Performance Evaluation of GNSS for Train Localization

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***Abstract*—Global Navigation Satellite Systems (GNSS) are applicable to deliver train locations in real time. This train localization function should comply with railway functional safety standards; thus, the GNSS performance needs to be evaluated in consistent with railway EN 50126 standard [Reliability, Availability, Maintainability, and Safety (RAMS)]. This paper demonstrates the performance of the GNSS receiver for train localization. First, the GNSS performance and railway RAMS properties are compared by definitions. Second, the GNSS receiver measurements are categorized into three states (i.e., up, degraded, and faulty states). The relations between the states are illustrated in a stochastic Petri net model. Finally, the performance properties are evaluated using real data collected on the railway track in High Tatra Mountains in Slovakia. The property evaluation is based on the definitions represented by the modeled states.**

***Index Terms*—Evaluation, Global Navigation Satellite Systems (GNSS), quality of service, railway Reliability, Availability, Maintainability, and Safety (RAMS), train localization.**

I. INTRODUCTION

GLOBAL Navigation Satellite Systems (GNSS) have been widely used in surface transportation, for example, vehicle navigation, railway fleet management, and train station passenger information [1]. Many researchers are expanding GNSS to safety-related applications in surface transportation [2], for example, railway train control systems. Determining train locations as accurately as possible is the basic requirement for it; GNSS receiver is a practical instance for performing train localization function. In addition, odometer, Doppler radar, and other sensors can be used together to deliver more accurate and also safe train locations. These sensors are installed on the train instead of along the track, thus offering the possibility to locate the train much more accurately, decreasing the maintenance work along the track, and improving safety. This paper aims at evaluating GNSS receiver for train localization performance. Furthermore, a universal evaluation methodology can be applied on other train localization sensors. The quantified performance values can be compared and integrated to form a safe train localization unit. All in all, the GNSS performance needs to be evaluated first.

GNSS localization service has set requirements into four properties: accuracy, continuity, availability, and integrity [3]. When the GNSS receiver, together with other localization sensors, fullfils the requirements, GNSS will be a promising localization source for safety-related applications in various transportation systems [1]. Railway applications call for the demonstration of Reliability, Availability, Maintainability, and Safety (RAMS) properties as stated in EN 50126 [4]. The two kinds of performance properties need to be migrated to form suitable properties for GNSS in railway applications.

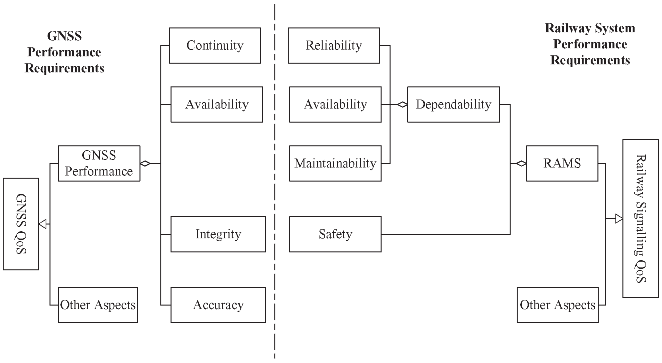

Fig. 1. GNSS and railway performance requirements comparison.

Having a safety case involved evaluation methodology that is consistent with the standards will lead GNSS receiver to be approved by railway authorities and assessment bodies [5], [6]. Researchers have been doing GNSS for railway safety-related applications using EGNOS data or by simulation methods. Filip *et al.* analyzed EGNOS performance and allocated the risks using fault tree, and completed RAMS evaluation methods were not stated. However, the work sets up a first example for evaluating GNSS performances for railway applications [7], [8]. Beugin and Marais evaluated GNSS performances in railway by simulation methods, availability and reliability aspects of different environments are analyzed, and safety is not an issue [9].

II. PERFORMANCE PROPERTIES MIGRATION

Both GNSS and RAMS performance properties are shown in parallell in Fig. 1. Among the properties, only availability is exactly the same term; the remaining six properties need to be analyzed, formally compared, and then migrated.

Accuracy property is the base for GNSS receiver location performance. It can be represented by two characteristics, i.e., trueness and precision. Trueness tells the deviation between the measured value and the true value; the true value is represented by a value measured by a multisensor reference system (see Section IV). The mean value of the deviations is denoted by μ. Precision is normally calculated through dispersion of measurement samples, called standard deviation, denoted as σ. Normally, $\mu \pm 2\sigma$ (95% if normally distributed) is used to express the accuracy level of the measurement system.

Continuity and **reliability** properties are related to their definitions. Continuity is required by GNSS performance as *the ability of the total system to perform its function without interruption during the intended operation* [3]. Reliability is required by railway RAMS and the definition is inherited from IEC 60050 as *the ability of an item to perform a required function under given conditions for a given time interval* [10]. The terminological difference exists between "*without interruption*" and "*required function*". GNSS for train localization requires not only continuous locations but also the required accuracy level to meet the "required function". The characteristic of reliability can be denoted as $R(T)$

$$R(T)=P(\text{required function})|_{\text{time interval \& given condition}}.$$

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Availability property requires to be evaluated from both performance requirements. The definition of availability is stated according to IEC 60050 as *the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided* [10]. The given instant of time is defined as T; the characteristic of availability is denoted as $A(T)$

$$A(T) = \left.\frac{\text{time(required function)}}{T\text{(time interval)}}\right|_{\text{given condition}}.$$

Maintainability property is not issued by GNSS receiver location performance since the GNSS signal in space (SIS) is not maintained by end users [11]. Therefore, in this paper, the maintenance of GNSS SIS is not considered.

End-user equipments call for integrity since maintenance is not included. **Integrity** is defined as *the trueness of the information supplied by a localization system* [3]; it means that integrity is related to measurement deviation. Safety property of a railway application is defined as *freedom from unacceptable harm* [4]; this calls for the quantified value of harm. **Safety integrity** is defined as a quantifiable property as *the ability to achieve required safety functions under all the stated conditions within a stated operational environment and within a stated period of time* [12]. The characteristic is normally allocated by hazard rate (HR) and is denoted as HR

$$HR = \left.\frac{\text{number of dangerous failures}}{T\text{(time interval)}}\right|_{\text{given condition}}.$$

The four properties concerning GNSS for train localization performance are formalized into characteristic equations by their definitions. The applicable four properties for evaluation are accuracy, reliability, availability, and safety integrity. The "required function" and "given condition" are both stated for every equation; "required function" is judged by GNSS location accuracy level, and "given condition" is related to the railway operation environment that is the railway track type (normally, three types, i.e., low-, medium-, high-density lines).

III. PERFORMANCE PROPERTIES MODELING

The migration process of the performance properties gives a clear direction of the characteristics to be evaluated, but the equations are still in context form thus not directly quantifiable. This modeling section brings measurement values into a formalized model for structuralized performance evaluation.

A. Assumptions

GNSS receiver is assumed, as always, powered on, and GNSS receiver hardware is running without systematic failure. Therefore, the failures of the train locations are caused by SIS, directly reflected on the deviations.

In order to measure deviations of GNSS receiver locations, corresponding reference locations are needed. Reference locations are assumed as much more accurate than GNSS receiver locations. The performance of the reference system will not be stated in this paper; more information can be found in the dissertation by Poliak [13] and a paper by Wegener and Schnieder [14].

B. GNSS Receiver and Reference Locations

The GNSS receiver calculates location using received SIS. The reference system integrates information from several location sensors and matches with a digital track map, thus generating reference location.

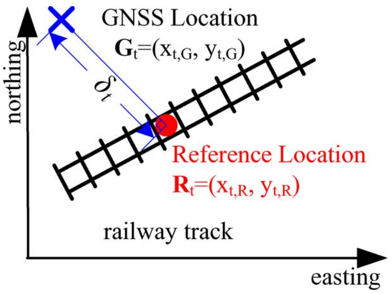

Fig. 2. Example of GNSS and reference location measurements.

Assume the GNSS receiver location to be given under a Gauß–Krüger coordinate and each location at time t is recorded as

$$\mathbf{G}_t = \text{GNSS}(x_{t,G}, y_{t,G}).$$

In that, x means Gauß–Krüger Easting, and y means Gauß–Krüger Northing. For each GNSS receiver location, a corresponding reference location is recorded at the same time t as

$$\mathbf{R}_t = \text{Reference}(x_{t,R}, y_{t,R}).$$

The norm of the vector $\overrightarrow{\mathbf{G_t R_t}}$ is called deviation, denoted as δ_t, calculated using the following equation:

$$\delta_t = |\overrightarrow{\mathbf{G}_t\mathbf{R}_t}| = \sqrt{(x_{t,G} - x_{t,R})^2 + (y_{t,G} - y_{t,R})^2}. \tag{1}$$

As shown in Fig. 2, GNSS receiver location is the cross sign called $\mathbf{G}_t$, reference location is the dot sign called $\mathbf{R}_t$, and both are in a Gauß–Krüger coordinate. Reference locations are always on the track using map-matching algorithms.

C. Modeling of δ_t Into States

According to the migration section, "required function" is judged by accuracy level, an acceptable accuracy level of the deviation δ_t can be abstracted as d_1, and the quantified harm of the localization function can be derived from another accuracy level as d_2. Both accuracy levels separate GNSS receiver locations into three states.

- Up State: GNSS receiver is powered up, and GNSS receiver locations are accurate. The GNSS receiver is performing the required function; the deviation δ_t: $\delta_t \leqslant d_1$.
- Degraded State: GNSS receiver is powered up, accuracy level is degraded but still can be used for train localization, and the deviation δ_t: $d_1 < \delta_t \leqslant d_2$.
- Faulty State: GNSS receiver is powered up; GNSS receiver locations are unreliable and unavailable due to GNSS signal loss or bad satellite geometry, etc.; and the deviation δ_t: $\delta_t > d_2$ or $\nexists\, \delta_t$.

Faulty state can be specified into two categories, i.e., dangerous faulty state $\delta_t > d_2$ and safe faulty state $\nexists\, \delta_t$. The states are clearly shown in Fig. 3(a) with deviation on the y-axis. With a statistical study of the deviations, the distribution of the deviations can be fitted. The deviations can be Log-normal distributed, as shown in Fig. 3(b).

D. Relation Between Performance Properties and States

A model based on stochastic Petri net according to standard IEC 62551 [15] is shown in Fig. 3(c) in adherence with the defined states. The stochastic Petri net is a means of description for modeling and analyzing discrete event systems [16]. GNSS location outputs can be regarded as a discrete event.

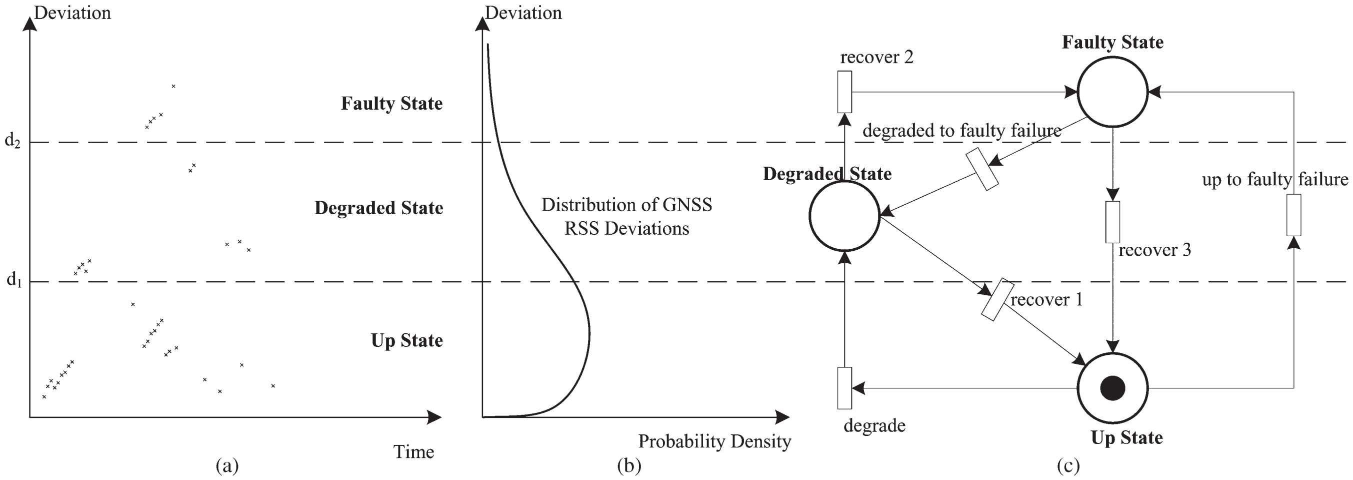

Fig. 3. Relation between defined states of GNSS receiver measurements.

Accuracy characteristics are evaluated by trueness μ and precision σ

$$\mu = \sum_{t=1}^{N} \frac{\delta_t}{N}$$
$$\sigma = \sqrt{\frac{\sum\limits_{t=1}^{N} (\delta_t - \mu)^2}{(N-1)}} \tag{2}$$

in that $\forall\, \delta_t, HDOP_t \leqslant 6$, and $N = \sum X(HDOP_t \leqslant 6)$.

HDOP means the horizontal dilution of precision; each GNSS location contains HDOP information, and it is one indicator of accuracy measurement. HDOP $\leqslant 6$ is regarded as the threshold for satellite geometry availability [11].

X is a Boolean-valued function, which is to say that X is a function of the type $f : X \to \mathbf{B}$, where X is an arbitrary set and $\mathbf{B}$ is a Boolean domain. A Boolean domain $\mathbf{B}$ is a generic two-element set formed by $\mathbf{B} = \{0, 1\}$, whose elements are interpreted as logical values: $0 =$ false and $1 =$ true [17].

Reliability property is defined as performing the required function. The required function is reliable if $\delta_t \leqslant d_2$ since the localization unit gives an alarm limit when the deviation is bigger than d_2. According to the relation between the performance terms stated in EN 50126, reliability of a repairable system can be represented by mean time to failure (*MTTF*); the individual time to failure (TTF) is estimated as

$$TTF_i = t_k - t_j + 1/f \quad (k > j, j \geqslant 2). \tag{3}$$

In that, $\forall\, \delta_t, t \in (t_j, t_k), \delta_t \leqslant d_2$, and $HDOP_t \leqslant 6$. f is the sampling rate of the GNSS receiver. In addition, the following two rules are provided as constraints:

$$\begin{cases} \delta_{t(j-1)} > d_2, & \text{or } \nexists\, \delta_{t(j-1)} \\ \delta_{t(k+1)} > d_2, & \text{or } \nexists\, \delta_{t(k+1)}. \end{cases}$$

Therefore, the total slots of TTF_i in the selected test runs are recorded as n, then *MTTF* is

$$MTTF = \frac{\text{time staying in up and degraded states}}{\text{entering faulty state numbers}} = \sum_{i=1}^{n} \frac{TTF_i}{n}. \tag{4}$$

Availability is represented as the percentage of all TTF_i and T; availability can be calculated as

$$A = \frac{\text{time staying in up and degraded states}}{\text{total states time}} = \sum_{i=1}^{n} \frac{TTF_i}{T}. \tag{5}$$

Safety integrity is reflected by faulty state in the Petri net model, particularly the dangerous faulty state. It is defined as the dangerous failure number in the test runs. The dangerous failures are counted when $(\delta_t > d_2) \cap (\delta_{t-1} \leqslant d_2)$; hence, the HR in the test runs is estimated as

$$HR = \frac{\text{entering dangerous faulty states numbers}}{\text{total states time}} = \sum_{i=1}^{m} \frac{X\left((\delta_t > d_2) \cap (\delta_{t-1} \leqslant d_2)\right)}{T}. \tag{6}$$

In that, m is the total number of dangerous failures.

IV. MEASUREMENT SYSTEM DESCRIPTION

An evaluation platform is built to understand real GNSS performance. In 2008 and 2009, the DemoOrt project was implemented in several test tracks [18]. The basic idea of DemoOrt is the setup of a vehicle side onboard platform, utilizing and integrating innovative technologies, with focus lying on satellite-based localization. A sensor data fusion on different sources of localization information is implemented. This also gives diversity and redundancy of the localization information, increasing safety, accuracy, and availability of the whole system.

A. DemoOrt Platform

The DemoOrt platform consists of three parts. The first part is the GNSS receiver itself; the second part is the reference track integrated by RFID sensors, RFID antennas, a Doppler radar, and a digital track map; and the third part is data process control [18]. The composition of the DemoOrt platform is shown in Fig. 4.

The data process control is called *qDemoOrt*, which processes all the information gathered from the sensors except GNSS receiver. A digital track map is used as the reference for sensor fusion, thus relating location data directly on the track. The fusion result of all the

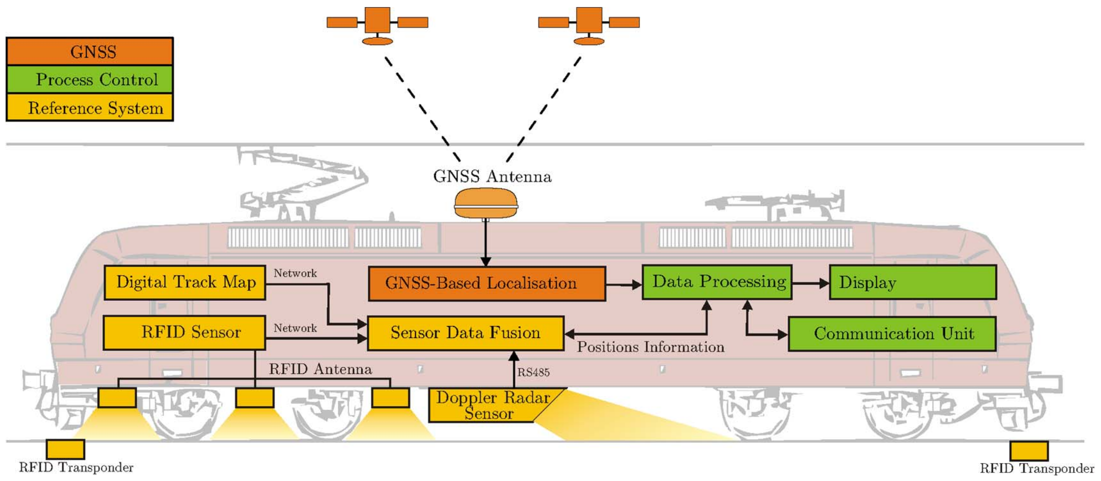

Fig. 4. DemoOrt platform structure.

TABLE I
STATES AND RELATED ACCURACY REQUIREMENTS

States	Requirements
Up State	$\delta_t \leqslant 10\ m$, and $HDOP_t \leqslant 6$
Degraded State	$10\ m < \delta_t \leqslant 20\ m$, and $HDOP_t \leqslant 6$
Faulty State	$20\ m < \delta_t$, or $HDOP_t > 6$, or $\nexists\ \delta_t$

sensors is synchronized with GNSS receiver location at the same time. The data output frequency of *qDemoOrt* is the same as GNSS receiver, which is 2 Hz.

B. Measurement Location

The GNSS and reference location data were collected along the High Tatra Mountain railway line from May 2008 to February 2009 in different climate conditions [13], [18], [19]. The reference locations are processed by *qDemoOrt* after data collection; the deviation between GNSS receiver and reference locations are calculated for performance evaluation based on the states in the Petri net model described in Fig. 3(c).

The High Tatra Mountain railway line is called *Tatranská elektrická železnica* in Slovakia. It is an electrified single-track narrow-gauge railway in the Slovakia side of the High Tatra Mountains. The whole line is 29.1 km long from *Poprad–Tatry* to *Starý Smokovec* until *Štrbské Pleso*. There are open areas and forests but no tunnels or railway bridges. Double tracks only exist on four station; thus, the line is a medium-density line as the given condition; the thresholds for the required train localization function are set as up state threshold as 10 m and alarm limit (degraded state higher threshold) as 20 m.

V. PERFORMANCE EVALUATION RESULTS

This section applies the states and the equations to calculate the values for each characteristic. The requirements for each state of medium-density line can be defined in Table I.

A. Accuracy Evaluation

Six test runs are analyzed for accuracy evaluation; four test runs are on May 16, 2008; and two test runs are on February 3, 2009. The two test days are in different seasons. The GNSS location deviations are fitted into Rayleigh distribution and Log-normal distribution shown in Fig. 5. The Log-normal distribution has much higher likelihood; thus, Log-normal distribution is chosen.

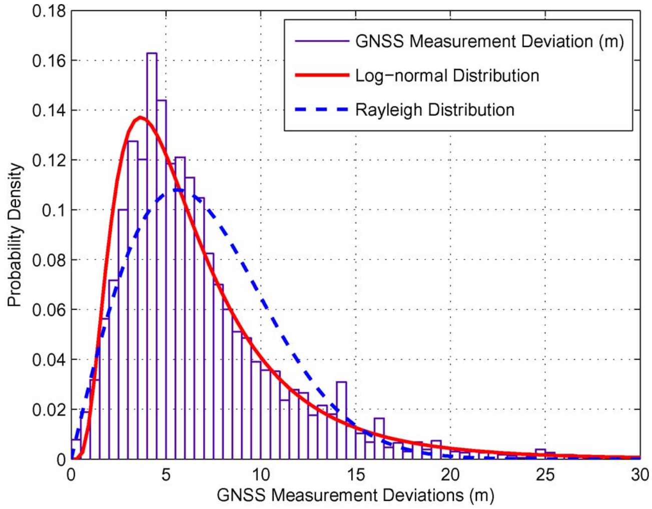

Fig. 5. δ_t distribution fitting of one test run.

TABLE II
ACCURACY OF EACH TEST RUN

Test Runs	1	2	3	4	5	6
μ (m)	6.02	6.31	5.57	6.84	4.02	8.69
σ (m)	29.71	14.13	27.51	24.11	10.07	52.73
δ_t 95% (m)	16.48	13.81	14.74	14.98	10.67	12.31

The other five test runs are also evaluated; μ, σ, and δ_t 95% threshold for each test run are listed in Table II. Moreover, 95% of the measurements can be regarded as 13.83 m based on the six test runs.

B. Reliability Evaluation

Based on the listed categorization of three states, reliability evaluation is considering both up and degraded states; the deviation requirements are defined in Table I. Faulty state is excluded since the measurement deviation has exceeded the alarm limit. The first test run used in accuracy evaluation result is also categorized into the three states according to d_1 and d_2 thresholds shown in Fig. 6.

MTTF of the test runs is shown in Table III. The mean MTTF based on the six test runs is

$$MTTF = 184.99 \text{ s.}$$

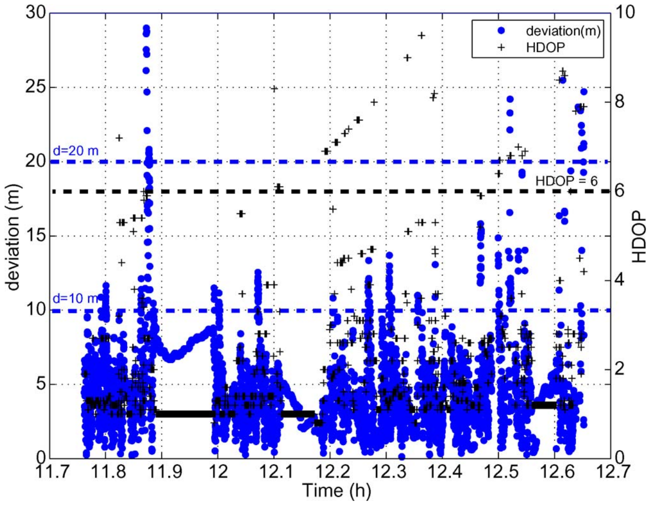

Fig. 6. Categorized three states and related HDOP.

TABLE III
RELIABILITY AND AVAILABILITY OF THE TEST RUNS

Test Runs	1	2	3	4	5	6
MTTF (s)	161.29	312.11	104.81	75.24	393.75	62.74
Availability	85.50%	80.30%	81.29%	72.31%	92.44 %	81.69%

Basically, MTTF can derive the failure rate (including both safe and dangerous failure rates) for train localization, which means that the GNSS could fail 19.45 times in 1 h. This is a very high failure rate for safety-related functions.

C. Availability Evaluation

Availability reflects the total operational percentage time. The operational time is related to both up and degraded states, as described in Table I. One detail still needs to be mentioned; $\nexists\, \delta_t$ is also included in the availability evaluation as part of the denominator. For instance, on May 16, 2008, test run 1 has dangerous failure time of 111.50 s, safe failure time of 353.50 s, and both up and degraded state times of 2742.00 s. Therefore, the availability of test run 1 is calculated as

$$A(T) = \frac{2742.00}{2742.00 + 111.50 + 353.50} = 85.50\%.$$

The other test runs in the accuracy evaluation part are also calculated, as shown in Table III. The results show that none of the test runs reaches the availability of over 95%. The mean availability percentage based on the six test runs is

$$\text{Availability Percentage} = 82.26\%.$$

D. Safety Integrity Evaluation

Considering safety integrity, the dangerous failures should be investigated. The given conditions of the railway track have different environmental scenarios as open area, forest, etc. Because of the length of this paper, only forest as a critical scenario affecting GNSS signal reception is analyzed in detail, but open area hazard rate (HR) is also represented for comparison.

In High Tatra Mountains, there are a few tracks surrounded or even covered by trees, as shown in Fig. 7. This level crossing is almost covered by trees; only the intersection with the road has a little sky view.

Fig. 7. Forest snapshot between *Pod Lesom* and *Nova Lesna*.

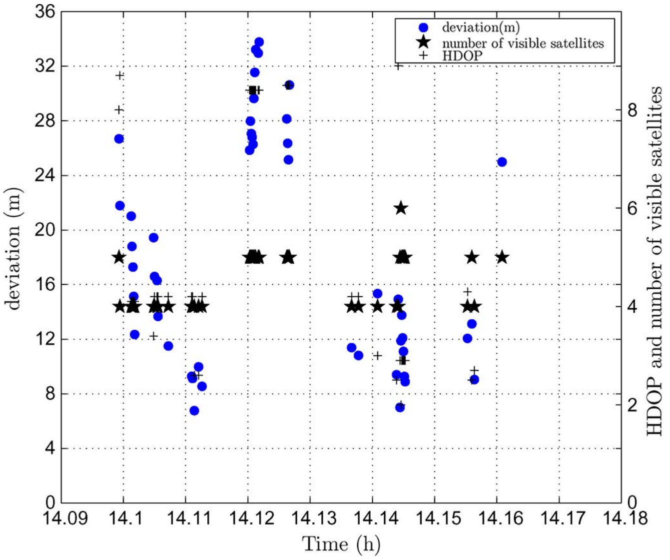

Fig. 8. Forest deviations, number of visible satellites, and HDOP (May 18, 2008).

The length of the track clip to be analyzed is 1.12 km. There are six test runs through this scenario on May 16, and the average time for traveling through this clip is 99 s. The deviations, number of visible satellites, and HDOP for one of the test runs are shown in Fig. 8. As shown in the figure, deviations can go greater than 30 m, HDOPs can go greater than 6, and there are also signal losses.

Using the required alarm limit as $d_2 = 20$ m, the HR for this scenario is estimated as

$$HR(\text{forest}) = 5.25 \times 10^{-2}/\text{h}.$$

This rate is really high. After an evaluation of all the test runs in May 2008, there are always signal loss problems in this scenario; hence, the HDOPs can go up to 10 accordingly. In addition, in every test run, there would be possibilities of huge deviation, thus causing dangerous failures. In order to use GNSS for train localization in the forest, other localization sensors should be installed to improve the performance in this critical scenario. Meanwhile, for the open area environmental scenario, the HR is only

$$HR(\text{open area}) = 5.22 \times 10^{-7}/\text{h}.$$

This is allocated to safety integrity level (SIL) 2. For the given condition of the medium-density line, SIL 2 is sufficient for the safety-related train localization function. However, for the whole track, GNSS should be supplemented with odometer or Doppler radar to fullfil the function all along track.

VI. CONCLUSION

GNSS is regarded as a very important instance of future train localization to get rid of trackside equipments and implementing next-generation European Train Control System Level 3. Hence, GNSS will play a crucial role in safety-related applications, including train localization. This paper has shown a method to evaluate GNSS performances according to standards, particularly RAMS. A stochastic Petri net model is established to illustrate the GNSS receiver location states, i.e., up, degraded, and faulty states. The states are then related to the migrated four properties providing the bridge for quantitative evaluation of the characteristics for each property.

The results indicate that GNSS is suitable for railway localization, but the performance of GNSS in different railway environmental scenarios varies a lot. The overall reliability and availability are evaluated as the basis for safety analysis. In open area, GNSS is shown as a good instance for stand-alone localization and fits the railway RAMS requirements quite well. However, in the forest, the GNSS performance cannot meet the requirements; other onboard localization sensors, together with GNSS receiver to provide sensor fusion structure, are required. Therefore, for the approval of the railway authorities, a localization unit composed by GNSS receiver and Doppler radar sensor together will be enough to meet the requirements. The performance of the localization unit can be also evaluated using the methodologies proposed in this paper.

As a result of the investigation, the methodology for performance evaluation according to standards and the setup of a reference system together can promote a standardized test scenario and procedure for GNSS quantitative assessments in the future.

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