Galileo Safety-of-Life Service Utilization for Railway Non-Safety and Safety Critical Applications*

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Abstract

Global Navigation Satellite System (GNSS) Galileo is expected to play an essential role in railway transport with view to reduce operational, investment and maintenance costs. However, quality requirements of the GNSS originate mainly from the aviation suggestions. Different safety philosophies used in aviation domain and in railway signaling complicate direct employment of the GNSS quality measures to the railway telematic applications. The objective of this paper is to outline the conception of railway requirements specification for the GNSS in order to cover a large amount of the appropriate applications in the non-safety and safety related domains. The elaborated methodology enables to provide specification of minimal quantitative requirements for GNSS system by means of railway attributes RAMS. This process generally represents contribution for GNSS system certification, when it is necessary to demonstrate that the GNSS system meets requirements, and the system outputs are correct. In the second level, certification of the specific GNSS application must follow subsequently.

Key words: Satellite Navigation System, Railway, Accuracy, Reliability, Safety, Sensor Fusion

1. Introduction

Classical railway positioning systems are always based on traditional infrastructure equipment (track circuits or transponders, axle counters, balises, beacons), which is not such effective due to the high investment, operational and maintenance costs. Moreover, European national railways use their own different and incompatible signaling systems. A lot of regional and secondary low traffic density lines in Europe are equipped with obsolete or no signaling at all, and railway safety on these lines mainly depends on a human factor. These facts evoke the expectation that GNSS technology has a great potential for railway systems to reduce costs significantly, improve interoperability, operational efficiency and safety.

Railway transportation applications and especially safety critical ones can profit from the European GNSS/ Galileo system with its certified and guaranteed Safety of Life (SoL) service (1). Especially, Galileo SoL Level A category should be exploited due to the most stringent quality attributes in terms of Signal-In-Space (SIS) accuracy, integrity, continuity and availability (2). Since Galileo SoL service specifications have been driven essentially by avionic needs, the GNSS SIS quality attributes do not correspond to railway RAMS according to the CENELEC standards EN 50126 (3) and EN 50129 (4). In spite of the different safety philosophies used in aviation and railway safety systems, the Galileo SIS
quality criteria can be described on the basis of railway RAMS (5)-(7). However, railways have not specified quantitative requirements for Galileo SoL service up to now and railway SIS reception environment is also very different.

This paper describes methodology by which railway requirement specification for GNSS SIS should be provided for a wide range of railway telematic applications. A possibility for GNSS performance improvement from the viewpoint of railway is also indicated. Improvement of availability and safety levels of the GNSS based Train Position Locator (TPL) has been realized by means of utilization of additional diverse sensors and Local Elements Technology (LET). Practical tests of the GNSS based TPL under real railway conditions have been performed in order to demonstrate the suitability of GNSS technique utilization for rail applications.

2. GNSS Quality Measures

The features of GNSS SIS quality measures are described in terms of accuracy, integrity, continuity and availability. Following section deals with some misunderstandings about the accuracy and proposal for achievement of higher integrity with regard to usage in railway safety related applications.

2.1 Accuracy

Accuracy is a statistical quantity associated with the probabilistic distribution of the navigation error. One of misunderstandings concerning the GNSS position accuracy is that probability for 2-sigma horizontal error bound corresponds to fixed 95 % probability. In the case of a one-dimensional position error (e.g. altitude) that follows Gaussian distribution, the 2-sigma error limit expresses the 95.4 % of navigation errors. But for two-dimensional position, the distribution of GNSS fixes of a horizontal position may be approximated by a general bivariate Gaussian distribution. The percentage of horizontal positions contained within the 2-sigma value varies from 95.4 % to 98.2 %, depending on the degree of ellipticity of the error distribution. Since the total length of the horizontal error is of interest, the isotropic standard deviation is considered to be the uncertainty in the estimation of horizontal position. It is equal to the semi-major axis of the error ellipse

\[
\xi = \sqrt{\frac{\sigma_x^2 + \sigma_y^2}{2} + \frac{(\sigma_y^2 - \sigma_x^2)^2}{2} + \sigma_{xy}^2}.
\]  

(1)

Horizontal Accuracy (HA) of Galileo SIS SoL service is specified by the horizontal error at the exactly 95 % confidence level (2). This HA is provided when the GNSS system is operating in nominal operational configuration. This configuration includes cases of no intentional jamming, no exceptional interference, no special atmosphere activities (ionosphere, troposphere), visibility more than 4 satellites, good user-satellite geometric conditions (low HDOP), and the fact that SIS reception is not affected by fading or significant multipath. Since no system failure is considered, the Galileo SoL HA of 4 m (95 %) is specified under the fault-free conditions as follows

\[
HA = K_{95\%} \cdot \xi_{95\%},
\]  

(2)

where \(K_{95\%} = 2.448\) is the confidence coefficient resulting from the 95 % confidence level.

2.2 Integrity

Total Integrity Risk (IR) for user is directly calculated at the vertical and Horizontal Alert Limit (HAL) (2)

\[
P_{\text{intd}}(VAL, HAL) = P_{\text{intd}}^\text{val}(VAL) + P_{\text{intd}}^\text{val}(HAL).
\]  

(3)
This integrity conception is especially designed for aviation requirements. However, it can be very useful for railway applications to scale the integrity risk at the HAL only since the train is moving in a horizontal plane. European railway user community has also specified requirements for GNSS TPL in a horizontal plane \((8)\). Then the IR can be determined by horizontal IR as the weighted sum of the combination of faulty and fault-free modes of all satellites \(^{(2)}\):

\[
P_{\text{hor}_1}\text{HAL_{i}} = P_{\text{hor}_1}\text{HAL_{i}} + P_{\text{hor}_1}\text{HAL_{i},f} =
\]

\[
= e^{\frac{-HAL_i}{2\xi^2}} + \sum_{i=1}^{N} P_{\text{sat fail}} \left[ 1 - \chi^2 \text{cdf} \left( \frac{HAL_i^2}{\sigma_{\text{HMI}}^2}, \mu_{\text{hor}, \text{f}(i)}^2, \sigma_{\text{f}(i)}^2 \right) \right]
\]

with the cumulative distribution function of a non-central \(\chi^2\)-distribution with degree of freedom 2, argument \(x\), and non-centrality parameter \(\delta\) as follows:

\[
\chi^2 \text{pdf} (x, \delta) = \frac{1}{2} e^{-\frac{x+\delta}{2}} \sum_{n=0}^{\infty} \frac{\left(\frac{x\delta}{4}\right)^n}{n!},
\]

\[
\chi^2 \text{cdf} (x, \delta) = \int_{0}^{x} \chi^2 \text{pdf} (t, \delta) \, dt.
\]

Tremendous reduction of IR can be demonstrated for the fault free mode of Galileo SIS SoL - Level A service. It can be derived from the performance requirements \(^{(1)}\) that \(P_{\text{vert}_1}\text{HMIP}_{f}\) achieves value of \(5.7 \times 10^{-7}\), whilst \(P_{\text{hor}_1}\text{HAL_{f}}\) is less than only \(8 \times 10^{-13}\) \((\text{from the Eq. 4})\).

It should be noted that specific inconsistency follows from definition of the IR. The IR is the probability that user should have been warned without having been warned but it is assumed that any excursion of PE beyond the HAL is considered to be the IR occurrence \(^{(3)}\).

Position from the TPL is correct when Position Error (PE) is maintained within a user defined HAL. Let’s denote the state of failure absence as \(H_0\). Under simplifying assumptions that the same variance is assumed in each direction and that the errors are independent and normally distributed, conditional probability of the correct position given the \(H_0\) hypothesis can be described by Rayleigh function:

\[
P_{\text{hor}_1}\text{H}_{\text{f},0} = P(PE \leq \text{HAL} | H_0) = 1 - e^{-\frac{\text{HAL}^2}{2\xi_f^2}},
\]

where confidence coefficient \(K_f\) results from tolerated unavailability in the fault-free mode. Mutual relationship between HAL and standard deviation in the fault-free case \(\xi_f\) is:

\[
\text{HAL} = K_f \xi_f.
\]

On the contrary, the position of TPL error exceeds a user defined HAL with the complementary conditional probability \(P(PE > \text{HAL} | H_0) = 1 - P_{\text{hor}_1}\text{HAL}_{f,0}\), which equals to the fault-free horizontal IR. Moreover, the IR should be scaled for railway applications. It means the adaptation of HAL values to the application.

3. Railway Requirements for GNSS

GNSS can be potentially applied in many railway applications. Document regarding a set of main applications of GNSS into railway industry was specified in Europe within the GNSS Rail Advisory Forum \(^{(8)}\). More than 50 non-safety and safety relevant railway applications of the Galileo system have been identified.
3.1 Non-safety Related Applications

Non-safety railway applications utilizing GNSS are divided into the following groups:

- **Passenger transportation**
  - Central information system
  - Check-in train terminals
  - Passenger attendance
  - Reservation systems

- **Freight transportation**
  - Position monitoring of trains, wagons, consignments or transport units
  - Logistic centers
  - Consignment integrity check
  - Dangerous goods monitoring

- **System management**
  - Rolling stock management
  - Energy saving
  - Management of connecting trains
  - Optimizing the capacity of the line
  - Performance charging of railway infrastructure

- **Traffic routes**
  - Surveying of objects, elements and reference points
  - Tracking and monitoring of track geometry
  - Evidence to the railway infrastructure
  - Check of machines alignment
  - Ensuring time synchronization during data origination

- **All transport segments**
  - Location determination for dispatching and warning system operators
  - Integrated rescue system
  - Infrastructure diagnostics

3.2 Safety Critical Applications

The main signaling applications are classified into the 5 groups as follows:

- **Infrastructure operation applications**
  - Infrastructure digital data map creation
  - Calculation of end of movement authority
  - Supervision to buffer stops

- **Train borne applications**
  - Speed profile calculation
  - Train location determination

- **Protection applications**
  - Level crossing protection
  - Train warning systems
  - Worker protection
  - Train awakening

- **Train control centre applications**
  - Geographical position of train
  - Track identification
Additional applications

- Power supply control
- Advisory station stop
- Door control supervision
- Train integrity detection
- Train separation
- Odometer calibration

3.3 Analysis of railway applications

Each of individual applications has been described in detail according to service and quality requirements. The applications have been grouped into three categories according to their accuracy, availability and integrity needs as proposed in Table 1. Category I has the highest requirements on accuracy, availability and integrity. Category II with the medium requirements on accuracy, availability and integrity is placed in the second order. Applications with the lowest requirements on their quality attributes belong into the category III. The only one application per category is shown in Table 1 since requirements in the same category are similar. In next part of the paper the description of the only one application from category I will be introduced. This category has been selected due to the highest requirements for GNSS.

<table>
<thead>
<tr>
<th>Category / Requirements</th>
<th>Railway applications</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Very high</td>
<td>Performance charging of railway infrastructure, Surveying of objects, elements and reference points, …</td>
<td>Train location determination – high traffic density lines, Digital map creation, Odometer calibration, …</td>
</tr>
<tr>
<td>II High</td>
<td>Position monitoring of trains, wagons, consignments or transport units, Check-in train terminals, Reservation systems, Energy saving, Rolling stock management, …</td>
<td>Speed profile calculation, Supervision to buffer stops, Level crossing protection, Track identification, Door control, Worker protection, Hazardous cargo, …</td>
</tr>
<tr>
<td>III Low</td>
<td>Infrastructure diagnostics, Passenger information system, …</td>
<td>Train location determination – low traffic density lines</td>
</tr>
</tbody>
</table>

3.3.1 Performance charging of railway infrastructure

Performance charging of railway infrastructure is a complex system for data acquisition, validation and storage. The application is used to calculate charges and collect fees for use of railway infrastructure. The mobile part (on board unit) is located on the driving vehicle. It transmits data to the stationary part, which is responsible for the data storage and validation. The data are concerned with the vehicle identification, position, traveled distance, train on-board staff information, time record of provided information and eventually any other supplementary information. Train position data can be transmitted online and/or offline. The acquisition of data in defined structures is carried out automatically or manually by the engine driver. Stationary part is used for storage of data from mobile part and validation with the primary data obtained from the current information system. The predefined data are compared with data from mobile part, verified and
subsequently saved. Saved data are used for charging calculation of the railway traffic, billing, promotion of trade and pricing. The data can be also used to obtain statistics, reports and information for public administration, regulation, audit and funds. The highest guarantee of position and direction of movement is required for this application. Data will be used as a primary input into the database of resources for calculation of railway infrastructure charging and for data validation from another information system. The traveled distance in kilometers should be recorded for each train according to its specific type and number. Offline data are sufficient in the case of service outage.

Advantages after the GNSS introduction:

- Automatization of data collection,
- Precise and accurate charging for the using of transport infrastructure in the Czech Republic,
- System reliability,
- Rationalization of railway traffic charging process,
- Possibility of introduction or charging of other infrastructure manager services for carrier (e.g. shunting),
- Mapping the performance of individual lines or sections and the subsequent variable charging for specific railway infrastructure; the variable charging is advantage or necessity,
- Possibility of marketing functions introduction for infrastructure manager, outputs for rail traffic controllers, for state funds and state administration in order to ensure uniform and correct data for deciding on the railway transport as a system,
- Provide accurate and relevant information for:
  - Investment in construction and reconstruction of railway infrastructure,
  - Creation of positive incentives for railway carriers on specific tracks,
  - Dependability improvement of railway transport infrastructure.

3.3.2 Train location determination

This application is fundamental to the safe operation and usage of train control system. It allows the detection of the presence / absence of train in the rail section, which is provided by means of track side equipment (track circuits, axle counters). The application based on GNSS TPL must provide train movement information (position, speed, acceleration, direction of movement, time data). If the application is used instead of ETCS, it must also provide traveled distance from the last reference point and confidence interval. If this application is used to enhance ERTMS/ETCS odometry, the train location must be based on the on-board equipment and train knowledge of traveled distance from the last reference point. Train length must also be provided on some lines. If the TPL replaces train localization using ETCS balises, then the TPL must meet the highest level of SIL 4. Location of the train on the basis of GNSS TPL will be very important for the needs of interlocking systems on low traffic density lines particularly for those which are not equipped with signaling at all. The train location determination can be used in a wide range of another applications: from monitoring of dangerous goods and management of industrial machines to the most demanding applications such as train initial position determination, discrimination of parallel tracks during a switch facing-point movement, shunting operations, implementation of moving blocks, etc.
Application advantages:

- Improvement of odometry availability,
- Overall improvement of train location accuracy,
- Reduction of safety distances between trains,
- Increase of the operational train density,
- Increase of the distance between trackside balises,
- Cost reductions (on-board equipment cost, reduction of balises).

3.4 Minimal requirements for applications

3.4.1 Performance charging of railway infrastructure

Requirement for HAL has been allocated to 10 m. If GNSS service maximum unavailability of 0.01% is chosen to be tolerated, the corresponding minimum confidence coefficient $K_{f,\text{min}} = 4.291$ is obtained from Eq. (7). Then requirement for the maximum position standard deviation can be derived from Eq. (8). Based on the assumption that the horizontal error is equal and normally distributed and considering that the HA is specified by the position error at the exactly 95% confidence level it follows from Eq. (2) and Eq. (8)

$$HA_{\text{max}} = K_{f,0.95} \frac{HAL}{K_{f,\text{min}}}.$$  \hspace{1cm} (9)

Table 2 summarizes minimum requirements for reliability and maintainability resulting from the application operational efficiency.

<table>
<thead>
<tr>
<th>Table 2 Minimal requirements for the application</th>
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<tbody>
<tr>
<td>Horizontal alert limit</td>
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<tr>
<td>Horizontal accuracy</td>
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<tr>
<td>Update time interval</td>
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<tr>
<td>Update rate</td>
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<tr>
<td>Failure rate</td>
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<tr>
<td>Service interruption at periodic 1 month check</td>
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<tr>
<td>Service interruption at periodic 6 months check</td>
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<tr>
<td>Service interruption after failure detection</td>
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</table>

Railway environment is very different from viewpoint of SIS reception (SIS shadowing objects along track, landscape profile, etc.). Due to the relationship between SIS reception and type of track lines the SIS availability levels must be considered for the assessment of application quality parameters. Let $A_{\text{SIS}}$ denotes SIS availability on track. The following levels will be further distinguished in the paper: i) practically hypothetical case of $A_{\text{SIS}} = 100$% SIS availability achieved on some sections of corridor lines or station tracks, ii) $A_{\text{SIS}} = 95$% SIS availability expected on main and middle traffic density lines, iii) $A_{\text{SIS}} = 70$% SIS availability on secondary, industrial and other low traffic density lines. Then mean down time per year in fault-free state is

$$t_{f,\text{max}} = \left(1 - P_{\text{tor,1}}^{\text{y}}\right)T_y A_{\text{SIS}},$$  \hspace{1cm} (10)

where $T_y = 365 \cdot 24$ h $= 8760$ h.

Dependability is investigated in terms of reliability, maintainability and availability. Maximum failure rate can be determined from the Table 2 as $\lambda_{\text{max}} = 1/24$ h$^{-1} = 4.17 \cdot 10^{-2}$ h$^{-1}$. The failure rate enables to derive minimal mean time between failures as $MTBF_{\text{min}} = 1/\lambda_{\text{max}} = 24$ h. Under the presumption of constant failure rate (period of normal
utilization) the reliability of correct position determination by GNSS corresponding to the exponential distribution is

\[ R_{\text{min}}(t) = \exp^{-\lambda_{\text{max}} t}. \]  

Unreliability of position determination function \( F(t) \) is one complement of \( R(t) \) and can be expressed as

\[ F_{\text{max}}(t) = 1 - R_{\text{min}}(t) = 1 - \exp^{-\lambda_{\text{max}} t}. \]  

The density failure rate is given by

\[ f_{\text{max}}(t) = \frac{dF_{\text{max}}(t)}{dt} = \lambda_{\text{max}} \exp^{-\lambda_{\text{max}} t}. \]  

Maximum time needed for execution of all maintainability activities per year \( t_{u,\text{max}} \) (see Table 2) is

\[ t_{u,\text{max}} = 10 t_{\text{SIM},\text{max}} + 2 t_{\text{SIM},\text{max}} = 5.7 \text{ h}. \]  

Maximum requirement for time of GNSS service interruption per year \( t_{o,\text{max}} \) is

\[ t_{o,\text{max}} = \frac{T_y}{MTBF_{\text{min}}} t_{\text{SIM},\text{max}} \approx 608 \text{ h}. \]  

Minimum mean time to repair \( MTTR_{\text{min}} \) is given by

\[ MTTR_{\text{min}} = \frac{MTBF_{\text{min}}(t_{u,\text{max}} + t_{o,\text{max}} + t_{f,\text{max}})}{T_y}. \]  

Repair rate is obtained upon the Eq. (16) as

\[ \mu_{\text{max}} = \frac{1}{MTTR_{\text{min}}} = \frac{T_y}{MTBF_{\text{min}}(t_{u,\text{max}} + t_{o,\text{max}} + t_{f,\text{max}})}. \]  

Availability parameters are characterized by means of mean down time \( MDT_{\text{max}} \), mean uptime \( MUT_{\text{min}} \), and application service availability \( A \)

\[ MDT_{\text{max}} = t_{u,\text{max}} + t_{o,\text{max}} + t_{f,\text{max}} + (1 - A_{\text{SIS}}) T_y, \]  

\[ MUT_{\text{min}} = T_y A_{\text{SIS}} - (t_{u,\text{max}} + t_{o,\text{max}} + t_{f,\text{max}}), \]  

\[ A = \frac{MUT_{\text{min}}}{MDT_{\text{max}} + MUT_{\text{min}}} = P_{\text{SIM},\text{max}} A_{\text{SIS}} = \frac{t_{u,\text{max}} + t_{o,\text{max}}}{T_y}. \]  

This application does not have an immediate impact on the safety of railway transport. Its usage cannot cause a decrease in operating performance of station and tracks, or delays in rail traffic. Some financial losses can originate from insufficient reliability, which is associated with major failure states. Therefore, the requirement for this application is SIL 0. The summary of dependability attributes are numerically expressed in Table 3.

| \( \lambda_{\text{max}} / MTBF_{\text{min}} \) | 4.17·10^{-2} h^{-1} / 24 h |
| \( \frac{K_{f_{\text{min}}}}{(1 - P_{\text{SIM},\text{max}})} \) | 4.291 / 10^{-4} |
| \( \frac{\xi_{f_{\text{max}}}}{HA_{\text{max}}} \) | 2.33 m / 5.7 m |
| \( MTTR_{\text{min}} / \mu_{\text{max}} \) | 1.68 h / 0.59 h^{-1} |
| \( A_{\text{SIS}} \) | 100 % / 95 % / 70 % |
| \( t_{f,\text{max}} \) | 0.9 h / 0.8 h / 0.6 h |
| \( MDT_{\text{max}} \) | 615 h / 1053 h / 3243 h |
| \( MUT_{\text{min}} \) | 8145 h / 7707 h / 5517 h |
| \( A \) | 93 % / 88 % / 63 % |
Evidently, Galileo SIS availability of 99.5% and especially SIS dangerous failure rate of $1.92 \times 10^{-3}$/h \(^{(7)}\) are sufficiently small values to fulfill dependability attributes of this non-safety related application.

### 3.4.2 Train location determination

Accuracy and HAL requirement have been set to 1 m and 2.5 m for the purpose of safe distinction between parallel tracks after switches on high traffic density lines. Other lines are less stringent for accuracy and HAL requirements as it is evident from Table 4. Availability requirements result from the safety and operational requirements for the entire transportation system. For example, if a system based on GNSS should replace ERTMS/ETCS odometry, then availability level of 99.99999% is required since mean downtime of odometry subsystem less than 3.15 s per year is required. With regard to safety considerations according to the CENELEC standards the system must fulfill SIL 4 level. Corresponding THR \(_{\text{system}}\) is $10^{-9}$/h, which represents a general estimate for signaling system upon EN 50129 \(^{(4)}\). On the basis of this value of tolerable hazard rate per hour the requirement for THR of whole TPL has been allocated between $10^{-10}$ to $10^{-11}$ per hour. Requirements are briefly summarized in Table 4.

Galileo SIS availability and hazard rate of $4.8 \times 10^{-6}$/h \(^{(7)}\) can not fulfill rigorous requirements for this safety critical application. Implementation of additional sensors and other techniques must be performed to achieve high availability and safety integrity of the GNSS based TPL.

![Table 4 Minimal application requirements](image-url)

4. **Performance Improvement of the Train Position Locator**

Integration of GNSS receiver together with additional sensors (INS) enables to improve availability of the TPL. In case of absence of SIS the absolute GNSS train position determination is substituted by relative positioning. The TPL accomplishes fusion and processing of INS data such as traveled distance measurements sensors (odometer, accelerometer, Doppler radar speedometer), and heading sensor (gyroscope). Odometer, accelerometer and radar form the odometry system which is used for traveled distance calculation and validation. Gyroscope is used for routing detection on switches. Practical
Tests have been experimentally realized. The influence of GNSS SIS unavailability has been mainly investigated. The TPL was composed of GPS Z-MAX dual frequency receiver, LTV14 axle opto-electronic odometer, Crossbow CXL01LF3 3-axis accelerometer, DRS05 24.1 GHz two-beam microwave Doppler radar sensor and KVH RA2100 fiber optic gyroscope. It is evident that INS errors significantly influence the error in train position determination, mainly on the track where SIS is unavailable. It is well known that the odometry error increases in dependence of the traveled distance, especially due to wheel slip/slide effects. This error can achieve as much as 5% of the traveled distance. High positional error can also originate from gyro drift. Accelerometer usage is limited due to the significant cumulative influence of the intrinsic drift, response to the gravitational acceleration and slight hysteresis characteristic. Doppler radar is unable for low speeds detection and data are affected by reflections from metal constructions.

Tests demonstrated that short-time SIS outages can be sufficiently substituted by the relative positioning. If the SIS is not temporarily available for the time duration exceeding tens of seconds, the potential sensor errors can easily introduce the positional error exceeding tens of meters. Positional accuracy can be improved by the relative positioning systematically confronted with the route map (map-matching technique).

However, safety relevant applications will require the highest performance of positioning service which cannot be guaranteed by the fusion of GNSS system with INS only. Especially in specific operational areas where the SIS is blocked the INS represents a crucial part of the TPL which cannot ensure providing of safe position determination. To improve the TPL performance for some local areas the alternate system of LET should be implemented. The LET is a complimentary to the GNSS system. It consists of ground-based satellite-like signals transmitters, differential reference and central processing stations, station responsible for local integrity monitoring function, and communication subsystem. Before practical implementation it was necessary to perform fundamental analysis of the LET usage under railway conditions. The intrinsic critical parameters have been investigated from viewpoint of terrain relief, the shape of rail yard, the area of coverage, near-far effect limitation, antenna radiation pattern, radio frequency interference in the receiver, transmitter geometry, the number of signal generators and their location, LET failures and noise (inaccuracy of transmitter clock, inaccuracy and stability of the synchronization, clock offset determination), time delay during the distribution of correction data, and the time to first fix.

NAVIndoor system has been chosen for the LET realization since it enables to configure all system parameters and receive raw data from the receiver. The system consists of four pseudolite signal generators GSG L1, two iTrax03 Fastrax receivers, suitable antennas and the local integrity monitor facility implemented within an appropriate SW. The entire LET system has been firstly installed in the laboratory conditions. Laboratory based experiments have been provided for verification of the system capabilities. Further, field tests have been realized by means of special track mobile robot on the industrial line near Pardubice station. These experiments have been focused on the configuration test of LET, configuration of radio network and stability of the synchronization in the external laboratory environment. Next, tests under the real railway conditions with daily operating 3 kV DC electric locomotive of 163 series were performed. The vehicle was equipped with Z-MAX receiver, INS, Fastrax iTrax03 receiver, GNSS and radio modem antennas on its roof. Z-MAX operating in RTK mode was used for accurate surveying of track axis with a centimeter level accuracy. Switch-point area near Rosice nad Labem station was chosen for the static LET installation with regard to the analysis of the LET and coverage of the radio network controlled from the laboratory.

Relatively large values of pseudorange noise have been found in measurements of each signal generators. Pseudorange accuracy reached 3.84 m (95 %, \(2 \sigma\)) for master generator.
In cases that pseudoranges are relative to the smoothed pseudorange of master generator, the pseudorange accuracies of other synchronized generators reached 3.17 m, 4.07 m and 8.66 m (95 %, 2 σ). If pseudoranges of other generators were relative to the unsmoothed pseudorange of master generator, then the accuracy is 5.24 m, 7.08 m and 9.57 m. The main reason for higher level of noise was worse stability of OCXO oscillator used in signal generators. The position of mobile receiver operating without corrections can be obtained from those measured pseudoranges in such limited area only if the initial position of the receiver is entered. However, the high value of pseudorange noise causes that over some time the task will not have any solution. Improved accuracy in laboratory conditions can be only achieved by using the principle of measuring of the carrier phase. This measurement method is not applicable in the short time interval under real railway conditions, where the infrastructure in the vicinity of lines (traction lines, lighting poles, pillars, etc.) results in frequent interruption of direct visibility between receiver antenna and signal generator. It was found that integrity monitor set a negative flag state of the system immediately since high level of measured pseudorange noise represents a significant failure to the integrity monitor when compared with other sensors.

The purchased specific LET system is insufficient for usage in railway safety relevant applications due to its poor unfiltered pseudoranges accuracy and low receiver measurement update frequency. Although theoretical solutions of the most of the LET imperfections are well known, these systems are mainly practically implemented and verified in laboratory conditions. In spite of these facts it can be assumed that further development of this new technology enables achievement of required system parameters for the possible usage in railway applications.

5. Conclusion

Before possible GNSS system usage in the field of railway non-safety and safety related applications, it is necessary to perform its certification. This paper deals with one step towards the certification process. Basic methodology for the specification of missing minimum GNSS requirements has been elaborated. In order to increase RAMS parameters of the GNSS TPL used for railway applications the design of TPL based on INS / LET and real tests have been realized. In the next step, it will be necessary to analyze the degree of fulfillment with proposed requirements. Development of validation and verification procedures based on statistical processing of measured data and probability description of GNSS quality measures should follow consequently. On the basis of these techniques it should be demonstrated that requirements for the intended use of the Galileo system in railway applications can be accomplished. The above mentioned facts, including the pilot verification of the selected certification procedure will be the subject of our future work.

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