



<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	1/20

## Low-Cost GNSS for autoMotive (LoCoMotive)

**Executive Summary report and Project Abstract**

<i>Written by</i>	<i>Responsibility</i>
F. ROZO	LoCoMotive project Manager
<i>Verified by</i>	
D. SERANT	LoCoMotive Technical Responsible
<i>Approved by</i>	
F. ROZO	LoCoMotive project Manager



<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	2/20

**CHANGE RECORDS**

ISSUE.REV	DATE	§ CHANGE RECORDS	AUTHOR
1.0	29/01/2021	First delivery of the document	TAS


	REFERENCE:	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
	DATE:	29/01/2021		
	ISSUE:	1.0	Page:	3/20

TABLE OF CONTENTS

1 INTRODUCTION ..... 6

1.1 SCOPE AND PURPOSE ..... 6

1.2 APPLICABLE DOCUMENTS ..... 6

1.3 REFERENCE DOCUMENTS ..... ERREUR ! SIGNET NON DEFINI.

1.4 ACRONYMS ..... ERREUR ! SIGNET NON DEFINI.

2. TEST OBJECTIVES ..... 7

3. SOLUTION DESCRIPTION ..... ERREUR ! SIGNET NON DEFINI.

4. TESTS LIST ..... ERREUR ! SIGNET NON DEFINI.

5. TEST RESULTS ..... ERREUR ! SIGNET NON DEFINI.

5.1 INTEGRATION AND VERIFICATION TESTS ..... ERREUR ! SIGNET NON DEFINI.

5.1.1 TEST CONFIGURATION ..... ERREUR ! SIGNET NON DEFINI.

5.1.2 JAMMING TESTS ..... ERREUR ! SIGNET NON DEFINI.

5.1.2.1 STATIC JAMMER AND STATIC RECEIVER ..... ERREUR ! SIGNET NON DEFINI.

5.1.2.2 STATIC JAMMER AND DYNAMIC RECEIVER... ERREUR ! SIGNET NON DEFINI.

5.1.2.3 DYNAMIC JAMMER AND DYNAMIC RECEIVER ERREUR ! SIGNET NON DEFINI.

5.1.3 RECEIVER SENSITIVITY TEST SIGNAL ..... ERREUR ! SIGNET NON DEFINI.

5.1.3.1 TEST PARAMETERS ..... ERREUR ! SIGNET NON DEFINI.

5.1.3.2 TEST RESULTS ..... ERREUR ! SIGNET NON DEFINI.

5.1.3.3 CONCLUSIONS ..... ERREUR ! SIGNET NON DEFINI.

5.1.4 SPOOFING TEST ..... ERREUR ! SIGNET NON DEFINI.

5.1.4.1 TEST PARAMETERS ..... ERREUR ! SIGNET NON DEFINI.

5.1.4.2 TEST RESULTS ..... ERREUR ! SIGNET NON DEFINI.

5.1.4.3 CONCLUSIONS ..... ERREUR ! SIGNET NON DEFINI.

5.2 EXPERIMENTATIONS TESTS ..... ERREUR ! SIGNET NON DEFINI.

5.2.1 TEST CONFIGURATION ..... ERREUR ! SIGNET NON DEFINI.

5.2.2 TEST RESULTS ..... ERREUR ! SIGNET NON DEFINI.

5.2.2.1 MONO-FREQUENCY ..... ERREUR ! SIGNET NON DEFINI.

5.2.2.2 MULTI-FREQUENCY ..... ERREUR ! SIGNET NON DEFINI.

5.2.2.3 MULTI-FREQUENCY – ADDITIONAL COLLECT ERREUR ! SIGNET NON DEFINI.

5.2.3 CONCLUSIONS ..... ERREUR ! SIGNET NON DEFINI.

6. CONCLUSION ..... ERREUR ! SIGNET NON DEFINI.

LIST OF FIGURES

FIGURE 1: SCHEMATIC OF TEST PLAN ..... ERREUR ! SIGNET NON DEFINI.

FIGURE 2: COMBINATION OF JAMMER DISTANCE AND POWER THAT PRODUCE OF J/S OF 45 DB AT RECEIVER ANTENNA  
..... ERREUR ! SIGNET NON DEFINI.

FIGURE 3: MA CALIBRATION RESULTS – WIDEBAND (LEFT) AND NARROWBAND (RIGHT) ..... ERREUR ! SIGNET NON DEFINI.

FIGURE 4: CAPON DIAGRAM BEFORE CALIBRATION (LEFT) AND AFTER (RIGHT) ..... ERREUR ! SIGNET NON DEFINI.

FIGURE 5: NUMBER OF SATELLITE USED IN PVT – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (RIGHT) .. ERREUR !  
SIGNET NON DEFINI.

FIGURE 6: PVT ERROR – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (RIGHT) ..... ERREUR ! SIGNET NON DEFINI.

FIGURE 7: INTERFERENCE DOA ESTIMATION – CAPON METRIC ..... ERREUR ! SIGNET NON DEFINI.



<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	4/20

FIGURE 8: ESTIMATED INTERFERENCE DOA OVER TIME ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 9: C/N0 OF SIGNAL USED IN PVT – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (RIGHT) .**ERREUR ! SIGNET NON DEFINI.**

FIGURE 10: C/N0/SIGMA CODE VALUES ON PRE-CORRELATION CAPON DIAGRAM..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 12 : JAMMING SCENARIO S-014 SIGNAL CONFIGURATION ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 13: MA CALIBRATION RESULTS – WIDEBAND (LEFT) AND NARROWBAND (RIGHT)..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 14: PVT ERROR – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (RIGHT)..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 15: NUMBER OF SATELLITE USED IN PVT – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (LEFT) ... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 16: INTERFERENCE DOA ESTIMATION INTERFERENCE DOA ESTIMATION – CAPON METRIC – 1<sup>ST</sup> PATH..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 17: INTERFERENCE DOA ESTIMATION – CAPON METRIC – 2<sup>ND</sup> PATH ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 18: RECEIVER TO JAMMER DISTANCE WRT DETECTION TIMESTAMP (RED CIRCLE) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 19: ESTIMATED JNR (RED DOTS) VS SIMULATED (BLUE LINE) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 20: ESTIMATED INTERFERENCE DOA ERROR ON THE 8 ESTIMATION POINTS ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 22 : GNSS DOA ESTIMATION – ELEVATION (LEFT) ERROR (UP) AND RAW VALUE (DOWN) AND AZIMUTH (RIGHT) ERROR (UP) AND RAW VALUE (DOWN) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 23 : JAMMING SCENARIO S-013 SIGNAL CONFIGURATION..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 24: MA CALIBRATION RESULTS – WIDEBAND (LEFT) AND NARROWBAND (RIGHT)..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 25: PVT ERROR – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (LEFT) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 26: NUMBER OF SATELLITE USED IN PVT – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (LEFT) ... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 27: INTERFERENCE DOA ESTIMATION – CAPON METRIC ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 28: ESTIMATED INTERFERENCE DOA OVER TIME ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 29: C/N0 OF SIGNAL USED IN PVT – WITH INTERFERENCE MITIGATION (LEFT) AND WITHOUT (RIGHT) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 30 : GNSS DOA ESTIMATION – ELEVATION (LEFT) ERROR (UP) AND RAW VALUE (DOWN) AND AZIMUTH (RIGHT) ERROR (UP) AND RAW VALUE (DOWN) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 31: C/N0 PROFILE FOR SENSITIVITY TEST – E1CBOC – DEFAULT RECEIVER PARAMETERS (LEFT) AND CUSTOM RECEIVER PARAMETERS (RIGHT) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 32: MA CALIBRATION RESULTS – WIDEBAND (LEFT) AND NARROWBAND (RIGHT)..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 33: PVT ERROR – PVT DETECTED AS AUTHENTIC WRT TO TRUE RECEIVER POSITION (LEFT) AND PVT DETECTED AS SPOOFED WRT SPOOFED TRAJECTORY (RIGHT) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 34: NUMBER OF SATELLITE USED IN PVT – FOR PVT DETECTED AS AUTHENTIC (LEFT) AND FOR PVT DETECTED AS SPOOFED (RIGHT) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 35: GNSS DOA ESTIMATION – POST-CORRELATION CAPON METRIC FOR PRN 12 – BEFORE SPOOFING (UP LEFT), AT SPOOFING BEGINNING (UP RIGHT) AND AT SPOOFING END (DOWN) ..... **18**

FIGURE 36: ESTIMATED SPOOFER DOA ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 37: C/N0 OF SIGNAL USED IN PVT – AUTHENTIC DETECTED PVT (LEFT) AND SPOOFED DETECTED PVT (RIGHT) **ERREUR ! SIGNET NON DEFINI.**

FIGURE 38 : GNSS DOA ESTIMATION – FOR PVT MEASUREMENTS DETECTED AS AUTHENTIC - ELEVATION (LEFT) ERROR (UP) AND RAW VALUE (DOWN) AND AZIMUTH (RIGHT) ERROR (UP) AND RAW VALUE (DOWN) ..... **ERREUR ! SIGNET NON DEFINI.**


FIGURE 39 : GNSS DOA ESTIMATION – FOR PVT MEASUREMENTS DETECTED AS SPOOFED - ELEVATION AND RAW VALUE (LEFT) AND AZIMUTH RAW VALUE (RIGHT) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 40: REFERENCE RECEIVERS (LEFT) AND LOCOMOTIVE ANTENNA AND DIGITIZER (RIGHT) ..... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 41: ANTENNAS (LEFT) AND DATA-COLLECT PC AND LOCOMOTIVE DIGITIZER (RIGHT) .... **ERREUR ! SIGNET NON DEFINI.**

FIGURE 42 : TRAJECTORY OF THE DATA COLLECT IN TOULOUSE WITH DENSE URBAN, ROAD AND LIGHT URBAN ENVIRONMENTS ..... **ERREUR ! SIGNET NON DEFINI.**


FIGURE 43: MA CALIBRATION RESULTS – WIDEBAND (LEFT) AND NARROWBAND (RIGHT) – GPS L1 (UP) AND GALILEO (DOWN) ..... **ERREUR ! SIGNET NON DEFINI.**

	<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
	<b>DATE:</b>	29/01/2021		
	<b>ISSUE:</b>	1.0	<b>Page:</b>	5/20

- FIGURE 44: CALIBRATION DIAGRAM FOR HIGHER GRADE CRPA ANTENNA (MVG CRPA\_304-071) ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 46: PVT ERROR – LOCOMOTIVE RECEIVER – MONO-ANTENNA – MULTI-CORRELATORS. **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 47: PVT ERROR – LOCOMOTIVE RECEIVER – MONO-ANTENNA – EMLP CORRELATORS... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 48: PVT ERROR – SEPTENTRIO RECEIVER – GPS/GAL (PVT BY RTKLIB FROM SEPTENTRIO L1/E1 RINEX) **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 49: PVT ERROR – UBLOX RECEIVER – GPS/GAL (PVT BY RTKLIB FROM UBLOX L1/E1 RINEX) ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 50 : NUMBER OF SATELLITE USED IN PVT – MULTI-ANTENNA, MULTI-CORRELATOR ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 51: C/N0 OF SIGNAL USED IN PVT – L5 BAND ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 52: C/N0 OF SEPTENTRIO RECEIVER – L5 BAND ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 53: PVT ERROR ON 250 FIRST SECONDS – L1 ONLY (LEFT) AND L5 ONLY (RIGHT) ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 54: NUMBER OF SATELLITE USED IN PVT ON 250 FIRST SECONDS – L1 (LEFT) AND L5 (RIGHT) .... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 55: PVT ERROR – LOCOMOTIVE RECEIVER – L1 ONLY (8 GAL, 12 GPS) ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 56: PVT ERROR – LOCOMOTIVE RECEIVER – L5 ONLY (8 GAL, 4 GPS) ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 57: PVT ERROR – LOCOMOTIVE RECEIVER – L1/L5 IONO-FREE – WITH GPS L5 ..... **ERREUR ! SIGNET NON DEFINI.**
- FIGURE 58: PVT ERROR – LOCOMOTIVE RECEIVER – L1/L5 IONO-FREE – WITHOUT GPS L5 ..... **ERREUR ! SIGNET NON DEFINI.**

### LIST OF TABLES

- TABLE 1: TECHNICAL REQUIREMENTS TO BE VERIFIED BY TESTS ..... **ERREUR ! SIGNET NON DEFINI.**
- TABLE 2: PVT ACCURACY FIGURES ..... **ERREUR ! SIGNET NON DEFINI.**
- TABLE 3: PVT ACCURACY FIGURES ..... **ERREUR ! SIGNET NON DEFINI.**
- TABLE 4: PVT ACCURACY FIGURES ..... **ERREUR ! SIGNET NON DEFINI.**
- TABLE 5: PVT ACCURACY FIGURES ..... **ERREUR ! SIGNET NON DEFINI.**
- TABLE 6: PVT ACCURACY FIGURES ..... **ERREUR ! SIGNET NON DEFINI.**
- TABLE 7: PVT ACCURACY FIGURES ON 250 FIRST SECONDS ..... **ERREUR ! SIGNET NON DEFINI.**
- TABLE 8: PVT ACCURACY FIGURES ..... **ERREUR ! SIGNET NON DEFINI.**

	<b>REFERENCE:</b> NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525
	<b>DATE:</b> 29/01/2021
<b>ISSUE:</b> 1.0	<b>Page:</b> 6/20


## 1 INTRODUCTION

### 1.1 SCOPE AND PURPOSE

This document includes the deliverable documents entitled "Executive Summary Report [ESR]" and "Project Abstract [AB]" written in the scope of the ESA project "EXPRO+NAVISP-EL1-010-Low Costs Antenna Arrays for Anti-Spoofing and Meaconing and Interference Mitigation" (called "LoCoMotive").

### 1.2 APPLICABLE DOCUMENTS

ID	Title
AD0	Statement of Work ESA Express Procurement EXPRO+ NAVISP-EL1-010-Low Costs Antenna Arrays for Anti-Spoofing and Meaconing and Interference Mitigation NAVISP1-SOW-ESA-010-00001, Issue 1.0 Dated 30 June 2017
AD1	Low-Cost GNSS Antenna Arrays for Improved Performance, Anti-Spoofing and Meaconing and Interference Mitigation ESA NAVISP-EL1-010 AO/1-9054/17/NL/MM/ek Proposal N° 0005-0007882736, Issue 2.0 Dated 20 Novembre 2017

	<b>REFERENCE:</b> NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525
	<b>DATE:</b> 29/01/2021
<b>ISSUE:</b> 1.0	<b>Page:</b> 7/20

## 2. EXECUTIVE SUMMARY REPORT

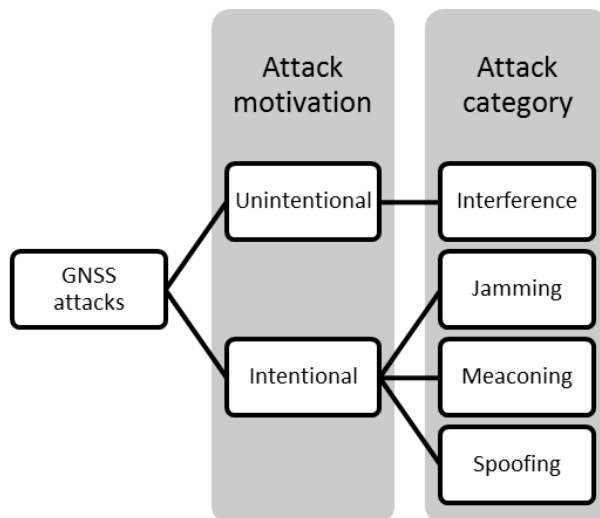
In the context of the autonomous vehicle roadmap and promising market, the LoCoMotive project aimed at assessing the feasibility and interest of embedding some innovative multi-antenna technologies in an appropriate Hardware device.

The project has been handled by a consortium composed by Thales Alenia Space, Telespazio and Saphyrion.

"LoCoMotive" stands for "Low-Cost GNSS for autoMotive" that points out one of the main drivers of the project: **the price**. In order to address the automotive market the integrated on-board unit has to fulfill a maximum recurring cost of 100€, that is achievable in considering a large production volume (at least 10,000 units).

At the top of the requirements is also **the size** that needs to be minimized in order to allow the vehicle to embed several devices for a performing ADAS (Advanced Driver Assistance System). As explained later the antenna part is a major contributor of the size, given that it is composed by an array of 4 antenna patches (that is the minimum number of patches for feeding multi-antenna algorithms). The processing part can take advantage of SOC (System On Chip) technology that is able of implementing the signal acquisition and processing. The target physical requirements are 30 cm in term of diameter and 5 cm height. The weight shall be below 1 kg.

Then the major concern studied in the frame of the LoCoMotive project is **the multi-antenna technology added value** for detecting and mitigating the RF (radio frequency) signal impairments that can be met by a vehicle. These impairments rely on some signal threats that are classified by the CEN-CENELEC as depicted in the following figure.



**Figure 1: GNSS Attack taxonomy (source CEN-CENELEC)**

These threats have various impacts on the GNSS receiver. For the most of them (**interference, jamming**) they can make inoperative the tracking of the signal coming from one or several GNSS satellites, making unavailable the corresponding

<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	8/20

measurements. In a worst case, when the number of measurement is too low, then the positioning is not possible at all. In a medium case, the positioning accuracy is degraded.

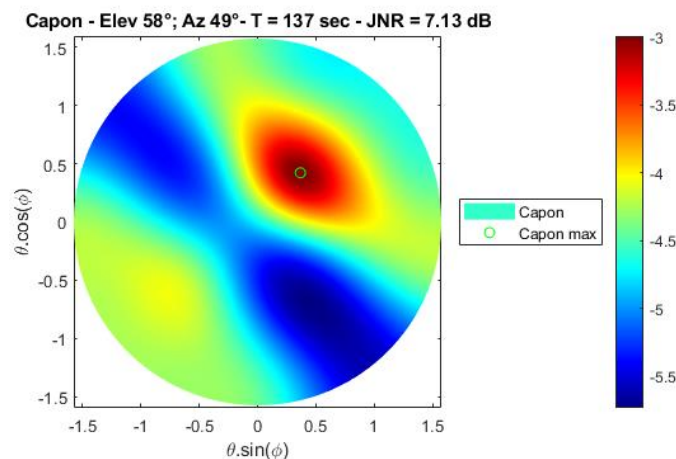
Some threats (**multipath**) can also induce a bias on the measurements that provokes also a degraded accuracy of the positioning.

Such degradations may be incompatible with the need of accuracy related to the autonomous vehicle use case that is expected to be less than 1 meter for horizontal position (with 95% confidence), and less than 2 meters in vertical position.

At the top of the threat is the **spoofing** (and **meaconing** that is a similar threat) attack that consists of sending a GNSS-like signal, consistent and representative to the one transmitted from space by a GNSS actual constellation. Such attack can strongly deviate the position estimated by the receiver from the actual position of the vehicle.

**Most threats are transmitted by a single RF source.** With a GNSS single antenna technology the RF source cannot be located. However with a multi-antenna device, it is possible to develop some beam-forming algorithms, that will combine the phase of each patches that compose the antenna array. In that way the **direction of arrival (DoA) of each signals can be determined**, either these signal are the authentic GNSS signal (coming from the GNSS systems), or they are spoofed ones (coming from a spoofing or meaconing source), or the signal is a jammer (or an interference).

The figure below exhibits the **detection of a jammer source** through a metric (called Capon metric) that points out the jammer at its highest value.



**Figure 2: Interference DoA estimation– Capon metric**

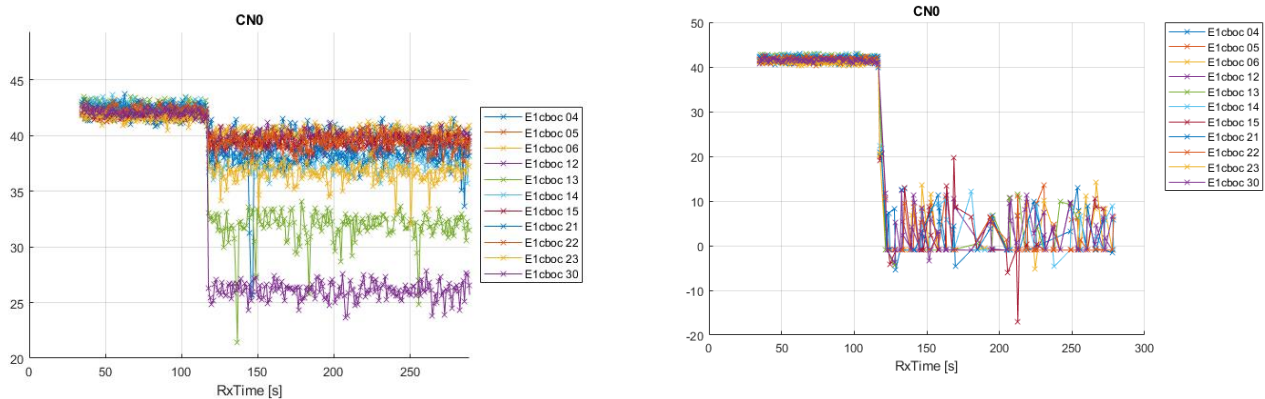
Based on this metric it is possible to estimate the DoA of the jammer source. When the metric is above a determined threshold (consistent with the minimum power where the jammer is supposed to impact the positioning), the algorithm has the capability to **blank a spatial area of the hemispherical zenithal lobe**. This blanking will cancel the jammer, however it will also cancel the useful GNSS signal for satellites located in the DoA of the jammer source. This results in the cancellation or the degradation of some measurements however the tests have shown that the positioning solution is still available and consistent, whereas without the



<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	9/20

mitigation and protection technics the positioning solution is either unavailable or strongly degraded.

The figure and table below provide results about the tracking performance (evaluated through the C/N0) and the positioning performance (evaluated through a set of metrics) for a scenario where the jammer is introduced after 120 second of simulation.



**Figure 3: C/N0 of the signal used in PVT – With interference mitigation (left) and without (right)**


The degradation of the C/N0 is clearly observed from 120 seconds. It is due to the blanking introduced by the multi-antenna algorithm.

	HPE_50	VPE_50	HPE_95	VPE_95	HPL_50	VPL_50	HPL_95	VPL_95	HMI	VMI	Availability
<b>With interf protection</b>	0.56	0.79	1.19	2.23	33.07	47.31	37.20	49.63	0.00	0.00	100.00
<b>With interf protection Before interference apparition</b>	0.15	0.11	0.27	0.44	28.12	44.29	28.15	44.55	0.00	0.00	100.00
<b>With interf protection After interference apparition</b>	0.67	0.57	1.33	1.23	29.79	48.98	30.92	54.12	0.00	0.00	100.00
<b>Without interf protection</b>	0.19	0.13	1921090.0	3531909.5	28.13	44.38	322.84	330.47	0.00	0.00	61.07

**Table 1: PVT accuracy figures (meters)**

For what regard the **spoofing mitigation**, the principle is to detect the DoA of the satellite that is supposed to transmit the GNSS signal. Then the algorithm checks if the detected satellite is consistent with its expected location, and whether a set of satellites are detected with the same DoA. Such observation would indicate that a single RF source is used to transmit a fake signal. The **spoofing detection function** is verified by simulating the following scenario, where the satellite with orange cells are simulated as spoofers (they have the same DoA, i.e. elevation and azimuth).

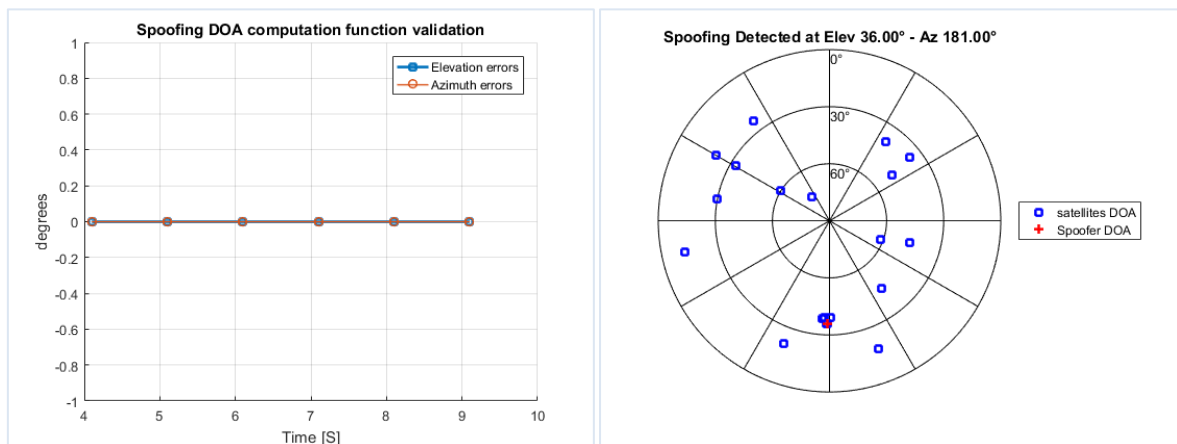
<b>Satellites</b>	<b>Elevation</b>	<b>Azimuth</b>		<b>Satellites</b>	<b>Elevation</b>	<b>Azimuth</b>
-------------------	------------------	----------------	--	-------------------	------------------	----------------

	<b>REFERENCE:</b> NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525	
	<b>DATE:</b> 29/01/2021	
	<b>ISSUE:</b> 1.0	<b>Page:</b> 10/20

(PRN)	(°)	(°)	(PRN)	(°)	(°)
1	36,66	182,18	12	36,66	182,18
2	62,68	113,10	13	16,97	201,10
3	33,93	49,59	14	59,12	303,60
4	10,91	299,96	15	36,66	182,18
5	9,40	256,57	16	21,88	323,58
6	33,31	303,10	17	76,96	329,88
7	36,66	182,18	18	44,43	140,92
8	46,66	105,03	19	36,66	182,18
9	29,70	279,47	20	40,61	35,68
10	49,63	53,93	21	36,66	182,18
11	14,04	159,00			

**Table 2 : Spoofing phenomenon simulation**

The **multi-antenna algorithm manages to estimate the DoA for every satellite** and then to sort which of them are on a single point of DoA (with a certain tolerance), meaning that a spoofer is present. As an interesting complement the algorithm estimated the probable DoA of the spoofer (by taking the average DoA of collocated satellites).




**Figure 4 : Spoofing DoA computation function errors and illustration of detection**

This result is obtained by simulating the RF propagation and considering an antenna array with perfect characteristics. The LoCoMotive project objective was to check whether the Hardware implementation allows obtaining sufficient performance for automotive application. For that purpose **a prototype have been developed** with the following driving assumptions:

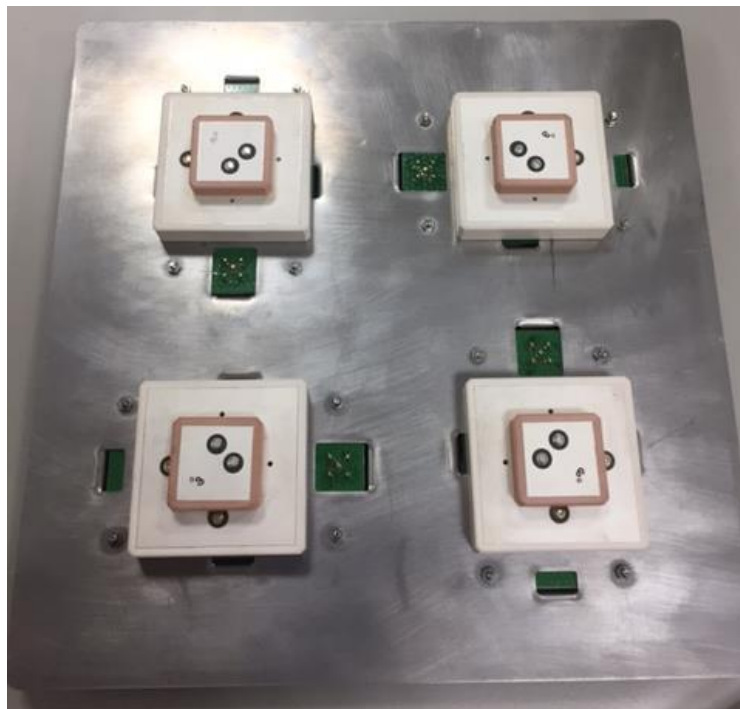
- The antenna array has to be representative to a low-cost antenna that would be selected for the end product.
- The collect (digitizer) and processing part is not constraint, as a next step for industrialization will be to implement these function in a system-on-chip.

The **LoCoMotive receiver prototype** have been developed based on the GEMS product (GNSS Environment Monitoring System) that is composed by a flexible RF part (supporting single or multi-antenna capabilities), various digitizer (GDAS suite from Saphyrion, USRP, ...)

	<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
	<b>DATE:</b>	29/01/2021		
	<b>ISSUE:</b>	1.0	<b>Page:</b>	11/20

and implementing a set of GNSS algorithms and processing shared between CPU and GPU (Graphical Processor Unit). GEMS is thus a SDR (Software Defined Radio) technology that already implements the basic functions of a GNSS receiver, and a large amount of specific algorithms related to the LoCoMotive project (in particular multi-correlator, multi-antenna, and mitigation algorithms associated to detection ones). In the frame of the LoCoMotive project an **improved digitizer have been developed (the DUAL GDAS-2S)** for getting the capability to process multi-antenna and multi-frequency at the same time. Besides, a dedicated antenna array has been designed and produced for the project.

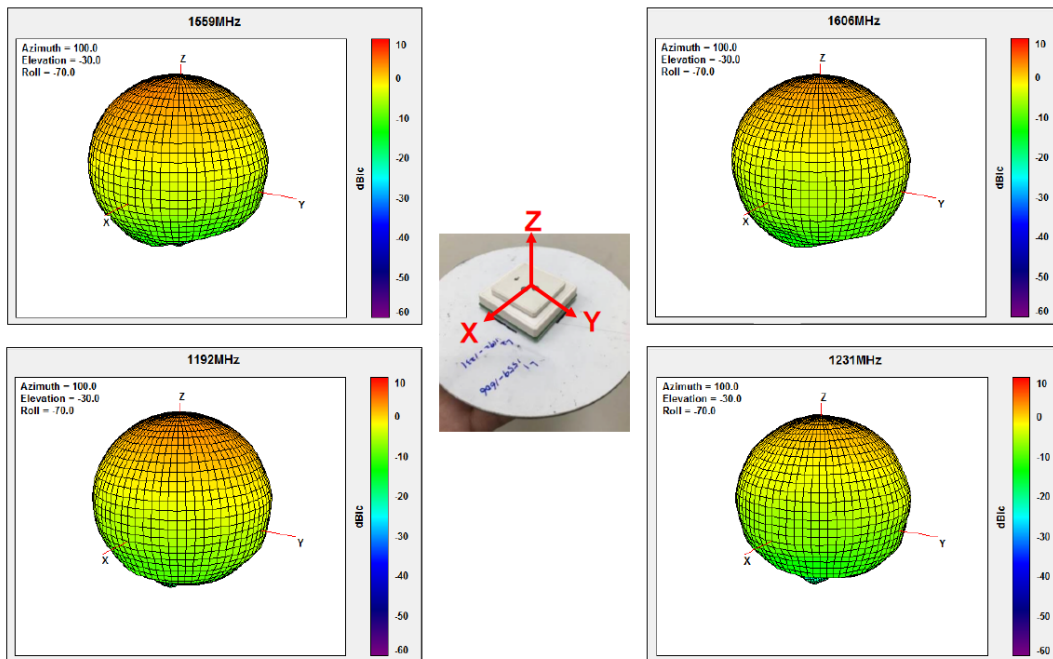
The **prototype antenna** is an assembly of 4 antenna patches that comply with the receiving requirements. In particular they are compatible with following services: GPS L1/L5, Galileo E1/E5a/E5b, Glonass G1, Beidou B1/B2-I. For optimizing the algorithm performances, the distance between patch centers is half the smallest wavelength to process, i.e. approximately 9.5 cm (corresponding to L1 frequency = 1575.42MHz).



**Figure 5:** LoCoMotive prototype antenna array

The antenna radiation pattern is omnidirectional with an axial ratio of 3dB.

<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	12/20

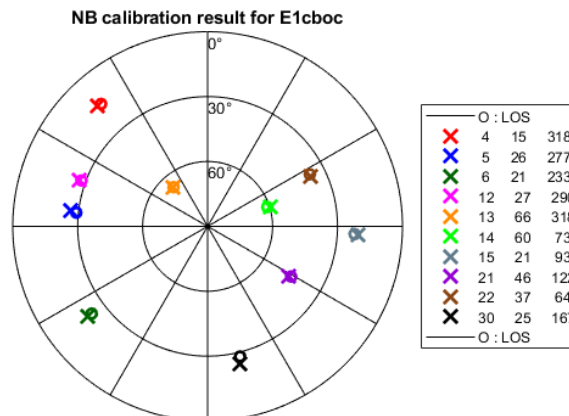


**Figure 6: Patch antenna radiation patterns.**

These low-cost patches are not perfect. In order to make operational the multi-antenna algorithms it is necessary to align the characteristics of the 4 of them. For that purpose a Thales Alenia Space patented technique is used to calibrate the algorithms. It considers the use of the GNSS actual satellite in visibility and the hypothesis that during the calibration period (that is made only once at the start-up of the receiver) there is no RF impairment.

**The calibration is performed in narrow band and in wide band.**

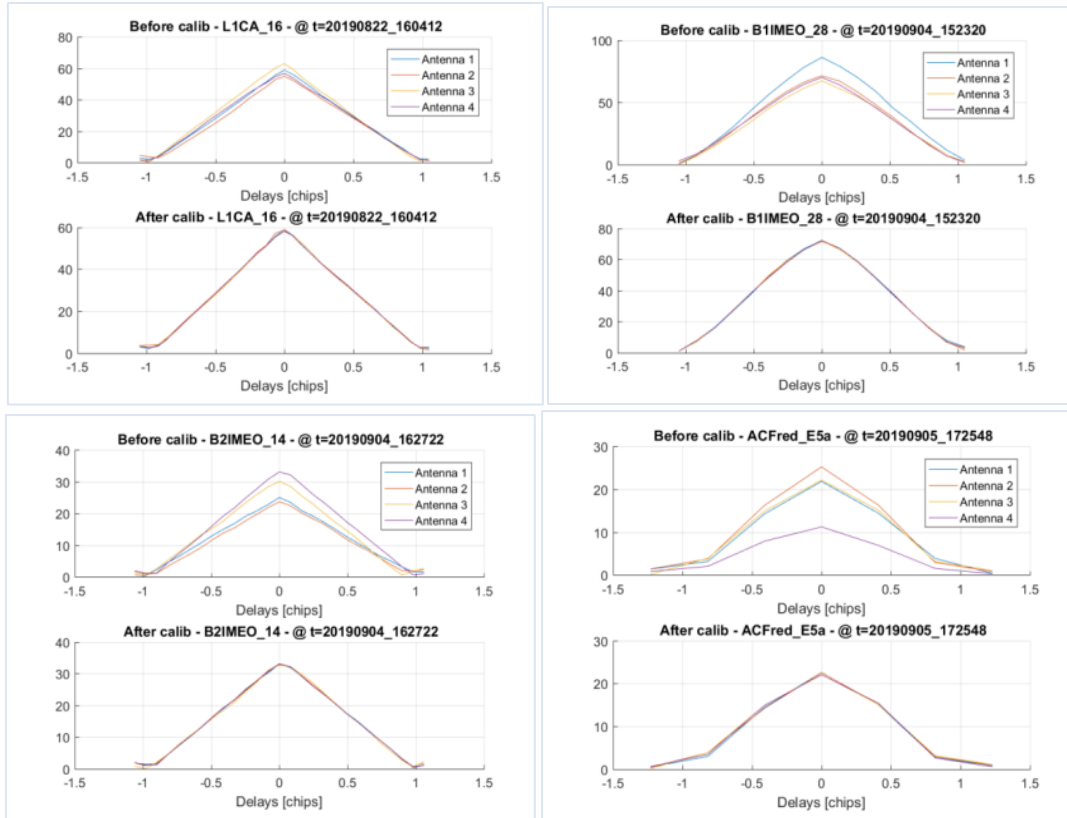
In narrow band the DoA of every satellite in visibility is checked and aligned to a reference DoA estimated from the ephemeris, by solving the unknown phase offset and orientation of the antenna array. Typical result is provided in following plot.



**Figure 7 : Narrow band calibration for Galileo E1 (circle: measured DoA after calibration, cross: reference DoA from ephemeris)**

<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	13/20

In wide band the correlation function is checked and aligned between each patches to compensate from RF chain impairment between antennas.




**Figure 8 : wideband calibration for L1, B1-I, B2-I and E5a bands signals**

Once the calibration step performed the algorithm is ready to operate the detection and mitigation. **Several tests have been performed:**

- **on laboratory tests**, bases on the NAVYS RF Constellation Simulator that offer the appropriate mission SW and RF output characteristics for testing multi-antenna algorithms. Indeed the NAVYS is capable of outputting 4 independent RF signals that can be connected to the LoCoMotive prototype. In particular, the NAVYS RFCS is capable also to simulate a spoofed signal in parallel to an authentic one.
- **on live tests**, in automotive condition of movement and urban environment. The GUIDE test vehicle ([www.guide-gnss.com](http://www.guide-gnss.com)) has been used for embedding the LoCoMotive prototype and providing an accurate reference trajectory.

The **main conclusions raised by the test campaign** are listed hereafter.

Firstly the protection against the jamming threat has been demonstrated: the algorithm improves the robustness of the tracking. However the tested jammer is a wide band one, that is the most demanding use case for the algorithm, and in such configuration the estimation of the DoA is not accurate. An optimization of the algorithm seems feasible to better estimate the DoA and focus the signal blanking on a more concentrated area.

	<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
	<b>DATE:</b>	29/01/2021		
	<b>ISSUE:</b>	1.0	<b>Page:</b>	14/20


Secondly, regarding the spoofing the algorithm is very efficient. The tests have nevertheless pointed out a critical period where the spoofer appears. A latency of 20 second has been observed for spoofing detection, which however depends on its power.

Moreover, on live test, more dedicated to the evaluation of multipath mitigation (as there is nominally no spoofer or too few sources of interference on actual conditions), the multi-antenna algorithms have behaved correctly (and have thus be validated) without however showing results as good as expected by simulation. It is suspected that the characteristics of the LoCoMotive antenna exhibit some limitations for that threat. Nevertheless the multi-correlator processing have shown its superiority compared to standard correlator processing by improving accuracy and availability in the most demanding situations, and also confidence in the measurement thus allowing a significant reduction of protection level.

Finally, the multi-frequency (L1/L5) tests have confirmed that multi-frequency iono-free outperforms the mono-frequency version in terms of accuracy. Protection levels are however slightly increased due noise augmentation of the iono-free combination, even if uncertainty on the ionospheric term is cancelled.

**As a synthesis, the LoCoMotive project has allowed us to go a step ahead** in the knowledge of the capability and limitations related to the multi-antenna algorithm, its added value for GNSS positioning and its industrialization in the frame of the automotive applications. Based on a representative prototype and some relevant tests, the improvements brought by the multi-antenna algorithms have been demonstrated, in particular for protecting against the jamming and the spoofing threats.

The project has shown that for such technology, the quality of the antenna is on the top of importance. Indeed the LoCoMotive prototype antenna is made of low grade patches and the live tests have pointed out some limitations. Nevertheless side tests performed by Thales Alenia Space with a higher grade antenna (that are also more expensive and thus out of LoCoMotive target) offer better performances. This point of attention is the major lesson learnt of the project. Nevertheless, it can be concluded that some adjustments remain to be done at algorithm level and HW implementation level for fully benefiting such technology, however they certainly offer the more promising advantage for guarantying an accurate, robust and reliable positioning solution.

	<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
	<b>DATE:</b>	29/01/2021		
	<b>ISSUE:</b>	1.0	<b>Page:</b>	15/20

### 3. PROJECT ABSTRACT

In the context of the autonomous vehicle roadmap and promising market, the LoCoMotive project aimed at assessing the feasibility and interest of embedding some innovative multi-antenna technologies in an appropriate Hardware device.

The project has been handled by a consortium composed by Thales Alenia Space, Telespazio and Saphyrion.

The project aimed at covering two major aspects for assessing the added value of a multi-antenna device embedded in an automotive:

- 1) the capability of the **multi-antenna to improve the positioning** of the vehicle,
- 2) the capability to **embed these device in a low cost equipment**, compatible with a mass market need and the physical requirements adapted to a vehicle.

The first points deals with several concerns: integrity, accuracy, availability.


The **integrity**, although being a major topic for critical applications such as autonomous vehicle, is not in the scope of the LoCoMotive project.

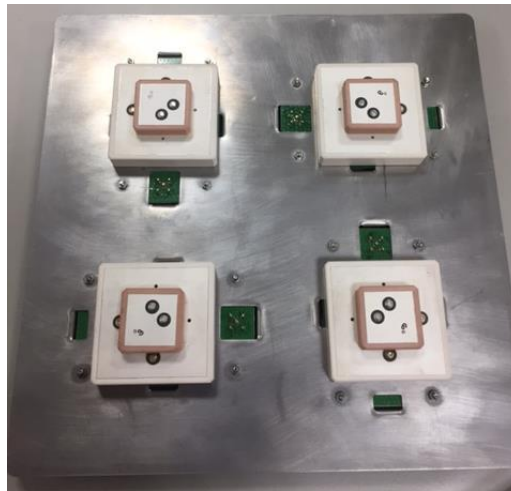
Instead, the project has focused on the improvement of the positioning related to the **accuracy**, for which target is less than 1 meter for horizontal position (with 95% confidence), and less than 2 meters in vertical position.

It has also taken care of the **availability** of the GNSS measurements or the positioning solution. This aspect is particularly important for the ADAS system (Advanced Driver Assistance System) in an autonomous vehicle for optimizing the management of the numerous sensors that contributes to the positioning (GNSS, IMU, odometers, radar, camera, ...).

For what regard the GNSS receiver these performance criteria's are jeopardized by possible **RF signal impairments**, such as the **jamming (or interference), spoofing (and meaconing) and multipath**. Some studies, among which those driven by Thales Alenia Space and integrated in its SDR receiver GEMS (GNSS Environment Monitoring System), have shown that **multi-correlator algorithms** allow the mitigation of some threats, in particular the multipath. Besides, **multi-antenna algorithms** are able to estimate the DoA (Direction of Arrival) of a RF source that provokes the degradation, particularly for a jammer or a spoofer.

The principle is to combine in phase domain the signal received from several antenna patches installed in array. A minimum of 4 antennae is necessary for a sufficient performance of the estimation of the DoA in azimuth and elevation. The prototype developed in the frame of the LoCoMotive project is a 4-antenna array with a spacing between patches of about 9.5 cm, that corresponds to half the minimum wave length (those of L1=1575.42MHz) of the GNSS signal to be studied.

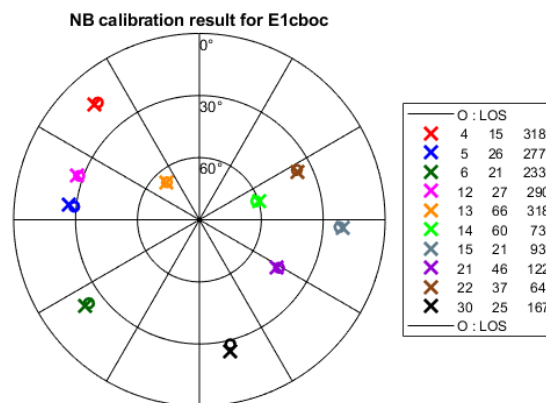
	<b>REFERENCE:</b> NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525
	<b>DATE:</b> 29/01/2021
<b>ISSUE:</b> 1.0	<b>Page:</b> 16/20



**Figure 9: LoCoMotive prototype antenna array**

Even if every antennas have the same technical characteristics, the algorithm need to be calibrated. For that purpose a Thales Alenia Space patented technique (US10578744B2/FR3047568B1 - Method of calibration a satellite radio navigation receiver) is used, that considers the use of the GNSS actual satellite in visibility and the hypothesis that during the calibration period (that is made only once at the start-up of the receiver) there is no RF impairment. The **calibration is performed in narrow band and in wide band**.

In narrow band the DoA of every satellite in visibility is checked and aligned to a reference DoA estimated from the ephemeris, by solving the unknown phase offset and orientation of the antenna array. Typical result is provided in following plot.

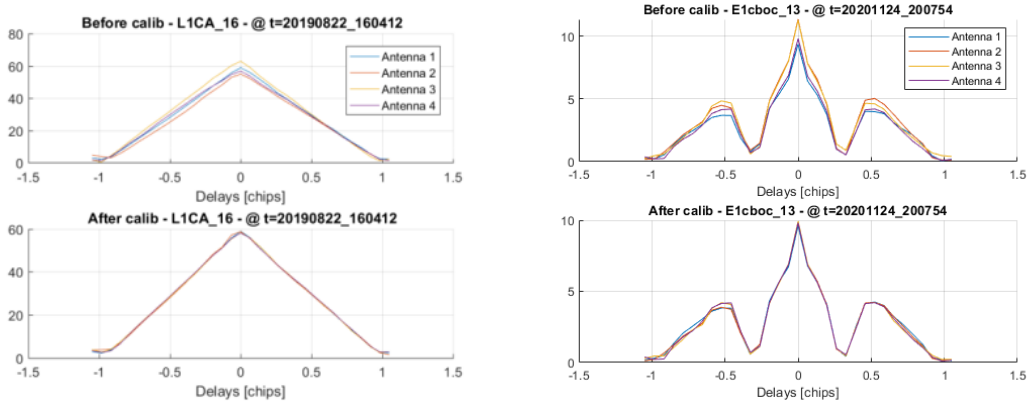


**Figure 10 : Narrow band calibration for Galileo E1 (circle: measured DoA after calibration, cross: reference DoA from ephemeris)**

In wide band the correlation function is checked and aligned between each patches to compensate from RF chain impairment between antennas.

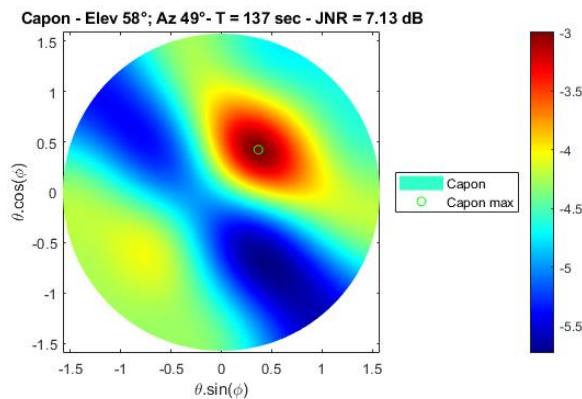


<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	17/20



**Figure 11 : Wideband calibration for GPS L1 and Galileo E1 signals**

Based on the calibrated antenna array, the multi-antenna algorithm computes a Capon metric as illustrated below, where the highest value corresponds to the estimated DoA of the threat source (here a jammer).

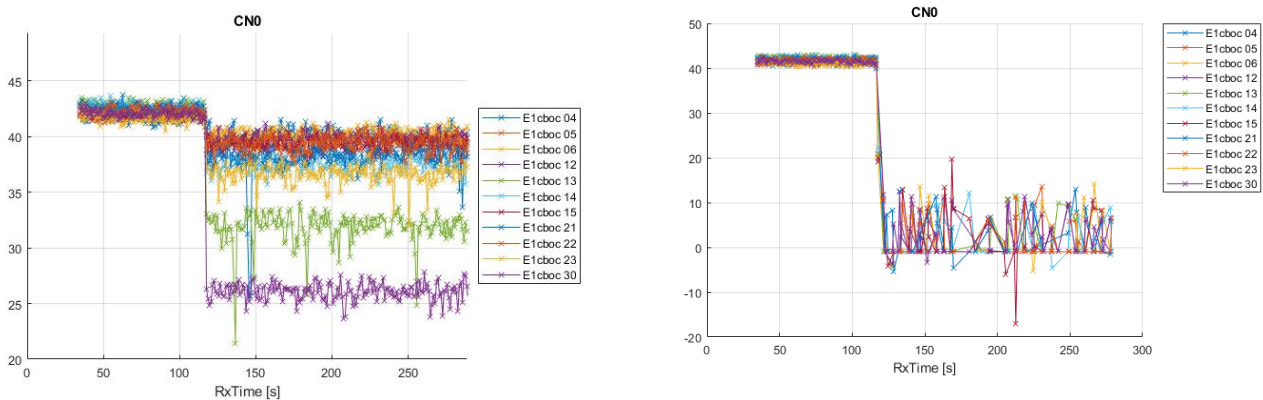


**Figure 12: Interference DoA estimation– Capon metric**

Once the interference detected and the DoA estimated the algorithm applies a mitigation process by blanking a spatial area around the DoA. This blanking cancels the jammer, however it also cancels the useful GNSS signal for satellites located in the DoA of the jammer source. This results in the cancellation or the degradation of some measurements however the positioning solution is still available and consistent, whereas without the mitigation and protection techniques the positioning solution is either unavailable or strongly degraded. The figure below provides results about the tracking performance (evaluated through the C/N0) for a scenario where the jammer is introduced after 120 second of simulation.



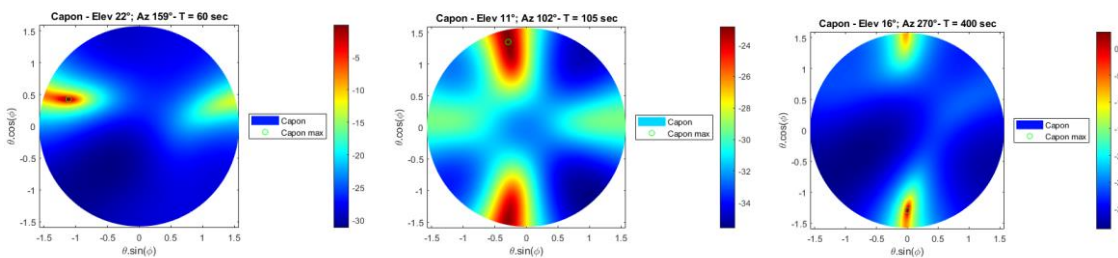
<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
<b>DATE:</b>	29/01/2021		
<b>ISSUE:</b>	1.0	<b>Page:</b>	18/20



**Figure 13: C/N0 of the signal used in PVT – With interference mitigation (left) and without (right)**

These simulations have been done on laboratory by using the NAVYS product (Thales property), that is a RF Constellation Simulator developed by Thales Alenia Space and ELTA, with the support of CNES, that is capable of simulating 4 parallel streams of RF signal corresponding to a 4-patch antenna. It has also the capability of simulating at the same time an authentic set of signals and also a spoofed one, whatever the receiver movement is.

In the tested scenario the spoofer is not transmitted at the beginning of the test, then is activated with a power of 3dB above the GNSS and moves toward North relatively to the receiver. The figures below focus on the DoA estimation of the PRN#12 that is authentically located at elevation 27° and geodesic azimuth 160°.




**Figure 14: GNSS DoA estimation – Post-correlation Capon metric for PRN 12 – Before spoofing (left), at spoofing beginning (middle) and at spoofing end (right)**

Before the simulation of the spoofer (T=60 sec, left plot) the DOA estimation is in accordance with the actual value. Then as soon as the spoofer is simulated (from T=100 sec), the DoA estimation focus on the spoofer, that is on the North of the receiver. The middle plot shows the resulting estimation of the DoA where the spoofer is predominant although the signature of the authentic signal is still present in a weaker level.

Then, when the spoofer is followed and the authentic PRN 12 is lost (T=400 sec, plot on right), only the DoA of the spoofed signal remains and is estimated.

When all the DoA are estimated for each PRN, then the algorithm performs a consistency check between them to verify if there is an acceptable solution for a common DoA. In that case it

 <p>ThalesAlenia <small>a Thales / Leonardo company</small> Space</p>	<b>REFERENCE:</b> NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525
	<b>DATE:</b> 29/01/2021
	<b>ISSUE:</b> 1.0
<b>Page:</b> 19/20	

estimates the DoA of the spoofer. In a next step, the receiver is ready to perform the exclusion of the spoofer.

The results presented above are valid if the antenna has a sufficient level of quality. The second major concern studied during the project is to check that a low grade antenna can fulfill this objective, in complying with the low-cost requirement, that is a recurring price of 100€. This target is achievable in considering a large production volume (at least 10,000 units) and the fact that the signal acquisition and processing SW can be embedded in a SOC (System On Chip) technology. Nevertheless the tests performed on live condition with the prototype antenna have warned about some possible limitations and a mandatory care to be put on that component for next activities.

**ESA UNCLASSIFIED**



	<b>REFERENCE:</b>	NAVISP1-RPT-TASF-010-ESR-AB 0005-0013088525		
	<b>DATE:</b>	29/01/2021		
	<b>ISSUE:</b>	1.0	<b>Page:</b>	20/20

**END OF DOCUMENT**

**EUROPEAN SPACE AGENCY CONTRACT REPORT**