MAGICA project: Crossed IFA Multi-frequency GNSS Integrated Cost-effective Antenna for Automotive Applications

Marco Antonio Vélez[a], Jose Javier Vicente[a], Joan Gemio[a], Laia Vilalta[a], Laura Tantinyà[a], Alberto Gil[b], Adrián Cardalda[c], Daniel Baños[a], Pere Mogas[a] and Joaquín Reyes[d]

[a] *Nextium by IDNEO Technologies, S.A.U, Carrer Rec de Dalt, 3, 08100 Mollet del Vallès (Barcelona), Spain*
[b] *SEAT S.A., Autovia A-2, km 585, 08760 Martorell (Barcelona), Spain.*
[c] *Rohde & Schwarz GmbH & Co. KG, Muehldorfstrasse 15, 81671 Munich, Germany.*
[d] *EUSPA, European Union Agency for the Space Programme, Janovskeho 438/2, 17000 Prague 7, Holesovice, Czech Republic.*

Abstract

The present work describes the project of a multi-band GNSS compact antenna for high precision positioning applications for the automotive industry (MAGICA project). The following results correspond to the final prototyping phase. The main objective of the project is to develop an innovative, compact, low-cost antenna for high accuracy positioning applications following the standards of the automotive market. The antenna operates in several frequency bands, including L1/E1, L5/E5 and E6, and can operate over different positioning satellite constellations like Galileo or GPS. The development of GNSS receivers for multiple band operation is consolidated in certain markets, but the challenges of the automotive market require a robust and high-performance antenna design in a compact solution at a competitive cost. The project is facing the final prototyping phase. There have been several design loops together with the mechanical department, to reach a feasible and cost-effective antenna system ready for mass-production, suitable for the autonomous driving operation. Before the definitive integration in vehicle, the prototype obtained provides really promising results in free space environment. The antenna, besides being technically and cost-competitive, fulfils the mechanical and electronic design requirements of the automotive sector.

Keywords 1

Antenna, compact, high accuracy, autonomous driving, multi-band, multi-constellation, GNSS, navigation, high precision, cost-effective, automotive industry, Galileo, E6

1. Introduction

Fully autonomous vehicles are expected to be a reality by 2040, but vehicles with autonomous capabilities will be a reality much sooner (2024-2025) [1]. One of the main challenges for autonomous vehicles is to have a high accurate, instant available and robust positioning. The vehicle should know in every moment its absolute position and its relative position with reference to the rest of the vehicles, objects and people in the surrounding; this is one of the key aspects for autonomous driving safety [2].

Absolute positioning makes reference to the ability to locate the vehicle in a map. The receivers rely on the GNSS service to provide the absolute positioning [3]. With the revitalization of the GLONASS constellation and the emerging constellations Galileo and BeiDou together with the traditional one (GPS), the possibility to get an available, reliable and accurate positioning has increased [3].

ICL-GNSS 2022 WiP, June 07–09, 2022, Tampere, Finland
EMAIL: marcoantonio.velez@nextium.com (M.A. Vélez); josejavier.vicente@nextium.com (J.J. Vicente); joan.gemio@nextium.com (J. Gemio); laia.vilalta@nextium.com (L. Vilalta); laura.tantinya@nextium.com (L. Tantinyà); alberto.gil@seat.es (A. Gil); adrian.cardalda-garcia@rohde-schwarz.com (A. Cardala); daniel.banos@nextium.com (D. Baños); pere.mogas@nextium.com (P. Mogas); joaquin.reyes@euspa.europa.eu (J. Reyes)
ORCID: 0000-0002-5191-6110 (M.A. Vélez); 0000-0002-0113-0726 (J.J. Vicente); 0000-0001-5589-7677 (J. Gemio); 0000-0003-4024-4627 (L. Vilalta); 0000-0001-8155-1231 (L. Tantinyà); 0000-0002-0875-2309 (A. Gil); 0000-0001-6018-1294 (A. Cardala); 0000-0002-3972-4183 (D. Baños); 0000-0002-3787-8808 (P. Mogas)

The work presents the measured technical results of a first prototype of the cost-competitive antenna for the automotive market, providing a multi-band and multi-constellation solution. Current antennas in the automotive market are commonly dual frequency antennas covering a combination of L1 with one of these two other GNSS frequency bands, L2 or L5. The antenna presented can receive simultaneously at least L1/E1, L5/E5 and E6 bands fulfilling the defined requirements. The L5 band lowers the risk of interference, improves the multipath protection and it also makes easier the reception of the non-data signals (pilot signal, synchronization...) in unfavourable and obstructed conditions. This is the reason why it was preferred to cover L5 as a design requirement over the L2 band. The operation capability on the E6 band is one of the distinguishing features of the design, E6 provides a high data rate transmission making it ideal for applications that require global, high-accuracy positioning. At later stages of the project, it will be evaluated the influence of the vehicle structure on the response of the antenna by means of vehicle level measurements of the antenna inside a real vehicle spoiler.

Multi-constellation and multi-frequency antennas can be found in other markets [4] [5], but they do not fit the specific constraints of the automotive sector: compact size, robustness, cost-competitive, and suitable for high dynamic receivers. The design should meet all those constraints while ensuring the needs of the safety for autonomous driving applications.

A common approach for the design of automotive GNSS antennas is to use ceramic patches with a narrow band response. This approach has been adequate for single band operation for being very compact, low-profile structures that can achieve a good performance at a low cost. However, to cover multiple bands with a higher bandwidth, this kind of solution is not optimal. In general, the approach of the antenna makers is the use of stacked patch structures to obtain this multi-frequency behaviour [6]. To achieve acceptable operating bandwidths, multiple and very large stacked patches are used making the weight and cost very high [7]. With lower patch bandwidths, the range of operation and/or the performance are not very suitable. In addition, a large ground plane would help maximize the performance of the GNSS patch antennas. However, the position of the antenna on the ground plane affects directly to an antenna particular tuning, with the direct impact on the integration in the vehicle.

In contrast, the MAGICA antenna is a solution based on a metal sheet volumetric topology, which allows the desired multi-frequency behaviour with a wide bandwidth, while remaining a low cost and a very low weight antenna. Being a standalone solution, the antenna does not need any additional ground plane for its optimal operation, improving the in-vehicle integrability.

One of the main challenges is to meet all the requirements while ensuring the manufacturability of the antenna, which has a major impact on the cost.

After the simulation stage (as presented in [8]), it is time to develop the prototypes that confirm the performance of the design. The results of this prototyping stage, the associated technical results of the measurements and the steps to follow will be explained through the paper.

Nextium by IDNEO is involved in the development of the design and the coordination of the consortium of the MAGICA stakeholders. Additionally, the consortium is composed by the car manufacturer SEAT S.A. which provides the requirements in terms of cost and integration and a specific vehicle model to integrate the antenna under test, and Rohde & Schwarz that develops and provides all the RF and instrumentation equipment necessary to test the antenna capabilities, including the novel Galileo E6 band.

The paper presents a brief explanation of the methodology applied during the project in section 2. It is followed by the results of the technical performance in section 3 including the measurements of the radiating element or passive antenna, RF front-end amplifier and also the entire system (active antenna) at prototyping stage. Section 4 presents main conclusions and the future next steps.

2. Antenna requirements and design methodology

The results presented in this paper are the consequence of all the design loops (i.e., component research and definition, simulation, prototyping and validation), manufacturability studies, economic analysis, etc. with the relevant disciplines involved in the whole process such as RF, HW, mechanical engineering, purchasing department among others. The main design target when checking whether the antenna is aligned to the project might seem the RF technical requirements that provide high accuracy positioning. However, there is also a cost-effective goal very important in the automotive sector that is strongly related to the manufacturing process. This manufacturing process not only has to be feasible to keep a reasonable cost, but also has not to alter the technical performance. Therefore, a trade-off among these three aspects is always present along the design phase of the project.

The design process has been performed in several steps.

The radiating element was designed with a 3D electromagnetic solver for antenna design and includes a polariser circuit; the RF front-end amplifier was developed by means of an electronic and electromagnetic solver for RF circuit design. Once a candidate design of the two electronic components was achieved, the prototype stage started, following the methodology aforementioned.

For its characterization, a multi-probe system in an anechoic chamber in free space condition has been used for near-field measurement of the radiation pattern measurement. The free space condition means that the antenna is in a condition in which there are neither interfering signals (reflections), nor objects or materials that might alter the antenna's radiation properties. As it is shown in Figure 1, the MAGICA antenna has been characterised in free space condition (antenna alone) as well as with the antenna integrated in the spoiler environment.

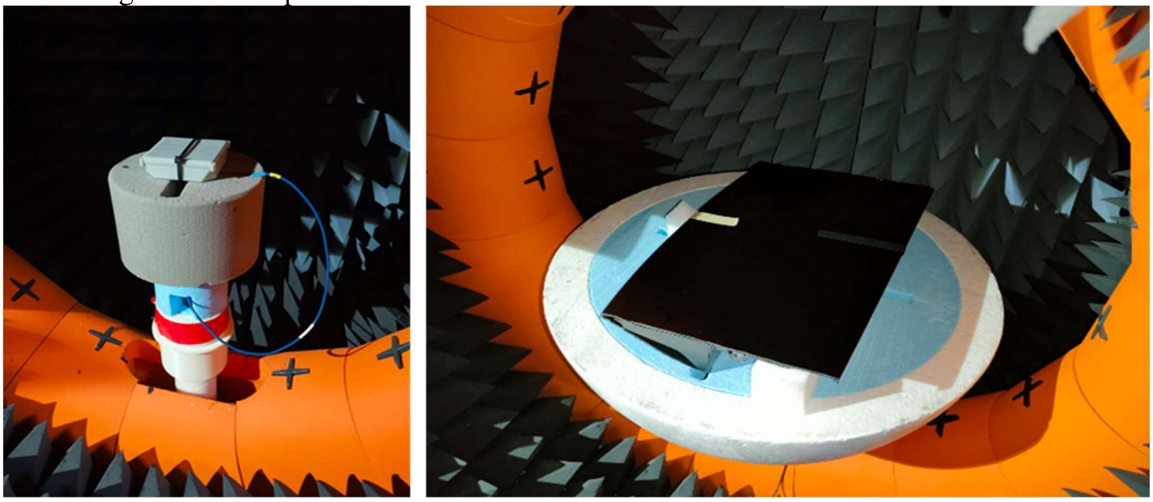

Figure 1: Radiating element inside the multi-probe system in an anechoic chamber for radiation pattern characterization in free space condition. Left picture: Antenna alone. Right picture: Antenna integrated in SEAT S.A. spoiler environment.

At the later stages of the project, the antenna performance is going to be evaluated integrated inside a vehicle (provided by SEAT S.A.) at JRC laboratories. On the other hand, Rohde & Schwarz is developing the proper RF test equipment and laboratory environment for the antenna plus GNSS high precision receiver testing including the E6 bands. Once all these milestones succeed, a positioning field test with the MAGICA antenna will occur, obtaining relevant metrics and characterising how well the antenna system developed during this project.

For the MAGICA antenna design, the more relevant technical requirements are summarised in Table 1.

Table 1
MAGICA project technical requirements specification for the GNSS frequency bands.

Parameter	Requirement
Frequency bands	1164 -1214 MHz (L5/E5a/E5b), 1260 - 1300 MHz (E6), 1559 - 1591 MHz (L1/E1)
Antenna Input Impedance	50 Ω
VSWR	2:1
Peak Realised Antenna Gain	> 2dBic at zenith
Axial Ratio at zenith	≤ 3 dB
GNSS Amplifier Gain	≥ 30 dB
Noise Figure (50 Ω)	≤ 3 dB

Phantom Supply Voltage	4.5 V - 5.5 V
Current Consumption	≤ 40 mA
Overall antenna dimensions	less than 100x100x30 mm

3. Results

The MAGICA antenna system presented in the paper consists of the following elements:

- The radiating element including the polariser circuit is responsible for antenna bandwidth, polarisation, radiation pattern, phase centre, multi-frequency characteristics.
- The RF front-end low noise amplifier (or RF front-end amplifier) with its frequency response defines frequency selectivity, noise factor, total antenna gain, phase centre stability, and complete antenna bandwidth.
- The housing is the plastic enclosure that protects the radiating element. Proper material selection to avoid any electrical influence on the antenna performance is required.

Each of the specific parts of the design has been simulated and optimised to get a feasible solution. The prototype of the MAGICA antenna has been manufactured and evaluated, and in the following subsections the relevant results of the prototype are presented showing: the performance of the radiating element, the performance of the RF front-end amplifier and the performance of the complete antenna system (in free space and in spoiler environment).

3.1. Measured results – Radiating element (without RF front-end amplifier)

The radiating element consists of a crossed IFA topology that covers the whole operating range. It has been prototyped using very thin metal sheets (0.5 mm) which offer a very low weight and a competitive antenna radiating element cost. The radiating element includes a polariser circuit to obtain the desired circular polarisation. The novel design of the radiation element offers very good performance covering all the required bands (including E6) with a compact size of 80 x 80 x 20mm and can be integrated in any area free of metal without the need of any additional ground plane. In this section, the isolated radiating element is evaluated, as a first step to ensure an adequate performance of the whole active antenna system.

The relevant results of the measurements of the radiating element are described below, please note that the measurements include the polariser circuit. This polariser circuit is based on artificial transmission lines approach, i.e., right-handed and left-handed transmission line combination for little phase shift deviation along the required bandwidth.

One of the characteristics of the antenna is the VSWR (Voltage Standing Wave Ratio), which gives an idea on how efficiently the radiofrequency (RF) power is transmitted from the source to the antenna. Typically for optimal operation, low values of VSWR are desirable.

The highlighted regions correspond to the specific operating bands. As shown in Figure 2, this requirement is almost met in all the bandwidth of operation. It is specially met in the range 1559 - 1591 MHz (L1/E1) and very close to be met in the lower frequency bands, 1164 -1214 MHz (L5/E5a/E5b), 1260 - 1300 MHz (E6). Some further adjustment with the prototype stage is on-going and with high confidence to be achieved.

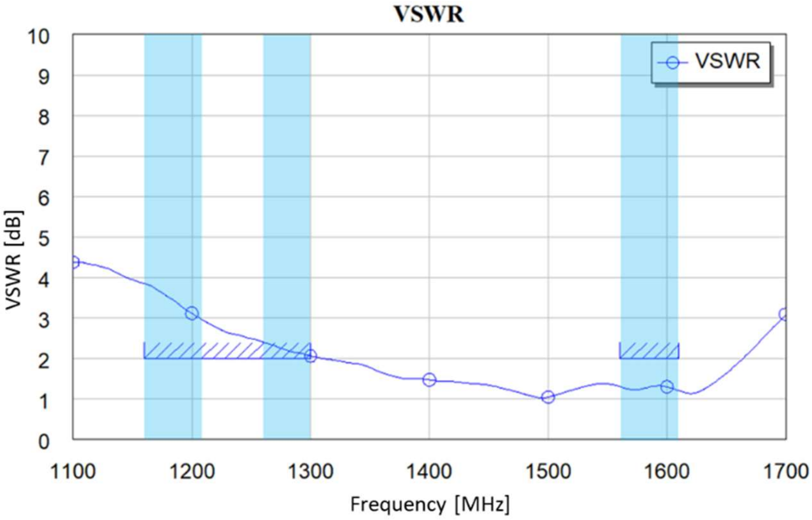

Figure 2: VSWR vs frequency of the radiating element of the MAGICA antenna including the polariser circuit

The 3D right-hand circular polarised (RHCP) gain and left-hand circular polarised (LHCP) gain radiation patterns of the radiating element at three representative frequencies of the GNSS service (1180 MHz, 1280 MHz and 1580 MHz) have been measured. As shown in Figure 3, at zenith, the performance is purely RHCP with peak gain values from 2 to 4dBic (Figure 4) in almost all the bands of interest and with a strong rejection to LHC polarisation.

The axial ratio is the ratio between the semi major and semi minor axis of a circularly polarised antenna pattern. It is another important parameter for circularly polarised antennas. For an ideal circularly polarised antenna both values should be the same, so the ratio is equal to 0 dB. Actually, it is hard to achieve a good axial ratio across all the requested frequency bands of operation, but as shown in Figure 5, the axial ratio of the measured prototype is below 3 dB in practically all the operating bands, which is the typical requirement for GNSS antennas, and as well in the MAGICA project.

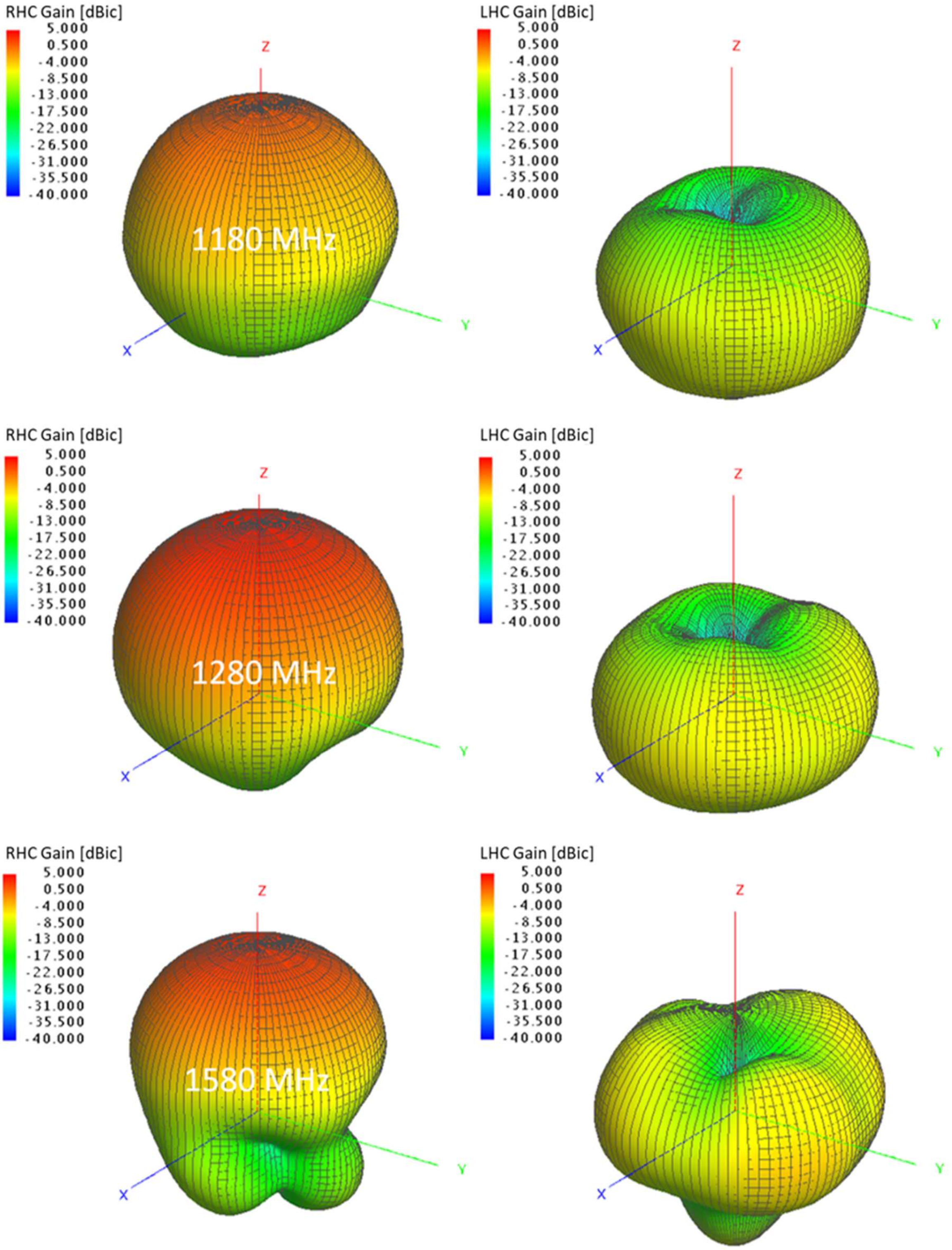

Figure 3: 3D RHCP and LHCP gain radiation patterns of the radiating element of the MAGICA antenna at 1180 MHz, 1280MHz, 1580 MHz, including the polariser circuit

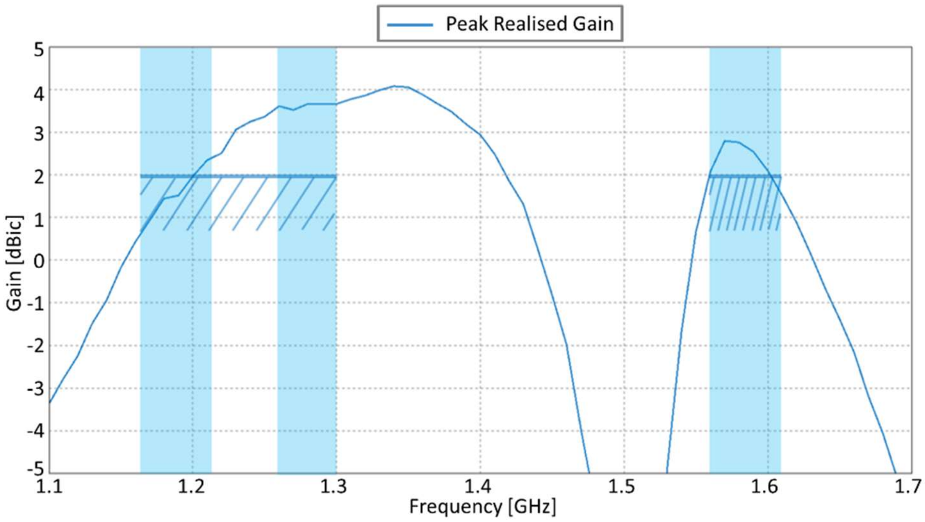

Figure 4: RHCP peak realised gain vs frequency of the radiating element of the MAGICA antenna including the polariser circuit

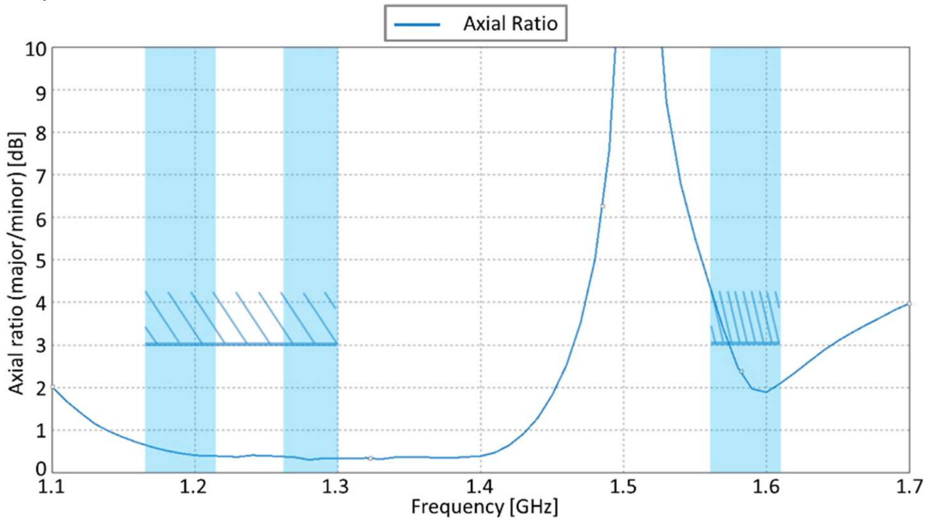

Figure 5: Axial ratio vs frequency at zenith (θ = 0) of the of the radiating element of the MAGICA antenna including the polariser circuit

3.2. Measured results – RF front-end low noise amplifier

The next element to take into consideration for the antenna system is the RF front-end amplifier. It consists basically of an amplification and filtering stage. The following section describes the measurement results of the active stage for the prototype.

The results of the measurements of the specific parameters of the performance of the active part are listed in the tables below. For convenience, the requirement specification values are presented in the last column on the right of the tables.

The active elements are phantom powered through the connector and present a wide range of power supply operating DC voltage.

Table 2.
MAGICA antenna RF front-end amplifier DC summary performance table.

DC Specification	Measured values			Requirement
	Min.	Typ.	Max.	
Voltage (VCC) [V]	3		5.5	4.5 – 5.5
Current Consumption @ 5V [mA]		34		≤ 40

Power Consumption [mW]	170	≤ 200

Table 3.
MAGICA antenna RF front-end amplifier performance summary table.

RF Specification (typ., 50 Ω)	Measured values				Requirement
	E5A/L5	E5B	E6	E1/L1	
Gain [dB]	30.2	30.5	30.25	30.4	≥ 30
Return Loss [dB] (at connector)	8.17	7	8.74	12.55	≥ 10
NF [dB] (room temp.)	< 1.7	< 1.7	< 1.7	1.5	≤ 3
GDR [ns] in-band	13.07	3.85	5.94	1.82	*
Stability (μ)	> 1	> 1	> 1	> 1	> 1
IP1dB [dBm]	-27	-27	-27	-27	-

* ~ 10ns in-band; ~ 50ns inter-band as maximum. Based on typical values of a commercial GNSS receiver for the automotive market

The relevant plots related to the RF front-end amplifier performance are illustrated below. Figure 6 shows its frequency response at the GNSS frequency bands of interest. The values in the figure make reference to the RF front-end amplifier transmission (S21) and the reflection (S22) coefficients. Note that the return loss and the reflection coefficient have the same magnitude when expressed in dB but opposite sign. The corresponding markers are placed on the previously stated GNSS bands. As shown in Table 3, the transference of power is above the specification, even though the reflection coefficient is not fully covering the targeted value. Additionally, an optimization loop is being carried out on the RF front-end amplifier output filter stage to improve this latter parameter.

On the other hand, the GDR at E5A/L5 band is slightly above the typical value of a commercial automotive GNSS receiver. This is due to the nature of the E5/L5, E6 SAW filter, since the significant bandwidth that is demanded is almost at the limit of the capabilities of this technology. Nonetheless, no degradation is expected as this only occurs at the lower edge of the band, where less energy of the signal is allocated.

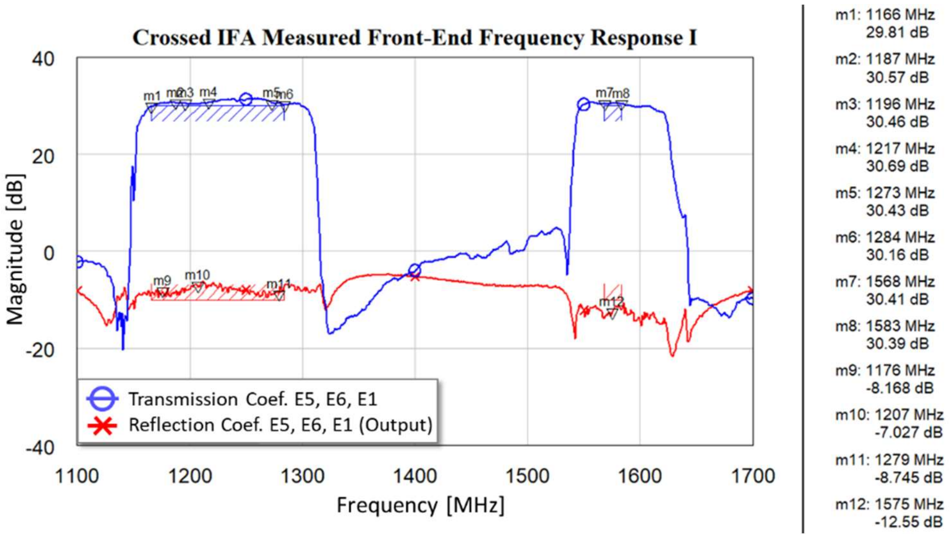

Figure 6: MAGICA antenna RF front-end amplifier transmission and reflection coefficients at the required GNSS frequency bands

On the evaluation of the RF front-end amplifier's response, one of the most relevant parameters is the noise figure. This parameter, together with the overall gain, gives an idea of the quality of the reception of the signals involved. Figure 7 shows the measured noise figure in the frequency bands of interest. This measurement, apart from the active components, includes the complete front-end circuit, with the frequency diplexer responsible for its frequency selectivity. It is important to note that the noise figure is below 3dB, which is the specific requirement defined in the project.

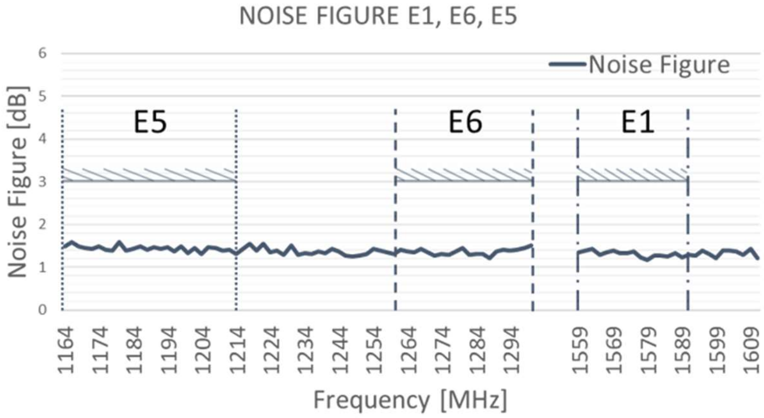

Figure 7: MAGICA antenna RF front-end amplifier noise figure at Galileo E1, E5, E6 frequency bands.

To minimise the error of the GNSS systems position and optimise the accuracy, the group delay ripple (GDR) of the RF front-end has to be controlled. The group delay ripple of the active part, Figure 8, shows a minimum delay either intra-band or inter-band.

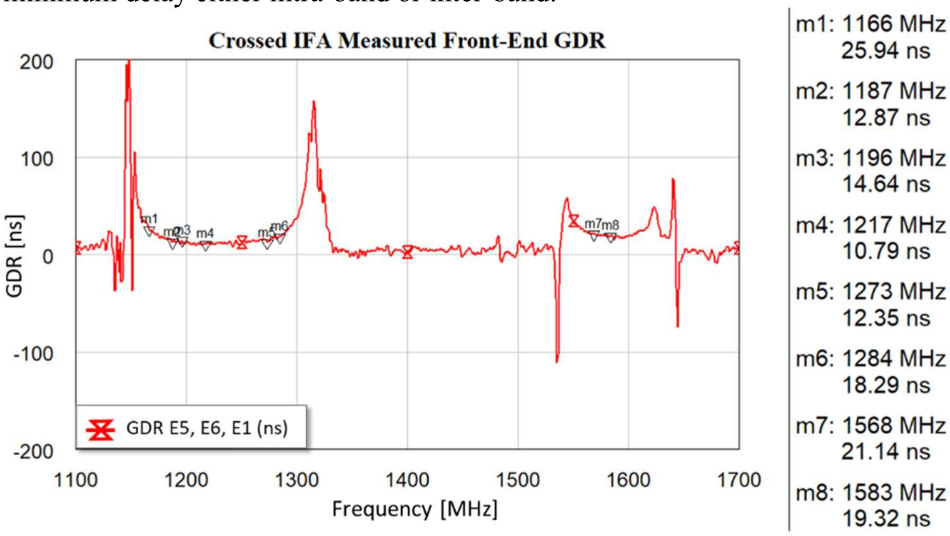

Figure 8: MAGICA antenna RF front-end amplifier group delay ripple at the required GNSS frequency bands

Despite not being a specific requirement inside the MAGICA project, the RF front-end amplifier should be capable of introducing a high level of rejection outside the operating bands. This is especially important in the case that the GNSS antenna is installed close to other antennas (i.e., telephony antenna, Wi-Fi antenna, …). Figure 9 represents the frequency response of the RF front-end amplifier but also considers the rejection at the GSM telephony frequency bands. GSM telephony is the most critical source of interference to the GNSS service due to the high-power levels operated by these systems. As it shown in Figure 9, good rejection from possible interfering GSM systems is achieved with more than 10 dB at GSM 1800 MHz and 24 dB at GSM 900 MHz.

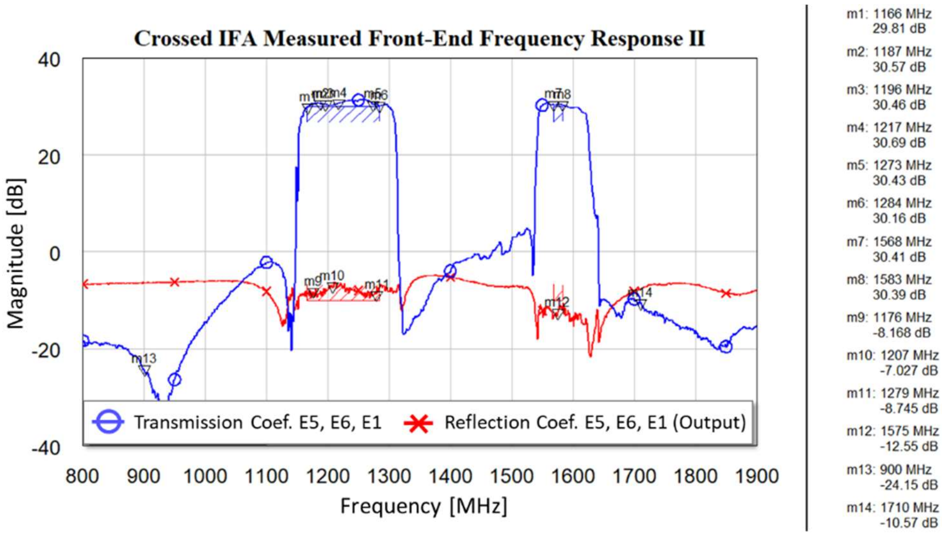

Figure 9: MAGICA antenna RF front-end amplifier rejection at GSM telephony frequency bands

Table 4 shows the measured values at the GSM telephony bands, as well as the 1 dB compression point at the input for these frequencies.

Table 4
MAGICA antenna RF front-end amplifier response at GSM telephony frequency bands.

RF Parameter at GSM (typ., 50 Ω)	900MHz	1800MHz
Rejection [dB]	24.15	10.6
IP1dB [dBm]	-16	-10

3.3. Measured results – Active antenna prototype

Once the antenna radiating element and the RF front-end amplifier have been designed and characterised individually, it started the next phase of the project which is the characterization of the complete antenna system. The active antenna prototype consists of the radiating element together with the RF front-end low noise amplifier and the housing.

The overall dimension of the active prototype is 91 x 91 x 26.5 mm. This compact design with reduced weight is attractive and feasible to be integrated in the vehicle.

Figure 10 shows the MAGICA active antenna prototype including the radiating element, the RF front-end amplifier and a coaxial cable pigtail at the left side of the image, blurred, and the housing which is the enclosure of the prototype on the right side of the image.

Figure 10: MAGICA active antenna prototype antenna structure (left) and housing (right). Blurred image due to patenting study on-going.

The antenna prototype including the RF front-end amplifier has been measured in a multi-probe system anechoic chamber in free space condition (see Figure 1 – left).

In a similar way as the radiating element was measured alone, the active 3D right-hand circular polarised (RHCP) gain and left-hand circular polarised (LHCP) gain radiation patterns of the active antenna prototype at three representative frequencies of the GNSS service (1180 MHz, 1280 MHz and 1580 MHz) have been characterised. The radiation pattern keeps the same shape as the passive antenna structure with a strong rejection of LHC polarisation, as shown in Figure 11, and with very good axial ratio performance (Figure 12). This latter fact leads to the expected peak gain values in the range of 32 to 34dBic.

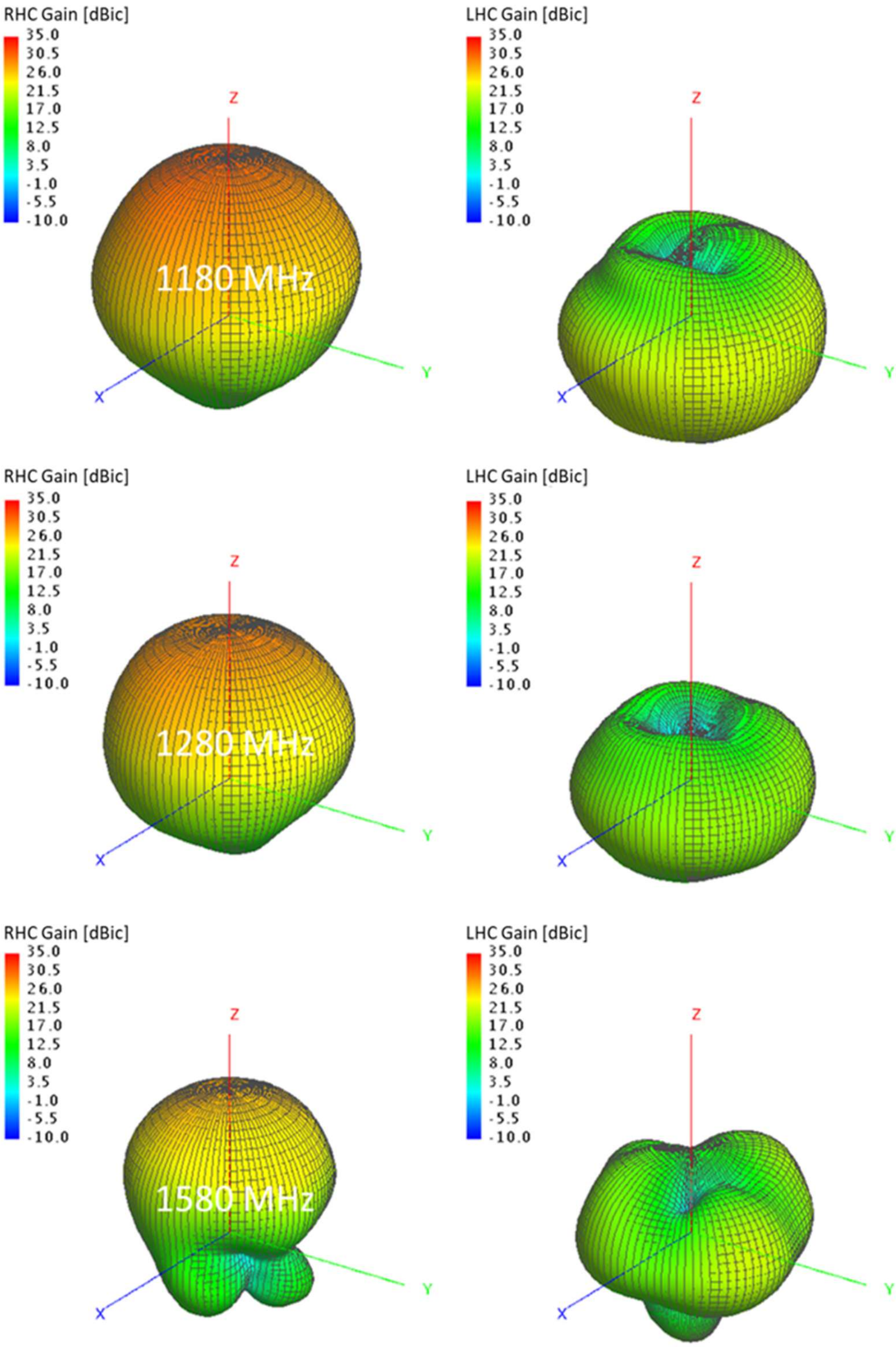

Figure 11: Active 3D RHCP and LHCP gain radiation patterns of the MAGICA antenna at 1180 MHz, 1280MHz, 1580 MHz

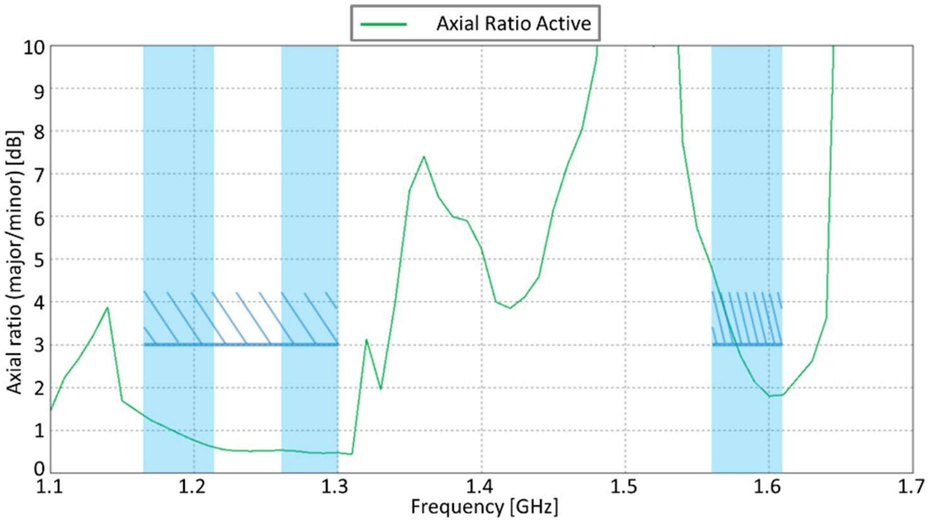

Figure 12: Axial ratio vs frequency at zenith (θ = 0) of the active prototype of the MAGICA antenna

3.4. Measured results – Active antenna prototype in spoiler environment

After measuring the active prototype in free space condition, with promising results, it was time to begin with the integration process in the vehicle. After discussing possible locations in the vehicle with our consortium partner SEAT S.A., it was decided to place the antenna inside the plastic spoiler of the car, that is "invisible" from the RF point of view and therefore, providing good sky visibility in terms of GNSS signals. The spoiler area does not have any metallic structure, which might be an issue for other typical GNSS patch antennas that require a big ground plane underneath for optimal performance. The MAGICA antenna designed in the project does not have this problem as it is a standalone solution that doesn't need any additional ground plane for optimal performance.

SEAT S.A. provided a vehicle spoiler where it was possible to install the antenna; this placement will be close to the final location in the car.

With the antenna located in the spoiler, it is possible to analyse the performance of the antenna considering the close vehicle environment and anticipate any effect that this can cause to the antenna.

The radiation pattern of the antenna has been measured, including the spoiler effects for three different and representative frequencies of the GNSS operating bands, as shown in Figure 1 – right.

It is important to notice that the shape of the radiation pattern is not distorted due to the spoiler effect keeping the expected and desired shape with peak gains pointing to the zenith and great discrimination of the LHC polarization (see Figure 13). The response of the antenna has been shifted down in frequency, as it was expected due to the dielectric and plastic effect, and the axial ratio of the integrated antenna now fits perfectly with the axial ratio requirement (see Figure 14).

The results of the measurements for the first prototype of the antenna system show an appropriate response of the system and they are in good agreement with the outcome from previous design steps, i.e., simulation results (see [8]).

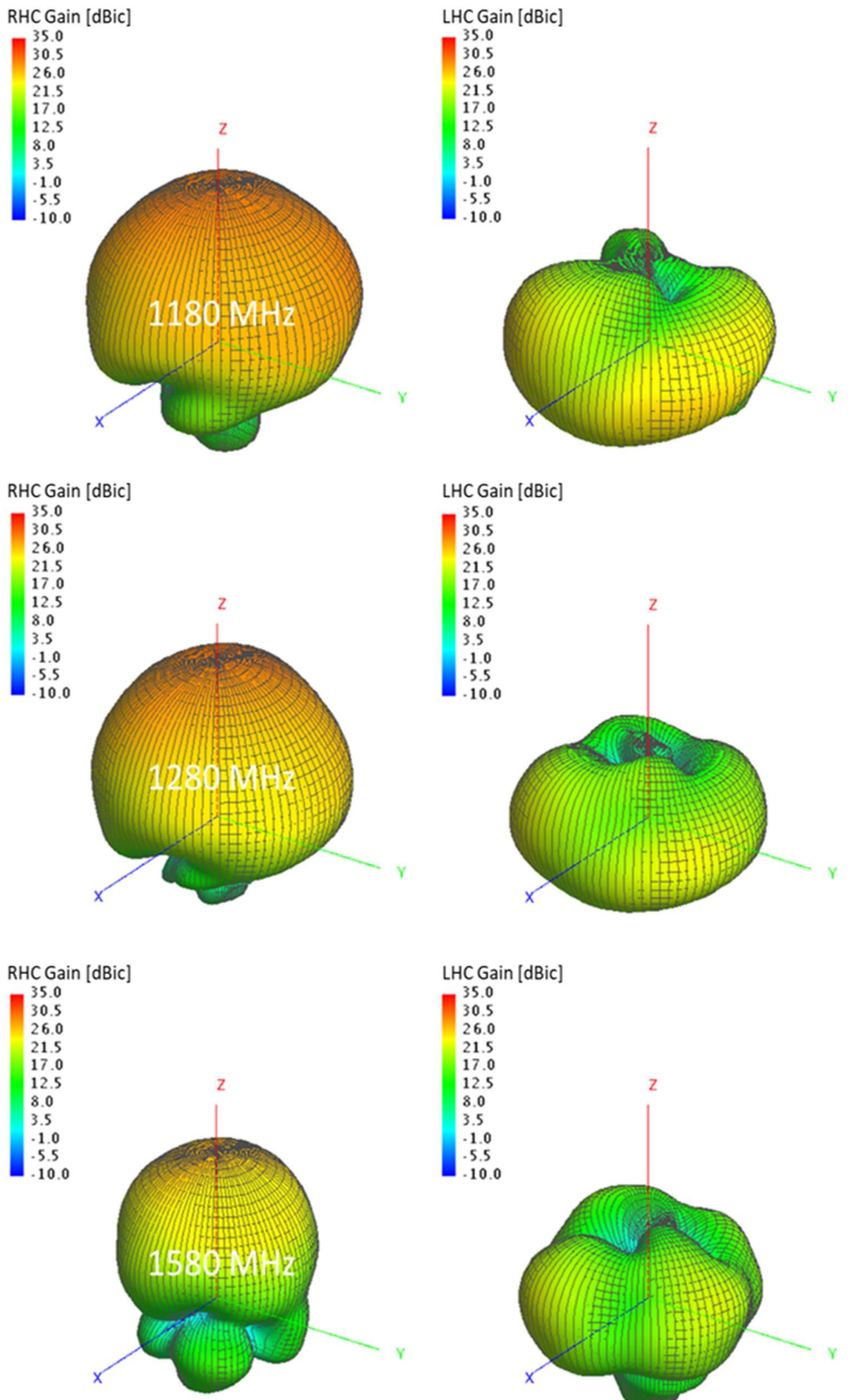

Figure 13: Active 3D RHCP and LHCP gain radiation patterns of the MAGICA antenna at 1180 MHz, 1280MHz, 1580 MHz installed in a piece of the spoiler environment

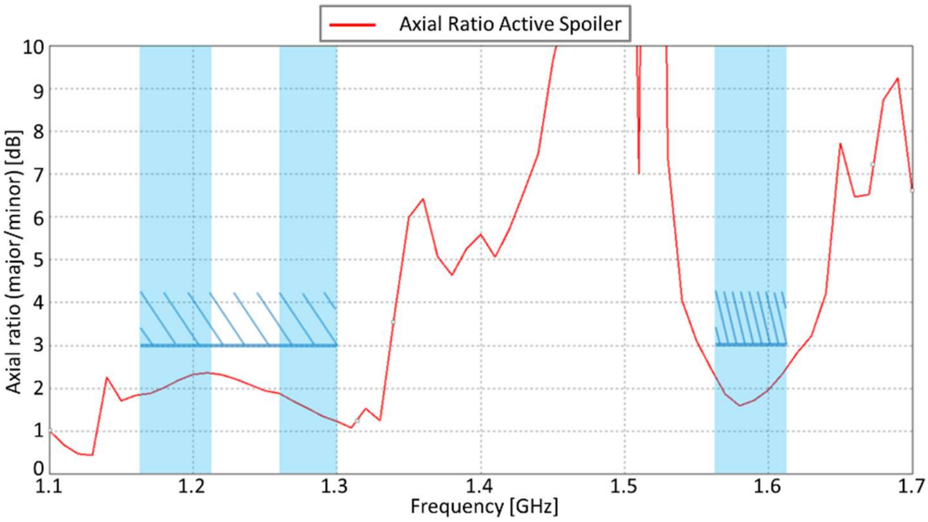

Figure 14: Axial ratio vs frequency at zenith (θ = 0) of the active prototype of the MAGICA antenna installed in a piece of the spoiler environment

4. Conclusions and Next steps

The present paper shows the prototype results of the antenna designed in the scope of the MAGICA project providing a multi-constellation and multi-band (L1/E1, L5/E5 and E6) solution ready to be integrated in vehicles for high precision applications mainly needed for autonomous driving.

The radiating element has been designed using a novel metal sheets structure that leads to a cost effective and reduced weight solution providing the broadband frequency response for the desired operating bands, 1164 -1214 MHz (L5/E5a/E5b), 1260 - 1300 MHz (E6), 1559 - 1591 MHz (L1/E1).

To improve the antenna bandwidth and be able to cover all the required bands with a single element with RHC polarisation, a broadband polariser circuit based on the combination of left-handed and right-handed transmission line sections has been used.

The prototype has been measured in passive mode, achieving great RHCP gain values between 2 to 4 dBic in all the required bands and good axial ratio levels below 3dB in almost all the desired frequency ranges. The RF front-end amplifier has been designed and adjusted in order to meet the broadband frequency response, achieving gains of 30 dB with low noise figure values below 2dB in all the frequency bands and with a low group delay dispersion.

The RF front-end amplifier design has been integrated with the radiating element in order to obtain the complete active antenna system.

The novel design developed in the project offers a high-performance compact antenna that can be used as a standalone solution because it does not require an additional ground plane for optimal performance. This gives a significant advantage as it can be installed in vehicle positions where large ground plane structures are not available.

After discussions with SEAT S.A., the spoiler area of the vehicle was selected as a good integration location for the GNSS antenna, to avoid any visual impact on the vehicle aesthetics, therefore the antenna design was optimised for this location. Measurements of the complete active antenna system integrated into the SEAT S.A. spoiler show good performance fulfilling the required antenna technical goals.

As it can be confirmed, the results are very promising, fulfilling the requirements needed for this kind of application. Small adjustments will be needed regarding the integration of the antenna in the housing and in the car structure. Indeed, this is one of the challenges of the project, the integration in a real vehicle model with limited space for the location of the antenna should not lead to a degradation of the performance of the design. The multi-band, multi-constellation GNSS antenna developed will be a feasible solution ready for the autonomous vehicle.

The way forward of the MAGICA antenna design will be focused on the analysis of the influence of the car structure in the radiation pattern of the integrated antenna design. The efforts will be focused together with the mechanical engineers on the manufacturing and the proper integration in the vehicle without a substantial degradation of the performance.

The proposed prototype antenna solution will be measured at vehicle level in a 3D anechoic chamber integrated in an actual SEAT S.A. vehicle model and system level tests including laboratory and field tests in several urban and rural areas will be performed.

This will be the closest case to that of a real scenario, in order to achieve a design ready for the mass-production stage.

Further information of the project could be followed through the website: www.gnss-magica.eu.

5. Acknowledgements

This work is supported by the EUSPA under the European Union's Fundamental Elements research and development program under grant agreement No. GSA/GRANT/01/2018.

6. References

[1] Autonomous Vehicles: Timeline, https://www.roadtraffic-technology.com/comment/autonomous-vehicles-timeline/, last accessed 2022/04/06

[2] Automated Driving – Challenges in Simulation, https://www.frost.com/frost-perspectives/automated-driving-challenges/, last accessed 2022/04/06

[3] Pan L., Cai C., Zhu J. and Cui X.: Kinematic Absolute Positioning with Quad-Constellation GNSS. In (Ed.), Kinematics - Analysis and Applications. IntechOpen (2019).

[4] Leica AR25 GNSS Antenna. https://leica-geosystems.com/products/gnss-reference-networks/antennas/leica-ar25, last accessed 2022/05/10

[5] Trimble GNSS Ti-V2 Choke Ring Geodetic Antenna. URL: https://www.trimble.com/Real-Time-Networks/Trimble-Choke-Ring-Antenna.aspx, last accessed 2022/05/10

[6] InPAQ Technologies GPS Antenna Manufacturer.URL: https://www.inpaqgp.com/index.php, last accessed 2022/05/10

[7] Amotech Antenna Solution. URL: http://global.amotech.co.kr/wp/antenna-solution_2/, last accessed 2022/05/10

[8] Filatov, E., Vélez, M.A., Gemio, J., Vicente, J.J., Capdevila, R., Tantinyà, L., Gil, A., Cardala, A., Baños, D., Mogas, P., Reyes, J.: MAGICA project: Development of a Multi-frequency Automotive GNSS Integrated Cost effective Antenna. In: WiP Proceedings of the International Conference on Localization and GNSS (ICL-GNSS 2021)

[9] Precise positioning for autonomous vehicles. https://www.controleng.com/articles/precise-positioning-for-autonomous-vehicles/, last accessed 2022/04/06