

Dual-Frequency EGNOS and Galileo-based GNSS Receiver and Antenna for Railway: TRENI Project

Marco Puccitelli¹, Chiara Manno¹, Livio Marradi¹, Gaetano Pastore², Hanaa Al Bitar³, Anne Marie Tobie³, Rodolfo Guidi⁴, Giovanni Galgani⁴, Francesco Inzirillo⁵, Filippo Rodriguez⁶, Alessio Martinelli⁶, Yuval B. Yossef⁷ and Daniel Lopour⁸

¹ Thales Alenia Space Italia., Via E. Mattei 1, 20064 Gorgonzola (Milan), Italy

² Thales Alenia Space Italia, Via Saccomuro 24, 00131 Rome, Italy

³ Thales Alenia Space France, Av. Champollion 26, 31100 Toulouse, France

⁴ EikonTech, Via Livornese 1019, 56122, San Piero a Grado (Pisa), Italy

⁵ Mermec, Via G. Oberdan 70, 70043 Monopoli (Bari), Italy

⁶ Telespazio Italia, Via Tiburtina 965, 00156 Rome, Italy

⁷ Saphyrion, Strada Regina 16, 6934 Bioggio, Switzerland

⁸ EUSPA, Janovského 438/2, 170 00 Prague 7, Holesovice Czech Republic

Abstract

The railway signalling system in Europe is currently undergoing a major change, converging towards interoperability and safety to be ensured by the ongoing deployment of the European Rail Traffic Management System - ERTMS. However, at present, ERTMS does not envisage the use of GNSS positioning technology for safety relevant train localization. Introduction of GNSS is an opportunity to contribute towards increasing of both safety and security or simplifying and reducing trackside equipment. It can also contribute to reducing overall signaling system costs which is instrumental especially for keeping the rural capillary lines competitive with other modes of transport. To enable such benefits and to contribute toward Green and sustainable transport services the European Commission and European Union Agency for the Space Program (EUSPA) are collaborating with the main rail and space stakeholders on the inclusion of GNSS into the future evolution of ERTMS.

This paper presents the TRENI railway GNSS receiver and antenna development, to be used directly or integrated in a train multi-sensor safe positioning platform, suitable for railway safety-related applications.

This project is part of “Fundamental Element” framework and is being conducted under a grant related to the development of a Galileo Receiver for localization in train signalling (GSA/GRANT/05/2019), supported by the European Union Agency for the Space Program (EUSPA) and coordinated by Thales Alenia Space Italia S.p.A (TAS-I), in collaboration with Thales Alenia Space France S.A.S. (TAS-F), MERMEC S.p.A. (Italy), Telespazio Italia S.p.A. (TPZ-I) and Saphyrion Sagl. (Switzerland).

Keywords

GNSS, EGNOS, GALILEO, RAIL, SAFETY, INTEGRITY, CRPA, HYBRID-PVT

1. Introduction

According to the latest EUSPA GNSS Market Report [1], GNSS plays an important role in many non-safety related applications and the introduction of GNSS in future safety-related applications is expected to increase railway network capacity whilst decreasing operational costs. However, the rail scenario introduces several challenges: it is a dynamic scenario, moving in different environments from rural to urban, with different visibility conditions of the GNSS signals and with varying RF environment

ICL-GNSS 2022 WiP, June 07–09, 2022, Tampere, Finland

EMAIL: marco.puccitelli@thalesaleniaspace.com (A. 1)

ORCID: 0000-0002-4956-3088 (A. 1);



© 2022 Copyright for this paper by its authors.

Use permitted under Creative Commons License Attribution 4.0 International (CC BY 4.0).

CEUR Workshop Proceedings (CEUR-WS.org)

conditions. In addition, the criticality of the application requires a GNSS system robust to threats that may occur during operations.

In this context, the TRENI project aims at implementing a double step forward with respect to current state-of-the-art GNSS railway solutions. On the one side, the GNSS receiver will provide a dual-frequency (L1/L5) Galileo/GPS multi-constellation platform, with enhanced robustness and integrity features granted by the capability to autonomously identify and counteract to failures resulting from GNSS constellations faults, RF environment threats or from the receiver itself. Key features in terms of robustness to harsh RF environments will be based on receiver digitally Controlled Radiation Pattern Antenna (CRPA) techniques, pre/post-correlation algorithms for Jamming or Spoofing detection & mitigation and lastly PVT hybridization with complementary PNT sensors (IMU and odometers) (Figure 1). On top of this, the integrity information broadcasted by SBAS (EGNOS) will be used for the evaluation of the Along-Track Protection Level (ATPL) and solution confidence intervals, with alerts provision in case predefined thresholds for the service are exceeded. The second innovative element brought by the TRENI solution consists in the antenna element design. Indeed, currently only single-band (L1) GNSS antennas certified for rail applications (i.e. designed and tested against EN applicable standards) are available on the market, raising the need to develop a dual-band (L1/L5) multi-element CRPA antenna capable to support the interference mitigation functionality and to comply with the EN standards, thus being certifiable for the use in railway environment.

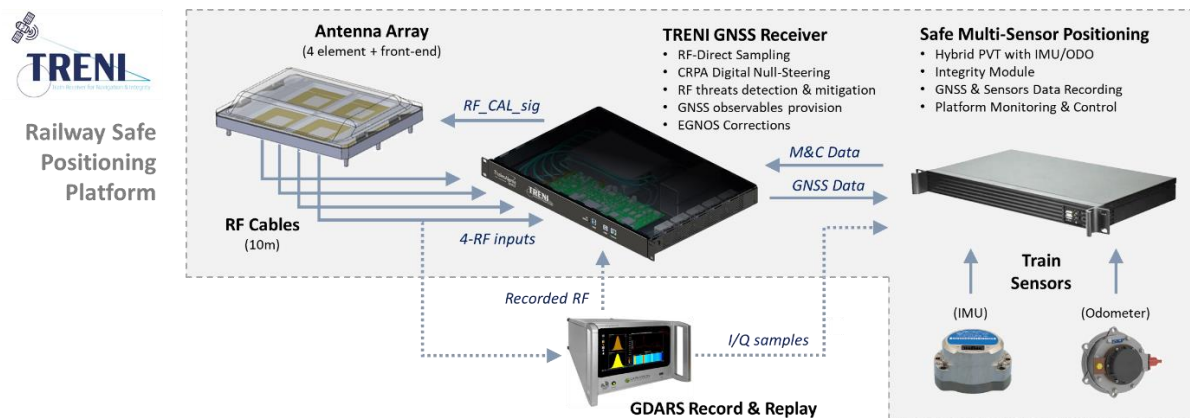


Figure 1: TRENI Platform functional diagram

2. Use Cases, CONOPS and Rail Environment Threat Scenario

GNSS may be used to increase the capacity of the railway network by allowing the development of future train operations such as moving block or virtual coupling. These systems are evaluated with the aim of ensuring fail-safe train location and location integrity. Moreover, GNSS is part of the digitalization that is reflected in the development of new applications, such as enhanced passengers information services, but also bringing benefits to railway operators and infrastructure managers because of the improved asset management and maintenance, thereby reducing the operational costs.

Different applications can be hence addressed by the TRENI platform, starting from primary safety systems, where GNSS is involved in direct safety chain of rail operations. As non-exhaustive examples, these primary safety systems encompass:

- Train integrity (i.e. train length monitoring);
- Train control (virtual balises, absolute positioning, guidance and navigation);
- Trains spacing over the line for traffic control systems.

In addition, overlaid safety systems can be considered as a potential use case, in which the GNSS could be to provide information to safety back-up systems, for instance:

- Simplified signalling (back-up) systems, capable of providing safety in operational conditions (e.g. cold movement detectors or level-crossing protection).
- Driving intelligent assistance (e.g. alarms to train driver);

Dealing with non-safety applications examples could be:

- Fixed asset management (e.g. infrastructure surveying and monitoring);
- Rolling stock management (e.g. fleet management, cargo monitoring, energy charging);
- Passenger Information (e.g. journey assistant, customer information, on-train reservations).

The main GNSS threats affecting accuracy and integrity of the position solution in the railway environment are listed in Table 1, which defines also associated models and anomalies that will be considered for the in laboratory validation campaign of the GNSS receiver.

Four critical scenarios have been selected to stress the performance of the GNSS receiver: the first two refer to the train in a stationary state respectively located at the station and in a rural area; the second two respectively refer to the train moving at low speed and located in urban environment and the train moving at high speed and located in rural area.

Table 1
GNSS threat sources, relative models and anomalies implemented in the emulation environment.

Threat Source	Models	Anomalies
Clocks	Atomic clock model for satellite clock, Quartz clock model for Rx clock.	Excessive acceleration, clock steps/ramps.
Ephemeris	Ephemeris model defined by NAVmsg.	Missing Update, Unflagged Maneuvers, Erroneous Broadcasting.
Ionosphere	NeQuick model for ionospheric error.	Spatial and temporal gradient.
Troposphere	RTCA DO-229F MOPS model for tropospheric error component.	Excessive troposphere components w.r.t. identified model.
Interference	Interference by analogue TV or DVTB, jamming by device on train or in station.	-
Spoofing	Spoofing attack performed by a device located either on board or in station.	-
Multipath & Rx noise	Multipath/RX noise pseudorange error mapped vs elevation (scenario dependent parameters and DSM model considered).	-
Signal Loss	Loss of signal based on visibility mask.	-

3. Dual-Band CRPA Antenna

The GNSS antenna for the TRENi project is asked to have features not available in commercial GNSS antennas currently on the market. Indeed the antenna is required to be dual band (i.e. L1/E1+L5/E5a) and to give the possibility to perform null forming by the receiver, in order to maintain integrity in presence of interference and spoofing. This leads to an antenna architecture of a 4-element array, necessary to apply beam forming strategies that give the additional requirement of an inter-element spacing within $\lambda/2$ at maximum operating frequency. Another constraint, not related to performance, is the need to design an antenna system keeping the cost within limits compatible with the railway market. An RF Front-End, capable to amplify the GNSS signal of about 25 dB and to reject quite demanding near and out-of-band interferences, is part of the antenna system. A calibration circuit allows the equalization of the four FEs. The whole antenna architecture is shown in Figure 2.

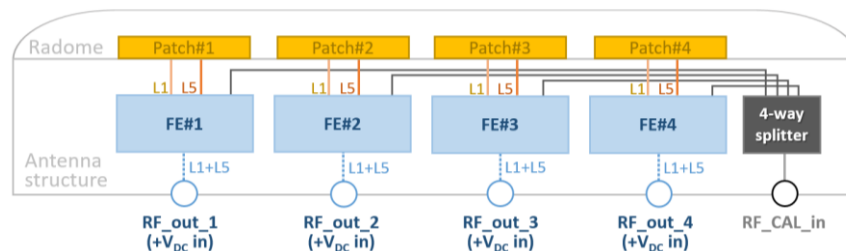


Figure 2: CRPA antenna high-level architecture

3.1. Radiating Elements & Array Design

The main characteristics of the radiating elements are listed below and shown in Figure 3 - Figure 4:

- Patch antenna technology for an easy and cheap manufacturing;
- Grounding pin not interfering with radiative performance, implemented as overvoltage protection from overhead catenary;
- Dual-band self-diplexed with two separated outputs (i.e. one for L1/E1, one for L5/E5), thus optimizing the front-end architecture;
- Sequential rotation applied to array layout, in order to assure axial symmetry during installation.

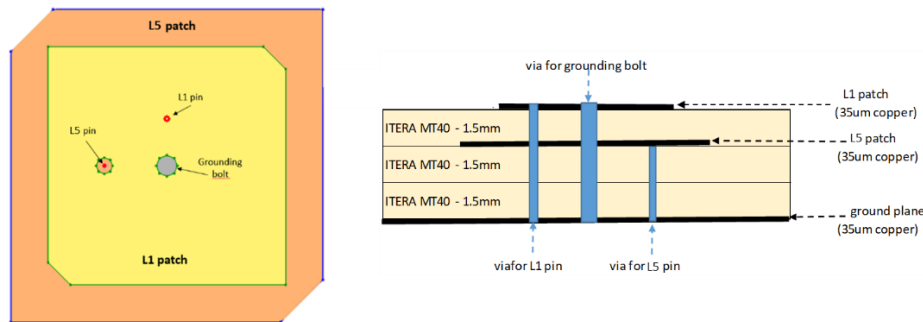


Figure 3: CRPA single antenna radiating element design & stack up

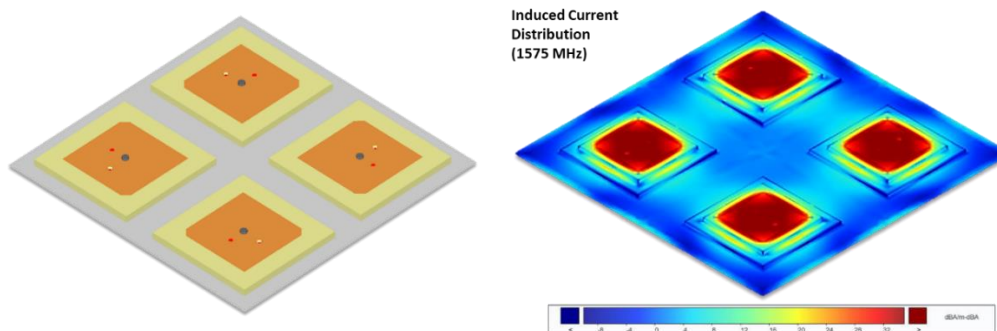


Figure 4: CRPA array sequential rotation layout (left) and induced current distribution (right)

The Single Element Return Loss (left plot in Figure 5), shows that the -10dB target in E5/L5 (i.e. in the band 1166 – 1186 MHz) and E1/L1 (i.e. between 1565 – 1585 MHz) is satisfied with a safe margin, allowing the matching of the requirement also at array level (right plot in Figure 5).

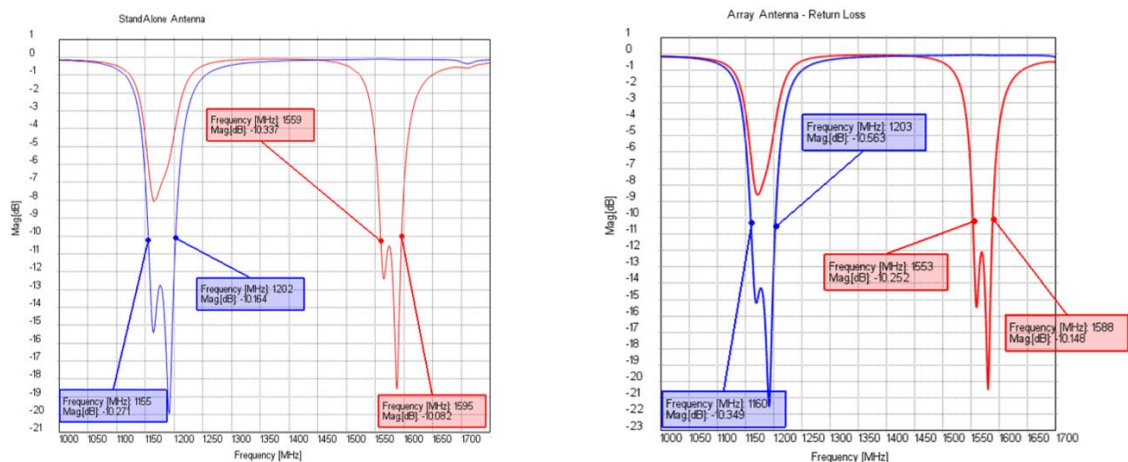


Figure 5: Single radiating element (left) and antenna array return loss (right) [dB]

Lastly Figure 6 show the expected antenna average gain for RHCP (blue lines) and LHCP (red lines) components, respectively at 1176 MHz (left) and 1575 MHz (right), for each stand-alone antenna patch.

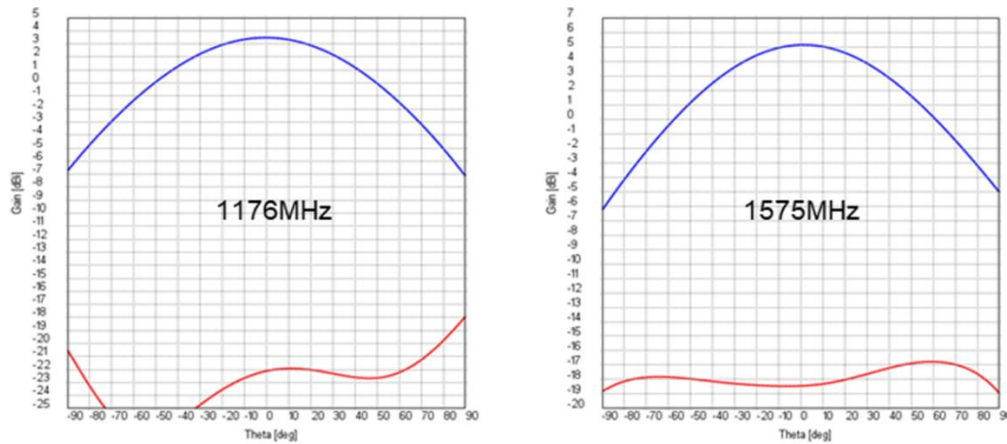


Figure 6: Single Element Antenna RHCP and LHCP Gain [dBi] in L5 and L1 bands

Regarding the antenna front-end (FE) architecture, it consists in a single amplification stage based on COTS amplifier components and custom design band-pass filters, with low insertion loss and steep transition regions, specifically tailored to cope with RF interference masks specified by [2],[3]. At the antenna FE level also coupling microstrip sections are foreseen to inject the RF calibration signal, provided by the GNSS Receiver for the end-to-end RF chain calibration (amplitude and phase).

4. TRENI GNSS Receiver

The TRENI GNSS Receiver is a customization of Thales Alenia Space Italia latest Test User Receiver (TUR) 19"-1U platform, already foreseen to be used for rail applications, as well as for avionic or maritime users. The baseline architecture is adapted to handle and process signals from up to 4 parallel RF inputs, with a future-proof design granted by the RF Direct Sampling and Digital Down-Conversion approach, intrinsically allowing the receiver to accommodate any GNSS signal scenario evolution in terms of frequency plan and signal modulations by simply updating FPGA FW and Receiver Application SW.

The high-level architecture of the receiver is presented in Figure 7, mainly consisting in a power supply module (i.e. a COTS AC/DC converter in the TRL7 prototype), an Analogue RF Front-End section (for RF signal filtering and antenna elements power feeding), a Digital Section (in charge of RF sampling, signal acquisition/tracking and navigation processing, calibration signal generation and external communication handling) and an I/O interface expansion module (for 1PPS and ERR/RESET TTL signals provision).



Figure 7: TRENI DFMC GNSS Receiver architecture layout (left) and interfaces (right)

Starting from the TUR building block, the TRENI Receiver implements specific functionalities, among which the following ones can be considered the most relevant ones w.r.t. future rail solution:

- GPS/Galileo multi-constellation satellite tracking and combined solution capability;

- PVT solution configurability (single to dual-constellation dual-frequency, L1/E1+ L5/E5a);
- Application of EGNOS corrections at receiver level based on SBAS MOPS [2] and DFMC [3] standards, provided either by live EGNOS SiS or available through EURORADIO link (e.g. according to EUG-CR1368 guidelines, [4],[5]);
- Techniques for improved receiver resilience with active anti-jamming (i.e. digital pulse blanking in the time domain, excision in the frequency domain), anti-spoofing (including Galileo OSNMA capability) and multipath mitigation (based on multi-correlators DLL discriminators);
- Capability to implement at digital pre-correlation level up to 2 run-time nulls in the direction of detected interference/jammer sources;
- RAIM algorithm for the mitigation of local threats, with fault detection and exclusion (FDE);
- Provision of accurate 1PPS signal for the synchronization of on-board equipment and sensors;
- Real-time provision of raw observables, navigation data as well as Measurements/Signal Quality Monitoring (MQM/SQM) outputs for service level evaluation;
- Compliance to main railway safety standards (EN50126, EN50128, EN50129, EN50159).

Besides the TRENI GNSS Receiver HW, the “Safe Multi-Sensor Positioning” equipment (i.e. a companion Host PC) will be interfaced to allow the receiver monitoring & control, GNSS raw observables real-time visualization and storage (e.g. for post-processing and test replay under different configurations and data-fusion with external sensors data for GNSS-IMU Hybrid PVT solution evaluation).

4.1. Digital Null-steering with CRPA

Among pre-correlation techniques considered within the TRENI Receiver for mitigation of unintentional RF interference and/or malicious jammer, a focus is here below proposed w.r.t. the well-known MULTiple SIGNAL Classification (MUSIC) [6] and Power Inversion (PI) [7] methods, applied to antenna pattern digital null-steering. Both the mentioned algorithms can be implemented at receiver FPGA level by conveniently combining the I/Q digital signal samples generated by the digital Down-Conversion Chains (DDCs), associated to the different radiating elements. In particular the Digital Board FPGA engine performs the following main tasks associated to the CRPA functionality:

- reception of 8 high-speed lanes (carrying I/Q samples from the 4 RF Channels) and feeding of the “covariance matrix” calculation block;
- covariance matrices computation engine & communication with DSP processor for provision of covariance indexes and reception of associated complex weights (computed by DSP for the following I/Q samples digital combination);
- management of the calibration signal synthesis through an external dedicated DAC.

The Eigen value decomposition of the covariance matrix, computed by the DSP processor as described above, gives a perfect interference detector: indeed without interference (i.e. without correlated signal at the antenna array), the correlation of the array matrix will be close to diagonal (signals of each antenna would consist in uncorrelated white noise) and the Eigen values will then correspond to the noise power. Otherwise, in presence for instance of one jammer, one Eigen value will increase to represent the power of the interference source.

Hence starting from the covariance matrix decomposition in eigenvalues and eigenvectors, the null-steered antenna element complex weights (ω^*) are computed with MUSIC or PI method and used to multiply the I/Q signal samples to generate a unique stream as follows:

$$y_{out} = \sum_{n=1}^{N_{ant}} y_n \cdot \omega^* , \quad (1)$$

The effects of a jammer on weighted signals combination, if properly managed, will result mitigated after the null-forming process. In general, despite the superior performance expected for MUSIC algorithm in terms of Direction of Arrival (DoA) estimation and maximum “peak-to-null” gain ratio (i.e. interference rejection), PI method is typically preferred in GNSS applications due to its simpler

implementation based on a “blind” approach (i.e. it does not require a-priori knowledge about antenna array such as antenna element orientation, gain/phase patterns, calibration values, etc.).

Before qualitatively assessing the null-steering capability, by assuming an AWGN only environment (i.e. no interference) as the nominal antenna operating condition, default CRPA weights can be defined, for instance, in order to optimize RHCP gain pattern at zenith. The results for the combination of antenna elements embedded RHCP gain patterns in a single equivalent one are reported in the following Figure 8.

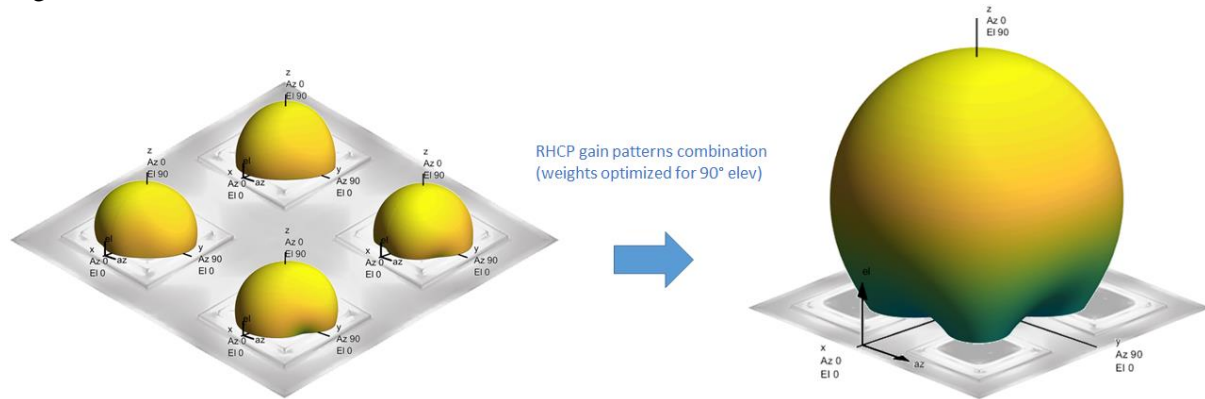


Figure 8: CRPA digitally combined pattern in AWGN only condition (weights optimized for zenith)

In case environmental conditions are characterized by the presence of EMI source(s), null-steering algorithm can be executed to mitigate interference effects at the receiver level. The maximum number of EMI sources that can be simultaneously (and effectively) mitigated by the current CRPA antenna design is approximately equal to $N_{RFI} \leq N_{ANT}/2 = 2$ (where $N_{ANT} = 4$ is the number of radiating elements).

In order to characterize the null-steering capability, a fixed JNR resulting in -3dB degradation of C/N_0 is considered in the figure below, in presence of two terrestrial interference sources simulated at 1176 MHz and with DoA1[azm=60°,elv=20°], DoA2[azm=-110°,elv=5°] (highlighted by red markers).

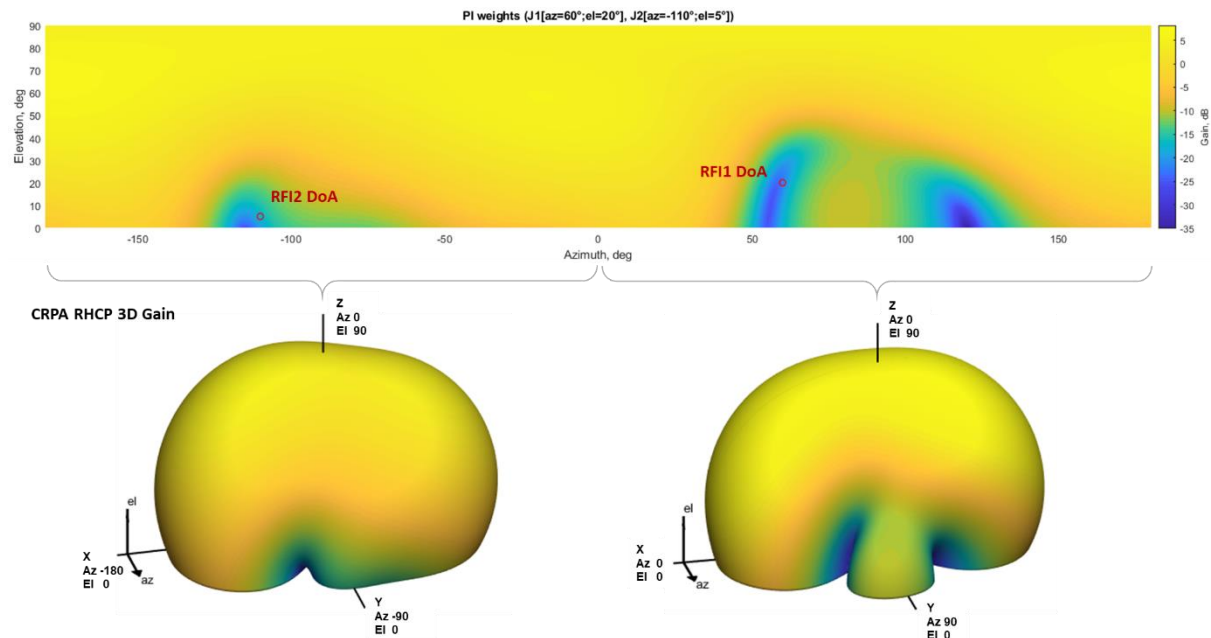


Figure 9: Digital Null-Steering capability example in presence of 2 RFI sources

Similarly to the previous example (i.e. given a fixed JNR resulting in -3dB C/N_0 degradation), the expected null-steering capability for the antenna patterns over L1 and L5 bands have been statistically characterized by simulating different jammers directions of arrival over entire antenna coverage area, with a spatial resolution of 10 deg (i.e. DoA bins defined by $azm=[0:10:360]$ deg, $elv=[5:10:85]$ deg).

Simulations results are provided in Figure 10, showing as expected a higher interference rejection for MUSIC (minimum P2N ratio in the order of 50dB), compared to the PI algorithm one (approx. 20dB).

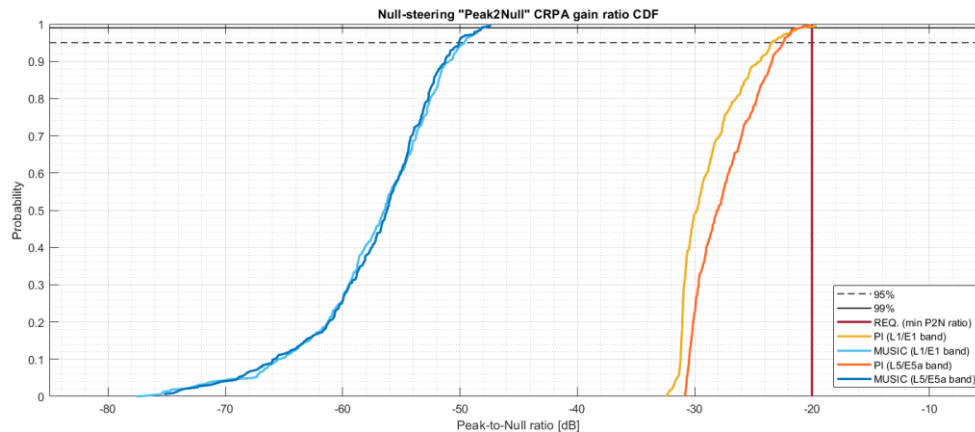


Figure 10: CRPA Peak2Null (P2N) gain ratio cumulative distributions for MUSIC and PI methods

5. Safe Multi-Sensor Positioning: Hybrid PVT & Integrity

Hybridized PVT solutions will be implemented and evaluated in order to demonstrate the enhancements brought by GNSS data hybridization with additional sensors installed on the test rolling stock. This integration will allow for:

- FDE capability to remove faulty ranges;
- Accurate train positioning even under GNSS signal limited-visibility conditions;
- Along track position, speed and the associated integrity protection level (ATPL).

Each of these steps are briefly described in this section. An IMU is a complete 3D dead-reckoning navigation system. Therefore, it does not allow to obtain an absolute positioning solution by itself, but can significantly improve the accuracy and the integrity of the positioning solution when combined with other sensors. In the TRENI project, the IMU will be hybridized with GNSS, odometer and possibly 2D maps.

In order to prevent unavailability of maps or unavailability of associated integrity information, it is proposed to limit the impact of the map on the navigation filter design while keeping its potential information useful. If available and associated with integrity, it has been proposed to use the map to correct the navigation solution after the hybridization filter. Since the cartography in the Railways domain is expected to be highly accurate (yet with no integrity data associated), it is proposed to assume it fault free for the integrity concept. The method consists in projecting the navigation solution on to the nearest point of the rail in the map.

If the map is available, FDE methods will have to be derived to ensure that, in case where 2 rails are side by side but heading in opposite directions, the navigation solution is projected to the correct rail.

Therefore, in this article, the focus is on the coupling scheme between GNSS, IMU and odometer. According to [8]; several hybridization schemes may be considered: loose (LC), tight (TC) and ultra-tight coupling (UTC).

The choice of the coupling strategy is not straightforward. A critical analysis has been performed and the TC is preferred for the TRENI hybridization module. The arguments considered are the following: the TC provides a more accurate solution than a LC and, a PVT can be computed even with less than 4 GNSS satellites but at the expense of a slightly more complex implementation. In addition, a TC solution requires the knowledge of the ephemeris as well as an accurate synchronization between the integrated navigation systems.

Following the previously defined TC solution, an integrity concept is also proposed. Solutions are designed at several levels (pre-processing techniques, error characterization and measurement rejection approaches) in order to meet the integrity requirements and Key Performance Indicators (KPIs).

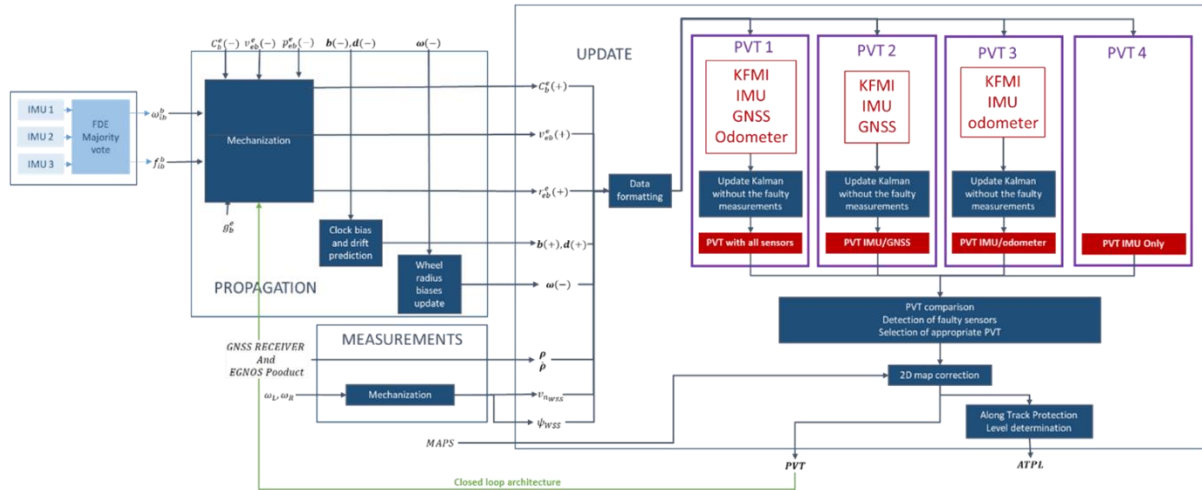


Figure 11: TREN Integrity concept – architecture overview

The proposed integrity concept is illustrated in Figure 11. On one side, the IMU is used to propagate the solution, and, on the other side, the odometer and GNSS are the measurements considered to update the solution.

The integrity solution leverages on a mixed use of Kalman Filter Measurement Innovation (KFMI) principle, and majority vote redundancy scheme. The FDE methods are applied both in the pre-processing step and in the update step. Majority vote method is applied in the pre-processing step to ensure the validity of the IMU measurements. Then, the combination of the KFMI based solution with majority vote solution is used to identify and reject potential faulty sensors.

In Figure 11, four PVT solutions are represented: a hybrid IMU/GNSS/odometer tight coupling filter (PVT 1), a hybrid IMU/GNSS tight coupling filter (PVT 2), a hybrid IMU/odometer tight coupling filter (PVT 3) and an IMU only filter (PVT 4).

In order to limit the computational burden, a first step will consist in computing PVT 2, 3 and 4. If all 3 solutions are identical (assuming a tolerable variance), then PVT 1 will be computed and will be the final solution.

For PVT solutions 1, 2 and 3, the KFMI is applied, therefore, it is expected that faulty GNSS measurements will already be detected and excluded. PVT 4, IMU only, is expected to be fault free since the pre-processing step is expected to have detected and excluded faulty IMUs (based on majority voting among 3 IMUs). The comparison of PVT 2, 3 and 4 will allow the detection of remaining errors and the exclusion of sensors if they are identified as faulty. Majority vote methods will be applied to identify these remaining faults. For example:

- If PVT 2, 3 and 4 provide the same solution (assuming a pre-defined tolerable difference) then the final solution will be PVT 1.
- If PVT 2 and 4 are equal but different from PVT 3, the odometer is detected as faulty, the final solution will be PVT 2.
- If PVT 3 and 4 are equal but different from PVT 2, the GNSS is detected as faulty, the final solution will be PVT 3.

Based on the final PVT choice, the 2D map can be applied to correct the position, to ensure that the train is on the correct rail. As explained above, the map is expected to be use in a post PVT step to correct the PVT, therefore, it is assumed that the map is correct and fulfils integrity requirements to be defined.

Finally, the last step of hybridization section is the definition of the PL, as illustrated in Figure 12. In fact, for the train case, the definition of PL can be simply projected on the train track in order to provide the ATPL (since there are no other degrees of freedom in the train motion, and thus the problem is essentially 1D).

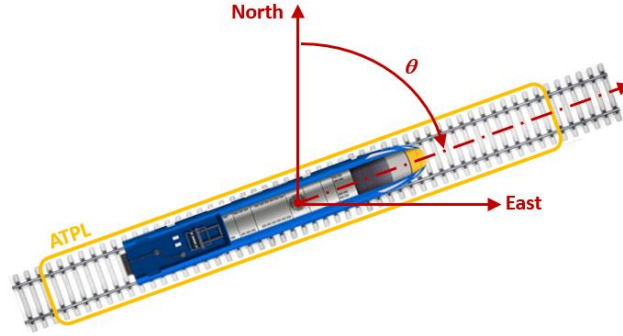


Figure 12: TRENi Integrity concept – along track protection level (ATPL)

In this way the horizontal PL “collapses” into a 1D PL in the horizontal plane. Hence the ATPL, computed using all non-excluded measurements, is defined as:

$$ATPL = K_{PMI} \cdot \sigma_{along} , \quad (2)$$

where K_{PMI} is a protection coefficient defined as a function of the integrity risk probability P_{MI} , and σ_{along} is the along track standard deviation defined as:

$$\sigma_{along} = \sigma_E \cdot \sin(\theta) + \sigma_N \cdot \cos(\theta) , \quad (3)$$

where θ is the azimuth of the track line segment on which the train has been determined to be situated, σ_E and σ_N are the East and North standard deviation components.

6. Way Forward & Conclusion

The TRENi platform will go through an extensive verification and validation activity. Different phases are envisaged starting from laboratory subsystems integration and functional verification, validation at Telespazio laboratories in Rome against worst case expected threats models generated by a realistic emulation test bed, and lastly relying on the field test campaign, supported by additional equipment that will record I/Q data streams from the GNSS antenna during the train runs on the Italian national railway line (RFI). The gathered data will be very useful to replay the experienced scenario in laboratory and will allow for the characterization of the RF environment during the field test runs, as well as allow for the testing and comparison of the different receiver algorithms and techniques on the replayed data. Moreover GNSS receiver measurements gathered along with the IMU & Odometer sensors data (but also with other external sensors data such as physical balises and geo-located reference points along the track), will finally allow for the definition of an a-posteriori reference “truth” trajectory, that will be exploited for the verification of GNSS performance achieved during the field tests campaign and verification of the hybridized PVT solution and integrity concept performance.

7. Acknowledgements

This project is part of “Fundamental Element” framework and is being conducted under a grant related to the development of a Galileo Receiver for localization in train signalling (GSA/GRANT/05/2019), supported by the European Union Agency for the Space Program (EUSPA) and coordinated by Thales Alenia Space Italia S.p.A (TAS-I), in collaboration with Thales Alenia Space France S.A.S. (TAS-F), MERMEC S.p.A. (Italy), Telespazio Italia S.p.A. (TPZ-I) and Saphyrion Sagl. (Switzerland).

8. References

- [1] EUSPA EO and GNSS Market Report issue 1/2022.
- [2] "Minimum Operational Performance Standards for Global Positioning System Satellite-Based Augmentation System Airborne Equipment", RTCA DO-229, Issue F.
- [3] "Minimum Operational Performance Specification for Galileo / Global Positioning System / Satellite-Based Augmentation System Airborne Equipment", EUROCAE ED-259, Issue 1.0.
- [4] "SBAS L1 Receiver Guidelines for Railway On-board Unit", ESSP-TN-25931 Issue 01-00.
- [5] "SBAS DFMC Receiver Guidelines for Railway On-board Unit", ESSP-TN-26136 Issue 01-00.
- [6] R. Schmidt, "Multiple emitter location and signal parameter estimation," in *IEEE Transactions on Antennas and Propagation*, vol. 34, no. 3, pp. 276-280, March 1986
- [7] D.-J. Moelker, E. van der Pol and Y. Bar-Ness, "Adaptive antenna arrays for interference cancellation in GPS and GLONASS receivers," Proceedings of Position, Location and Navigation Symposium - PLANS '96, 1996, pp. 191-198,
- [8] P.D. Groves, "Principles of GNSS, inertial and multi sensor integrated navigation systems", Artech House, 2007.