RUNE (Railway User Navigation Equipment): Architecture & Tests

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Abstract. Due to European on-going developments (EGNOS, GALILEO), satellite navigation is now an interesting innovation for all fields of transport. One of them is the railway domain, which could considerably profit from the implementation of autonomous on-board positioning systems. For railway transportation, satellite navigation offers new opportunities to increase accuracy of positioning and to implement safety standards everywhere, from high speed trains to local and regional railway lines, enabling a cost-effective modernization and increase of efficiency. Train control poses high demands on positioning with respect to availability, reliability and integrity. Meeting these requirements with a GNSS-based navigation system is the objective of several projects and still needs to be proved.

RUNE is a project developed for the European Space Agency by Alcatel Alenia Space Italia (Laben Directorate), leading a team comprised of VIA Rail Canada Inc. (VIA), Ansaldo Segnalamento Ferroviario (ASF), and INTECS HRT. In this project, the European Geostationary Overlay Service (EGNOS) has been used as part of an integrated solution to improve the train driver's situational awareness.

RUNE integrates positioning sensors with signalling and speed constraint information from a control centre. This can improve safety as a result of a better situational awareness and can also speed up the deployment of drivers on new routes. The primary objective is to demonstrate the improvement of the train self-capability in determining its own position and velocity with limited or no support from the track side, still complying with European Railway Train Management System (ERTMS) requirements. The achievement of such objective could lead to the reduction of physical balises distributed along the track line and needed to reset the train odometer error. Substituting physical balises with GNSS-based virtual balises can lead to reduction of infrastructure costs.

The RUNE project development has gone through a HW-In-the-Loop laboratory set-up up to field-testing. Field tests of the equipment were performed in Italy on the Torino-Chivasso line in April 2005, on board a Trenitalia ALE-601 experimental train. The unit included an LI GPS/EGNOS receiver, Profibus and CTODL interfaces to the train odometer and BTM, an IMU sensor for dead-reckoning positioning, virtual balise and velocity profile databases. This paper presents an overview of RUNE and provides results of the analysis performed on the data collected from the experimental train test campaign. Although testing duration was limited, collecting and analysing real data is important for building expertise in system behaviour and for algorithms evaluation and tuning. Those initial results show achieved performance in the real environment and the capability of the system to provide In-Cab Signalling and Virtual Balise functionalities. It is recognized that only through extensive field testing and validation of the system architecture and algorithms it will be possible to build a robust certifiable GNSS-based train navigation system.

1 Introduction

The railways have a consolidated experience using other means of navigation, which may not always be ideal, but are well known and familiar to the operators. On the other hand, railways, like other modes, have to cope with a number of new challenges. Alternative and more flexible train and freight tracking systems, in combination with existing techniques, are expected to prove attractive, if not indispensable, to be able to meet the new challenges (increased capacity and productivity, higher operating speeds, increased safety requirements, environmental protection), and to cope with the pressure to improve and optimize the economy and profitability of their operations.

Traditional rail operation is based on defined and fixed blocks (length of track of defined limits), the use of which is governed by block signals, cab signals or both. Train movement is constrained by the fixed nature of the block, which impacts the speed and track occupancy. The advantages of GNSS satellite-based systems over traditional rail navigation systems are mainly attributable to the ability to compute real-time accurate and autonomous on-board position and velocity data and provide this information to the on-board Train Control equipment, to the Operations Control Center and to the locomotive engineer. With all of the location and trajectory of each train in the system, a RUNE based operation complemented by conventional practices will provide the flexibility needed to have a "block" move with the train, as opposed to the train moving within a block, thus increasing track capacity while preserving or enhancing safety.

The RUNE system is designed to take advantage of the current EGNOS integrity and wide area differential correction service and extend its availability through an hybrid navigation system based on a Navigation Kalman Filter that integrates data from three main on-board sensors:

- GNSS Receiver: provides a GPS/EGNOS-based PVT solution in addition to EGNOS integrity data;
- Inertial Measurement Unit (IMU): provides three-axis accelerometer and three-axis gyro data for propagation of the solution, specially in case of unavailability of GNSS signals;
- Train Odometer Unit: provides continuous along-track velocity information from two toothed wheels.

Moreover the RUNE equipments uses data contained in a Virtual Balise Map database (VB Map) containing balise identifications with their 3D geographical position and the associated along track distance.

The objective of a such equipment is to introduce an autonomous positioning system into the ERTMS/ETCS architecture in order to:

- Integrate the odometer function by enhancing its accuracy, robustness and integrity estimation function;
- Reduce the need for trackside signalling by substituting as much as possible the physical balises with the virtual balise concept (see section 1.5);

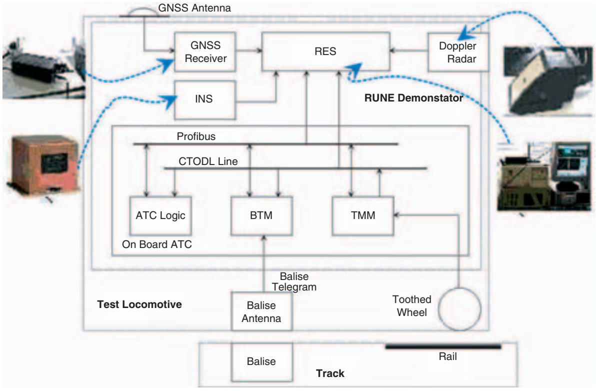
– Provide real time accurate track information to the Train Control equipment and to the locomotive engineer for speed profile supervision, breaking profile computation and alerts to approaching trackside signals.

2 RUNE Architecture Overview

The developed prototype implements the functionalities of the final application together with facilities and functionalities for a real time performance evaluation. The prototype SW allows also to perform off-train tests using the data collected on-board. This capability helps in simulating visibility gaps or slip and slide phenomena or other environmental conditions that cannot be easily to reproduce during a test in a real railway environment.

The RUNE demonstrator is composed of the On Board ATC, the Navigation Sensors and the Recording and Evaluation System (RES) that includes the Navigation Data Fusion Filter (see the figure).

The On Board ATC includes the following modules:



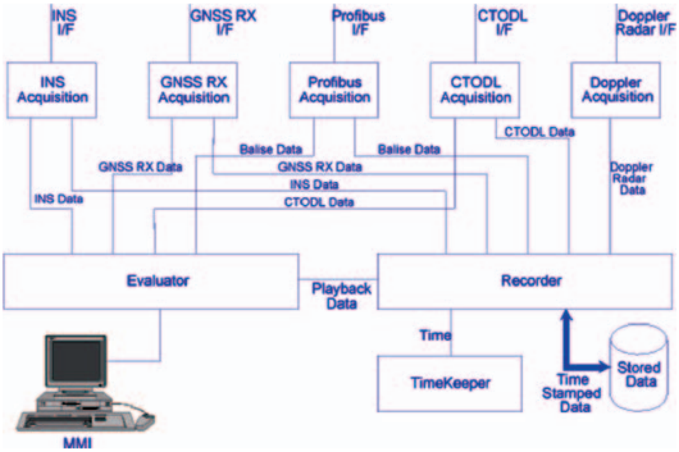
RUNE architecture overview.

- TMM: Train Management Module, which is devoted to the management of the locomotive devices such as the braking system, the juridical recording unit and the toothed wheels for odometry
- ATC Logic: Automatic Train Control Logic which is devoted to the computing functions to control the train speed
- BTM: Balise Transmission Module, which is devoted to read the wayside balises and telegrams
- On Board communication network: based on the field bus PROFIBUS, it is used to exchange data between the on board modules. The use of a field bus minimizes wiring.

In the RUNE demonstrator the On Board ATC is in charge of acquiring and processing the signals generated by the Toothed Wheels and Balises and provide the relevant data on the CTODL Line and PROFIBUS respectively.

The RES software is the heart of the demonstrator: it acquires the Navigation Data generated by the navigation sensors, performs real-time filtering and data fusion to compute the best solution (position, along-track velocity, along-track distance and attitude), performs run-time verification of computed solution accuracy against reference sensors data (eg. Doppler Radar and/or physical balises), records all raw and processed data to allow off-train post-processing, monitors overall RUNE functionality, maintains status logs and provides the Man Machine Interface towards the Test Engineer and the Locomotive Engineer.

The following figure shows the Data Flow Diagram as implemented in the RUNE Architecture.



RUNE architecture data flow diagram.

2.1 The RUNE Navigation Data Fusion Filter

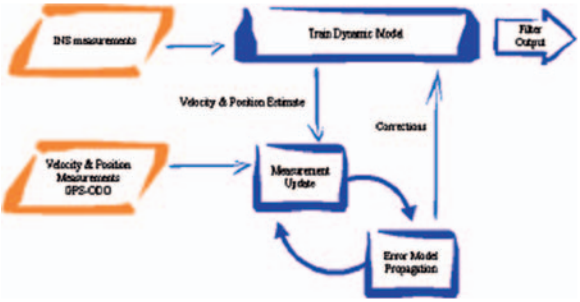
Train navigation is somewhat different from all the other type of navigation (aerial, naval, car): train position has only one degree of freedom: the traffic control centres need of the position along the track and not the geographical position.

The odometer is the best suited sensor for such type of measurement; a GNSS sensor, providing absolute position, needs to be assisted by some external aiding information such as, for example, a railway map or inertial sensor in order to correctly translate absolute position into along-track distance.

Odometers performance are typically compromised by slip, slide and creep phenomena; this causes the position error to increase with time and the difficulty to have an accurate velocity profile during brakes (in case of slips). ERTMS foresees the balise as navigation aiding for odometer error reset, and track ambiguity resolution. RUNE inspects the concept of virtual balises. The virtual balise is powered by the GNSS absolute positioning capability. Accuracy and integrity is enhanced by the use of EGNOS and by sensor measurements integration and redundancy. The virtual balise could substitute the physical balise most of the time, offering an unparalleled cost effective solution and adding flexibility to the train management system.

The use of a navigation filter, integrating multiple sensors, solves the problems of odometer error drift, slip/slide and availability and allows to obtain an accurate position and velocity profile estimation.

A Kalman filter is the best method of integrating GPS, IMU and ODO measurements for a number of reasons, not the least its ability to provide a real-time solution. It also has the favourable attributes of being computationally efficient, relatively flexible in that it is able to accept a variety of different measurement types and rates, and has the ability to estimate error sources.



Filter kernel.

The Kalman filter implemented in the RES SW is a time-variant filtering process that deduces the minimum error estimate of the state vector (the unknown parameters) of a linear system, while taking into account knowledge of the system dynamics, measurement model, and the statistics of the system noise and measurement errors.

The set of parameters (8 in RUNE application), called the Kalman state vector, $\vec{x}$, which is allowed to change along the track's path. is defined as:

- ○ [δPx,δPy,δPz]: error on the ECEF position
- ○ [δPS,δVs]: error on the along track position/velocity
- ○ [δA1,δA2,δA3]: error on attitude wrt the navigation frame

The Computation Algorithm of the Filter is based on the following states:

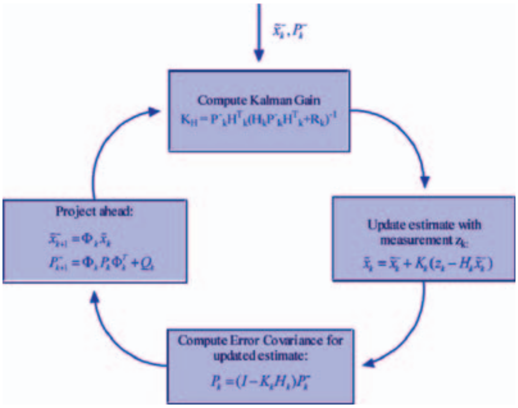
- ○ $\hat{x}_k^- \in \Re^n$: a priori state at step k
- ○ $\hat{x}_k \in \Re^n$: a posteriori state estimate at step k
- ○ $e_k^- = x_k - \hat{x}_k^-$,: a priori estimate errors
- ○ $z_k - \hat{z}_k^-$: the measurement innovation, or the residual.

From these derives a posteriori state estimate $\hat{x}_k = \hat{x}_k^- + K(z_k - \hat{z}_k^-)$ and a posteriori estimate errors $e_k = x_k - \hat{x}_k$.

The matrix K is chosen to be the gain or blending factor that minimizes the a posteriori error covariance

$$K_k = C_k^- H_k^T (H_k C_k^- H_k^T - R_k)^{-1}$$

Here below has been graphically represented the Kalman filter loop.



Kalman filter loop.

2.2 The RUNE Performance and Objectives

The RUNE main objective is to satisfy, if not improve, ERTMS levels 2 and 3 performance and integrity requirements.

The main issue of this project is to demonstrate the train capability to self-determine position with an accuracy of 3m and speed with an accuracy of 2Km/h, and through the use of EGNOS, to provide a protected distance of 50m and raise timely alerts when this cannot be guaranteed.

	ERTMS	RUNE objectives
Position Accuracy	5m + 5 % of travelled space	3 m, 95% (GNSS + WAAS/EGNOS)
Velocity Accuracy	2 km/h v < 30km/h 12km/h v < 500 km/h	2 km/h 95% (GNSS + WAAS/EGNOS)
Position Confidence	> 99.9%.	> 99.9%. for a 50 m Protected distance
Availability	better than 99% (Level 3 applications)	better than 99%
Time to Alert	< 5 s	better than 5 sec (Safety Level 3 applications)

The table here reported summarizes ERTMS main requirements and RUNE objectives.

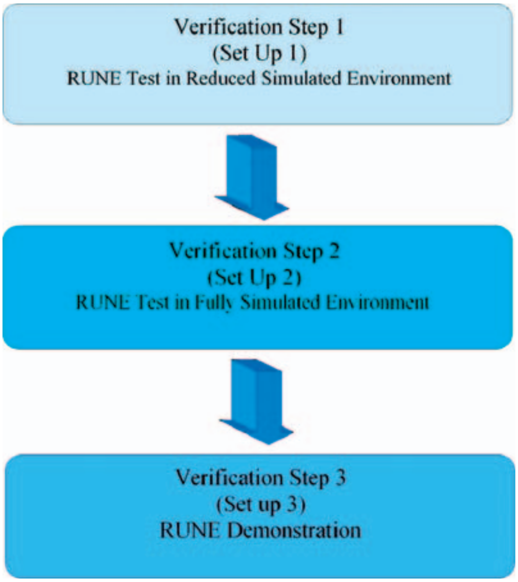
2.3 The Validation Phases

The RUNE equipment validation has been carried out through different incremental demonstration phases. These can be rearranged in three incremental Verification steps as described hereunder:

Step 1. Verify the software performance in a reduced simulated laboratory environment. This step has been performed to mitigate the risk of involving hardware without having clearly verified that the software meets its requirements specification.

Step 2. Build a fully representative RUNE Demonstrator unit and perform a complete validation of the hardware/software equipment in a fully simulated laboratory environment.

Step 3. Perform the RUNE Demonstration on selected railway equipment to verify the performance of the equipment by confirming the data obtained during the above laboratory tests, and to demonstrate the selected user applications.



Rune verification steps.

The figure here reported shows the Verification steps as described before: In the following, we will focus our attention on the demonstration phase (step3) providing also the main results of the performance evaluation.

3 RUNE Demonstration Objectives

The RUNE demonstration was performed on the Torino-Chivasso line, on a Trenitaila ALE 601 locomotive located in the "Torino Smistamento" Rail Station (Fig. 1).

The purpose of the test was to collect data to verify the functionality of the RUNE equipment in a real environment, after having performed extensive HW-in-the loop laboratory tests. Demonstration in a real environment is needed also to facilitate the technology acceptance by the railway user communities with respect to ERTMS railway applications.

Fig. 1. The "Ale 601" test train in the "Torino Smistamento" rail station.

The primary objectives of this demonstration were:

- to validate the design of the demonstrator prototype hardware/software;
- to verify sensors behaviour and performance on field to assess typical noise, calibration needs, availability;
- to verify positioning accuracy with respect to trackside references and to assess continuity and availability in a typical railway environment;
- to demonstrate equipment functionality in two user applications including in-cab signalling to assist the locomotive engineer and virtual balises detection for train positioning.

Extensive HW-in-the-loop laboratory testing was carried-out prior to the train demonstration. Summary results of these tests are reported in [1], [2], [3]. Alcatel Alenia Space (AAS-I) laboratory facility includes all necessary simulation tools and equipment: GPS/EGNOS multi-channel simulator, EGNOS receiver, IMU simulator, ASF Balise and Odometer HW equipment and trajectory simulators. This facility has allowed to carry-out RUNE performance verification and sensitivity analysis in representative railway scenarios. In particular those tests included sensitivity of the positioning solution to acceleration, curvilinear trajectories, slip-slide odometer effects and GPS/EGNOS obscuration in tunnels of different length.

3.1 The Torino-Chivasso Route Demonstration

However, it is believed that only through real field testing it is possible to assess the system behaviour, and therefore this paper focuses the attention on the data collected from the train tests. The RUNE equipment installed in the ALE-601 test car is shown in Figs. 2 and 3.

Figure 4 shows the map of the test route from Torino to Chivasso and return. The distance from departure in Torino Smistamento Rail station to Chivasso Rail station is about 20 km. The track offers different scenario conditions, including a tunnel when crossing the city of Torino, curves in the tunnel and straight lines with the train travelling at a max velocity of about 150 Km/hr. Those different conditions allowed to extract interesting information on the equipment behaviour and performance. Figure 4 shows the continuous positioning solution obtained by RUNE during the whole track (bold line) despite the fact that GPS visibility was obscured in the

Fig. 2. Rune installation on ALE-601.

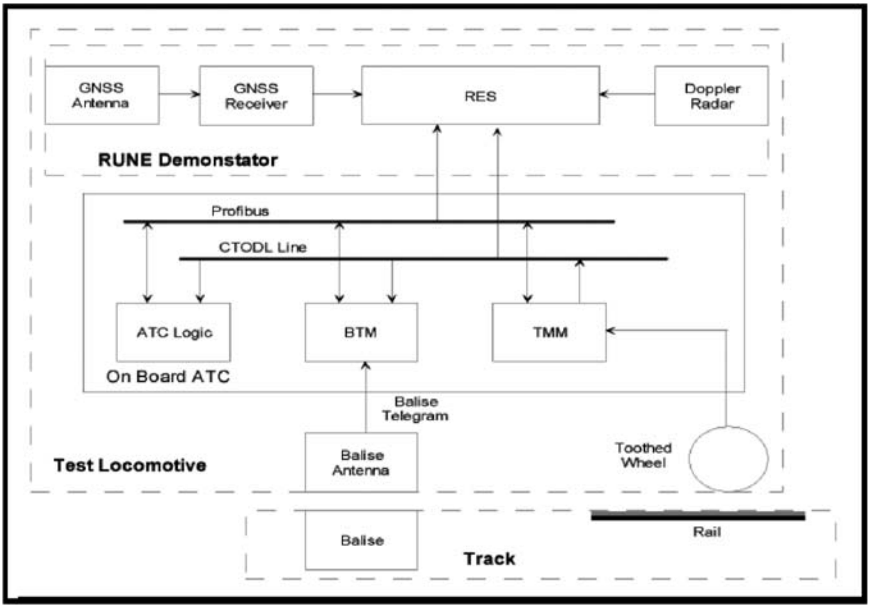


Fig. 3. On train demonstrator set up.

Fig. 4. RUNE solution on the To-Ch route.

Torino tunnel. EGNOS tracking was very limited during the To-Ch route, while during the Ch-To return route PRN 120 was instead in tracking to the receiver for a long period of time.

This is partly explained by the fact that, due to installation constraints, the GPS antenna was applied on the lateral external wall of the train car with only about half-sky visibility.

The RUNE prototype equipment SW allowed to record all received sensors raw measurements during the test run. A fundamental feature of the RUNE SW is to allow off-line playback of collected raw data into the RUNE Data Fusion Filter SW (DFF). This feature was extensively used to analyse RUNE behaviour, applying different calibrations and pre-processing to the raw measurements and, also, allowed to fine-tune the Kalman filter for optimal performance. The only independent position reference that was available during the tests for accuracy performance evaluation was the travelled distance and time information recorded by the on-board train computer (SCMT) when passing over the installed track physical balises. Each balise provides the exact along-track distance from the preceding one.

The following key issues are investigated:

IMU sensors: main issue is related to the misalignment of the IMU axis with the train reference frame, and to the analysis of typical train car vibration noise to apply suitable low-pass filtering;

GNSS receiver: along-track velocity and absolute position accuracy is compared to the balise markers and to the combined-sensors RUNE DFF solution. Integrity information availability in terms of Protection Levels is assessed;

In-Cab Signalling: verify the capability of displaying to the Locomotive Engineer MMI the information on approaching signals and velocity profile warnings based on a pre-stored route database;

Virtual Balise: capability to detect the passage on a Virtual Balise from the VB database (absolute ECEF position and travelled distance) and to generate a balise message on the RUNE Equipment Interface.

3.2 IMU Calibration

IMU calibration in terms of correction of misalignment errors (Fig. 5) and vibration noise filtering is needed before use of the data in the solution DFF. Such calibration was performed in post-processing, having identified suitable phases during the train test, such as train stopped condition, acceleration phase, etc. In an operative system, such calibration could typically be performed on-train, sporadically, during dedicated self-test phases.

During operational phases, the RUNE DFF design disables estimation of IMU biases and misalignment, to reduce processing. Appropriate filtering on acceleration (a_x, a_y, a_z) and angular rate (w_x, w_y, w_z) measurements is determined measuring the noise floor in train stopped, acceleration and turn conditions. Figure 6 shows an example of a_x noise frequency spectrum when train is stopped. A low-pass filter with 0.5 - 1 Hz bandwidth was selected to filter the IMU data for the ALE-601 test train. Gross misalignment errors were calibrated-out by comparing IMU measurements

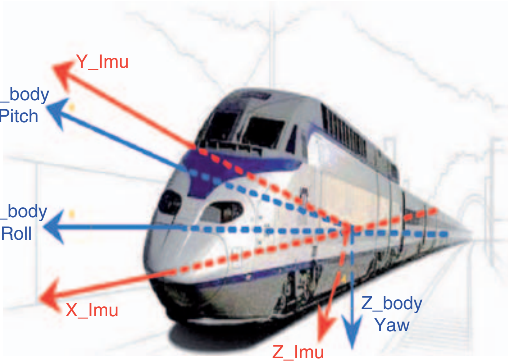


Fig. 5. IMU axes and train axes.

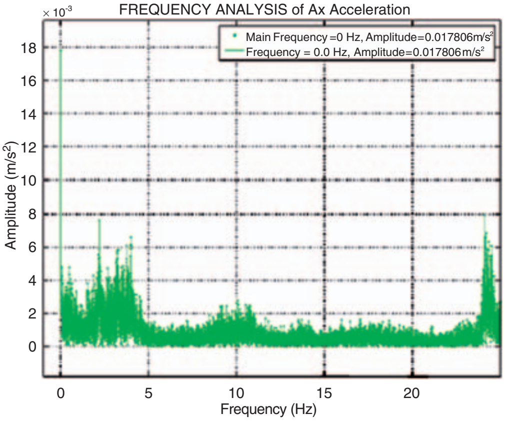


Fig. 6. a_x noise floor.

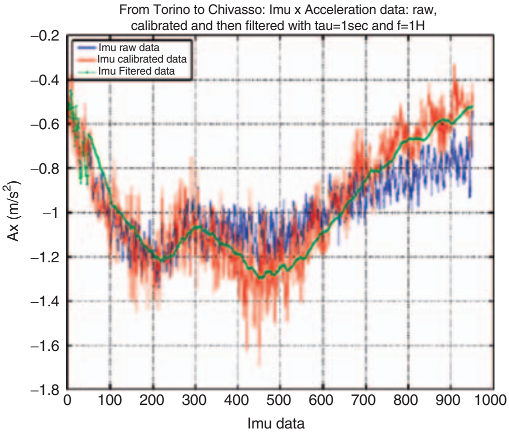


Fig. 7. a_x and w_z calibrated and filtered at 1 Hz.

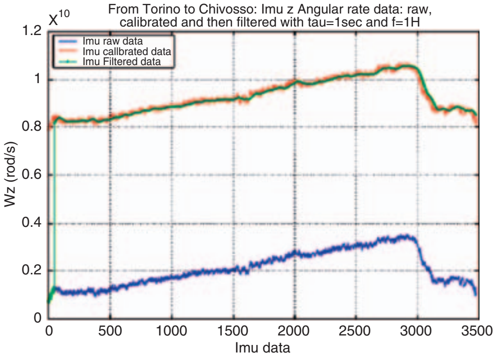


Fig. 8. a_x and w_z calibrated and filtered at 1 Hz.

against expected gravitational and centripetal accelerations with train stopped in horizontal position. Those errors are removed by applying an angular rotation calibration matrix to the IMU data (Figs. 7 and 8).

3.3 RUNE Behaviour and Performance

The accuracy of the RUNE odometry-like function is estimated in terms of accuracy of travelled distance and along track velocity by the RUNE DFF against the balise fixed markers detected and logged by the SCMT along the track. To compare data generated by different sources a time re-alignment of the balise time crossing was necessary.

Figures 9 and 10 show the comparison of velocity profile and along-track estimated distance from RUNE DFF and SCMT/balises after re-alignment. Physical balises are installed in couples on the To-Ch line on a segment of approximately 15 Km with a mean distance of 150m between each balise couple. Figure 11 shows the error in RUNE estimated along-track distance during the runs from To-Ch and return. The error is computed as difference between the distance provided by each physical balise and the along-track distance provided by the RUNE DFF when crossing each balise.

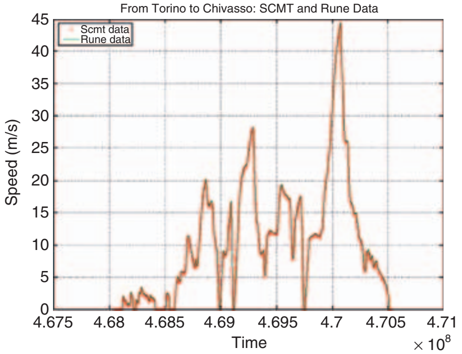


Fig. 9. RUNE along-track velocity vs. SCMT logged velocity.

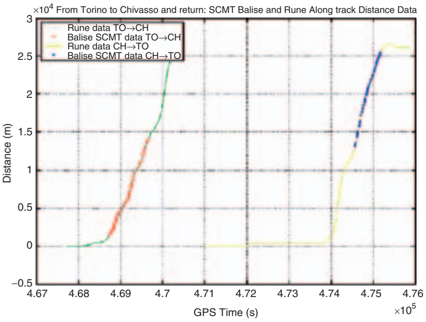


Fig. 10. RUNE along-track estimated distance vs. balise positions.

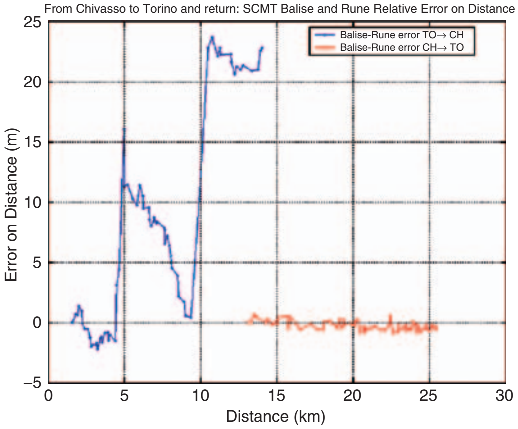


Fig. 11. RUNE along-track distance error vs. physical balise.

No virtual balise was used in this test, therefore this represents the total error accumulated by RUNE over 15 Km. It can be seen that RUNE along-track performance is always well below 2m in the Ch-To return run, while there are two large error spikes in the To-Ch run.

Those were identified as being caused by an incorrect time stamping of sensor raw measurement data samples by Rune. Such an event would have been detected by the raw data integrity checks prior to entering the DFF. Those checks were, however, disabled during the train test data collection. Figure 12 provides the GPS absolute position error on the two runs, showing the accuracy of the solution with and without EGNOS availability. Large error spikes are attributed to multipath effects and to poor SVs geometry also due to the lateral pointing installation of the GPS antenna. The GPS estimation has provided, on average during the runs, an error of 10m in position and 0.5m/s in velocity.

The position in ECEF (in terms of latitude and longitude of the track) estimated by RUNE and recorded from GPS are shown in Figs. 13 and 14 both for To-Ch and return.

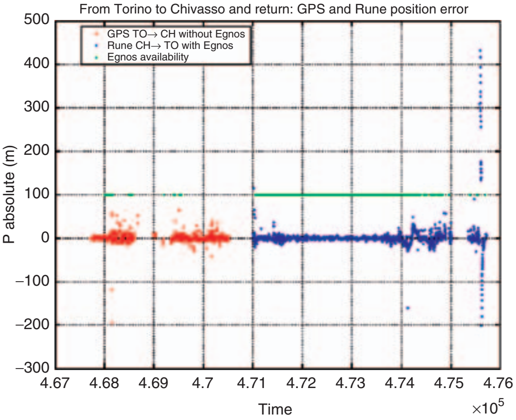


Fig. 12. GPS RMS absolute position error with & without EGNOS (EGNOS solution flag in upper position).

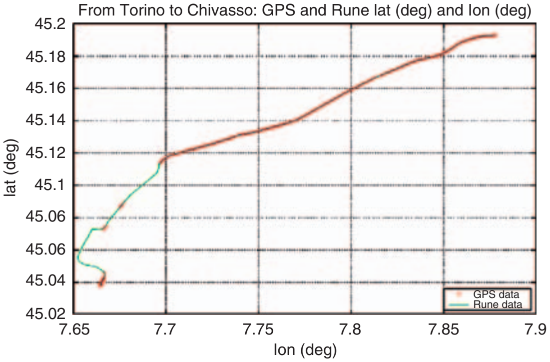


Fig. 13. GPS and RUNE latitude and longitude.

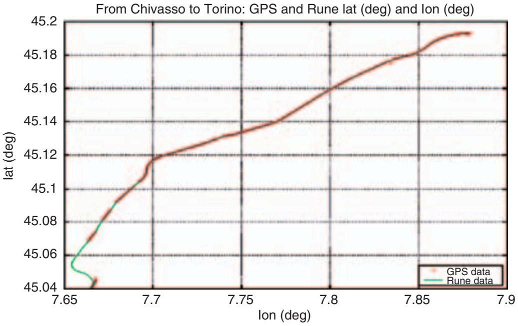


Fig. 14. GPS and RUNE latitude and longitude.

The light line is referred to RUNE DFF solution, and is continuous, while the dark line, represents the GPS solution which is discontinuous when signal is unavailable.

3.4 GNSS Solution Statistics

From the analysis of the GPS files recorded during the test, Fig. 15 shows a histogram of the number of SVs used in the solution and Fig. 16 provides the percentage of time for the three GPS solution cases: no solution, GPS-only, GPS + EGNOS. Figure 17 summarizes the GPS PVT solution availability, subdivided in the different types of environment crossed by the train.

3.5 EGNOS Status During Tests

The EGNOS SIS is broadcast by 3 GEO SVs:

PRN 120 – Inmarsat AOR-E
PRN 124 – ESA's Artemis
PRN 126 – Inmarsat 3F5 IOR-W

The EGNOS system is at present in its Initial Operation Phase (IOP), managed by ESSP, and its performances are increasing and stabilising; it will be soon qualified in order to provide, from the next 2007, a certified service for Safety of Life applications.

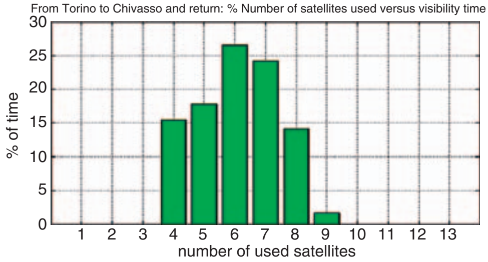


Fig. 15. % Number of SVs used.

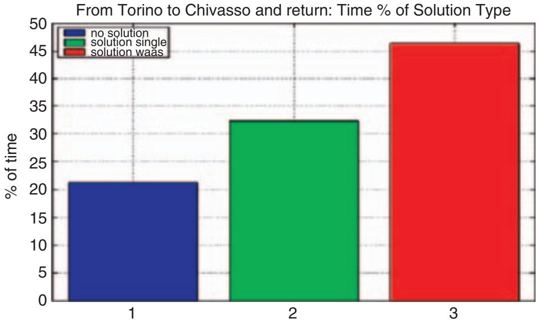


Fig. 16. Global % of solution type.

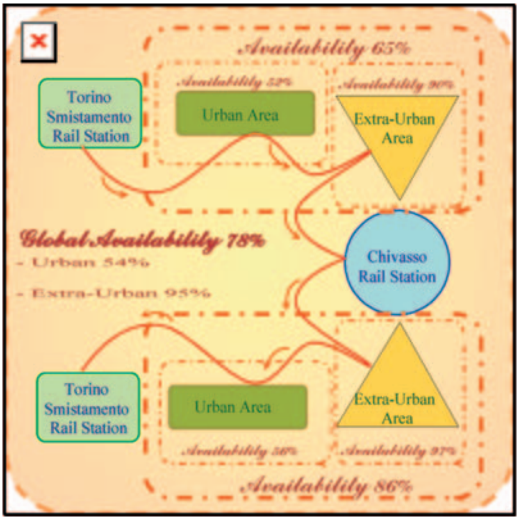


Fig. 17. GPS availability in urban and extra-urban areas.

At the time when the trials have been performed (April 2005), the EGNOS system was under the preparation of the Operation Readiness Review, and as such was subjected to many tests from the Industry and ESA: as a consequence, it was characterised by discontinuity events.

According to the technical reports provided by the IOP consortium, at the date of the trials the satellite better performing was the PRN 124, unfortunately not monitored during the demo. The GNSS receiver used in the demo was able to track only one GEO at a time. The GEO SV tracked in the tests was PRN 120, dedicated to the ESTB activities.

The PRN 124 is going to broadcast the EGNOS message until Jan 2006. PRN 120 will continue to be dedicated to the ESTB, and the PRN 126 reserved to Industry activities.

3.6 GNSS Protection Levels

Using the EGNOS PRN 120 information downloaded by the GPS receiver, the HPL/VPL values have been computed. Figure 18 shows the HPL/VPL during the route Ch-To. A strong increase in HPL/VPL can be observed in the middle of the graph, which seems to be due to bad geometry conditions as confirmed by the PDOP value. If we restrict the analysis to geometry conditions with PDOP <6, we obtain the HPL/VPL values shown in Fig. 19. The HPL mean value is in the order of 10m. Limiting the PDOP to 6 guarantees the availability of the HPL in the 86% of time (Fig. 20). It is important to notice that the HPL concept is defined for a 2D position, while for the railway application a new 1D along-track position protection level indicator needs to be defined (Fig. 21).

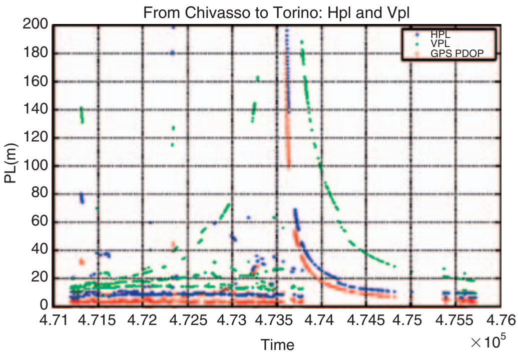


Fig. 18. HPL, VPL and PDOP.

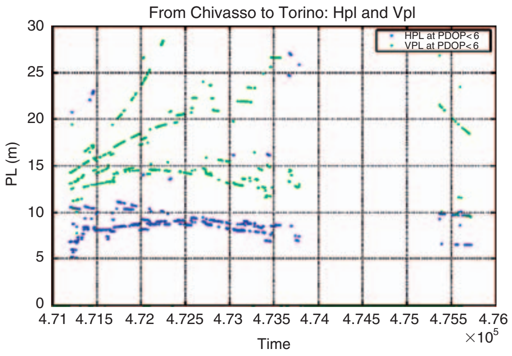


Fig. 19. HPL and VPL at PDOP <6.

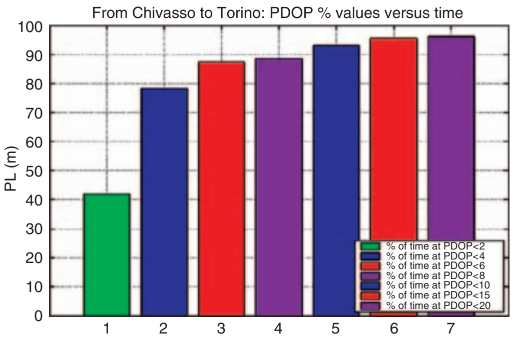


Fig. 20. PDOP % of time.

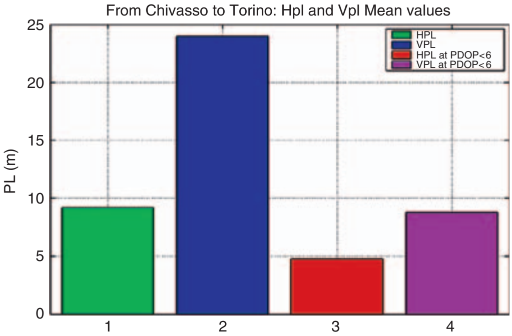


Fig. 21. HPL and VPL mean values.

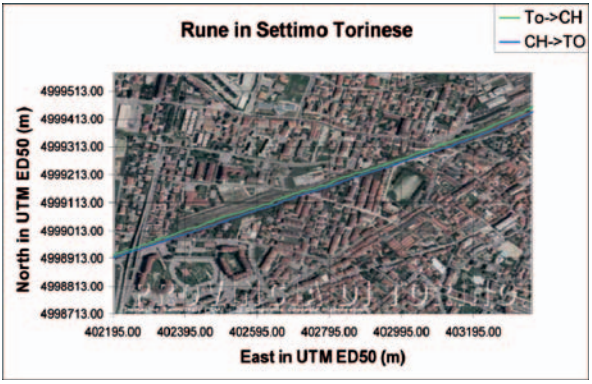


Fig. 22. RUNE in settimo Torinese.

3.7 Track Visualization on Cartographic Maps

Another way of verifying the position estimation obtained by RUNE is to visualize the computed train track on referenced geographical maps.

This data provides the CGR IT2000 Flight in UTM ED50 coordinates. The RUNE position solution during the train test was converted into this coordinate frame and superimposed to the maps. Starting from the Torino Smistamento Rail station, the train passed through the Settimo-Torinese Town and through Brandizzo up to the Chivasso Rail Station.

Figures 22 and 23 show a zoom of the track in Settimo Torinese town (one square = 200m) and a zoom of the train track estimated by RUNE trip when passing close to the Torino-Milano Highway (one square = 50 m). Note that the light line represents the To- Ch route were a GPS-only solution was available, while the dark line represents the return track in which a GPS + EGNOS solution was available. The dark line estimation is clearly more accurate if compared with the underlying picture of the real railway track.

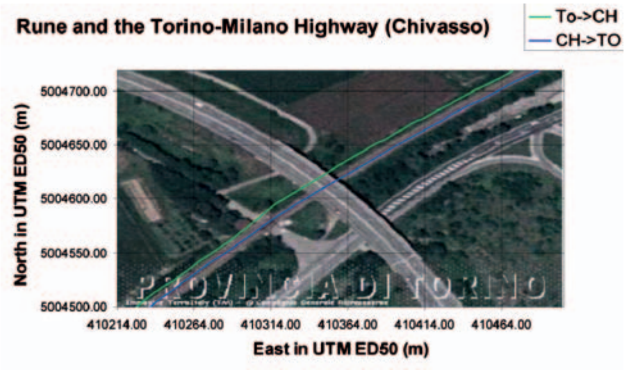


Fig. 23. Rune and the torino-milano highway.

3.8 Future Issues

In the frame of the on-going Galileo Joint Undertaking programmes, the RUNE architecture concept is going to be extended to Galileo within a consortium that includes the major railway signalling companies. This, together with a deep study of the safety issues involved in ERTMS/ETCS standards, will help in the future acceptance of a GNSS-based train on-board navigation system.

References

[1] Genghi A. et al., The RUNE project: Design and Demonstration of a GPS/EGNOS-based Railway User Navigation Equipment, *ION 2003*, Sept. 2003, Portland Oregon USA
[2] Albanese A., Marradi L. et al., The RUNE project: navigation performance of GNSS-based railway user navigation equipment, *Navitec 2004*, Dec. 04, Nordwijck ESA/ESTEC
[3] Albanese A., Marradi L. et al., The RUNE project: Navigation and Integrity Performance of GNSS-Based Railway User Navigation Equipment, *JRC2005*, 2005 Joint Rail Conference, March 16–18, 2005 Pueblo, Colorado.