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PROJECT FINAL REPORT

Grant Agreement number: 287207

Project acronym: ADVANSYS

Project title: Design of ADVanced ANtenna and multi-Sensor hYbrid receiver for machine control in harsh environment

Funding Scheme: Collaborative project [Galileo.2011.3.1-1]

Period covered: from December 1, 2011 to February 28, 2014

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PART 1 - FINAL PUBLISHABLE SUMMARY REPORT

1. Executive Summary

This report relates the ADVANSYS project trajectory and main achievements. During the first quarter, the focus of the project has been refined, based on a thorough market analysis conducted by SAT and SSN (D111) and a state-of-the-art survey conducted by DLR (D121). This resulted in basic customer requirements (D112) that were baselined during the first progress meeting and which were used as starting point to specify, during the second quarter of the project, the overall demonstrator concept (D122) and its building blocks: beamforming antenna (D131) and hybrid GNSS/INS receiver (D132).

The third, fourth and fifth quarters were dedicated to design activities:

- The antenna element and front-end have been designed, documented in D211 and manufactured. Two iterations were needed to stabilize the front-end while the antenna element has been iterated 3 times.

- The receiver board has been designed, documented in D221 / D222 and manufactured. Most of the functionality was first-time right, at the exception of the baseband fabric that needed a short iteration to enable to full capacity of the channel matrix

- Besides, algorithmic approaches for beamforming and GNSS/INS integration have been refined and documented in D311 while the concept of using vision-aiding for more cost-effective GNSS/INS solution has been researched (D321), including a concrete test campaign conducted by UNOTT and SSN in Leuven.

Those results were reviewed at MTR, after what, focus was set on implementation and test:

- A first version of the antenna array was designed (D213), assembled (D214), measured at SATIMO (D215) and characterized together with the hybrid receiver in operational static conditions at SSN (D411, D412), respectively during the sixth, seventh and eighth quarters. The ninth quarter was focused on kinematic testing (D421, D422), showing promising results notably in DGNSS under dense canopy.
- The GNSS/INS approach developed during the first part of the project has been implemented on SSN AsteRx3 board and deployed in a GNSS/INS product in collaboration with an INS partner. Although also usable in Machine Control applications, the eventual product was primarily targeted to Mobile Mapping applications, which have also to cope with very harsh operational conditions.

- In parallel again, beamforming algorithm research has been further advanced leading to D311 v2.0 and the redundant IMU and vision researched pursued, leading to D321, D322, D323 and D324

This document relates the main public result achieved during the course of the project.

Project Context and Objectives

1.1. Context

Machine Control is one of the fastest growing professional GNSS market segments both in terms of addressable market and in revenue. SSN, the coordinator of this proposal, has a multi-year track-record in delivering GNSS hardware and software solutions notably for machine control in various fields of application such as Precision Agriculture, Land and Offshore Construction or Dredging. Several cutting-edge technologies have been pioneered in this segment such as attitude determination through multi-antenna processing or moving-base Real Time Kinematic (RTK) for cm-accurate relative positioning between vehicles. These innovations contributed in a great extend to the growth of the company and its leadership at European scale.

With the increasing acceptance of GNSS technologies in professional applications, competition – especially with US companies – is increasing dramatically and disruptive innovation is mandatory to consolidate leadership at European scale and ambition capturing a significant part of the global market growth.

The ADVANSYS project aimed at supplying the seeds for such disruption, addressing one of the key limitations of GNSS solutions in Machine Contol applications: their ineffectiveness in non-benign environment.

1.2. Objective

In Machine Control applications, GNSS is a preferred technology thanks to its global availability and easiness to deploy and operate ("Plug and Play" character). Common requirements in all high precision Machine Control applications are:

- Sub-meter down to centimeter positioning or guiding accuracy (RMS).
- Attitude (at least heading) determination with accuracy <1° (RMS).
- High Availability and Continuity (24/7 operation, 90%+ availability)
- High Reliability (wrong fix yields major cost)
- High Robustness (resilience to dust, obstruction, high vibration, low motion)

Those requirements are met by high bandwidth, multi-constellation, multi-frequency GNSS receivers enabled with carrier phase-based positioning technologies such as differential Real-Time Kinematic (RTK) or real-time Precise Point Positioning (PPP). Such systems were considered as the baseline of the project

Although very successful, such GNSS-only technologies suffer however from fundamental limitations that make them not-fited in non-benign environment:

- Carrier phase-based techniques such as RTK require high quality phase measurements to properly fix and maintain estimation of the phase ambiguities in order to provide a non-biased positioning solution.
- at least 6 satellites should be in view with good Dilution of Precision (DOP) in order to guaranty cm-level accuracy

Overcoming these limitations is mandatory to extend the field of application outside benign environments and, hence, extend the addressable market. Important opportunities for disruption are identified in enabling applications such as:

- Forestry which yield the need of operating under foliage.
- Mining which yield the need of operating in canyon, with continuously bad DOP.
- Warehouse (Extreme case) where dead-reckoning or backup navigation is required.

Addressing those environments requires the following improvements:

- High sensitivity GNSS (low acquisition and tracking threshold) to maximize the number of satellites that can be exploited in the positioning solution.
- Effective multi-path mitigation to maximize phase measurement quality
- Multi-sensor aiding to overcome possible GNSS outage

Multi-antenna **beamforming** and **GNSS/INS hybridization** are two complementary technologies to achieve high sensitivity GNSS. In forestry for instance, state-of-the-art receivers tend to lose lock and suffer from heavy multipath when working under dense foliage. Even if the actual signal masking by the tree only lasts, say, one second, it typically takes 5 seconds or more to recover full lock onto the carrier phase of the signal. This means that the availability of RTK in forestry applications is seriously degraded.

Beamforming offers a potential solution to that problem: having beams directed to the satellites improve the signal-to-noise ratio, and will allow the receiver to maintain track even under dense foliage. This will remove long relocks periods, significantly improving the availability.

But, beamforming alone is not sufficient. For precise positioning, the receiver must accurately measure the propagation delay of the satellite signal. When the satellite signal passes through the branches and trunk of the trees, it is retarded, causing a bias in the delay measured by the receiver. So, while beamforming will allow tracking the signal under trees, the resulting delay measurements will be corrupted, and not usable for high accuracy positioning. The solution to that problem is to combine INS and GNSS. During the (usually short) periods where the GNSS signal is biased by the propagation through materials, the INS can still produce valid update of the receiver position while phase prediction can be exploited to reduce the phase measurement noise and distortion.

The purpose of the ADVANSYS project was to provide a disruptive, high value-added, multi-technology positioning/guidance solution addressing the identified limitation of current professional GNSS offering for Machine Control in non-benign environment.

Therefore, the following technologies were developed and implemented into a prototype:

- solutions for high sensitivity and high resilience GNSS including an integrated multi-element antenna array and a multi-antenna multi-constellation GNSS receiver with built-in beamforming digital signal processing capabilities
- multi-sensor GNSS-aiding solution including
  - Tighter coupling between the GNSS engine and a multi-sensor navigation system based on a cost effective INS solution
  - In order to achieve cost effective INS, enabling the use of lower grade IMU through
    - the exploitation of a redundancy of IMU
    - the hybridization with at least one complementary technology: vision-based motion determination

1.3. Team

The meet this challenging objective, the talent, previous experience and background of a well balanced team were exploited. The team was made of:

SEPTENTRIO SATELLITE NAVIGATION, N.V. was founded in January 2000, as a privately held company for the development and production of high-end dual frequency GNSS receivers. Headquarters are in Leuven's DSP Valley, close to Brussels, Belgium. Septentrio is an Original Equipment Manufacturer (OEM), providing both the hardware and the software for high-end satellite navigation equipment for precise positioning, time and time-transfer applications, and attitude determination applications. We actively support customers with customization, prototypes, field tests and application integration.

DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT (DLR) is Germany's national research center for aeronautics and space. Its extensive research and development work is integrated into national and international cooperative ventures. As Germany's Space Agency, DLR has been given responsibility for the forward planning and the implementation of the German space program by the German federal government as well as for the international representation of German interests. Approximately 5,100 people are employed in DLR's 31 institutes and facilities at 8 locations in Germany.

SATIMO Industries, S.A.S .is a private company founded in 1986. The core activity of SATIMO concerns the development, the industrialization and the commercialization of antenna measurement systems based on multi-sensor technology. Recently, SATIMO has introduced its real-time multi-sensor technology in industrial sectors like quality control and 3D imagery. Since 2000, SATIMO is involved in the design, industrialization and commercialization of specific high performance antennas dedicated to measurement systems, military applications, GNSS reference fixed stations and GNSS professional applications. Headquarters are in Villebon-sur-Yvette, close to Paris, France. The antenna team is composed by 17 persons and is present in Villebon, Brest and Rome. Additional offices in Atlanta, Hong-Kong, Goteborg and Tokyo ensure to SATIMO a global coverage and a strong reactivity with its customers in terms of commercial contact, installations, upgrades, after sales services and maintenance.

UNIVERSITY OF NOTTINGHAM excels in world-changing research. Ranked by Newsweek in the world's Top 75 universities, its academics have won two Nobel Prizes since 2003. UNOTT and the East Midlands Development Agency (emda) have recently signed a formal agreement which will see a £9m state-of-the-art GNSS/Galileo Research and Application Centre of Excellence (GRACE) built in Nottingham, capitalizing on existing world-leading research and training at the IESSG to support industry, including SMEs and entrepreneurs. The IESSG is part of the Department of Civil Engineering, one of the leading of its type in the UK, with a large multidisciplinary research portfolio, with a particular emphasis on knowledge transfer. The IESSG has a longstanding research record on GNSS and on Galileo, and currently employs 8 full-time and 1 part-time academic staff, 10 post-doctoral researchers and 3 senior experimental officers.

2. Main S&T Results and Foreground

2.1. Introduction

The ADVANSYS project aimed at developing basic technologies that were anticipated to be highly relevant for high added value high-precision (<10cm) Machine Control applications. The core of the project focused on two main topics:

- Beamforming technology for increased GNSS signal reception sensitivity (tracking pseudo-range and phase of weaker signals) and integrity (attenuating undesired multi-path/alternate-path signals). This was expected to lead, eventually, to increased DGNSS and RTK availability, accuracy and reliability
- Advanced GNSS/INS integration technology to further increase positioning availability and accuracy when a GNSS only solution is not possible. In view of the targeted <10cm precision, hybridization with Fibre Optics Gyro (FOG) IMU was considered primarily.

Besides, two “parallel paths” were pursued to explore cost reduction of the GNSS-INS system. The first focused on hybridization between vision-based positioning (visual odometry) and MEMS IMU based INS. The second explored the possible usage of the multiple redundant MEMS IMUs to improved INS performance.

In this report, we review the technical outcome of the project workpackage per workpackage:

- Section 3.2 and 3.3 review the outcome of WP1000, respectively the targeted application requirements and the system concept.
- Section 3.4 focuses on the beamforming antenna array design, specification and implementation (WP2100).
- Section 3.5 reviews the beamforming receiver design, specification and implementation (WP2200)
- Section 3.6 and 3.7 focus on WP3100 with, on the one hand, the beamforming algorithm exploration and implementation and, on the other hand, the new GNSS/INS integration concept and its implementation
- Section 3.8 relates the results of the first parallel path: hybridization with vision (WP3200)
- Section 3.9 reports on the second parallel path: redundant IMU (WP3200)
- Finally, section 3.10, 3.11 and 3.12 expose the results of the field testing of the beamforming and GNSS/INS integration technologies (WP4100 and WP4200)

General conclusions, from the technical perspective, are drawn in section 3.13

2.2. WP1100 Market and Customer Requirements

As a very first step in the project, a thorough market study has been conducted to qualify and quantify the market gap that can be closed by the technology targeted to be developed in ADVANSYS. The outcome of said study has been used to derive specific customer requirements which were later used as guidelines in the derivation of the system specifications.

2.2.1. Main outcome of the market analysis

The market study looked separately to the different segments typically addressed by high precision GNSS: precision agriculture, construction (machine control and survey), maritime and mining applications.

2.2.1.1. Precision Agriculture

A clear trend to higher accuracy has been identified. More than 90% of the respondents to our survey indicated they would be able to do more jobs when having a higher accuracy. This trend is addressed by a slow but continuous migration from meter-level accuracy DGNSS / SBAS systems to cm-level accuracy RTK systems or dm-level accuracy PPP systems, depending on the availability of a RTK network in the considered area.

The market survey revealed a need for quicker startup times and shorter signal outage times compared to systems that are currently on the market (higher availability). The majority of the respondents are encountering problems in areas near trees.

Besides, robustness and ease-of-installation have been identified to be important: systems that only require one cable between the antenna on the roof of the tractor and the display inside the cab are preferred (>60% of the respond-ents). Respondents to the survey indicated that a device measuring 25cm in di-ameter and 12cm in height with a weight of maximum 5kg is acceptable. A power consumption of 10W is not considered to be an issue but robustness in harsh environment (shock, vibration, dirt and dust) is key.

Reliability is of paramount important. This is particularly true for RTK systems which are still known to show sporadic wrong fix issues.

Finally, the agriculture market is very cost sensitive. A large increase in price for the new technology won't be accepted. Still, more than 50% of the potential customers who replied to the survey are ready to pay 10-20% more for a system that will allow them to work in area with lower GNSS availability, typically close to trees (Figure 1).

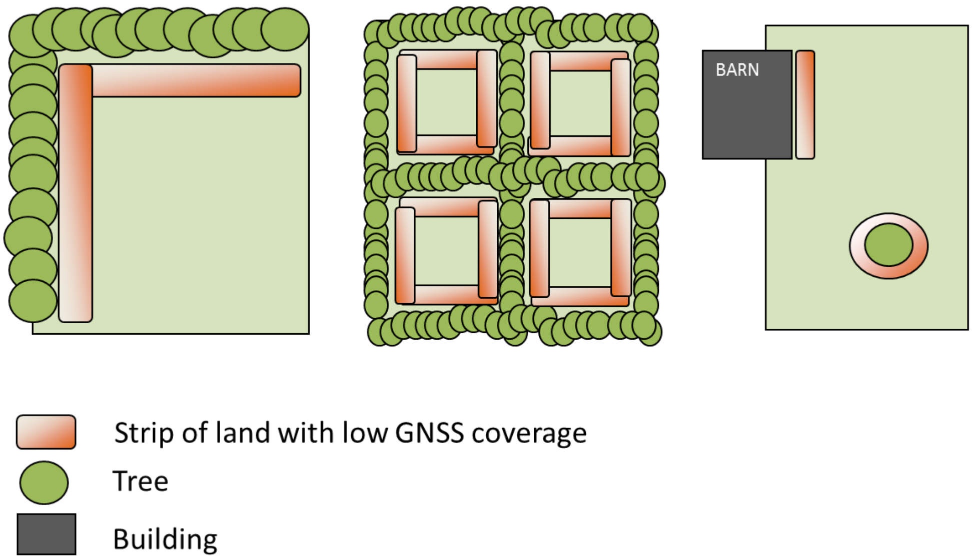

Figure 1 Typical areas of low GNSS coverage

2.2.1.2. Forestry: Demand for position solution with accuracies of at least 50cm under canopy

As a natural extension of the precision agriculture market, forestry is envisioned as a high potential market in case the current limitations of high precision GNSS technologies under canopy can be overcome.

According to our survey, a solution that could provide an accuracy of 50cm under canopy would open the door for many new applications in the industry (e.g. automation of biomass harvesters, Figure 2).

In such applications, as the vehicles operate in forests, the risk of damage to the antenna by low hanging branches is a real problem. Therefore, it is preferred to separate the antenna (lowest cost) and the receiver (higher cost) to limit the cost of replacing a damaged antenna.

Figure 2 Biomass Harvesting

2.2.1.3. Construction

Like the users of GNSS equipment in agriculture, machine control users in construction are looking for increased availability (near trees, buildings…) and reliability. All applications in construction (graders, bulldozers, excavators…) require accuracies of a few cm for their operations. Contrarily to agriculture, accuracy of the height component is important as GNSS is often used to control the height of the blade on a bulldozer or grader to level a terrain.

Integrated smart antennas are less common in construction. As the antennas are often mounted on the blade or another heavy vibrating part of the vehicle, they are considered as expendable items. The high-value device, the receiver, is preferably mounted inside the cabin where it is less subject to extreme vibrations and shocks.

2.2.1.4. Maritime

Centimeter to decimeter accuracy is common in Maritime survey applications. As for land survey, accuracy of the height component is of paramount importance. Availability in obstructed environment (e.g., near to a platform) and reliability are, here again, the most demanded enhancement.

As specificity, maritime applications often used differential correction received via Inmarsat link operating in L-band. Improving L-band reception (notably at high latitude) would be a strong argument in that segment.

Smart antennas are not wanted on ships. Antenna are mounted on the mast and wired (long cable) to the deck. Instruments are often arranged in racks.

2.2.1.5. Mining

GNSS is used in open pit mines both for low accuracy application (1m, e.g. asset tracking) as high accuracy applications (<10cm, bulldozers and excavators). The low availability of satellite signals due to the limited view of the sky provides a big challenge to GNSS based positioning systems.

Current solutions use local infrastructure to cope with this (e.g. pseudolites, Locata), however an affordable vehicle centric approach is preferred to avoid the large setup and maintenance costs of fixed infrastructure. Increased availability and accuracy in reflection and blockage intensive environment would hence create an opportunity.

2.2.2. User requirements

The market study shows that there is, in all applications, a trend towards greater accuracy. RTK and PPP are the positioning techniques that will be the most demanded at the time ADVANSYS will deliver its outcome on the market.

For all applications, the main demand is a maintained availability in non-benign conditions

In the applications relying on RTK, there is no explicit demand to increase accuracy further. What is however of paramount importance is to increase reliability, notably to eliminate wrong ambiguity fixes that can cause meter level outliers.

The main focus of the ADVANSYS project is hence set to:

- **Increase both code and phase GNSS measurement availability**
- **Improve GNSS measurement quality indicators and validation to help the positioning algorithm to correctly estimate and eventually correctly fix the ambiguity**
- **Ultimately coast the absence of GNSS measurements e.g., using inertial measurements.**

The integration of the system as a smart antenna would be of interest in the Agriculture application but not in the other applications, this will hence not be a focus of this project. Optimizing the power consumption is also not a primary request, still it remains a differentiating factor.

Importantly, the developed technology shall not imply any significant (>20%) increase of the solution cost-of-ownership.

In order to translate those needs in factual requirements, a set of test cases have been defined and documented in D1.1.2:

- RTK survey close to partial canopy
- Reproducible track under partial/full canopy
- RTK survey close to building / in urban canyon

For each test case, requirements in terms of increased availability and decreased rate of wrong fixes have been defined. **Globally, we aim to an improvement of 10% in availability and an elimination of wrong fixes**.

Besides, general feature specifications have been identified based on competition analysis.

2.3. WP1200 - System concept and specification refinement

2.3.1. General aspects

Based on the user requirements discussed above, we decided to build a prototype combining a separate antenna and receiver (no smart antenna) so that applicability in the different market segments is kept. To meet availability requirements, the prototype shall track all signals from GPS, GALILEO and GLONASS constellations and run RTK positioning using at least the GPS and GLONASS constellations (multi-constellation is the primary means of increasing availability). Update rate will be 100Hz for measurements and 25Hz for PVT.

Interfaces (hardware and software) will be inherited from existing SSN product (PolaRx4).

Optimization for size and power consumption will not be focused on. This would be part of a following productizing phase. The prototype is expected to consume about 10W.

2.3.2. Achieving performance requirements in the targeted environments

Increasing availability while zeroing the occurrence of wrong fixes requires:

1. to increase the receiver sensitivity so that more satellites can be tracked
2. to mitigate the intrinsic sources of wrong fixes

As illustrated in Figure 3, sensitivity increase is a first and direct benefit of using a beamforming antenna. The figures depicts the C/N increase for all satellites in view, obtained using existing DLR 4x4 array compared to using only one element from the array.

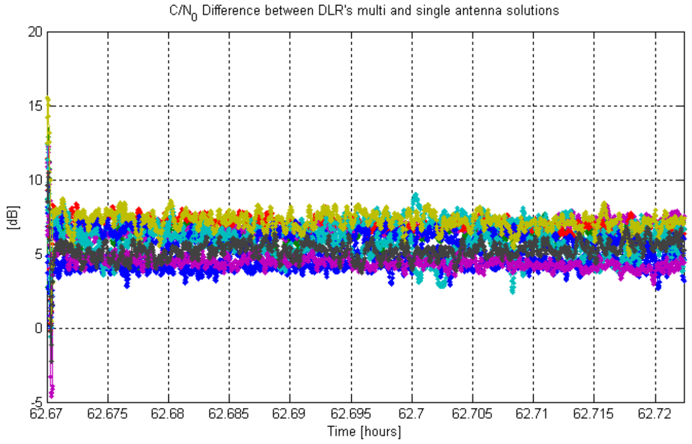

Figure 3 Sensitivity increase with beamforming (DLR 4x4 antenna)

Secondly, strong multipath is identified as the main source of non- or wrong RTK fix in the targeted test scenario’s. (Figure 4).

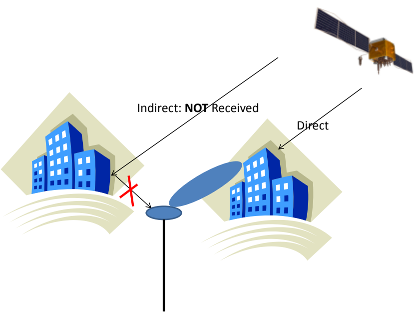

Figure 4 Alternate path as main cause of non or wrong fixes

An extreme case of multipath is when no LOS signal is received (Figure 4b). This situation, called alternate path makes it impossible to get a correct fix if the alternate path cannot be detected and the satellite eliminated. This is very difficult in time domain as the signal can be received non-degraded and with good C/No.

As illustrated in Figure 5, which show results obtained during an ADVANSYS field test campaign, using existing DLR 4x4 antenna array, the spatial selectivity provided by beamforming is effective in mitigating alternate path.

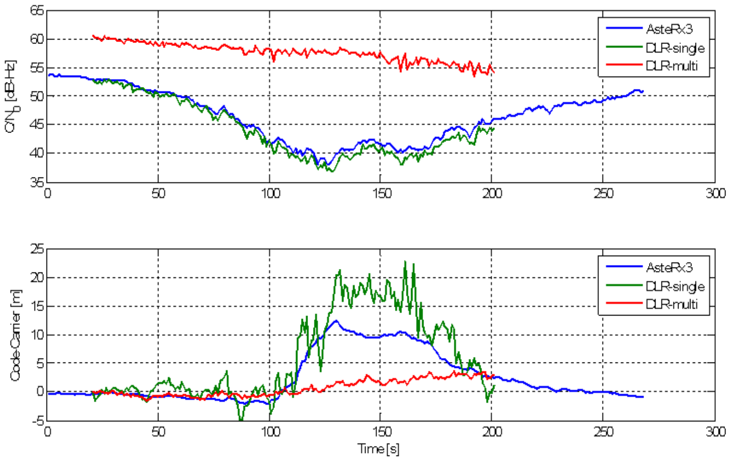

Figure 5 Mitigation of strong multipath / alternate path by beamforming (DLR 4x4 antenna)

A beamforming antenna will hence be an effective tool to achieve our goal of increasing availability and zeroing of wrong fixes. It would however not be sufficient to meet our availability goals in all situations. As illustrated in Figure 6, in some circumstances, due to blockage, there might simply not be enough satellites in view to resolve ambiguity and compute a RTK position. In those circumstances, the way forward is to complement the GNSS measurements with inertial ones. The availability of inertial measurements will also be used to derive array attitude, which combined with ephemeris information can be used to provide direction of arrival information to the beamforming algorithm.

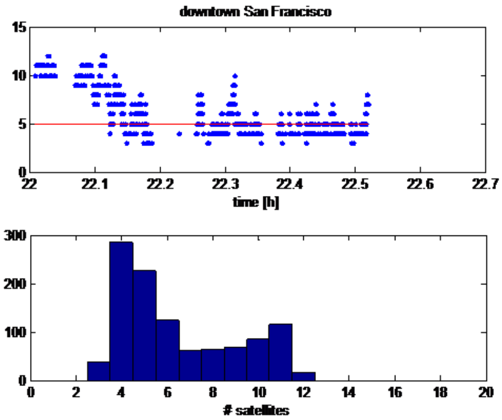

Figure 6 Satellites visible in kinematic test downtown San Francisco

Antenna element, antenna array and receiver have been specified to enable prototyping these concepts. Specifications are detailed in D1.3.1 and D1.3.2. Their design, as well as the beamforming and GNSS/INS hybridization approaches, are discussed in the following sections.

2.4. WP2100 Antenna Array Design, Specification and Implementation

2.4.1. Antenna Element Concept

According to the specifications and state-of-the art analysis, an antenna element based on microstrip and stripline technology is proposed. The design resulted from an optimization for different parameters, e.g. reception properties, integration capability, but also cost, size, complexity and manufacturability.

The antenna element is conceived on a stacked-patch architecture for the dual-band operation. The patches are excited by vias and capacitive circles on the top patch. The two feeding points are fed by an external off-the-shelf 90°-hybrid coupler. This way circular polarization is ensured. The antenna consists of six substrate layers: 4xRO3003 of 3mm thickness and 2xRO6006 of 1.27 mm thickness.

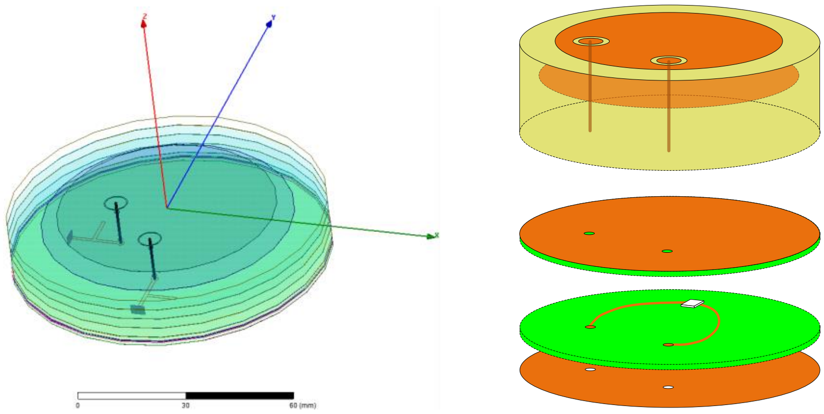

Figure 7 Antenna model in HFSS simulator and assembly

2.4.2. Antenna Element Implementation and Measurement

In order to reduce the risk of manufacturing failure, the antenna elements were produced both in glued and non-glued version with separable layers. The non-glued approach allowed for eventual manual interventions and tighter control of the production. Assembly was ensured by plastic screws which do not impact the structure electrically but allow for flexible prototyping.

Slight variations were introduced in each of the manufacturing iterations in order to achieve the resonance of the patches that complies with the requirements for the frequency characteristic. Furthermore, optimization at the array level complemented the element design.

Tree iterations have been conducted throughout the project. Measurement of the final isolated antenna elements yielded results which matched rather well the simulated prediction with slight degradation regarding axial ratio and radiation pattern (e.g. Figure 8 and Figure 9).

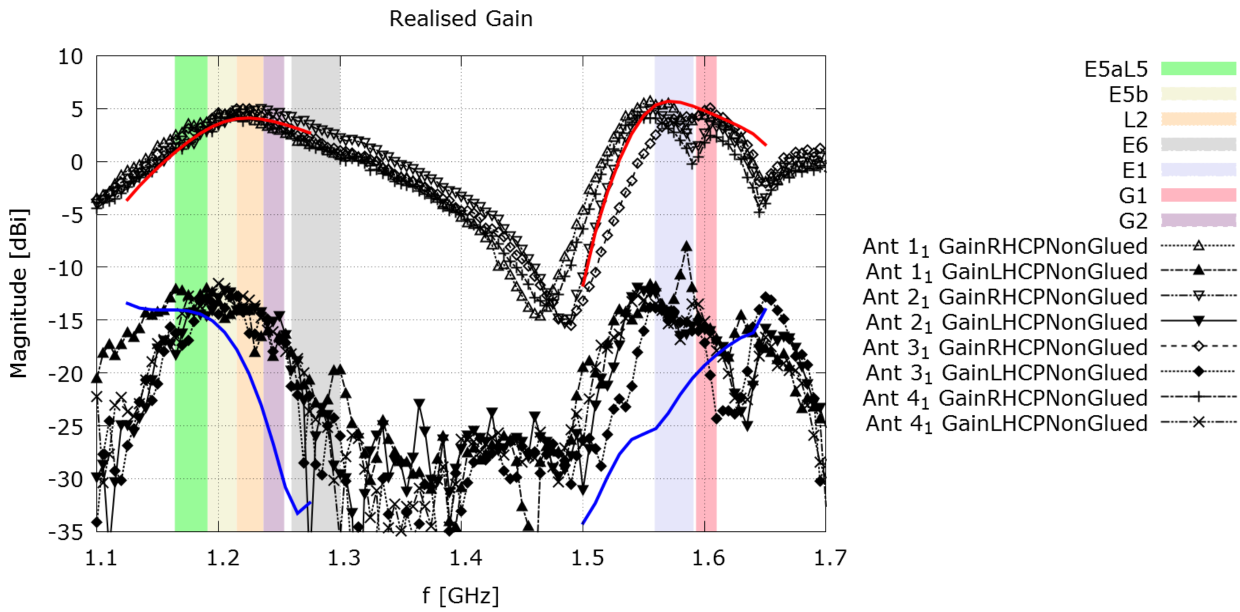

Figure 8 Frequency characteristic of the realized gain – non-glued antennas (first iteration). The red and blue lines are simulation results.

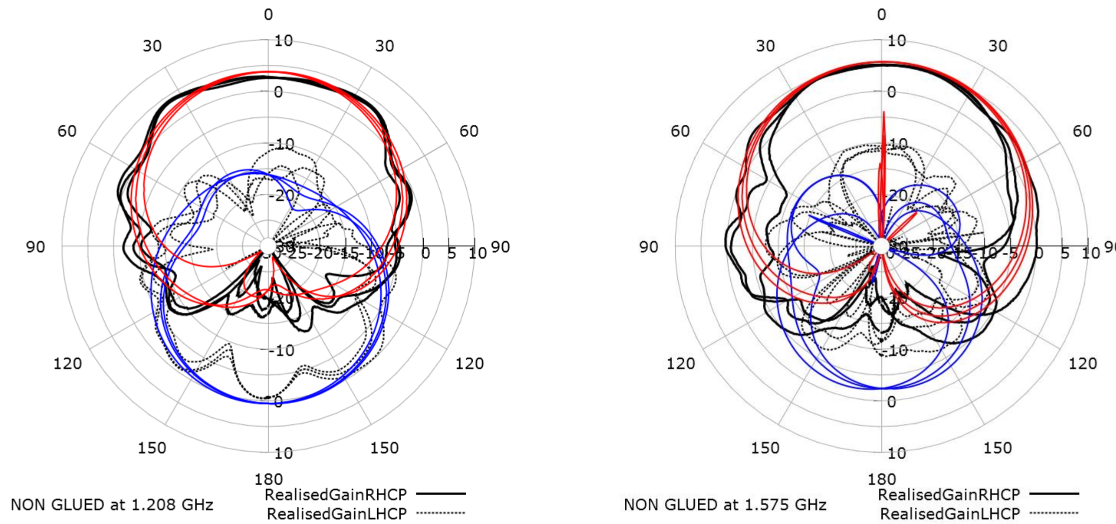

Figure 9 Radiation patterns of one manufactured antenna (first iteration): 0°, 45° and 135° azimuthal cut. The red and blue lines are simulation results.

2.4.3. Antenna Front-end Concept and Measurement

The RF-front-end is located between the radiating elements and the receiver. It is composed of the receiving paths and the calibration paths. The receiving path (Figure 10, Figure 11) is the way by which the signal received by the radiating element is pre-filtered, amplified and transmitted to the receiver. The calibration path (Figure 12, Figure 13) is the way by which a reference signal generated by the receiver is amplified, divided, and transmitted back to the receiver through the coupled ways of the calibration couplers and the pre-filters and pre-amplifiers. Such on-line calibration signal path is necessary for the receiver to continuously measure group delaying variations between the paths and due to environmental conditions

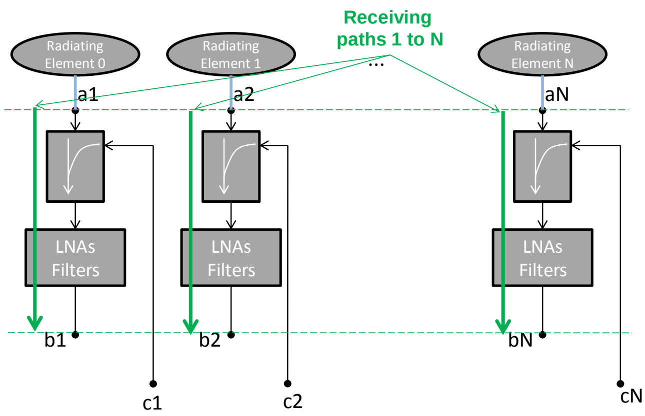

Figure 10 - Receiving paths of the RF front-end (7 receiving paths shown in green) including the direct way of a calibration coupler, the L1 filters for the six single frequency peripheral elements, the L1/L2 filters for the dual frequency central element, one LNA

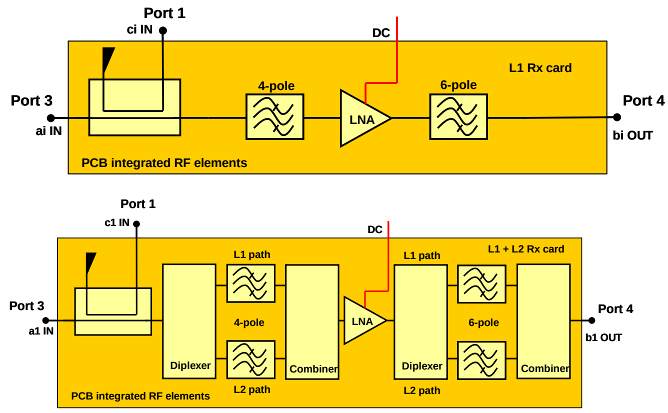

Figure 11 – Block-diagram of the receiving paths (top: 6x L1 receiving paths for the single frequency peripheral elements - bottom: 1x L1/L2 receiving path for the dual frequency central element)

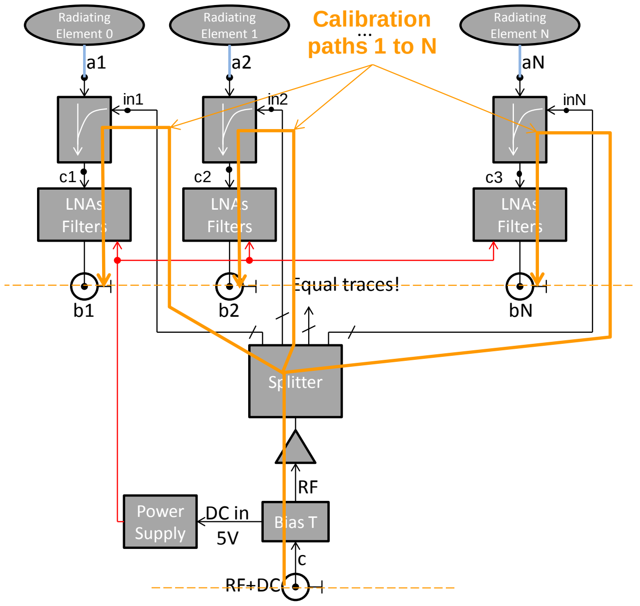

Figure 12 - Calibration bloc of the RF front-end (7 calibration paths shown in orange) including the Bias T, the amplifier, the splitter, the coupled way of a calibration coupler, the L1 filters for the six single frequency peripheral elements, the L1/L2 filters for the dual frequency central element, one LNA

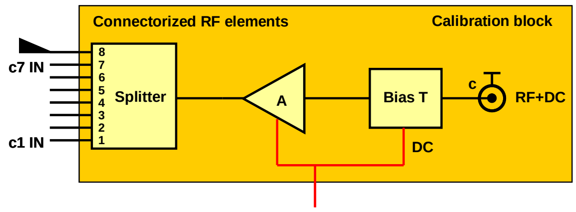

Figure 13 – Block-diagram of the calibration bloc (7 calibration paths)

According to the specifications and previous experience, the receiving paths were designed as printed boards in stripline technology (R03003 substrates) and the calibration paths were designed using connectorized components. The aim of this modular approach was to ensure maximum versatility (and success) for the array demonstrator in a short time. In the case of the receiving boards, the design was performed with a series of prototyping activities for each sub-functionality (calibration coupler, L1 filter, L2 filter, L1/L2 diplexer and combiner, LNA amplifier). The calibration block was designed by cascading dedicated RF stand-alone components (bias T, Tx amplifier, splitter). Once each element had been designed, manufactured or procured, the complete paths were measured by cascading the different elements. Finally, the complete receiving boards were manufactured (Figure 14) and the calibration block was integrated.

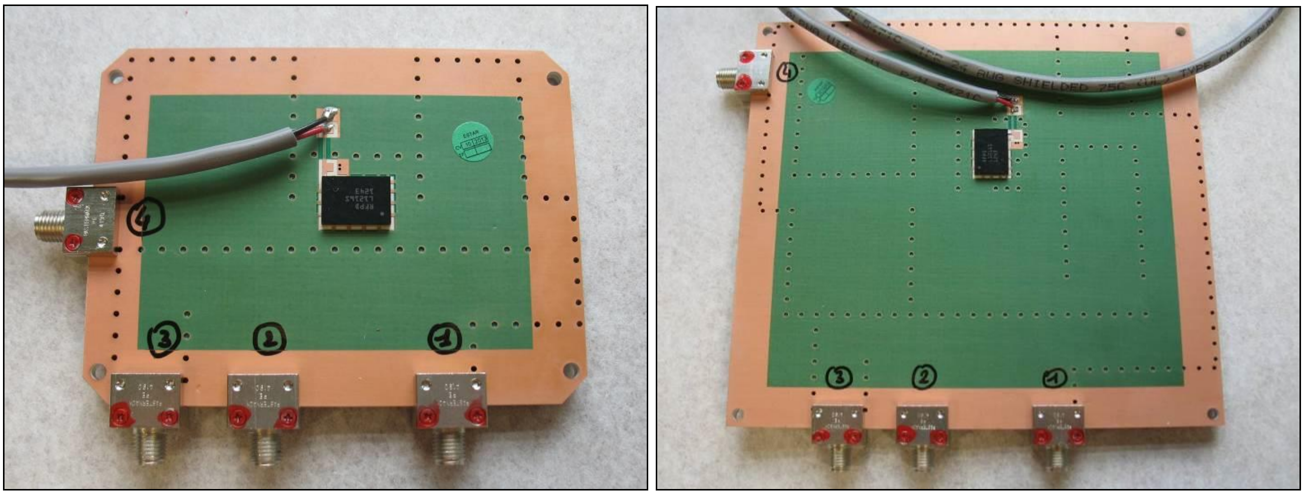

Figure 14 - Manufactured single L1 receiving boards (left) and dual L1/L2 receiving boards (right)

Concerning the receiving boards, measurements of the main parameters (reflection at antenna port side and transmission from antenna port side to receiver port side) are shown in Figure 15 and Figure 16. Concerning the calibration block, measurements of the main parameters (transmission and phase mismatch between the input of the calibration block and the 7 outputs of the splitter) are shown in Figure 17. The measured results were compliant with the specifications and thus validated the design of the RF front-end.

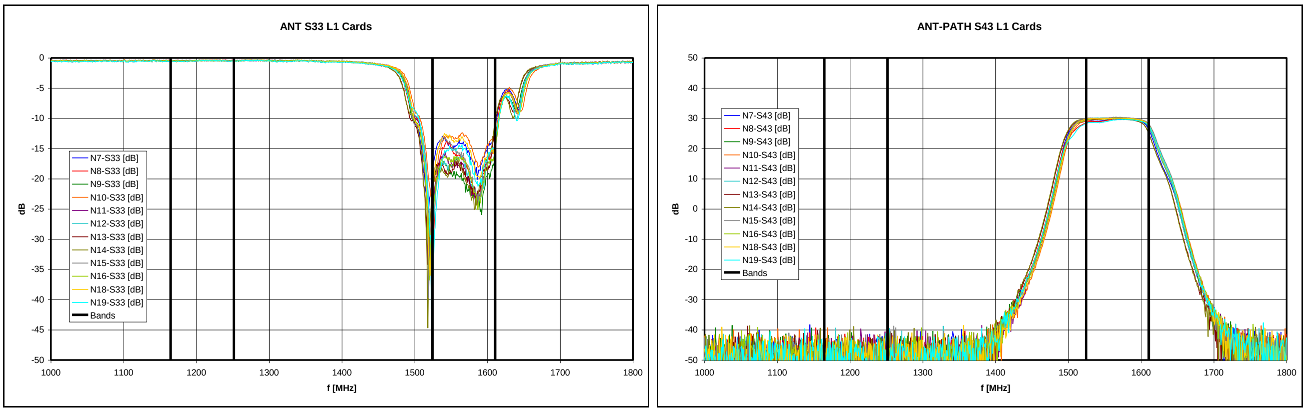

Figure 15 – Measured reflection at antenna port side (left: L1 boards – right: L1/L2 boards)

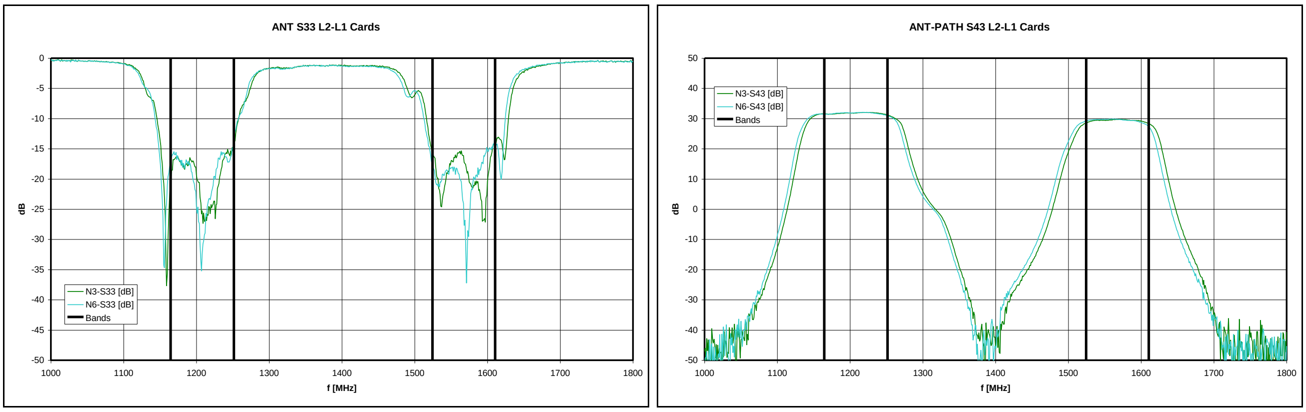

Figure 16 – Measured transmission from antenna port side to receiver port side (left: L1 boards –right: L1/L2 boards)

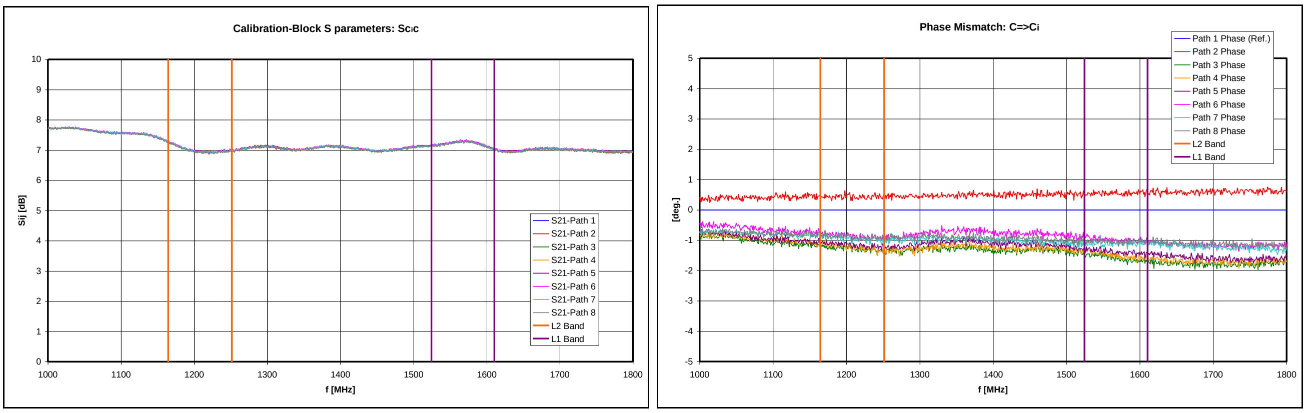

Figure 17 – Measured transmission (left) and phase mismatch (right) between input of calibration block and 7 outputs from splitter

2.4.4. Antenna Array Design

Starting from the state of the art study, different topologies of the array antenna were investigated in terms of multi-path mitigation. In the end, the topology of the hexagonal grid with six elements located at the periphery and one center element showed the best results in terms of multipath mitigation. In addition, the hexagonal grid configuration having a smaller spacing of about 0.4λL1 between elements showed better performances than with a larger spacing of about 0.6λL1. In order to be compliant with the limited number of receiver inputs available and with the use of both L1 and L2 signals to increase positioning accuracy, a configuration with the central element operating in dual frequencies L1/L2 and the 6 peripheral elements operating in single frequency L1 was finally chosen as the best compromise in terms of performances.

In order to obtain a versatile demonstrator and to reduce the number of iterations in the design of the array antenna, it was decided to practically implement 7 multi-frequency antenna elements with 6 of them having only the E1 output used. This would also open all possibilities in terms of antenna bandwidth and future evolution. Concerning the array architecture, the preferred solution at this stage was a configuration using isolated facetted elements where each of the antenna elements were separated islands, independent from the rest. This allows more flexibility for the developments in the frame of the project.
A top view of the array antenna layout and a transversal block-diagram of the array antenna are presented in Figure 18. The transversal block-diagram shows the antenna architecture with the array elements, the support plate, the feeding network, the calibration network, the pre-filtering layer and the pre-amplification layer.

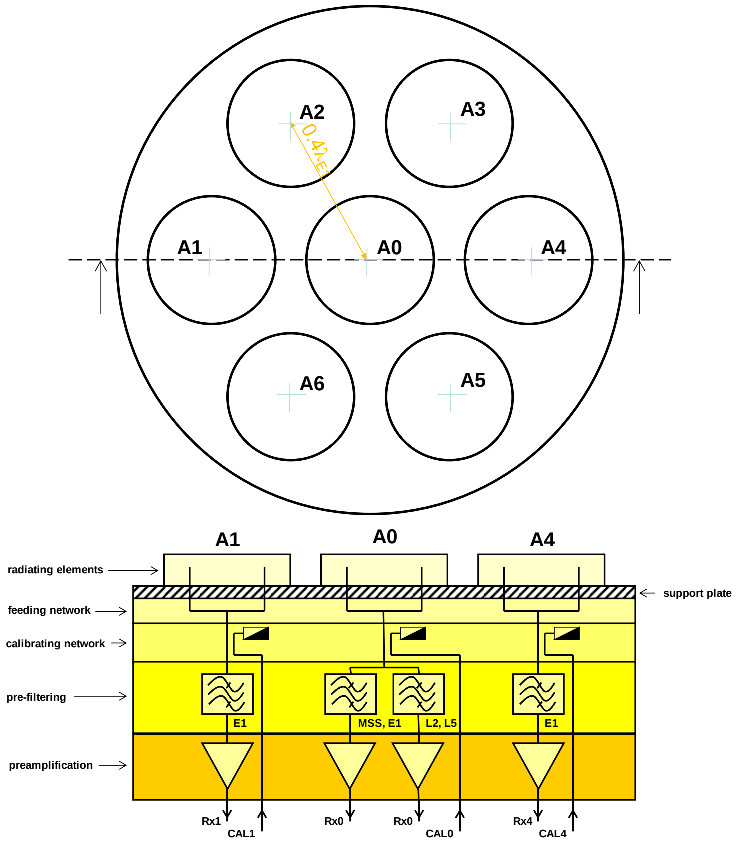

Figure 18 – Array antenna layout in terms of topology of the radiating elements (top) and Array antenna transversal block-diagram with reception of dual frequency signals L1/L2 for the center element (bottom)

Then, using the first iteration antenna elements whose performances have been shown in Figure 8 and Figure 9, an experimental optimisation of the inter-element distance and of their orientation was performed on a representative circular ground plate of 300 mm diameter. The photographs of the test set-up are shown in Figure 19. The S-parameters and the radiation pattern of each element in presence of their neighbours was measured for different inter-element distances (90 mm, 95 mm and 100 mm) as well as for 2 possible orientations (parallel case and star-like case) of the elements within the array.

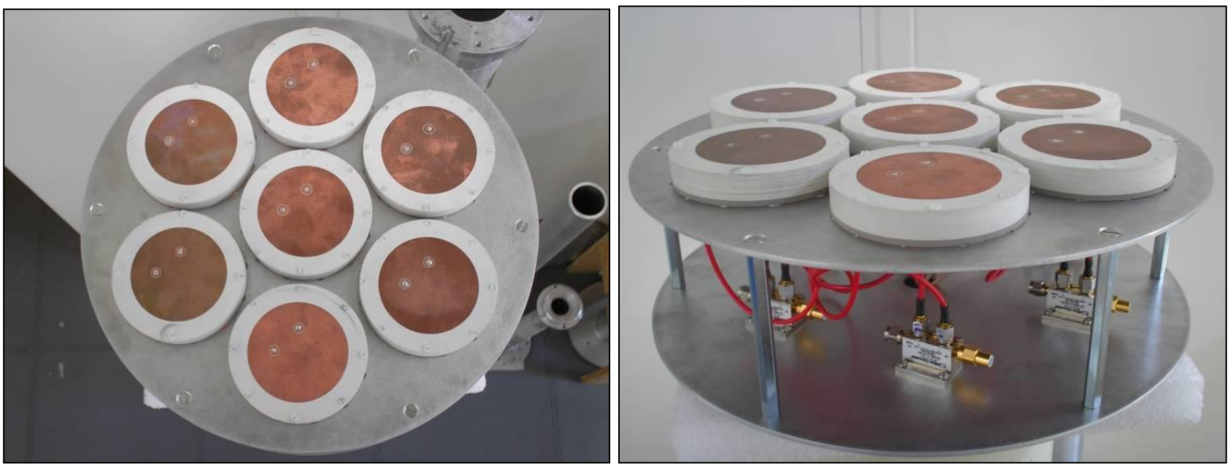

Figure 19 – Test set-up used to investigate the inter-element distance and their orientation

In the case of beamforming applications, two main points are to be taken into account. The first one is the level of coupling between antenna ports. The tendency that was observed for both parallel and star-like configurations was the greater the inter-element distance, the lower the coupling levels. But this parameter improvement was limited to about 2 or 3dB maximum in the best cases for a mean coupling level around -20dB. The second one concerns the variation of the radiation pattern levels function of the position of the single elements inside the array matrix. Indeed for beamforming applications, it is important to have individual antenna radiation patterns that present the lowest magnitude variations versus theta angle to avoid loss of gain in the target direction. The measured magnitude variations showed statistically that the parallel configurations had better performances than the star-like configurations. In addition, considering the full elevation range, it was better to have greater inter-element distance. Therefore the parallel configuration and the inter-element distance of 100mm were selected for further steps.

In terms of mechanical design, the whole antenna structure is protected by a radome. As presented in Figure 20 there are 3 inner stages that contains the antenna array, the receiving boards and the calibration components. A main mechanical plate mounted onto the mast supports the whole structure. The radome is mounted onto this main plate.

Figure 20 – Array mechanical design (left: overview – right: 3 main stages)

Below the radome, each antenna is placed in a parallel way oriented toward the north direction. The inter-element distance is 100 mm. The antennas numbering is taken as in Figure 21 (left).
The RF and mechanical interfaces are presented in Figure 21 (right). The 8 TNC connectors placed on peripheral positions correspond to the 7 receiving antenna ports and to the common calibration port. A special adapter is placed below the back plate to enable mounting onto a standard 5/8-11 UNC termination.

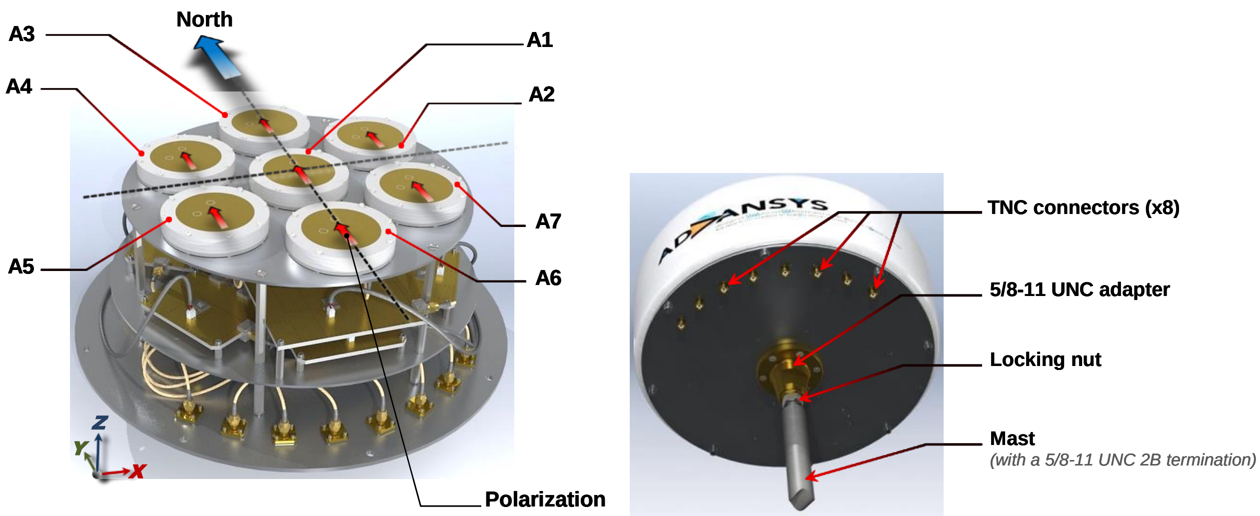

Figure 21 – Antenna element directions and numbering (left) and RF and mechanical interfaces (right)

2.4.5. Array Measurement

The array antenna was manufactured and integrated inside the mechanical structure covered by a radome and ready for use onto a mast. Prior to the pattern measurements, the accessible S-parameters of the array antenna were measured and confirmed (S11 parameter measured from common calibration port, S11 parameters of 7 receive output ports, S21 parameters of 7 calibration paths measured from common calibration port to 7 output ports). Then the radiation patterns were measured in the Satimo SG-24 system in Brest. The measurements were performed with the first iteration and the third iteration of the DLR antenna elements. The second iteration was discarded because tested malfunctioning due to production mistake.

Figure 22 – Manufactured array antenna measured inside the Satimo SG-24 system in Brest

This section shows typical results obtained with the first iteration. The full 3D measurements were measured from 1165 to 1251 MHz and from 1525 to 1610 MHz frequency with 5 MHz resolution. The measured zenith gain and the maximum gain are shown in Figure 23 for each antenna element.

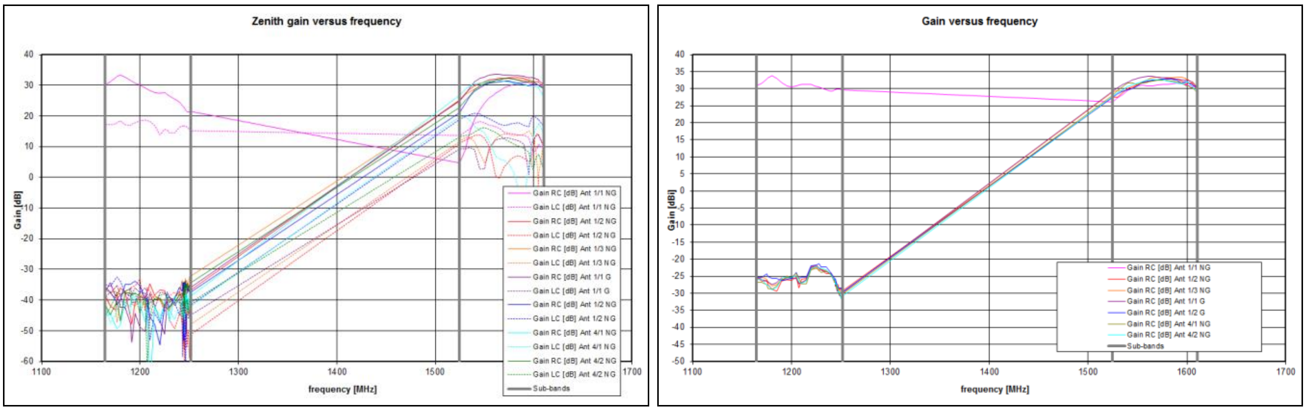

Figure 23 – Zenith gain (left) and maximum gain (right) of each antenna element within the array

In the following Figure 24, Figure 25 and Figure 26, the measured pattern cuts of the dual frequency L1/L2 central element (ref. Ant1/1 Non-Glued) and of the single frequency L1 diagonal upper left element (ref. Ant1/1 Glued) are presented for typical frequency points.

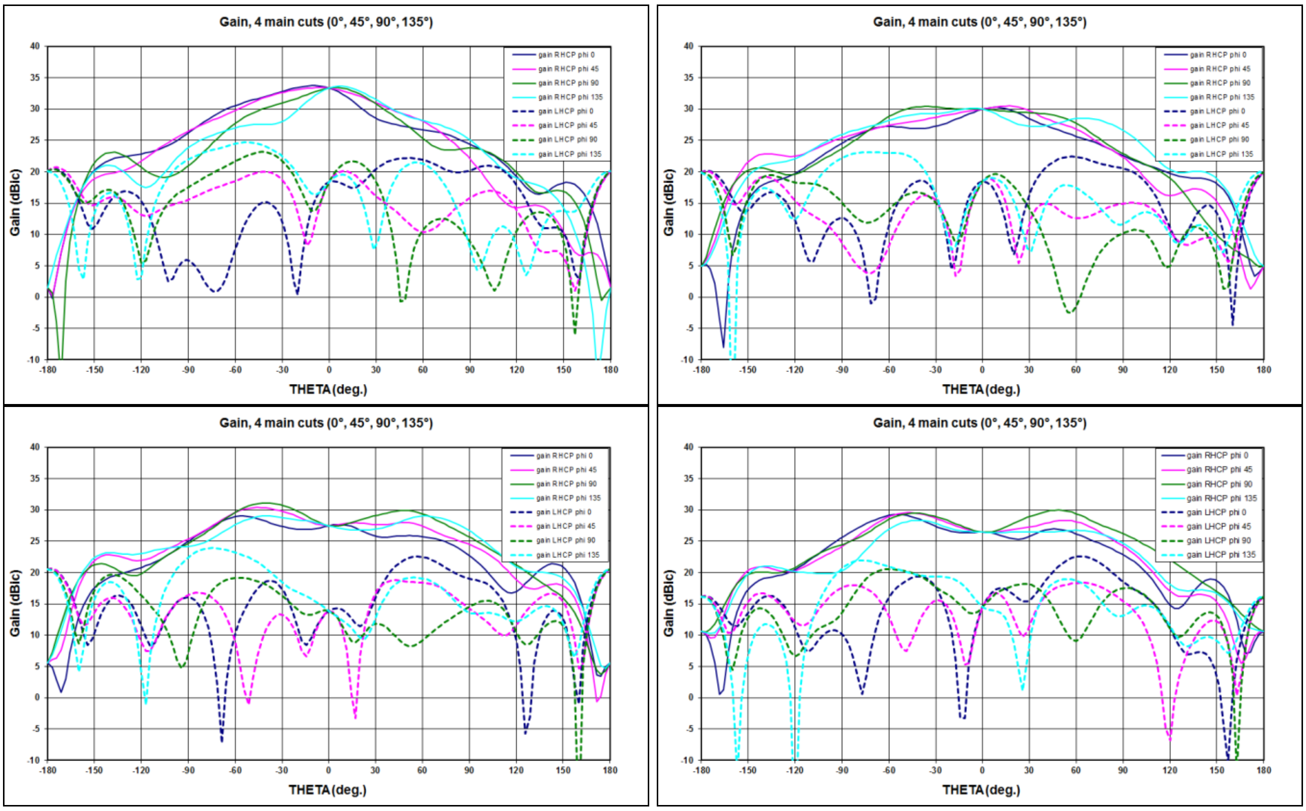

Figure 24 – Radiation patterns of dual frequency L1/L2 central element (top left: 1180 MHz, top right: 1200 MHz; bottom left: 1220 MHz, bottom right: 1230 MHz)

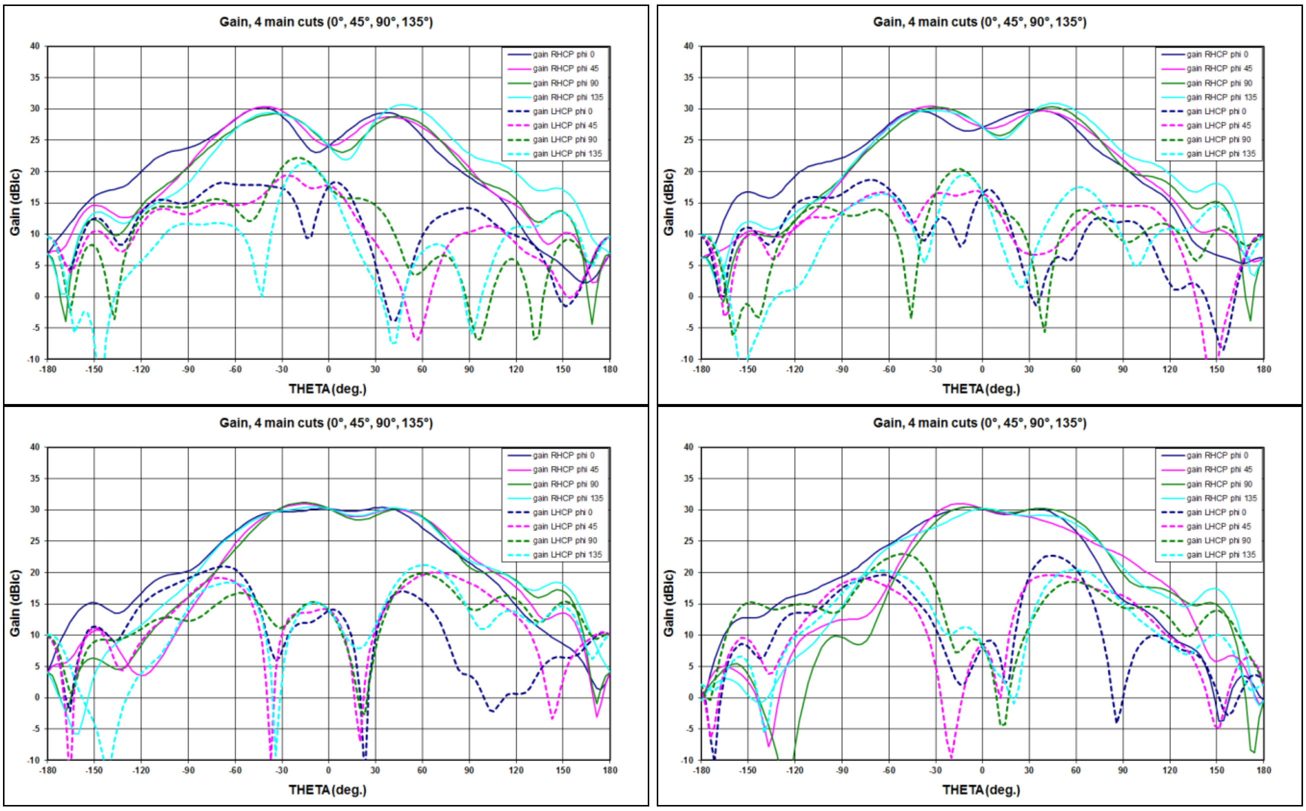

Figure 25 – Radiation patterns of dual frequency L1/L2 central element (top left: 1550 MHz, top right: 1560 MHz; bottom left: 1580 MHz, bottom right: 1600 MHz)

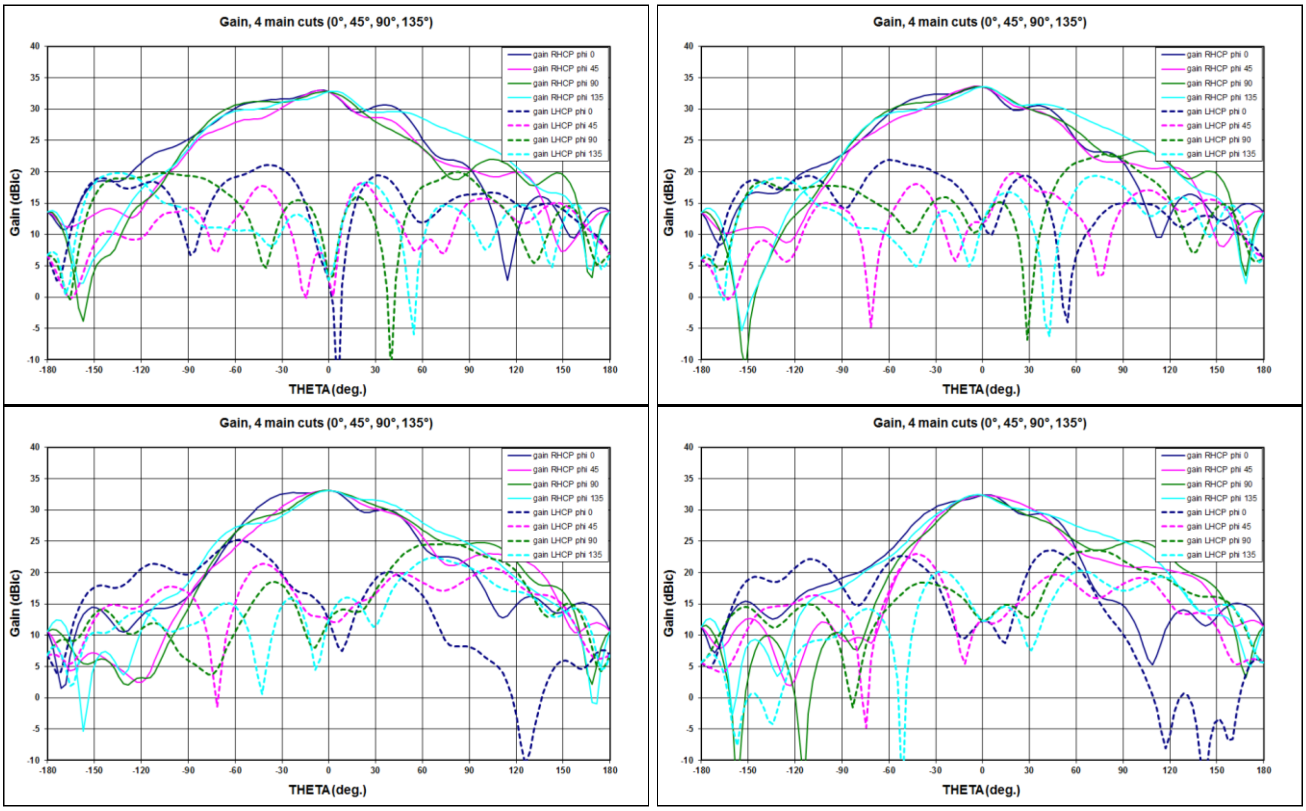

Figure 26 – Radiation patterns of single frequency L1 peripheral upper left element (top left: 1550 MHz, top right: 1560 MHz; bottom left: 1580 MHz, bottom right: 1600 MHz)

Finally, the phase centers of the antenna elements were calculated from the 3D radiation patterns. The phase center of the central element was contained within a sphere of 33.5mm diameter for L2 band and 18 mm diameter for L1 band. The phase center of the peripheral element was contained within a sphere of 17.7mm diameter L1 band.

The array-level measurement campaign concluded that the array#1 based on first iteration element was eventually the test. Gain and radiation patterns for the L1/E1 frequencies were sufficient for state-of-the-art GNSS signal reception. L2/E5 gain and radiation pattern for the central element was however sub-standard.

2.5. WP2200 GNSS Receiver Design, Specification and Implementation

Based on the system specification derived from the user scenario and requirements, a GNSS receiver was developed with sufficient RF front-ends and baseband channels to operate either in a 4x4 multifrequency configuration (High band receiving MSS, L1 GPS, L1 GLO and E1 GAL, low band receiver L2 GPS, L5 GPS, L2 GLO and E5ab GAL) or in a 6+1 configuration (1 main multifrequency receiver path and 6 L1 GPS/GLO/GAL auxilary paths). The receiver has been designed as a single board (Figure 27) reusing proven building blocks available at SSN. The board is enclosed in SSN standard “PRO” housing, including its ODU front panel (Figure 28).

Figure 27 The ADVANSYS receiver board with 6SF + 1DF or 4DF antenna input and calibration output connectors to the right. Left hand pane with digital ODU connectors compatible with Septentrio standard PRO housing front panel.

Figure 28 The ADVANSYS receiver fitting is Septentrio standard PRO housing (left). Details of the ODU front panel (right)

The receiver top level architecture consists of 8 wideband demodulators that can be flexibly configured to receive either a high band 1525-1610MHz or a low band 1165-1259MHz. Each demodulator feeds an ADC that is connected to an FPGA. 4 pre-existing GNSS baseband ASIC (SSN GReCo3) are also connected to the FPGA, providing sufficient tracking channel capacity to implement 4 multi-frequency receiver paths.

The FPGA connects via a bus to a CPU sub-system reused from SSN commercial development. The subsystem is built around a TI processor, featuring a ARM CortexA8 core that can be clocked up to 800MHz.

The CPU runs a dual-kernel linux-based real time operating system (Figure 29). The linux kernel allows us to easily support many peripheral features such as MicroSD card for data logging, USB device for control and USB host for connectivity and mass storage. In the same time, the RT patch guaranty hard real time operation for the closure of the tracking loops using the correlators implemented on the GReCo3 and for execution of (post correlation) beamforming algorithms implemented in software.

Finally, SSN generic firmware (Figure 30) was ported on the new platform, which is made easy by its POSIX compliance. This implies that all PVT modes (including RTK and PPP) are available on the platform.

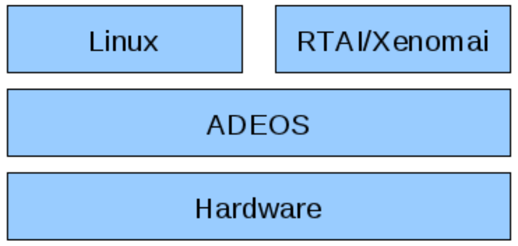

Figure 29 Receiver software run on top of a dual linux/RT kernel

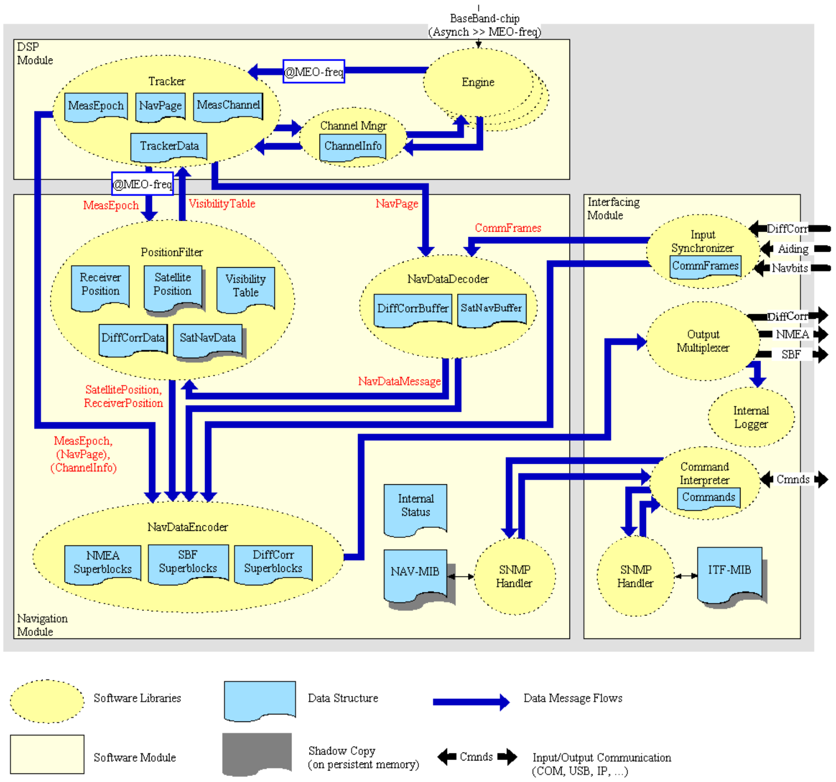

Figure 30 Receiver functional software architecture

2.6. WP3100 – Algorithms for beamforming

The system that was designed within the ADVANSYS project provides high accurate and robust positioning in harsh environments. Especially, shadowing of the satellite line-of-sight (LOS) signals and multipath are the effects that are considered as challenges for the overall system.

The ADVANSYS system includes multi-antenna GNSS (Global Navigation Satellite Systems) signal processing algorithms including digital beamforming as well as GNSS+IMU (Inertial measurement Unit) attitude determination together with smart GNSS-INS (Inertial Navigation System) close coupling. This set-up enables:

1. Enhanced robustness with respect to multipath,
2. Higher sensitivity especially with respect to shadowing due to the array processing gain,
3. Increased accuracy in pseudorange and positioning domain.

In harsh environments, the developed multi-antenna GNSS signal processing algorithms enhance the capability of the overall system to maintain lock with higher accuracy for visible satellites and the smart GNSS-INS coupling maintains measurement quality for positioning.

2.6.1. Concept

In Figure 31 the overall architecture of the GNSS receiver with beamforming and attitude determination is depicted. The interference suppression block was not treated in detail in the ADVANSYS project. In this architecture the attitude determination is performed combining both the information from inertial sensors as well as the directional information about the GNSS satellite. The direction information can be used because satellite ephemerides are provided by the GNSS system and the satellite positions can be calculated at any time. The user position is also continuously estimated and so the expected directions of arrival (DOAs) of the satellite signals can be computed for a given user in its local coordinates coordinate frame. Since the array receiver (see Figure 31) is also capable of estimating the DOAs in the antenna coordinate frame by using corresponding array processing techniques, the array attitude can be estimated by looking for the rotation matrix (i.e. Euler angles of the antenna attitude) which produced the best match between the expected and measured DOAs. The attitude solution delivered by the DOA-based approach then can be combined with the corresponding solution based on the inertial sensors in the way that is similar to GNSS/INS combination on positioning-level. Such a combination is helpful for handling the biases and long-term angular drifts existing in the inertial sensors. On the other hand, the short-term noise of the DOA-based attitude solution can be significantly reduced due to high short-term stability of the inertial sensors.

The information about the attitude of the antenna array available in the proposed receiver architecture (see Figure 31) is very helpful for beamforming process if spatial constraints can be calculated and utilized in order to avoid the occurrence of antenna induced biases on code- and carrier-phase range measurements. The mitigation of the antenna-induced biases requires the knowledge of the array manifold. One part of the array manifold that is due to the RF-front-end and cabling effects is estimated by using an online calibration procedure based on the generation and tracking of a dedicated calibration signal. Another part of the array manifold, namely the radiation patterns of the array elements, is assumed to be known with a sufficient accuracy from the antenna measurements (empirical measurement of embedded patterns of the antenna array).

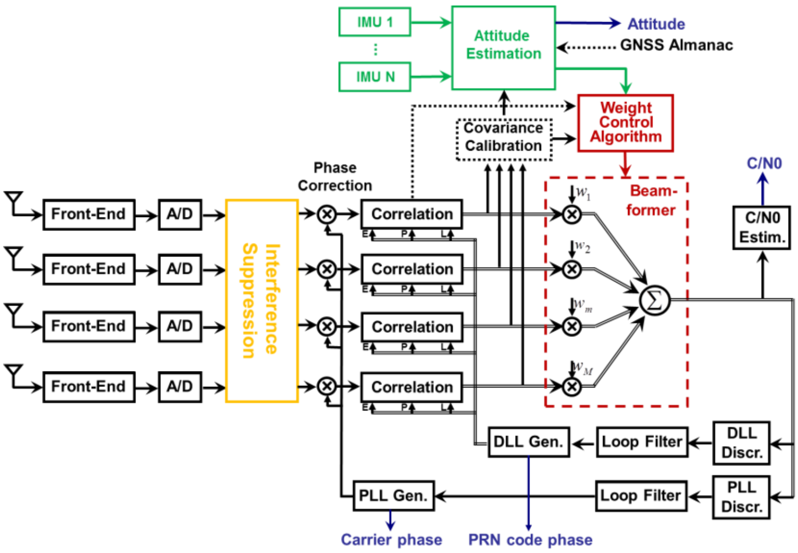

Figure 31: Beamforming and attitude estimation architecture

The two beamforming algorithms that were further developed and considered in the ADVANSYS project are the minimum variance distortion-less response (MVDR) and secondly a deterministic algorithm. The deterministic beamformer was chosen as baseline approach for implementation activities within the project, due to its robustness with respect to calibration, modeling, and pointing errors as well as low complexity.

In order to enhance multipath suppression capabilities of the MVDR algorithm and in order to achieve higher robustness and sensitivity, innovative array interpolation methods were developed within the project and assessed by computer simulations. With these signal adaptive array interpolation methods forward-backward averaging (FBA) and spatial smoothing (SPS) techniques can be applied. FBA and SPS de-correlate highly correlated or even coherent signals and thus allow separation of multipath and LOS signals and consequently suppression of multipath errors.

Concepts for attitude determination using fusion of the solution obtained with the information about DOAs of GNSS LOS signals and the solution delivered by inertial sensors were developed. The block diagram of the proposed basic architecture is depicted in Figure 32.

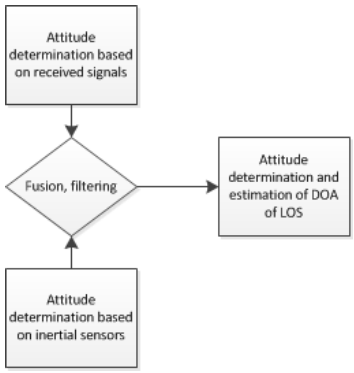

Figure 32: Attitude determination architecture

A low-complex but robust DOA estimation algorithm based on a Maximum Likelihood (ML) estimator was derived which is based on an adaptive cascaded grid search with different resolution and size of search space using prior information from previous measurement epochs. Two different algorithms were developed which determine the attitude of the antenna array based on DOA-estimates for the LOS signals.

To fuse the inertial based and antenna array based attitude, an error-state Kalman filter (KF) was derived. A block diagram of the investigated scheme can be seen in the Figure 33. The difference between the inertial based and antenna array based attitude is used as filter input of the KF. That is the difference of the inertial attitude error and antenna attitude error is fed into the KF. Due to the different nature of the array attitude error, which can be considered as white noise, and the inertial attitude error, which is mainly determine by a time increasing bias, the inertial drift can be modeled nicely with the error-state KF. The obtained drift estimated is then applied to the inertial attitude. This corrected attitude information together with the almanac information is finally used to obtain the DOAs of the satellites which are fed into the beamformer algorithm.

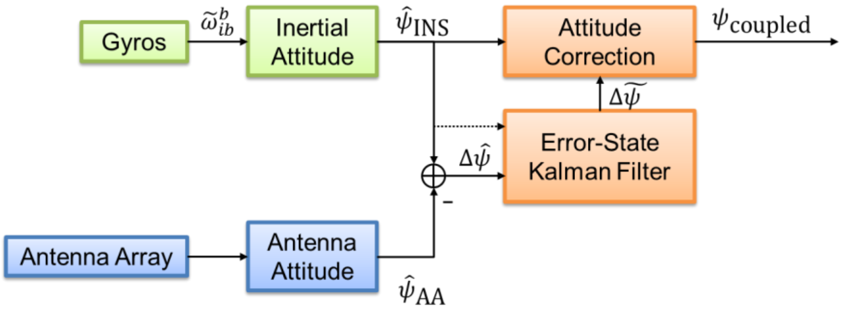

Figure 33: Forward antenna array and inertial attitude fusion via error-state Kalman filter

2.6.2. Simulation Results

In the following some results of the estimated pitch, roll and yaw angles of the designed ADVANSYS system are shown in Figure 34, Figure 34, Figure 35, and Figure 36. The pictures refer to the attitude estimation performed at different stages:

- Only attitude: the attitude estimation is based only on the LOS DOA estimates provided by the ML-DOA estimator.
- Attitude+IMU: the attitude estimation based on both LOS DOA and IMU, obtained after fusion and filtering.

The results given in Figure 34- Figure 36 demonstrate high accuracy and robust attitude determination using the in ADVANSYS develop algorithms and methods.

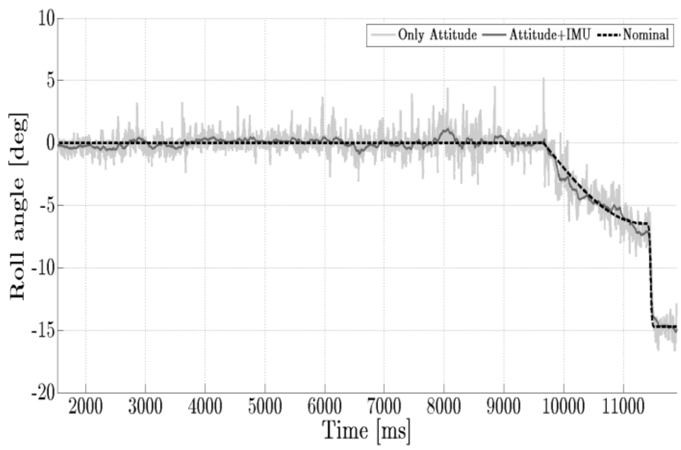

Figure 34: Roll angle estimation

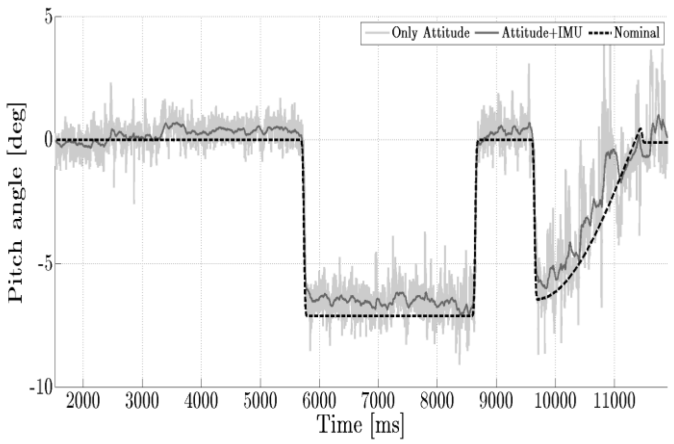

Figure 35: Pitch angle estimation

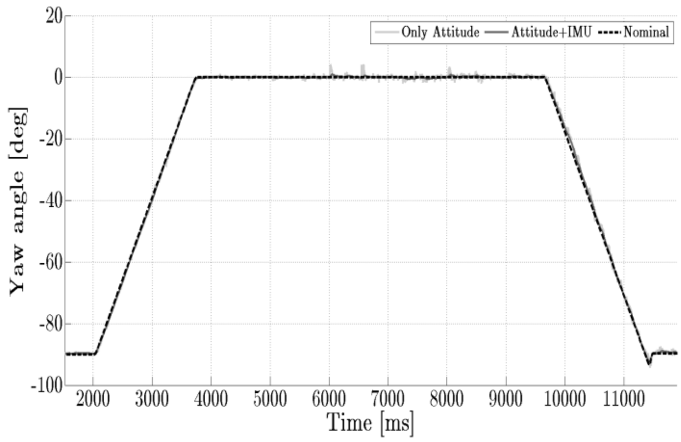

Figure 36: Yaw angle estimation

In Figure 37 and Figure 38 tracking results and sensitivity analysis are shown for the satellite with PRN 6 which is affected by shadowing and multipath. The results show high gain in sensitivity and rather stable and accurate code and carrier phase tracking. More simulation results and a detailed discussion and analysis of the behaviour of the proposed algorithms and methods can be found in D3.1.1. and D3.2.1.

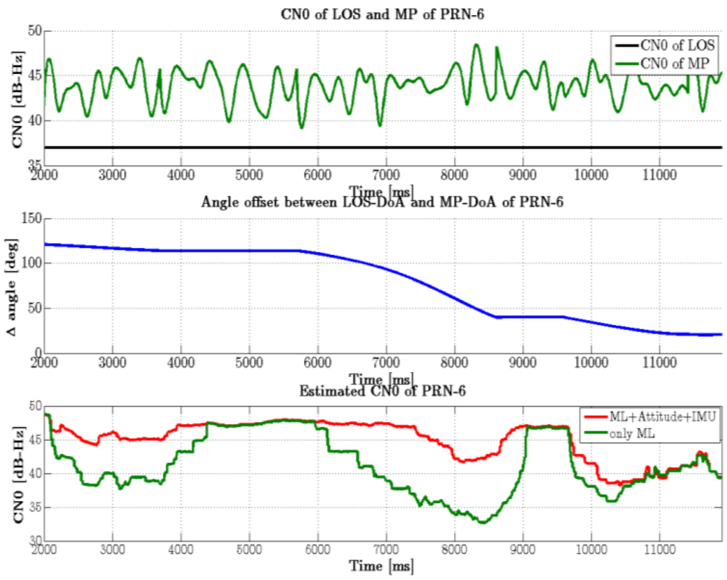

Figure 37: Satellite PRN6 plots of a) Nominal C/N0 of LOS and multipath; b) Angle deviation between LOS DOA and multipath DOA unitary vectors; c) Estimated C/N0

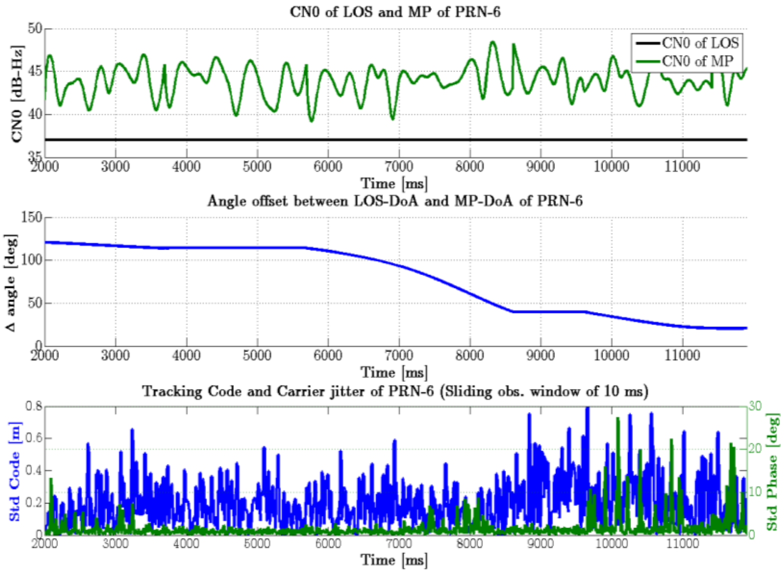

Figure 38: Satellite PRN6 plots of a) Nominal C/N0 of LOS and multipath; b) Angle deviation between LOS DOA and multipath DOA unitary vectors; c) Code and Carrier tracking results (averaged over 10ms)

2.6.3. Implementation

Based on the outcome of the algorithm exploration described above, it has been decided to implement a deterministic beamformer. Beam steering is applied post-correlation on all SV individually. Beam direction is determined based on the comparison of the array attitude with the constellation ephemeris.

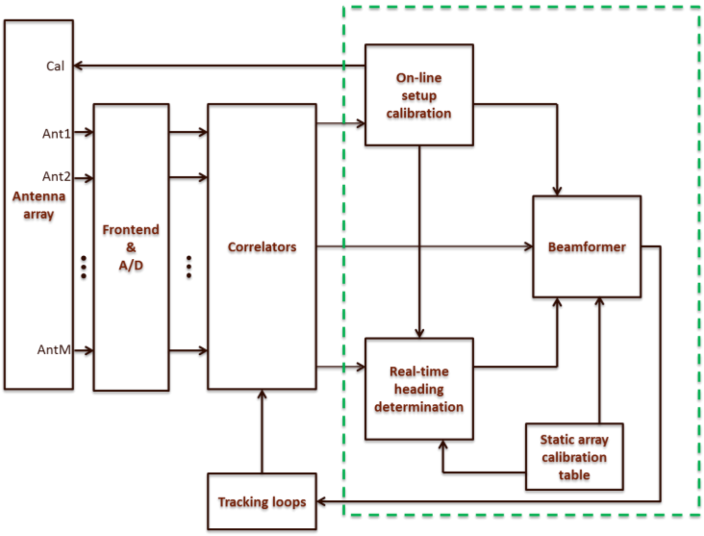

Figure 39 Overall architecture of the beamformer

Figure 39 shows the overall functional architecture of the signal tracking/beamforming in the ADVANSYS receiver. The components of the software dedicated to beamforming, which constitute the new developments in the ADVANSYS project, are within the dashed green rectangle. The beamforming software is divided into four main components:

1. The static array calibration table, which contains the pre-calibrated steering vectors on a 2x2-degree azimuth/elevation grid (Figure 40). This table was extracted from the array radiation pattern measurements done by Satimo.

2. The on-line setup calibration module, which measures the phase, amplitude and delay of a calibration signal injected at the output of the antenna elements and compensate for the asymmetries in cabling and antenna front-ends. This implies generating a calibration signal, with the same modulation as the signals of interest (GPS CA code), but using a non-existing PRN code to avoid correlation with the signals of interest and measuring the post-correlation amplitude, phase and delay of this calibration signal when received from the different antenna elements.
3. The real-time heading determination module, which determines the array heading angle by maximizing the beam power averaged over all the satellites.
4. Finally, the beamformer itself, which combines the correlation values from the different antenna elements to produce a beam in the direction of the satellite of interest. Our beamformer is implemented in 3 stages: correlation, calibration and beamforming.

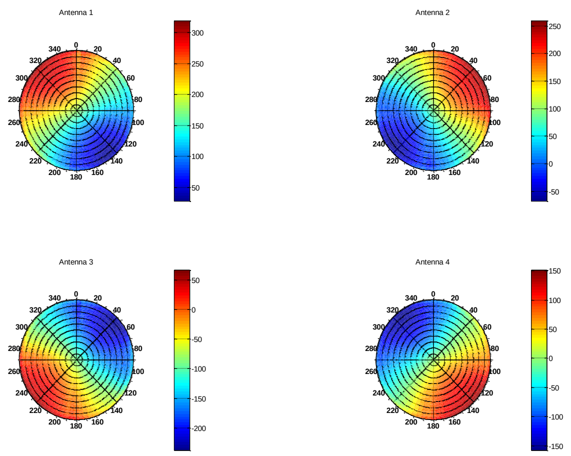

Figure 40 2x2 array static phase calibration data, in degrees, for the DLR 2x2 antenna array.

2.7. 00 – Algorithms for GNSS-INS hybridization

2.7.1. Concept

Beyond the beamforming that can only increase availability and integrity when satellites are not completely blocked, a coupled GNSS-INS navigation engine was designed to leverage the IMU in order to further increase positioning availability and integrity. In view of the sub-10cm requirement, hybridization with FOG IMU was considered as state-of-the-art MEMS are not yet sufficiently stable to reach that level of strapdown precision.

In deliverable 3.1.1, we reviewed the pros and cons of various level of coupling between the GNSS and INS engine and proposed an hybrid approach delivering the major part of the benefit of close coupling in terms of availability and robustness while mitigating the main pitfalls: the risk of bias propagation in the GNSS – INS loop and the higher computational complexity. The proposed approach was implemented in collaboration with IMU provider iXblue and therefore referred to as "SIGIL", standing for Septentrio – Ixblue Gnss Ins Link.

As illustrated in Figure 41, the main data flow consists of a standard GNSS only extended Kalman filter, producing GNSS-based position, velocity and related co-variances at 1Hz epochs, followed by an INS Kalman filter, operating at 200Hz, which jointly integrate the velocities and positions output by the GNSS filter with inputs from a so-called strap-down navigator, which process the IMU raw data. This standard loose-coupling setup is enhanced with a feedback of accurate short term information computed by the INS filter to the GNSS engine. The feedback is provided at 10Hz via a dedicated interface. This extra feedback is used in the GNSS engine at two levels:

1. Improvement of the ambiguity fixing speed and reliability through the reduction of the search space
2. Improvement of the receiver autonomous integrity monitoring (RAIM) through the use of more accuracy apriori information instead of traditional aposteriori (residuals) information.

Eventually, the only difference with full close-coupling in terms of benefits is that coasting capabilities is not improved in case of visibility of <5 satellites. Such situation are less and less usual with the increasing number of constellations and less problematic if a higher grade IMU is used (drift <1degree/hr), as here. In the future, such drift performance could also be obtained by combining MEMS IMU, possibly redundant, and vision processing (see WP3200).

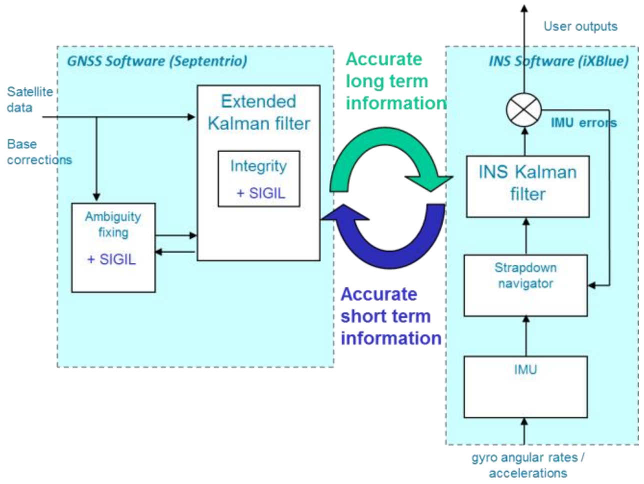

Figure 41 The SIGIL GNSS-INS integration concept

2.7.2. Implementation

The SIGIL method has been implemented in SSN AsteRx3 OEM receiver firmware and PPSDK post-processing library. This comprises:

- An dedicated SIGIL input interface, using proprietary RTCM-alike messages that can be received at up to 10Hz from any port of the receiver module
- The necessary modifications in the RTK Kalman filter steps, ambiguity fixing procedures and RAIM algorithms

The resulting modified firmware and post-processing library have been further integrated respectively in the iXBLUE ATLANS-C INS (which has been modified to host the AsteRx3 GNSS receiver module, Figure 42) and the iXBLUE DELPHINS GNSS/INS post-processing tool (Figure 43).

Figure 42 The ATLANS-C implementation (based on SSN Ax3 and iXBLUE IMU50

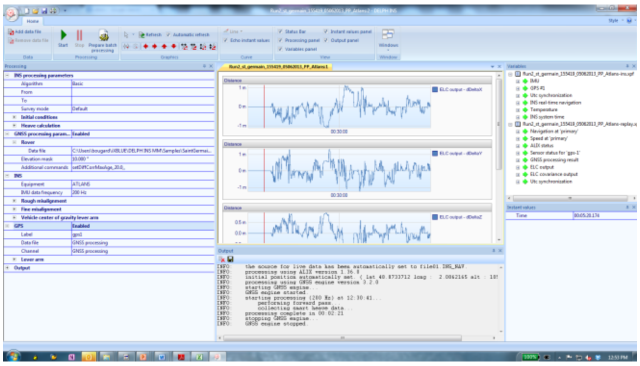

Figure 43 The DELPHINS GNSS-INS post-processing software (based on SSN PPSDK and iXBLUE PostProINS engines)

2.8. WP3200 – Advanced Topic: Hybridisation with vision

2.8.1. Concept

The concept of a vision-aided navigation system lies within the field of computer vision, whereby methods exist for processing and analysing images acquired from cameras. Various computer vision algorithms exist for estimating the relative pose of cameras or of a camera's motion on a frame by frame basis. These algorithms are maintained by the computer vision community and are stored in libraries of which OpenCV and Matlab are the most notable.

The basic concept of a vision-aided navigation system and processing stream in computer vision for aiding navigation is as follows:

1. Image acquisition
2. Detect, extract, and match features such as corners
3. Perform automatic image registration to estimate the geometric transformation
4. Output
    a. Homography (x, y, z axis displacement (m/s) and number of inliers)
    b. Essential Matrix (roll, pitch, yaw angular rotation rate) for calibrated cameras

The performance of a vision-aided navigation system is greatly enhanced if combined with other sensors, particularly a GNSS and INS. . For example, it may be possible to assume that GNSS will be used to provide an initial position estimate in a global coordinate system. GNSS may also be available for regular position updates, which are beneficial for resolving issues such as scale uncertainty using single cameras. Also the INS is available which can provide continuous navigation for situations where images contain few features (and are therefore unable to provide useful measurements for positioning). The INS can also contribute to reducing issues such as non-linearities that occur when the position and orientation of the camera become very uncertain.

The hybridised vision-aided navigation system conceived as the ADVANSYS prototype employs a forward facing and downward facing camera, with the image data processed according to the scheme outlined above. The computer vision displacement and rotation results are then integrated with measurements from the GNSS and INS via a Kalman filter to provide estimates of position and velocity, with the aim that a vision/INS only system should be capable of providing a centimetre accuracy solution in environments in the absence of GNSS or prone to high multipath errors.

2.8.2. Experiments and Results

For proof of concept of the proposed system a number of field trials were undertaken in a variety of environments, including a smooth urban road, a smooth rural road, a muddy track, ploughed field and a forest road. The main system components comprised forward and downward facing Prosilica GX1660 high resolution 2 Megapixel CCD cameras (acquiring image data at 10fps), a low-cost Xsens IMU (sampling at 20Hz) and GNSS (sampling at 10Hz). The downward facing camera was placed 1.75m above a reference ground plane (the smooth urban road).

The image data were processed using the Bag of Words software developed jointly by UNOTT and the Geospatial Research Centre, Christchurch, New Zealand and the derived velocities and rotations were integrated using UNOTT's POINT Kalman filter software. The initial results showed that the system made good estimates of velocity in the *y*-axis (forward/reverse directions) from the homography matrix for the smooth urban road, but that the system underestimated velocity in the *x*-axis (left/right directions) and failed to measure slight changes in direction. For the smooth rural road, the velocity in both *x* and *y*-axes was under estimated and noisy due to the ground plane being represented by a grass verge, containing an element of perspective.

For the ploughed field and forest track, the velocities were similarly underestimated and noisy, due in part to the perspective contained within the imagery and also to changes in the height of the camera above the ground plane. This affected the scaling factor used to derive the camera platform's velocity. For the muddy track environment, deriving estimates of velocity proved more problematic, due to the effects of perspective and a variable scaling factor combined with considerable roll in the platform's attitude.

An improved performance in the vision solution for all but the muddy track environments proved possible by substituting the scaling factor with a moving average of the GNSS velocity in the *x*, *y* and *z*-axes, collected over the last 10 epochs and by weighting the values according to a moving average of the GNSS covariance values collected over the same period. Despite this improvement, the system still fails to detect slight changes in velocity in the *x*-axis as shown in Figure 44.

A further improve the system's performance is made by integrating the essential matrix derived from the forward facing camera, which proved more effective in detecting motion in the *x*-axis. Nevertheless, these measurements still proved noisy for all environments; in addition, the essential matrix derived from the raw image data suffered significant drop-out.

Experiments proved that it is possible to reduce the drop-out in the essential matrix by employing an edge enhancement algorithm. This has the effect of reducing the noise in the imagery and aids the Bag of Words algorithm in detecting rotation about the yaw axis (see Figure 45).

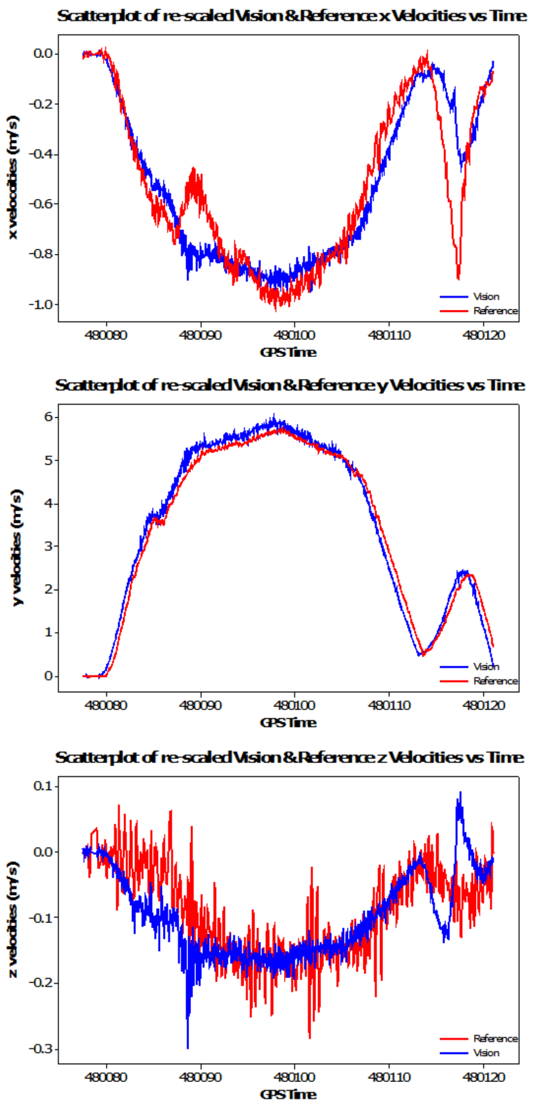

Figure 44 - Vision velocities (blue) re-scaled using the moving average of GPS velocities and GPS covariance plotted alongside the Reference velocities vs Time in the *x* (top), *y* (middle) & *z* (bottom) axes

However, this only proves to be effective in the smooth urban road environment where many strong edges exist in the imagery. This being the case, it is recommended that the prototype system be developed in the urban environment.

Analysis of the results also identifies systematic noise, particularly in the *x*-axis velocity and in the yaw angular rotation rate. The algorithm proposed states that, if the *x*-axis velocity is less than the system noise, any change in direction detected does not represent an actual change in direction. If the *x*-axis velocity is greater than the system noise, then this represents an actual change in direction and the Vision solution is altered accordingly.

In situations where the yaw angular rate is less than the system noise, then no change in direction has taken place and the *x*-axis velocity is accepted. However, when the yaw rate exceeds the system noise, this signals that a change in direction has occurred. The yaw rate is then compared to the *x*-axis velocity, which if it underestimates the change in direction or does not detect the change at all, then the *x*-axis velocity is adjusted accordingly. The system operating within these parameters has been shown to constrain displacement errors to <20cm as shown in figure 38.

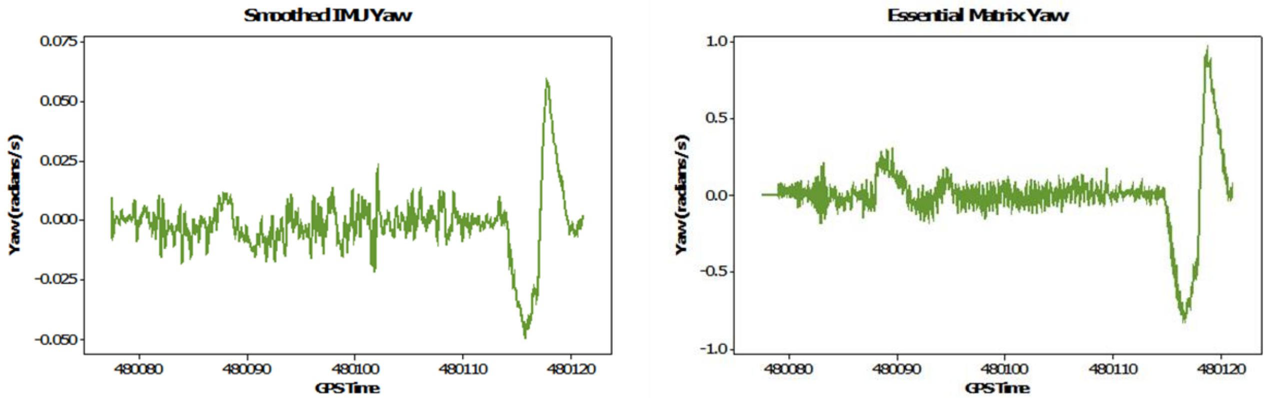

Figure 45 - Plots of smoothed IMU yaw (left) and Essential Matrix yaw (right) vs. GPS time

Figure 46 - Comparison of the Reference solution (red), unadjusted Vision solution (blue) and the yaw adjusted solution (green)

2.9. WP3200 – Advanced Topic: Redundant IMU

For an INS/GPS combined system, the achievable position accuracies dependent strongly on the performance of the two individual sensors, i.e. GPS receiver and inertial measurement unit (IMU). However, it has been shown that the velocity and orientation accuracies have exposed to be less sensitive to the quality of GPS observables. Since in the ADVANSYS project a full system solution is mandatory, a quite robust IMU is absolutely essential. Hence, two possibilities can be envisaged: Firstly the usage of a higher-grade IMU can be considered, which fulfils the requirements on the one hand but is expensive, big and heavy on the other hand. Secondly the exploring of redundant low-cost sensors might comply with the required performance quality while remaining lower cost, volume and weight consumptions than high-grade IMUs.

Low-cost IMUs have been frequently the focus of past and current research and development activities. On the downside, they have a relatively low accuracy performance due to their large systematic errors such as biases, scale factors and drifts, which are strongly dependent on temperature. To improve the inertial error performance while remaining low system costs and complexity, a network of redundant low-cost MEMS IMUs is investigated and analysed in the ADVANSYS project. By exploring the emerging measurement redundancy with suitable combination strategies and appropriate sensor distributions, the inertial performance can be significantly improved and optimized. Due to the size and price decreasing trend of the sensors, the investigation of sensor networks is a very promising approach with respect to economical and ergonomic consequences. For instant, skew-redundant IMUs (SRIMUs) consist of a redundant number of inertial sensors skewed against each other. Their configuration encapsulates a maximum amount of information depending on the number of sensors and the configuration geometry.

2.9.1. Concept

For the ADVANSYS project different levels of inertial redundancy evaluation, geometrical considerations about the spatial configurations of inertial sensors, as well as the theoretical basis of noise reduction achieved with sensor redundancy have been theoretically discussed. The performance of the different sensor distributions such as orthogonally-redundant IMUs and skew-redundant IMUs were investigated. Furthermore, most commonly used Fault Detection and Isolation (FDI) algorithm, the parity space method, was outlined. It was shown that firstly, noise estimation can be achieved directly from the data and the stochastic parameters are hence closer to reality. Secondly, that the noise level can be reduced and defective sensors, spurious signals and sensor malfunctioning can be detected and isolated. Furthermore, sensor error calibration (and hence orientation estimation) becomes conceivable even during uniform motion or static initialization. Due to the improved navigation accuracy, redundant IMUs bridge the gaps in the GPS data more effectively. Finally, more accurate orientation determination is expected with redundant IMU configurations.

2.9.2. Experiments and Results

To validate the theoretical investigations and results, we designed a platform for five identical, skew-redundant IMUs. The platform is optimized to provide maximum information in the vertical direction of the vehicle. The platform has a pentagonal base. Each side of the pentagonal pyramid was designed to hold one MTi Xsense sensor. This can be seen in Figure 47. For reference and comparison reasons a GNSS antenna can be place on centre top of the platform. The GNSS data can also be used for INS/GNSS integration later. The whole setup can be seen on Figure 48.

Figure 47 Sensor platform optimized for five skew-redundant inertial sensors

Figure 48 Measurement campaign setup with five MTi xSense inertial sensors and Septentrio Asterix receivers

Both static as well as kinematic tests have been undertaken in Leuven, Belgium by Septentrio and the raw measurements have been provided to the DLR. The first results show that the theoretical derived reduction of the measurement noise can also be also achieved in the field. Furthermore they point out that the errors on the turn rates are uncorrelated and independent, whereas the errors on the accelerations are strongly correlated with the vehicle vibrations produced by the engine. This should be taken into account both when resolving the sensor redundancy into a synthetic IMU and when resolving the redundancy in the system domain (large filter modelling all five sensors separately). Furthermore these discoveries can be used for FDI and sensor bias identification and monitors.

The second results cover the impact on the strap-down solution and show paradigmatically the effect of the skew-redundant compared to the single sensor case. In general to achieve an improvement in the strap-down performance, the synthetic/skew-redundant IMU should show a reduction in the resulting bias of the measured quantities. That is the biases on the turn rates and accelerations are integrated over time within the strap-down algorithm. Consequently, the bigger these biases are the stronger the errors on the attitude, velocity and position will grow over time. However it is observed during the campaigns that the bias of the synthetic IMU is not significantly reduced compared to the single IMU case. The bias of the synthetic IMU is equivalent to an averaged bias of the rotated single IMUs biases. Consequently, we cannot see a significant improvement in the performance of the strap-down algorithm. However, we can ensure to achieve a middle performance which lies between the worst and best single IMU solution (this can be seen in Figure 49 and Figure 50, for example).

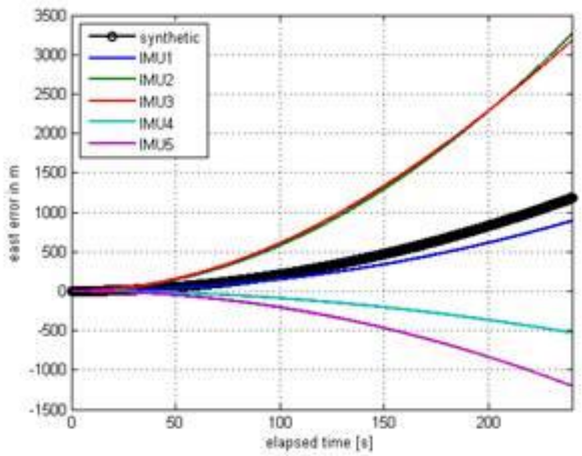

Figure 49 Comparison of strap-down position error evolution in east direction

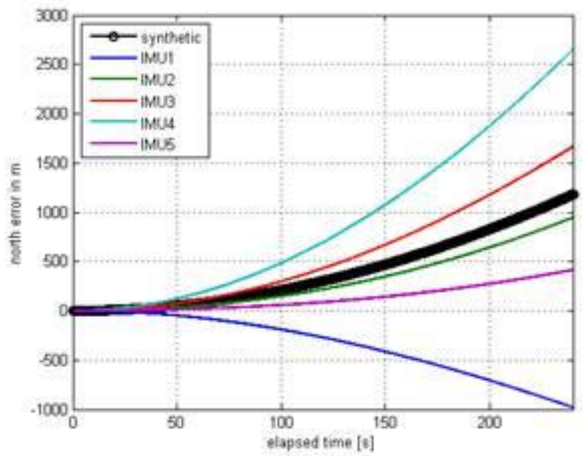

Figure 50 Comparison of strap-down position error evolution in north direction

2.10. WP4100 – Static test of the Beamforming System

To validate the beamforming antenna and receiver implementation at system level prior to do kinematic tests in the targeted environments, the beamforming system has first been evaluated in static benign conditions.

Therefore, the antenna array (based on first iteration elements, as measured best by Satimo) has been installed in SSN rooftop antenna test range and wired to the ADVANSYS receiver installed into the service shaft. The beam gain, translating to C/No increase (Figure 51), 24h DGNSS 2DRMS (Figure 52) and 24h RTK 2DRMS (Figure 53) were compared with the same quantities for a co-located reference Choke Ring antenna connected to a commercial AsteRx3 receiver running latest SSN trunk firmware.

On average, C/N_0 from the beam is 4-5dB higher than C/N_0 from the reference antenna (measured with the 6+1 array). However, we found out that the beam gain highly depends on the direction. It is postulated that this weakness originates from the limitation of the antenna element in view of the irregular radiation pattern.

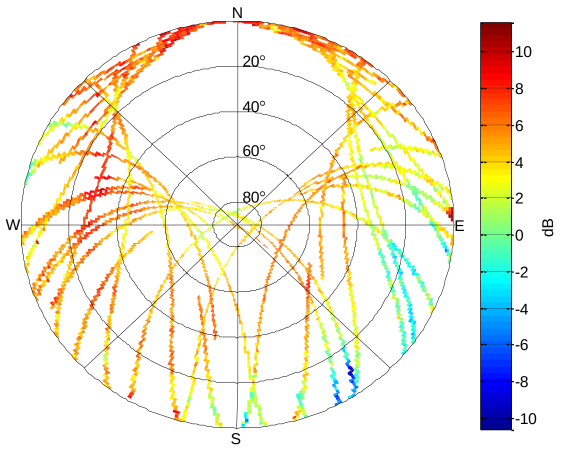

Figure 51 Beamforming C/No gain compared to Choke ring antenna

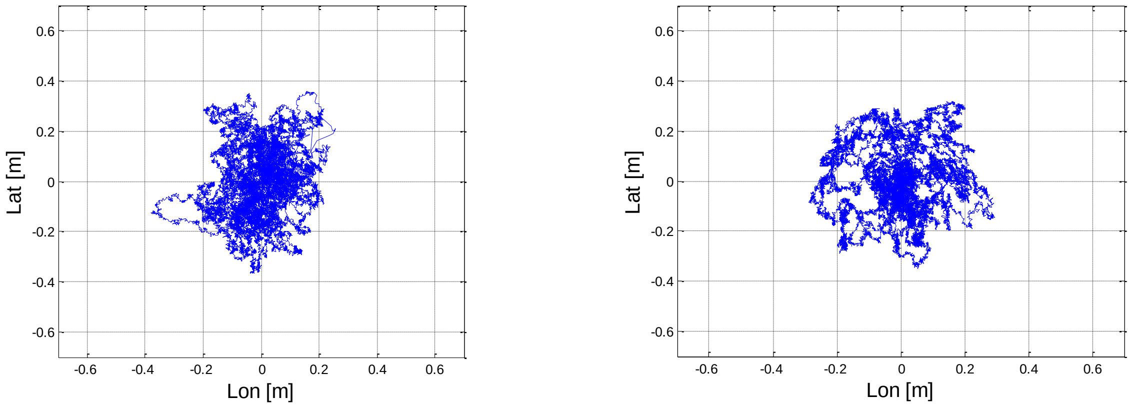

Figure 52 24h DGNSS static accuracy in benign conditions. ADVANSYS (left) showing 34cm 2DRMS accuracy compared to Reference (right) showing 33cm 2DRMS.

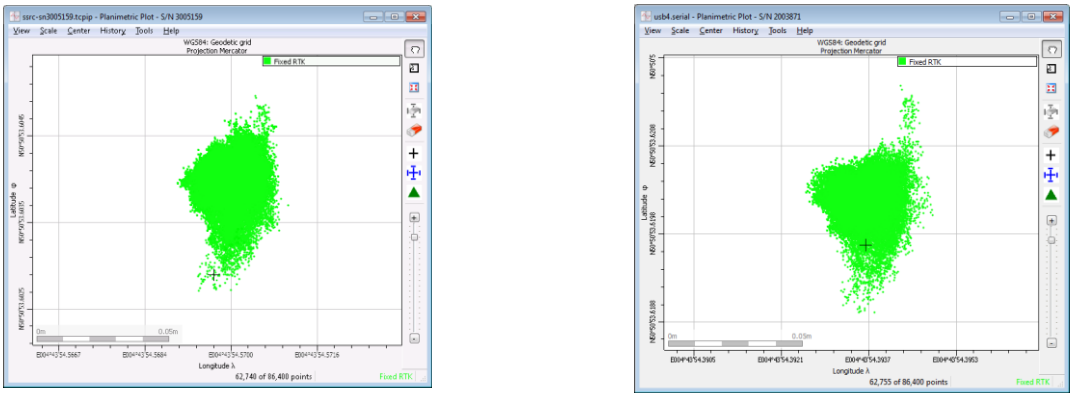

Figure 53 24h RTK static accuracy in benign conditions. ADVANSYS (left) showing 2cm 2DRMS accuracy compared to Reference (right) showing 1.8cm 2DRMS

2.11. WP4200 – Kinematic Testing of the GNSS-INS System

Next, to evaluate the benefit of the novel GNSS/INS integration method developed in WP3100 and further implemented in the ATLANS and DELPHINS project, an extensive benchmarking test was organized in Paris suburb (StGermain-en-Laye, Marly-le-Roi), still in close collaboration with iXBlue. For logistic and timing reason, this was done independently of the beamforming test.

A mobile mapping vehicle (Figure 54) was equipped with a prototype ATLANS unit (including an SSN Ax3), a very high grade iXBLUE MARINS unit (as reference) and an Applanix PosLV420 as competitive benchmark. This vehicle was driven around a 2h30-long trajectory in suburban environment (Figure 55) out of which 1h15 is in difficult conditions for non-aided RTK. The remainder of the discussion relates to those difficult subsections. The collected GNSS and INS raw measurements were post-processed with DELPHINS (including SSN PPSDK library) using the new GNSS/INS integration methods (SIGIL) and compared to standard loose coupling (non SIGIL) and similar post-processing (by of third party mobile mapping consultant) of the PosLV data.

Figure 54 GNSS/INS benchmarking setup

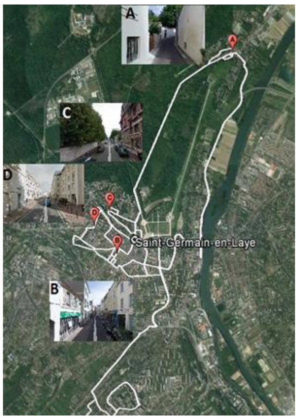

Figure 55 GNSS/INS benchmarking trajectory

Analysis of the RTK availability (Figure 56) showed that fix availability is increased by about 10% between the SIGIL methods and standard GNSS/INS loose coupling. This translate (Figure 57) to a significantly increased accuracy (in particular in the highest percentile) of the GNSS/INS integrated solution. Comparison with Applanix was very favourable to the ATLANS/Ax3 both with SIGIL as, astonishingly, with standard loose coupling too. Further investigations revealed that this is due to more effective fixing of GLONASS ambiguities in the SSN RTK algorithm.

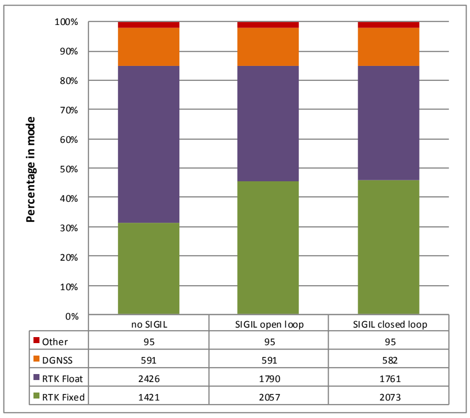

Figure 56 RTK Fix availability benefit from SIGIL GNSS/INS integration

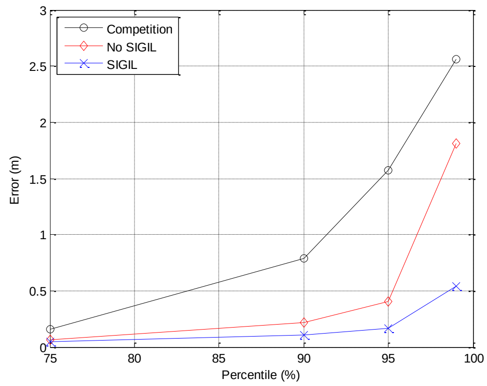

Figure 57 Improvement of the error (percentiles) of the integrated solution (compared to trusted reference). Blue (SIGIL), Red (No SIGIL), Black (PosLV)

2.12. WP4200 – Kinematic Testing of the Beamforming System

As a last step in the project, the ADVANSYS beamforming system (DLR/Satimo antenna array#1) combined to SSN ADVANSYS receiver running SSN latest PVT firmware (trunk) was compared to standard state-of-the-art AsteRx3 receiver / PolaNt antenna in scenarios corresponding to the use cases identified in WP1000. This was done using Septentrio test vehicle, equipped with an ATLANS GNSS/INS system as reference to compare accuracies.

This test campaign showed that **the DGNSS (L1 only) performance of the ADVANSYS system significantly outperforms state-of-the-art reference**. This is visible in the test under dense canopy (Figure 58) where the altitude accuracy is significantly improved (Figure 59). This can be explained by the tracking of extra satellites reaching acquisition threshold with beamforming and their positive effect on the dilution-of-precision. Positive impact of beamforming is also visible in the multipath/alternate-path rich environment (Figure 60) where, again improvement is most noticeable in the altitude component.

RTK performance is however not improved as illustrated in Figure 61. This is due to the weakness of the L2 reception by the central antenna element. Eventually, the gain in L1 yield by the beamformer is of no use for RTK fixing as corresponding L2 information is not available due to low L2 antenna gain. Accuracy is further slightly degraded by the slight instability of the equivalent phase centre, as found during reproducible track test conducted in the installation of the University of Nottingham (Figure 62).

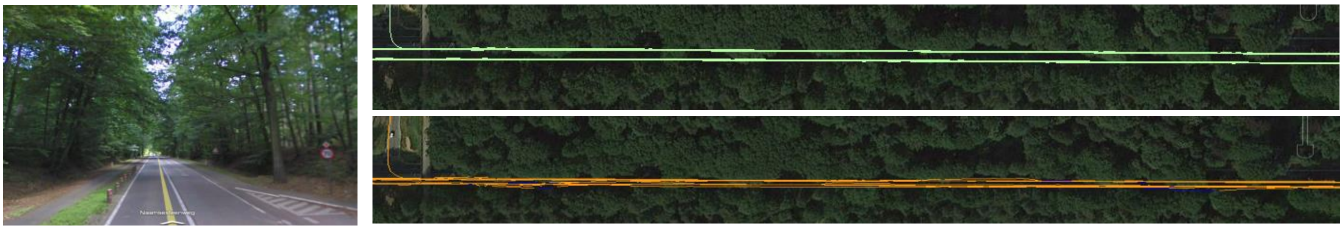

Figure 58 Improvement of the DGNSS precision with beamforming (green) compared to Standard PolaNt antenna/Ax3 under dense canopy

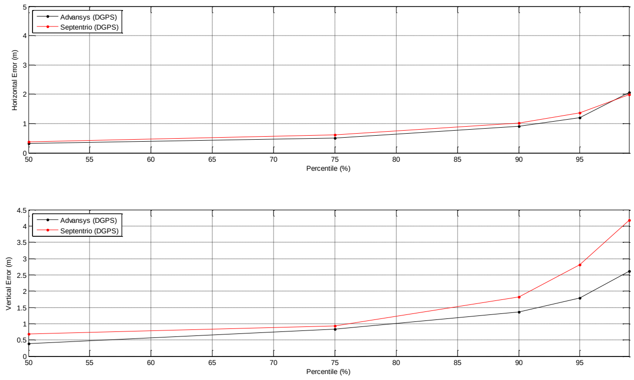

Figure 59 DGNSS accuracy percentiles compared to trusted GNSS/INS reference (Black: ADVANSYS; Red: Ax3/PolaNt)

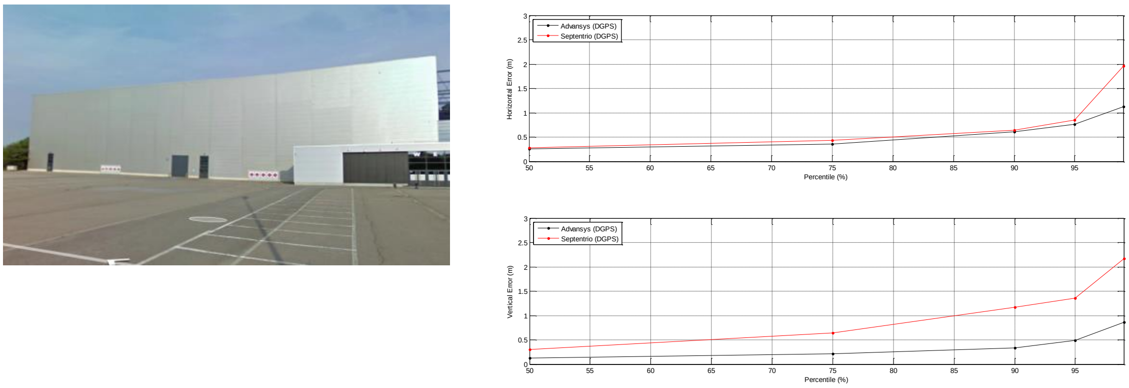

Figure 60 DGNSS accuracy in multi-path/alternate path rich environment

Parameter	Advansys	Septentrio
Percentage RTKFixed epochs	79.25%	85.87%
Planimetric median error	2.6 cm	2.3 cm
Planimetric 95% percentile	7.2 cm	6.1 m
Planimetric 99% percentile	12 cm	10 cm
Vertical median error	1.9 cm	1.4 cm
Vertical 95% percentile	7.6 cm	5.4 cm
Vertical 99% percentile	14 cm	9 cm

Figure 61 RTK fix performance in the multi-path rich environment (same as Figure 65)

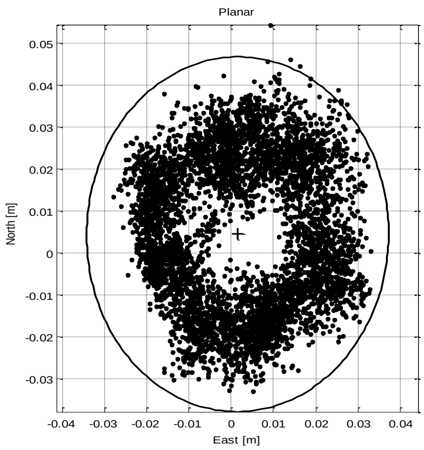

Figure 62 Inaccuracy of the RTK phase center exposed during reproduceable track test in UNOTT

2.13. Technical conclusions

The ADVANSYS project aimed at developing advanced technologies for high added value high-precision (<10cm) Machine Control applications. The core of the project focused on two main topics: (1) beamforming technology for increased GNSS signal reception sensitivity and integrity, leading eventually to increased DGNSS and RTK availability, accuracy and reliability ; (2) GNSS/INS integration technology to further increase positioning availability when a GNSS only solution is not possible.

The first technology was implemented in a demonstrator comprising a 7-element antenna array and corresponding GNSS receiver. Extensive testing in representative Machine Control scenarios reveals that DGNSS availability and accuracy could significantly to improved, in particular in dense canopy environment. RTK was achieved with performance close to state-of-the-art standard geodetic receiver and antenna but not improved. This is due to a weakness in the antenna array implementation (poor L2 reception).

The second technology was implemented into a Septentrio Ax3 receiver and PPSDK post-processing library, further proven to lead to 10% increase in RTK fix availability and significantly improved integrated solution accuracy in the targeted environment. These implementations were further used as OEM components into two new products, ATLANS and DELPHINS, further brought to market by iXBlue.

Besides, two “parallel paths” were pursued to explore possible future cost reduction of the GNSS-INS system. The first focused on hybridization between vision-based positioning (visual odometry) and MEMS IMU based INS. The second explored the possible usage of the multiple redundant MEMS IMUs to improved INS performance. The first showed promising results that will be further developed in future projects.

3. Impact

The objective of the topic to which this proposal was submitted was to provide research funding opportunities to participants in the area of receiver technologies, support prototyping and implementation activities of innovative solutions and aid development of final products.

The proposed project met the Receiver Prototype Development section of the topic. Not only prototypes of a beamforming GNSS and a hybridized GNSS-INS system were developed but the developed technology could be licensed and implemented into two products during the course of the project.

The **main innovation was be to enable and demonstrate GNSS-based Machine Control applications in environment where current state-of-the-art GNSS-only solution doesn't perform at all**, notably under dense foliage.

According to the GSA market report (ed. 2011) the overall GNSS market size (cumulated revenue) is estimated at 1260 billion between 2010 and 2020. GNSS devices shipments (both antenna and receivers) is expected to grow with 10% per year.

GSA market segmentation (Figure 64) comprises location based service (LBS), aviation, road and agriculture. Our target (Machine Control) is hence spread between the agriculture and road segments. Other studies s.a. from ABI Research, tend to provide a more detailed segmentation (Figure 63) where all **Machine Control applications account for 2.5% of the global GNSS revenue.**

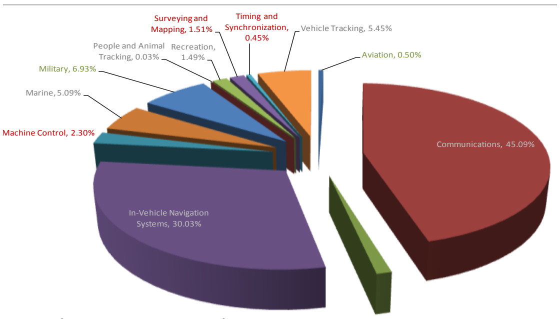

Figure 63 Total GNSS revenue 2008 and ABI segmentation

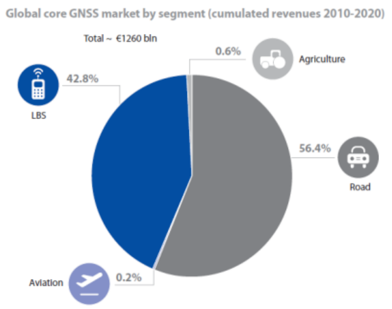

Figure 64 Expected cumulated GNSS revenue 2010-2020 and GSA segmentation

Focusing on agriculture (which is only a part of the target market for this project), it is observed that shipments have more than doubled in the last 5 years, corresponding to a CAGR of 26%, way above the overall GNSS market average. Comparable levels of growth have been experienced in other machine control applications (**31% CAGR** according to ABI).

In terms of annual shipments, agriculture applications made 105kUnits in 2009 [GSA], roughtly one fourth of the total Machine Control shipments (extrapolating from ABI), Assuming 5% are high precision, we can estimate the **targeted market size to 21kUnits/year** while **annual growth is expected to be between 16% (GSA) and 25% (ABI)**

Next, contrarily to other segments, pricing (and hence margin) on the high precision devices for machine control is not expected to erode significantly, provided that one keep following the technology evolution. GSA forecasts a **price erosion of only 2%/year**; the total system cost being currently around 12kEUR with almost half of it being the GNSS system (antenna, OEM receiver module and sensors).

The considered high precision machine control market is currently dominated by hardware offering mainly from non-EU industry, with notably Trimble (US), Topcon (US), John Deere/Navcom (US), next to Leica (CH). Partner SSN (BE) occupies a solidly establish outsider position, fueled notably by their “always first” innovation approach and significant niche products such as combination of RTK and multi-antenna attitude determination.

Based on the prototype hybrid receiver developed in the ADVANSYS project, the European Industry now have the capability, to prepare a highly differentiated offering that has the potential to significantly increase its share in the Machine Control market.

The Net Present Value (NPV) of the project for Europe in the hypothesis that the European Industry would increase its market share by 1%, 2%, 5% is calculated in Table 1.

The calculation is done for the period 2014-2020 in the hypothesis of an annual growth (in shipment) of either 16% (pessimistic scenario, GSA estimation) or 25% (optimistic scenario, ABI). Pricing and margins assumption are those known to be typical in the industry. Price erosion is set to 2% as estimated by the GSA. Discount rate is set to 20%.

Table 1 Net Present Value Analysis

Market Share Increase	***Pessimistic (16% annual growth)***	***Optimistic (25% annual growth)***
	NPV	***NPV***
1%	*3MEUR*	*6MEUR*
2%	*7MEUR*	*13MEUR*
5%	*20MEUR*	*34MEUR*

Even in the most pessimistic scenario, in case the result of the project would conduct to the increase by only 1% of the European Industry market share, the NPV of the project would be almost 2x the total project budget. A factor more than 10x would be applicable if 5% of the market would be conquered.

Furthermore, by tackling environment where such applications are currently not feasible, not only the market share is increased but also the addressable market is made larger. For instance, as part of the agri market, one will be able to provide machine control solution to forestry machinery, which are currently not in reach of state-of-the-art GNSS only solutions.

The success of ADVANSYS provides a real European cornerstone to professional GNSS for machine control market. A market in which there is established and increasing competition with USA and potentially, in a close future, Russian and Chinese offering.

Resulting increase of the globally addressable market and the European share in that market will directly lead to value-added and employment creation at the different level of the supply chain from component manufacturing to turn-key system integration and GNSS-augmentation services.

Finally, the project will also benefit to the adoption of Galileo. Multi-constellation is become a must in the considered market. Current offering however mainly focus on GPS and Glonass combination. Through its potential to significantly increase the market share of the European Industry in the targeted market, we will be able to promote the usage of Galileo in such multi-constellation solution. Galileo tracking and use in the positioning solution is part of the technical requirement.

Implementation thereof is made possible by the reused of technology building blocks available to the partners (background).

Such results were made possible by the fact that the partners capitalized of technologies and knowhow already available to the consortium:

- DLR: proof of concept of beamforming antenna and receiver
- SSN: all receivers building blocks from front end to RTK/PPP implementation, GNSS-INS integration with low cost sensor
- SAT: all building blocks and test facilities to design the antenna
- UNOTT: libraries and proof-of-concept of vision-based INS aiding

This approach maximized the Impact/Investment ratio of the project. Besides, the **focus** was not so much on the further development of such technologies, which are already well mastered by the partners, but on their **streamlined combination and synergies in view of realizing the main project objective: performance increase, under cost and manufacturability constraints**.

On top of this, the project also explored more advanced technologies (vision-based INS aiding, redundant IMU) that were expected to be fundamental to meet the project objective in terms of cost/performance. Although no breakthrough was made, the video-hybridization technology has been confirmed to be a valid technology for multi-domain hybridization and likely the closest mean to reduce cost of ownership of high precision positioning systems, leveraging the constant decrease of the cost and increase in performance of camera systems. This has the potential to further increase the market penetration.

Part 2 - Use and dissemination of foreground

A. Dissemination of Results (Public)

The key persons involved in ADVANSYS have a long track record of contributing to scientific publications targeting the global scientific community. This tradition was continued to promote both the results and the project itself. The following means were used:

Project website A web portal was established to share applicable public documents and contribute to awareness at European level (https://fp7.advansys.eu).

Academic cooperation The academic partners partake in a number of exchange programs with other universities and research institutions where the project and its results will be presented and discussed. Such activities not only provide a venue for dissemination but also for cross-fertilization as results are discussed with leading scientists from all over the world.

Conference and Publications Research results will be submitted to scientific conferences and journals with a special focus on event attended by customers.

The eventual objective of dissemination and awareness activities is **to maximize the commercial impact of the project**. Therefore, the following sub-objectives are defined:
Objective 1 – GNSS Awareness in application markets not yet addressed by high precision GNSS
The ADVANSYS project will develop and demonstrate techniques that have the potential to extend the footprint of the GNSS Machine Control Market, enabling notably applications in domains and segments where such techniques are still mainly unknown. One objective of the awareness activities will hence be to advertise the value of vehicle centric high precision positioning and guiding techniques for those applications.
Objective 2 – Awareness about the GNSS limitations that ADVANSYS will alleviate.
The ADVANSYS project will provide differentiation through the improvement of high precision GNSS based Machine Control system in non-benign environment. To maximize impact, awareness within the user communities about those limitations is very important.
Objective 3 – Create awareness over the value-added and uniqueness of the ADVANSYS outcome when available
When the project will deliver its results, special focus shall be set in the dissemination activities on the demonstration of the value-added and uniqueness of the proposed solution. This is best done through benchmarking demonstration and publication.

A main distinction is made between two categories of publications or dissemination activities:
- Category A: Results that will be commercially exploitable during or shortly after the project. Concretely, the criterion to fit in this category is to be proven on the real time demonstrator.
- Category B: Results that will be exploitable only after further development, constituting a sufficient entry barrier for third players

A second distinction is made between :
- Results at conceptual/algorithm level
- Results at implementation level

For results of Category A, either at conceptual/algorithm or implementation level:

- Activities will focus more on Marketing events.
- Disseminations and publications will focus on the WHAT and not on the HOW
- Disseminations and publications will insist on the value-added and uniqueness of the result depicting for instance benchmarking results.

For results of Category B,

- Activities will focus more on Scientific events
- As far as conceptual/algorithm results are concerned, publication can concern both the WHAT and the HOW
- As far as implementation is concerned, publication would only concern the WHAT

A.1 List of scientific publication

According to the dissemination plan, the following publication strategic types were defined.

NO.	Event	Owner	Title	Date	Place	Type of audience	Size of audience	Strategic Type
1	ION International Technical Meeting 2013	A. Konovaltsev (DLR)	Performance Analysis of Joint Multi-Antenna Spoofing Detection and Attitude Estimation	30th Januaray 2013	San Diego, U.S.A.	Scientific	200	B
2	ION International Technical Meeting 2014	Anja Grosch (DLR)	Robust Inertial Aided Beamforming for GNSS	28th January 2014	San Diego, U.S.A.	Scientific	200	B
3	Inertial Sensor and System Symposium (ISS)	Bruno Bougard (SSN)	SIGIL: A Novel GNSS/INS Integration for Challenging Environment	16th September 2013	Karslruhe, Germany	Scientific	200	A
4	ION GNSS+ 2013	Richard Deurloo (SSN)	SIGIL: A Novel GNSS/INS Integration for Challenging Environment	16th September 2013	Nashville, USA	Scientic and commercial	1000	A

5	ION International Technical Meeting 2014	Felix Antreich (DLR)	Improved Array Interpolation for Reduced Bias in DOA Estimation for GNSS	28th Januaray 2014	San Diego, U.S.A.	Scientific	200	B
6	IEEE/ITG Workshop on Smart Antennas WSA 2014	Felix Antreich (DLR)	Reduced Rank TLS Array Interpolation for DOA Estimation	12th March 2014	Erlangen, Germany	Scientific	200	B
7	EUGIN European Navigation Conference (ENC GNSS)	Richard Deurloo (SSN)	Decentralized GNSS/INS Integration with GNSS Aiding for Challenging Environments	15th April 2014	Rotterdam, the Netherland	Scientific	200	A
8	IEEE International Conference on Acoustics Speech and Signal Processing (ICASSP) 2014	Felix Antreich (DLR)	A Signal Adaptive Array Interpolation Approach with Reduced Transformation Bias for DOA estimation of Highly Correlated Signals	5th May 2014	Florence, Italy	Scientific	2000	B

A.2 List of dissemination activities

template A2: list of dissemination activities								
NO.	Type of activities	Main leader	Title	Date/Period	Place	Type of audience	Size of audience	Countries addressed
1	Press release	SSN	Smart coupling of iXBlue and Septentrio technologies creates ATLANS-C for superior mobile mapping in urban environments	17 February 2014	Leuven	GNSS industry	global	world
2	Demonstration	SSN	Demonstration of the ATLANS-C and DELPHINS post-processing system	17/2/2014	Denver	Mapping industry	100s	US

B. Exploitation of foreground (Confidential)

B.1. Application for patents, trademarks, registered designs

No patent or other IPR applied for. High level principles are published to guarantee freedom-to-operate while necessary details to make the technology work in real condition maintained under secrecy.

Template B1: List of applications for patents, trademarks, registered designs, etc.					
none					

B2. Exploitable foreground

Type of Exploitable Foreground[1]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[2]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
Design	Multi-channel GNSS receiver	YES			Professional GNSS	TBD	/	SSN
Design	Antenna element	YES			Professional GNSS	TBD	/	DLR
Design	Antenna array	YES			Professional GNSS	TBD	/	SATIMO
Software	**GNSS/INS hybridization method**	**YES**			**Professional GNSS, Mobile Mapping**	**Integrated in iXBLUE ATLANS-C and DELPHINS**	**license**	**SSN**

SSN is Europe's leading GNSS OEM developer and manufacturer for the professional markets. SSN commits to implement the outcome of its main activity in ADVANSYS specifically the development of a turn-key GNSS/INS solution comprising beamforming antenna (productized and commercialized OEM by SAT), hybrid receiver and third-party IMU sensor. This offering is perceived by SSN to have the potential not only to boost its market share in the current Machine Control market but also to address new markets (e.g., forestry application) and hence increase the addressable basis.

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[2] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

DLR, as a research institute will exploit the results of ADVANSYS and the respective experience in order to conduct master and PhD thesis, to write scientific publications, and also to introduce the developed practical experience into teaching at affiliated universities in Germany.
SAT is an industrial company whose expansion is based on new and innovative products. Antennas represent today a growing sector of activities for SATIMO with about 10% of its sales. The ADVANSYS antenna array is typically within the frame of the strategy of SATIMO proposing high added value products answering specific needs. In addition, a complementary offer of the receivers manufactured by Septentrio and the antenna arrays manufactured by SATIMO could lead to increased sales for both industrial companies. Therefore SATIMO commits to implement the outcome of its main activity in ADVANSYS, especially the development and industrialization of the antenna array.
UNOTT Institute of Engineering Surveying and Space Geodesy (IESSG) is a postgraduate research and teaching institute. The exploitation goals of the IESSG for the ADVANSYS outcomes are research and education oriented, rather than commercially driven. Improving the performance of GNSS and positioning technology in difficult environments continues to be one of the main areas of research in the IESSG, and developments in the ADVANSYS project are expected to benefit many areas of research and teaching. UNOTT will present the scientific results of the project at international conferences and workshops, such as EUGIN ENC, the ION annual GNSS meetings and other relevant conferences. UNOTT is committed to the encouragement of the next generation of scientists and engineers. For instance, the IESSG is a leading partner in the 'Space Academy' project, funded by the East Midlands Development Agency, which addresses the decline in STEM subject uptake by secondary school students using space exploration and applications technology as an inspirational theme. The IESSG input is on the technology and applications of satellite navigation systems. The Space Academy provides an ideal channel to disseminate information and the findings of this project and at the same time inspire future generations. Finally, the IESSG runs MSc courses on Engineering Surveying and Geodesy, Positioning & Navigation Technology, and GNSS Technology. One of the key aims of these courses is to present state-of-the-art developments in these fields to the students to enable them to transfer this knowledge to their companies when they graduate.

PART 3 - REPORT ON SOCIETAL IMPLICATIONS

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information (completed automatically when Grant Agreement number is entered.	
Grant Agreement Number:	**287207**
Title of Project:	**Design of ADVanced ANtenna and multi-Sensor**
Name and Title of Coordinator:	Dr. Bruno Bougard

B Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	No
2. Please indicate whether your project involved any of the following issues (tick box) :	YES
Research on Humans	
• Did the project involve children?	
• Did the project involve patients?	
• Did the project involve persons not able to give consent?	
• Did the project involve adult healthy volunteers?	
• Did the project involve Human genetic material?	
• Did the project involve Human biological samples?	
• Did the project involve Human data collection?	
Research on Human embryo/foetus	
• Did the project involve Human Embryos?	
• Did the project involve Human Foetal Tissue / Cells?	
• Did the project involve Human Embryonic Stem Cells (hESCs)?	
• Did the project on human Embryonic Stem Cells involve cells in culture?	
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	
Privacy	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	

• Did the project involve tracking the location or observation of people?	
Research on Animals	
• Did the project involve research on animals?	
• Were those animals transgenic small laboratory animals?	
• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	
Research Involving Developing Countries	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	
Dual Use	
• Research having direct military use	0 Yes X No
• Research having the potential for terrorist abuse	No

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	4
Work package leaders	1	5
Experienced researchers (i.e. PhD holders)	1	5
PhD Students	0	0
Other	1	5

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	None
Of which, indicate the number of men:	

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?	O X	Yes No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective				Very effective
❑ Design and implement an equal opportunity policy	O	O	O	O	O
❑ Set targets to achieve a gender balance in the workforce	O	O	O	O	O
❑ Organise conferences and workshops on gender	O	O	O	O	O
❑ Actions to improve work-life balance	O	O	O	O	O
O Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

O Yes- please specify

X No

E	Synergies with Science Education	
8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)? X Yes- please specify Several interns involved at DLR ○ No		
9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)? ○ Yes- please specify X No		
F	**Interdisciplinarity**	
10. Which disciplines (see list below) are involved in your project? X Main discipline[3]: 2.2 ○ Associated discipline[3]:	○ Associated discipline[3]:	
G	**Engaging with Civil society and policy makers**	
11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*	○ X	Yes No
11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)? ○ No ○ Yes- in determining what research should be performed ○ Yes - in implementing the research ○ Yes, in communicating /disseminating / using the results of the project		
11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No
12. Did you engage with government / public bodies or policy makers (including international organisations)		
○ No X Yes- in framing the research agenda ○ Yes - in implementing the research agenda ○ Yes, in communicating /disseminating / using the results of the project		
13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers? ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible) ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible) X No		
13b If Yes, in which fields?		

[3] Insert number from list below (Frascati Manual).

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- ○ International level

H Use and dissemination			
14. How many Articles were published/accepted for publication in peer-reviewed journals?			2 in preparation
To how many of these is open access[4] provided?			0
How many of these are published in open access journals?			0
How many of these are published in open repositories?			0
To how many of these is open access not provided?			2
Please check all applicable reasons for not providing open access:			
X publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[5]: ……………			
15. How many new patent applications ('priority filings') have been made? ("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).			0
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark		0
	Registered design		0
	Other		0
17. How many spin-off companies were created / are planned as a direct result of the project?			0
Indicate the approximate number of additional jobs in these companies:			
18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:			

[4] Open Access is defined as free of charge access for anyone via Internet.
[5] For instance: classification for security project.

X Increase in employment, or ❑ Safeguard employment, or ❑ Decrease in employment, ❑ Difficult to estimate / not possible to quantify	X In small & medium-sized enterprises X In large companies ❑ None of the above / not relevant to the project
19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs: Difficult to estimate / not possible to quantify	Indicate figure: 4FTE ❑
I Media and Communication to the general public	
20. As part of the project, were any of the beneficiaries professionals in communication or media relations? O Yes X No	
21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public? O Yes X No	
22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project? ❑ Press Release ❑ Media briefing ❑ TV coverage / report ❑ Radio coverage / report ❑ Brochures /posters / flyers ❑ DVD /Film /Multimedia	 ❑ Coverage in specialist press ❑ Coverage in general (non-specialist) press ❑ Coverage in national press ❑ Coverage in international press ❑ Website for the general public / internet ❑ Event targeting general public (festival, conference, exhibition, science café)
23 In which languages are the information products for the general public produced? ❑ Language of the coordinator ❑ Other language(s)	 ❑ English

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

Fields of science and technology

1. Natural Sciences

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 Engineering and technology

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. Medical Sciences

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. Agricultural sciences

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. Social sciences

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. Humanities

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]

4. Justification of costs

SSN

Personnel, Subcontracting and other Major Cost Items for Beneficiary The University of Nottingham		
Item Description	Amount in Euro	Explanations
Personnel RTD Costs (Direct Cost only)	447094.42	Specification work in WP1000 Receiver development in WP2000 Implementation of beamforming and GNSS/INS algorithms in WP3000 Tests of beamforming and GNSS/INS algorithm in WP4000 For a total of 10949.8hr (timesheets audited by KPMG)
Personnel MNG Costs (Direct Cost only	32583.28	Project management and coordination in WP6000 for a total of 639.60hr (timesheets audited by KPMG)
Other Expenses	45596.65	Material cost (prototypes): 38104.87 Travel expenses: 7209.38 IT expenses (website): 282.4
Indirect Costs	315164.62	
TOTAL COSTS	840438.97	

SAT

Personnel, Subcontracting and other Major Cost Items for Beneficiary SATIMO INDUSTRIES			
WP	Item description	Amount in EUR	Explanations
	Personnel costs (Direct cost only)	110 770.59	*Personnel costs were slightly higher than initially budgeted (100 k€ budgeted) due to hourly rate for one researcher higher than budgeted*
	Subcontracting	0	
	Travels	6 658.81	*Travel were very well contained and under budget (1.6k€ less than budgeted)*
	Other expenses	40 812.99	*We are above budget (24k€ more than budgeted) due to additional iterations for prototyping of RF Filters and for determining optimal antenna array configuration*
	Indirect Costs	33 147.39	*Indirect costs are lower than budgeted due to a higher rate initially budgeted.*
	TOTAL COSTS	191 319 .77	*We are slightly over budget (186 k€ budgeted) due mainly to the purchasing items*

DLR

Personnel, Subcontracting and other Major Cost Items for Beneficiary SSN			
WP	Item description	Amount in EUR	Explanations
210, 310, 320, 420	Personnel costs	210838,13	Personnel Costs , 10 scientists 35,03 PM, 2 engineers 3,38 PM
210	Subcontracting	17952,00	Subcontract to PROTECNO for manufacturing of several batches of antenna elements for an antenna array
210, 310, 320, 420	Indirect costs	147886,03	Indirect costs
210, 320, 310, 130	Other direct costs	8998,20	Other: Insurance for equipment for measurement campaign; Hospitality costs, progress meeting September 2013; book on development of kalman filters, simulation software development; mounting structure for sensor platforms, measurement campaign; Antenna test range
310, 210, 320	Other direct costs	10134,69	Travelling:- 26.02.-01.03.2013 Brüssel, CSI WG and ADVANSYS Meeting, 1 scientist; 19.06.-21.06.2013 Paris, ADVANSYS Meeting, 2 scientists; 11.11.-13.11.2013 Brest, ADVANSYS Meeting with PROTECNO, 1 scientist, 1 engineer; 11.12.-12.12.2013 Leuven, ADVANSYS Meeting, 3 scientists; 26.02.-07.02.2014 Leuven, ADVANSYS Final Meeting, 3 scientist

UNOTT

Personnel, Subcontracting and other Major Cost Items for Beneficiary The University of Nottingham		
Item Description	Amount in Euro	Explanations
Personnel Costs (Direct Cost only)	67236.77	Underspend of 19723.23 Euro due to late appointment of staff
Subcontracting	0	-
Other Expenses	12818.57	Overspend of 6253.57 Euro due to travel costs being higher than budgeted, and a one-off software purchase (3308.88 Euro) for processing trials data

Indirect Costs	48033.20	Underspend of 8081.80 Euro due to lower personnel costs
TOTAL COSTS	128088.54	Underspend of 21551.46, driven by lower staff costs