AUGMENTATION AND INTEGRITY MONITORING NETWORK AND EGNOS PERFORMANCE COMPARISON FOR TRAIN POSITIONING

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ABSTRACT

The paper describes the performance comparison between EGNOS system and an Augmentation & Integrity Monitoring Network (AIMN) Location Determination System (LDS) designed for train positioning in terms of PVT accuracy and integrity information. The proposed work is inserted in the scenario of introduction and application of space technologies based on the ERTMS architecture. It foresees to include the EGNOS-Galileo infrastructures in the train control system, with the aim at improving performance, enhancing safety and reducing the investments on the railways circuitry and its maintenance.

The performance results will be shown, based on a campaign test acquired on a ring-shaped highway (named Grande Raccordo Anulare (GRA)) around Rome (Italy) to simulate movement of a train on a generic track.

***Index Terms*— Global Navigation Satellite System (GNSS), Signal In Space (SIS), European Geostationary Navigation Overlay Service (EGNOS), European Railways Train Management System (ERTMS), Position, Velocity and Time (PVT) estimation, Safety Integrity Level (SIL).**

1. INTRODUCTION

The use of GNSS technologies is largely proliferating in many contexts. In railway signaling applications the exploitation of GNSS is starting to emerge at the aim of reducing life-cycle costs of existing signaling systems, and then allowing for new cost-efficient safety protection where no signalization exists.

The target is to reach a fully automatic (unmanned) railway transportation system, without increasing the complexity of the wayside equipments and reducing the safety. In railway scenario, it is mandatory to fulfill the very stringent safety levels indicated by SIL-4 requirements of Comité Européen de Normalisation Électrotechnique (CENELEC) railways norms (*i.e.*, Tolerable Hazard Rate (THR), $10^{-9} \leq \text{THR} \leq 10^{-8}$), [1]. In order to satisfy the SIL-4 requirements, the GNSS architecture should be comprised of a dedicated AIMN as well as the use of multi-constellation receivers.

The principle of an AIMN Network is that a significant portion of spatially correlated errors due to local effects (ionospheric, tropospheric and ephemeris) are estimated by network reference stations and this information is provided to rovers located at distances up to 40 km from the next station. Among spatially correlated errors, ionosphere is most difficult to model and contributes the largest error for AIMN users in terms of reliability and availability.

Satellite Based Augmentation Systems (SBAS) have been already developed with the principal aim to improve accuracy and integrity performance in satellite localization for big areas, as Wide Area Augmentation Systems (WAAS) in United States of America or EGNOS in Europe [2].

In such a system, several reference stations are deployed in very large areas and estimated positioning errors are reduced exploiting data coming from these stations. EGNOS has been developed by European Space Agency (ESA), European Commission and EuroControl.

Nevertheless, by using an AIMN it is possible to reach higher level of accuracy than a SBAS (such as EGNOS), thanks to the compensation of local effects (in particular ionospheric phenomena).

The work shows a performance analysis based on comparison of PVT estimation errors achieved by applying EGNOS differential corrections and differential ones coming from of a local AIMN, respectively. Moreover, the Stanford diagram with the calculus of Protection Level (PL) versus positioning errors, is shown [3]. Section II describes EGNOS system, while Section III shows the adopted local AIMN. Then, Section IV illustrates the comparison results. Finally, the conclusions are carried out in Section V.

2. EGNOS SYSTEM OVERVIEW

SBAS complements and augments the existing GNSS performance by broadcasting differential corrections and integrity messages of satellites that are monitored by a network of reference stations deployed across the world.

SBAS compensates for certain disadvantages of GNSS in terms of accuracy, integrity, continuity and availability. In fact, most of effects that have negative impact on satellite positioning performance are due to local effects as ionospheric and tropospheric anomalies, geometric distribution of satellites, multipath and shadowing phenomena [4]. Moreover, SBAS includes ground control center and a small constellation of geostationary satellites too.

Several countries have implemented their own SBAS. Europe has EGNOS which covers Western Europe and North Africa. The United States of America has developed the WAAS. Japan is covered by its Multi-functional Satellite Augmentation System (MSAS). India has launched its own SBAS program named Global Navigation System (GPS) and GEOstationary (GEO) Augmented Navigation (named GAGAN) to cover the Indian subcontinent [5].

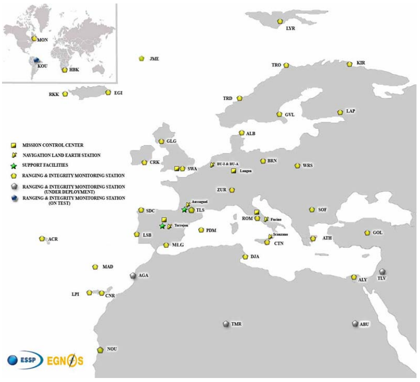

Figure 1: Displacement of EGNOS RIMs around the world.

Focusing the analysis on European SBAS, the following lines deeply describe the EGNOS system. It consists of: (i), a space segment that has in charge of broadcasting EGNOS signal and it is composed of three GEO Space Vehicles (SVs) with associated a unique Pseudo Random Noise (PRN): PRN 120, PRN 124, PRN 126; (ii) a ground control segment that processes EGNOS signal and manages the system and finally (iii) a user segment that includes a set of EGNOS compliant receivers developed for different types of users [5]. Moreover, the ground segment comprises 41 Ranging and Integrity Monitoring (RIM) Stations mostly deployed in Europe and few terminals are in the North Africa and in America. **Error! Reference source not found.** shows the displacement of EGNOS RIMs all over the world [6].

All the RIMs collect data coming from GNSS satellites and send them to the Master Control Center (MCC) that has in charge the processing, validation and distribution of EGNOS messages.

3. AUGMENTATION AND INTEGRITY SYSTEM ARCHITECTURE

The proposed overall GNSS Location Determination System (LDS)) system is a modular architecture capable of acquiring both data coming from a local AIMN as well as SBAS system, i.e. EGNOS. It consists of: (i) AIMN, that consists of a set of Reference Stations (RS) with Ranging & Integrity Monitoring functionalities, distributed along the railway, and a Track Area LDS Safety (TALS) server that jointly processes the RS data and produces the augmentation data to feed On Board Units (OBU) installed on each locomotive of train [7]. In particular, AIMN provides information on SIS integrity and the differential corrections to be applied by the GNSS LDS OBUs for compensating the effects produced by satellite ephemerides and clock offset errors and variations in the propagation delay introduced by ionosphere and troposphere; (ii) EGNOS/TALS switch module that receives differential corrections both from AIMN and EGNOS system. This component operates as a switch that alternatively uses corrections from TALS (only TALS mode) or EGNOS (only EGNOS mode) and passes them to OBU; (iii) a sub-system that acquires EGNOS data and sends them to EGNOS/TALS switch module through EGNOS adapter. The EGNOS adapter has in charge also the SBAS updating functionalities, and finally (iv) a GNSS LDS OBU, providing PVT estimates as well as an indication of their accuracy.

Finally, each AIMN RS is equipped with:

- two different GNSS low-cost receiving chain singularly constituted by one single frequency GNSS receiver equipped with one its own single GNSS antenna. The antenna subsystem in both chains is the same, while the receivers are developed by separate manufacturers to avoid common modes of failure;
- a local processor;
- a communication module.

A functional overview of the main subsystems in the GNSS LDS system is shown in Figure 2. It is clear as EGNOS/TALS switch module system has in charge the integration of corrections coming from different Augmentation network (AIMN and SBAS). Two operational modes can be determined:

1. *Only TALS mode*;
2. *Only EGNOS mode*;

When Only TALS mode is enabled, the outputs of TALS (inputs of EGNOS/TALS switch) are, for each epoch k, j-RS and each satellite i in view: *(i)* pseudorange residuals $\zeta_j^i(k)$; *(ii)* ionosphere error $c \cdot \delta t^{ion}$ (computed by means a Klobuchar model [2]), where c is the speed light; *(iii)* troposphere error $c \cdot \delta t^{trop}(k)$ (computed by using the

Saastomeinen model [2]) and *(iv)* satellite clock offset $\delta t_{sat}(k)$.

When this mode is enabled, EGNOS/TALS switch subsystem will sum these terms for each epoch and every RS:

$$Corr_j^i(k) = \zeta_j^i(k) - c\delta t_{sat}(k) + c\delta t_j^{ion}(k) + c\delta t_j^{trop}(k)$$

Finally, those values will be sent to OBU.

Otherwise, when Only EGNOS mode is enabled, the inputs of EGNOS/TALS switch sub-system are, for each epoch *k*: *(i)* Ionosphere/troposphere corrections grid, *(ii)* short term and long term errors on satellite clocks, $\delta t_{sat}(k)$; *(iii)* errors of satellite orbits $(\Delta x^{Sat}, \Delta y^{Sat}, \Delta z^{Sat})$ to be used for computing satellite positions; *(iv)* and integrity information with list of satellite to be considered.

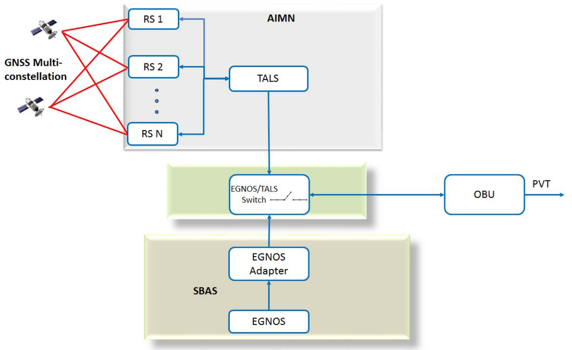

Figure 2: Overview of GNSS LDS System

Those inputs are read from EGNOS corrections (EGNOS Message Server (EMS) file).

In the last case, it is not possible to send to OBU only one term for each epoch, *k*, but there are three different messages to be passed to OBU:

1. term $corr(k) = c \cdot \delta t^{atm}(k) - c\delta t^{Sat}(k)$;
2. errors on satellite orbits $(\Delta x^{Sat}, \Delta y^{Sat}, \Delta z^{Sat})$ to be used for computing satellite positions;
3. integrity information as released by EGNOS.

Only EGNOS mode represents a useful comparison with AIMN system for testing accuracy and integrity.

Each GNSS LDS OBU is equipped with: one or more GNSS receiver(s); a local processor performing the PVT estimation starting from local raw data (i.e. pseudoranges), a track database and augmentation data received from the TALS server/EGNOS module.

To guarantee enough growing capability with respect to integrity and availability requirements, the GNSS LDS OBU architectural design supports the deployment of configurations making use of: multiple GNSS antennas for increasing availability and multipath mitigation, each characterized by its own phase center and radiation diagram; two or more different GNSS receivers developed by separate manufacturers to avoid common modes of failure; multiple independent processing chains; and finally a complementary set of integrity mechanisms (e.g. self check). Moreover, the OBU algorithm for determining the train location explicitly accounts for the fact that the train location is constrained to lie on railway track [7]. This constraint allows to estimate train location even when only two satellites are in view. Effective reduction in the number of required satellites to make a position fix when track constraint is applied depends on track-satellite geometry. In essence, satellites aligned along the track give more information than those at the cross-over. Satellites in excess can then be employed either to increase accuracy or to increase integrity and availability.

4. PERFORMANCE RESULTS

The performance of the proposed GNSS LDS system have been assessed and compared with EGNOS corrections as loaded by EGNOS Data Access Service (EDAS). EDAS disseminates EGNOS data in real time without relying on the signals from the three EGNOS satellites. EDAS is the point of access for the data collected and generated by the EGNOS infrastructure. It is available through a ground network without requiring direct access to an EGNOS satellite. It can therefore be used in constrained environments such as when signals are blocked or are disturbed by interference. The used set of data has been acquired during a measurement campaign along the GRA, that is an annular ring highway of Rome. For AIMN, although 3 RIMs displaced along the highway (each equipped with 2 receivers (NVS NV08C-CSM and U-BLOX NEO-6P) and two antennas (Tallysman TW-2410)) were deployed, the RS located in Conca *D'Oro* site was affected by a strong multipath. Therefore, it was not employed in the performance assessment. The remaining two RIMs were respectively located in RadioLabs (East area of Rome) and nearby the Alitalia facilities (South-West part of Rome). A car also equipped with both types of receivers has been used as rover.

The assessed performances are in terms of position estimates w.r.t ground truth, velocity estimate w.r.t. ground truth and, also Stanford diagram is compared for both cases.

Figure 3 shows the position estimate of the train w.r.t. the ground truth when Only-EGNOS-mode (a) is enabled and when Only-TALS-mode (b) is enabled. When only EGNOS corrections are used, the position error is, on average, lower than using Only-TALS-mode. In presence of tunnels and overpasses in both cases we have peaks in position errors due mostly to multipath; however, we can notice that at those epochs, position errors for EGNOS Only-mode (a) go at 4 meters while the position errors for Only TALS mode (b) is bounded between [-2,+2] meters. Hence, the proposed augmentation network can better compensate the local effects. The difference between the two systems lies in fact that EGNOS is a Wide Area Augmentation System and the ionosphere error model is derived by a grid with a European coverage, while our proposed system is a local network and the ionosphere error model is locally calculated (by means of Klobuchar model). Figure 4 shows the velocity estimate by means of Doppler values in both cases: (a), when using Only EGNOS mode and (b) when using Only-TALS-mode. We can notice that we have similar trends for both cases. In Figure 6, the histogram of position errors w.r.t. ground truth is depicted when EGNOS mode is enabled and in Figure 7, the histogram of position errors when only TALS mode is enabled. Figure 5 shows the Stanford diagram for both cases: (a) when using Only EGNOS mode and (b) when using Only TALS mode. The horizontal axis is the position error as calculated by OBU with respect to the surveyed antenna location. The vertical axis is the PL computed for each navigation solution. Each bin tabulates the number of occurrences of a specific (error, PL) pair and the color of each grid indicates the total number of epochs that pair occurred. Note that the color scale is logarithmic.

The Alarm Limit (AL), indicated by the horizontal and vertical lines, is set at 30m. Points, where the PL are above the alarm limit, constitute at least a loss of availability and possibly a continuity failure. Points where the PL is under the alarm limit but the error is greater than the AL indicate a breach of integrity. In any case, the position error should always be less than the PL and should lie in the Normal Operation region.

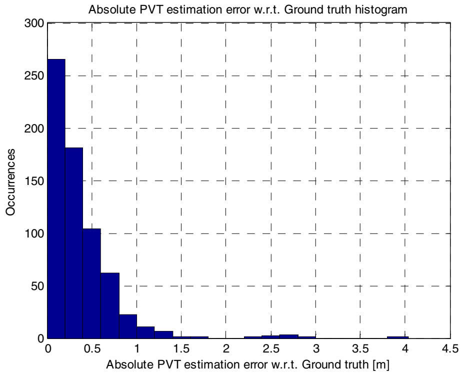

Figure 6: Histogram of position estimation error - Only EGNOS Mode

5. CONCLUSIONS

The work has investigated the performances comparison of a Local AIMN and EGNOS system in terms of PVT and PL versus error position errors. Real data have been acquired by a car during a test campaign along an important highway in the city of Rome. The simulation results have shown that using EGNOS system, the position errors is, on average, lower than using AIMN system. However in presence of tunnels and overpasses, the proposed augmentation network has lower position errors due to a better (local) compensation of local effects, *i.e.* ionosphere errors and multipath.

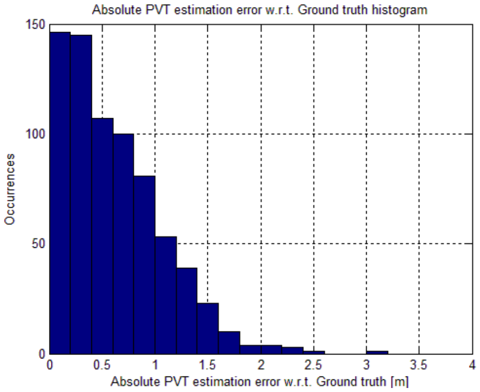

Figure 7: Histogram of position estimation error - Only TALS Mode

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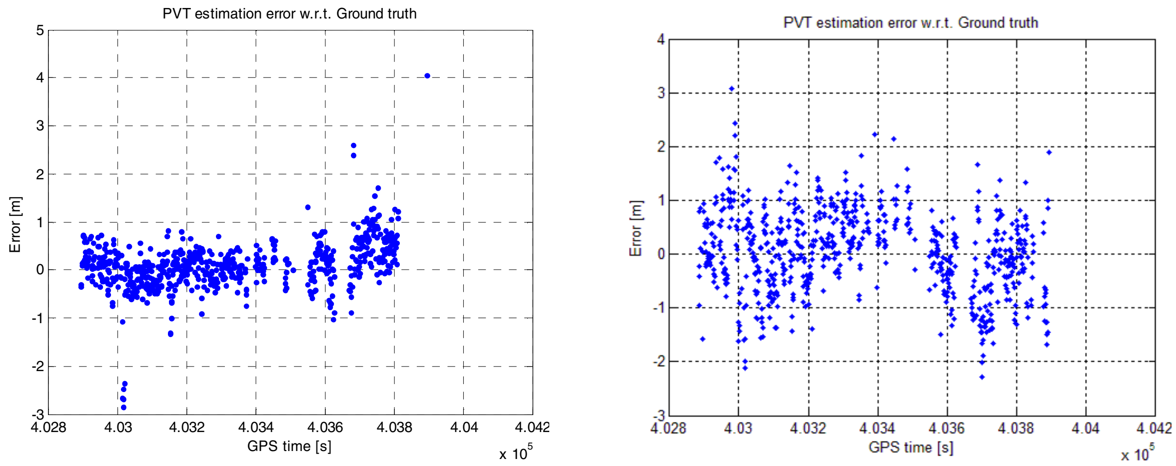
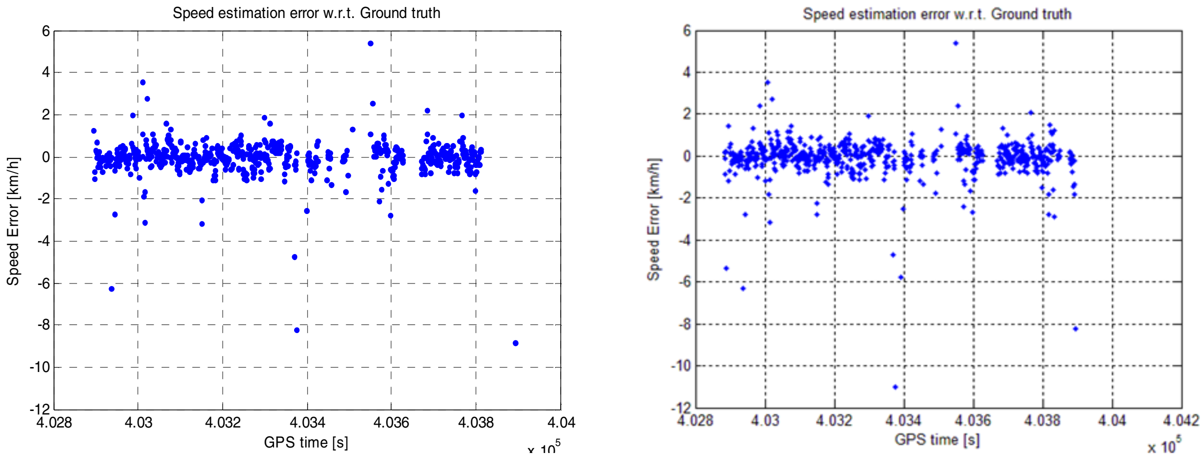


(a) EGNOS mode

(b) TALS mode

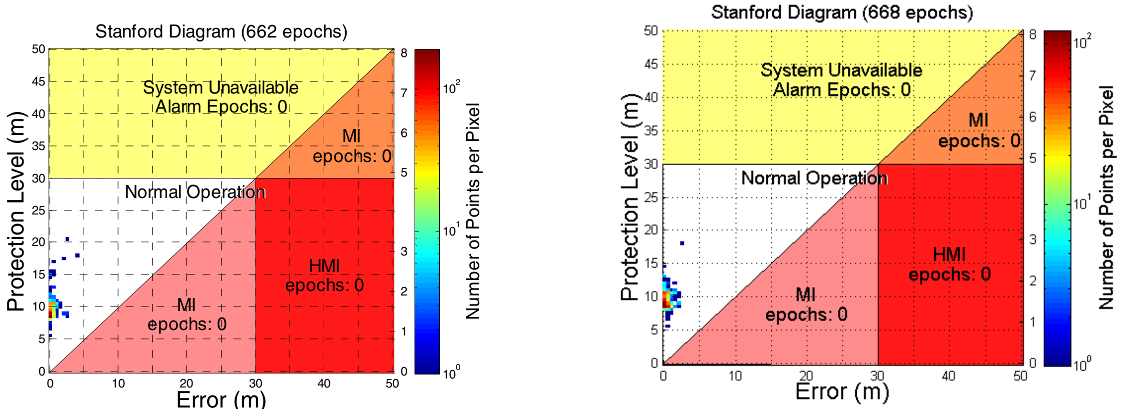
Figure 3: Position Error w.r.t Ground Truth. (a) EGNOS mode and (b) TALS mode



(a) EGNOS mode

(b) TALS mode

Figure 4: Velocity Estimation w.r.t Ground Truth. (a) EGNOS mode and (b) TALS mode



(a) EGNOS mode

(b) TALS mode

Figure 5: Protection Level w.r.t Error. (a) EGNOS mode and (b) TALS mode