SAFE DUAL-FREQUENCY EGNSS RECEIVER FOR RAILWAYS: THE TRENI PROJECT

HANAA AL BITAR[1], ANNE-MARIE TOBIE[1], MARCO PUCCITELLI[2], LIVIO MARRADI[2], GIOVANNI GALGANI[3], RODOLFO GUIDI[3] & DANIEL LOPOUR[4]
[1]Thales Alenia Space France, France
[2]Thales Alenia Space Italia, Italy
[3]EikonTech, Italy
[4]EUSPA, 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 signalling 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.
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 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 and mitigation and lastly PVT hybridization with complementary position navigation timing (PNT) sensors (IMU and odometers) (Fig. 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

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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.

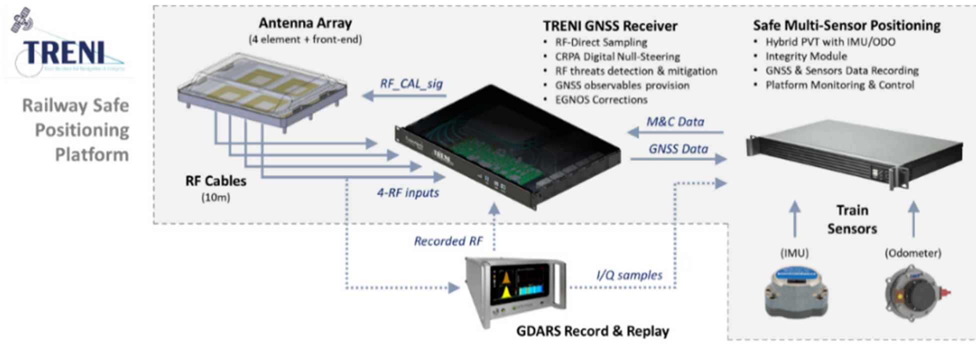

Figure 1: TRENI platform functional diagram.

2 USE CASES AND CONOPS

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, etc.);
- Passenger information (e.g. journey assistant, customer information, on-train reservations).

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 four-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 (FE), 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 Fig. 2.

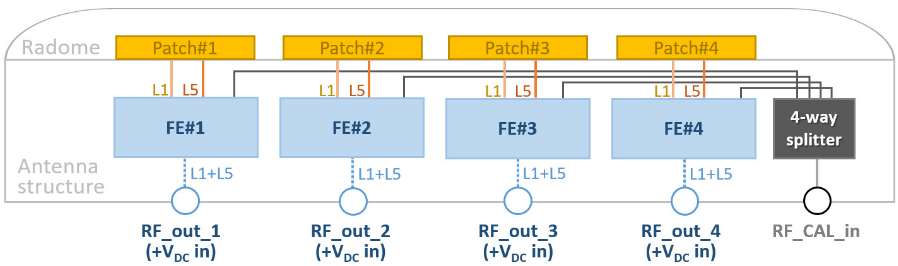

Figure 2: CRPA antenna high-level architecture.

The radiating elements main characteristics are listed below and shown in Fig. 3:

- 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.

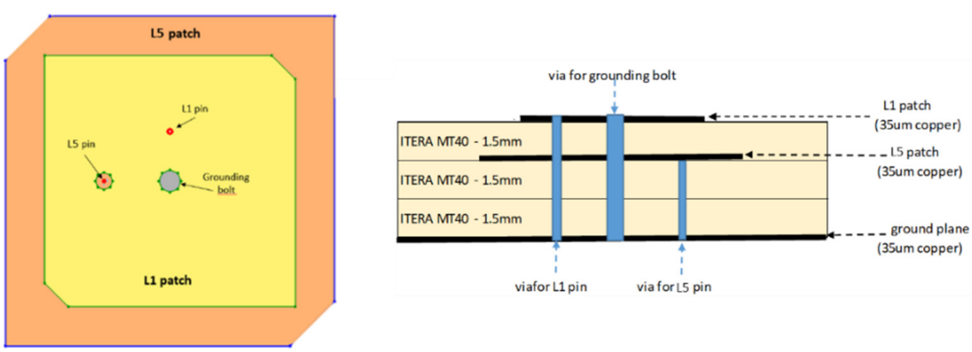

Figure 3: CRPA single antenna radiating element design (left) and stack up (right).

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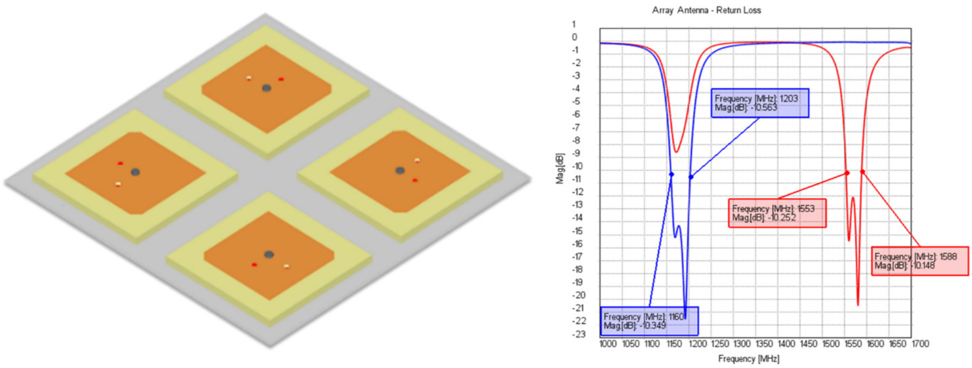
The antenna array return loss (Fig. 4), shows that the −10 dB target in E5/L5 (i.e. in the band 1166–1186 MHz) and E1/L1 (i.e. between 1565 and 1585 MHz) is satisfied with a safe margin, allowing the matching of the requirement also at array level.



(a) (b)

Figure 4: (a) Array sequential rotation layout; and (b) Antenna array return loss (dB).

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).

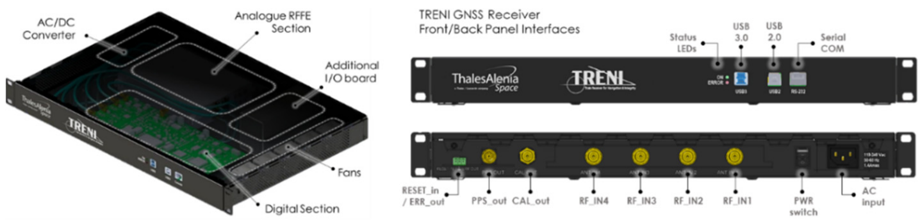
4 TRENI GNSS RECEIVER

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 Fig. 5, 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).

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 for higher position accuracy and availability;
- PVT solution configurability (single to dual-constellation dual-frequency, L1/E1+ L5/E5a);



(a) (b)

Figure 5: TRENI DFMC GNSS receiver architecture layout (a) and interfaces (b).

- 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 two 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 and 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).

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 eight high-speed lanes (carrying I/Q samples from the four RF channels) and feeding of the "covariance matrix" calculation block;
- covariance matrices computation engine and 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:

$$y_{out} = \sum_{n=1}^{N_{ant}} y_n \cdot \omega^*. \tag{1}$$

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 Fig. 6.

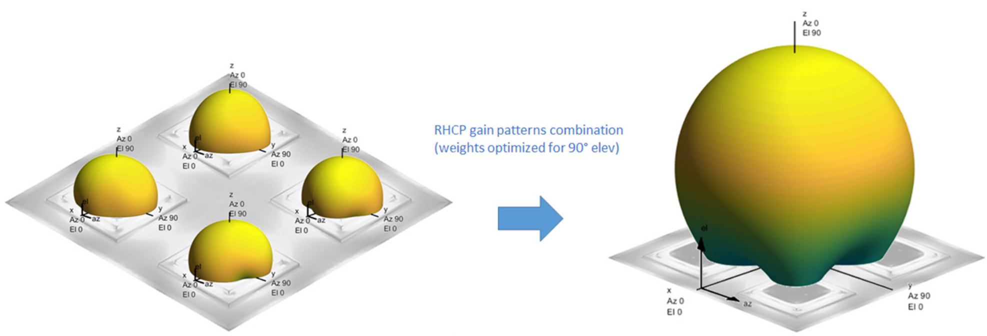


Figure 6: CRPA digitally combined pattern in AWGN only (weights optimized for zenith).

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 Fig. 7, 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).

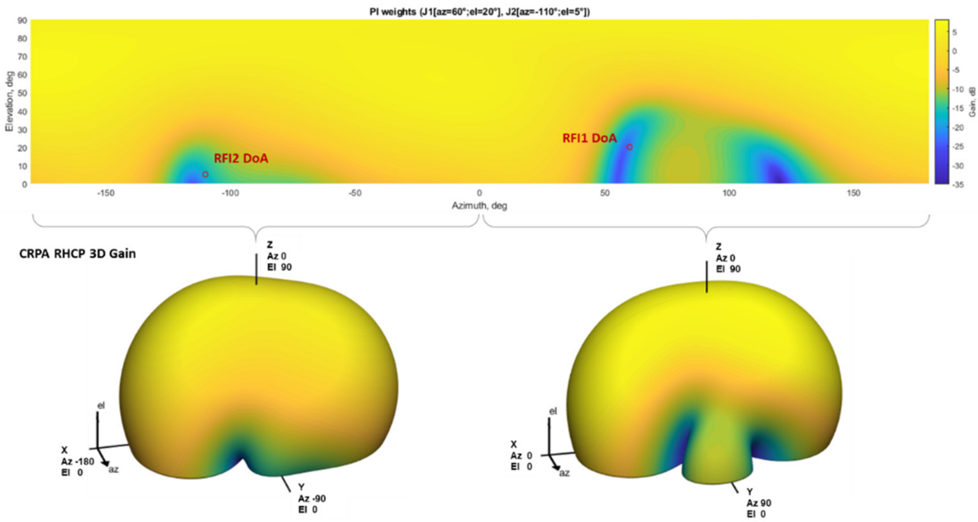


Figure 7: Digital null-steering capability example in presence of two RFI sources.

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 Fig. 8, 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).

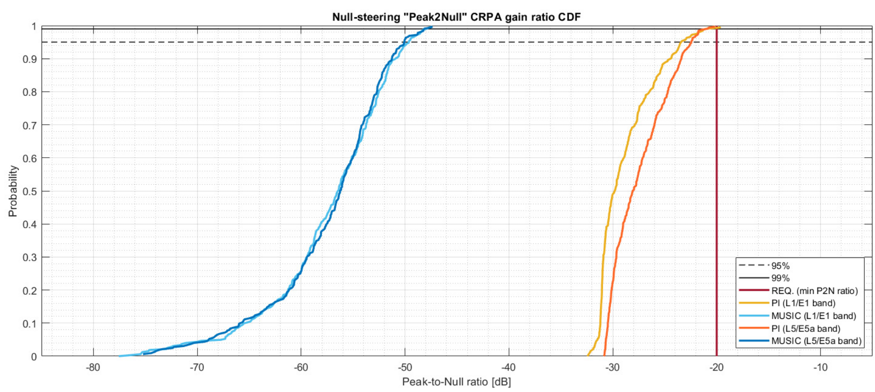


Figure 8: Peak-to-null gain ratio cumulative distributions for MUSIC and PI methods.

5 SAFE MULTI-SENSOR POSITIONING: HYBRID PVT AND 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, the focus is on the coupling scheme between GNSS, IMU and odometer. According to Groves [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 four 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).

The proposed integrity concept is illustrated in Fig. 9. 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.

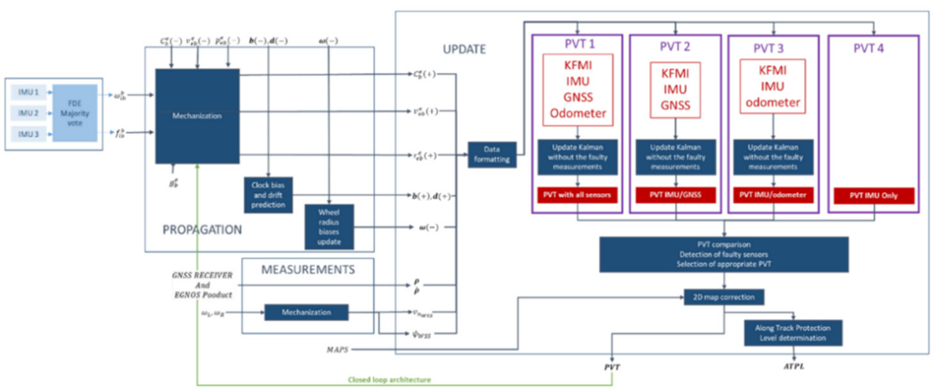


Figure 9: TRENI Integrity concept – architecture overview.

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 Fig. 9 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).

- 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. This association of hybridization with majority voting and GNSS processing techniques is a key enabler for the determination of a navigation solution that is highly available and safe (regarding the target integrity risk).

Finally, the last step of hybridization section is the definition of the PL, as illustrated in Fig. 10. 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).

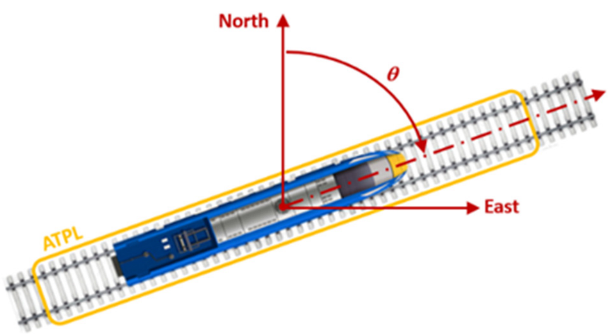


Figure 10: TRENI integrity concept – along track protection level (ATPL).

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:

$$ATPL = K_{PMI} \cdot \sigma_{along}, \tag{2}$$

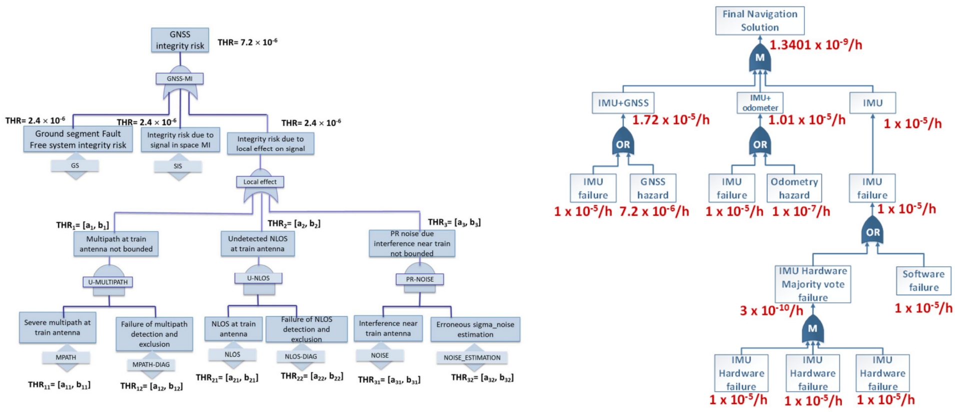
where K_{PMI} is a protection coefficient defined as a function of the integrity risk probability P_{MI}, and σ_{along} is the along track standard deviation defined as:

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

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.

In order to complete the integrity concept design, a safety analysis has been performed. It relies on a thorough analysis of the sensor failures.

On one hand, the GNSS failures have been identified and quantified as proposed in Fig. 11(a). As it can be observed, the GNSS safety analysis gathers all local effect related failures as well as signal in space or ground segment failures. It conducted to a tolerable hazard rate (THR) of $THR = 7.2 \cdot 10^{-6}/h$.



(a) (b)

Figure 11: TRENI integrity concept – safety analysis. (a) GNSS part; and (b) Complete hybrid system.

On the other hand, the INS and odometer failures have been analysed. There is not much information in the literature concerning these sensor failure rates. Nevertheless for both, the TRENI safety analysis relies on a probability of failure given as a function of mean time between failure (MTBF) and expressed as follow:

$$P = 1 - e^{-\frac{1}{MTBF}}. \tag{4}$$

For the INS failures, according to the literature, they come from either hardware or software failures. The hardware failure rate varies generally around $10^{-6}/h$ and $10^{-5}/h$ according to sensor quality (the risky case will be considered in the TRENI analysis). The software failures, or algorithmic failures, strongly depend on the algorithms and the error models used for the INS system. Navarro Madrid et al. [9] proposed that the failure rate due to stochastic modelling of Kalman filter for a GNSS/IMU system is $10^{-5}/h$.

For the odometer, Flammini et al. [10] mentioned that the MTBF of a train-embedded odometer is 10^7 hours. As a result, the corresponding failure rate is $10^{-7}/h$.

Based on the sensor failure analysis and the integrity concept proposed in Fig. 9, the integrity tree illustrated in Fig. 11(b) is proposed. It ends up with a THR of $THR = 1.3401 \times 10^{-9}/h$ which fulfils the requirements for a safety integrity level 4 function, the highest level of safety.

6 WAY FORWARD AND CONCLUSION

In this paper, the different applications addressed by the TRENI platform have been presented; even though safety related applications are a must for the TRENI project, non-safety related applications are also addressed (such as passenger information). Then the need for a specific antenna has been highlighted and its design detailed; as a reminder, the TRENI 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. Finally, the TRENI GNSS receiver and the hybrid PVT and integrity software have been presented. This software is designed such that it guarantees that the trains navigation solution fulfils the performance requirement associated to safety-of-life rail applications.

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. 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 and 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.

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