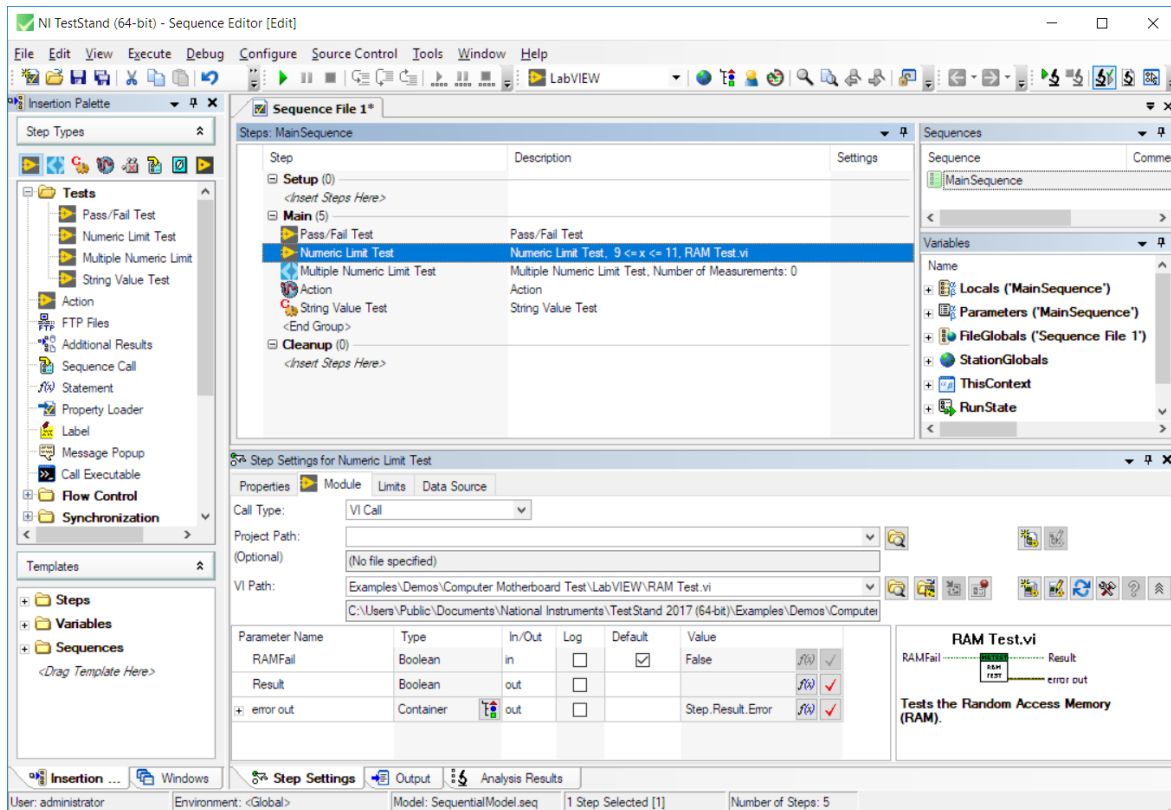


Figure 29 Example of NI TestStand’s Sequence Editor [58].

4.5.2. USER INTERFACE

Since the TestStand’s Sequence Editor Interface includes a vast array of functionalities and was designed with test sequences development in mind, it is not user-friendly for a tester operator. For that reason, it is usual to develop an operator interface in some other software which receives information regarding the test execution from TestStand and displays it in a way that is more easily read and understood. These types of implementation also allow for a more personalized interface, adjusted to display the more critical aspects for the correct operation of the system, while hiding/blocking sensitive data which, when altered, may damage the equipment or prevent its correct performance.

For this tester, the user interface was developed in NI LabVIEW [45], a graphical programming language which allows for a front panel to be developed along with the actual code. Being both National Instruments’ products, LabVIEW and TestStand are well-prepared to work in conjunction with one another. TestStand manages the required tests for validating the UUT and may use code modules developed in LabVIEW to communicate with instruments and compute steps which require more complex actions. The added

benefit in using both software together comes from the simple implementation of the TestStand API in LabVIEW code. The default installation of the LabVIEW development version includes a palette of functions (VIs) that directly access the TestStand or generate the needed references, *i.e.* the reference to TestStand's engine or the Application Manager. Implementing the test sequencer API in the user interface allows for the deployment of a single application which manages the synchronization between test steps and information displayed.

The communication between LabVIEW and TestStand may be achieved in multiple ways:

- LabVIEW's user interface works as a simple display of what is occurring in TestStand, receiving the data through message queues;
- LabVIEW receives data through message queues but also writes information in TestStand variables through its API. The write operations are very restricted due to the lack of synchronization between the applications in this method, allowing for race conditions;
- LabVIEW's user interface works as a simple display of what is occurring in TestStand, receiving the data through TestStand's user interface messages (UIMessages) [59];
- LabVIEW receives data through UIMessages but also writes information in TestStand variables through its API. UIMessages allow for synchronization between the two applications, avoiding race conditions and assuring the most recent information is displayed.

For this tester, the communication will be established according to the last method. This guarantees that the data will be exchanged with no risk of race conditions and will rely on a method (UIMessages) developed by National Instruments specifically for this situation.

The data displayed in the user interface will mainly consist in the following points:

- Table with the tests being executed;
- Overall statistics of the tester displaying number of units passed and failed;
- Overall input signals of the machine;
- Overall input signals of the current unit nest;
- Status of the TestStand application running in the background:

- Statistics page with more detailed statistics;
- Configurations page with some overall machine settings;
- Manual mode page for manual control over the PLC outputs;
- Alarms page describing any alarm or critical error that may occur during functioning.

The user interface shall work as the main application running in the tester, allowing for the entirety of the system’s functionality to be controlled through one single application (Figure 30).

Once the application is started, it programmatically launches the TestStand application and runs its main sequence and state machine, initializing all equipment and preparing the tester for the tests beginning.

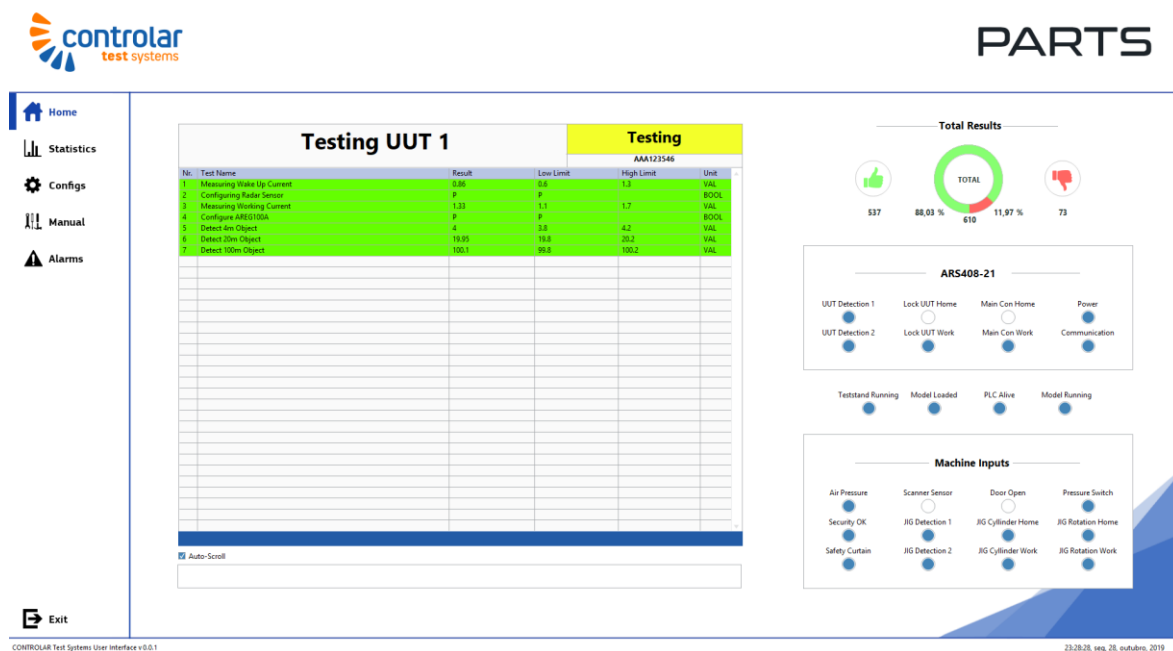


Figure 30 The user interface used in the tester.

4.5.3. PLC CONTROL

The control of the machine signals and motors will be made by the OMRON NX1P2-9024DT1 PLC [60] coupled with a DC input unit, ID5442, a DC output unit, OD5256 and a unit power supply, PF0730 (Figure 31). The PLC will manage the machine inputs, *i.e.* cylinder sensors, unit detection, buttons, pressure switch and others, while also being responsible for activating the control, *i.e.* buttons LEDs, cylinders actuation, unit locking, among others.

Besides the machine I/O's, the PLC will also control the motors for linearly moving the AREG100A's frontend module and rotating the plates inside the anechoic chamber by communicating with controllers described in 4.4.2 Motors and Motor Controllers. The software for the PLC was developed in OMRON's Sysmac Studio [61].

The PLC will handle the overall state machine, controlling all the complex, *e.g.* the one described in 4.4.1 Pneumatic Cylinders, and, as such, must be in constant communication with the TestStand application in order to assure all actions are made in sync with the other device/software. The PLC communication is done using the FINS protocol developed by OMRON [62]. The protocol will be managed by a LabVIEW function which will work as a server, continuously reading the PLC inputs and writing into its outputs. The server will also continuously write the read inputs into TestStand's memory variables and read said variables related to data to be transferred from TestStand to the PLC. This assures the programs in PLC and in TestStand run synchronously and the information in each is always up to date.

Besides the data exchange between TestStand and the PLC, the server will also update the information displayed in the user interface related to the machine I/O's by using NI Shared Variables [63], a method for sharing application within LabVIEW applications developed by National Instruments. The variables are published in a network, a local one within the machine in this tester case, and different applications may access the variables within this network server with controlled read/write permissions, assuring all applications are instantly updated once the variable changes in any situation.

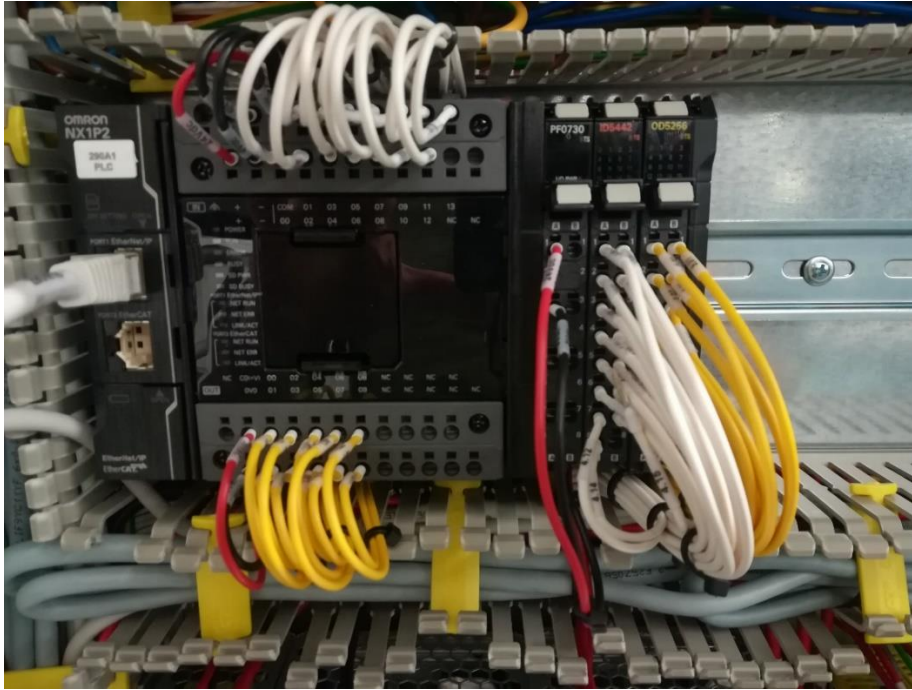


Figure 31 The tester's PLC and additional units.

4.5.4. OVERALL ARCHITECTURE

The overall software architecture of the system will consist in all the described software for machine control and the protocols for their communication coming together and working simultaneously. As such, the main communications may be demonstrated in a simple diagram (Figure 32).

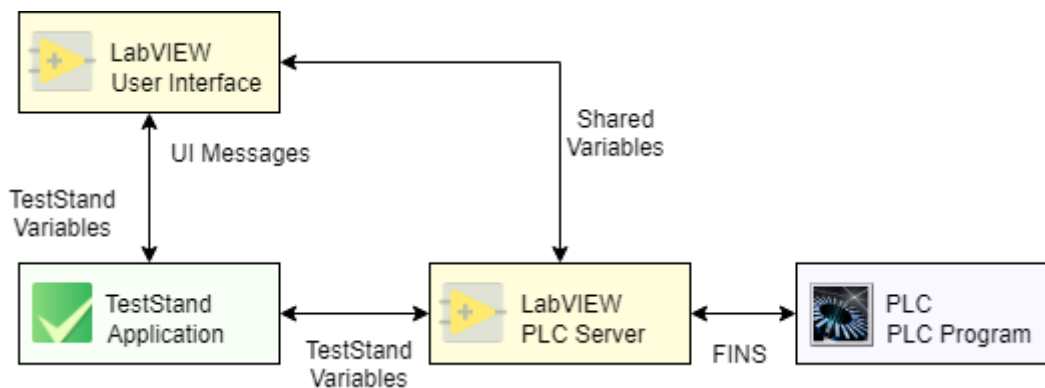


Figure 32 Overall software communication architecture.

Communication with different equipment and devices present in the system, *e.g.* the programmable power supply, the AREG100A, the CAN controller, etc. will be accomplished by implementing LabVIEW-based driver controllers, called by TestStand as individual code modules.

5. SENSORS IMPLEMENTATION

In this chapter the implementation of the radar sensors specified in 4. Tester Components is more thoroughly analysed. Communication with the radar sensors chosen for the system validation is a key topic and, as such, the configuration of said sensors and the parsing of the data transmitted by the devices must fully understood.

5.1. TEXAS INSTRUMENTS' AWR1642 EVM BOARD

Besides the use of the mmWave Demo Visualizer, the communication with the sensor may also be established by the end-user in its own application. In order to more accurately emulate a manufacturers product under test, implementing the communication with the sensor through another application is a must. As such, a communication driver must be implemented, either using the same serial communication the demo visualizer relies on, or through the CAN interface, emulating a more realistic product. In either case, an analysis of the data frames returned by the device is necessary.

5.1.1. AWR1642'S DATA PACKET PARSING

Said frames returned by the device in this demo follow a specific structure. Information regarding the structure of the data frames may be found in the demo documentation located in the SDK installation folder (Figure 33) [64]. The data is streamed from the sensor to the XDS110 Class Application/User UART port.

The structure is composed of a header with some general information, followed by the detected objects data packets which hold information regarding the objects detected by the device. The structure also includes a range profile of the relative power measured at different distances, a noise profile of what is considered "noise" by the mmWave sensor at different distances, a range azimuth heat map with information regarding angular position of the objects referencing the device, a Doppler heat map containing information of radial

velocity for the different targets and finishes with packets holding information about the device overall performance and statistics.

An analysis of the detected objects packets and the range profile should result in a comprehensive study of the information the radar sensor is measuring.

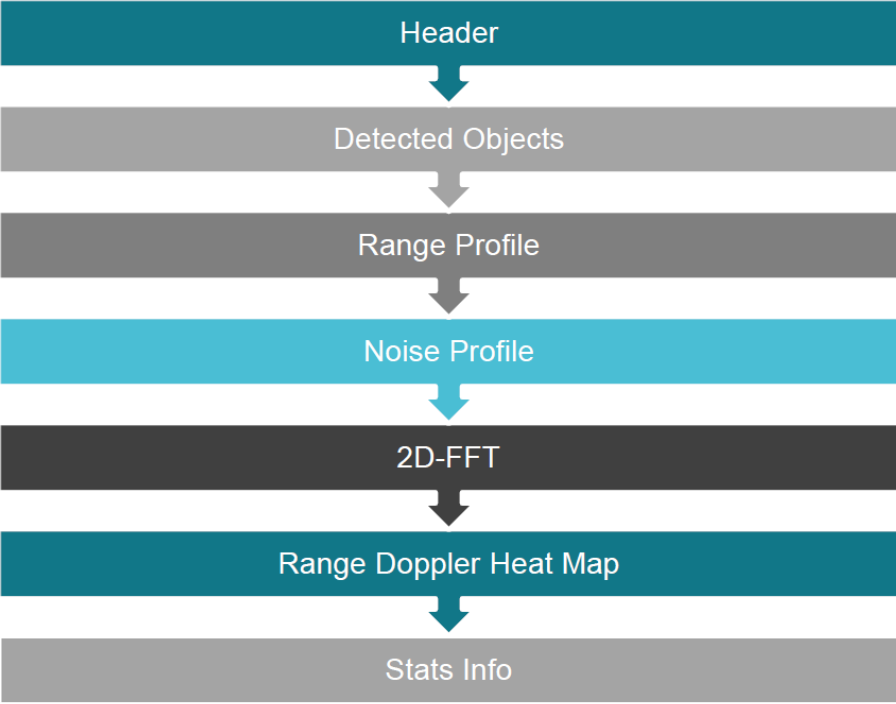


Figure 33 AWR1642’s data structure as described by Texas Instruments [64].

Since the device is continuously transmitting frames that may vary in size (dependent on the number of objects detected) it is important to find the beginning of the data packet. For that purpose, the header includes a Magic Word, an 8-byte synchronization signal (Table 9).

Table 9 Header’s magic word.

0x02	0x01	0x04	0x03	0x06	0x05	0x08	0x07
------	------	------	------	------	------	------	------

Once a magic word is detected, and since the header is of fixed structure always amounting to 40 bytes, the remainder of the header may be decoded and the information that follows may be analysed (Table 10).

Table 10 Data packet header's formatting.

Data	Size
Magic Word	8 bytes
Version	4 bytes
Total Packet Length	4 bytes
Platform	4 bytes
Frame Number	4 bytes
Time (CPU Cycles)	4 bytes
Number of Detected Objects	4 bytes
Number of Data Structures in Package	4 bytes
Sub Frame Number	4 bytes

In order to find the magic word and the corresponding header in the middle of the entire transmission of unknown size, the following algorithm is used:

```
Finding the magic word
  START Loop

  READ 8 bytes
  CONCATENATE to previously read bytes
  IF MAGIC WORD found THEN
    READ (32 - Non-MAGIC WORD) bytes
    DECODE HEADER
    READ (TOTAL PACKET LENGTH - 40)
    bytes
    RETURN DECODED HEADER
  END IF

END Loop
```

As such, the algorithm will continuously read 8 bytes of data and concatenating them together until the magic word is found. Once it is found, the remainder header is read from the serial buffer and decoded, retrieving the total packet length of the entire packet. From that length the remaining bytes related to the header can be obtained and the data analysed.

The succeeding data holds the detected objects information (Table 11). The main structure includes multiple sub-structures with data regarding, for instance, the peak value detected and X, Y and Z coordinates. The number of sub-structures is directly correlated to the number of detected objects, and the data is formatted according to the following data structure:

Table 11 Detected object’s data structure [64].

Data	Size	Structure
Structure Tag	4 bytes	Main Structure
Length of Structure	4 bytes	
Descriptor	4 bytes	
Object N Range Index	2 bytes	Detected Objects Structure
Object N Doppler Index	2 bytes	
Object N Peak Value	2 bytes	
Object N X coordinate	2 bytes	
Object N Y Coordinate	2 bytes	
Object N Z Coordinate	2 bytes	

The structure tag identifies the current structure and the length of the structure defines the termination of said structure. The descriptor describes the number of detected objects in the first 2 bytes and the Q Format to apply to the coordinates in the second pair of bytes (In this situation, to apply the Q Format one must simply assume the read value as an 16-bit integer, use 2 to the power of said value and divide the coordinates by the resulting number).

In order to obtain the data for all the detected objects a loop may be ran the as many times as there are detected objects. In said loop, the all the information for each object may be extracted.

The first 12 bytes are, as already seen, related to the structure identification and number of objects. As such, the first object range index will be 2 bytes starting at byte number 12 (starting index as 0), the doppler index for the same object will be 2 bytes starting at byte

number 14, peak value will correspond to the 2 bytes starting at byte number 16 and the X,Y and Z coordinates the pairs of bytes starting at bytes 18, 20 and 22, respectively. The data related to the second object will be offset by the 12 bytes of data of the previous object, *i.e.* range index starts at byte 24, the doppler index at byte 26, and so on.

Once the detected objects structure finishes, the range profile data structure begins (Table 12).The profile illustrates the measured magnitude at different distances and may be used to understand the peaks corresponding to the detected objects when compared to the surroundings where no objects were registered. It consists of an array of profile points at 0th Doppler, or stationary objects.

The structure is composed of a tag, its length and the actual range profile which varies in size, being dependent on the number of samples defined in the configuration of the radar.

Table 12 Range profile data structure [64].

Data	Size
Structure Tag	4 bytes
Length of Structure	4 bytes
Range Profile	# ADC Samples rounded up to nearest power of 2 * 4 bytes

From the number of detected objects obtained in the previous structure, it is simple to identify the beginning of the range profile data structure, allowing for a correct evaluation of the packet's length. From the packet's length, the range profile may be correctly obtained, disregarding any sort of padding bytes that can be included by the sensor to the end of the stream to ensure the entire packet's length is a multiple of 32 bytes.

For the AWR1642, the data in the range profile may be read as the sum of the binary logarithms, \log_2 , of the magnitudes detected by the receiving antennas expressed in Q8 format. The data in the array may then be analysed or plotted for a more user-friendly visualization.

These two structures hold the most critical information for the application in mind and, as such, will serve as the starting point for the remainder of the radar sensor implementation.

5.1.2. AWR1642'S CONFIGURATION

Before starting the sensor and acquiring measurements, it's essential to configure the board to the desired settings. An in-depth configuration of the radar device requires the analysis of a vast number of documents spread through different sources, such as the mmWave SDK and the mmWave DFP (device firmware package). For the simple demonstration purposes of this device required for the application, the profiles may be defined in mmWave Demo Visualizer and the configurations exported from there and applied to the new application.

The main feature to configure is the bandwidth, allowing for both the 76-77 GHz band and the 77-81 GHz band to be used (Table 13). When using the mmWave Demo Visualizer to configure the sensor for these bandwidths, the following commands are run for applying the configuration:

Table 13 mmWave Demo Visualizer's configuration for both bandwidths.

76-77 GHz	77-81 GHz
sensorStop	sensorStop
flushCfg	flushCfg
dfeDataOutputMode 1	dfeDataOutputMode 1
channelCfg 15 3 0	channelCfg 15 3 0
adcCfg 2 1	adcCfg 2 1
adcbufCfg -1 0 0 1 0	adcbufCfg -1 0 0 1 0
profileCfg 0 76 473 7 20 0 0 50 1 64 5333 0 0 30	profileCfg 0 77 429 7 57.14 0 0 70 1 256 5209 0 0 30
chirpCfg 0 0 0 0 0 0 1	chirpCfg 0 0 0 0 0 0 1
chirpCfg 1 1 0 0 0 0 2	chirpCfg 1 1 0 0 0 0 2
frameCfg 0 1 16 0 100 1 0	frameCfg 0 1 16 0 100 1 0

lowPower 0 1	lowPower 0 1
guiMonitor -1 1 1 0 0 0 0	guiMonitor -1 1 1 0 0 0 0
cfarCfg -1 0 0 8 4 4 0 5120	cfarCfg -1 0 0 8 4 4 0 5120
cfarCfg -1 1 0 4 2 3 0 5120	cfarCfg -1 1 0 4 2 3 0 5120
peakGrouping -1 1 1 1 1 255	peakGrouping -1 1 1 1 1 255
multiObjBeamForming -1 1 0.5	multiObjBeamForming -1 1 0.5
clutterRemoval -1 0	clutterRemoval -1 0
calibDcRangeSig -1 0 -5 8 256	calibDcRangeSig -1 0 -5 8 256
extendedMaxVelocity -1 0	extendedMaxVelocity -1 0
bpmCfg -1 0 0 1	bpmCfg -1 0 0 1
lvdsStreamCfg -1 0 0 0	lvdsStreamCfg -1 0 0 0
nearFieldCfg -1 0 0 0	nearFieldCfg -1 0 0 0
compRangeBiasAndRxChanPhase 0.0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0	compRangeBiasAndRxChanPhase 0.0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0
measureRangeBiasAndRxChanPhase 0 1.5 0.2	measureRangeBiasAndRxChanPhase 0 1.5 0.2
CQRxSatMonitor 0 3 4 37 0	CQRxSatMonitor 0 3 5 123 0
CQSigImgMonitor 0 31 4	CQSigImgMonitor 0 127 4
analogMonitor 1 1	analogMonitor 1 1
sensorStart	sensorStart

Some of these commands are self-explanatory and of interesting implementation in various moments of the process, such as “sensorStop” and “sensorStart”. The other commands will mainly remain unchanged, excepting the “frameCfg” which allows for an increase in the frames per second output of the stream. The frames output rate may be increased from a frame at every 100 ms to a maximum of 33 ms at which the command results in: “frameCfg 0 1 16 0 33 1 0”. According to the mmWave Demo Visualizer, this increase in frame rate

performance may result in poorer performance, so its value shouldn't be fixed, but configurable.

Having the basic "Start" and "Stop" commands and the configurations necessary for both types of bandwidth, it's now possible to develop a basic controller application for the device that may be implemented in the tester.

5.2. CONTINENTAL'S ARS408-21

The connection with the ARS408-21 is achieved through a high-speed CAN interface of 500kbit/s baud rate. The sensor assigns a message ID for each message purpose, with each message being formatted as CAN 2.0A (typical 11-bit ID addressing) (Table 14) [65].

The device is prepared for starting data transmission with the default configurations as soon as the sensor is powered. The sensor can output either cluster or objects. Clusters hold information about the position, velocity and signal strength of the radar reflections detected and their values refresh at each cycle. Objects hold history regarding previous detections and, as such, consist of tracked clusters, so the cluster analysis will demonstrate all reflections detected and the objects represent the points where more reflections are bundled together. For the case in study, the application shall read the objects information, hence the most critical messages to process are:

- Object status (0x60A), for the number of near scan and far scan objects that are sent afterwards;
- Object general information (0x60B), for the position and velocity of the object. This message is sent repeatedly for all the detected objects, starting at near scan with far scan following.

Table 14 Sensor CAN messages.

Message ID	Message Name	Content
0x200	RadarCfg	Sensor Configuration
0x201	RadarState	Sensor Status
0x202	FilterCfg	Filter Configuration
0x203	FilterState_Header	Filter Status Header
0x204	FilterState_Cfg	Filter Configuration Status
0x300	SpeedInformation	Vehicle Speed
0x301	YawRateInformation	Vehicle Yaw Rate
0x400	CollDetCfg	Collision Detection Configuration
0x401	CollDetRegionCfg	Collision Detection Region Configuration
0x402	CollDetRegionState	Collision Detection Region Status
0x408	CollisionDetState	Object List Interface Version
0x600	Cluster_0_Status	Cluster Status
0x60A	Obj_0_Status	Object Status
0x60B	Obj_1_General	Object General Information
0x60C	Obj_2_Quality	Object Quality Information
0x60D	Obj_3_Extended	Object Extended Information
0x60E	Obj_4_Warning	Object Collision Detection Warnings
0x700	VersionID	Software Version Identification

0x701	Cluster_1_General	Cluster General Information
0x702	Cluster_2_Quality	Cluster Quality Information
0x800	CollDetRelayCtrl	Control Message for Relay

In order to correctly analyse the data transmitted by the device, it is important to understand how the sensor builds the message frames. The message that shall start the reading cycle is the Object Status (0x60A) (Figure 34 and Table 15). This message holds information regarding the number of objects detected by the sensor, the measurement cycle in which the message was transmitted and the CAN interface version.

Table 15 Object Status (0x60A) data.

Data	Starting Bit	Lenght
Number of Objects	0	8 bits
Cycle Counter	16	16 bits
Interface Version	28	4 bits

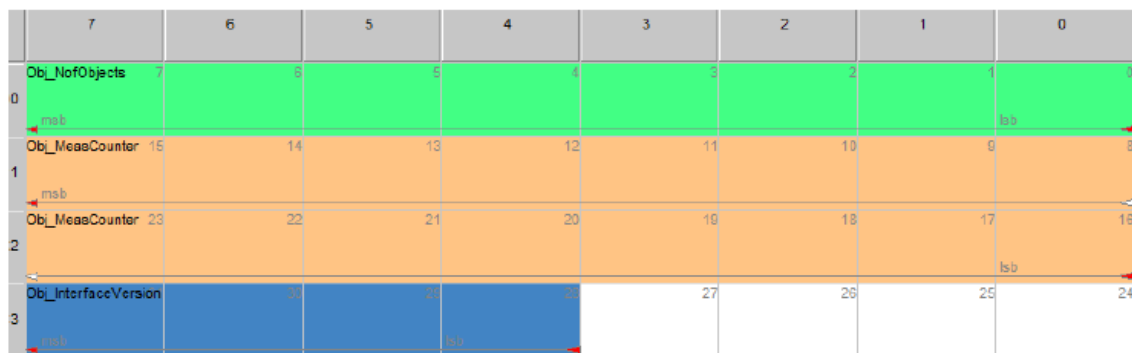


Figure 34 Object Status (0x60A) frame structure [65].

Once the number of objects is known, the Object General Information (0x60B) (Figure 35 and Table 16)⁴ message shall be read the same number of times, once for each detected object. From these message frames, the data regarding the object position, relative velocity and radar cross section may be extracted.

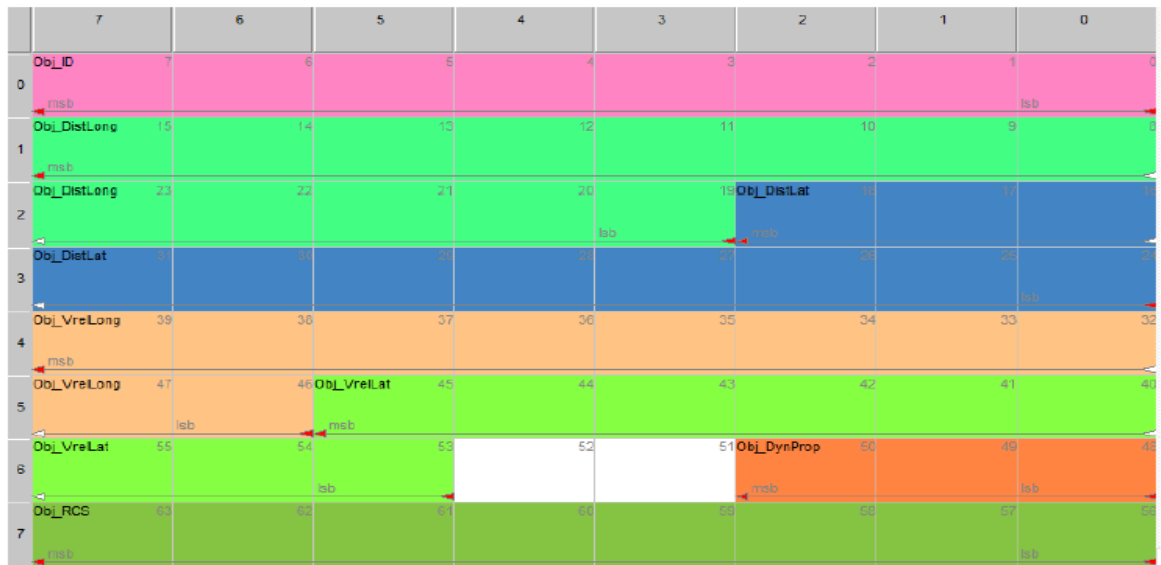


Figure 35 Object General Information (0x60B) frame structure [65].

Table 16 Object General Information (0x60B) data.

Data	Starting Bit	Length
ID	0	8 bits
Longitudinal Coordinate	19	13 bits
Lateral Coordinate	24	11 bits
Longitudinal Relative Velocity	46	10 bits
Lateral Relative Velocity	48	3 bits
Dynamic Property	53	9 bits
Radar Cross Section	56	8 bits

⁴ The measurements cycle counter data starts at bit 16 (LSB) and ends at bit 15 (MSB) with a length of 16 bits, effectively requiring an 8-bit bitwise logical left shift to the first read byte. This is a recurring theme throughout the device message frames requiring more caution when parsing the data

Information on how to parse the entirety of the frame may be found in the device technical documentation. For the purpose of this application, only the coordinates shall be analysed.

The longitudinal coordinate may be obtained as such:

```
Byte1_ = Byte1 << 5; //Apply logical left
                    shift to the first
                    byte
Byte2_ = Byte2 & 0xF8; //Apply 0xF8 mask
                    to the second byte
Byte2 = Byte2_ >> 3; //Apply logical right
                    shift to the masked
                    byte
ByteData = Byte1_ | Byte2; //Apply binary
                        OR to resulting
                        Bytes
DistLong = ByteData * 0.2 - 500
//Apply the 0.2 m resolution and the offset
as specified in the documentation
```

The lateral coordinate may be obtained as such:

```
Byte2_ = Byte2 & 0x07 //Apply 0x07 mask to
                    The first byte
Byte2 = Byte2_ << 8; //Apply logical left
                    shift to the result
ByteData = Byte2 | Byte3; //Apply binary
                        OR to resulting
                        bytes
DistLat = ByteData * 0.2 - 204.6
//Apply the 0.2 m resolution and the offset
as specified in the documentation
```

After all individual object frames are read, the cycle may restart by once again reading the Object Status (0x20A) and proceeding from there.

5.2.1.ARS408-21 CONFIGURATION

For the radar device to output objects instead of clusters, a few configurations need to be applied upon powering the unit. The first one is obviously related to the type of data the radar will output and the second relates to the filtering of the transmitted frames. Since the radar device will process the data of the clusters of points detected and from that data predict which cluster might represent a detected object, the end-user may configure the

tolerance the radar will use when determining said objects. The message IDs used for these configurations are as follow:

- Radar Configuration (0x200), for selecting the desired type of output (clusters or objects);
- Radar State (0x201), for confirming the desired configuration is applied to the device. This message is sent periodically by the unit, more specifically, once a second;
- Filter Configuration (0x202), for selecting the tolerance or “probability of existence” of real targets from the data collected by the sensor;
- Filter State Configuration (0x204), for confirming the desired filter configurations were applied to the unit. This message is sent by the device as a response to the 0x202 message.

For the radar configuration (0x200) (Figure 36), the only change to apply from the default configurations regards the output type of the sensor, changing it from clusters to objects. In order to achieve this, the message sent should indicate the configuration to alter (through the “Valid” parameters) (Table 17) and the desired value in the corresponding byte. For this specific case, the 4th bit of the 1st and 5th byte should be set to “1” and the remainder be left unchanged at “0”, resulting in message “08 00 00 00 08 00 00 00”.

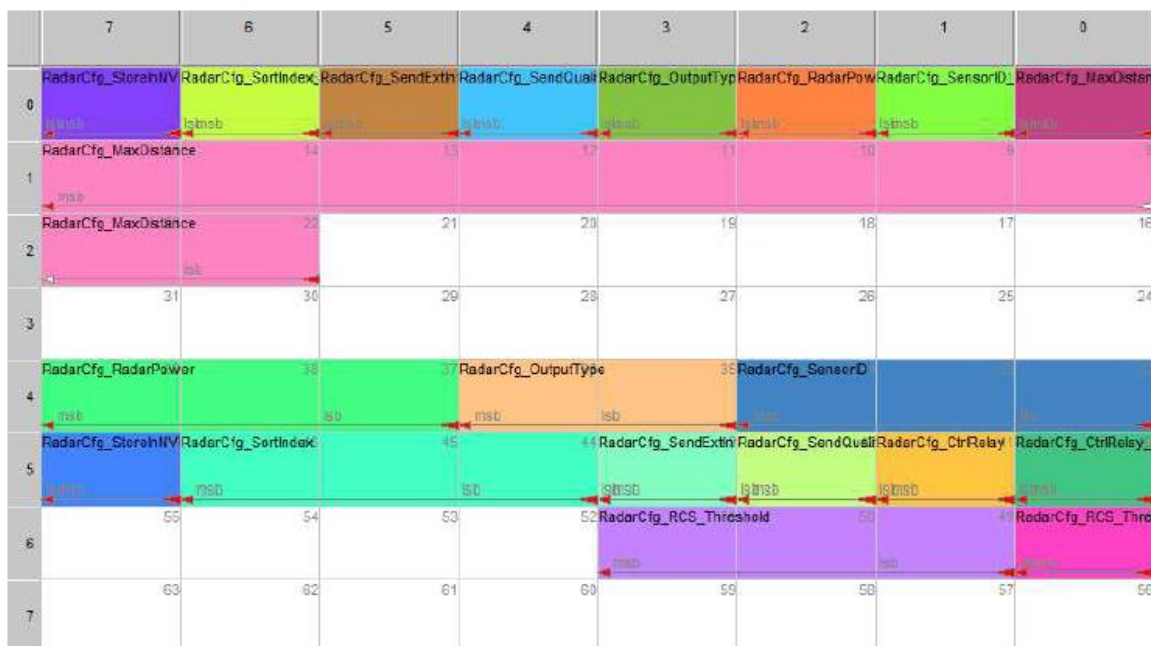


Figure 36 Radar configuration (0x200) frame structure [65].

Table 17 Radar Configuration (0x200) data.

Data	Starting Bit	Length
Max Distance Valid	0	1 bit
Sensor ID Valid	1	1 bit
Radar Power Valid	2	1 bit
Output Type Valid	3	1 bit
Send Quality Valid	4	1 bit
Send External Info Valid	5	1 bit
Sort Index Valid	6	1 bit
Store in NVM Valid	7	1 bit
Max Distance	22	10 bits
Sensor ID	32	3 bits
Output Type	35	2 bits
Radar Power	37	3 bits
Control Relay Valid	40	1 bit
Control Relay	41	1 bit
Send Quality	42	1 bit
Send External Info	43	1 bit
Sort Index	44	3 bits
Store in NVM	47	1 bit

The correct configuration of the desired parameters may be confirmed through the Radar State (0x201) message (Figure 37 and Table 18). For this specific case, the 3rd and 4th bits of the 6th byte should equal 0x01 (0x00 equals “no output”, 0x01 equals “output objects” and 0x02 equals “output clusters”).

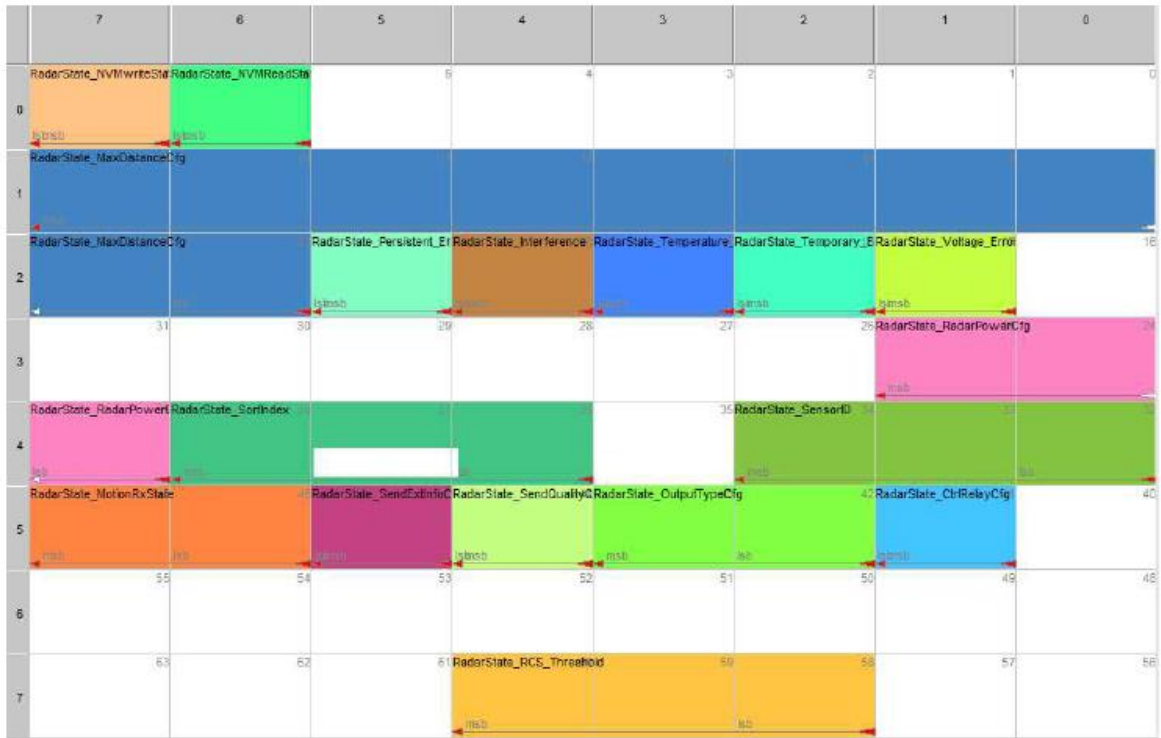


Figure 37 Radar State (0x201) frame structure [65].

Table 18 Radar State (0x201) data

Data	Starting Bit	Length
NVM Read Status	6	1 bit
NVM Write Status	7	1 bit
Max Distance Config	22	10 bits
Persistent Error	21	1 bit
Interference	20	1 bit
Temperature Error	19	1 bit
Temporary Error	18	1 bit
Voltage Error	17	1 bit
Sensor ID	32	3 bits
Sort Index	36	3 bits
Radar Power Config	39	3 bits
Control Relay Config	41	1 bit

Output Type Config	42	2 bits
Send Quality Config	44	1 bit
Send External Info Config	45	1 bit
Motion RX State	46	2 bits
RCS Threshold	58	3 bits

Once the output type is configured, only the filter configuration remains. The objects and clusters filters configurations can be achieved using the message with ID 0x202 (Figure 38) and for this specific application, only the probability of existence will suitable for change. When tests are carried out in open space it is important to limit the output of the sensor to high probability objects in order to reduce the effects of clutter and multipath reflections, while in anechoic chamber tests, the minimum probability may be reduced since the shielded chamber itself will limit the effects described. The desired configuration is achieved by setting the 2nd, 3rd, 7th and 8th bit of the first byte to “1”, indicating the sensor apply the configuration sent, activating the filter, indexing the “Probability of Existence” parameter and applying it to objects, resulting in 0xC6 (Table 19 and Table 20). The following 2 bytes specify the minimum values for the desired parameter and the 4th and 5th byte the maximum values. As such, configuring the sensor to only output objects with a probability of existence, for example, between 99% and 100% is achieved through message “C6 00 05 00 07 00 00 00” (Table 21).

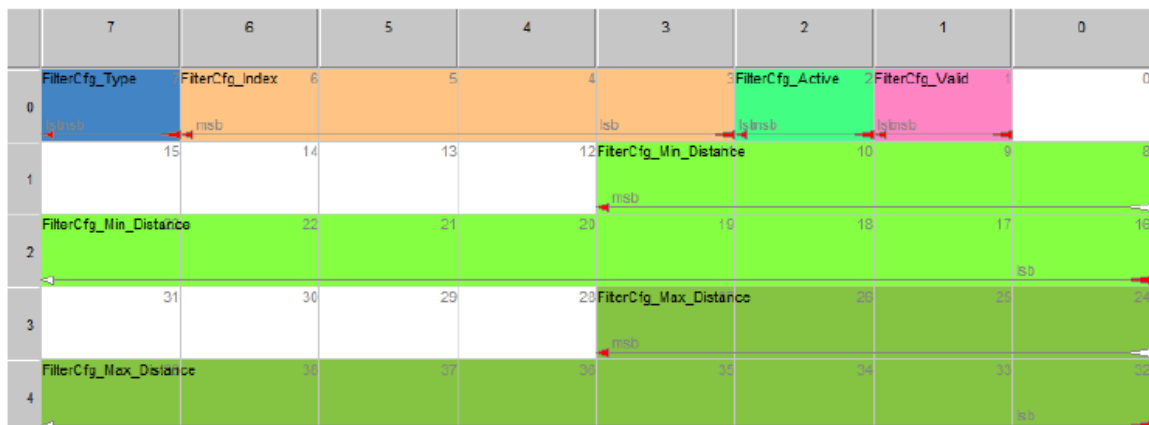


Figure 38 Filter Configuration and Filter State (no FilterCfg_Valid) structures [65].

Table 19 Filter Configuration (0x202) and Filter State (0x204) data.

Data	Starting Bit	Length
Valid (N/A to 0x204)	1	1 bit
Active	2	1 bit
Index	3	4 bits
Type	7	1 bit
Minimum Value	16	12 bits
Maximum Value	32	12 bits

Table 20 Filter Parameters indexing.

Index Byte	Parameter
0x00	Number of Objects/Clusters
0x01	Distance
0x02	Azimuth
0x03	Relative Velocity Oncome
0x04	Relative Velocity Depart
0x05	Radar Cross Section
0x06	Lifetime
0x07	Size
0x08	Probability of Existence
0x09	Coordinate Y
0x0A	Coordinate X
0x0B	Y Velocity Right-Left
0x0C	X Velocity Oncome
0x0D	Y Velocity Left-Right
0x0E	X Velocity Depart

Table 21 Probability of existence possible values.

Byte	Probability of Existence
0x00	0%
0x01	25%
0x02	50%
0x03	75%
0x04	90%
0x05	99%
0x06	99.9%
0x07	100%

The confirmation of the correct filter configuration may be achieved analysing the response with ID 0x204 to the 0x202 command. The response consists of the same structure as the command except it does not include the “Valid” bit. As such, for the example command of “C6 00 05 00 07 00 00 00” the expected correct response would be with the ID 0x204 and data “C4 00 05 00 07 00 00 00” (Figure 39).

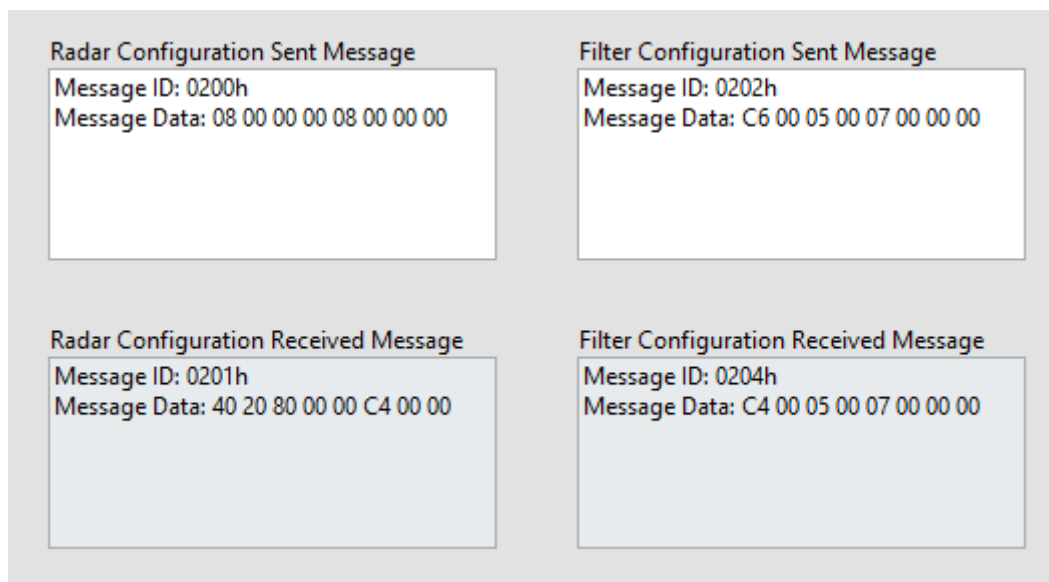


Figure 39 Example of a possible configuration.

6. TESTS & RESULTS

In this chapter some of the tests implemented through the development of the system and the corresponding results are exposed. The tests aim to validate the correct use of the different components of the tester, including the demonstration radar sensors. The tests should also expose the differences between the measurements obtained from the radar sensors in open space, open space with absorbing foam, open space with an echo generator and inside an anechoic chamber.

6.1. RADAR SENSORS IN OPEN SPACE

In order to fully understand the demonstration radar devices which will undergo tests in the system behaviour, said devices were placed at a fixed distance to a metal object of around 125 cm (Figure 40 and Figure 42). The devices were then configured, and their measurements observed and analysed. For the AWR1642, at a resolution of 4,3 centimetres, the closest detected object corresponding to the placed metal object recorded coordinates [X;Y] of [-0,12;1,26] m (Figure 41). Since the test was carried out in open space, more objects were detected, resulting from other objects in the room and from clutter from undesired reflections.

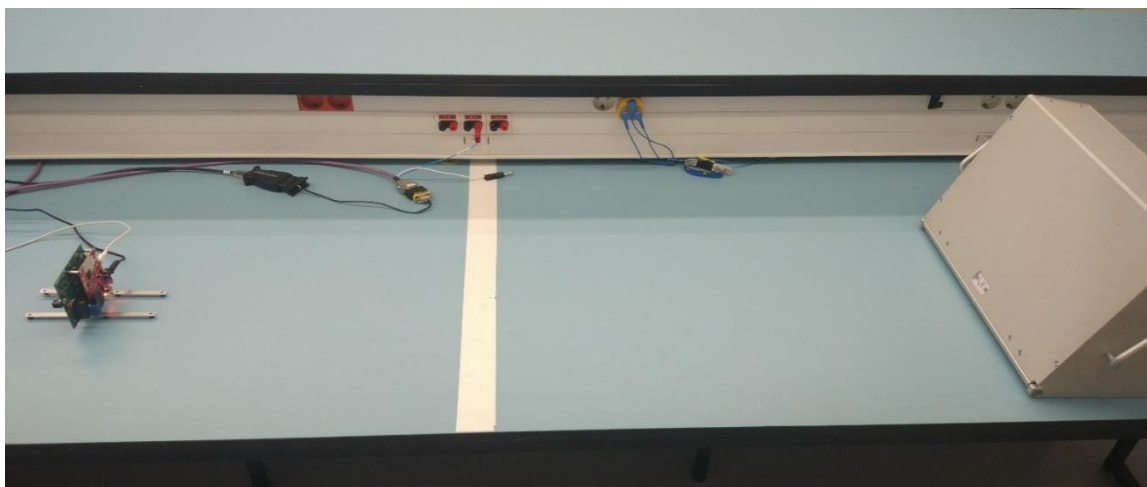


Figure 40 AWR1642's 125cm test setup.

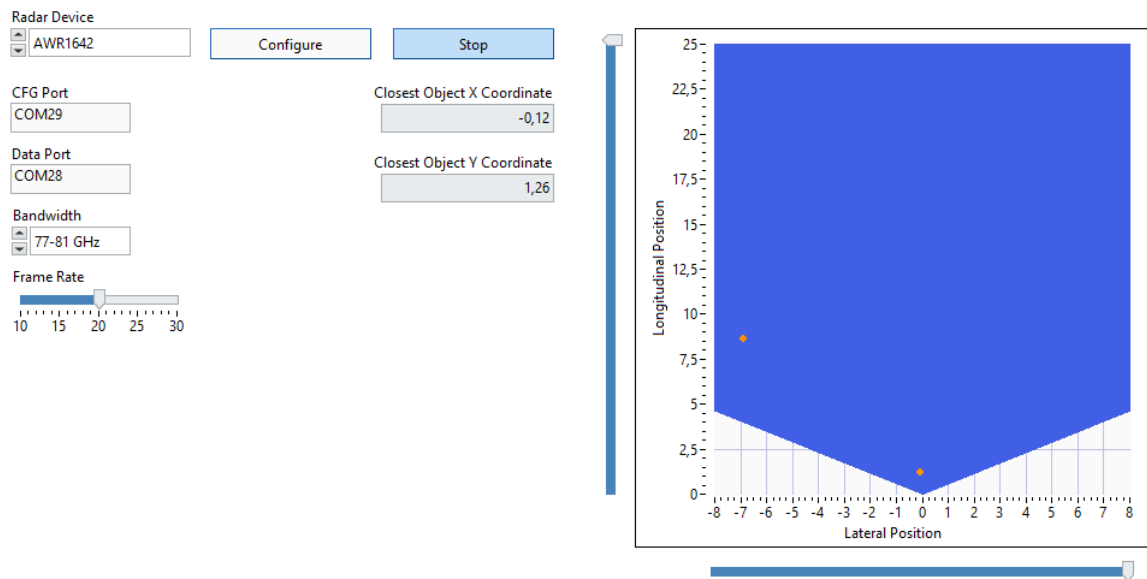


Figure 41 AWR1642's 125cm test results at 4 GHz.

Regarding the ARS408-21, working at a resolution of 20 centimetres, the closest object corresponding to the placed metal object recorded coordinates of [0;1,20] m (Figure 43). When compared to the AWR1642, this sensor as a lower resolution, a trade-off for the higher detectable range, and a higher sensibility to other objects in the room. As such, this radar should benefit more from the tests carried out inside a shielded anechoic chamber. Besides the benefits of carrying out test inside the shielded anechoic chamber, this radar sensor also requires an analysis of nearly its entire range, a goal only obtainable through the implementation of the radar echo generator.

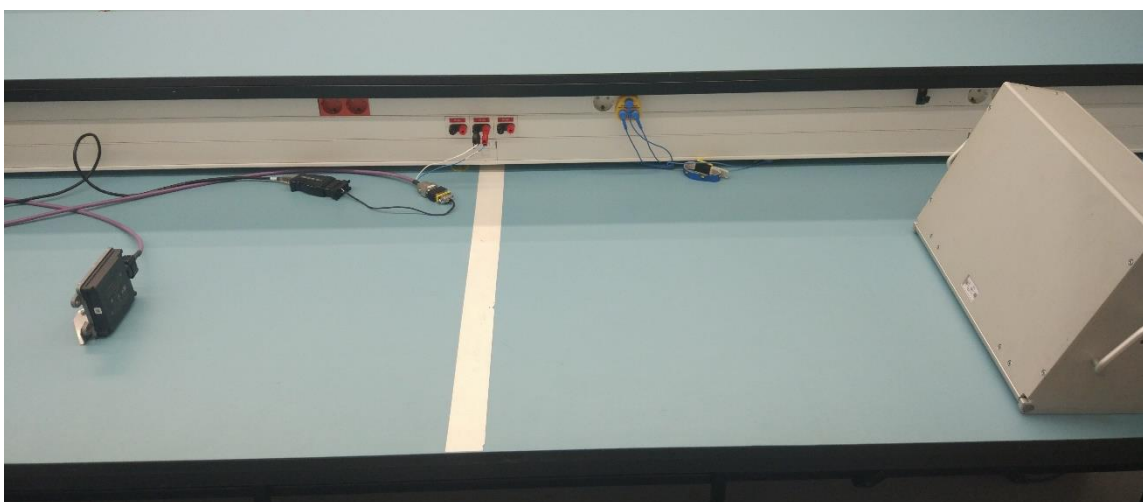


Figure 42 ARS408-21's 125cm test setup.

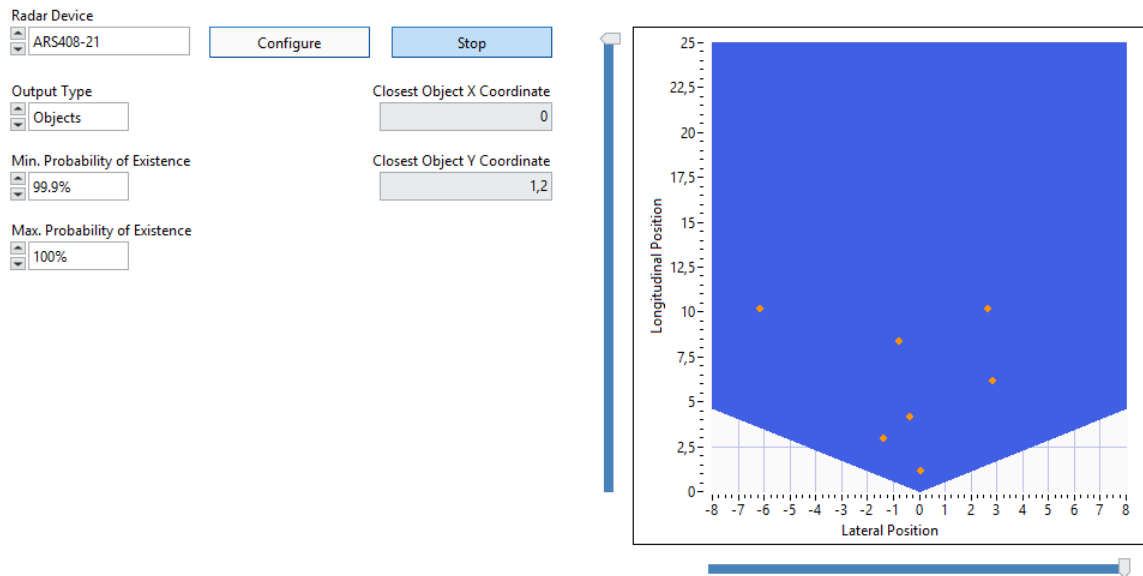


Figure 43 ARS408-21's 125cm test results.

6.2. RADAR SENSORS INSIDE ANECHOIC CHAMBER

To verify the effect of surrounding the radar devices with absorbent foam glued to the inside of the anechoic chamber, the sensors were placed at the bottom of the chamber and at the top stood the support for the echo generator front end module. It is worth noting that at this point the tester was not fully assembled and, as such, the anechoic chamber was not offering its best performance (Figure 44).⁵ As such, the test results will not reflect the final results achieved once the tester is completely assembled and the antenna for the echo generator is applied. Besides the incomplete reflection the final situation, the tests shine a new light into the effect of the absorbent foam when compared to the tests in open space.

⁵ The anechoic chamber, when the tests were realized, had some openings for the shielded interfaces to the outside and an opening that allows for the unit to enter and exit the anechoic chamber which will close and open automatically during testing by actuating a pneumatic cylinder. Figure 37 demonstrates said opening. The side where the picture was taken was closed before tests were started and the door was closed.

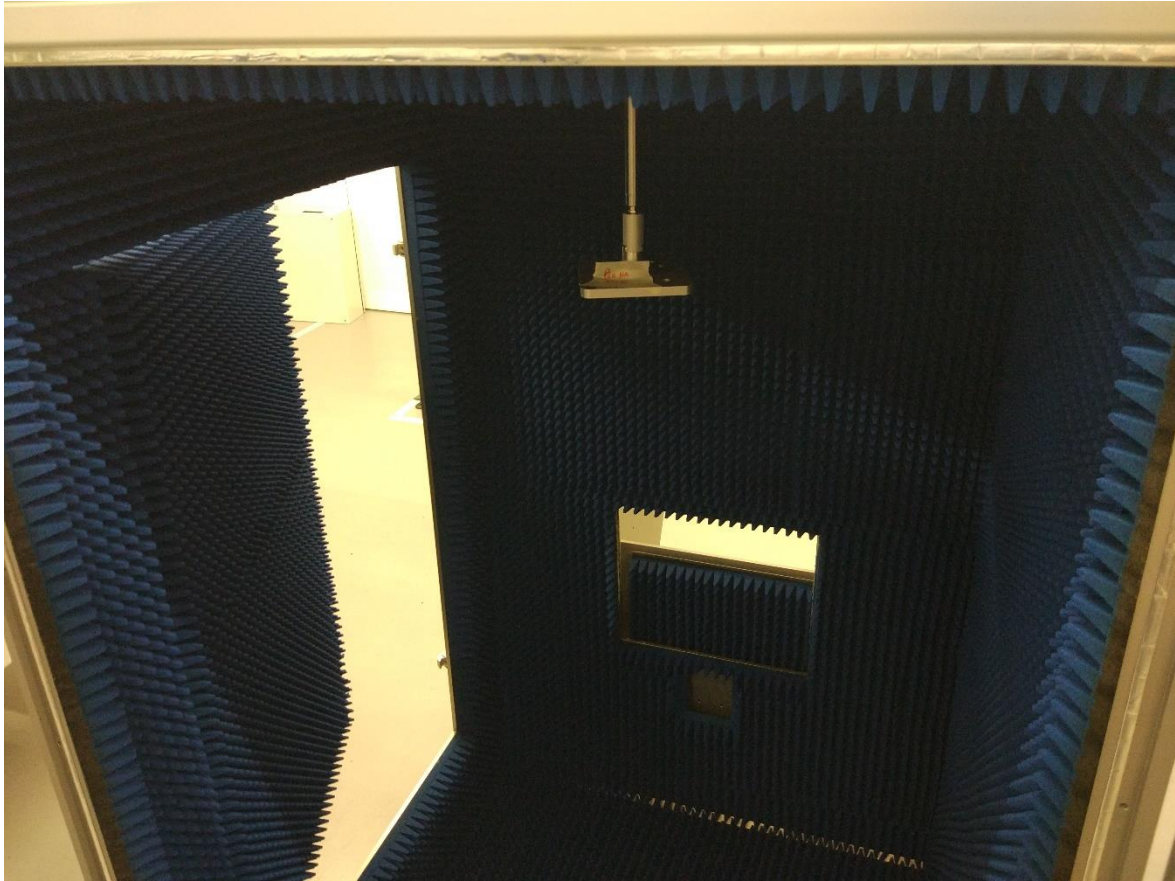


Figure 44 State of the anechoic chamber when the tests were carried out.

The expected results for the tests include a reduction in the number of objects detected and in the noise profile detected by the AWR1642's board. It is important to note that the only detectable object inside the anechoic chamber is, disregarding some of the openings already exposed, the support for the echo generator's antenna and the radar sensor itself (Figure 45). Both objects have reflective characteristics and, as such, some multipathing is also to be expected. Said effect should be reduced or eliminated by the application of the antenna of the echo generator which should capture the radio waves transmitted by the sensor for transformation instead of merely reflecting them. The support is placed at around 125 mm from the radar sensors, a similar setup to the one used in open space. Besides the same analysis of the detected objects by each sensor, in this situation it might be interesting to also compare the profile of signal magnitude perceived by the AWR1642's sensor in both the open space setup and inside the anechoic chamber.

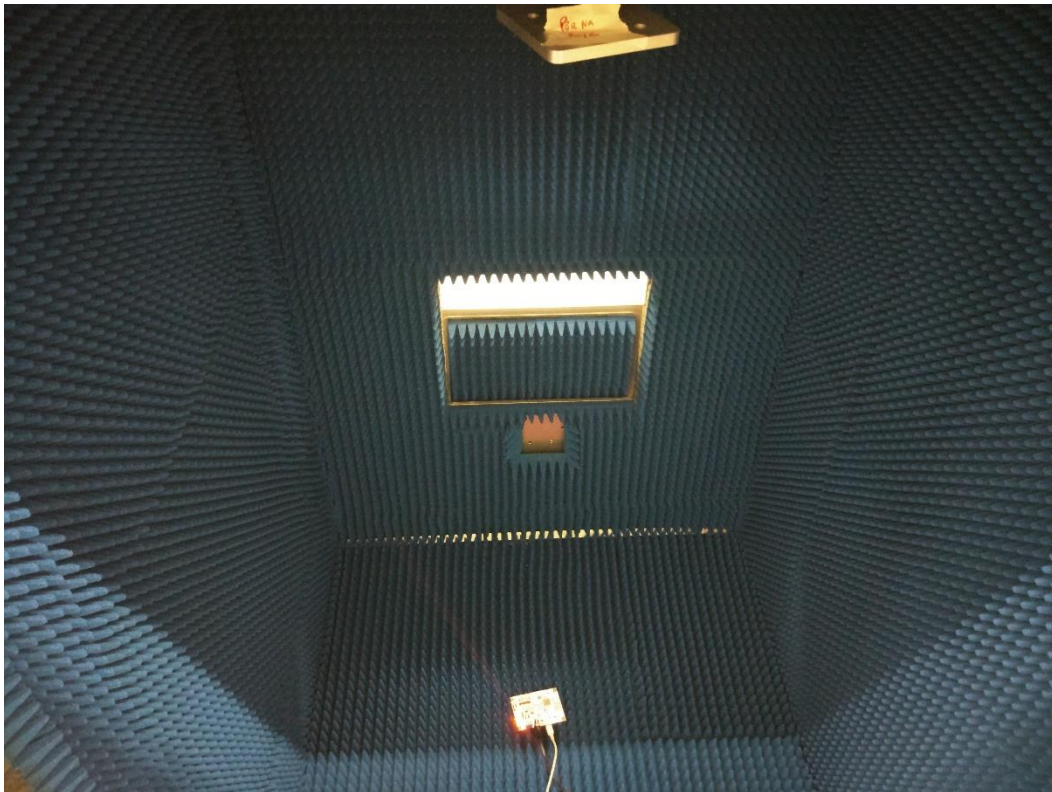


Figure 45 AWR1642 radar sensor inside the anechoic chamber .

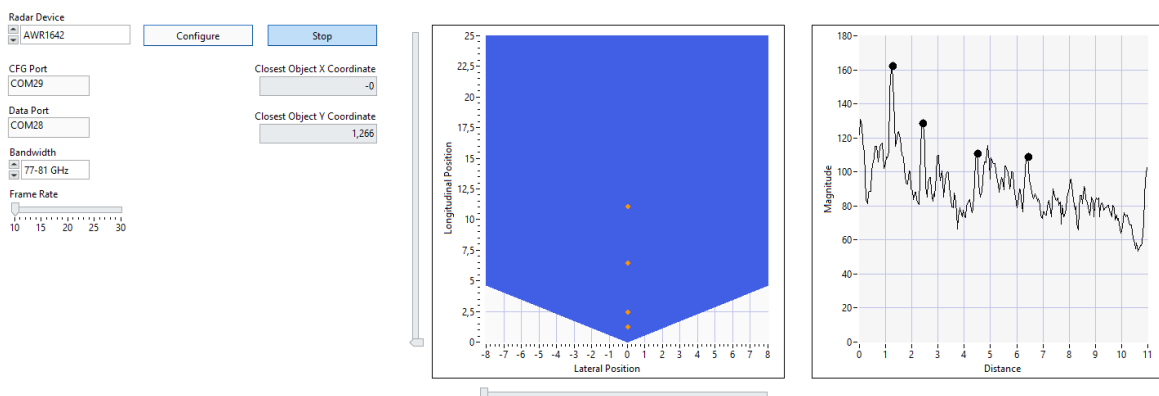


Figure 46 AWR1642 sensor results at 4 GHz inside the anechoic chamber.

At 4 GHz the results align with what was expected when analysing the detected objects: only one object is detected but its reflections generate multipathing effects which are later represented as multiple objects. The profile of the signal magnitude, shown in Figure 46 (right), explains in some way why the multipathing is more evident inside the anechoic chamber: the medium of the noise detected tends to be lower and, as such, any reflection will generate a higher peak when compared to its surroundings, deceiving the sensor into defining them as objects.

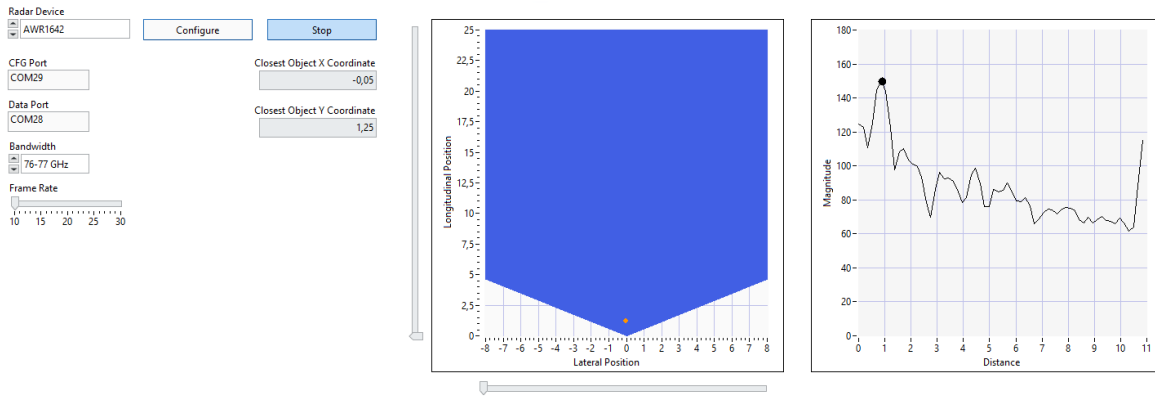


Figure 47 AWR1642 sensor results at 1 GHz inside the anechoic chamber.

Interestingly, at 1 GHz bandwidth the multipathing effect doesn't take place and only the support is detected (Figure 47). When analysing the signal profile, only one distinctive peak is observed, corresponding to the detected object, opposing to the 4 GHz bandwidth case where the multipath reflections generated more distinctive peaks.

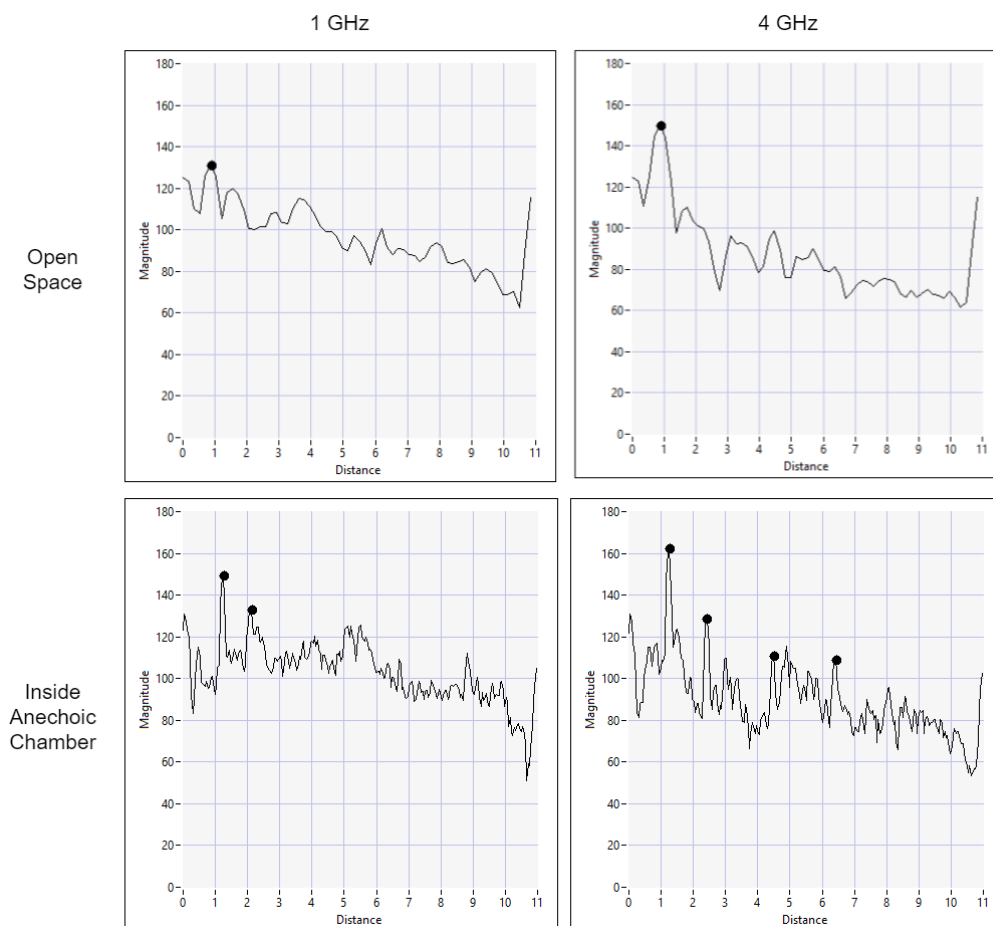


Figure 48 AWR1642's calculated signal profiles.

This might result from the sensor resolution which might not allow as good a differentiation between small distances at 1 GHz when compared to 4 GHz case. Said effect might become more evident when taking a closer look to the signal profiles where the 4 GHz profile is composed of multiple distinctive small peaks, whereas in the 1 GHz profile the peaks tend to blend into larger blocks. Both these situations may be observed in Figure 48, as well as the difference in the signal profiles when the sensor is used in open space or inside the anechoic chamber.

Besides the already described difference between bands, it is also more evident the improvement in signal-to-noise ratio when sensor is placed inside the anechoic chamber. In both the 1 GHz band and 4 GHz band cases, the peaks for detected objects are more distinctive from the existing noise, an effect also to be expected from the anechoic chamber characteristics.

6.3. R&S AREG100A'S IMPLEMENTATION

After an initial analysis of the radar sensors behaviour in a testbench and the effects of the anechoic chamber, it is now possible to validate the radar performance in its final application: inside the anechoic chamber, surrounded by RF absorbent foam and detecting targets generated by the R&S AREG100A. The expected results are the detection of whichever object the AREG100A is generating, assuming the correct attenuations are set, and possibly the detection of the frontend module itself at a distance similar to the air gap between the UUT and the module. This detection must be ignored during testing as it is expected and irrelevant to the tests carried out. It is also important to note that at the time the tests were carried out, the unit nests were not finalized and, as such, it is also expectable to find some variation in X axis, as the unit is not perfectly centred with the frontend module.

6.3.1. ARS408-21'S TESTS

For the first tests, the Continental ARS408-21 was placed inside the anechoic chamber, powered up and established the connection with the device. The anechoic chamber was

then closed and the R&S AREG100A was initialized. The target generator was setup for the correct air gap between the radar sensor and its frontend module of 1 m. Considering said air gap, the AREG100A could generate objects at the distances of 4,2 m, 6,2 m, 80,2 m and 200,2 m (Figure 49). The defined frequency was 76 GHz, since the ARS408-21 operates in the 76-77 GHz band.

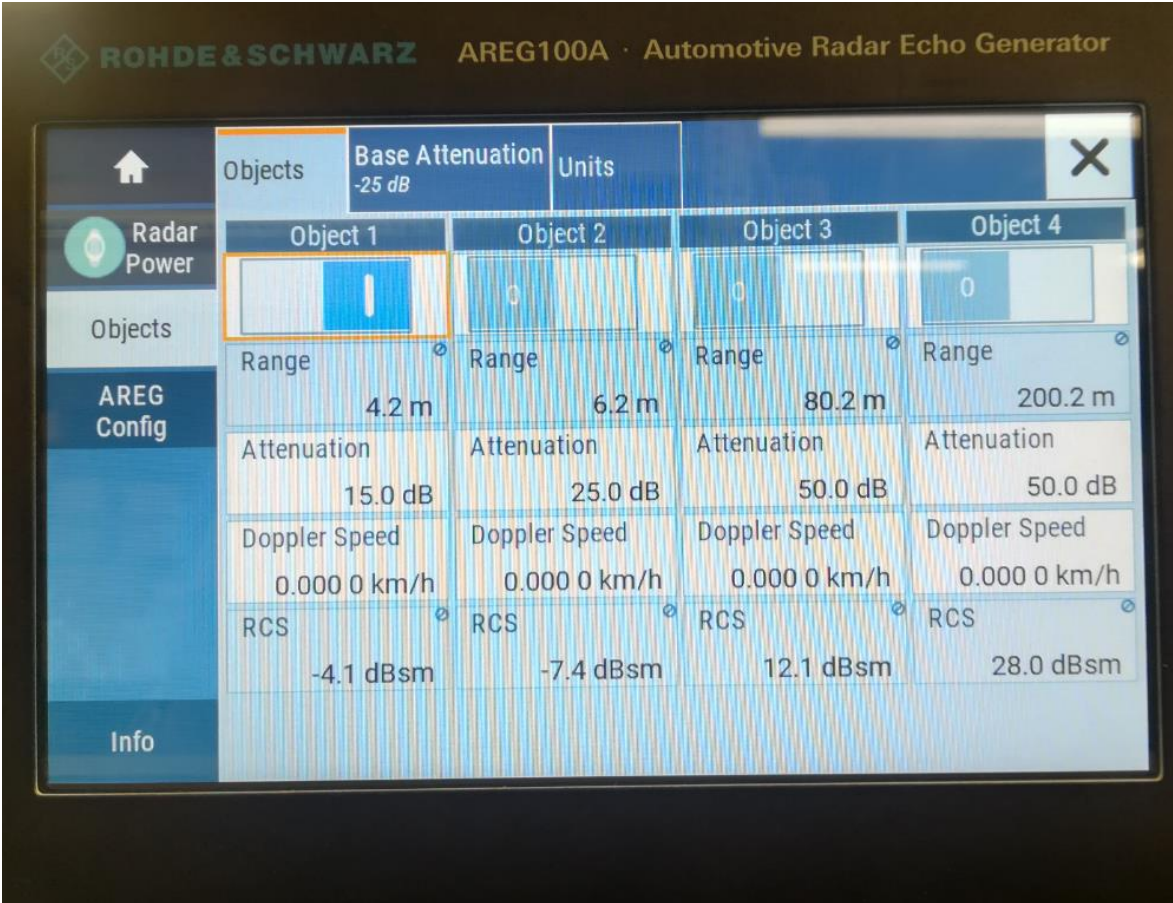


Figure 49 Available objects in the AREG100A at 1 m air gap.

The first object enabled was the closest one of 4,2 m and the results were tremendously satisfactory as the radar sensor correctly detected an object at X,Y coordinates of [0,2;4,2] m (Figure 50), correctly assessing the distance generated by the AREG100A and not detecting any other objects or multipath reflections. The 0.2 m deviation in the X axis is explained, as already addressed, by the possible misalignment in the position of the radar sensor.

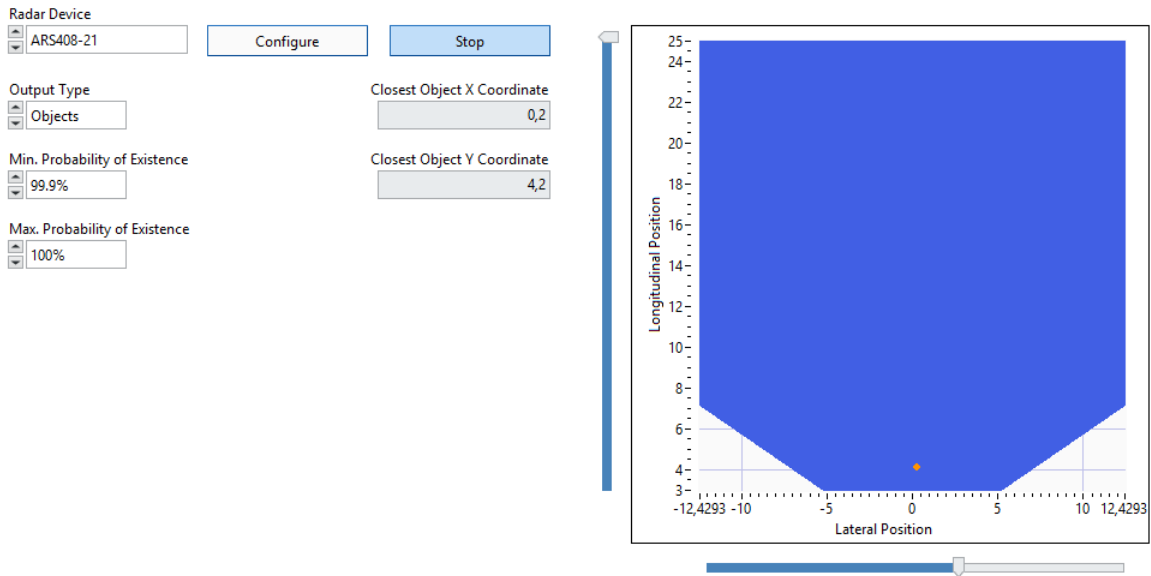


Figure 50 ARS408-21 – 4,2 m far object (AREG generated).

The second test consisted in disabling the first object and enabling the second one at a 6,2 m distance. Once again, the results were satisfactory with the radar sensor detecting an object at coordinates [0,4;6,4] m (Figure 51). The deviation in the X axis is still present and amplified by the growing emulated distance, an expected occurrence during this test. The Y axis this time around is not exactly equal to the one specified in the AREG100A but a 3.2% deviation from the expected value, specially at lower distances considering the 0,1499 m resolution at 1 GHz bandwidth (Table 1), is an acceptable value.

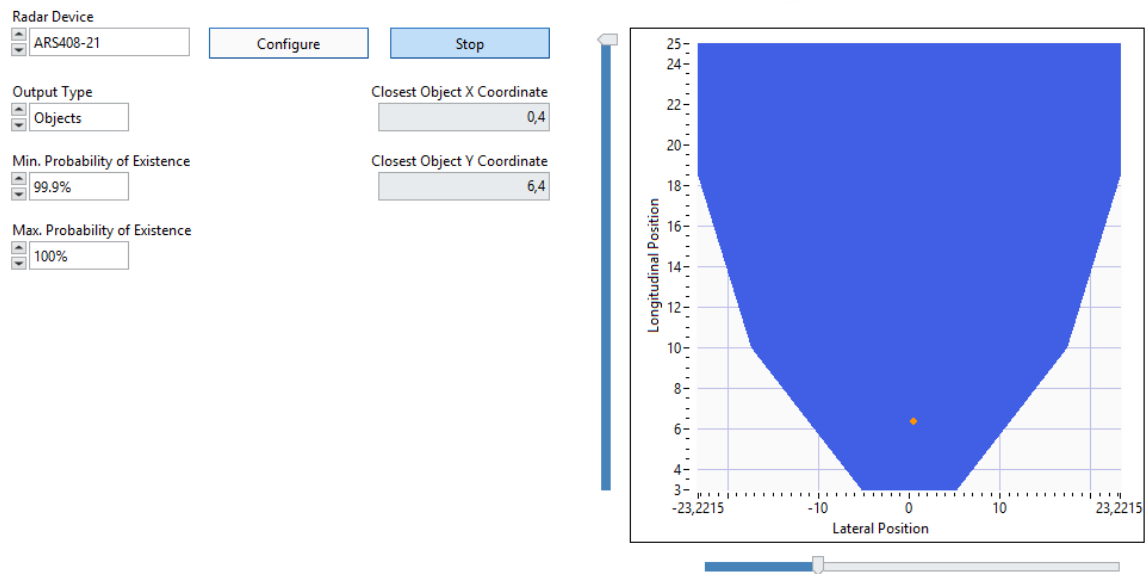


Figure 51 ARS408-21 – 6,2 m far object (AREG generated).

Once the second object is tested, the same object is disabled, and the third one of 80,2 m is enabled. The third test delivers another satisfactory and expected result of [3,6;80,2] m (Figure 52), maintaining and amplifying the X axis deviation and achieving the exact expected value in the Y axis.

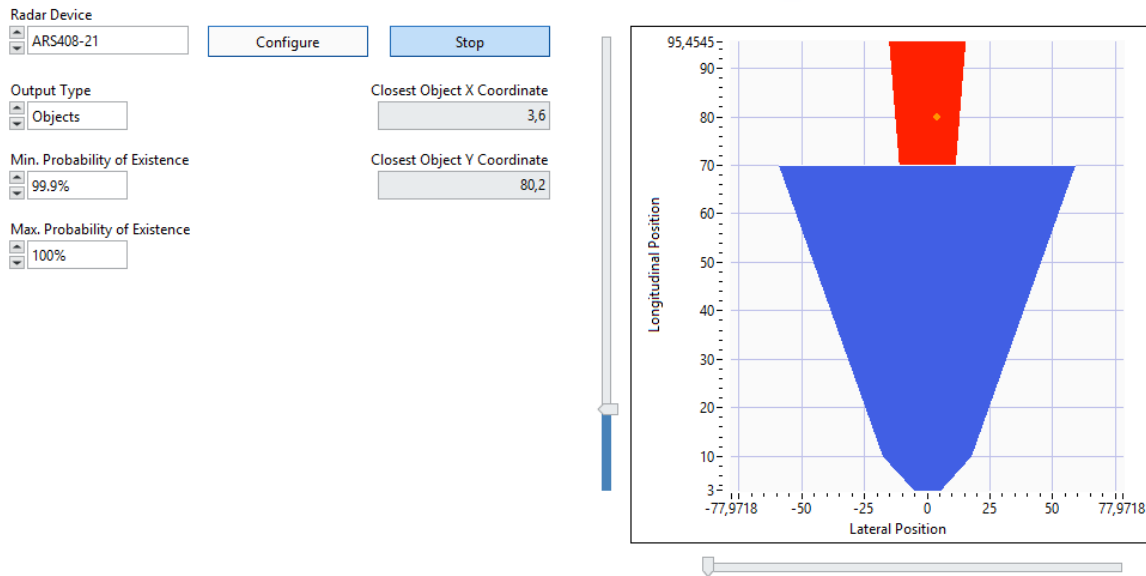


Figure 52 ARS408-21 – 80,2 m far object (AREG generated).

For the final individual object test, the furthest object is the only one enable, at 200,2 m. The tendency stays the same with detected object coordinates being [7,6;200,2] m (Figure 53), once again amplifying the X axis deviation and measuring the exact expected value for the Y axis.

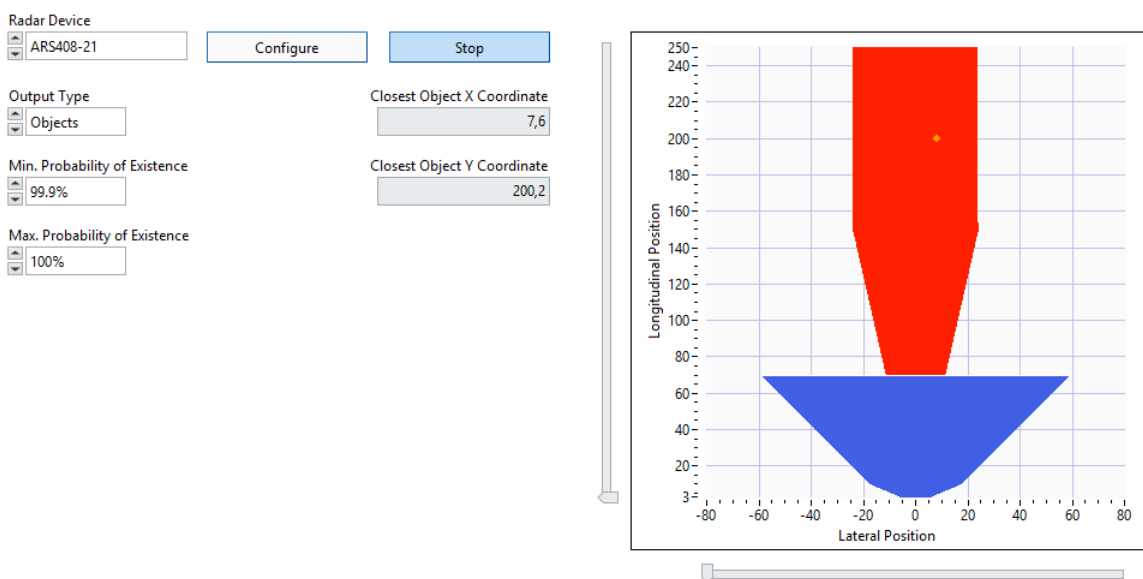


Figure 53 ARS408-21 – 200,2 m far object (AREG generated).

To understand the behaviour of the sensor in the presence of multiple targets, a final test was done in which all the objects were enabled (Figure 54). All objects were correctly detected, and the closest detected object was the frontend module itself, an object to ignore in actual testing.

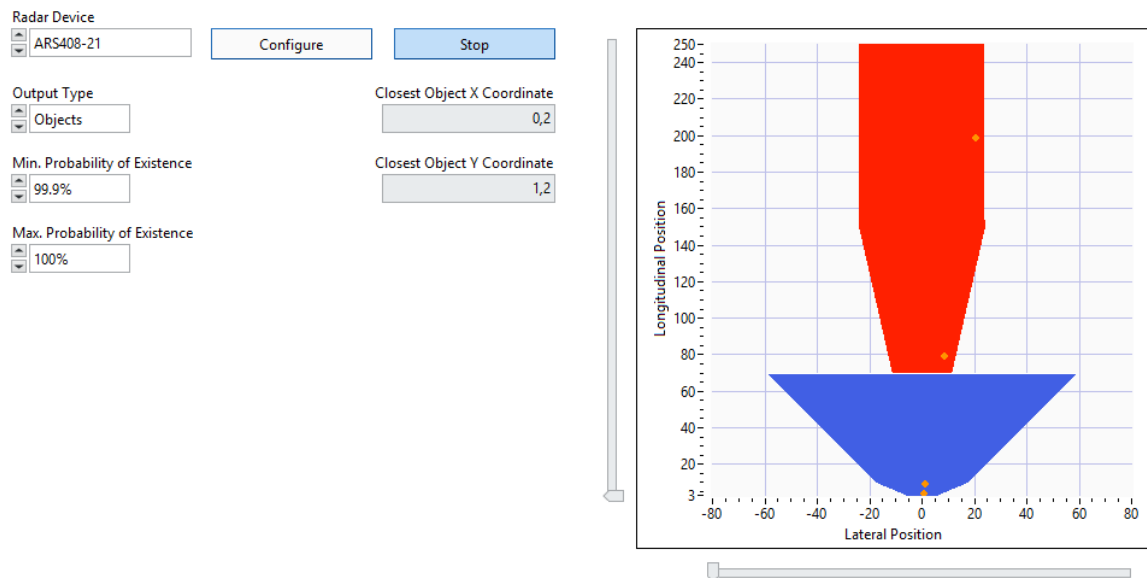


Figure 54 ARS40821 – All AREG generated objects.

Overall, the tests may be considered a success as the behaviour of the radar sensor was exactly as expected and the results validate the implementation of the AREG100A for radar sensors in the 76-77 GHz bandwidth.

6.3.2. AWR1642's TESTS

As for the AWR1642, the overall setup is the same, except for the R&S AREG100A's working frequency being changed to 78 GHz, a frequency within the 77-81 GHz band at which the AWR1642 is operational. The tests were carried out in a similar way to the ARS408-21 ones but limited to the first two objects as the maximum range for the AWR1642 stands at 50 m, drawing the focus on to the range profile returned by the sensor.

For the first test, with only the 4,2 m object being generated, the X, Y coordinates for the detected object were of [0;4,318] (Figure 55). At a resolution of 0,0375 m at a 4 GHz operating bandwidth (Table 1) and a deviation of 2.9%, the results are acceptable but as satisfactory as the ones with the ARS408-21 sensor. More interesting might be the analysis

of the range profile returned by the sensor, displaying a clear reduction in the noise inside the anechoic chamber, as expected, and a highlighted peak at the object's distance.

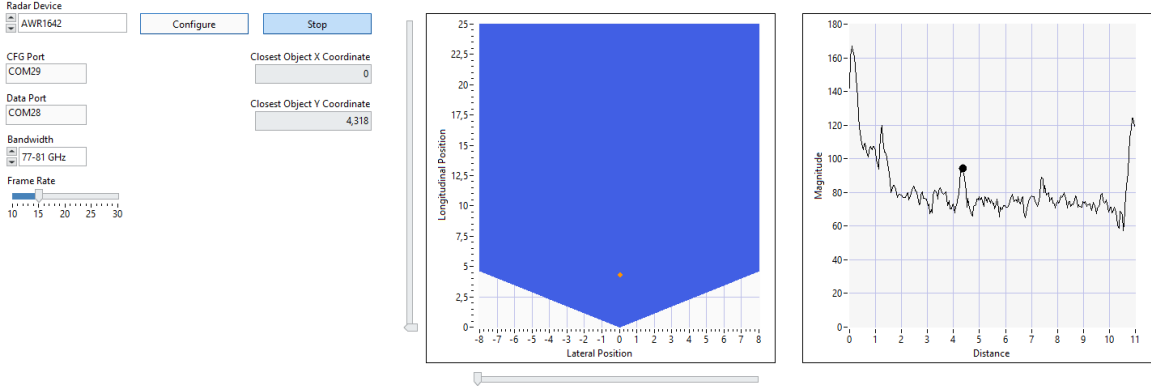


Figure 55 AWR1642 – 4,2 m far object (AREG generated).

The second test, with the 6,2 m far object, displayed similar results. The obtained X,Y coordinates of [-0,2;6,367] (Figure 56) result in a deviation in the Y axis of 2.8% and the range profile displays a similar behaviour to the one in the 4,2 m test, except for an extra detected object resulting from the highlighted peak in the end of the profile⁶.

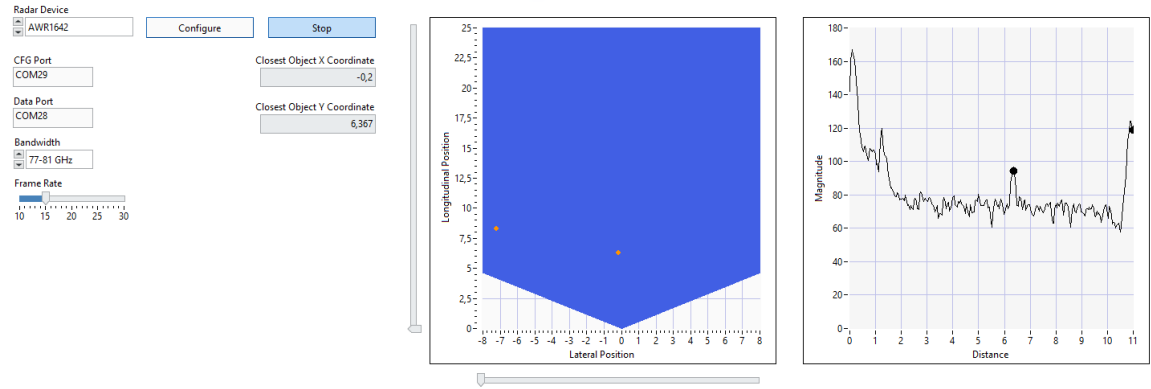


Figure 56 AWR1642 – 6,2 m far object (AREG generated).

In order to understand the possible struggles the radar sensor may encounter with multiple objects, a final test was conducted where both objects were enabled. The sensor doesn't return any object found but the range profile shows the peaks at the expected values but

⁶ The range profile for the AWR1642 sensor includes one highlighted peak in the beginning of the profile and another in the end. This pattern is present in every configuration and setup for the radar and, as such, is presumably a result of the demonstration firmware processing and may be disregarded.

not highlighted enough for the sensor to consider them as objects (Figure 57). The results in this situation could be improved by tweaking the attenuation values in the radar target generator.

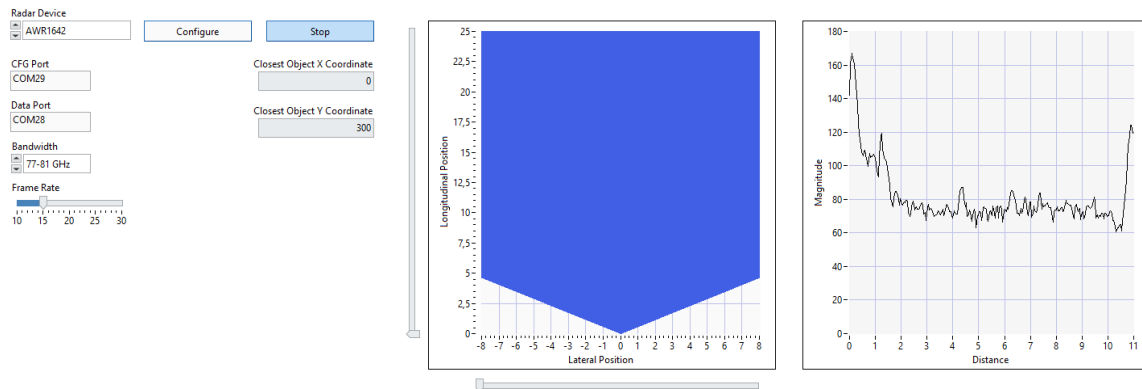


Figure 57 AWR1642 – 4,2 m and 6,2 m far objects (AREG generated).

The analysis of the tests carried out reveals that the concept for automotive radar testing in the shielded anechoic chamber developed for this tester with the AREG100A generating targets is valid. Some better results could have been obtained with the unit nest, correctly aligning the unit the frontend module. The differences in performance were not substantial when considering the better resolution in the AWR1642 but also the fact that it is an evaluation board running a demonstration program and, as such, may not be optimized to detect objects with shorter, but still highlighted, peak values in the range profile.

7. CONCLUSIONS

Throughout the entirety of this document the reasons for the need and demand for automotive radar test systems are exposed, reasons which push tester developers into analysing the multitude of requirements for these systems to be standard compliant. Once the requirements are known and understood, some complications may arise for developing a complete, compact and ergonomic tester, as these demand for either components of unusual dimensions for a manufacturing plant or highly versatile, and expensive, equipment.

CONTROLAR proposed a solution with automatized unit transposing, to cover all standard requirements, while keeping the test system at dimensions typical for production-lines. The system proposed was of considerable complexity and required a multitude of components or applications to operate in sync with each other. Once defined the overall architecture

for the software and equipment communication for the tester, the system could insert the units into the test position. In this position, the radar sensors are powered up and the two core components in an automotive radar test system, the shielded anechoic chamber and radar target generator, create the conditions to successfully evaluate the performance of the UUT.

Being such an essential part for the correct functioning of the tester, the main focus in the 6. Tests & Results chapter was validating that the behaviour of automotive radar sensors in test conditions was as expected and offered enough tools to assure the unit tested was, conclusively, in good or bad conditions, to either finish production or advance on to the next assembly step.

The results obtained assure that the R&S AREG100A is a suitable device for these types of test systems, especially when considering the effects of the shielded anechoic chamber, a core component which delivered the expected effects and guarantees that it may be successfully included in future automotive radar testers. Some other tests could have been made to validate the viability of this concept for test systems, *e.g.* more tests with products currently available in the market, inclusion of EIRP testing and Doppler Effect testing and analysis.

In an overall analysis, the concept initially proposed fits the needs for automotive radar testers and offers satisfying performance when validating automotive radar testers object detection, its core functionality. The test system also has ergonomic positions for the operator to work and dimensions suitable for manufacturing plants. The conjunction of this factors renders the tester's concept as a valid solution to be offered to possible clients looking for systems to validate performance of their radar sensors.

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Appendix A. Published Paper

In the following appendix is found a conference paper developed on automotive radar testing by myself together with my colleagues Renato Ribeiro, Ph.D. Pedro Cruz and my advisor, Ph.D. Paula Viana for 2019 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), published September 2019 and with doi: DOI: 10.1109/APWC.2019.8870448

Automatized Solution for Over-the-Air (OTA) Testing and Validation of Automotive Radar Sensors

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Abstract—The growing importance of Radar solutions in automotive applications results in new standards to be met and more demanding performances to be assured. As such, Radar developers require testers capable of guaranteeing compliance with the specified criteria. This paper presents a preliminary approach to allow over-the-air (OTA) testing and validation of 76-77 GHz and 77-81 GHz Radar units in production lines, covering not only pass/fail conditions, but also determination of the Radar antenna array radiation diagrams (in azimuth and elevation) through a calibrated external power sensor. Preliminary measurements on an open environment test bench are shown for different Radar bandwidths (1 GHz and 4 GHz), illustrating the importance of a clean and shielded anechoic chamber environment as a baseline approach.

Keywords—Automotive radar, target simulator, tester, European Standards, anechoic chamber.

I. INTRODUCTION

RADAR stands for **R**adio **D**etection **A**nd **R**anging, expressing the technology main application: target detection and ranging employing radio waves. Most of technology developments were made before World War II and were mainly focused on military applications, with some of the most relevant contributions coming from the Soviet Union, United States of America and Great Britain [1], [2]. As the potential for targeting enemy troops and vessels became evident, new and optimized functionalities, such as better resolution and portability, were developed attending to the technology capabilities. It was just a matter of time until the use of radars in civil scenarios came to consideration. For the automotive industry, detecting vehicles in situations where collisions would mean high costs, serious injuries and potential death, this technology may contribute greatly. For this purpose, the radar systems are required to be of small dimensions, high resolution and, most importantly, low cost.

Small radar systems can contribute for implementing several car features such as adaptive cruise control (**ACC**), blind spot detection, rear collision warning and autonomous emergency break (**AEB**), promoting safer driving and paving the way for advanced driver assistance systems (**ADAS**) growth. Being autonomous driving such a sought-after goal in the current automotive industry and radar one of the more predominant technologies in the race towards it, radar technology regained a new focus in development and performance requirements [3], [4].

The impact that these new applications may have in human everyday safety, introduced the need to define standard testing

approaches which consider all aspects needed to assure the new radar devices working in bandwidths such as 76-77 GHz and 77-81 GHz will be thoroughly tested under the correct conditions. The EN 301 091, EN 302 264, EN 303 396 and EN 301 489 [5], [6], [7], [8] define the set of tests and the conditions for testing equipment before it goes to the market.

II. RADAR WORKING PRINCIPLE

The implementation of radar devices in public vehicles and autonomous driving is supported by the technologies' characteristics and its resilience in poor weather [9]. Despite the same working principle as the ultrasonic sensors that are sometimes used as parking sensors and the LiDAR (Light Detection And Ranging), the radar differentiates itself in the electromagnetic waves it uses for its signals – radio waves with frequency bands ranging from 16 kHz to 248 GHz (radiolocation purposes). According to the International Telecommunication Union (ITU), the frequency band 77.5-78 GHz is reserved for short range radar for ground-based applications, including automotive radar. Allied to the ITU reservation of the frequency band, there is also the IEEE designation for radio-frequency bands that assigns letter “W” for the band that ranges from 75-100 GHz. Both the assignments allowed the automotive industry to accommodate the 76-81 GHz band for the current automotive radars since both the 74-76 GHz band and 81-84 GHz are employed by mobile and broadcasting services [10], [11].

Regardless of all the regulations applied to the frequencies available for each kind of service, the method for detecting objects remains the same – the radar device emits a signal through its transmitter, uses a duplexer to switch its antenna from transmitter to receiver and uses said antenna to capture the reflected waves from possible objects in view [9].

Radars can then be divided in mainly two types: pulsed radars and continuous wave (**CW**) radars. Pulsed radars emit high frequency pulses travelling at the speed of light, c , and obtain the distance, R , to the target from the elapsed time, Δt , between the emitted signal and its reflection:

$$R = \frac{c\Delta t}{2} \quad (1)$$

CW radars operate in a different way and present themselves as more interesting solution for automotive radar, especially frequency modulated CW radars (**FMCW**). In those kind of radars, the device emits a signal with a known frequency, f_0 , and detects continuous signals with frequency f . The difference in frequencies is known as the Doppler-shift.

In non-modulated cases it is solely possible to detect the target relative velocity, Δv :

$$f = \left(1 + \frac{2\Delta v}{c}\right) f_0 \quad (2)$$

Modulating the frequency of the emitted signal, like in a FMCW radar, makes possible to obtain both a frequency shift, Δf , and a time shift, Δt . This way it is possible to obtain the target's range due to the direct proportionality between frequency shift and travelled distance:

$$R = \frac{c}{2} \Delta t = \frac{c}{2} \frac{\Delta f}{df/dt} \quad (3)$$

III. EUROPEAN STANDARDS

A. EN 301 091

The EN 301 091 [5] is an ETSI, European Telecommunications Standards Institute, standard applied to short range devices and radar equipment operating in the 76-77 GHz range. The first part of this standard relates to ground based vehicular radar and mainly covers the device specifications in terms of signal power by the transmitter, the working frequency and the radiated power by the receiver. Aspects related to specific applications such as wanted performance and its relevant properties (e.g. range, relative speed, azimuth angle) are to be declared by the manufacturer.

B. EN 302 264

The EN 302 264 [6] is an ETSI standard applied to radar equipment operating in the 77-81 GHz band. The first part of this standard describes the technical requirements the tester should comply with, along with the methods used to carry out the test for the device. It includes the specification of some of the critical components in the tester, such as the shielded anechoic chamber and pyramid absorber to be applied on internal walls.

C. EN 303 396

The EN 303 396 [7] is an ETSI standard applied to short range devices. This standard describes measurement techniques for automotive and surveillance radar equipment. Required measurements may be made following a variety of procedures, each with its own limitations. Some of the conformance measurements are the radiated peak power, signal-to-noise ratio, etc.

D. EN 301 489

The EN 301 489 [8] is an ETSI standard responsible for covering the Electromagnetic Compatibility (EMC) requirements for short range devices working in both 76-77 GHz and 77-81 GHz bands.

In order to achieve a radar tester capable of covering both the longer-range radar of 1 GHz bandwidth (76-77 GHz) and the shorter-range radar of 4 GHz bandwidth (77-81 GHz), all four European Standards referred must be considered. The compliance with these standards shapes the tester into an extremely well-prepared system, but it also exponentially increases the complexity of such a solution. This high complexity may result in some testers being brought into the market with a large focus in verifying the device overall performance, disregarding some of the imposed standards requirements.

IV. OTA TESTING AND AVAILABLE SOLUTIONS

In order to comply with the standards specified, a controlled environment simulating free space conditions for over-the-air (OTA) testing must be considered. These conditions shall be assured by a shielded anechoic chamber to guarantee that the Radar device to be tested can be assessed under different conditions. This anechoic chamber becomes one of the most important components of the tester and shall be designed in such way that it guarantees the external interferences mitigation and distance between the device under test (DUT) and target generator antenna as specified by the standards for the product to be tested.

The critical aspects of the chamber consist in shielding the surrounding walls and coating them with RF absorbers. The ETSI EN 302 264 proposes a shielded chamber 5 metres high with a base area of 10 by 5 metres along with absorbers approximately 1 metre high. This kind of chamber is obviously unsustainable for a production line environment due to its dimensions, being more focused on highly mandatory R&D environments.

In order to reduce the size of the anechoic chamber and still guarantee the correct functioning of the radar device and validation of its performance, the Fraunhofer distance, is a condition to be met. Such a distance represents the differentiation point between near- and far-field in physically larger antennas. These are electromagnetic fields around the transmitting antenna and the main idea to retain is that in the far-field the transmitting waves assume more consistent and predictable behaviours making it the ideal region for carrying out tests. The Fraunhofer distance, R , can be calculated from the largest dimension of the transmitting antenna, D , and the wavelength of the transmitted signal, λ , like such [12]:

$$R = \frac{2D^2}{\lambda} \quad (4)$$

Assuming an antenna in which its largest dimension is 3 centimetres long (DUT to be utilized later on for measurement examples), for a 78 GHz signal, i.e., a wavelength of 0.00384 metres, the Fraunhofer distance is 0.468 metres. As such, the anechoic chamber can be reduced to accommodate such a distance between the DUT and the tester antenna, keeping its testing validity and assuring also margin for absorbers (something like 10 centimetres on top and bottom walls), reserved distance for larger antennas and safe zones for moving both the antenna and DUT, a typical length for an anechoic chamber could be around 1.5 metres in height.

Considering the dimensions of the anechoic chamber, even after shrinking it to more reasonable sizes, the overall height (in case of a vertical tester) or length (in case of a horizontal tester) it becomes clear that one of the biggest limitations of the tester will reside in keeping its ergonomic form factor and acceptable sizes for a production plant.

Important metrics to be emulated by the target generator system include characteristics like: signal delay (to represent objects at different distances), frequency or doppler shift (to represent objects at different velocities/directions, and signal attenuation (to represent different object dimensions and reflection levels, also known as radar cross section – RCS).

RCS is a parameter of utmost importance to be emulated by the Radar target reflector. It is important being able to produce power-controllable echo signals to represent the reflectivity coefficient of a given simulated object, as for example, a truck, a pedestrian or even a fixed traffic signal. This concept is mathematically characterized by the radar

cross section (RCS), typically given in square meters (m^2) or decibels relative to one square meter (dBsm), [9].

Next sections will briefly cover the possibilities to construct Radar target reflectors from the theoretical ones to the commercially available solutions.

A. Passive Target Reflector

When it comes to simulating objects inside the anechoic chamber, the simplest way passes by using a passive echo reflector, which could be represented by corner reflectors made with different metallic shapes and sizes (e.g. triangular anodized aluminium) or by a short/open wound-up waveguide with a horn antenna. Another well-known passive radar reflector is the Luneburg lens, which provides a radar cross section (RCS) much higher than metallic shapes and is recognized as the most efficient passive radar reflector. Even though a huge variety of objects with different RCS patterns, this brings the disadvantage of being unpractical to fit such a solution inside smaller anechoic chambers, because to emulate high distances must be accomplished by at least half of that distance in real situation and due to the difficulty to create doppler shifts. Further information is available in [9].

B. Semi-Active (Electronics-based) Target Reflector

Other options consider the use of electronic devices to construct more competent Radar reflectors, capable of emulating all the main functions needed for a fixed scenario. This type of generator, typically, captures the signal emitted by the Radar device with a dual antenna system (bistatic) or with a single antenna and an isolator (monostatic), converts the millimetre-wave (mmW) radio signal to a light-based signal via an electro-optic converter and makes it travel through an optical fiber generating the round-trip delay needed, reconverts it again to a mmW radio signal and sends it back to the Radar device. The radar device will then receive the signal and compute the distance of the object as the distance travelled through the optical fiber. Most of these generators also offer the possibility of including amplifiers, attenuators, phase-shifters in the shorter distance emulated targets in order to achieve radial velocity simulation caused by Doppler/frequency shifts.

Their major disadvantage is the impossibility of varying the distance offset applied. In order to get different distances generated, a new device with altered specifications is necessary. This limitation turns these semi-active echo generators into an unsuitable device for highly specialized R&D labs focused testers, despite being ideal for mass production OTA testing. Having fixed distances for all devices to be tested throughout the tester's lifecycle is a point in favour of such solution along with its price range. The only requirement to assure the viability of a fixed distance target simulator is the number of objects it emulates. A minimum of 2 objects will always be required, either for testing both a short distance target and a larger one on the same DUT or testing different DUTs, such as a short-range radar and its longer-range counterpart.

Some passive generators already available in the market are the Keysight's E8707A Radar Target Simulator [14] and the Rohde & Schwarz's AREG100A Automotive Radar Echo Generator [15]. Some of their core features include:

- Support for 24 GHz and/or 76 GHz to 81 GHz;
- Up to 4 GHz bandwidth (limited to 1 GHz in the baseline option);

- Up to 4 simultaneous simulated targets;
- Minimum target distance of 3 to 4 metres;
- Emulated distances up to 300-400 metres.

As expected, these two simulators cover most needs for mass production-based testing, having their targets defined and set from the moment they are manufactured.

C. Active Target Reflector

When it is required to test devices still in development phases or for simulation of realistic driving scenarios, the simulator should, ideally, be able to generate different kinds of real-time characteristics. For such kind of purposes, simulating multiple variable targets is a must and thus, the tester should not be performed by a passive or semi-active simulator, but an active one. The demanding processing needs of a real-time application responsible for computing the simulated targets may be accommodated by an FPGA allowing engineers to create different tests according to their current needs. This represents the utmost solution for OTA Radar testing.

One of the current market solutions for this sort of simulator is the NI's Vehicle Radar Test System (VRTS) [16]. The system is based on a PXI-based system including the PXIe-5480 VST with an onboard FPGA. The emulator presents the following key features:

- 76-81 GHz frequency range;
- Maximum of 1 GHz bandwidth
- Minimum distance target from 4 metres to more than 300 metres;
- 1 to 4 objects in the full range;

In summary, for a laboratory tester, the NI's active target simulator should be the one to select. If the focus of the tester is a mass production line, then a passive or semi-active target emulator like Keysight's and Rohde & Schwarz's could be perhaps the best compromise between price and capabilities.

V. PROPOSAL FOR AUTOMATED MEASUREMENTS

In order to achieve a tester that matches the essential requirements of the referred standards, ergonomic needs and acceptable dimensions for a production line, an automated solution should be proposed including the important target generator and other relevant features. Fig. 1 shows the layout of the tester proposal for the OTA automated load/unload Radar testing solution.

The tester is designed to include a shielded anechoic chamber that meets the requirements of the standards, as well as keeping an ergonomic loading position for the DUT. The design also contemplates the possibility for some scalability at the top while maintaining an acceptable height under 2.20 metres commonly accepted as the good height for factory production lines.

The target simulator selected for this tester was the R&S AREG100A because it enables the emulation of up to 4 objects and brings the possibility to cover the entire 76-81 GHz frequency range. It includes an undisclosed solution for automating the loading of the DUT into its working position inside the anechoic chamber. The DUT may also incur in pan and tilt movements, extending the range of

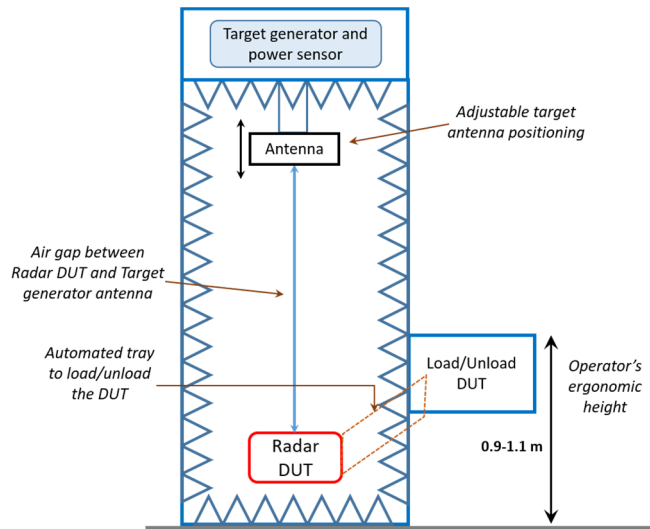


Fig. 1. Schematic of proposed OTA automated Radar unit tester.

possible tests to be made, namely extracting the Radar's radiation diagram. Finally, it also allows to change linearly the air gap distance between the DUT and the target antenna (both bistatic and monostatic options are valid).

A. Preliminary Measurements

In order to fully understand the challenge of Radar testing and the importance of an anechoic chamber, a test in an open scenario was carried out employing a Texas Instruments (TI) evaluation board, AWR1642EVM [13].

Firstly, in a test bench, the board was pointed to a cardboard object positioned 65 cm apart with a metal object located behind it to the left at around 1.20 meters to the board. A measurement of the detected objects and the relative power, in decibels, in the range of 0 to 11 metres was obtained with the radar working at 77-81 GHz band (Fig. 2).

As expected, both the cardboard and the metal objects were correctly detected at 0.70 metres and 1.17 metres, respectively. Some clutter is present from the surrounding objects in the test bench. These interferences cannot exist in the tests carried out in a tester and its removal is the main goal of the anechoic chamber, as well as blocking reflections from the original signal and reduction of noise levels.

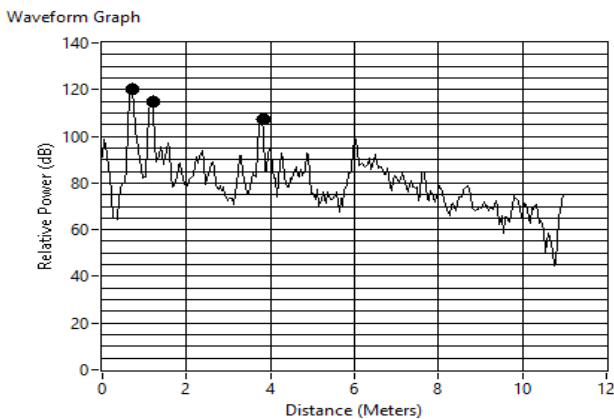


Fig. 2. Relative power and objects obtained for 77-81 GHz band operation.

A second test was carried out in the same conditions with Radar DUT working in the 76-77 GHz band (Fig. 3).

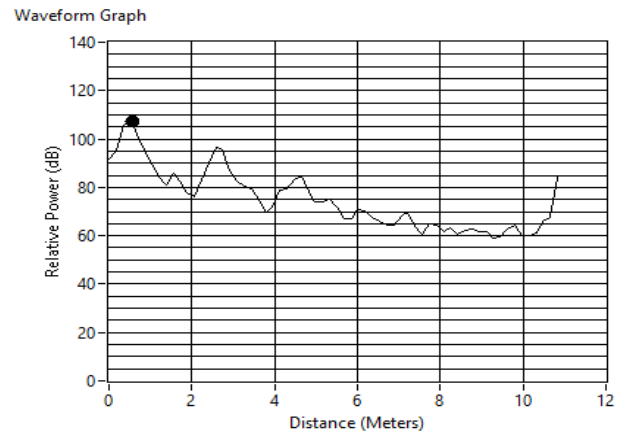


Fig. 3. Relative power and objects measured with 76-77 GHz operation condition (lower bandwidth).

This time only the cardboard object is detected at 0.75 meters. With the device's default configuration, the 76-77 GHz bandwidth offers a worse resolution, approximately 25 cm, while the 77-81 GHz bandwidth provides resolution in the order of 4 cm. For this reason, in the second test the radar is neither capable of differentiating the two objects nor measure distances in less than 25 cm intervals. These are acceptable results, since the 76-77 GHz bandwidth is reserved for longer range automotive radars and the 77-81 GHz for shorter ones, requiring better resolution.

In both cases there is some noise from the surrounding objects and reflections of the main signal. These are the faults the tester's anechoic chamber aims to solve – the partial or complete removal of all clutter that could come from external interferences, by being shielded, and from the original signal, by using absorbers preventing it from bouncing off the walls. This should guarantee that only the emulated target should be highlighted enough to be detected.

VI. CONCLUSION

The proposed automated load and unload OTA Radar test solution covers all requirements for a production line tester. In the case this same automated needs to be employed in R&D or more realistic scenarios, the final solution would need to consider just the change of the target simulator in use, exchanging the current one for an active one.

Preliminary measurements on an open laboratory environment using a commercially available Radar DUT (TI's AWR1642EVM) were presented contemplating the two modes of operation in what regards to bandwidth (1 and 4 GHz). Results shown the good functioning of the DUT in the higher bandwidth mode, by achieving a precise detection of physically located objects, but also demonstrated the need to employ such kind of measurements and DUT validation in a clean and shielded anechoic chamber environment to reduce interferences and ambient noise level.

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